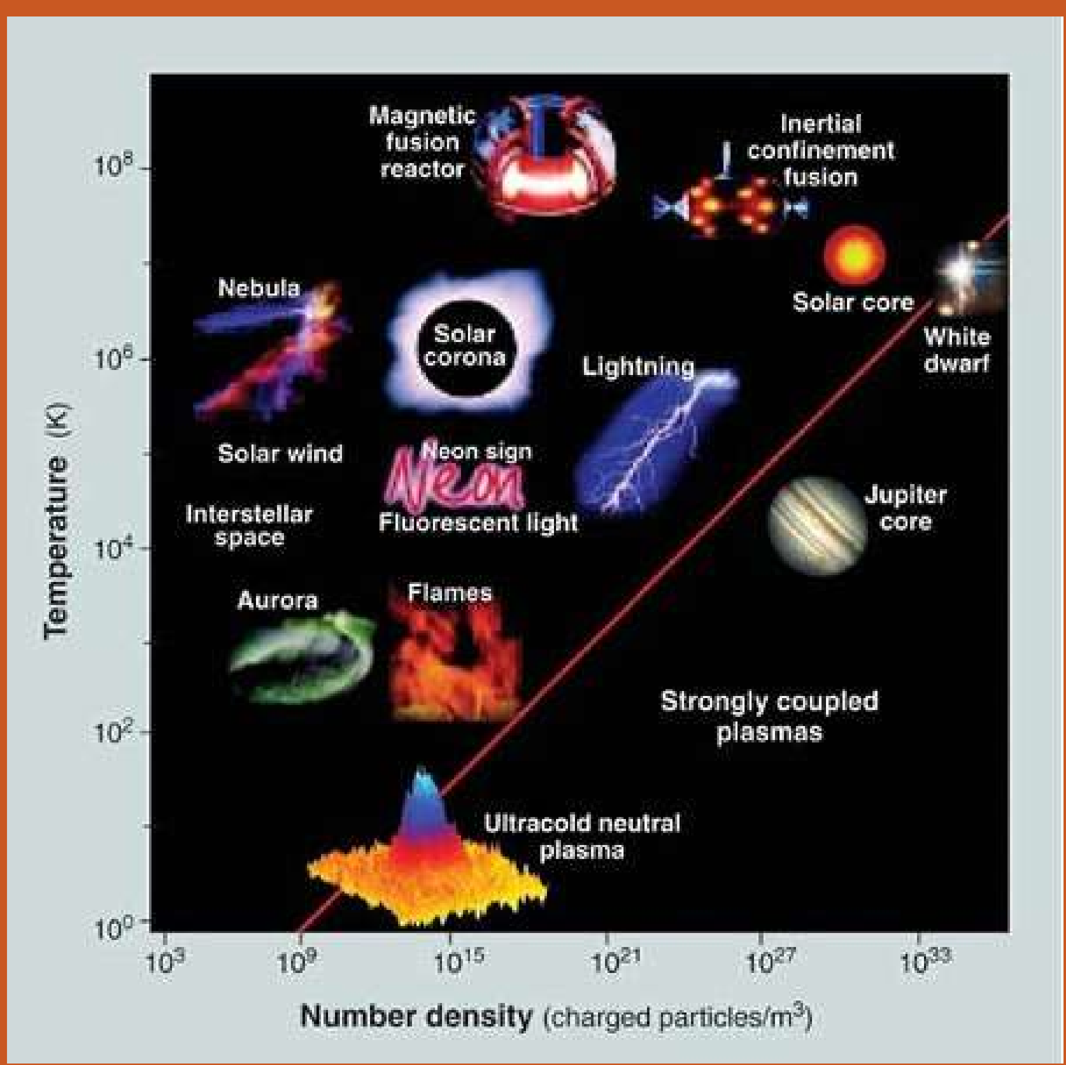
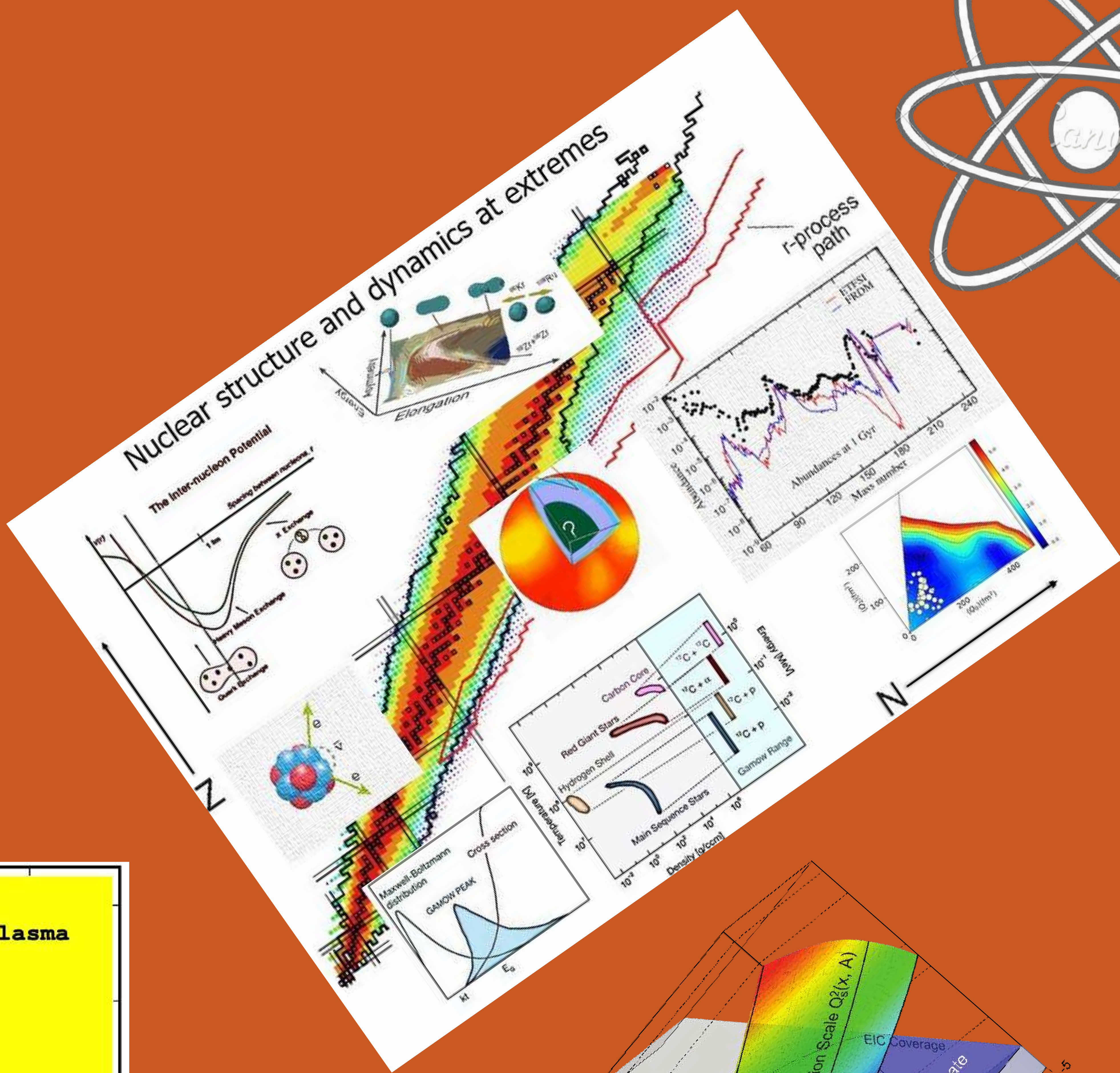
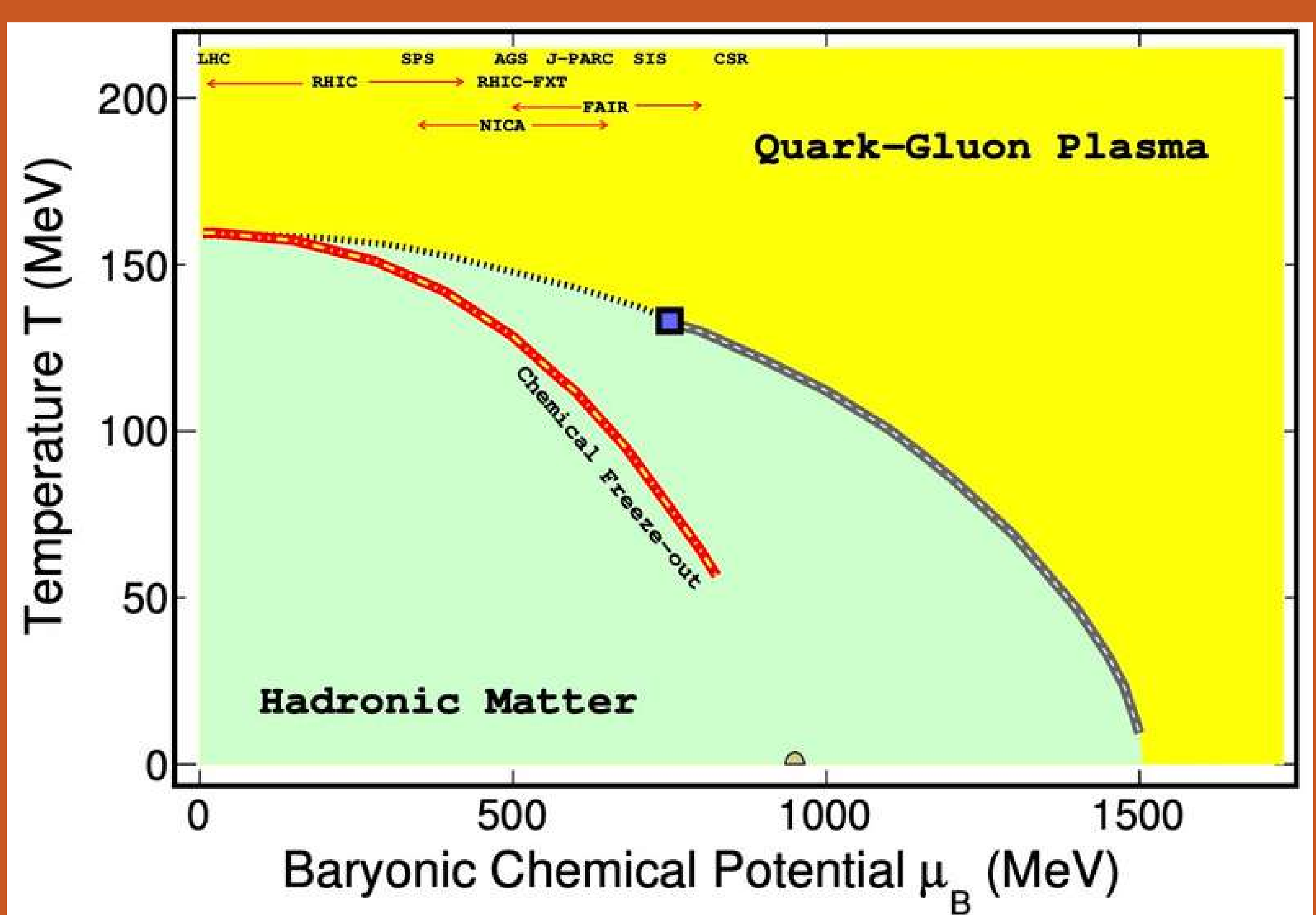
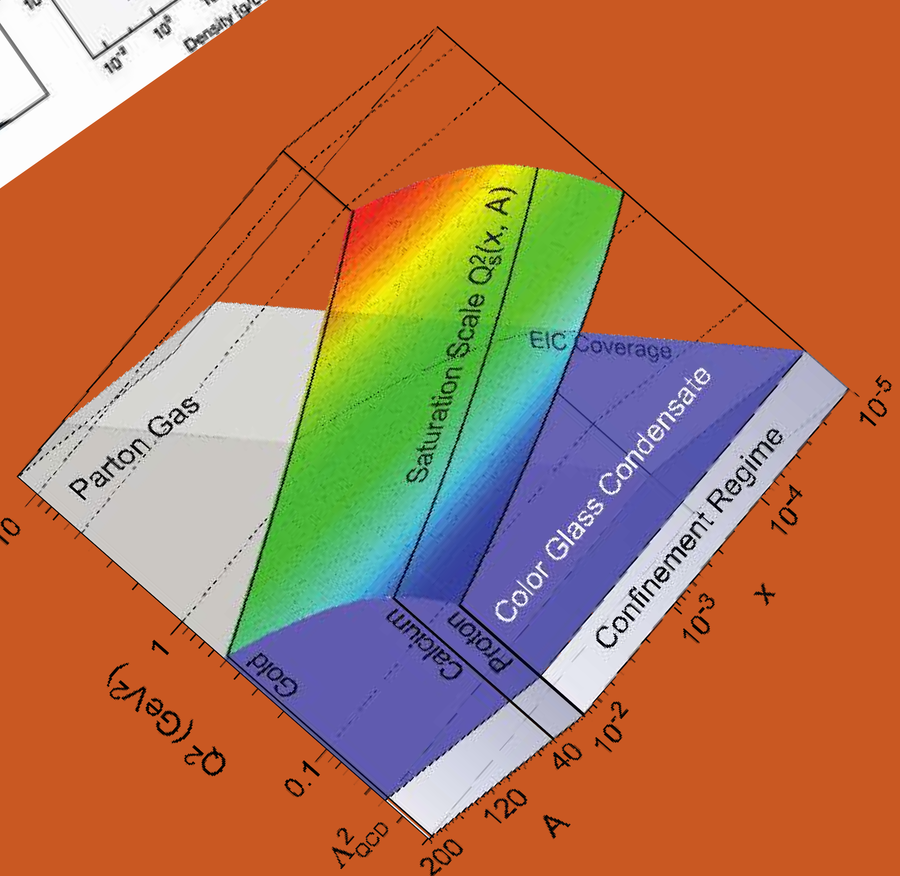
MEGA SCIENCE VISION - 2035 NUCLEAR PHYSICS

A ROADMAP PREPARED BY THE INDIAN NUCLEAR PHYSICS COMMUNITY









MEGA SCIENCE VISION – 2035
NUCLEAR PHYSICS

A roadmap prepared by
the Indian Nuclear Physics Community
with TIFR, Mumbai
as the Nodal Scientific Institution

and

submitted to
The Office of the Principal Scientific Adviser to the
Government of India

अजय के. सूद
भारत सरकार के प्रमुख वैज्ञानिक सलाहकार
Ajay K. Sood
Principal Scientific Adviser to the Govt. of India

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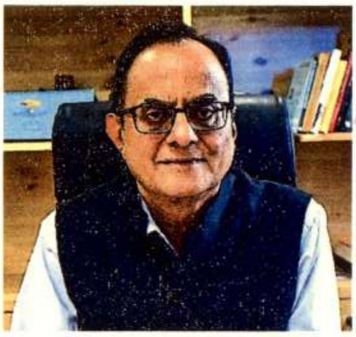

MESSAGE

I am happy to receive the Mega Science Vision-2035 Report in the area of Nuclear Physics that has been prepared by the entire Indian nuclear physics community. May I thank the Tata Institute of Fundamental Research, Mumbai, for having agreed to be the nodal institution for carrying out this exercise.

Given the scientifically and technologically complex as well as resource-intensive nature of Mega Science Projects (MSPs), all scientifically-mature nations in the world undertake widespread and vigorous national consultations among the concerned scientific communities before choosing to undertake such major national or international projects. In India too, such consultative exercises have been periodically undertaken over the past three decades, and these have come to be known as "Vision Exercises" over time. I am happy that the latest such exercise, the Mega Science Vision (MSV)-2035 Exercise, has been facilitated by the Office of PSA to the Government of India. The Report before us is the result of this Exercise in the area of Nuclear Physics; a field where MSPs have been required for carrying out scientific investigations for a long time.

This might also be the first time that this national "Vision Exercise" has come out with such a comprehensive report. The credit must go to the members of the Drafting and Working Groups, and the entire Indian nuclear physics community, who have devoted considerable time and effort in putting this all together. And, also to the group of eminent national and international experts for sparing their precious time for carefully reading the entire document and offering their valuable suggestions before the document was finalized.

I am sure, this Report will serve as an extremely useful guide for the concerned funding agencies and any other organization concerned with promotion of R&D in Nuclear Physics in the country. I am also confident that this Report will be read with great interest by the international nuclear physics community as well.

I wish the Indian nuclear physics community all the best for organizing themselves and taking the next required steps to turn the vision outlined in this Report into a reality.

(Ajay K. Sood)

Dated: 14th September, 2023

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डॉ. (श्रीमती) परविन्दर मैनी
वैज्ञानिक सचिव
Dr. (Mrs) Parvinder Maini
Scientific Secretary

सत्यमेव जयते

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FOREWORD

I am extremely happy that the Mega Science Vision (MSV)-2035-Nuclear Physics Report prepared by the Indian nuclear physics community, which has been facilitated by the Office of the Principal Scientific Adviser to the Government of India (O/o PSA to GoI) as part of the MSV-2035 Exercise, is now ready. Nuclear Physics was one of the first disciplines that encountered the need for Mega Science Projects (MSPs) globally. Naturally, Nuclear Physics figures prominently among the disciplines that are being considered under the MSV-2035 Exercise.

This comprehensive document surveys the emerging scientific horizons of nuclear physics, carefully measures the capabilities of the Indian nuclear physics community, and then puts forward a plan for undertaking MSPs in Nuclear Physics in the time frame of 2020-35. It also lists the steps necessary to bolster the larger national R&D eco-system in Nuclear Physics, without which either undertaking the MSPs would be difficult, or without which the returns from such major scientific engagements would not be optimal.

The Report also prioritises its plans for undertaking mega science activities in two different growth scenarios, viz. Modest Growth Scenario and Aspirational Growth Scenario. Arriving at a consensus regarding this required considerable community-wide effort. Attempt has also been made to roughly estimate the resource requirements. A fairly exhaustive list of industries has also been provided, which have participated in, and benefited from, such projects technologically. An attempt has also been made to present the publicly-available information about the monetary returns that have accrued to the Indian industry as a result of their participation in such projects, beyond the project-specific commitments. These special features make this Report especially valuable for researchers, funding agencies, mega science planners and policy makers.

The Drafting and Working Groups in Nuclear Physics, set up by the O/o PSA to GoI, have made enormous efforts in putting the Report together and taking it through an elaborate national and international consultative process. The Directors (Prof. Sandip Trivedi, Prof. S. Ramakrishnan and Prof. Jayaram Chengalur) and Prof. Amol Dighe of TIFR, who closely guided the evolution of this Report need to be profusely thanked for their immense contributions towards this national exercise.

Dr. Praveer Asthana, PSA Fellow, and Dr. Arun Bhardwaj, Scientist-F, from the O/o PSA, anchored this activity and helped in putting this exercise in its wider national and historical perspective. The IT Team in the O/o PSA extended valuable help in electronically facilitating the national consultation on the document. These colleagues deserve our heartfelt thanks.

I am confident that this MSV-2035-Nuclear Physics Report will serve as a valuable guide for all researchers as well as funding agencies while focusing their efforts towards realizing the goals laid out in the Report.

PMaini

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ABOUT THE MEGA SCIENCE VISION-2035 EXERCISE

Mega Science Projects (MSPs) are scientifically and technologically complex projects, requiring collaboration among scientists, engineers, technicians, project managers, funding organizations, industry, etc. on a large scale – occasionally from institutions and organizations in different nations across the world. MSPs, quite often, are also large in physical size and require large monetary, capital, human and intellectual resources. MSPs are also very long-term engagements – typically taking ten years for planning, another ten years for construction and, finally, remaining in operation anywhere from 20-50 years. It follows as a corollary that, at any given time, only a few such projects can be taken up nationally, or even globally.[1]

It is natural that the decision regarding which projects to launch nationally, or which projects to participate in internationally, is always taken through wide national consultations among the concerned scientific communities. This is the way it is done the world over. And, this is the way it has been done in India, at least over the past three decades. Such structured and periodic national consultations in India have been known by several names in the past. From some point of time, they have come to be known as "Vision Exercises". Since the disciplines of nuclear physics, high energy physics and accelerator science and technology and applications were the first to experience the need for MSPs, the Vision Exercises in India in the past were facilitated by the Department of Atomic Energy (DAE) and the Department of Science and Technology (DST). In the case of Astronomy & Astrophysics, the Astronomical Society of India has been periodically organizing such exercises.

In the Indian context, by 2020, a number of MSPs that had been identified in the earlier Vision Exercises, had moved further towards funding and implementation. It was, therefore, felt that a time had come to carry out the next Mega Science Vision (MSV) Exercise. It was also realized that the country had travelled a long-way from the days of India-CERN Collaboration, which could aptly be called the turning point for India's engagement with MSPs. There were a number of national as well as international projects which India had nationally launched, or in which India was participating internationally. The concerned scientific communities in India had also grown more confident and ambitious about getting involved in more such projects. Also, large collaborations had become necessary in a number of other science disciplines too. It was, therefore, decided to make the MSV Exercise more structured, inclusive and comprehensive.

In consultation with DAE and DST, which had been facilitating such exercises earlier in a few disciplines, it was decided that it would be better if the Office of the Principal Scientific Adviser to the Government of India (O/o PSA to GoI) facilitated the Exercise this time – given its pre-eminent S&T policy-making and coordination role in the GoI. The centre of activities thus got shifted to the O/o PSA to GoI. The O/o PSA to GoI decided that the Exercise this time would be carried out not only in Nuclear Physics, High Energy Physics, Astronomy & Astrophysics and Accelerator Science & Technology and Applications, but also in two additional areas, viz. Climate Research and Ecology & Environmental Science. Both these areas also require large-scale experimentation, data-gathering and analyses, and in many ways have been involved in MSPs without calling it by that name or realizing the same. The outcome of the MSV Exercise was expected to be comprehensive Roadmap Reports, one in each of the six areas. Given the typical time frame of MSPs, 2020-35 was decided as the period of focus for this MSV Exercise. Hence was born the Mega Science Vision-2035 (MSV-2035) Exercise in the six areas mentioned above.

For carrying out the MSV-2035 Exercise in Nuclear Physics, the O/o PSA to GoI requested the Tata Institute of Fundamental Research (TIFR), Mumbai to act as the Nodal Institution, to which they readily agreed. TIFR also nominated Prof. Amol Dighe as the Nodal Scientist. In consultation with TIFR, a Working Group (WG) was constituted under the chairmanship of

Director, TIFR, and with Prof. Amol Dighe as the Member-Secretary. A smaller sub-group of the WG acted as the Drafting Group (DG). The O/o PSA to GoI also laid down the goals of the Exercise and the methodology for national as well as international consultations during the Exercise.

The DG made exemplary effort in putting together several drafts of the document by reaching a large number of leading nuclear physicists in the country. They met almost every week over a protracted period of a year and a half. The WG also met several times to look at the evolving draft and offered valuable suggestions. A discussion was also organized among all the six WGs to exchange ideas about several issues that were common to all the six disciplines – for example, management structures for MSPs, aspects of fund flow, manpower development, outreach efforts, etc. Finally, a draft of the MSV-2035 Nuclear Physics Report got evolved which was approved by the WG for wider national consultations. The Draft Report was put up as a separate webpage on the PSA Office Website along with an electronic Comments Form. The link of the webpage was sent by e-mail to about 4000 scientists working in nuclear physics and other proximate areas in the country. About 60 comments were received and the draft was further modified in view of those comments. In the final leg of the consultative process, a group of about 20 eminent national and international nuclear physicists was set up by the Chairman of the WG, the Draft Report was sent to them in advance and finally discussed with them in a virtual meeting. The draft was once again revised based on the comments made by them during the meeting. The draft so developed was presented before the PSA to GoI, prior to its submission, and his comments and suggestions were also incorporated to the maximum possible extent. After all these steps, this final MSV-2035-Nuclear Physics Report has emerged.

This MSV-2035-Nuclear Physics Report is a "Roadmap" prepared by the national nuclear physics community outlining their hopes and aspirations for mega science activities till 2035, as best as they can foresee today. Needless to say, if there are some momentous changes in the field in this period, it might change some of the projections contained in this Report. And, a similar Exercise will again take place after another 5-6 years where this Report will get updated.

It must be emphasized that this is a 'nuclear physics community document', the preparation of which has been facilitated by the O/o PSA to GoI. Apart from putting the Report on the PSA Office website, it is planned to circulate the Report to various Ministries/Departments and Funding Agencies. It is sincerely hoped that the Report will be found useful by everyone associated with MSPs in the country in any manner. It is also hoped that the Report will be found useful by the international nuclear physics community as well.

Praveer Asthana

(PRAVEER ASTHANA)
PSA Fellow, O/o PSA to GoI

Arun Bhardwaj

(ARUN BHARDWAJ)
Scientist-F, O/o PSA to GoI

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Mega Science Vision-2035
(Nuclear Physics)

The Report

PREFACE

In the last few decades, the Nuclear Physics community of India has periodically discussed the future of its participation in large experiments. The last such exercise was carried out in the year 2014. In December 2020, the Office of the Principal Scientific Advisor to the Government of India formed six Working Groups for preparing the Mega Science Vision (MSV) document(s) for the country in six areas, with Nuclear Physics being one of them. The mandate, in brief, was: (a) to report the state-of-the-art in the field and make a strength, weakness, opportunities and threat (SWOT) analysis for India in the time window of 2020–2035, (b) to enunciate the need for continuing and undertaking new Mega Science projects, (c) to examine the relevance of such Mega Science programs for India's scientific and technological goals and (d) to suggest appropriate evaluation, funding and management structures for such programs. While this charge was given to the Drafting Group and the Working group members, there was a community-wide consultation exercise and a very large fraction of the Nuclear Physics community in India actively contributed to developing this report.

To begin with, it might be worth taking a brief look at the growth and development of Nuclear Physics in the country. Nuclear physics research in India could be said to have started around 1920, with the building of a cloud chamber by D.M. Bose and S.K. Ghosh at the University of Calcutta. D.M. Bose and Bibha Chowdhuri pioneered the use of photographic emulsion plates in cosmic rays and developed the method of mass estimation of charged tracks, which was the technique later followed by C.F. Powell in his discovery of the pion. Another group was started at Allahabad University by M.N. Saha and A.C. Banerji. Saha and D.S. Kothari produced a new theory of beta decay (1933). Isolated works on nuclear physics came from M.F. Soonawala at Jaipur (1928) and from B.M. Sen at Presidency College, Calcutta (1933). At the Presidency College, K.C. Kar and his group developed a precursor of the shell model to explain the nuclear energy levels. At Wilson College in Mumbai, H.J. Taylor, a scientist-missionary, with V.D. Dabholkar, started studying photographic plates to detect nuclear reactions in cosmic rays (1940s). At the Tata Institute of Fundamental Research (TIFR) during the 1950s, several exotic nuclei were discovered by the cosmic-ray group led by Bernard Peters. After independence, a 4 MeV cyclotron was assembled at Calcutta under the leadership of M.N. Saha (1955) and an active group was set up, which grew into the Saha Institute of Nuclear Physics (SINP). Both at Calcutta and at TIFR in Mumbai, Cockroft-Walton generators were built. The new Atomic Research Establishment built a Van de Graaff generator at Trombay. By the 1960s, nuclear physics studies were in full swing at TIFR, Bhabha Atomic Research Centre (BARC), SINP, the new Institute of Mathematical Sciences (IMSc) and various universities, such as those at Delhi, Calcutta and Aligarh. During the 1970s, a cyclotron at Panjab University, Chandigarh was commissioned out of the components of a variable energy cyclotron at the University of Rochester. Important studies on nuclear physics were also carried out by V. Sarabhai's group at the Physical Research Laboratory (PRL), Ahmedabad.

The 1960s saw the growth of Nuclear Physics in Indian universities and institutes, Ph.D. programs were initiated, project fundings and international interactions stepped up, and the Electronics Corporation of India (ECIL) was established to provide industrial support to the science programs. The period between the 1960s to the1980s saw the setting up of various accelerators across the country, such as the Pelletrons at TIFR-BARC and Nuclear Science Centre (now called Inter-University Accelerator Centre (IUAC)), the Cyclotron at the Variable Energy Cyclotron Center (VECC) and the research reactors at the Indira Gandhi Center for Atomic Research (IGCAR) and BARC. About two decades ago, superconducting linear accelerators were added in order to boost the beam energies obtained from the Pelletron accelerators. This has expanded the region of nuclei that can be investigated using these accelerators.

During the late 1980s and early 2000s, there was close coordination between nuclear physics in universities and facilities being run within the ambit of the Department of Atomic Energy (DAE), in which the formation of the UGC-DAE Consortium for Scientific Research played a major role. This period also saw the development of the Synchrotron Radiation Source Facility at Raja Ramanna Centre for Advanced Technology and the beginning of the era of industrial accelerators with the setting up of an electron beam experimental facility at Trombay (later moved to the Board of Radiation and Isotope Technology (BRIT)). It also saw the establishment of the Nuclear Power Corporation of India Limited, which had its origins in the earlier Nuclear Power Board, to harness nuclear power for societal needs. India also carried out experiments related to the thermonuclear fusion process as a power source using the tokamak ADITYA and its subsequent versions, leading to our participation in the combined global efforts in mid-2000s.

Individual and institutional participation by Indian scientists in large-scale nuclear physics programs has a history of more than 50 years. Scientists working on nuclear emulsions had visited CERN in the early 1960s to expose emulsion stacks to pion, kaon and proton beams utilizing the CERN Proton Synchrotron. However, a truly mega science collective effort in nuclear physics started around 1990, when a team of scientists from national laboratories and universities started a collaboration for heavy-ion experiments in the WA93 experiment at the CERN Super Proton Synchrotron for the search and study of Quark-Gluon Plasma (QGP). They followed the footsteps of similar activities in high energy physics. In 1993, the Indian team joined the WA98 collaboration and there was a quantum leap in Indian contributions.

In 1991, the DAE entered into a major collaboration agreement with CERN, which continues till today. The Department of Science and Technology (DST) also joined the activities at CERN in the 1990s and provided the major source of support for the universities. Since then, the Indian Nuclear Physics community has been participating in many such mega science projects within India and abroad; to name a few: the Relativistic Heavy-Ion Collider (RHIC) facility, the Large Hadron Collider (LHC) facility, the Facility for Antiproton and Ion Research (FAIR), the International Thermonuclear Experimental Reactor (ITER), the Indian National Gamma Array collaboration (INGA). It has also been using facilities at BARC, IUAC, TIFR and VECC.

The Plasma Physics Program had been set up at PRL in 1982 by the Department of Science and Technology, Government of India under the programme called Intensification of Research in High Priority Areas (IRHPA). Its charter was to initiate India into the field of magnetically confined high-temperature plasma research by building a tokamak. By 1986, the Plasma Physics Program moved to a new campus in Bhat village and was upgraded into the Institute for Plasma Research. In 1989, the tokamak, ADITYA, was commissioned and went into a phase of routine operation. Currently, one of the major thrusts of the Institute for Plasma Research is on the development of the ITER.

With the above foundation in place, the MSV-2035-Nuclear Physics has been presented here with a realization that we need to fully exploit the results from the past investments in such programs, tap on international links to further boost the technology capacity building in niche high-tech areas in collaboration with the industry, start complementary national initiatives and also look into translating some components of basic science research to applications. While the proposed plans would require a modest increase in research funding for nuclear physics in the coming decade, it, in turn, would certainly allow the large pool of existing young scientists to take up worldwide leadership role in nuclear physics research, address some of the fundamental science questions and further create a unique talent pool for development of science and technology in the country in the long term.

THE DRAFTING AND WORKING GROUPS

Director TIFR, Mumbai – Dr. Jayaram Chengalur / Dr. S. Ramakrishnan / Dr. Sandip Trivedi	Chairperson
Members from the Drafting Group	
Dr. Alphonsa Joseph Palakkel, IPR, Gandhinagar	Member
Dr. Aradhana Srivastava, BARC, Mumbai	Member
Dr. Bedangadas Mohanty, NISER, Bhubaneswar	Member
Dr. Rudrajyoti Palit, TIFR, Mumbai	Member
Other expert members	
Dr. Akhil Jhingan, IUAC, New Delhi	Member
Dr. Javed A. Sheikh, Kashmir University, Srinagar	Member
Dr. Lokesh Kumar, Panjab University, Chandigarh	Member
Dr. P. K. Atrey, IPR, Gandhinagar	Member
Dr. Rajdeep Chatterjee, IIT-Roorkee	Member
Dr. Sadhana Dash, IIT-Bombay	Member
Dr. Subhasis Chattopadhyay, VECC, Kolkata	Member
Dr. Vaishali Naik, VECC, Kolkata	Member
Dr. Vandana Nanal, TIFR, Mumbai	Member
Dr. Vishwajit Jha, BARC, Mumbai	Member
Agency representatives	
Dr. Purushottam Shrivastava, RRCAT, Indore (Nominee of Secretary-DAE)	Member
Shri S. K. Varshney, DST (Nominee of Secretary-DST)	Member
Representatives of the O/o PSA	
Dr. Praveer Asthana, National Coordinator	Member
Dr. Arun Bhardwaj, O/o PSA	Member
Nodal Scientist - Dr. Amol Dighe, TIFR, Mumbai	Member-Secretary

TABLE OF CONTENTS

EXECUTIVE SUMMARY

Nuclear physics is a broad field that encompasses (i) the creation and study, in the laboratory, of a plasma of fundamental constituents of visible matter that existed in a microsecond old Universe, viz. quarks and gluons, (ii) understanding the formation and properties of protons, neutrons, as well as the structure and evolution of various nuclei and (iii) exploring the processes of nuclear fission and fusion to harness the tremendous power generated by them. The physics of nuclei and their constituents are fundamental to our understanding of the evolution of the Universe and, at the same time, play an important role in our everyday life. Specifically, various technological developments in detectors and accelerators that are used in the field, find widespread applications in industry, medicine, agriculture, environment, culture and heritage and national security. In this document, a vision for the field in terms of the science goals, facilities, applications, strategies for the future and links to other fields has been presented.

The vision presented here is based on the foundations built through past scientific investments, as well as the participation, achievements and pioneering efforts by Indians in Mega Science Projects (MSPs). The experimental contributions initiated during the WA93 and WA98 programs abroad, large national accelerator-based research programs, national detector instrumentation programs and impactful theoretical ideas have provided a strong basis for national MSPs and continued Indian participation as a significant partner in several international MSPs.

Currently, the field is geared towards a thorough understanding of the complex structure of nuclei under extreme conditions, reactions dynamics in different energy ranges and properties of nuclear matter under conditions close to different astrophysical scenarios. The field also uses the atomic nucleus as a unique laboratory for a variety of investigations in fundamental physics. The developments in this area have strong implications for the fundamental science questions in high energy physics, astronomy and astrophysics.

❖ SCIENCE QUESTIONS

Nuclear science is a broad field that requires facilities of diverse kinds. Some of the key science questions in the field as a whole that are to be addressed in the coming 15 years are as follows:

- What are the phase structures of quantum chromodynamic (QCD) matter?
- How do the strong interactions amongst the quarks and gluons inside the nucleons result in confinement and collectively result in their properties such as mass and spin?
- How does a nucleus look in terms of its partonic content? Do nucleons and nuclei, viewed at near-light speed, behave as gluonic matter with universal properties?
- How did visible matter emerge in the present Universe?
- How does the equation of state of nuclear matter decide the properties of neutron stars?
- How are heavy elements formed in the Universe and what are the crucial observables required to model the process of nucleosynthesis?
- How does a finite nucleus organize itself across the nuclear landscape and how does the ordering of the quantum states alter in the case of nuclei far away from the line of stability?
- Is the role of the fundamental interactions in various nuclear structure phenomena and the limits of existence of nuclei completely understood?
- What is the origin of the neutrino mass and are they their own antiparticles?
- Are there neutrino species beyond the Standard Model?
- What is dark matter and what are its constituents?
- What are the physicochemical processes involved in plasma-liquid/solid interactions?
- Will a collective ultracold plasma usher a new era in quantum computing?
- How can astro-plasmas be understood using multiscale collision-less reconnections?

The details of the abovementioned points have been presented in this document. An investigation of these points requires a substantial collaborative effort in experiment and theory within and outside the country, as well as the creation and utilization of state-of-the-art facilities.

In this vision document, the progress in understanding some of the above questions has been described and some aspects that should be explored in future have been pointed out. The proposals have been driven by the identification of science questions, which are globally recognized and are required to be addressed in the coming decade. This document provides a blueprint for the path forward from the Indian Nuclear Physics Community to the various funding agencies and the public in general. The following is a list of recommendations from the community.

❖ RECOMMENDATIONS ON MEGA PROJECTS

RECOMMENDATIONS FOR QCD

The study of the emergent properties of QCD matter is one of the most compelling science problems in nuclear physics. It includes mapping the phase diagram of the QCD matter, measuring the properties of the QCD matter subjected to extreme conditions of temperature, pressure, baryon density, electromagnetic fields and angular momentum, finding out the partonic content of a nucleus and the fundamental mechanisms behind the properties of nucleons, such as its mass and spin.

We recommend continued participation in heavy-ion programs at LHC, RHIC and FAIR, the collision energies of which, only when taken together, allow to map the QCD phase diagram. While the CBM experiment, which is under construction at FAIR, should be the focus for the high-energy nuclear collisions in the near future, we also recommend participation in the upcoming Electron-Ion Collider experiments to address the fundamental questions in nuclear physics.

RECOMMENDATIONS FOR LOW-ENERGY NUCLEAR PHYSICS

Investigation of the structure of nuclear matter at the extremes of isospin/angular momentum is a major goal in nuclear physics research. Another aspect of the field is to understand the various reaction mechanisms for the production of super-heavy elements and nuclei away from the line of stability. This will help in gaining a new insight into the role of strong interactions on the nuclear scale and in understanding the nuclear processes that drive the evolution of the stars, galaxies and the Universe.

We recommend development of new accelerator facilities within India for radioactive-ion beams (RIBs), high-current stable beams and underground laboratories for the low-energy nuclear physics programs. State-of-the-art detector systems at the existing accelerator facilities will be essential to cope with the developments in the field. We recommend a strong participation in the experiments at FAIR and other international nuclear physics facilities for RIBs and photon beams. A consortium can be formed to facilitate the usage of some of the international facilities by the low-energy nuclear physics groups in India.

RECOMMENDATIONS FOR PLASMA PHYSICS

The physicochemical processes involved in plasma-liquid/solid interactions must be investigated to understand the role of plasma in inactivating the growth of microorganisms during sterilization and many other applications. An in-depth study of collective ultracold plasma and astro-plasma using multiscale collision-less reconnections will help open a new era in quantum computing and to understand the astrophysical and fusion plasmas. Applications of plasma processes for global warming mitigation should also be explored.

We recommend setting up plasma-based systems for generating an Ultracold Plasma Trap for quantum computing and an Astroplasma Simulator at Lab Scale. It is proposed to build a moderate-sized spherical tokamak that can be used for the production of radioactive sources for medical purposes, production of tritium for conventional fusion reactors, or as the core of a fission-fusion hybrid reactor. Similarly, we recommend setting up a high-energy (MJ), high-power (TW) pulsed-power facility for producing intense soft X-ray bursts.

❖ RECOMMENDATIONS ON INFRASTRUCTURE-BUILDING INITIATIVES

For the success of the science goals listed above, several new initiatives need to be taken. Some of them are listed below:

A. Detector and accelerator research and development: One of the key and crucial drivers for sustained advancement of the Indian Nuclear Physics community in MSPs is the capability to develop state-of-the-art detection facilities. Establishment of a few National Detector Development and Training Centres (NDDTC) having clear scientific goals is recommended, preferably at places which are hubs of activities in nuclear physics. These are essential for the long-term success of MSP activities and should be open to all the scientists and engineers involved in MSPs. In order to make India an attractive place for hosting MSPs, steps should be taken towards building a world-class multi-purpose underground laboratory facility, identifying and opening research reactor facilities, and building a state-of-the-art photon beam facility of 10 PW capacity to conduct nuclear physics research with extreme electromagnetic fields.

B. Centre for Nuclear Theory: It is suggested that a Centre for Nuclear Theory (CNT) be set up in order to have an inclusive and diverse research environment where theoretical scientists can focus on key frontier areas of the field, including those crucial to the success of the existing and future experimental and computational facilities. This centre could be set up initially in a virtual mode and could later become a physical facility at an appropriate place. It would host visitors and organize workshops to develop strong collaborations with experimentalists.

C. High-performance computing: To perform cutting-edge research and to maintain international competitiveness, it is essential for scientists pursuing research in mega sciences to have access to adequate resources in high-performance computing for handling large amounts of data and the associated sophisticated analysis tools. We envisage the need to build 4 big data-centres around the country for Nuclear and High Energy Physics, with a total computing power of 100 petaFLOPS (PFLOPS) and storage systems of 250 PB. The Plasma Physics Program would be looking at an additional need of about 500 PFLOPS computing power in order to perform simulations of various physics aspects of plasma devices.

D. Human resource development programs: The role of trained human resources for MSPs must not be understated. Not only do we need scientists interested in the science outcomes but also scientists and engineers capable of building the required instrumentation for detectors. While the current education system in the country focuses on training students in one particular discipline, it is important to widen the scope of their expertise, especially in areas related to the MSP activities that they will be a part of. Special training courses need to be organized regularly for this purpose, for example, accelerator physics, detector and instrumentation, medical and radiation physics, to name a few. Given the increasing number of activities in this area, one should aim to enhance the number of Ph.Ds as well as job opportunities in the field of Nuclear Physics in universities, Indian Institutes of Technology (IITs), Indian Institutes of Science Education and Research (IISERs) and other research institutes. The formation of an Indian Nuclear Science Society is also recommended.

❖RECOMMENDATIONS ON FUNDING AND PHASED DEVELOPMENT OF MSP's

MSPs are typically long-term projects involving multiple institutes, scientists, detectors, technologies and facilities. In addition, they require significant resources. A successful MSP would need sustained funding over a long-term period with appropriate monitoring mechanisms.

We recommend the following in this aspect:

(a) *Creation of a centralized project submission forum, which could be a separate Board, a cell in the office of the Principal Scientific Advisor or a separate mega science forum at the national level*

(b) *Formation of a Standing Review Committee of experts for each proposal for its regular monitoring and phase-wise approval*

(c) *Community Planning Exercise for the initiation of new mega projects and creation of a Consultative Group to facilitate potential MSPs at an early stage*

(d) *Inclusion of mega science in the call for bilateral projects between India and partner countries by various funding agencies*

(e) *Facilitating industry participation in MSPs, specifically, augmentation of mechanisms to foster translations of spin-off technologies, and a wider and deeper participation by the domestic industry in MSPs in India and abroad.*

This document has six chapters. It begins with a presentation of the science goals in each of the sub-disciplines of nuclear science: understanding finite nuclei and nuclear matter in extreme conditions in terms of the fundamental interactions, key nuclear properties relevant for astrophysics, neutrino-related nuclear physics, theoretical aspects, and fusion and plasma physics. Then, an overview of the facilities available for nuclear physics research has been presented. This is followed by a discussion of the current mega projects and those planned in future. Highlights of the wider impact of nuclear science on society and its contributions to capacity building of various kinds have also been presented. The document concludes with a discussion on developing strategies for funding and monitoring such mega projects and their intimate relation with other fields in science.

Although this is primarily a Nuclear Physics mega science document, the field of nuclear physics is not a silo. The scientific questions it addresses, as well as the techniques and technologies it uses, have a large overlap with High Energy Physics, Astronomy and Astrophysics, as well as Accelerator Science and Technology, each of which has a mega science vision of its own. Coordination among the activities in all these areas is crucial for successful mega science ventures in the country.

Finally we note, as Neils Bohr had pointed out, *"Prediction is very difficult, especially if it's about the future"*. While this document attempts to give a comprehensive vision of nuclear physics for the next 15 years, there could be new ideas which may emerge that are not covered in this document. There could also be unforeseen circumstances which might impact the vision presented here. The vision will therefore have to be flexible and nimble to accommodate such unforeseen developments as the milestones on the roadmap are crossed.

⌘

1 SCIENCE GOALS OF NUCLEAR PHYSICS IN THE NEXT DECADE

This chapter gives an overview of the outstanding science issues that are being explored in the field of Nuclear Physics. They range from the nature of strong interactions (quantum chromodynamics), the structure and properties of nuclei, nuclear astrophysics and photonics, to fusion processes and plasma physics. These issues are being addressed by performing experiments at particle colliders, nuclear reactors, accelerators and are also being theoretically investigated using the development of techniques such as the lattice gauge theory and ab-initio calculations. Neutrinos are also emerging as a great tool for understanding the nuclear structure and monitoring nuclear reactors. Conversely, the nature of neutrino masses can be probed efficiently via nuclear physics experiments. Unique properties of plasma have made it possible to be used for many applications, though several of the underlying mechanisms are yet to be understood and exploited.

1.1 QUANTUM CHROMODYNAMICS

Strong interaction is one of the four fundamental interactions in nature. It is the force that binds the fundamental constituents of visible matter, the quarks and gluons, to form hadrons such as protons, neutrons and pions. It is also responsible for binding the nucleons inside a nucleus. The underlying theory of strong interactions is quantum chromodynamics (QCD). The scientific program related to the study and understanding of the properties of QCD matter involves an intricate combination of *experiment, theory and simulation*. The success of the program requires a combination of all three aspects, along with the need to develop state-of-the art *accelerator facilities, detector systems and computing infrastructure*. The experiments require novel detectors, whose research and development (R&D) often leads to potential *societal applications* and development of innovative data analysis techniques, such as machine learning approaches. The theoretical efforts, on the other hand, are based on the quantum field theory of relativistic matter, the simulation of which requires high computing resources. The next generation discoveries will take place in facilities that operate on the frontiers of energy and intensity, with the collaboration between experiment and theory.

Some of the fundamental physics questions to be addressed in QCD are as follows:

1. What are the phase structures of QCD matter?
2. How do the strong interactions amongst quarks and gluons inside the nucleons result in confinement and collectively result in the properties such as mass and spin of the nucleons?
3. How does a nucleus look in terms of its partonic content? Do nucleons and nuclei, viewed at near-light speed, behave as gluonic matter with universal properties?

The study of the emergent properties of QCD matter has been categorized into two parts in this document for the sake of presentation, although both the parts are interrelated. They are: (a) Hot QCD, dealing with the first of the abovementioned questions and (b) Cold QCD, dealing with the second and third questions.

1.1.1 HOT QCD

One of the important goals of high energy nuclear physics is to map the phase diagram of strong interactions by studying the QCD matter produced in heavy-ion collisions by varying the temperature and density. Exploring the properties and the phase structure of the quark and gluon matter has also been identified as a key program in the US [Aprahamian 2015] as well as the European Long Range plans [Alahari 2017] in Nuclear Sciences. The ultimate goal is to fully map out the phase diagram (the temperature plotted as a function of the baryonic-chemical potential) for matter that undergoes strong interactions. The richness of the phase diagram encompasses, at one end (at high temperature), the physics of the early Universe and at the other end (at high baryonic-density), the physics of astrophysical objects such as neutron stars. It provides a gold mine to statistical physicists, as it allows for the possibility of not only several QCD phases [Braun-Munzinger 2009] but also a first order phase transition, crossover and a critical point [Gupta 2011].

The specific scientific question to be addressed in this case is: how do the many-body interactions of the quark and gluon fields decide the phase structure (phases, critical point, order of transition, etc.) and phase properties (viscosity, opacity, diffusion/drag coefficient, etc.) in the QCD phase diagram? The goal is the experimental and theoretical realization of the QCD phase diagram, which is still largely conjectured to a reasonable accuracy.

<u>QCD Phase Diagram:</u>

The status of the conjectured QCD phase diagram is shown in Fig. 1 [Adam 2021]. A first-order phase transition is expected to occur between the hadronic gas phase and quark-gluon plasma (QGP) phase at large baryon chemical potential (μ_B) and small temperature (T). The phase boundary is shown as a solid line and it curves towards smaller μ_B and larger T. The point where the first-order phase transition line ends is called the QCD critical point. This is shown as a square and its position in the phase diagram is currently being searched theoretically as well as experimentally. The quark-hadron transition at smaller μ_B has been established theoretically to be a crossover and it is shown by a dashed line in the figure. The value $\mu_B/T = 2$ is shown by the blue dot-dashed lines. A comparison between the experimental data and the lattice QCD calculations disfavors the possible QCD critical point being located at $\mu_B/T < 2$. The red-yellow dotted line corresponds to the chemical freeze-out (where inelastic collisions among the constituents of the system cease) that has been inferred from the particle yields in heavy-ion collisions using a thermal model. The liquid-gas transition region features a second-order critical point (red circle) and a first-order transition line (yellow line) that connects the critical point to the ground state of the nuclear matter (T ~ 0 MeV and μ_B ~ 925 MeV). The regions of the phase diagram accessed by the past (Alternate Gradient Synchrotron (AGS) and Super Proton Synchrotron (SPS)), the ongoing (Large Hadron Collider (LHC), Relativistic Heavy Ion Collider (RHIC), SPS and RHIC operating in the fixed target mode) and the future (Facility for Antiproton and Ion Research (FAIR) and Nuclotron-based Ion Collider fAcility (NICA)) experimental facilities are also indicated [Xu 2021].

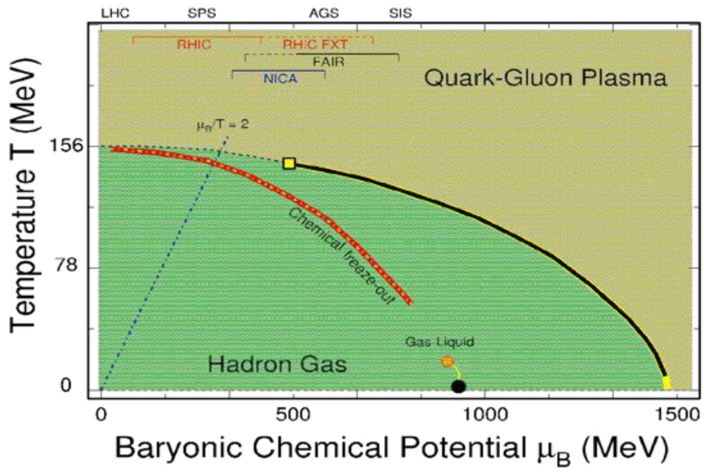

Figure 1: Conjectured QCD phase diagram

A large part of the phase diagram is still unexplored. Locating the critical point in the phase diagram experimentally will make the phase diagram a reality, clearly demonstrating the existence of two distinct phases, a first-order phase transition and a crossover, and therefore reinforce the earlier discovery of the deconfined phase of quark-gluon-plasma [Adam 2005]. In addition, the measurements related to the baryon number susceptibilities will enable us to know the properties of the last scattering surface of the hadrons in detail, which could have profound implications in high energy physics, as was provided by the last scattering surface of photons in the evolution of the Universe.

From experiments at RHIC and LHC there is a substantial body of evidence based on multiple observables of QGP formation in relativistic heavy-ion collisions. One of the key questions that is currently being addressed is: what happens to these observables as one changes the system size? Naively, one does not expect to produce a QGP in these cases. However, results from the LHC and RHIC have thrown surprises in terms of the existence of sizable azimuthal anisotropies in the hadron production in the highest multiplicity classes. This has led to speculations that one can generate a QGP in such relatively rare events. The interpretation of results is an active area of study as higher statistics data collection is also in progress to extend the measurements in small colliding systems for a variety of observables.

1.1.2 Cold QCD

The common notion of atomic nuclei and nucleons, as read in textbooks of schools and colleges, is that the proton or neutron has a simple three-valence quark structure. This traditional view of the structure of the atomic nuclei and the nucleons they contain has undergone a transformation in the last few decades. We now know that a nucleon is rather a complex many-body system with a large number of gluons and a sea of quarks. It is now a validated fact that the spin ½ of a proton is not entirely due to its valence quarks. It is expected to be generated from all its quark and gluon constituents; the exact detailed understanding is missing. The quantitative study and understanding of nucleons requires a novel sophisticated tool, such as the Electron-Ion Collider (EIC) experiments [Accardi 2016] [Aschenauer 2019] [Khalek 2021]. It is important to mention here that the simple fact that the proton carries spin ½, is exploited daily in thousands of images obtained worldwide from magnetic resonance imaging. Further, what is the exact process by which quarks and gluons get confined to form hadrons is an unsolved problem in QCD. The EIC will provide valuable information for understanding the process of evolution from partons to hadrons.

The specific scientific question to be addressed in this case is: how do the many-body interactions of the quark and gluon fields lead to a confined structure and to the properties of hadrons (spin, mass, parton content, etc.)?

We know from the de Broglie equation that a fast-moving probe can resolve the matter structure in terms of its constituents at increasingly smaller length scales. Previously, quarks and gluons were believed to form a nearly free gas of weakly interacting partons (denoted as parton gas in Fig. 2) at very high resolution, Q^2 (the square of the momentum transferred), and very strongly interacting confined matter/regime on lower (shown in Fig. 2), hadron-size resolution scales. By colliding electrons with heavy nuclei at relativistic speeds, the EIC will provide access to a unique regime in the phase diagram shown in Fig. 2, where abundant gluons saturate in density (shown in the colored region) and dominate the behavior of the nuclear matter. Electron collisions with heavy nuclei at the EIC will map the predicted saturation surface (colored surface) with the Color Glass Condensate (CGC) region below that surface. The CGC theory states that at very high energies, the properties of gluon matter in a nucleus are independent of its detailed structure; they can be expressed entirely in terms of ratios of Q_S (scale at which the probe no longer resolves the individual quarks and gluons in the nucleus but rather samples the strongly correlated matter) and the resolution momentum scale, Q, of the external probe. Because of the claim that it controls the bulk of the strong interaction phenomena at high energies, the study of this conjectured universal gluon matter is of high scientific interest and curiosity.

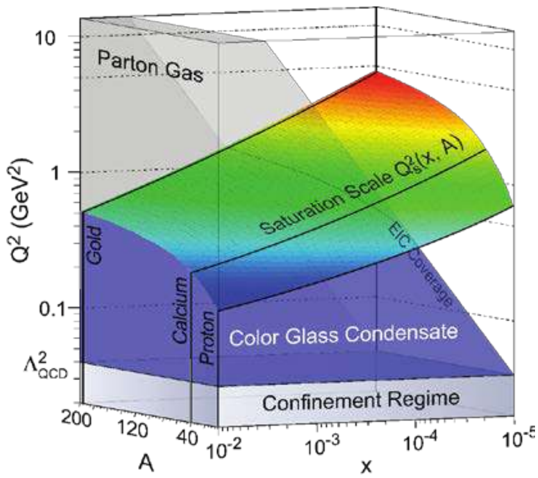

Figure 2: The conjectured QCD landscape showing the resolving power of the probe (increasing upward) vs. energy (increasing toward the right), as a function of the atomic number of the nucleus being probed.

In addition, the question of how the proton gets its spin requires the study of the distributions of quarks and gluons — in space, in momentum and in spin preference — from low to high resolution scales. Besides these fundamental interests, information from the EIC on the location, fluctuations and correlations within the saturated gluon matter in the nuclear wave functions will provide a unique complementary perspective to the properties of hot QCD matter from heavy-ion collisions (at RHIC and LHC). It will allow us to probe one of the possible origins of the observed emergent property of the perfect fluid QGP, i.e., the initial saturated gluon states of the colliding nuclei. Further, recent observations at RHIC and LHC have shown evidence that might indicate the formation of small QGP droplets even in light-ion-heavy-ion collisions and high multiplicity proton-proton collisions, thus leading to the speculation of them acting as perfect baselines for QGP interpretation. In that case, the EIC experiments should not show similar effects and thus will provide the true baseline for the physics of hot QCD in heavy-ion collisions.

1.2 NUCLEAR STRUCTURE AND REACTION DYNAMICS

Low-energy nuclear physics focuses on the fundamental issues related to the nature of strongly interacting matter in the Universe, starting from its creation. It explores the emergent properties of matter from the basic interactions between quarks in baryons and mesons, to the shell structures in nuclei. It also addresses the question of how nuclei are synthesized in stars and supernova explosions. It therefore connects intimately with the basic research in particle physics and astrophysics. Furthermore, it is technologically highly challenging. As a discipline, it examines 99.9 % of the mass of the visible Universe. Research in this field deals with the questions of the existence of atomic nuclei and their properties at the limits of neutron-to-proton ratios, angular momentum and excitation energy. It also aims to explain the large-scale dynamical processes, such as fission, in terms of the microscopic methods involving nucleons. One of the long-term goals is to develop a predictive understanding of nuclei and their interactions based on the fundamental QCD and electroweak theory. The subject of nuclear astrophysics focuses on the scientific questions dealing with the chemical history of the Universe, the role of nuclear properties in the evolution of stars and stellar explosions and the nature of dense matter. Some of the overarching questions [NationalPress 2013] [Aprahamian 2015] [Alahari 2017] [UKNP2018] which will define the priority in this research field are as follows:

- How do the properties of nuclei explain the evolution of the Universe?
- How do nucleons and subnucleon degrees of freedom control various emergent phenomena in nuclei?
- How do different parts of the nucleon-nucleon (NN) interactions influence the structure of visible matter?
- How can the basic research in nuclear science best be used for technology required for benefiting the society?

Various probes namely, stable ions, radioactive ions, photons, neutrons and electrons are required to address open questions in the field of low-energy nuclear physics and nuclear astrophysics.

1.2.1 NUCLEI AT EXTREMES

The atomic nucleus is a fascinating many-body system consisting of protons and neutrons, whose structure is most decisively governed by the strong force. Over the decades, tremendous progress has been achieved in the theoretical modelling of the nuclear structure, from the large-scale shell models, to the '*ab initio*' calculations of light nuclei, based on the bare NN interactions and mean-field methods using the modern density functional theory. One of the challenges of nuclear theory is to explore the connections between the various nuclear models to develop a unified description of the nucleus. Another important part is to develop new methods to describe the nuclei far away from stability, where exciting new phenomena are to be explored. Studies of atomic nuclei are closely linked with the field of research of the subnucleonic degrees of freedom and of fundamental interactions. The simple excitation patterns of nuclei and the associated amazing regularities in these excitations remain a subject of active research. The emergence of simple modes of excitation at varying angular momentum and isospin is connected to the symmetries of the nuclear many-body system. New symmetries might be playing a crucial role for these drip-line nuclei. Compared to the stable nuclei, some of the properties of the loosely bound nuclei near the drip lines will be very different. For example, nuclei with halos and skins have been observed in neutron-rich exotic nuclei. One also expects to observe new decay modes, regions of nuclei with special deformations, new shell structures, new isospin pairing phases and new collective modes for these drip-line nuclei. The nucleonic clustering could change for these exotic nuclei, giving rise to unusual nuclear properties. Direct reactions in inverse kinematics, e.g., (p,d) and (d,p), can be employed for studying exotic nuclear shapes (halos and neutron skin), cluster structures, the shell structure and nuclear pairing far from stability.

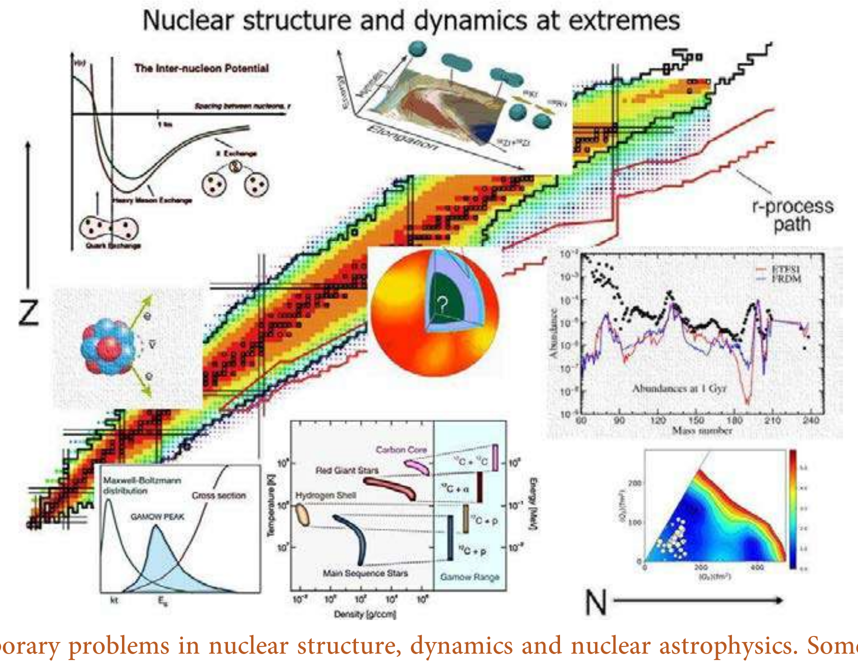

Figure 3: Contemporary problems in nuclear structure, dynamics and nuclear astrophysics. Some parts of the figure have been taken from [Wiescher 2009], [Andreyev 2010].

The main research activities in this subtopic of nuclear physics will focus on investigating various nuclear structure properties and the reaction dynamics involving the neutron-rich and neutron-deficient nuclei along the nuclear chart. New experimental data on exotic nuclei will help to develop new understanding and theoretical formalisms. One of the priorities will be to find the appropriate effective interactions in new regions of density and isospin.

Exotic Neutron-rich Nuclei

The upcoming RIB facilities will extend the present limit of the neutron drip line from Z = 11 to approximately Z = 25 [Blumenfeld 2013]. For nuclei with atomic numbers beyond this, even though the drip line cannot be reached, the manifestation of weak binding and isospin dependence on the nuclear structure can be studied. Lower binding energy is expected to bring about extended surface zones of neutron-enriched low-density matter, as has already been observed in lighter nuclei such as ^{6,8}He, ^{11}Li, ^{11}Be, ^{19}B, ^{22}C, etc. [Geesaman 2006] [Kubota 2020]. The study of these exotic shapes (neutron skins or halos) provides knowledge of the effective interactions in nuclear environments [Al-Khalili 2017]. In addition, it may also provide a new insight into the equation-of-state of cold neutron matter between saturation and low density. For nuclei having weakly bound valence nucleons, pairing becomes important due to the residual interactions, which could result in cluster and molecular-type of structures. Nuclear reactions at sub-barrier energies display a rich interplay between the nuclear structure and its reaction dynamics. To study the role of weak binding and exotic shape on the various reaction channels, such as elastic scattering and fusion, is a topic of current interest. Investigations of the most neutron-rich isotopes are linked to nuclear astrophysics as it offers direct access to a part of the rapid neutron-capture process (r-process) path.

Proton Drip Line and N = Z Nuclei

Neutron-deficient nuclei, with N = Z, at or near the symmetry line are of specific interest in many ways and the heaviest self-conjugate nucleus, ^{100}Sn, is one such example. Nuclei near N = Z = 20 are ideal to search for hyper-deformation at high spins. These nuclei are also the microlaboratories for testing the Standard Model with high precision. Proton-rich nuclei are of interest to explore the isospin-symmetry breaking effect in heavy nuclei, a proton-neutron pairing and a recently observed rare decay mode of two-proton radioactivity [Woods 1997] [Bentley 2013] [Blank 2008] [Giovinazzo 2021]. These nuclei are also found to be important for the study of the astrophysical rapid proton-capture process (rp-process) path [Schatz 2017]. The stable beam as well as RIB-based experiments will give new insights into this subject. High-current stable beam facilities along with modern electromagnetic spectrometers, high-resolution gamma detector arrays, such as the Indian National Gamma Array (INGA) and particle detectors will be essential for studying these neutron-deficient isotopes [Cederwall 2020].

Single-particle and Collective Degrees of Freedom

The two extreme degrees of freedom of the atomic nuclei, namely, the single-particle and the collective degrees of freedom, bring a lot of surprises to the field of nuclear structure. Their coupling manifests a rich variety of phenomena in nuclei with changing isospin and angular momentum. One of the main ingredients of the single-particle degrees of freedom is that the magic numbers of the naive nuclear shell model are not valid across the nuclear landscape. The residual interactions, which, in turn, depend on the occupation of the neutron- and proton- orbitals, modify the magic gaps and magic numbers of the nuclei [Otsuka 2020]. At the extreme, the low neutron binding energy in very neutron-rich nuclei provide a diffused mean field and a weak spin-orbit interaction. This results in the modification of the shell gaps. These modifications of shell gap affect the evolution of nuclear shapes and the collective modes along the isotopic chains. Using the radioactive beam facilities, hitherto unexplored regions of exotic nuclei will be accessible using fission and fragmentation processes. Another dimension to this problem is the investigation of various phenomena at high angular momentum resulting from the coupling of single particles and collective shape degrees of freedom of nuclei (see related discussion in section 3.1.4). New generation of efficient detector arrays for particle and gamma-ray spectroscopy will lead to many exciting research programs [Fallon 2016] [Korten 2020]. Measurement of the hyperfine structure is also one of the tools to explore the extended nuclear shape and evolution of single-particle structure.

Cluster States

Light nuclei have been known to exhibit cluster structure, with alpha particles being the most well-known of clusters that commonly occur in light and even heavy nuclei [Freer 2018]. For the states of nuclei that lie near the cluster-decay threshold, clustering phenomenon becomes important. Clustering is closely connected with continuum coupling. The Hoyle state, a resonant state consisting of three alpha particles in a continuum, is a classic example of clustering in nuclei. Clustering is predicted to be an important property in neutron-rich to extremely neutron-rich systems. Such resonances can be investigated to study the structure of nuclei above the particle decay thresholds in detail. Cluster states populated via inelastic reactions, breakup and transfer reactions can be studied using highly segmented and large solid-angle charged-particle and gamma-detector arrays.

Equation of State of Nuclear Matter

Understanding the equation of state (EOS) of asymmetric nuclear matter is one of the important questions in the field. This EOS is a valuable nuclear physics input which is required for modelling the physics of type II supernovae, isolated/binary neutron stars and neutron star mergers (see related discussion in section 6.2). One can produce nuclear densities of $\rho \sim 3\rho_0$ (ρ_0 being the normal nuclear density) using relativistic heavy-ion collisions of isospin asymmetric nuclei that will be available in the high-energy RIB laboratories such as FAIR. From these collisions, the behavior of the symmetry energy at supra-saturation densities can be investigated [Russotto 2016].

Search for Superheavy Elements

The existence of a relatively stable region of superheavy elements, an island of stability predicted by nuclear models to have longer half-lives, still remains elusive. Once this island of stability is reached, it will open new frontiers in nuclear physics and technology, leading to the production of superheavy nuclides [Oganessian 2017]. The heaviest element produced in the laboratory is Oganesson (Og) with atomic number Z = 118. Multi-nucleon transfer has also been investigated as a promising pathway to synthesize nuclei near the superheavy region. Progress in the field will require a comprehensive understanding of the fission process and the competing decay modes. Formation of a fused system using neutron-rich nuclei will have a better chance of survival, as it will be closer to the valley of stability and hence would offer better chances to synthesize super heavy elements. Currently, along with production, research is also focused on understanding the ground state and chemical properties of nuclei in the superheavy region (Z > 104). Rapid nuclear chemical methods for isolating single-atom quantities of these elements have been developed and are currently being improved. Sophisticated techniques for atomic mass measurements of the heaviest species have been proposed, which will aid the conclusive identification of species.

Isomers and Nuclear Clock

Nuclear isomers are metastable states in nuclei that provide unique tools to test the nuclear structure models and new opportunities in fundamental research [Dracoulis 2016]. A class of isomers, now termed as "Extremely Low Energy (ELE) isomers," have emerged as those quantum states of nuclei whose decay is hindered only due to very low excitation energy. The unique lowest-energy isomer observed in ^{229}Th [Beeks 2021] has attracted a lot of attention because of its potential use in realizing the dream of the first nuclear laser, the development of the most precise nuclear optical clock, testing of temporal variation of fundamental constants and observing the effect of the chemical environment on nuclear decays. This will trigger a new era of nuclear quantum optics.

Nuclear Ground State Properties and Their Importance

Experiments with low-energy radioactive beams can explore the fundamental symmetries, modification in the shell structure, the decay properties of the drip-line nuclei near the rp and r-process paths and the determination of ground-state nuclear moments. The experiments for measuring these properties involve instruments, viz., atom and ion traps for accurate mass measurement, charged-particle and gamma-ray detectors for decay spectroscopy studies, a low-temperature nuclear orientation facility and a beta nuclear magnetic resonance (NMR) apparatus.

1.2.2 Nuclear Astrophysics

Since time immemorial, investigating the true origin of matter, that we see around us has been a subject of intense intellectual exercise. It is now believed that the Big Bang produced copious amounts of hydrogen, some helium and trace amounts of lithium (the lithium puzzle is not fully solved, though). While these were created about 15 minutes after the Big Bang, approximately 2 % of hydrogen and helium have been converted to all higher mass elements some 14 billion years later. Understanding the present abundance of elements is the prime goal of nuclear astrophysics [Wiescher 2009] [Arcones 2017] [Johnson 2019].

Nucleosynthesis is an ongoing process in which atomic nuclei are produced in a stellar environment during the lifetime of a star and also at the time of its destruction. The remnants of these processes are dispersed back into interstellar space during stellar explosions in the dying moments of a star. Eventually, the gas and dust, of which they form a part, will contract and serve as the seeds for a new generation of stars and their companions, such as our Sun and the Earth [deBoer 2017] [Strieder 2008]. This constitutes the famous "Hoyle-cycle".

The primary reasons why nuclear physics plays a fundamental role in astrophysics are as follows:

- nuclear reactions are an important source of energy
- nuclear reactions alter the isotopic abundance of elements

Astrophysicists and nuclear physicists, thus, work closely together to

- understand the formation, evolution and final fate of stars
- determine the stellar sites, pathways and time scales involved in the synthesis of the elements.

Whereas the temperature, density, pressure and chemical composition of the stellar environment are the primary inputs sought from astrophysics and astronomical observations, vital information such as masses, Q-values, half-lives and nuclear reaction rates of the participating nuclei are fundamental inputs from nuclear physics. Radiative capture reactions, charged-particle-, neutron- and photon-induced nuclear reactions [Nunes 2020] are commonly involved in these nuclear transmutations.

One also has to keep in mind that the majority of these reaction rates are often needed at and near the respective Gamow peaks, which in most cases are at very low energies. Therefore, actual measurements of these reaction cross-sections, at low energies relevant to astrophysics, in terrestrial laboratories are very challenging.

Additionally, nuclear properties depend on how well the nuclear structure of the participating nuclei are described. Given that the nuclear network calculations for nucleoynthesis require them as vital inputs, the actual pathways of nucleosynthesis and stellar evolutions are contingent on how well the structure and reactions of the participating nuclei are described. These aspects will be emphasized again when we discuss nuclear network calculations for nucleosynthesis in section 1.4.5.

The $^{12}C(\alpha,\gamma)^{16}O$ Reaction

An outstanding challenge, as of today, is the $^{12}C(\alpha,\gamma)^{16}O$ reaction rate. Triple-α to ^{12}C, and subsequently, the $^{12}C(\alpha,\gamma)^{16}O$ rate determines the $^{12}C/^{16}O$ ratio at the end of He-burning in massive stars. This ratio strongly influences the subsequent hydrostatic burning stages and affects

- the pre-supernova stellar structure,
- the explosive nucleosynthesis
- the nature of the remnant (neutron star or black hole) left behind after core-collapse.

Given the numerous astrophysical environments and burning stages where the $^{12}C(\alpha,\gamma)^{16}O$ reaction plays a role, it is estimated that the reaction rate needs to be accurately known within an uncertainty of 10 % or less for a wide range of Gamow energies from as low as 150 keV to as large as 1.5 MeV or more. This is compounded by the fact the electric dipole and quadrupole contributions to the reaction cross-section are important and their interference cannot be neglected. The structure of ^{12}C itself has open questions. There are indications that the second 0^+ level, the celebrated Hoyle-state of ^{12}C, could be a Bose-Einstein condensate of α particles. If that is so, then the implication on the $^{12}C(\alpha,\gamma)^{16}O$ reaction is yet to be investigated.

Theoretical and experimental measurements of the $^{12}C(\alpha,\gamma)^{16}O$ reaction cross-section, thus, pose a grand challenge in nuclear astrophysics and are worthy problems to be pursued in the next decade. It would also be very useful to study the cluster transfer reaction of ^{7}Be to populate the states of ^{16}O that dominantly contribute to the α-capture reaction, $^{12}C(^{7}Be,^{3}He)^{16}O$, in the He-burning process in nuclear astrophysics.

The $^{12}C + ^{12}C$ fusion cross-section is also important to understand the dynamics of massive stars and their evolution. Although some data is available above 2 MeV, especially for the type Ia supernovae, the uncertainty in the measured S-factor is still of an order of magnitude. For a temperature range relevant to the evolution of massive stars, the uncertainties span several orders of magnitude. Therefore, measuring this reaction rate, especially at energies less than 2 MeV, relevant for massive stars, will be a key advancement in nuclear astrophysics. Also important are fusion reactions such as $^{12}C + ^{16}O$ to understand the evolution of massive stars towards supernovae or for modelling novae on the surface of white dwarfs.

Nuclear Reactions using Radioactive-ion Beams for Astrophysical Studies

Studies related to the properties of unstable nuclei and the reactions involving them are essential for explaining the explosive astrophysical scenarios, as they influence the path of nucleosynthesis and energy generation in novae, X-ray bursters and supernovae. Major advances have been achieved for a wide range of explosive H- and He-burning scenarios, including measurements relevant to cosmic γ-ray emitters (e.g., ^{18}F, ^{26}Al, ^{44}Ti) and for non- solar isotopic abundances in meteorites.

Nucleosynthesis of most of the elements beyond iron (A > 60) occurs via the r-process at different sites in the Universe, which have an environment rich in neutrons. The process depends on the stellar conditions such as the temperature range, neutron density, etc. The most probable sites for the r-process are expected to be supernovae, neutron star mergers and X-ray bursts, as they are characterized by extremely high temperatures and neutron densities. The abundances of seed nuclei and the exact sites for r-process nucleosynthesis are still fraught with large uncertainties, and therefore, pose open questions for the future.

The elements produced via the r-process lead to the formation of neutron-rich unstable nuclei. The structure of these exotic nuclei and reactions involving them are still not known. Using beams of neutron-rich radioactive nuclei, these regions of the nuclear chart can be explored. Facilities such as Facility for Rare Isotope Beams (FRIB) in the US, FAIR in Germany, GANIL in France and RIKEN in Japan have already invested substantial resources to synthesize and initiate reactions involving radioactive-ion beams. In India, successful efforts were made to synthesize one of the purest low-mass radioactive beams, ^{8}B, a couple of decades back at IUAC. It was used to study the $^{7}Be(p,\gamma)^{8}B$ reaction rate which is a vital input to the solar neutrino problem. It is important to retain this expertise in radioactive-ion beam physics and augment its application in nuclear astrophysics and related areas at major Indian nuclear facilities.

Stable Beam Facilities for Astrophysical Reaction Rates

In our country, using the existing accelerator facilities, indirect methods for deducing cross-sections of astrophysical interest are being carried out by performing measurements of capture, transfer and breakup reactions. The Facility for Research in Experimental Nuclear Astrophysics (FRENA) facility at SINP will provide opportunities for research in the field of low-energy nuclear astrophysics for the first time in India. FRENA will help to address important queries related to different astrophysical scenarios, especially those related to the fusion of heavy-ions such as ^{12}C, ^{16}O and ^{20}Ne. With the development of a neutron facility at a later stage, neutron-induced reactions would be studied for investigating the slow neutron-capture process (s-process) nucleosynthesis. It would also provide scope for studying specific reactions in the H- and He-burning phases of stars and the p-process reactions. In addition, the necessary infrastructure will be developed to undertake large-scale simulation work essential for modelling the relevant nuclear processes. The details can be found at the Facility website [FRENA].

A non-exhaustive list of reactions, mostly involving stable targets, that could be studied are: $^{14}N(p, \gamma)^{15}O$, $^{12}C(\alpha,\gamma)^{16}O$, $^{13}C(\alpha, n)^{16}O$, $^{22}Ne(\alpha, n)^{25}Mg$, etc. They would impact the seed abundance distribution of core-collapse supernovae, thermonuclear runway and the p-process.

The Need for Underground Laboratories for Nuclear Astrophysics

As stated earlier, most often, one needs to measure nuclear reaction rates relevant to astrophysics at very low energies. This inevitably results in low cross-sections, the measurement of which on a terrestrial laboratory poses a challenge with a substantial cosmic-ray induced background [Best 2016]. For example, a typical cosmic-ray-induced neutron flux on the Earth's surface is of the order of 10^{-3} cm^{-2} s^{-1}, whereas in an underground laboratory, such as the Laboratory for Underground Nuclear Astrophysics (LUNA) in the Gran Sasso mountain of Italy, the cosmic-ray flux is six orders of magnitude less. This has allowed them to measure several reactions operating in the pp-chain, in the solar interior, at or near the Gamow peak energy.

Elsewhere, in the erstwhile Homestake Gold Mine, South Dakota, USA, the Sanford Underground Research Facility has started operating the Compact Accelerator System for Performing Astrophysical Research [CASPER], close to one and a half kilometers underground. They will focus on measuring (α,n) reactions to identify the sources of neutrons for the s-process in dying stars, which is of very recent interest. Using high-efficiency neutron detectors and ensuring a low-background environment, will ensure measurements with low count rate at appropriate stellar energy conditions.

We, in India, are very well placed to enter this field of measuring stellar reactions with low-energy accelerators by constructing underground laboratories, in a geologically stable region. In fact, it would be most appropriate to enhance the scope of the already proposed INO project by including an appropriate low-energy accelerator to study the reactions relevant to the r- and s-processes at stellar energies. This will not only complement the already existing FRENA facility at SINP but also will make India an attractive destination for nuclear astrophysics.

1.2.3 Nuclear photonics

Nuclear photonics is an emerging field of research which will explore the properties of nuclei with the new generation of gamma-ray sources. A number of fundamental and applied problems, including nuclear safety assurance, production of low-energy positron beams, phase-contrast X-ray imaging, are studied in this field. Nuclear Photonics combines the research fields of laser and plasma physics, nuclear physics and accelerator science [Howell 2022].

Nuclear Structure: Collective Excitations

Collective excitations in nuclei can be studied with high-resolution photon beams employing nuclear resonance fluorescence (NRF) techniques [Zilges 2022]. This method can provide a complementary tool to investigate various vibrational excitations, e.g., giant and pygmy resonances, in addition to studying various details of the gamma strength function. Actinides with long lifetimes of the order of thousands of years can be studied using the new generation of gamma beams. Photofission enables the study of fission isomers in the deep sub-barrier region with very low cross-section. High-resolution studies with quasi-monochromatic photon beams can be used to study the fine structure of the isomeric states seen with bremsstrahlung and to explore, in detail, the shape of isomers in the deep sub-barrier region with very low cross-section. Another unique feature of photofission is the possibility to measure the g-factors of the isomeric states. Further, various isomeric studies can be pursued using the neutron-rich nuclei produced with a photon-induced RIB facility.

Fission Studies at Very Low Excitation Energies

Though the super-deformed second minimum in the potential energy surface of the fission barrier is well explored, the existence of a third minimum is still an open question and demands more experimental efforts to resolve the underlying picture. Photofission enables selective investigation of extremely deformed nuclear states in the light actinides, providing a better understanding of the multiple-humped fission barrier landscape [Balabanski 2015]. A future study on photon-induced fission can enable one to study the entrance channel effect, in addition to reaching the deep sub-barrier region, which cannot be reached via other reactions. Ternary photofission has not been studied yet. A polarized photon beam can fix the geometry of the process, which is an advantage over neutron-induced and spontaneous fission experiments performed for conducting detailed studies of this rare fission mode. The mechanism of emission of ternary particles and the role of the deformation energy, the role of the spectroscopic factor and the formation of heavier clusters are some of the related open problems.

Applications in fast reactors

For reliable design studies and safety assessments of future nuclear reactors, precise nuclear fission data are an essential prerequisite. Prompt-fission gamma and neutron decay studies are important for reactor applications. These have been investigated using neutron-induced reactions and surrogate reactions. Photon-induced fission can provide selective access to the second-chance fission channel, i.e., (γ, f) corresponding to (n, nf). This is important, in particular, in fast reactor applications. With all the new experimental and theoretical efforts, one can solve the mystery of the heat excess in the near future.

Nuclear Astrophysics with High-energy Photons

High-resolution beams of photons can respond to the need of nuclear astrophysics to perform accurate measurements of low cross-sections. Measuring the capture reactions by means of the inverse photodisintegration reaction has the advantage of having a different systematic uncertainty than those of the characteristic charged-particle-induced reactions measured at low energies of astrophysical interest. Such systematic issues may lead to different systematic errors allowing one to resolve the conflicting data. One can study the p-process by using the (γ,p) or (γ,α) reaction.

1.3 NEUTRINO-RELATED NUCLEAR PHYSICS

Nuclear physics experiments have played a significant role in testing different fundamental symmetries. This has led to stronger foundations for theories upon which nuclear and high energy physics are based. Pathbreaking discoveries of the violation of these symmetries have led to major leaps in our understanding of nature.

For example, neutrinos owe their discovery to the observation of beta decays of nuclei. The knowledge of nuclear structure and spectroscopy has played an important role in many significant advances in neutrino physics. This goes back to the discovery of parity violation by Wu et al. (^{60}Co), the identification of neutrino helicity by Goldhaber (^{152}Eu), the discovery of solar neutrinos by Davis (^{37}Cl, Nobel 2002), radiochemical experiments such as Gallex (^{71}Ga), the solution of solar neutrino problem at Sudbury Neutrino Observatory (SNO) using heavy water (Nobel 2015) and extends to even future detectors for supernova neutrinos that will use ^{157}Gd as a neutron absorber.

The topics discussed in this subsection belong to the overlap of high energy physics and nuclear physics. Although the physics issues involved are of crucial importance to high energy physics, the knowledge of nuclear structure and spectroscopy, as well as the experimental techniques needed, need the expertise of the nuclear physics community. Therefore, it is envisaged that these projects will be led and executed by nuclear physicists.

1.3.1 Neutrinoless double beta decay

The origin of neutrino masses is a fundamental question for which no answer has been found so far. One of the important steps in this quest is to determine whether neutrinos are Majorana or Dirac particles, i.e., if they are their own antiparticles or not. The only concrete, feasible and unambiguous way of determining this is to look for a neutrinoless double beta decay (NDBD) reaction in any nucleus. Such a reaction can occur only if neutrinos are Majorana particles. There are more than a dozen experiments worldwide, that are using different nuclei and different techniques, and are trying to reduce their background to levels where such a process could be observed. The lack of knowledge of the values of the relevant nuclear matrix elements makes it difficult to predict which nuclei will be able to show the first evidence of such a decay.

1.3.2 Sterile neutrino search and reactor neutrino monitoring

There are three species of active neutrinos in the Standard Model – electron neutrino, muon neutrino and tau neutrino. However, the presence of one more light neutrino, which does not interact via weak interactions but mixes with the active neutrinos, has not been ruled out yet. These sterile neutrinos, of masses ~eV, might be able to explain some of the anomalies at accelerator experiments such as the Liquid Scintillator Neutrino Detector (LSND) or the Mini Booster Neutrino Experiment (MiniBooNE), where a deficit in the number of active neutrinos has been observed. They might also help in accounting for the formation of supermassive stars and might form part of the dark matter. Since sterile neutrinos with eV masses lead to neutrino oscillations at very short distances, experiments to look for sterile neutrinos are set up close to nuclear reactors or as near detectors in long baseline experiments.

Scintillation detectors set up close to the nuclear reactors (at 10–100 m from the core) would be able to measure the deficit in the expected number of electron antineutrinos produced in the reactors, and hence the extent of their oscillations into sterile neutrinos. Multiple detectors at different distances can provide us better control over the measurements of neutrino masses and mixing. These detectors can increase our capability of monitoring the powers of the reactors. Technologies for the remote monitoring of nuclear reactors, including the ideas of creating a worldwide network for such monitoring, are being developed and pursued worldwide (e.g., the Water Cherenkov Monitor for Antineutrinos (WATCHMAN) in the USA). Developing such capability is not only of scientific but also of strategic importance. The Indian Scintillator Matrix for Reactor Antineutrinos (ISMRAN) experiment using antineutrinos from the ~100 MW Dhruva reactor, BARC, has been started in recent years.

1.3.3 Low energy solar neutrinos

The long-standing problem of the missing solar neutrinos has now been solved via the mechanism of neutrino oscillations. The mechanism implies the so-called large-angle Mikheyev-Smirnov-Wolfenstein (MSW) region in the parameter space of neutrino masses and mixing. This parameter space implies that the survival probability of electron neutrinos from the Sun is almost constant for $E > 5$ MeV. At these energies, the spectrum can be reconstructed using large water Cherenkov detectors such as the SuperKamiokande. Theory suggests that the survival probability of the electron neutrinos increases at low energies, the "upturn" expected to be sharp in the energy range of 1–5 MeV. Experiments that detect neutrinos in this range are crucial for confirming the solar neutrino solution over the complete energy range. Such experiments, if located in locations close to the equator, would also be sensitive to the matter effects through the core of the Earth, which give rise to the so-called "day-night effect", which has not been seen so far. This could be an opportunity for India to make a major contribution to the understanding of solar neutrinos, and the feasibility of specialized detectors for this purpose, such as those using deuterated liquid scintillator (DLS), should be explored.

Further, neutrino observations focusing on specific aspects of solar neutrino would enrich our knowledge of the interior of the Sun. For example, the standard solar model predicts a line spectrum of ^{7}Be electron capture neutrinos. Such a line spectrum cannot be observed at any of the current neutrino detectors such as Borexino or Jiangmen Underground Neutrino Observatory (JUNO), since they are based on Compton scattering, where the electron carries an unknown fraction of the neutrino energy in each interaction. An Indium-based low-energy electron neutrino detector could measure, in real time, solar neutrinos using the charged current interaction with a "peak" response to ^{7}Be neutrinos. Apart from an accurate measurement of the solar neutrino spectrum at low energies, it could be the first one to directly measure the temperature at the core of the Sun, by determining the width of the ^{7}Be spectral line.

1.3.4 Neutrino-Nucleus Interactions

The detection of neutrinos via new interaction channels, in new energy realms, have historically led to the discovery of physics beyond the Standard Model and to new insights into astrophysical sources. This has most famously been manifested in the fields of solar neutrinos and atmospheric neutrinos, which led to the discovery of a non-zero neutrino mass. Neutrinos are now being identified from extragalactic sources, opening up a high-energy realm that has been previously inaccessible. At the lowest accessible energies, neutrinos also provide a window into physics beyond the Standard Model, in particular, through the detection of coherent elastic neutrino-nucleus scattering (CENNS). This process is not only important for new physics searches through the neutrino sector but also relevant because it sets a possible ultimate background for direct dark matter detection.

The experiments would need a megawatt reactor-based facility having a movable core providing meter-scale proximity to the core, combined with the low-threshold cryogenic detectors developed for dark matter or neutrinoless double beta decay searches with the reactor. The low-energy threshold detectors will allow the detection of coherent scattering of low-energy neutrinos that are yet to be detected in any reactor experiment. The primary challenges in this investigation are: (a) availability of a low-threshold detector technology, b) reducing the background levels and c) proximity to the core.

Such experiments will open windows to exciting new physics of immediate, such as (a) precision CENNS measurements, (b) search for sterile neutrinos as a possible deficit in the predicted Standard Model rates using a precisely movable core, (c) searches for light and heavy Z' and (d) axion searches. In the international scenario, the Mitchell Institute Neutrino Experiment at Reactor (MINER) is a reactor-based experiment at Texas, which has Indian participation [Agnolet 2017]. At the national level, research reactor facilities to do such experiments need to be explored. Specifically, there are attempts to set up such experiments in the APSARA reactor by initiating a collaboration called India-based COherent Neutrino Scattering Experiment at Apsara-U (ICONSEA). This could be in combination with the sterile neutrino search and neutrino monitoring projects (see Sec. 1.3.2).

In addition, the role of theoretical calculations of the neutrino-nucleus cross-sections will be very crucial in understanding many features of their experimental measurements.

1.4 THEORETICAL NUCLEAR PHYSICS

1.4.1 Lattice QCD and Quantum Field Theory

Strong interactions between quarks and gluons are a fundamental force in our Universe and many important questions in fundamental physics are related to it. The physics of strong interactions is the reason for the emergence of almost all of the visible mass in the Universe and the understanding of the properties of subatomic particles. It might also play a role in the understanding of dark matter. The deconfined quark-gluon-plasma at the very early stage of our Universe, its phase transition to subatomic particles through complicated dynamics, the nuclear force that leads to the formation of all nuclei and also matter at extreme densities, e.g., in astrophysical objects such as the neutron stars: understanding of all of these require a detail knowledge of strong interactions. A large class of experiments at various high-energy laboratories, including the LHC, the upcoming FAIR facility, as well as EIC, are linked to various aspects of strong interactions physics [Gyulassy 2005] [McLerran 1994] [Shuryak 1980] [Aoki 2006].

QCD, the theory of strong interactions, is a gauge theory. It is highly non-perturbative in its low-energy domain, and so far, no analytical solution of this theory is available for investigating the physics mentioned above. Numerical computations, assisted by formalisms of the effective field theory, have become integral to understanding the physics of strong interactions.

From algorithmic developments to the design of large-scale supercomputers, physicists in this area of research have made tremendous contributions to the field of numerical simulations, including algorithmic developments for quantum computers. It is also envisaged that the application of machine learning to the physics of strongly interacting hadronic matter will not only help us in understanding this physics but will also lead to important understanding in deep-learning networks.

The future of research will consist of a judicious use of theoretical tools, supplemented with insights from experiments in order to understand strong interaction physics in its various aspects, starting from the early Universe to constructing tomography of nucleons. Using large-scale high-performance scientific computing, new algorithms and analysis techniques will be constructed and predictions on strong interactions in physics as well as other quantum systems will be made. Some of the investigations will comprise machine learning. In addition, development of algorithms for studying this physics on quantum computers is a part of our vision.

Some of the key ideas are listed below:

(i) Physics of the early Universe: This investigation would involve understanding the physics of nuclear matter under extreme conditions, such as that at the early stage of our Universe. In particular, the existence of a critical point in the phase diagram of nuclear matter, as well as the role of symmetry breaking at different phases of matter, through a synergy of large-scale numerical studies, exploration of new algorithms (lattice QCD methods), the formalism of effective field theory and real time dynamics of the early Universe deconfined phase of matter. A first-principles study of the first few nuclei is also crucial for understanding the formation of nuclei in the early Universe, particularly to understand the carbon cycle. Along with the lattice QCD findings, the effective field theoretical methods, in principle, can provide information about the bindings of higher nuclei. Study of scattering processes, particularly involving light nuclei, employing lattice QCD methods will be of immense importance to understand the nuclear reactions of light as well as heavier nuclei.

(ii) Emergence of mass and spin: The investigation of the emergence of mass and spin in all visible composite matter is of utmost importance in our understanding of nature. Lattice QCD methods provide a unique tool to study it from first principles with controlled systematics. Lattice QCD methods can already calculate the nucleon mass with an accuracy at a percent level. However, it is still intriguing how the collective interactions of tiny quarks and gluons emerge into a massive hadron. It is of fundamental interest to find how the mass of a composite subatomic particle, through the dynamics of strong interactions, decomposes into various parts, namely contributions from the quark condensate, the quark energy, the gluon field energy and the trace anomaly. Similarly, one can also study the emergence of spin of a composite particle from a combination of various parts, namely, quark spin contribution, gluon angular momentum contribution and the orbital motion of quarks. In fact, the future EIC will investigate the emergence of mass and spin. Detailed theoretical studies comprising lattice QCD calculations are very much necessary along with the EIC experiments to obtain the tomography of nucleons and other hadrons, which might also lead to new technological developments, including their applications to medical sciences.

(iii) Heavy hadrons, exotics and beyond the Standard Model: Investigations into the properties of heavy hadrons, particularly those having one or more bottom quark(s), are important because of their possible connection to the physics beyond the Standard Model and precision determination of a few Standard Model parameters, such as the decay constants and mixing parameters required for the Cabibbo–Kobayashi–Maskawa (CKM) matrix elements. A large number of exotic subatomic particles have recently been discovered with the valence quark content beyond the normal mesons (quark-antiquark pair) or baryons (three quarks). The theory of strong interactions allows the existence of such states and it is expected that more of such states, such as tetraquarks, pentaquarks, hexaquarks, hybrids, etc., will be discovered in the future. However, the quark structures of these exotic states still remain elusive and further detailed theoretical as well as experimental investigations are required.

(iv) Quarkonia and open quantum systems: The study of heavy quarkonia states in thermal media is an important tool for investigating various phenomenological aspects of the QGP produced in a heavy-ion collision and in the understanding of the dynamics of open quantum systems. At temperatures relevant to heavy-ion collisions, the coupling constant is not weak, and for quantitatively-controlled results, one needs to find the evolution equations without using weak coupling techniques. A powerful approach to do this is the utilization of the effective field theories which allows one to write the general structure of the Lagrangian based on general constraints such as symmetry. The coefficients of the terms in the Lagrangian can be computed using non-perturbative techniques.

(v) Sign problem, algorithmic developments for quantum computers: Although numerical methods have made tremendous advancement in the topic of strong interactions physics, for systems where dynamics is involved (equilibration of the quark-gluon plasma produced in heavy-ion colliders or in the early Universe), or at high densities (properties of matter inside neutron stars), the same numerical methods on classical computers require an exponentially large time with increment of sizes. To solve the impasse, known as the sign problem, novel conceptual works are necessary to make further progress and this is an important future direction of research. Significant progress on algorithmic developments using worldline methods involving cluster, meron and fermion-bag algorithms are being worked out that will enable us to access many strongly interacting quantum systems with the sign-problem. In addition, new theoretical techniques using quantum link models or qubit regularization are under development. Further, it will be worthwhile to investigate the efficacy of tensor networks as well as machine learning methods in the data-intensive field of numerical quantum field theory computations.

(vi) Connecting exotic theories: Recently, there has been a lot of progress in validating the gauge-gravity duality conjecture by studying the strongly coupled quantum field theories at finite temperature using lattice Monte Carlo simulations. Lattice simulations have been performed in the one-, two- and three-dimensional maximally supersymmetric Yang-Mills (MSYM) theories, which in the large-N limit, is dual to various types of black holes in Type II supergravity. Lattice simulations have shown that the temperature dependence of the MSYM free energy agrees well with the black-hole prediction from the perspective of gravity. Many other interesting features are still present in these models that are awaiting to be explored with the help of large-scale computer simulations. Numerical simulations of the models with complex fermion determinant, which are relevant for the holographic duality conjecture, would be an interesting endeavour. The new and rapidly expanding research strategy based on the complex Langevin dynamics can be used to simulate such theories, in addition to using the traditional Monte-Carlo-based approaches. This also has a connection to some other areas of research, such as the string theory and condensed matter physics.

1.4.2 Effective Field Theory

The derivation of nuclear physics from the Standard Model of particle physics requires methods that can deal with the complexity of QCD. This is a gauge theory written in terms of quark fields representing matter, and gluons, which are the gauge bosons of the strong interactions. However, proceeding from this to nuclear physics is difficult for two reasons. First, for quantities of interest in nuclear physics, the gauge coupling of QCD is large and thus prevents the use of the perturbation theory. For certain observables, one can use numerical techniques for the lattice formulation of

QCD in Euclidean space-time (as discussed in section 1.4.1). However, for the rest, the lattice techniques fail, essentially due to the intractability of the "sign problem". Second, the asymptotic states of QCD are hadrons and we do not know how to write their creation and destruction operators in terms of those of the quark and gluon fields. The generation of multiple length scales of hadronic physics obstructs the formulation of a renormalizable quantum field theory within which to describe the interactions of hadrons with an arbitrarily high accuracy. The method of effective (quantum) field theory (EFT), which developed out of the theory of renormalization, deals with this problem [van Kolck 1999].

This method has been applied to a host of problems across all branches of physics: particle physics, cosmology, plasmas and atomic physics, condensed matter physics, and of course, nuclear physics (see also section 1.4.3). Wherever multiple length or energy scales might complicate the physics, if some quantities of interest involve energy scales low enough that complications due to the higher energy scales do not enter directly, then this method can be used. The effect of other energy scales can be subsumed into effective constants, through which high energy (short distance) physics appears. Simple classical examples can help to build an intuition for this. When one studies the interactions of extended objects in classical dynamics, it is often useful to treat the bodies as nearly rigid. Then, the atomic-scale physics, which has been neglected so far, appears through material properties such as elastic coefficients. The dynamics of rigid or slightly deformable bodies are effective (classical) theories. One can also understand the origin of fluid mechanics in this way. The long-distance properties of fluid motion can often be treated with a neglect of the molecular degrees of freedom. The latter appear only through material properties such as viscosities and heat or charge conductivities. The resulting theories, the Navier-Stokes equations, or the magnetohydrodynamic (MHD) equations of a plasma are effective (classical) theories. Effective (quantum) field theories become useful in computing material properties from the interactions of atoms and molecules in these examples. In the following, we outline how EFTs are used nowadays in nuclear physics:

(i) QCD at finite temperature: Lattice QCD predicts the phase diagram of the equation of state of QCD and also the static correlations such as Debye screening (see also section 1.4.1). Using this information, EFTs have been constructed at finite temperatures, which are able to predict the dynamical properties, such as the conductivity in the QCD plasma, baryon diffusion coefficients and other material properties, that go into the construction of the bulk hydrodynamics and transport theory (also see section 1.4.3).

(ii) Nucleosynthesis in hot matter: Bethe's theory of stellar thermonuclear fusion depends on a low-energy approximation to reaction amplitudes which is equivalent to a non-relativistic EFT. The extension of this theory to other stellar reactions and to Big Bang nucleosynthesis are cornerstones of nuclear astrophysics. This EFT fails for nucleosynthesis in the extreme environment of heavy-ion collisions and a different EFT has to be used. More than one approach has been developed in recent years that explains the nucleosynthesis process and have testable predictions. Some of these also seem to have application to nucleosynthesis in other extreme situations, such as in the merger of neutron stars. See also section 1.4.6 and 1.4.7.

(iii) Neutron stars: The era of multimessenger astrophysics raises new challenges for nuclear physics in the form of a detailed and accurate understanding of the forms of nuclear matter in a strong gravitational field. EFTs based on QCD can provide screening and correlation properties of this matter in sufficient detail to test the formation of various condensates in this extreme form of nuclear matter. The presence of flavoured condensates changes the pathways for exotic nucleosynthesis during the mergers of neutron stars and therefore have further observable consequences.

(iv) The nuclear force and light nuclei: Following Weinberg's pioneering work, there has been enormous progress in the use of EFT techniques in reproducing nucleon-nucleon phase shifts. The methods utilized update the old ideas of current algebra using chiral EFTs and pionless nucleon EFTs. This has led to a significant progress in the understanding of the structure and reactions of nuclei with A = 2, 3 and 4. With a burgeoning data set on hypernuclei, these methods can be extended from two-flavour QCD to the broken three-flavour symmetry of QCD.

(v) Halo and cluster nuclei: EFTs have been written for understanding the structure, spectrum and reactions of halo nuclei. One very well-explored consequence is the emergence of Efimov states in some of these nuclei. The extension of these theories to four-body halo systems has also been investigated in detail. Different EFTs can be written for cluster nuclei, such as ^{8}Be, ^{12}C and ^{16}O, all of which are important in stellar astrophysics. See also section 1.4.6 and 1.4.7.

(vi) Neutrino interactions: Parity-violating terms are induced in nuclear EFTs due to weak interactions. Chiral EFTs as well as pionless EFTs have been used to describe the data on NN scattering. Computations of the corresponding form factors, to be used in neutrino interactions, is an active field. These form factors are of interest for neutrino detectors and for the computation of rates in dense neutrino-nucleus systems, such as in the early stages of supernovae after the formation of a neutrinosphere. Similar T-violating terms are also under investigation.

(vii) Detection of dark matter: Since galactic dark matter has very low energy in the Earth's frame of reference, interactions of dark matter with elementary particles is often described using EFTs. However, their detection involves interactions with complex nuclei. Nuclear EFTs allow the computation of structure factors for these nuclei to interact with dark matter. Such inputs are crucial for experiments designed to detect dark matter.

1.4.3 Phenomenology of Quark Gluon Plasma

Understanding the properties of the QCD medium holds the key to many important fundamental questions. Currently, the only way to access it in terrestrial experiments is relativistic heavy-ion collisions. Research in relativistic heavy-ion collisions provides an opportunity to study various phases of QCD including the location of a possible critical point [Gyulassy 2005] [Shuryak 1980]. An extremely small value of viscosity extracted from hydrodynamic analysis of the experimental data is close to the anti-de-Sitter/conformal field theory (AdS/CFT) predictions, which provides an attractive venue for the application of non-perturbative techniques developed by string theorists. A comprehensive understanding of all these factors will ultimately lead to a better understanding of the non-perturbative gauge field theories that can unravel the mysteries of the early Universe, Big Bang nucleosynthesis, neutron star physics and many more. The research field is diverse in the sense that it involves application of several areas of physics such as the quantum field theory, statistical mechanics, fluid dynamics, nuclear and particle physics, as well as big data analysis that needs machine learning techniques. Some of the highly relevant theoretical topics are the following:

- The QCD phase diagram and the QCD critical point
- The emergent phenomenon of a strongly coupled classical fluid-like behavior of the quark-gluon plasma (QGP) from the weakly coupled quantum system
- Nucleosynthesis of light nuclei and hypernuclei in the temperature range significantly above their respective binding energies
- Application of machine-learning and big-data-driven analysis to understand the equation of state of the nuclear and quark matter
- Phenomenology of heavy quarks and its relation to the thermalization of the femto-scale QCD matter produced in heavy-ion collisions
- Understanding the spin-orbital angular momentum interactions in relativistic heavy-ion collisions.
- QGP thermodynamics to the highest possible loop order within resummed perturbation theory
- Formulation of relativistic fluid dynamics with spin and magnetic fields
- Formulation of the first-order causal hydrodynamics and a chiral kinetic theory
- Estimation of the last scattering surface of hadrons in heavy-ion collision experiments
- Understanding the observations that are generally attributed to the QGP phenomenon seen in high multiplicity proton-proton collisions
- Understanding relativistic hadronic collisions using phenomenological approaches as used in heavy-ion collisions

Within the relativistic transport and dissipative hydrodynamic model calculations, some of the above topics have been semi-quantitatively approached. Discovery of the critical point has so far been elusive but is a key part of the program. One of the primary objectives would be to study the existence of the QCD critical point using a hydrodynamical simulation incorporating more data from experiments. To investigate the QCD critical point, viscous hydrodynamic models would be employed via modifications in the equations of state and coupling to models with phase transition such as the three-dimensional (3D) Ising model mapped to T – μ_B plane in QCD. In the Boltzmann transport simulations, the critical point would also be embedded via a mean-field equation of state and an appropriate collision cross-section. Furthermore, machine learning could also be utilized for estimating the Bayesian parameters by using emulators of hydrodynamic and transport models and employing bulk and jet observables, as well as to explore high-level representation of data using multiple processing layers trained by the QCD bulk observables in the models. Another direction is developing a framework of the coupled Boltzmann transport equations for open heavy flavor and quarkonium states. This can be incorporated in transport simulation, such as a multi-phase transport (AMPT) model that encodes soft and hard light jet production and rescattering until hadron production. Complementarily, the heavy flavor transport can be coupled with a relativistic viscous hydrodynamic simulation model. The methodologies can be used to simultaneously study open as well as hidden heavy flavor observables in QGP and quantify the transport coefficients and the QCD equation-of-state. The Bayesian parameter estimation methods would also be employed to the transport and hydrodynamic models and a large body of experimental data, and the temperature and baryon chemical potential dependence of the QGP properties can be accurately estimated.

Opportunities for theoretical efforts: Ultra-relativistic collisions of heavy atomic nuclei in experiments at existing facilities such as RHIC, BNL and LHC have provided measurements that are deeply related to the above topics. A wide range of physics opportunities exist with the advent of future collider experiments such as the EIC at BNL and the Compressed Baryonic Matter (CBM) experiment at FAIR, GSI and NICA, JINR. The recent discovery of gravitational waves has opened new windows to study the equation of state of the neutron star matter which is expected to be similar to that to be produced at future low-energy heavy-ion experiments such as CBM and NICA. This opens up exciting interdisciplinary research possibilities by combining our knowledge from gravitational wave detectors with that from heavy-ion experiments. To date, the theoretical framework for carrying out equilibrium, perturbative gauge field theory calculations are well developed. However, in our quest for a complete understanding of nature, the out-of-equilibrium non-perturbative methods are indispensable. While theoretical tools are being developed to make advances on this front, relativistic heavy-ion collisions provide us with a unique opportunity to put these techniques to test and provide positive feedback that can, in turn, guide the experimental endeavors in the right direction.

1.4.4 Modern ab-initio approach for nuclear theory

With the recent advancement in the many-body theory, it is now possible to predict nuclear properties using modern ab-initio theory very precisely [Barrett 2013] [Manea 2020] [Nunes 2021]. This can be achieved by constructing an NN or NN+3N interactions derived from the different approaches such as the chiral effective field theory and forces derived from meson exchange [Machleidt 2011]. Finally, one has to solve the Schrodinger equation for A particles, using modern many-body methods such as: the no-core shell model (NCSM), coupled cluster (CC) theory, Green's function Monte Carlo (GFMC), lattice effective field theory, symmetry-adapted no-core shell model (SA-NCSM), many-body perturbation theory (MBPT) and in-medium similarity renormalization group theory (IM-SRG). These approaches build upon "first principles". With these modern approaches, it is possible to answer several puzzles in the nuclear structure, nuclear reactions and astrophysical problems.

The major questions that drive the quest for a microscopic theory of finite nuclei include:

- How do the nuclear shell and collective models emerge from the underlying theory?
- What are the conventional properties of nuclei with extreme neutron/proton ratios?
- What controls nuclear saturation?
- Can nuclei provide precision tests for the fundamental laws of nature?
- Under what conditions do we need QCD to describe nuclear structure and reactions?
- How precisely can we calculate the nuclear transition matrix elements (NTMEs) using an ab-initio theory for double and neutrinoless double beta decay?
- Is it possible to predict weak-interaction processes, such as allowed and forbidden beta decay, more precisely?
- Is it possible to precisely locate the drip line for exotic nuclei?

The requirements and goals in the next decade are as follows:

1. Modern computational facilities dedicated to ab-initio theory are required.
2. It is very important for Indian nuclear physics groups to propose an experiment using the INGA facility to verify the ab-initio prediction where experimental data are not available.
3. To motivate Ph.D. and Post-doc students in the direction of ab-initio theory as much as possible. This will require developing a strong foundation at the undergraduate level to equip students to opt for theoretical work beyond the Bachelor's degree.
4. To strengthen our collaborative work with international labs where radioactive-ion beam facilities are available.
5. To extend the theory beyond the current limitations toward medium mass and heavier nuclei and larger model spaces.
6. To study multiple branches of physics such as astrophysics, neutrino physics and applied physics using the first principles theory

1.4.5 Density Functional Theory

The density functional theory (DFT) has turned out to be the most promising tool for investigating the rich and fascinating properties of the quantum many-body systems [Schunck 2019]. In particular, in nuclear physics, it allows us to investigate the properties of nuclei across the entire Segre chart, which is impossible using the wavefunction-based approaches. Following the pioneering work of Skyrme, the DFT approach in nuclear physics has been extended to include fractional density dependence terms in the energy density functional in order to describe the compressibility of nuclear matter. It has been demonstrated that there is a direct correlation between the density dependence and the compressibility parameter, and a fractional density dependence is required to explain the empirically deduced compressibility parameter from the breathing mode. The fractional density dependence can be explained using the Kohn-Hohenberg theorem of DFT, originally introduced in atomic physics.

Although the Skyrme DFT approach describes the ground-state properties of atomic nuclei reasonably well, it has been shown that the accuracy of the obtained results cannot be improved further using the standard density functional. The parameters of the energy density functionals are fitted to the observed properties and it has been established that the inclusion of more data points in the fitting protocol does not improve the results. It is, therefore, imperative to enrich the basic density functional in order to have a better quantitative description of the experimental data. There are several avenues for advancing the basic framework of the energy density functional in nuclear physics.

Recently, attempts have been made to improve the isospin dependence of the density functionals. The standard functionals violate the isospin symmetry with the neutron and proton degrees of freedom treated separately. In the isospin conserved DFT approach, all the three possible terms of the isovector and the isoscalar terms are treated on the same footing. Preliminary results using this isospin invariant approach has revealed that drip lines can be altered with the inclusion of all the possible terms as mandated by the isospin symmetry.

The isospin invariance has been included in the particle-hole channel, and in order to perform realistic calculations, it is imperative to include the isospin symmetric particle-particle channel in the DFT approach. The development of the isospin conserved energy density functional for atomic nuclei shall form the major research activity in the future. Further, it is also important to develop beyond mean-field models in the DFT approach [Sheikh 2021], which shall form another major research endeavor of the present work.

1.4.6 Dynamical nuclear reaction calculations

Nuclear reaction theory continues to be one of the most relevant contemporary research topics in physics. On one hand, for light systems, exact or nearly solvable models can be used, and on the other hand, in heavier and more complicated many-body systems, one has to live with more approximate methods. However, in recent times, we are beginning to see a new level of sophistication, where, even in many-body systems, one is able to study the details of the individual quantum states. It is this excitement that gives the low-energy nuclear reaction theory very attractive prospects [Johnson 2020] [Bonaccorso 2018] [Chatterjee 2018].

Advances in analytical methods along with the advent of new capabilities in computing systems and new types of algorithms are playing a major role in this field. India is particularly poised to take advantage of these at the present juncture. It will not be an overstatement to say that we must remain at the forefront in nuclear reaction theory or, in general, in nuclear theory itself if we want to lead in science and technology of the 21st century. This field continues and will continue to have a bearing even on day-to-day problems as diverse as energy, food, medicine and security.

Constructing dynamical reaction theories applicable across the nuclear chart is still an interesting challenge. Currently, there seem to be three approaches that look promising.

(i) A fully microscopic approach in which all nucleons in the scattering process are considered and antisymmetrization of the nuclear many-body wave function is treated exactly. In the 3- or 4-nucleon sector, the Faddeev-Yakubovsky technique describes scattering or reaction observables starting from the NN and NNN interactions. The *ab-initio* techniques using the resonating group method (RGM) with the NCSM or the antisymmetrized molecular dynamics (AMD) model has been used to describe the reactions involving light nuclei with semi-realistic NN interactions with adjusted parameters. EFT techniques have also been used to model reactions involving light exotic nuclei. Though computationally intense, it would be interesting to study their extensions to the medium and higher mass region of the nuclear chart.

(ii) The second approach, which is increasingly relevant today, is to construct a unified theory of nuclear structure and reactions. This involves the coupling of bound (or quasi-bound) states with those of the continuum within the same theory. This would involve working with non-hermitian Hamiltonians, which technically brings the study of nuclear physics under the ambit of 'open quantum systems'.

(iii) Among all attempts, the third and arguably the most popular is a "few-body" approach that describes the process of scattering among "structureless" clusters (inert cores) and usually involves nucleon-nucleus (optical) potentials fitted to some reaction observable. Reactions involving nuclei with low and medium mass as well as heavy-ions have been modelled with this approach. It would be interesting to carry forward this approach with more microscopic inputs in reaction calculations.

In future, one looks forward to more robust theories for processes such as breakup, transfer and heavy-ion reactions involving these approaches. One would then be ready with theories to confront data on exotic nuclei far from stability emanating from new radioactive-ion beam facilities across the world. Further applications for societal needs, including modelling reactions relevant for energy generation in nuclear reactors, would be a very welcome step.

1.4.7 NUCLEAR NETWORK CALCULATIONS FOR NUCLEOSYNTHESIS

The core ideas in the pioneering work of B^2FH [Burbidge 1957] and Cameron [Cameron 1957] are still relevant today in our quest to decipher the origin of baryonic matter that we see around us. Nuclear reaction rates, most often at low energies, determine the elemental abundance, and in turn, the fate of stars. Astrophysics thus requires various inputs from low-energy nuclear physics such as masses, Q-value, beta-decay rates, capture cross-sections to model and stellar evolutions, and eventually, stellar explosions. These data are primarily based on the study of stable nuclei or are stochastic [Lippuner 2017] [Arcones 2017] [Nunes 2020]. However, with the study of nuclei far from stability gaining prominence in the last few decades, even foundational concepts such as "magic numbers" are being revised. We can now distinguish the effects of even individual quantum states in nuclei in the nuclear reaction observables. These fundamental advances in low-energy nuclear physics will have a profound impact on astrophysics.

The abundance of elements, even the light and medium mass ones, are far from being fully understood. Even for the lithium abundance problem, solutions involving nonextensive Tsallis statistics are being proposed. While the s-process creates elements at or near the valley of stability, the r-process is mainly responsible for creating neutron-rich nuclei. The question of the actual sites for the r-process is still open. The recent observation of a kilonova, resulting from a binary neutron star merger, has also opened up the possibility that kilonovas are sources of copious r-process elements [Metzger 2010]. How can the abundance of r-process elements be affected in a strong magnetic field environment, such as that in a neutron star, is also an open question.

Very recently, observations in carbon-enhanced metal-poor stars, lead-deficient metal-poor stars and some others have confirmed the existence of an intermediate nucleosynthesis process (i-process). It is termed as intermediate because it leads to the production of isotopes that are not as neutron-rich as those expected from the r-process, and yet, are further away from the typical stable s-process isotopes.

Therefore, this is a very opportune time to support programs for network calculations for the nucleosynthesis process. Robust theories and measurements of radiative captures, transfer reactions, beta-decay rates and nuclear masses would be vital prerequisites. One would require reliable data for stable nuclei and exotic systems far from the valley of stability. Given the scarcity of data in this region, one often relies on global assumptions about the nuclear properties and cross-sections extracted from stable nuclei. In order to account for these uncertainties, sensitivity-analysis calculations also need to be performed. They typically involve varying the input data within their error bars and then checking for the fluctuations in the final results. Recent advances in big data analyses could be helpful in such calculations.

1.4.8 Electric dipole moments

The electric dipole moment (EDM) of an electron would be a result of the parity (P) or time-reversal (T) violating interactions. Although these discrete symmetries are broken by the weak interactions, the values of EDMs predicted in the SM are orders of magnitude smaller than the current upper bounds determined experimentally. Certain extensions of the SM predict higher EDMs and these could be tested by future experiments trying to measure this quantity precisely. Thus, even though these indirect tests of the SM are, in principle, unable to identify the underlying fundamental theory, they are sensitive to the physics at a much higher energy scale than that accessible at colliders.

An atom or a molecule could also possess an EDM due to the possible existence of (i) the electron EDM, (ii) P- and T-violating (P,T-odd) electron-nucleus interactions and (iii) the hadronic charge-conjugation and parity (CP) violation. Limits on the electron EDM can also be obtained by measurements of atomic or molecular systems such as the paramagnetic Tl atom or the diamagnetic ^{199}Hg atom. Precise calculations of these atomic or molecular environments, that use the state-of-the-art relativistic many-body methods, have been undertaken by some Indian groups.

1.5 FUSION AND PLASMA PHYSICS

1.5.1 Physicochemical processes in plasma-liquid/solid interactions

As plasmas cover orders of magnitude in density, temperature and elemental composition, they can be used for various practical applications such as surface modifications, environmental remediation, medicine, agriculture, aerospace, food, textile, etc. [Chen 1984]. In the last two decades, several plasma-based technologies have been developed/deployed at the Institute for Plasma Research (IPR) and various institutions (BARC, AIIMS, TMC, Anand Universities, etc.) in India. For the development of these devices, better understanding of the underlying mechanisms behind the working of these devices is very important. Some examples to understand the key factors responsible for the intended functions are given below:

Application	Challenging issues
Air purification	Plasma chemistries during interaction with polluted air
Water purification	Physical and chemical processes in various electric field conditions at the plasma-liquid water interface
Plasma sterilization	Role of ultraviolet (UV) and reactive oxygen nitrogen species (RONS) during their interaction with solid surfaces.
Agriculture	Various interactions between the plasma (e.g., reactive oxygen species (ROS), reactive nitrogen species (RNS) and UV) and the seed surface for seed-borne pathogens, and cellular homeostasis
Climate	Plasma processes in the context of global warming mitigation

There are many other challenging unanswered questions that are less explored today. Efforts should be made towards quantifying and validating the repeatability of the effects of plasma for the abovementioned applications. A balanced research focus consisting of application research is required to reap maximum benefits of plasma-based technologies. This will enable India to be Atma Nirbhar providing novel and cheap technologies for the benefit of the society.

1.5.2 Thermodynamic and transport properties of plasmas under extreme conditions

A pulsed-power approach to inertial fusion energy (IFE) requires production of large yields (Megajoules) of soft X-rays at high power (100s of Terawatts) [Prestwich 1992]. This thermal radiation falls on a solid (hohlraum), producing intense shock waves and compression/ignition of deuterium-tritium (D-T) fuel capsule to fusion conditions. India has developed many systems based on pulsed power, such as the fast capacitor bank, Marx generator, Tesla transformer, pulsed X-ray system and its diagnostics at lower scale, e.g., a 1.25 MJ. 44 kV fast bank, KALI-5000, etc. More than 20 institutions in India are working in these areas, including BARC, IPR, Indian Institute of Science (IISc), Raja Ramanna Centre for Advanced Technology (RRCAT), etc.

Scientific issues include instabilities during implosion, coupling the equations of radiation transport to MHD in the dense plasma resulting from the implosion, study of the equation of state (EOS), opacity and resistivity of dense plasmas, and the non-equilibrium behavior of the dense plasmas. Several technological challenges have to be met, e.g., fast capacitor bank, fast flux compression generator (FCG), coaxial and disk explosive magnetic generator (CEMG/DEMG), pulsed forming lines (vacuum, magnetically insulated), fabrication of thin foils and wire arrays, etc. The understanding obtained by addressing these issues will help us understand the behavior of plasmas in extreme conditions.

1.5.3 Quantum entanglement in ultracold plasmas

As against a classical binary digit or "bit", which obviously takes only two distinct values or states, viz. "0" or "1", quantum bits or qubits can be structured to have a large number of distinct quantum states due to their superposition and N-body quantum entanglement [Nielsen 2010].

While the RF-based linear quadrupole Paul traps have been successful in providing a physical implementation of qubits, RF-driven ion-heating is known to work against laser cooling, thus increasing the de-correlation effects. Similarly, the slow motion of the heavy ions in a shared trapping potential is known to restrict the "Gate" speed. This ion motion also limits coherence and increases the control errors and scalability. To increase the number of "distinct" states for quantum computing, increasing the number of particles, N, that are quantum-entangled is expected to help, but has not been achieved yet in any experimental setup. Using quantum-entangled electrons or ions in a toroidal geometry might be the key to alleviating several of the abovementioned challenges. N-body quantum entangled gates using ultracold plasmas will be the future of quantum computing.

Involvement of experts in quantum computation algorithms is essential for accomplishing the final goals of this project.

1.5.4 Multiscale kinetic processes in plasma systems

Simulation of plasma involves scale length of a few micrometers (gyration of a charged particle) to a few meters (device size) and the time scales vary from a few nanoseconds (plasma oscillation period) to a few tens of hours (steady-state operation). Usually, plasma dynamics involves plasma production (atomic/molecular processes), plasma transport (diffusion, cross-field, anomalous, etc.), instabilities, plasma-wall interaction (secondary emission, sputtering, ablation and erosion), plasma chemistry, sheath formation, turbulence, high-field effects, etc. In each plasma device, it is a complex interplay of many of these phenomena. Thus, such simulations require techniques such as particle-in-cell (PIC), Monte-Carlo (MC), molecular dynamics (MD), kinetic/gyro-kinetic, MHD and multi-scale methods. Integrated tokamak modeling (ITM) is a worldwide activity carried out to integrate plasma physics phenomena relevant to the tokamak plasma to predict its performance, and IPR is also part of it through the ITER project.

1.5.5 Magnetic reconnection in lab plasmas

The enormous range in length and time scales of various astrophysical phenomena can be "mimicked" in large-scale laboratory experiments, as the governing equations are known to be invariant under certain "similarity scaling" of length L, time T and other dimensional parameters. Based on such "similarity scaling", several laboratory-scale astroplasma experiments are under operation worldwide and several more have been proposed.

Magnetic reconnection, which involves the topological reconfiguration of magnetic fields, is a fundamental process that is believed to be important for understanding charged-particle heating and acceleration, reconnection and transfer of energy across huge scales in space and time via turbulence [Tripathi 2010]. This process is believed to be universal: from the near-Earth plasmas to helioplasmas to magnetospheres to interstellar medium to supernovae, and to the extreme space weather, as well as for the success of laboratory fusion plasmas.

The plasma resistivity, h, the speed of plasma flow, V_A, and the length L determine whether a plasma is "collisional" or "collisionless" via a dimension-less Lindquist number, $S = \mu_0 L V_A/h$. In the near-Earth, helio- and astro-plasmas, S varies over a wide range, and hence, from collisional to collisionless physics. Investigating the rate of reconnection on S requires control on V_A (the plasma flow conditions), on the L scale, and on h in the laboratory, which is a major challenge in understanding the dependency of the reconnection rate on S even in near-Earth and helioplasmas, let alone astro-plasma conditions, where high-energy relativistic effects are expected.

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2 NUCLEAR AND PLASMA PHYSICS FACILITIES

The modus operandi of most nuclear physics research programs worldwide is based on “facilities”, that provide access to the production and acceleration of nuclear isotopes. Adequate infrastructure of such facilities would form the basis on which future mega projects can operate and their availability is crucial for interesting and feasible scientific ideas to even be conceived. In addition to the accelerators, reactors and photon or neutron sources around which the current nuclear physics and plasma physics research is built, modern facilities such as high-intensity lasers, pulse-power for inertial fusion energy and plasma traps for quantum computing are some of the cutting-edge technologies that need to be developed. High-performance computing forms the backbone of a major fraction of theoretical as well as experimental activities. The availability of an underground laboratory in the country would allow scientists access to a much wider canvas of scientific questions to address.

2.1 ACCELERATORS

In India, during the last 30 years, a lot of leading research activities have been performed using the stable-ion beam facilities at Mumbai (BARC-TIFR Pelletron LINAC Facility at TIFR), Delhi (Pelletron-LINAC at IUAC) and Kolkata (cyclotron at VECC). It is absolutely necessary to upgrade these accelerators to continue the physics programs at these three accelerator centers [Vision2014]. A high-current low-energy accelerator has been installed at SINP, which will be used for nuclear astrophysics. Table 1 provides the details of the accelerators within India that are used for low-energy nuclear physics experiments. In order to take our scientific endeavor to the level of current international pursuits, it is desirable to build a new facility for rare-ion beams that will open up a large avenue for new discoveries. The current and proposed R&D efforts on the production of RIBs using existing ion accelerators and the upcoming electron accelerator within the country is already a major step in this direction. The new RIB facility can have strong involvement of different research institutes and universities from the beginning, to take advantage of the scientific and engineering expertise available within the country. Modular design, flexibility in the procurement procedures for readily available components and focused developmental efforts are essential for a timely implementation of the project. Foreign collaboration and consultation need to be strongly supported for this facility.

These facilities have a strong user base across many countries and play a vital role in the basic research carried out by researchers using state-of-the-art instrumentation. Visiting programs could be organized at such facilities to encourage international researchers to start scientific collaborations.

Table 1: Details of currently operating accelerator facilities in the country for nuclear physics users

Accelerator	Available Beams	Energy and Current	Major Experimental Programs	Beam Lines and Major Experimental Facilities	Current Users
BARC-TIFR Pelletron-LINAC Facility, TIFR, Mumbai	^{1}H, ^{4}He, $^{6,7}Li$, ^{9}Be, $^{10,11}B$, $^{12,13}C$, ^{14}N, $^{16,18}O$, ^{19}F, ^{22}Na, ^{24}Mg, ^{27}Al, $^{28,30}Si$, $^{32,34}S$, $^{35,37}Cl$, ^{38}K, ^{40}Ca, ^{48}Ti, ^{58}Ni, ^{107}Ag, ^{127}I, SF_6 molecular beam	5–8 MeV/A up to Ni. 1–5 pnA (for some of the beams such as Li and C, one can get up to 10–20 pnA)	• Nuclear Physics • Atomic Physics • Condensed Matter Physics • Radiochemistry • Agriculture • Terahertz Devices • Medical-isotope R&D • Accelerator Mass Spectroscopy (AMS) • Industrial and Space-science related applications	12 Beam Lines 1. 6M high current proton irradiation facility, 2. Two general purpose scattering chambers 3. Large HPGe array (INGA) 4. Neutron array 5. High-energy gamma detector 6. Fission MWPC detector array 7. Charged particle scattering chamber (CPSC) 8. Strip detector array 9. Low background facility 10. g-factor measurement setup with a 7 T magnet 11. Beam scanner 12. Isomer studies with beam chopper	260 Users – National, International Institutes/Centres, Universities, IITs, ISRO, etc.
K130 Room Temperature Cyclotron, VECC, Kolkata	H, ^{4}He, ^{14}N, ^{16}O, ^{20}Ne, ^{32}S	1–10 MeV/A 1enA–4 eμA	• Nuclear Physics • Atomic Physics • Material Science • Radiochemistry • Analytical Chemistry • Biology • RIB production	4 Beam Lines 1. Facilities for irradiation 2. General purpose scattering chamber 3. INGA 4. VENUS and VENTURE arrays 5. An array of neutron detectors 6. An array of large-area	National Institutes/Centres, Universities, IITs, ISAC(ISRO), IIEST, etc.

				modular BaF_2 detector (LAMBDA) 7. Fission PPAC and MWPC detector array 8. Charged-particle detector array	
IUAC Pelletron-LINAC and LEIBF facility, New Delhi	^{1}H, ^{6,7}Li, ^{9}Be, ^{10,11}B, ^{12}C, ^{14,15}N, ^{16,18}O, ^{19}F, ^{24}Mg, ^{27}Al, ^{28,29,30}Si ^{31}P, ^{32,34}S, ^{35,37}Cl, ^{40}Ca, ^{45}Sc, ^{46,48}Ti, ^{51}V, ^{56}Fe, ^{58}Ni, ^{63}Cu, ^{64}Zn, ^{74}Ge, ^{79}Br, ^{107,109}Ag ^{120}Sn, ^{127}I, ^{197}Au	3–8 MeV/A 1–5 pnA	• Nuclear Physics • Material Science • Device Fabrication • Radiation Biology • AMS • Radiation Physics	8 Beam Lines 1. Gamma Detector Array (GDA) 2. INGA 3. Heavy-ion Reaction Analyzer (HIRA) 4. HYbrid Recoil mass Analyzer (HYRA) 5. General purpose scattering chamber (GPSC) 6. National Array of Neutron Detectors (NAND) 7. ASPIRE (Automatic Sample 8. Positioning for Irradiation in Radiation Biology Experiments 9. Beam-foil spectroscopy apparatus	100 research groups (covering all accelerator-based research) from nearly 160 Universities, 85 Colleges and 60 other National laboratories.
FRENA Tandetron facility, SINP, Kolkata	^{1}H, ^{4}He, Heavy ions	0.2–3 MeV 50–300 μA	• Astrophysics	5 Beam Lines 1. Small target chamber for gamma spectroscopy and neutron detection	
Folded Tandem Ion Accelerator (FOTIA), BARC, Mumbai	^{1}H, ^{6,7}Li	6–12 MeV, 1–5 pnA	• Nuclear Physics • Atomic Physics • Radiochemistry • Biology	1. General purpose scattering chamber 2. PIXE 3. Rutherford Backscattering 4. PIGE	

Future Plans for Existing Facilities

BARC-TIFR Pelletron-Linac facility: The heavy-ion accelerator augmentation is in progress with the new accelerating tubes for the pelletron and the replacement of the Pb-based superconducting RF cavities by the Nb cavities in the entrance module. The upgradation of this accelerator is expected to be completed in the next 2-3 years.

IUAC: There has been considerable progress in the plan to develop a high current injector (HCI) for the superconducting linear accelerator (LINAC). A radiofrequency quadrupole, one unit of drift tube LINAC and a prototype Nb low-beta cavity have been designed and fabricated. The HCI will allow heavy-ion beams to overcome the Coulomb barrier for high-Z systems in the next five years.

VECC: A K500 superconducting cyclotron has been constructed at VECC. It comprises India's largest superconducting magnet that produces a magnetic field of 5 T (maximum). Recently, a significant milestone has been achieved by successfully extracting 252 MeV nitrogen-ion beam (i.e., 18 MeV/A) from the K500 superconducting cyclotron, which was delivered in the 0° line to the user target/scattering chamber.

SINP: The Facility for Research in Nuclear Astrophysics (FRENA) is a unique facility in the country that is most suitable for low cross-section measurement of astrophysical reactions. At present, only one beamline is ready and a total of five beamlines are planned. sA windowless gas target and/or gas jet target is being developed. Recoil separators also form a part of the long-term future plan in the expansion of FRENA. A future extension to an underground facility will enable the study of H- and He-burning reactions around the Gamow energy (of the order of 10s of keV).

Upcoming/Proposed Facilities

RIBs:

RIBs are accelerated beams of radioactive nuclei. The conventional particle accelerators accelerate beams of stable isotopes available in nature such as ^{4}He, ^{16}O, ^{14}N, etc., to name a few. However, there is a big demand for beams of unstable or radioactive nuclei for various experiments in materials science, radiobiology, nuclear physics and nuclear astrophysics. Because the radioactive nuclei have a finite half-life, one needs to first produce them by bombarding a suitable target with stable isotope beams and reaccelerate the radioactive nuclei after separating them online in an isotope separator. The intensity of an RIB depends on the intensity of the primary stable isotope beam, the production cross-section, the thickness of the target and efficiencies of various stages, namely, production, ionization, separation and reacceleration. There is an intense R&D ongoing worldwide for optimizing these processes with the aim of accelerating copious variety and quantity of RIBs. Almost all leading research labs such as CERN, RIKEN, GSI, Michigan State University (MSU), GANIL and TRIUMF have built RIB facilities and are constructing the next generation facilities.

At VECC, a low-energy RIB facility has been built around the K130 cyclotron with the aim of conducting R&D on the production technology for RIBs. The work completed so far includes the design development and commissioning of the online electron cyclotron resonance (ECR) ion source, online isotope separator, two heavy-ion radio-frequency quadrupoles (RFQs), three interdigital H-type (IH) LINACs, three rebunchers, etc. The maximum beam energy obtained currently is 5.8 MeV for nitrogen, and the facility is mostly being utilized for ion-beam based materials science studies. Two more LINAC cavities have been installed in the beam line and a maximum energy of 14 MeV for the nitrogen beam will be available once these are commissioned. A superconducting heavy-ion LINAC has also been designed for accelerating ion-beams to higher energies. So far, a few RIBs e.g., ^{14}O, ^{42}K, ^{43}K, ^{111}In have been produced using the proton/alpha-particle beam from the cyclotron. A ^{7}Be beam was developed in IUAC in 2001 and an experimental campaign was organized. In BARC-TIFR, PLF experiments with radioactive targets have been initiated.

Recently, a 3 MV pelletron accelerator has been set up in Guru Ghasidas University, Bilaspur. More of this type of low-energy and small sized accelerator facilities can be built, operated and maintained on a typical university campus. These facilities can be used for nuclear physics and application-based research. To ensure uninterrupted operation of these facilities, their maintenance and necessary upgrade needs to be done in a centralized way [Joshi 2020].

Van de Graaff Accelerator:

It has been proposed to build a low energy accelerator facility based on a single ended 5 MV Van de Graaff accelerator. The first phase envisages the setting up of a ^{14}C dating facility that uses the positive ion mass spectroscopy (PIMS) technique. This will be only the 2nd facility worldwide, have a very compact footprint and cater to the archaeological research in the northeastern region. In the second phase, the facility will be setup along with a recoil mass separator and will be used mainly for (i) measuring nuclear cross-sections around the Gamow energy that are crucial for understanding stellar core “burning”, including measurements with rare-gas beams in inverse kinematics and (ii) generating intense neutron beams that will be used for measuring neutron cross-sections relevant to fission and fusion reactors and for the accelerator-driven Boron Neutron Cancer Therapy (BNCT). Research in this area would enable India to compete with just a few labs available worldwide. There also are other applications in condensed matter (study and seeking of beneficial effects of swift-ion irradiation of materials) and life sciences (using microbeams to cause mutations).

The time scale envisaged for the PIMS facility is 2.5 years and for the full project is 9 years. The total cost is estimated to be about ₹300 cr. Additionally, new accelerator proposals from Panjab University and Mangalore University have also been under consideration. Further information about the proposed new accelerators will be a part of the Accelerator-based Science and Technology MSV2035 document.

High-intensity Ion Beam Facility

A new high-intensity ion beam facility, with energies at and above the Coulomb barrier, is considered to be one of the important issues of the nuclear physics community. The facility should be capable of accelerating ions from proton to uranium and deliver high-intensity beams at the target position. Selected physics problems to investigate rare events in nuclear physics using modern high-resolution spectrometers and detectors can be addressed using such a facility. Research with high-intensity beams of stable nuclei continues to produce high-impact science. We also need to remember that discoveries at exotic beam facilities will raise new questions, the answers to which are accessible with stable beam facilities. One of the possible configurations will be a LINAC that can provide high-intensity beams from H to U with energies up to 10 – 20 MeV/A.

The combination of high-intensity stable ion beams and an isotope separator online (ISOL) or in-flight separator equipped with a gas catcher technique can provide intense and exotic beams of low-energy radioactive ions. Using multi-nucleon transfer reactions, one can produce neutron-rich heavy isotopes. A mass-separator of radioactive isotopes ionized by the laser resonance ionization method will be a powerful source for decay spectroscopy study of rare isotopes. In addition, such a machine will be useful for BNCT, high-productivity isotope generation and material science.

Proton-driver-based RIB:

Phase-wise development of the proton accelerator has already started for the 1 GeV Accelerator Driven Sub-System (ADSS) project that will be constructed at Visakhapatnam. As a part of it, a 3 MeV beam of proton with 300 μA current has been achieved at the Low Energy High Intensity Proton Accelerator (LEHIPA) facility. This accelerator is planned to be used as the driver accelerator for RIB once it reaches 50 MeV of proton energy. This will be complementary to the photofission-based facility. With the availability of a proton beam, it will be possible to not only produce neutron-rich radioactive ions via fission but also slightly proton-rich ions through transfer reactions. At later stages, if and when very high energy proton beams are made available at the accelerator complex at Visakhapatnam, fragmentation reactions can be used to produce an even broader range of radioactive ions. It is important to have a national RIB facility at Visakhapatnam with the possibility of multiple RIB species to perform research in frontier topics.

The post accelerator can be connected to two separate ECRs for multiplying the charge state of the stable and radioactive ions, respectively. Thus, the post accelerator can provide a high-current stable-ion beam as well as RIB.

The cost of the above two projects will be around ₹1000 cr. The time-scale will be 8 to 10 years from the approval of the project.

Nuclear Physics at the Proposed New 6 GeV Synchrotron Facility at Indore:

The inverse Compton scattering (ICS) process finds a very special place as a dominant radiative process in most astrophysical environments. It is recognized as an important source of very high energy gamma-ray photons as well as an energy sink for electrons in the pure leptonic models. The development of a terrestrial compact source of gamma-ray photons with high intensity and tunable energy based on the ICS process will enable to study the physics of Compton scattering in the classical (Thomson) and quantum mechanical (Klein-Nishina) domains and phenomena of gamma-gamma collision for pair production. These two processes are critical for explaining the non-thermal emission and propagation of very high energy gamma-ray photons in the astroparticle physics research.

It is proposed to have a beamline for the ICS experiments (ICSE), producing high-energy tagged polarised photon beams, which will usher an era of doing experimental hadron spectroscopy, studies on vector meson properties, excitations of baryonic states of nucleons, K-meson production and parity measurements. The gamma beams available at RRCAT will allow for the performance of photonuclear reactions aiming to reveal the intimate structure of the atomic nuclei, nuclear resonance fluorescence, photofission, photodisintegration reactions, studying the dipole response of nuclei, the structure of the Pygmy resonances, nuclear processes relevant for astrophysics, production and study of exotic neutron–rich nuclei. In particular, focus will be on the precision measurement of the photonuclear cross-sections of reactions on light nuclei and measurements of the key nuclear reaction rates relevant to He-burning in stars, with emphasis on the Hoyle state and Hoyle analog states in α-clustered nuclei.

2.1.2 International accelerator facilities

In this subsection, we briefly discuss the available facilities to carry out the mega science nuclear physics program in the coming decade. There are three categories of accelerator facilities for the community:

(a) The accelerator facilities where India already has a direct stake in the building of the facility (RHIC, LHC and FAIR)

(b) The accelerator facilities where collaboration is continuing at a modest scale (SPIRAL2, ISOLDE)

(c) The international accelerators facilities with new experimental proposals (EIC, ELI-NP, NICA, SPES, etc.)

In addition, RIB facilities in South Korea and South Africa are expected to come up in the near future, where Indian participation might be possible.

At present, an RIB facility is not available in India, whereas the frontline research on properties of exotic nuclei are being pursued in RIB facilities worldwide. The low-energy nuclear physics community in India can benefit by using these facilities till we get our own RIB facility. A consortium can be formed to facilitate the usage of some of the RIB facilities by the low-energy nuclear physics groups in India. The consortium can also organize topical workshops relevant to the research programs of these international facilities. This is possible with a modest investment. The existing facilities complement each other in terms of the beam energies and the availability of ion species, and thus different kinds of research problems can be addressed. New contacts with scientists in Asia, East Europe and Russia have emerged in recent times and offer exciting opportunities for collaborative work in experiments and theory. Some of these points have already been discussed in a previous vision document by the Indian Nuclear Physics community [Vision2014]. These facilities are easier and cheaper to access. Notable among these facilities are the Joint Institute for Nuclear Research (JINR), Dubna, Russia, famous for its work in super-heavy elements (SHE). Another important role of the consortium can be to organize workshops to encourage international scientific collaborations. This consortium can be used as a platform to coordinate collaborative efforts towards the development of new detectors and their usage in different national and international facilities.

ISOLDE: This RIB facility, located at CERN, is the precursor of the ISOL-type installations worldwide. ISOLDE makes use of a beam of protons at 1.4 GeV from the proton synchrotron booster on thick targets. At a maximum average current of 2 μA, the protons initiate fission, spallation and fragmentation reactions to produce exotic nuclei. A newer LINAC, namely, HIE-ISOLDE, accelerates radioactive ions to energies close to 10 MeV/A. HIE-ISOLDE beams are sent to three experimental stations: an array of high-purity germanium detectors known as Miniball, the ISOLDE solenoid spectrometer, which uses a former magnetic resonance imaging (MRI) magnet and a third beam line consisting of a large vacuum chamber that is used for scattering experiments. With the different setups, measurements related to the ground state and the decay properties of the radionuclides at low energies, as well as nuclear reactions and structure studies near the Coulomb barrier, are performed.

SPIRAL2: The SPIRAL2 facility is under construction at GANIL (Caen, France). It is based on a high power, CW, superconducting LINAC, delivering 5 mA of deuteron beams at 40 MeV (200 KW) directed on a C converter + Uranium target and thus produces more fissions/s. The expected radioactive beam intensities in the mass range from A = 60 to A = 140 will surpass any existing facilities in the world by two orders of magnitude. These unstable atoms will be available at energies between a few KeV/A to 15 MeV/A. The same driver will accelerate high-intensity (100 μA to 1 mA), heavier ions (from Ar up to Xe) at a maximum energy of 14 MeV/A. Under the LIA agreement, India has supplied diagnostic elements for high-intensity beams from SPIRAL2 and are a part of detector collaborations (EXOGAM, PARIS and GRIT). In future, physics experiments of mutual interest will be performed using the accelerator facilities of India and France.

SPES: SPES is another upcoming ISOL facility at the Laboratori Nazionali di Legnaro, Italy, that will use a proton driver, a 70 MeV cyclotron. The reacceleration stage with the superconducting LINAC ALPI will produce high-quality beams with regard to intensity and energy spread. The final energy interval (5–15 MeV/A) is ideal for investigations of nuclear reactions between medium-heavy nuclei close to the Coulomb barrier.

FRIB: The FRIB facility being built at MSU will take the primary accelerated beams from a 400 kW, 200 MeV/u heavy-ion driver LINAC. An in-flight production target, followed by a high momentum and angular acceptance three-stage fragment separator will provide a wide variety of high-quality beams of radioactive ions with large intensities. Along with the fast beam, the accelerator beams will also be available by stopping the beam on a gas or solid stopper. These beams can be post-accelerated using a superconducting LINAC.

RIBF-RIKEN: The Radioactive Ion Beam Factory (RIBF) at RIKEN has been operational since 2007. It is the first next-generation in-flight RIB facility that can achieve final energy of 350 MeV/A up to the heaviest ions using a high-power heavy-ion accelerator system consisting of three ring cyclotrons. The RIBs are selected by a high acceptance superconducting fragment separator, BigRIPS. The experimental devices already available for various studies include three spectrometers (ZeroDegree Spectrometer (ZDS), Superconducting Analyzer for Multi-particles from Radioisotope beams (SAMURAI) and SHARAQ).

The ISOL-based RIB facilities have a strong overlap with physics programs at accelerator facilities in India, whereas the RIB facilities based on inflight methods provide higher beam energies (100–200 MeV/A) and access to short-lived radioactive nuclei. Experiments can be proposed in facilities based on this technique, e.g., FRIB and RIKEN RIB factory, to perform studies related to the study of the shape and single-particle configuration of nuclei near the drip line.

Extreme Light Infrastructure Nuclear Physics: The upcoming Extreme Light Infrastructure Nuclear Physics (ELI-NP) facility in Romania will create a new European laboratory to consistently investigate a very broad range of science domains, from new fields of fundamental physics, nuclear physics, astrophysics and other areas. A very high intensity laser, where beams from two 10 PW lasers will be coherently added to obtain intensities of the order of 10^{23}–10^{24} W/cm^2 and electric field of a few V/m, will be established. In addition, a very intense (10^{13} γ/s), brilliant γ beam, 0.1 % bandwidth, with $E\gamma > 19$ MeV, obtained by incoherent Compton backscattering of a laser light off a very brilliant, intense, classical electron beam ($E_e > 700$ MeV) produced by a warm LINAC, will become operational at ELI-NP, which is fully funded by the European Union. It offers opportunities to carry out new kinds of nuclear physics experiments that are not possible elsewhere. Collaboration with this facility will yield rich dividends in the future.

RHIC:

This facility, situated at Brookhaven National Laboratory, USA, is dedicated for the scientific program of heavy-ion collisions that includes investigating how the critical QGP properties emerge and change with temperature (i.e., beam energy) and resolving power. The Electron Beam Ion Source (EBIS) provides a wide variety of ion beams up to uranium nuclei. The stochastic cooling for bunched beams and electron cooling has allowed acceptable high-energy heavy-ion collision rates from the center-of-mass energies between 7.7 GeV to 200 GeV. It also has the capability to collide beams of polarized protons. The RHIC detector suite comprises of major multi-subsystem detectors, STAR, [Ackermann 2003] and a new sPHENIX detector.

LHC:

This facility is situated at CERN, Switzerland. It not only collides protons but also heavier nuclei relevant for nuclear physics programs. So far Pb + Pb, Xe + Xe and p + Pb collisions at multiple energies have been used for studying the collective behavior of the QCD matter at extreme energy density and temperature. The LHC heavy-ion program was driven mainly by the requirements of the specialized ALICE (A Large Ion Collider Experiment) experiment [Aamodt 2008]. The designed Pb–Pb luminosity is 10^{27} cm^{-2}s^{-1} at the maximum beam energy of $\sqrt{s_{NN}} = 5.5$ TeV for Pb ions. Other multipurpose experiments, namely, CMS and ATLAS, have also actively participated in the heavy-ion program.

FAIR:

This facility is situated in Darmstadt, Germany and is getting constructed in a staged approach, starting with a modularized start version: a superconducting synchrotron, SIS100, with a circumference of about 1,100 m and a magnetic rigidity of 100 Tm. It also houses a complex system of storage-cooler rings and experiment stations, including a superconducting nuclear fragment separator (Super FRS) and an antiproton production target. In addition to heavy-ion beams, FAIR will supply RIBs and antiproton beams with high intensity and quality. A multidisciplinary research program will be conducted covering QCD studies with cooled beams of antiprotons, QCD matter and QCD phase diagram at the highest baryon density, nuclear structure and nuclear astrophysics investigations with nuclei far away from the line of beta stability, precision studies on fundamental physics, atomic and materials science studies, radiobiological investigations and other application-oriented studies.

NICA:

This facility is now under realization at JINR, Russia. NICA aims to study hot and dense nuclear and baryonic matter in heavy-ion collisions and spin physics research using polarized proton and deuteron beams. The center-of-mass energies from 4 to 11 GeV/A will be available in the heavy-ion research mode. Polarized proton collisions can be studied over an energy range up to 27 GeV. Physics detector setups, namely, the MultiPurpose Detector (MPD), Spin Physics Detector (SPD) and Baryonic Matter at Nuclotron (BM@N), are in the designing and construction stages. An average luminosity in the collider mode is expected to be 10^{27} cm^{-2}s^{-1} for Au79+ collisions. Extracted beams of various nucleus species with maximum momenta of 13 GeV/c (for protons) will be available.

EIC:

This upcoming facility will be situated at Brookhaven National Laboratory, USA. It utilizes a new facility based on an Energy Recovery LINAC (ERL), which is to be built inside the RHIC tunnel, to accelerate electron beams and collide them with the existing high-energy polarized proton and nuclear beams at RHIC. The EIC requirements in terms of beam polarization, beam species, range of center-of-mass energies and high collision luminosity will push the accelerator design to the limits of the current technology and will, therefore, need significant R&D.

The Table below summarizes some of the key aspects of the abovementioned facilities for nuclear physics research in the coming decade.

Table 2: Details of the international accelerator facilities for nuclear physics.

Facility	Features	Experiments	Science	Users
RHIC	Commissioned in 2000. Heavy-ions: deuteron to Uranium Collision energy: 7.7 to 200 GeV Typical luminosity: 10^{-27} cm^{-2} s^{-1} Polarized proton collisions possible.	STAR, sPHENIX	Study the phase diagram of strong interactions and the properties of QCD matter under extreme conditions	Currently scientists from more than 14 countries and 70 institutes participate. Typical number of active users for the nuclear physics program is 1000
LHC	Commissioned in 2010. Heavy-ions: Pb and Xe Collision energy: 2.76 TeV to 5.44 TeV Typical luminosity: 10^{-27} cm^{-2} s^{-1}	ALICE, CMS, ATLAS	Properties of QCD matter under extreme conditions	Currently scientists from more than 42 countries and 170 institutes participate. Typical number of users for the nuclear physics program is 1600
FAIR	Under construction. Primary beams from the SIS100 synchrotron with energies up to 29 GeV for protons, up to 11 AGeV for Au and up to 14 AGeV for nuclei with Z/A=1/2. High interaction rates of up to 10^7 collisions per second.	APPA, CBM, NuSTAR, PANDA	Atomic and plasma physics and applied sciences in the bio, medical and materials sciences. Physics of hadrons and quarks in compressed nuclear matter, hypernuclear matter. Structure of nuclei, physics of nuclear reactions, nuclear astrophysics and RIBs. Hadron structure and spectroscopy, strange and charm physics, hypernuclear physics with antiproton beams.	More than 2500 scientists and engineers from more than 50 countries
NICA	Under construction. The center-of-mass energies from 4 to 11 GeV/A will be available in the heavy-ion research mode. Polarized proton collisions can be studied for energies up to 27 GeV. Typical luminosity: 10^{-27} cm^{-2} s^{-1} for Au ions.	Physics detector setups MPD, SPD and BM@N are in the designing and construction phases.	In-medium properties of hadrons and the nuclear matter equation of state; the onset of deconfinement and/or chiral symmetry restoration; phase transition, mixed phase and the critical end-point; possible local parity	Multi-institute and multi-country collaboration.

			violation in strong interactions.	
EIC	Will be commissioned around 2032. Highly polarized (~ 70%) electron and nucleon beams. Ion beams from deuteron to the heaviest nuclei (U or Pb). Variable center-of-mass energies from $\sqrt{s} \approx 20$ to 100 GeV, upgradable to ~140 GeV. High collision luminosity of L ~$10^{33\text{-}34}$ cm^{-2} s^{-1}	Separate detectors at two different interaction regions are expected.	Precisely image gluons in nucleons and nuclei. Understand the origin of the nucleon spin and explore a new QCD frontier of ultra-dense gluon fields, with the potential to discover a new form of gluon matter predicted to be common to all nuclei.	Multi-institute and multi-country collaboration. Collaboration is in the formation stage.
Other potential facilities related to nuclear physics research				
J-PARC-HI, Japan Proposed	It will provide heavy-ion beams up to uranium for center-of-mass energies of 2−6.2 GeV. The experiment will have the highest beam rate capability, up to 100MHz.	Under discussion	To explore the QCD phase diagram at very high baryon densities	Multi-institute and multi-country collaboration
CEE@HIAF, China Under construction	The machine is designed to deliver bright ion beams of protons and heavy nuclei such as uranium with the center-of-mass energy up to 10 GeV and 4 GeV, respectively.	CEE+ Under construction	Main physics focus is on the measurements of proton, light nuclei, including hypernuclear production and the correlation functions for understanding the QCD phase structure.	Multi-institute and multi-country collaboration
ISOLDE at CERN, Switzerland Operational since 2001	Primary beam of protons Energy = 1.4 GeV on thick targets to initiate fission, spallation and fragmentation reactions to produce a wide range of exotic nuclei. A newer linear accelerator HIE-ISOLDE accelerates the radioactive ions to energies close to 10 MeV/A.	An array of high-purity germanium detectors known as Miniball, the ISOLDE Solenoid Spectrometer which uses a former MRI magnet and a third beam line where a large vacuum chamber is used for scattering experiments.	With the different setups, measurements related to the ground state and decay properties of radionuclides at low energies and nuclear reactions and structure studies near the Coulomb barrier are performed.	Multi-institute and multi-country collaboration expected. Indian groups already participating.
SPIRAL2 at GANIL, France Commissioned in 2021	Primary beam: 5 mA of deuteron beams at 40 MeV (200KW) directed on a C converter + Uranium target and producing neutron-rich RIB, therefore more fissions/s. The expected radioactive beam intensities in the mass range from A = 60 to A = 140	PARIS, EXOGAM, GRIT, DESIR, AGATA	Structure and reaction dynamics of exotic nuclei	Collaboration with National labs in India already present.
SPES at Laboratori Nazionali di Legnaro, Italy	Upcoming RIB facility. Primary beam using a proton driver, a 70 MeV cyclotron, on UCx target, fissions/s. Re-acceleration stage	PRISMA, recoil separator	Investigations of nuclear reactions between medium-heavy nuclei close to the Coulomb	Multi-institute and multi-country collaboration expected

Under construction	with the superconducting LINAC ALPI. Final energy interval (5–15 MeV/A) of a wide range of neutron rich RIBs (fission fragments)		barrier.	
FRIB at MSU, USA Operational since 2022	Upcoming RIB facility. Primary accelerated beams from 200 MeV/A heavy ion driver linac. Both inflight and re-accelerator beams will be available.	GRETA, SECRA, HRS	Nuclear structure and reaction study for dripline nuclei and nuclear astrophysics	Multi-institute and multi-country collaboration expected
RIBF at RIKEN, Japan Operational since 2007.	Inflight second-generation RIB facility, final energy of 350 MeV/A up to the heaviest ions	Three spectrometers (ZDS, SAMURAI and SHARAQ) and detection systems	Structure of exotic nuclei	Multi-institute and multi-country collaboration expected

2.2 RESEARCH REACTORS

Research reactors are primarily used to produce neutrons for various studies and applications. As the main objective of research reactors is not the production of electricity, they are smaller in size compared to nuclear power reactors and are characterized by thermal power and not by the electrical power. The other important characteristics include the density and the minimal energy of neutrons within the core of the reactor. These parameters decide the ability of the reactor for performing a certain research program. The neutrons from the reactor find wide applications in industry, agriculture, medicine, etc.

In India, after the permanent shut down of APSARA and CIRUS in 2010, DHRUVA and the newly commissioned APSARA-U at BARC are available for various activities such as the production of radioisotopes for various societal applications, basic research in nuclear physics, material science and radiation shielding, shielding experiments, neutron activation analysis, neutron radiography, testing of neutron detectors, etc. At Dhruva, R&D activities related to the irradiation of Ge to produce an nTD Ge thermistor were carried out. It will be used for low-temperature measurements using the Tin-bolometer, which is being developed for neutrinoless double beta decay studies.

A dedicated facility for nuclear structure studies, namely, Dhruva Utilization in Research using Gamma Array (DURGA) has been recently commissioned at DHRUVA. It will employ prompt (n,γ) reactions and fission fragment spectroscopy to investigate the properties (shape and structure) of the neutron-rich fragment nuclei.

In future, a high-flux research reactor with polarized cold neutron beam facility dedicated to particle and nuclear physics experiments would be desirable. Such a facility, along with an array of highly efficient high purity germanium (HPGe) detectors, can be used for performing nuclear structure studies, by measurement of the gamma-rays emitted after neutron-capture and fission reactions. These detectors can be arranged in a suitable geometry to carry out very precise measurements for angular and directional-polarization correlation.

2.3 UNDERGROUND LABORATORIES

Many of the envisaged nuclear physics projects need background-free environments. This is especially important for sensitive experiments that are looking for rare phenomena such as neutrino interactions, neutrinoless double beta decay, dark matter detection, low-energy accelerators for nuclear astrophysics, etc. Backgrounds for these experiments are expected from cosmic rays and radioactivity in the surrounding materials. The cosmic muon background becomes insurmountable if the detectors are on the surface. However, as one goes deeper underground, muons get absorbed in the surrounding materials and thus the signals of rare events can be correctly identified from the background. Indeed, the Kolar Gold Fields, at which the first atmospheric neutrinos were discovered, was such an underground location.

An underground laboratory with 1 km rock coverage from all sides would be able to decrease the cosmic muon flux in the GeV range by almost a factor of a million, which would be crucial for the success of many experiments, both, planned and to be planned. The Gran Sasso laboratory in Italy is a great example of how multiple experiments such as LVD, Borexino, OPERA, ICARUS can thrive in such an underground laboratory. The India-based Neutrino Observatory (INO) project (see HEP report) has already proposed such a facility, which will have some extra caverns for other experiments. It is desirable to create an infrastructure of such underground facilities, possibly at different depths, such as 500 m, 750 m and 1000 m. Often, the existence of infrastructure encourages thinking in ambitious directions in which it can be utilized to do projects that were not dreamed of before. This infrastructure would also be useful for other disciplines such as life sciences or geological sciences, for which such facilities would provide radiation-free surroundings.

An underground laboratory (approximately 5 m × 5 m × 2.2 m), named as Jaduguda Underground Science Laboratory (JUSL), has already been established at a depth of 555 m (1600 meters water equivalent vertical rock overburden) in an existing mine of the Uranium Corporation of India Limited (UCIL), located at Jaduguda in India. The primary goal of this facility is for exploring the feasibility of having a dark matter (DM) search experiment. One of the goals of this rare event search experiment will be designed to look for the signature of DM candidates by observations of extremely tiny amounts of nuclear recoil or electron recoil events in a suitable crystalline detector medium. Some of the rare decay nuclear physics experiments such as the 2-photon decay and decay of long-lived isomers can be carried out in such an underground laboratory.

As mentioned in Section 1.2.2, it would be essential to set up an appropriate low-energy accelerator to study reactions relevant for nuclear astrophysics at stellar energies in an underground laboratory. This will complement the already existing FRENA facility at SINP.

2.4 HIGH-INTENSITY LASER FOR NUCLEAR PHYSICS

The advances made in high power lasers, along with the modern devices available from the accelerator technology, have broadened the scope of nuclear physics research and applications for nuclear medicine. Ultra-intense lasers, with intensity going up to 10^{21} W cm^{-2}, can produce radiation formerly available in nuclear facilities. These lasers could release high-energy ions having energies in the MeV range, which can be further used for triggering nuclear reactions in secondary targets. The laser intensity and the target parameters driving the acceleration mechanism determine the energy of the laser-accelerated particles. Modern laser-driven technologies have tremendous potential in terms of their available parameter range, size and cost. Though many of the current laser-driven experiments do not match the specifications of radiation sources available in their nuclear facility counterparts, they offers complimentary opportunities. It has been demonstrated that X-ray photons are generated using high-order multiphoton scattering by a single electron with a high-power laser and a laser-driven electron accelerator. Such setups can help in studying isomer depletion using all optically generated X-rays. Another emergent idea is to explore the coherent control of electrons by photons to the attosecond timescale to probe the unprecedented applications in basic nuclear physics. This class of controlled experiments will provide wider possibilities for choosing the electron and photon energies, their relative time delay, light polarization and intensity. With these experiments, unexplored resonance effects can be investigated for the study of excitation of the nuclei. A new possibility will be to generate higher intensities of protons or neutrons from the laser-matter interaction, which can be used for nuclear reaction studies in plasma conditions. In future, such measurements can become possible within the country by collaborative efforts between the laser physics groups and the accelerator-based nuclear physics groups.

2.5 DETECTORS AND INSTRUMENTATION

Crucial to the sustained advancement of the Indian Nuclear Physics community is the capability to develop state-of-the-art detection facilities and a strategic connection to the opportunities that they offer [Demarteau 2016] [STFC 2021]. At the same time, it is essential to upgrade the existing detection facilities with new technologies. Some of the key detector systems required for different types of radiations and particles are listed in the following subsections. We have also discussed the developments required for the associated instrumentation electronics. The need for a center for detector design fabrication has also been highlighted in the end.

2.5.1 CHARGED-PARTICLE DETECTORS

<u>Semiconductor, Scintillator and Gas Detectors for Low-energy Nuclear Physics Experiments:</u>

Multilayered strip detector telescope arrays are being developed for studying various aspects of nuclear structure, reaction and nuclear astrophysics. The double-sided strip detectors (DSSDs) used in such arrays allow for higher granularity, larger solid-angle coverage and particle identification capabilities to perform kinematically complete measurements. Arrays of these DSSDs are operational at different accelerator facilities. A Charged particle detector Array for Kinematic Reconstruction and Analysis (CHAKRA) has been developed at VECC to facilitate high resolution, high granularity and kinematically complete measurement of reaction events by detecting all ejectiles individually. R&D towards double-sided nTD Si strip detector is in progress to achieve pulse shape discrimination capabilities. For certain experiments, it is important to detect low-energy (1–3 MeV/A) particles, depending on the kinematics and scattering angles. In such cases, gas detectors are, in particular, very useful as gas pressure can be adjusted to adjust the thickness, and thus make them transmission type, enabling differential energy loss measurements. The 4π hybrid detectors consisting of a gas detector as the ΔE detector and a silicon-CsI combination as the E detector will be used. At extreme forward angles, detectors such as the position sensitive gas proportional counters or micro-channel plate detectors can be used for reconstructing the kinematics using the time-of-flight (TOF) technique.

These detectors will be used for experiments performed using the accelerators within India as well as at FAIR and SPIRAL.

<u>Electron Spectrometers for Conversion Electrons and Pair Decay:</u>

Conversion electron spectroscopy is an important tool for building up the level scheme involving even high-spin/high-energy states. It is also an important tool to reveal the collective nuclear structures involving magnetic dipole and quadrupole bands. If done in inverse kinematics, low-energy electrons can be measured at 0°. Solenoidal electron spectrometers and time projection chambers can also be used tostudy the e^+e^- pair decay in the $0^+ \rightarrow 0^+$ E0 transitions or even to look for light pseudoscalar/scalar /vector particle searches in nuclear decays.

<u>Active Target – Time Projection Chambers:</u>

These are state-of-the-art detector systems in which the chamber gas acts as detector as well as a target. Experiments with RIBs have the limitation of low beam intensities and low cross-sections, which can be overcome by an active target-time projection chamber (TPC). Active targets allow reactions to be conducted in inverse kinematics, with the possibility of having a thick target without loss of energy resolution, to measure the low energy recoil particles. Active target combined with TPC provides a 3D reconstruction of high-multiplicity events. Such a device can be used in existing RIB facilities worldwide and in the upcoming RIB facilities in India, to study exotic decay modes (e.g., 2-proton radioactivity), nuclear structure via transfer and breakup reactions, equation of states via giant resonances and also reactions of astrophysical interest.

<u>Development of THGEM-based Detectors for Nuclear Fission Studies:</u>

To optimize the exploration of superheavy elements (SHE), the key challenge is to understand the dynamics of fusion and fission reactions by measuring the mass and angular distributions of the fission fragments. For the detection of fission fragments, position-sensitive multiwire proportional counters are usually used. However, these detectors are fragile and not easy to transport. A detector based on the robust THick Gaseous Electron Multiplier (THGEM) is being developed at VECC.

Muon Detection System for the CBM Experiment at FAIR

A large-size muon detection system consisting of muon chambers (MuCh) is being developed by the Indian collaborators for the CBM experiment at FAIR. To handle relatively low momentum muons from the collisions at CBM, a segmented absorber-based MuCh has been conceptualized. MuCh, for the SIS100 energy will consist of five absorber segments made of graphite (1st absorber) and iron plates. Three detector layers, each separated by 10 cm gap, will be placed by forming a detector station. The detectors placed downstream and the regions radially away from the beampipe will face gradually reduced particle density due to absorption and 1/r dependence. As per GEANT simulation, the highest density of the space points to be faced by the inner zone of the 1st station will be about 400 KHz/cm^2, the rates in the stations downstream reduce to 5 KHz/cm^2.

It is therefore necessary that the detector stations need to handle high particle rate, high radiation and have low noise, apart from the mandatory requirements of high efficiency (>90%), high position resolution (~mm) and high time resolution (tens of ns). Keeping these criteria in mind, two detector technologies have been decided to be used i.e., the gas electron multiplier (GEM, 1st and 2nd stations) and the high-rate resistive plate chamber (RPC, 3rd and 4th stations). Large-size sector-shaped prototype GEM modules have been developed and production will start only after rate capability tests. For the RPC, relatively low resistivity RPC modules are being tested before finalizing. There will be about 120 modules of each type. A special cooling plate arrangement using Al-plates and water cooling has been developed and tested. The prototype detectors have been tested in AA collisions at 1.2A GeV at SIS18, GSI. Several specialized configurations have been made for the GEM chambers.

A custom-built self-triggered radiation-hard application-specific integrated circuit (ASIC), named STS/MuCh-XYTER, is being used for data readout. CBM will collect all data above the predefined thresholds and the processing will be mostly online for data reduction and sending them the first level event selector (FLES). The detectors, readout ASIC and field programmable gate array (FPGA)-based data acquisition (DAQ) form the readout chain.

Charged-particle Tracking and Vertexing Detector Systems for Experiment at EIC:

Charged particle tracking and collision vertexing are crucial to the success of the experiments to be performed at EIC. Two different technologies are under consideration. One of them uses semiconductors, where sensors collect electron/hole pairs caused due to the passage of charged particles. The other uses a gaseous medium, where ionization of the gas occurs due to the passage of the charged particle through it. Both the technologies use the knowledge gained in the past and the ongoing experiments at RHIC and LHC. The detectors have to be highly granular and satisfying the tracking (vertexing) resolutions of better than 5 mm (3 mm). They must be built to maintain a low material budget for the detector system in the experiment. The third-generation of monolithic active pixel sensors is under development as a joint effort between the EIC and the ALICE ITS3 vertex tracker upgrade under the semiconductor technology side. In the gaseous detector sector, developments on the micropattern gaseous detectors, such as GEMs, mMEGAs or mRWELL, which provide electron amplification before read-out on high-granularity anode printed circuit boards, are taking place. These detectors can also offer particle identification at lower momentums.

Particle Identification Detector Systems for Experiments at EIC:

The physics at EIC requires charged-particle (pion, kaon and proton) identification to a considerable momentum value, along with significant suppression of pion/election and better than 3σ resolution for pion, kaon and protons for the angular regions of the detector system covered. To achieve these demanding requirements, based on the experience of the past and current experiments, Cerenkov light emission and TOF measurements techniques are required. In Cerenkov detectors, identification is based on the light emitted by charged tracks that correspond to faster than speed of light in the detector medium. Different radiator media will be a requirement in the electron endcap, barrel and hadron endcap due to the different momentum ranges of particles in those regions. A CsI ring imaging Cerenkov (CsI RICH) detector, a novel approach of using nano diamond powder instead of CsI and a dual RICH (dRICH) with a gas and an aerogel radiator are under consideration. R&D on the TOF particle identification at low energies by conducting precision timing measurements in large-area picosecond photon detectors (LAPPD) are also under consideration.

2.5.2 Detectors for photons, π^0 and neutrons

Photon and π^0 Detection at Forward Angles in ALICE at LHC

A forward electromagnetic and hadronic calorimeter (FoCal) has been proposed as an upgrade to the ALICE experiment, to be installed for data-taking in 2027–2029 at the LHC [Acharya 2020]. The FoCal is a highly granular Si+W electromagnetic calorimeter combined with a conventional sampling hadronic calorimeter. The FoCal provides unique capabilities to measure small-x gluon distributions via prompt photon production and will significantly enhance the scope of ALICE for inclusive and correlation measurements with mesons, photons and jets to explore the dynamics of hadronic matter at small x. For the electromagnetic calorimeter (FoCal-E), a small shower size is desirable to have optimized cell occupancy and photon shower separation. Therefore, tungsten is the absorber material of choice due to its small Moliere radius and radiation length. The FoCal-E detector will consist of a Si+W sampling calorimeter hybrid design using two different Si read-out technologies: (a) pad layers, with transverse cell sizes of approximately 1cm^2 and (b) pixel layers, with a digital read-out and a cell size of 30 × 30 mm^2. ALICE-India proposes to contribute to FoCaL-E. As per the plan, if R&D is successful, the contribution will be approximately half of the pad sensors. The pad sensors will be fabricated in an Indian foundry and tested by the read-out chip suitably for all pad layers.

Modern Neutron Detectors for Spectroscopy:

Fast neutron spectroscopy has gained a lot of interest for the spectroscopy of neutron-rich nuclei and nuclear astrophysics at the upcoming RIB facilities. Recently, there have been developments in detector technology, which allows for the direct measurement of fast-neutron energies from the pulse height or charge integration spectrum instead of the traditional TOF spectrum. The examples of these kind of detectors are Cs_2LiYCl_6:Ce (CLYC) and ^{3}He proportional counters. Alternatively, fast neutrons can also be measured using elastic scattering from a hydrogen or deuterium target. Deuterium target, on the other hand, produces a distinctive recoil peak. Deuterated Stilbene and Benzene-d6 (EJ315) detectors fall into this category. The neutron energy can be extracted from the response of these detectors using the method of spectrum unfolding.

Development of Neutron Detectors for MONSTER collaboration:

With experience and expertise achieved in the fabrication of this type of neutron detectors, it has been proposed and sanctioned that India will build 42 similar liquid-scintillator-based neutron detectors for the MOdular Neutron SpectromeTER MONSTER array at FAIR, Germany. MONSTER will consist of a total of ~ 100 numbers of BC501A liquid-scintillator-based neutron detectors. The array has been proposed for the measurement of the beta decay properties of neutron-rich isotopes in the decay spectroscopy (DESPEC) experiment.

Gamma Ray Detectors for Low-energy Nuclear Physics

DEGAS:

The DESPEC Germanium Array Spectrometer (DEGAS) is a high-purity germanium gamma-detector array for high-resolution spectroscopy of gamma decays from exotic nuclear species. It is a key instrument of the DESPEC experiment at FAIR [DEGAS 2014]. The construction of DEGAS will have three phases. For phase I, it is planned to use cluster detectors along with a new cryostat to optimize the solid angle. Cryostats will be electrically cooled to facilitate a compact detector arrangement. In phase II, Advanced GAmma Tracking Array (AGATA)-type gamma-ray tracking detectors are planned to replace the most background-affected EUROBALL detectors. The third phase is planned to include the results of long-term developments of highly segmented planar Ge detectors for the ultimate “imaging” array. A highly segmented planar HPGe detector has been proposed as an implanter detector for the study of very low energy transitions and internal conversion electrons. Groups from India will be involved in the research and development of the third phase, for which new funding will be required.

Scintillator array with imaging capability:

A multilayer and segmented detector is proposed based on the next-generation scintillators coupled to silicon photomultipliers. The higher energy, time and position resolution will provide the imaging capability for many nuclear physics experiments as well as applied fields. For the rare second-order electromagnetic decays, such a detector array, which can provide new information about nuclear polarizability, will be essential. This technology is insensitive to magnetic fields and could be developed for gamma-ray detection near magnetic spectrometers. Research and development funding will be required prior to a full project proposal.

2.5.3 Detectors for neutrinos and dark matter search

Cryogenic Bolometers:

Cryogenic bolometers, where the energy of an incident particle is converted to heat, thus leading to a measurable rise in temperature, are desirable for high-resolution spectroscopy and have found applications in a wide range of topics such as rare-event studies, infrared/X-ray astronomy, nuclear physics, etc. Any superconducting or insulating material can be made into a bolometric detector at sufficiently low temperature. Milli-Kelvin thermometry is a crucial component involving sensors as well as readout electronics. Efforts for developing tin cryogenic bolometers have been initiated to search of neutrinoless double beta decay in ^{124}Sn. Neutron transmutation doped (NTD) Ge sensors for temperature measurements in the 20–100 mK range have been indigenously developed. These sensors have been prepared by irradiating device and detector grade Ge with thermal neutrons at the DHRUVA reactor, BARC, Mumbai. Resistance measurements have been performed on NTD Ge sensors in the temperature range 100–350 mK. The observed temperature dependence has been found to be consistent with the variable-range hopping mechanism. Development of low-temperature front-end amplifiers is underway. This technique can be extended to sapphire bolometers for high-resolution alpha/beta spectroscopy studies.

Cryogenic Semiconductor Detectors for Rare-event Experiments:

The process of CENNS that was considered too difficult and rare to detect was observed by the COHERENT experiment in 2017 from an accelerator-based source. Many experiments around the world are planned and are running to detect this process by using the neutrinos obtained from reactors. Detecting the process from reactors has several benefits ranging from fundamental physics to applied neutrino physics. The CENNS process can be used for monitoring nuclear reactors in the same way several experiments around the world are trying to use the inverse beta-decay process. The advantage would be a reduction in the detector mass by at least two orders of magnitude, making portable detector deployment even more feasible. However, the challenge lies in the reduction of backgrounds and in achieving very low detection thresholds (<100 eV). Semiconductor detectors (made of Ge or Si) at cryogenic temperatures (~10 mK) have been demonstrated to achieve very low thresholds, as low as a few eV (1 e^-/h^+ pair level) [Iyer 2021]. Several configurations and modifications of these detectors can also provide significant reduction in cosmic backgrounds as well. The Mitchell Institute Neutrino Experiment at Reactor (MINER) is one such experiment that aims to detect CENNS using these types of cryogenic semiconductor detectors. The physics goals of the experiment are: (i) detection of CENNS, (ii) detection of sterile neutrinos, (iii) search for an anomalous neutrino magnetic moment and new mediator bosons and (iv) search for dark matter and axion-like particles. The application goal of the experiment is to utilize CENNS for civil nuclear applications such as reactor monitoring and nuclear non-proliferation. India is already involved in the experiment and is currently contributing to the experiment and detector R&D. It would certainly be beneficial to invest in this technology so that such detectors can be fabricated and utilized in India for physics and civilian applications. The cryogenic detector technology would offer complementarity to Indian technologies relying on Inverse Beta Decay for reactor monitoring applications.

Indium-based Solar Neutrino Detectors:

Indium-based detectors, as described in Sec. 1.3.3, would be able to detect the ^{7}Be neutrino line from the Sun and probe the temperature at its core directly. While such a detector was envisaged in 1976, it poses many challenges, including a reduction of background from the radioactivity occurring in ^{115}In itself. A small prototype had been successfully built in the shallow Kimbleton mine in the US. The Indium detector could be based on an In-doped liquid scintillator or a cryogenic In-bolometer. It could be built at a depth of 500–1000 m. Expertise exists at Virginia Tech and BNL (USA) on metal-doped liquid scintillator, including water soluble liquid scintillators, and collaboration to help develop this technology in the Indian industry is possible. Development of a very different approach using quasiparticles in a superconductor of Indium is also possible at a detector development center such as Inter Institutional Center for High Energy Physics (IICHEP).

The technologies of liquid scintillators, metal-loaded liquid scintillators, cryogenic detectors and large-area picosecond photon detectors (LAPPD) will find wide applications in many other areas such as security, low-noise electronics and photon counting. Since nobody has built such a detector(s) before, it will be a one-of-its-kind in the world and also produce frontier science results. A conscious effort to build as much of the cryogenics as possible in India will also help in other areas such as superconducting quantum interference device (SQUID) arrays for medical research and diagnostic applications, and quantum computers.

2.5.4 Spectrometers and the associated detectors for accelerator-based nuclear physics

Detectors for Magnetic Spectrometers:

Magnetic separators are used for producing secondary beams (i.e., RIBs) using the in-flight separation technique. Focal plane detection systems generally consist of a position sensitive gas proportional counter followed by a gas ionization chamber for energy measurements and particle identification. For implantation-decay measurements, proportional counters are followed by silicon strip detectors. The focal plane is the target chamber for secondary reactions in such cases. Secondary targets can be surrounded by charged-particle detector arrays as discussed above. Gas proportional counters and ionization chambers are placed at extreme forward angles or zero-degree detection. If the primary beam energies are very high, then the target chamber is generally preceded by a tracking detector system consisting of a position-sensitive gas proportional counter and also ionization chambers to identify the secondary beam species and beam profiling.

Multireflection TOF Spectrometer:

In recent years, multi-reflection time-of-flight mass spectrographs (MRTOF-MSs) have been used as isobar separators, for precision mass measurements and even in half-life measurements [Ayet San Andrés 2019]. This spectrograph consists of a pair of coaxial electrostatic mirrors between which ions reflect back and forth. This arrangement provides an extended flight path of ions. It is well suited for low-yield, heavy and short-lived nuclei. It achieves mass resolving powers of $R_m > 100\,000$ with flight times shorter than 20 ms for even the heaviest nuclei. Developmental work on this spectrometer will be carried out for accelerator facilities within India. This could be an ideal detection system for the future RIB facility in India.

2.5.5 Electronics and instrumentation

Radiation detectors along with their associated electronics form the core of experimental nuclear physics. For these detectors, the main challenge is to cope with signals consisting of a small number of free charge carriers generated due to interactions of radiations in the presence of potential noise sources. Instrumentation electronics are required for the detectors to extract useful information from the signals obtained from detectors and suppress noise. These instrumentation electronics consist of several subparts, e.g., the front-end electronics for amplification and filtering the signals generated in the detectors, digitization systems, triggering systems, data transfer systems, data storage systems, high voltage systems for biasing the detectors and slow control. Timely upgrade of the associated hardware and software are necessary in nuclear physics experiments for the best utilization of the emerging technologies to enhance the physics capabilities.

Based on the physics requirements, the detectors can have a wide range of requirements in terms of the energy resolution, time resolution, high granularity, high count-rate capability, large detection efficiency, high quality factor for particle identifications and least deadtime. The signal characteristics should be extremely stable and not susceptible to the variation in the external parameters, such as temperature. Fast electronics are required for signal processing with a complex digital readout scheme. In order to achieve this, sophisticated control, acquisition, digital recording and simulation and/or analysis engines are required. In addition, an efficient data transmission system and bulk data storage are also essential for nuclear physics experiments, which run for extended periods and generate big-scale data. The acquisition and storage systems vary depending on the experiments which could range from a few observables (signals) to few tens of thousands. Of particular interest is the innovation in the design of the readout electronics and its effective implementation in real detectors. A flexible and modular design with a high degree of reliability is essential for these readout and digitization electronics. The overall cost per channel is also another important criterion.

The number of electronic channels of the detectors can vary from 10 to *around tens of thousands* in nuclear physics experiments. Depending on the total number of channels, one has to plan for discrete or integrated front-end electronics. The effort will be to continue improving on the design of low-noise preamplifiers with low power consumption for various types of semiconductor, scintillator and gaseous detectors. The other scheme is to develop front-end ASICs for signal processing data from various highly-segmented detectors. Development of low-noise amplifiers and filters as well as fast analog-to-digital and time-to-digital converters for precision amplitude and timing measurements will be the priority. Another direction of R&D will be the development of front-end ASICs for highly segmented detectors with a possibility of obtaining good energy and time resolutions with a large dynamic range.

Depending on the scale of the number of signals, the acquisition systems can be classified as small-, medium- and large-scale acquisition systems, and, in turn, storage systems. To acquire voluminous data, it is proposed to have a universal acquisition system that can bridge the gap between the abovementioned classification. The proposed system is nothing but a digital signal processor attached to every transducer, which could preprocess the signal along with a distributed timestamp, thereby providing the necessary information such as energy, time, rise-time, fall-time and timestamp. This type of system is highly scalable and hence acts as a universal system that bridges the gap between large and small acquisition systems. All these signals are also stored in a distributed fashion, which helps us in keeping off the shelf components while achieving higher throughput. In a way, it is triggerless at the collection end, and yet these can later be middle ware triggered. In other words, techniques such as global trigger and synchronization (GTS), which is used with the AGATA can be adapted to delay the trigger or select the event of interest before digitally recording them. Employing different communication links, the data can be transported to analysis engines for complex analysis procedures.

The combination of ASIC and FPGA technologies will be vital for the digital electronics design. In the same experimental setup, one can have different types of detectors with independent data acquisition systems. Optimum triggering schemes should be designed to synchronize the different systems based on the global timestamp techniques. The ability to transfer data through and out of detectors at high speed and high volume will be challenging for the next-generation of detectors. The new developments need to have standard digital interfaces and protocols for compatibility with commercial devices.

The analysis process gets more complicated with such voluminous data (~1 PB). To analyze, compare with simulation results and to also correct for some minimalistic predefined or well-documented error correction methodologies (e.g., neutron damage simulation using gamma cameras) a high-performance computer farm, which is, in nature, a hybrid system consisting of FPGA and GPU-based engines over multi-core open message passing interface (MPI) interconnected using a high-speed communication link is proposed. (e.g., non-blocking InfiniBand @ 40 Gbps). The total computational power requirement estimated is around 1 petaFLOP.

2.5.6 Detector design and fabrication facility

Silicon detectors are at the heart of many different areas with applications in nuclear physics, high energy physics, optical spectroscopy, medicine, among others. Some of the detectors that are of current interest are silicon microstrip detectors for beam tracking, silicon photomultiplier arrays for imaging, spectroscopy, single-photon detection and very precise time-resolution applications. To design and fabricate these devices, one would need a simulation tool similar to Silvaco, which offers device as well as process simulations. For circuit simulations, one would need Altium or similar tools for backend electronics such as preamplifiers.

For making these devices, one would need a silicon fabrication line, including a mask aligner for UV lithography, a 150 keV variable-energy ion implanter for doping silicon, an etching tool that supports Bosch process plasma etcher for deep silicon etching, a sputter deposition system for metals and bonding for making electrical contacts. For submicron features, one would need an electron beam lithography system or a nanoimprint lithography system suitable for large-area writing. To characterize the devices, one would need a probe station for the current-voltage (I-V) and capacitor-voltage (C-V) measurements, and an optoelectronic measurement setup for measuring their optical response, such as photoinduced carriers and electroluminescence. An optical microscope for visual characterization will be needed. To house the abovementioned equipment, 1500 sqft. class 1000 clean room with dry and wet benches would be essential with a spin coater.

Futuristic optoelectronic device ideas that integrate nano-photonic structures with electronic devices are evolving, and these would combine the ideas such as perfect absorption and bound state in continuum with electronic devices to improve as well as achieve novel functionalities. For these evolving optoelectronic devices, one would require deposition systems such as RF- and DC-magnetron sputtering, plasma enhanced chemical vapor deposition (CVD) and atomic layer deposition systems for submicron thick layer deposition of metals and dielectrics. In India, among the existing facilities, Bharat Electronics Limited (BEL) has already developed strip detectors and has provided hybrid ΔE–E detectors on 4-inch Si wafers in collaboration with BARC. Presently, double-sided strip detectors are being developed at Semi-conductor Laboratory (SCL), Chandigarh.

The capabilities and experience of the groups in the Council of Scientific and Industrial Research (CSIR) laboratories, engineering departments of IITs, NITs and different engineering colleges will be extremely useful for the R&D towards detector-related materials, instrumentation and electronics. Collaboration of nuclear physics groups with these laboratories, institutes and engineering colleges should be enhanced. This will help in drawing engineering faculty and students to R&D on detectors, accelerators and their industrial applications.

2.6 HIGH-PERFORMANCE COMPUTING

In the modern era, computing plays a central and indispensable role in most of the mega science activities. Here, computing includes theoretical calculations, as well as storing and processing of data. The nature of computing is also undergoing changes, with artificial intelligence (AI) and machine-learning (ML) starting to become important. A rapid expansion in computing-intensive and data-driven fields of research through these new directions is expected in the coming days.

Nuclear Physics and High Energy Physics:

On the experimental front, the amount of data to be collected in nuclear and high energy physics experiments has been increasing and will continue to see a steady growth. With the increase in the number of experiments, one anticipates the need for about 100 PB data in the next decade. These data need to be analyzed using specialized numerical techniques and large computational resources. We anticipate multi-petaflop usage required for the data analysis of nuclear physics and high energy physics experiments. For example, for the data analysis at LHC, the process of deciphering jet structures as well as for finding beyond Stadard Model physics using ML would require this level of computing resources.

On the theoretical front, it is the investigation of strong-interaction physics that needs the largest computational resources, where one needs to perform extensive simulations for the first-principles calculations using the lattice gauge theory. Along with this, hydrodynamical simulations of quark-gluon plasma, nuclear shell structure calculations and simulations for jet physics in high energy physics experiments, such as LHC, also needs substantial computing resources. Calculations of the lattice gauge theory are performed on finite-size lattices, whereas physical results can only be obtained at the infinite volume and continuum limits. Going to smaller and smaller lattice sizes, with larger and larger volumes, implies exponentially growing needs for computing resources. Hydrodynamical simulations of QGP also need to be performed with finer grids for getting answers closer to the continuum.

Other Related Computing-intensive Disciplines:

We are at a juncture when large-scale high performance scientific computing is becoming essential in almost all areas of science. Other diverse areas of sciences, including astrophysics and cosmology, biological sciences, condensed matter (including material science) and statistical physics, chemistry, fluid dynamics (including climate research) also depend crucially on the availability of high-performance computing (HPC). As far as expertise is concerned, India has more than 1000 scientists in the abovementioned areas, who already use multi-teraflop computing resources. Interlinked to this is the anticipated advancement of quantum computing. However, before the arrival of any big-scale quantum computer, one needs to test and design algorithms through quantum simulators for which big-scale classical computation is essential.

There is a lot of synergy among these diverse disciplines as far as their computing requirements are concerned. This commonality exists from the technical aspects of software all the way to the hardware for executing such computations. For example, solutions of multidimensional partial differential equations, various aspects of linear algebra, including large-scale matrix diagonalization through linear solvers, Monte Carlo methods, etc. are common to various branches of sciences and engineering. Statistical analysis is common to all big-data-oriented sciences and a common set of hardware will be beneficial to all.

Furthermore, ML aspects are bringing various research areas under the same umbrella, with the same set of tools and requirements for essentially the same computing hardware. These include the analysis of big-data coming out of various high-energy particle physics and astrophysics experiments for exploring the Universe, ranging from elementary particles to cosmological scales, solutions for exotic condensed matter systems, including designs of novel materials, a vast area of biological sciences ranging from protein-folding to drug designing, medical sciences, climate research, as well as various aspects of engineering. Statistical physics plays a major role in understanding the theoretical puzzles inside these AI networks, ranging from unsupervised learning to deep learning. Together with statistical physicists, computer scientists could provide solid theoretical as well as algorithmic inputs to other scientists working in ML, which would be essential for any fruitful implementation of ML-related activities in India. The Indian monsoon, in particular, is a dramatic multiscale, multiphysics event that has a profound impact on the food security of a billion people. An understanding of the basic dynamical system of the monsoon and its accurate prediction needs adequate computing resources and involvement of scientists from various disciplines under a common platform. There is also scope to build a synergy between plasma simulations, simulation for climate research, hydrodynamic simulations and magneto-hydrodynamics simulations of astrophysics. In view of these points, bringing all HPC- related activities on a common platform is absolutely essential to participate and for reaching excellence in this new age of science.

Computing Resource Requirements for Nuclear Physics and High Energy Physics:

The expected computing resource requirements for HPC related to nuclear physics and high energy physics are given in the table below.

System	0-5 years	5-10 years	10-15 years	Total in 15 years
Machine - PFLOP	25	35 (+10)	40 (+30)	100 (+40)
Storage (PB)	50	75	125(+50)	250 (+50)

The numbers inside the brackets indicate the resources required to replace the older resources that have become outdated. Typically, the computing machines – CPU/GPU – have to be replaced after 5–7 years and the memory has to be replaced after 10 years. This level of resource would be needed for the Indian science in these areas to be as productive and competitive with their peers outside the country. For example, scientists in the US, EU, China and Japan either already have access to this level of resources or would get them in the near future.

Currently, there are a few dedicated HPC facilities that are used and operated by different institutions, scattered over the country. Based on the experiences of peer institutions and R&D establishments worldwide, it appears that the allocation of computing resources to individual institutions is not necessarily optimal, since it misses out on the synergies that are derived from a unified computing resource center. In view of this, a few centralized large Data Centers around the country could be envisaged, each of which would be connected to higher education institutions and universities through the fastest possible bandwidth lines.

One of the major factors that will need to be considered while building Data Centers is the power requirement. Most of the applications needed for nuclear and high energy physics require CPUs that consume large amounts of power. For example, the 25 PFLOPS computing resources projected to be available at the end of the first 5 years would require about 8 MW power. Such an amount of power might not be available in big cities, where the demand for power is already quite high. For this reason, it would be prudent to establish multiple Data Centers distributed in different states, so that the availability of sufficient continuous power can be guaranteed.

One can build four big Data Centers around the country, each with 25 PFLOPS computing resources and about 60-65 PB data storage systems. Considering the necessity of a variety of computations of different users across India, it is proposed to have three different types of computing servers rather than a single supercomputer at each of these Centers. Each of these Data Centers could incorporate: (i) a 10 PFLOPS GPU-CPU server, (ii) a 10 PFLOPS CPU cluster with fast connection and (iii) a 5 PFLOPS CPU-farm with a certain percentage of its nodes having higher memory. The envisaged computing facilities will also uniquely provide a common platform to many Indian scientists working in the areas of AI, ML and broadly in data sciences. A close symbiotic relation would also be built with the computing industry.

The resources projected in the first five years would cost about ₹ 1000 cr, including the building of Data Centers, the electricity required for them, etc., but without accounting for the salaries of the personnel. Those in the next five years would need ₹ 1200 cr and those in the last set of five years would need ₹ 1500 cr. These calculations have included some estimations of decrease in the prices of the the electronic components over time. Note that these resources are projected as the combined requirements of Nuclear Physics and High Energy Physics communities, which have a large overlap between them and will be used by scientists in both these fields.

Research Software Collaboration:

While we invest in computing hardware which has a limited lifetime, it is also important that we invest in software which stays longer and can evolve over time. Software has become the critical element for the full and long-term exploitation of large data-intensive science projects, such as those in particle and nuclear physics, astrophysics and astronomy. Unlike hardware, software elements could often, in principle, be shared across multiple experiments and/or can be passed from one generation of an experiment to the next. In addition, the use of, and interoperability with, data science and ML tools developed by other parts of the academic and industrial world is becoming ever more important to science. Software is an intellectual product, not just a tool. An open science approach is the key to enabling international collaborations as well as multidisciplinary collaborations between physicists, computer scientists and other data science practitioners. Therefore, building a research software collaboration, which would not be strictly tied to a single science project/experiment/facility and (as required) would add value to the broader scientific and data science ecosystem, should be a part of the vision document. This philosophy has already been adopted by mega science projects in high energy physics [SoftwareF]. This will also be beneficial for low-energy nuclear physics software activities.

Virtual Plasma Machines on Exascale HPC:

Plasma physics needs dedicated HPC facilities that are speed-intensive. The development of virtual fusion and plasma machines need to couple physics and engineering aspects of the device. For such a study, the expected computational facility is ~500 PFLOPS. The existing numerical codes have to be integrated via proper interface so that data can be shared between codes. These codes are mainly focusing on plasma physics aspects that have to be coupled with engineering packages to build a virtual plasma machine. The goalposts of this project are as follows:

- Short term goals (up to 3 years): an HPC with a computational capability of ~100 PFLOPS will be commissioned and existing numerical codes will be ported to the system.
- Mid-term goals (up to 7 years): an HPC with a computational capability of ~200 PFLOPS. The existing and newly developed codes will be used to predict the integrated performance of plasma devices.
- Long-term goals (up to 15 years): a ~500 PFLOPS HPC. This will be used to make production runs of virtual fusion and plasma machines.

Note that the computing resources required for this application can be in the form of GPUs, which have a lower power requirement.

2.7 PLASMA-RELATED SYSTEMS

2.7.1 FUSION-BASED VOLUMETRIC NEUTRON SOURCE

Spherical tokamaks (STs) are very tight aspect ratio tokamaks (with major radius/minor radius ≤ 1.5), which are excellent candidates as volume neutron sources (VNSs) of a high flux of 14 MeV DT fusion neutrons, that can be used for a variety of purposes, e.g., production of radioactive isotopes such as ^{32}P, ^{56}Mn, ^{60}Co and ^{99}Mo for medical purposes, production of tritium for conventional fusion reactors, or acting as the core of a fission-fusion hybrid reactor [Stambaugh 1998]. STs have an advantage over conventional tokamaks in that they can reach much higher plasma beta (ratio of plasma pressure to magnetic field pressure) and still have stable operation. Due to this, STs can operate at much lower magnetic fields compared to conventional tokamaks and still achieve higher performance as fusion output scales as a square of the plasma beta. Thus, STs can be operated with copper magnets instead of high-field superconducting magnets in conventional tokamak reactors such as the ITER and hence can be built at a much lower cost.

In India, so far, no spherical tokamak has been built. IPR has invested mainly in the conventional aspect ratio (major/minor radii) tokamak, ADITYA, with an aspect ratio of 3 that was commissioned in 1989 and is still in operation as ADITYA-U, whereas SST-1, with an aspect ratio of 5.5, had its first plasma operations in 2012. All the magnets in ADITYA are made of copper whereas SST-1, designed as a steady state device, has a mixture of superconducting (NbTi) and copper magnets. Both, ADITYA-U and SST-1, are now routinely operated, with ADITYA-U already achieving (in fact, exceeding) its original design parameters. Both these tokamaks have given the plasma community rich experience in building, commissioning and operating short pulse as well as long pulse tokamaks. In addition, ITER participation and successful delivery of ITER components has also provided enough experience, confidence and technical expertise in cutting edge technologies. As the functioning of STs is not greatly different from conventional aspect ratio tokamaks, it should be possible to build a spherical tokamak for the first time in India. Building the world's first ST-based VNS in India can potentially put India in a dominating position in fusion research in the world.

It is proposed to build a moderate-sized ST-based VNS of these approximate parameters: major radius = 1.5 m, minor radius = 1 m (aspect ratio = 1.5), toroidal magnetic field = ~2 T made of copper magnets and a plasma current = ~8 MA with a plasma pulse duration of ~5 s, operated with D-T fuel. Initial estimates show that such an ST-based VNS can have a net fusion power of ~15 MW with a neutron yield of ~5×10^{18}/s. This can be an excellent device for breeding of radioactive medical isotopes in sufficient quantities.

A reasonable timeline for such a project could be as follows:

- T0+3 years: Completion of the physics and engineering design and prototyping with design review
- T0+10 years: Completion of construction
- T0+11 years: Completion of assembly and commissioning, and the first plasma operations
- T0+15 years: First full power 50-50 DT operations

The VNS will be a national facility and will require involvement of a wide range of institutions along with IPR, e.g., IITs for designing various subsystems, Universities/IITs for the design/procurement/operation of diagnostic systems, and various units of the DAE for tritium handling, remote handling of radioisotopes and neutronics.

2.7.2 Pulsed-Power Plasma-Based Thermal Radiation Facility

A pulsed-power approach to inertial fusion energy (IFE) requires the production of large yields of soft X-rays at high power (100's of TW). Implosion velocities of 100s of km/sec produce a hot, dense plasma, which releases a burst of intense soft X-rays. This thermal radiation falls on a solid (hohlraum), producing intense shock waves and compression/ignition of D-T fuel capsule to fusion conditions. A range of such facilities has been set up around the world, e.g., the Z machine at Sandia (Soft X-ray pulse of 2 MJ, 200 TW, few ns). The large magnetic pressure in such pulse-power facilities have also been used to directly compress matter to the 1–5 Mbar range. The Procyon facility at Los Alamos National Lab (LANL) has driven Z-pinch and has produced a 1.5 MJ soft X-ray pulse. More than 20 institutions in India are working in these areas, including BARC, IPR, IISc and RRCAT, with over three decades of experience.

In India, there is a plan is to set up a high-energy (MJ), high-power (TW) pulsed-power facility for producing intense soft X-ray bursts. Sophisticated diagnostics is required for studying multi-MV, TW, ns-duration wire-array and foil implosion. The scope of work for making this facility will involve the installation of a pulsed-power generator of 10 MJ energy and 7 MA current to produce 1.5 MJ of soft X-rays from a wire-array consisting of 50–100 wires, each having a diameter around 50 µm. The plan has been divided into steps of three years, seven years and 15 years.

- Deliverables during the first three years: Design document of pulsed-power system and single module operation at 2.5 MJ, producing a current of 1.7 MA.
- At the end of seven years: Study of ablatively-driven shock waves at thermal radiation intensities of around 10–100 TW/m^2, study of the EOS for a variety of materials in the pressure range of 1–2 Mbar.

- Deliverable at the end of 15 years: Fully-indigenous design, fabrication and operation of a national facility called the "High Energy Thermal Radiation Facility (HETRF)", and its application to the study of EOS, opacity, resistivity, photoionization, etc. An improved understanding of wire-array physics will enable the scaling of this source to larger facilities for IFE.

2.7.3 Toroidal Ultracold Plasma Trap for quantum computing

Quantum computers based on qubits are expected to perform a certain class of operations, such as prime factorization, much faster than any classical computer. Worldwide, RF-based linear quadrupole Paul traps have been used to "hold" a few heavy atomic ions using an RF field and an axial magnetic field. Laser cooling to sub-milli-Kelvin results in quantum entangled states of $N \simeq 2-3$ ions. These states are called qubits, and one can construct and operate "quantum gates" using them. It is proposed to use both heavy ions and electrons as the "working medium". IPR has pioneered toroidal magnetic field traps at small aspect ratios, wherein about ~109-1011 electrons are held using a guide magnetic field in the toroidal direction. Space-charge electric-field self-generated by electrons and the external guide magnetic field makes the application of the RF field for confinement redundant. Using this toroidal geometry and Tesla-level guide magnetic field, it is proposed to start by "holding" like-signed charges starting from $N \simeq 102$ and systematically "miniaturize" the geometric size and N to smaller values. In parallel, experiments on tangential laser cooling will be initiated along with computer simulations. Collaborations will be made with IISc (for quantum algorithms and simulations, quantum many-body problems, quantum control electronics and signal processing) and with TIFR (for quantum measurement and control lab using squid-based scalable three-qubit quantum computers).

The facility will be developed in two phases listed below:

- Phase-1 (0–5 years): Magnetic fields of the order of 1 T or above can be created using modern superconducting strips. Using superconducting magnetic fields in low, tight aspect ratio geometry, a large number of like-signed charges at low density will be confined for a long time. It has recently been shown using computer simulations that it is possible to confine electrons "forever" in such tight aspect ratio toroidal traps. In terms of diagnostics, imaging and charge-dumping-based density measurements with automatic "load-hold-dump" cycle at a repetition of 1–50 Hz will be set up. In tandem, computer simulations using the HPC facility at IPR employing the PIC code, as well as molecular dynamics code, will be performed.
- Phase-2 (5–12 years): In the second phase, the number of charges and the radius of the trap will be reduced so that a smaller number, N, of charged particles can be held. In parallel to this effort, experiments will be conducted on tangential laser cooling to achieve ultracold like-signed charged species, which can then be used for quantum many-body entanglement resulting in high qubit states. A semiclassical (quantum) simulation of this new class of toroidal equilibria will be attempted. Several other alternative magnetic geometries will be explored from the point of view of optimizing the trap.

2.7.4 Astroplasma Simulator at Lab Scale (ASaS)

Worldwide, several experiments are underway in the topic of astroplasmas. For example, the Large-volume Plasma Device (LAPD) at the University of California, Los Angeles was the first to study flux rope dynamics at the laboratory scale. The newly proposed Facility for Laboratory Reconnection Experiments (FLARE) at Princeton University, USA will focus on the various states of reconnection using preformed plasmas and plasma guns. Observational astroplasma physics at large scales, satellite observations at helioplasma-scales and laboratory experiments complement each other; where any one among them alone is insufficient to understand this important multiscale phenomenon. Theory and very-large-scale computer simulations using kinetic, fluid and hybrid methods are also necessary. Therefore, a combination of laboratory experiments and numerical simulations has become a necessity.

To experimentally span the length scales from kinetic to fluid scales, a 20 m long cylindrical plasma, with 3 m radius, supported by plasma sources, controllable external B-field, automated diagnostics and an appropriate vacuum chamber is proposed to study regular and rapid reconnection and related physics challenges described earlier. In tandem, to support the experiments, the development and integration of 3D multiscale kinetic-fluid simulation codes is proposed which would exploit large-scale HPC facilities in IPR and elsewhere in India.

The experimental setup will be modular in nature, with each module designed for achieving a set of major physics goals.

- Phase-1 (0–4 years): During the 1st phase, a single plasma source along with a plasma gun will be installed. Experiments will be conducted with the plasma in a guide field colliding with the plasma from the gun, resulting in magnetic reconnection. In parallel to this, fluid, kinetic and hybrid codes would be run in the HPC system at IPR to understand the experiments. Training of Ph.D. students in experiments and simulations is also envisaged to take place in the later part of this phase.
- Phase-2 (4–7 years): During the 2nd phase, the length of the modular setup will be extended to 12 m along the plasma sources. Experiments on the long-length-scale flux tubes at various Lindquist numbers, S, and their interaction will be completed along with computer simulations using fluid, hybrid and kinetic models. A large number of faculty members from IPR and elsewhere are expected to participate in this stage along with training of Ph.D. students.
- Phase-3 (7–15 years): Final phase comprising a 20 m long plasma consisting of two plasma sources and several plasma guns will be completed. This will facilitate exploring a range of Lindquist values experimentally. About 40-50 Ph.D. students and a large number of faculties from IPR and elsewhere are expected to have participated by the end of this phase.

Participation by Other Labs:

ISRO: India's first dedicated solar space mission, ADITYA-L1 (L1 = Lagrange point-1), to measure the solar corona and its dynamics, using six payloads for measuring plasma parameters, should be ready in 2021–22 and data should become available soon after. A comparison of the data from the proposed ASaS Phase-1 and 2, large-scale computer simulations along with those from the ADITYA-L1 measurements should shed light on one of the unsolved mysteries of solar coronal heating.

IISERs, IUCAA, IIA, PRL and IITs: IISER Pune, IISER Kolkata, IIA and PRL pursue exciting research in solar corona and related areas. Experiments on ASaS can be expected to be very useful for these labs. Similarly, IUCAA and IITs interested in the laminar and turbulent dynamos and intergalactic B-field generation could also gain from ASaS.

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3 CURRENT AND PLANNED MEGA PROJECTS AND FACILITIES

This chapter summarizes the current status of the Nuclear Physics mega projects (and potential mega projects) being pursued in India currently. These include Indian participation in the relativistic ion collider experiments, such as STAR and ALICE [Aamodt 2008] [Ackermann 2003] [Abelev 2014], International Thermonuclear Experimental Reactor (ITER) and Facility for Antiproton and Ion Research (FAIR) [Durante 2019]. These well-established projects already have future planned facilities such as EIC and ELI-NP.

The current mega science projects have direct links to the research and development for the future/proposed projects. This is particularly true in the case of detector developments, read-out electronic systems, data acquisition systems, simulation framework and computing techniques and infrastructure. The mega science participation has evolved from few thousands of channel detectors to millions of channels, from scintillator-based, to gas-based and more complex micropattern gaseous detectors (MPGDs) and hybrid systems. The simulation framework has moved from being FORTRAN-based to object-oriented-programming-based. The knowledge gained at each step has been utilized to enhance the capabilities in each of the above sectors for the new experiments, where challenges of handling higher luminosity, particle fluxes and radiation are encountered. As an example, the developments in resistive plate chambers, MPGDs and silicon-based detectors at CERN, RHIC, FAIR and in the INO-based programs will certainly benefit the R&D on such detectors for the experiments at EIC and the Future Circular Collider.

3.1 ONGOING PROJECTS AND ACTIVITIES

3.1.1 STAR and ALICE - Heavy ion experiments

Recent Important Achievements:

Indian institutes and universities have been participating in recent years in the Physics programs of ALICE [Aamodt 2008] [Ackermann 2003] [Abelev 2014] and STAR [Ackermann 2003] experiments at LHC and RHIC, respectively, towards the search and characterization of a deconfined state of matter called the QGP [Carminati 2004] [Adam 2005] [Alessandro 2006]. India has played a significant role by contributing in these experiments in terms of the development, installation and running of the detector systems, development of the associated systems, such as electronics and readout, development and maintenance of the associated software and physics analyses. These are briefly discussed below:

Photon Multiplicity Detector:

Indian collaboration has designed and developed a fully indigenous proportional-counter-based high granular large-area gas detector for detecting photons in the forward rapidity region ($2<\eta<4$) known as the photon multiplicity detector (PMD) for the ALICE and STAR experiments. The PMD was installed in these experimental sites, was used for data-taking and was later decommissioned after a successful completion of the required data acquisition [Dellacasa 1999].

Muon Tracker:

India has built two stations (out of five) of the Muon Tracking System (low-thickness cathode pad chambers) in ALICE for the detection of the forward-angle muons in ALICE. The detector has been installed and is participating in the ALICE data-taking since 2009 [ALICE 1999].

Muon Forward Tracker:

India is playing a key role in the building of a silicon-based Muon Forward Tracker (MFT) detector and the readout for the muon tracker upgrade to extend the precision measurements of the QGP properties at forward rapidity in the ALICE experiment [Adam 2015].

Development of the MANAS chip in collaboration with Indian industry:

The development and manufacturing of the front-end electronics (FEE) for collecting signal from the muon and photon detectors was done in India, in collaboration with Indian industries, e.g., SCL, Chandigarh, developed and fabricated the Multiplexed ANAlog Signal Processor (MANAS) ASICs that were used in ALICE.

Common Readout Unit:

Indian collaborators contributed in the design and development of a common readout unit (CRU), which is an FPGA-based high-tech unit, to provide the crucial interface between the detector front-end electronics and DAQ by performing data aggregation and distribution of timing, trigger and control information. The Indian contribution was in the development of two fully assembled prototype-I boards, development of PCBs, pre-series prototype boards, delivery of 370 fully tested CRU boards and the development of firmware and software as per the requirement of the ALICE-CRU team.

Forward Electromagnetic and Hadronic Calorimeter:

A Si-W-based high-granular forward electromagnetic and hadronic calorimeter (FoCal) has been proposed as an upgrade to the ALICE experiment, which is to be installed at the LHC during Long Shutdown-3 for data-taking in 2027–2029. This calorimeter will provide unique capabilities to measure small-x gluon distributions via prompt photon production and will significantly enhance the scope of ALICE for inclusive and correlation measurements with mesons, photons and jets to explore the dynamics of hadronic matter at small-x down to $\sim 10^{-6}$ [Acharya 2020]. Indian groups were one of the early initiators of this idea and have been involved in the R&D of the detector as well as studying its physics performance through simulations. They have developed full-depth prototype detectors using W-absorber and n-type Si with a maximum wafer size 4 in as detection elements in collaboration with BEL, Bengaluru and BARC, Mumbai. They have also contributed to the physics simulations for FoCal.

Important Physics Analyses and Measurements:

The experimental measurements of QGP properties (energy density, temperature, transport coefficients) allow us to test the fundamental predictions of QCD, the theory of strong interactions. Several physics observables are predicted, experimentally measured and studied for qualitative as well as quantitative understanding of the QGP properties.

India has played an important role in this endeavor by analyzing hadron-hadron (pp), hadron-nucleus (pA) and nucleus-nucleus (AA) collisions at RHIC and LHC energies. Some of the highlights are mentioned below:

- India has played pioneering roles and contributed significantly in exploring the QCD phase diagram and in searching for the QCD critical point via measurements of K/π, net charge fluctuations and moments of net-charge, net-proton, net-kaon and their mean transverse distributions. In addition, charged-neutral correlations, identified correlations and balance function analyses have been performed effectively.
- India has contributed in the understanding of the global properties and freeze-out conditions via measurements of charged and identified particle yields and photon multiplicities at mid and forward rapidity. The photons are being detected using the indigenously-built PMD detector.
- The established longitudinal scaling of charged particles was also demonstrated to hold for photons measured by the PMD.
- India has primarily demonstrated the ability of STAR and RHIC to run below the nominal energy than what was originally planned at RHIC.
- India has contributed in the new technique of measuring the energy loss of the identified particles using the relativistic rise.
- Indian scientists have, for the first time, demonstrated the evidence of spin alignment of the vector mesons in Pb-Pb collisions.
- The study of QGP properties by measuring collectivity is one of the areas where India has a long history and has remarkable contributions.
- India has played an important part and made vast contributions in the study of resonances, production of nuclei and understanding of the hadron phase.
- One of the first analyses at the LHC on (anti-) nuclei was done by an Indian group and first demonstrated that the ratio of anti-nuclei to nuclei is unity at the LHC energy.
- India led the search for an antimatter ^{4}He nucleus at STAR as well as ALICE.
- India has contributed to the study and understanding of quarkonia and heavy flavor production at forward rapidities using indigenously-built muon detector in ALICE.
- Measurements of jets provide a testing ground for the theory of perturbative QCD (pQCD) in pp collisions and helps in understanding the energy loss mechanisms and jet-medium interactions in heavy-ion collisions. Indian groups have contributed to the measurements of jet production cross-sections and properties in hadronic and nuclear collisions.

Plans for the Next 15 years and Expected Major Outcomes:

The experiments at BNL and CERN will help in addressing many important questions as discussed below:

(A) At BNL – Solenoidal Tracker At RHIC: In the near future, STAR will continue to analyze the data collected in the Beam Energy Scan II (BES-II) experiment in order to complete one of the major goals, i.e., searching for the critical point and the first-order phase transition between QGP and hadrons. The discovery of a QCD critical point would constitute a major scientific achievement in heavy-ion physics. Indian groups are playing a crucial role in the search for the critical point.

For the years 2023-2025, STAR will investigate its other important major goal, i.e., probing the inner workings of the QGP by resolving its properties at shorter length scales. STAR has several years of operating experience. Recently, there was an upgrade to the Inner Time Projection Chamber (iTPC), and there will be installation and operation of the forward detectors of STAR. This will be combined with the prospect of a substantial increase in beam luminosities. As a result, RHIC will be uniquely positioned to perform a detailed exploration of the microstructure of QGP.

With the unique capabilities of STAR and RHIC, it will be able to address the following important questions pertaining to the inner working of QGP:

- What is the precise temperature dependence of the shear viscosity (η/s) and bulk viscosity (ζ/s)?
- What is the nature of the 3D initial state at RHIC energies?
- How does a twist of the event shape break the longitudinal-boost invariance and decorrelate the direction of an event plane?
- How is global vorticity transferred to the spin angular momentum of particles on such short time scales? How can the global polarization of hyperons be reconciled with the spin alignment of vector mesons?
- What is the precise nature of the transition near $\mu_B = 0$ and where does the sign change of the ratio of the sixth-order susceptibility to second-order susceptibility take place?
- What is the value of the electrical conductivity of the medium and what are the chiral properties of the medium?
- What can we learn about confinement and thermalization in a QGP from the charmonium measurements?
- What are the underlying mechanisms of jet quenching at RHIC energies?
- What do jet probes tell us about the microscopic structure of the QGP as a function of the resolution scale?

As demonstrated in point 1, Indian groups have good experience in the abovementioned physics analyses and should be able to contribute in addressing these physics goals.

Other important measurements that will be provided by the STAR experiment deal with the physics of cold QCD matter using polarized p+p and p+A collisions at s = 510 and 200 GeV. In view of the upcoming EIC facility, a few important measurements remain to be performed at RHIC. These studies will form the basis for the EIC, scientifically as well as in terms of guiding the experimental requirements of the physics program, and hence are the automatic next steps towards the EIC. These measurements, when combined with those from future EIC measurements, will provide a broad foundation to a deeper understanding of fundamental QCD. To establish the validity of factorization and universality, it is essential to have data from lepton-ion as well as proton-ion collisions. The STAR experiment will be able to provide the essential p+p and p+A collisions data. It will be able to explore the interesting regimes of high-x (largely valence quark) and low-x (primarily gluon) partonic physics with excellent precision. While using pp 510 GeV data and with forward upgrade, STAR will be able to access the forward jet physics at perturbative scales, thus enabling measurements at high and low-x values. A combination of the two runs of pp 510 GeV and 200 GeV will allow STAR to measure the fundamental properties, such as the Sivers and transversity distributions over nearly the entire range $0.005 < x < 0.5$. STAR will have an excellent opportunity to probe the quark-gluon structure of heavy nuclei and the regime of low-x non-linear gluon dynamics, as predicted by the saturation models. It will also explore how a nucleus, serving as a color filter, modifies the propagation, attenuation and hadronization of colored quarks and gluons. Indian groups have started collaborating in EIC physics and are in the process of formalizing the EIC-India collaboration. As mentioned before, the abovementioned physics goals of the STAR experiment are very much related to EIC physics in which the Indian groups will be able to contribute significantly.

(B) At CERN – A Large Ion Collider Experiment (ALICE): The LHC and ALICE experiments are currently taking data in their Run 3, which will continue till 2025. After that, there will be a long shutdown LS3 (2026–2028), after which Run 4 is planned from 2029 to 2032. During the shutdown period, there will be upgrades on the LHC machine side as well as on the ALICE detector side. From the LHC side, instantaneous luminosities for pp will be a factor of five larger than the nominal value of the LHC. In addition, there will be improvements done to operate with potential peak Pb–Pb luminosities that are an order of magnitude larger than the nominal value. On the ALICE detector front, there will be upgrades in almost all subcomponents to improve various measurements as well as to accept the higher peak luminosity.

Indian groups are participating in the development of a new detector named FoCal that will provide unique capabilities to study small-x gluon distributions via prompt photon production and will also significantly enhance the capabilities of ALICE for general photon- and jet-related measurements. The small-x structure of nuclei in the presence of large gluon fields is described by the color glass condensate (CGC) model. FoCaL measurements will also help to allow testing the x and Q^2 dependence of QCD evolution in many complementary ways. They have decades of detector hardware experience starting from WA93 experiment, where we mostly relied on foreign groups to build a scintillator-based PMD, to WA98, for which we built the PMD hardware indigenously but took help from collaborators for electronics, to STAR and ALICE experiments where all components of gaseous detectors, PMD, and the ALICE muon chamber was developed indigenously, including electronics to measure the forward-angle photons and muons. With this vast experience of building detectors for forward-angle measurements, India is now in a good position to contribute to the FoCal project. In this endeavor, there are plans to collaborate with Indian industries, e.g., BEL, Bengaluru and SCL, Chandigarh.

The following four major physics goals have been identified to be address by the ALICE in future:

- Characterizing the macroscopic long-wavelength QGP properties with unprecedented precision
- Accessing the microscopic parton dynamics underlying the QGP properties
- Developing a unified picture of particle production from small (pp) to larger (p–A and A–A) systems
- Probing parton densities in nuclei in a broad (x, Q^2) kinematic range and searching for the possible onset of parton saturation
- Understanding thermalization, diffusion and drag using heavy flavor as a probe

Indian groups have good experience in performing these analyses and will be able to contribute to these goals.

Beyond 2030, there is an interest in developing a new LHC experiment dedicated to the high-statistics study of the production of heavy flavor hadrons and of soft electromagnetic and hadronic radiation produced in high energy proton-proton and nuclear collisions. The detector technology would be based on an ultra-low mass silicon tracker made with the complementary metal-oxide-silicon (CMOS) monolithic active pixel sensors (MAPS) technology. This would allow us to reach down to the very soft region of phase space to measure the production of very low transverse momentum lepton pairs, photons and hadrons at the LHC. This would provide significant advances in several areas such as heavy-flavor and quarkonia, low-mass dileptons (low mass continuum, $0 < m < 3$ GeV, chiral symmetry restoration and the temperature of the hot QGP fireball), soft and ultrasoft photons. Indian scientists have planned to contribute in this endeavor. These efforts, named as ALICE 3, have yielded a Letter of Intent, which provides a roadmap for exciting heavy-ion physics starting in 2035. The proposed novel detector concept is demonstrated to perform well from small to large collision systems, i.e., from pp to the most central Pb-Pb interactions, with unprecedented tracking and vertexing capabilities that reduce the instrumental background and previously irreducible physics background to a minimal level.

The total number of institutes involved in the project currently is 16, viz. Aligarh Muslim University, Aligarh; Gauhati University, Guwahati; Indian Institute of Technology, Indore; Rajasthan University, Jaipur; Jammu University, Jammu; Bose Institute, Kolkata; Calcutta University, Kolkata; Jadhavpur University, Kolkata; Indian Institute of Science Education and Research, Tirupati; Indian Institute of Technology – Bombay, Mumbai; Panjab University, Chandigarh; DAV college, Chandigarh; National Institute of Science Education and Research, Bhubaneswar; Institute of Physics, Bhubaneswar; Saha Institute of Nuclear Physics, Kolkata; and Variable Energy Cyclotron Centre, Kolkata. The total number of Indian scientific and engineering members in the project is around 120, with the median age below 30 years. This is expected to grow to about 180 in the next 15 years. About 70 students have completed their Ph.D. degree from the STAR-ALICE-India collaboration.

The SWOT Analysis (Strength, Weaknesses, Opportunities, Threats) for the Project and its Future:

Strengths:

- ALICE-STAR-India collaboration is composed of premier educational institutes of India
- Includes a large pool of scientists, engineers, research associates, Ph.D. students and technicians with a broad spectrum of expertise

- Working on the emerging topics in high-energy physics using cutting edge technologies
- Effective participation and leadership positions in several international collaborations
- Successful development, installation and commissioning of PMD in the STAR experiment at BNL and ALICE experiment at CERN, and the muon chamber in the ALICE experiment at CERN
- Significant contributions in software development, simulations, data-taking and data analysis
- Several publications in high impact factor journals covering a wide variety of analysis topics
- Development of high-end grid computational facilities in India
- Efficient collaboration with Indian industries for technology development
- Strong collaboration with the Theoretical High Energy Physics community

Weaknesses:

- Minimal absorption of manpower trained in the field in terms of job hiring at the faculty level
- Lack of full-steam involvement of Indian industries in mega science projects
- Low participation of scientists from the engineering stream

Opportunities:

- Development of high technically-skilled manpower (human resource development)
- Using cutting-edge technologies for societal benefits, e.g., medical science
- Taking the lead role in future high energy physics experiments
- Potential of constructing world-class high-energy physics facilities in India
- Development of interdisciplinary research across different fields
- Developing and integrating high-end computing facilities; data handling
- Promoting research in basic sciences through outreach programs

Threats:

- Lack of sufficient employment opportunities for high-quality researchers and technical personnel

3.1.2 International Thermonuclear Experimental Reactor (ITER)

Controlled thermonuclear fusion holds great promise for an alternative future source of energy and as a long-term replacement to fossil fuels because of (1) its advantage as a virtually inexhaustible and universally available fuel source, (2) the intrinsically safe nature (no nuclear chain reaction), (3) a very high energy density for large-scale production of electricity and (4) the acceptable environmental impact from point of view of operation and waste generation. ITER, which is under construction in the south of France, is based on the 'tokamak' concept, and aims to demonstrate scientific and technological feasibility for the generation of energy using nuclear fusion reactions between deuterium and tritium (D-T), which are different isotopes of hydrogen. ITER aims to achieve a fusion power amplification of Q = 10, i.e., with a 50 MW of input heating power, the fusion reaction will produce 500 MW output. Success achieved in the Joint European Torus in achieving D-T fusion with Q = 0.67 and established scaling laws have generated the confidence that ITER will achieve its goal. The ITER machine is a giant structure consisting of a large toroidal vacuum vessel (~1000 m^3) with 18 coils for the toroidal field and several other coils, all of which are superconducting. It also has an extensive array of cryogenics, high-power RF systems, neutral-beam injection system, pellet injectors, associated diagnostics, etc. The machine is enclosed in a cryostat that is 30 m in diameter and 30 m tall.

When successful, ITER will show us how to control plasma and let D-T fusion reactions happen in a controlled manner, paving the way for designing future fusion reactors capable of generating power at a commercial level. It will also offer an opportunity to test concepts of the tritium-breeding technology, which is important for any commercial exploitation of D-T fusion. Structural and shielding materials for a commercial-scale reactor would still remain a subject for development to be done through domestic R&D.

India is one of the seven members (other members: China, EU, Japan, Russia, South Korea and USA) of the ITER Scientific Collaboration established by an intergovernmental agreement in 2006. ITER-India, IPR, is the domestic agency for delivering Indian contributions to ITER. Starting from 2007, ITER and ITER-India have made significant progress towards the construction of the ITER project. As of the end of December 2020, about 72 % physical progress has been reported for assembly towards components and systems required for the first plasma operation at the ITER site in France. Assembly of the ITER tokamak was formally inaugurated on 28th July, 2020. The following is a list of recent achievements in the project.

Recent Important Achievements:

A. *Progress of ITER at the International Level*

1. Assembly of the tokamak has started with the installation of the cryostat base section, followed by the lower cylinder at the tokamak pit.
2. First of the nine vacuum vessel sectors has been received at site and preparation is in progress for installation inside the cryostat.
3. Toroidal Field coils have been received at the site and are being assembled with the vacuum vessel sector.
4. First poloidal field coil is ready after all qualification tests, whereas other coils are getting ready for test.
5. Plant systems are making good progress:
    a. 400 kV electrical switchyard has been commissioned
    b. Liquid He/N cryogenic plants for the superconducting coils are being installed
    c. Cryogenic transfer lines and distribution network are being installed
    d. Coil power supplies have arrived at the site and are being installed
    e. Cooling water system components have arrived and are being installed and commissioned.
6. Building construction is progressing in phases: major buildings (like assembly hall, tokamak building, etc.) have already been constructed, and assembly and installation of equipment are in progress.

B. *Progress in the Indian in-kind Contribution*

Indian deliveries have been organized in nine packages and achievements are mostly engineering and development of different deliverables.

1. Cryostat, the outer vacuum vessel (and also the second confinement barrier) is a first-of-a-kind vacuum vessel of approximately 30 m height and 30 m diameter. It holds the entire tokamak and also serves as a secondary confinement barrier for ITER. It has been built in several pieces in Indian factories and is now complete and ready for the final integration to be done at the ITER site. The lower two sections have already been installed in the tokamak pit and the final closure will happen after all other ITER components are placed inside.
2. The manufacturing process involved (a) manufacturing of very large and heavy components with strict tolerances (0.33 %), (b) thick plate welding (200 mm) with distortion control, (c) compliance to French nuclear safety requirements and (d) a novel nondestructive testing (NDT) technique for weld qualification.
3. In-wall Shield Blocks for neutron shielding of the vacuum vessel are precision-cut blocks made of special quality steel. These have been assembled by European and Korean manufacturers as inserts between the two walls of the vacuum vessel. Manufacturing of all blocks was completed in December 2020.
4. Cryogenic transfer lines and a distribution system for liquid (and gaseous for the return path) He and liquid N for the superconducting coil system of ITER has been delivered by India. The process lines have up to six pipes at various temperatures and handle all cryogenic fluids in ITER. Manufacturing has almost been completed and site installations are ongoing, expected to be complete in three more years.
5. The cooling water system for the nonnuclear part for the heat removal from the ITER is supplied by India. The system has been designed in India, all components have already been supplied, and site installation and commissioning is in progress. While completing the system, the following new developments have been made

by the Indian industry: (a) largest capacity (4 MW) chillers developed in India, (b) largest capacity (510 MW) cooling towers developed in India and (c) development of unique pipe-in-pipe concept, developed for buried pipe spools without trench.

6. High-power RF sources are two other Indian deliveries to the ITER.
   a. A 2.5 MW RF source in the 35–65 MHz range for the ion cyclotron heating of plasma has gone through the R&D phase for establishing technical feasibility before the manufacture of nine systems.
   b. After a successful test of the 1.5 MW power level using Diacrode/Tetrode tubes (2017), R&D for passive components, e.g., RF transmission lines, 3 MW combiner, splitter, etc., has been completed now.
7. Procurement for ITER deliverables will continue till 2026–27.
8. A 1 MW RF source at 170 GHz for electron cyclotron heating of plasma is based on gyrotrons. An integrated test system has been established and is expected to start operation towards the second half of 2022.
9. A 100 kV/72 A neutral beam injector for diagnostics is another ITER deliverable. The injector uses a high-power RF (1 MHz) plasma source and R&D is going on for establishing the beam parameters in a smaller setup. Development of special copper alloys and special material jointing techniques has been a part of new developments. A full-length test system has also been installed for the characterization of the system before its delivery prior to 2027.
10. Power supply systems for the systems mentioned in points 5 and 6. Above are the other Indian deliverables. These include a series of high-power fast-acting controlled converters in operating ranges of 3–7 MW and 14–100 kV, which are built based on technology developed by the institute. Two power supplies have already been delivered to ITER and the rest are scheduled along with the corresponding systems.
11. Diagnostic systems of ITER are extensive and India is responsible for four different diagnostic systems (viz., X-ray charge exchange spectroscopy, electron cyclotron emission (ECE) diagnostic) and one port that becomes part of the vacuum vessel. R&D for all these diagnostics are being pursued and deliveries are scheduled starting from 2025.

Plans for the Next 15 Years and the Expected Major Outcomes:

As major deliveries of ITER are still under progress, the activities for the next five years would continue to focus on the completion of the remaining deliveries to ITER. The same is expected to be completed by 2027, as some components would be used by ITER only at a date later than its first plasma operation, which is, otherwise, the engineering commissioning of the machine.

The ITER machine has complex interfaces and several first-of-its-kind systems. Continued engagement during the assembly and integration of the machine would be important to understand and assimilate issues and resolutions thereof in the assembly of a large facility such as ITER. ITER is being built in compliance with the French nuclear regulations and extensive learning scope exists in the safety and regulatory issues apart from the functional aspects.

Subsequent to the commissioning of ITER with the first plasma operation (2025), which targets modest plasma of several hundred kA, several other auxiliary systems will be installed in phases. Two rounds of operations are planned in the ITER Research Plan. Gradually, full plasma current (15 MA) operation will be achieved in Hydrogen and Helium plasma. By 2034, the machine will be ready with all installations required for tritium operation and fusion reactions in deuterium and tritium plasma. The Indian program in the next few years needs to attempt absorption of knowledge to the maximum extent and prepare for the start of construction of Fusion Demonstration Reactors (DEMO) as soon as ITER experiments establish feasibility of the same.

Figure 4: Experimental Operation Schedule of the ITER (intermediate upgrades have been omitted)

Keeping this objective in view, the following vision has been planned:

1. Indian in-kind contributions are expected to complete by 2027–28. It is also prudent to supply complex equipment to be supplied 'just in time' as some of the components are required at a later phase. Associated activities will continue.

2. Speeding up domestic research program in the meantime is necessary for full utilization of the knowledge gained from ITER experiments.

   a. Theory, experiments and modelling/simulation activities in basic plasma physics as well as applications need to be accelerated. Examples of such activities are:

      (i) Plasma for People; for exploiting plasma-based technology applications

      (ii) Exascale computing facility (>200 PFLOPS) to be established for using them for simulating complex-scale scientific problems

      (iii) Ultracold plasma experiments, relevant in quantum computing

      (iv) High-energy thermal radiation facility to explore alternative concepts of fusion.

      (v) Astrophysical plasma facility for experimental studies in space plasma, also used for training of future human resources in plasma physics.

   b. Participation in ITER experiments provides opportunities for sharing knowledge and new technologies. This will require

      (i) Training of scientific manpower for conducting Indian-lead experiments in ITER during its D-T operation phase

      (ii) Continuation and expansion of the National Fusion Program, interconnecting universities and institutions at the national level for absorbing technology and scientific outcome from ITER

      (iii) Experiments in domestic tokamaks in newer areas of plasma control, shaping, heating and disruption control, to concurrently train manpower for the operation phase of ITER

      (iv) Efforts towards R&D in areas not addressed in ITER, such as

         I. Fusion-based VNS: This will be a reactor much smaller and simpler than ITER, which will use the knowledge from ITER construction and would have application in areas as diverse as specialized isotope production using 14 MeV neutrons, radiation damage studies in fusion reactor materials and physics of spherical tokamaks.

         II. Tritium breeding technology development: ITER will offer the option to test Indian system during its fusion power operation phase.

3. Material development for extreme conditions of heat, neutron flux and electromagnetic forces is essential for exploiting fusion in future. Materials research and the VNS mentioned above will be useful for testing such materials.

4. Technologies for Auxiliary systems, e.g., neutral beam, RF power source, cryogenic system, etc., need to be upgraded to the level of ITER systems. Activities for the development of materials for neutron shielding and the necessary improvements in electronics to work in harsh environments are to be initiated.

ITER-India has collaborations with numerous universities and institutions in India such as Saha Institute for Nuclear Physics (SINP), Bhabha Atomic Research Center (BARC), Indira Gandhi Center for Advanced research (IGCAR), IIT Madras, IIT Delhi, IIT Gandhinagar, IIT Guwahati, Institute of Advanced Study in Science and Technology (IASST), National Institute of Science Education and Research (NISER), Institute of Physics (IOP), Kalinga Institute of Industrial Technology (KIIT), Institute of Minerals and Materials Technology (IMMT), Raja Ramanna Centre for Advanced Technology (RRCAT), Raman Research Institute (RRI), Cochin University of Science and Technology (CUSAT), Physical Research Laboratory (PRL) and Birla Institute of Technology (BIT) Mesra. The ITER team responsible for in-kind deliveries has 120 scientific and technical staff, with the median age in the range of 35–45 years. It is important that the Indian Domestic Fusion Research Program is scaled up to a level similar to other ITER member countries who intend to exploit the outcome from ITER for immediate application. It is expected that the above number grows to at least double by 2027–28 to start assimilating the outcome of ITER, and to approximately 1200 by 2035 for readiness to start a fusion-energy-generating reactor by the time ITER results are available.

The SWOT Analysis for the Project and its Future:

Strengths:

- Construction and operation experience in smaller tokamaks (ADITYA, ADITYA-U and SST-1) and fission nuclear expertise/technologies from DAE Units.
- Access to the intellectual property generated during the construction of ITER are available equally to all member states. These will help in accelerating the fusion-related R&D in the domestic program.
- Access to the scientific data to be generated during the operation phase of ITER is open to all members.
- Industry preparedness, attained through participation during the construction of ITER, in different areas (exposed through in-kind deliveries) enhance the capability in several core and ancillary systems in a fusion reactor.

Weaknesses:

- Small sub-critical effort level in domestic R&D program in tokamaks. India has only two smaller tokamaks (1 m^3 plasma volume as compared to 800 m^3 of ITER) for conducting any fusion-relevant experiments as compared to multiple big and small systems in other ITER member countries.
- Small strength of manpower trained in the field of theory, design, construction, operation and experiments in tokamaks.
- Weak industrial ecosystem in several high-tech areas, e.g., superconducting materials, sensors and diagnostics systems, materials for extreme conditions of heat/mechanical/neutron loads, precision manufacturing, etc.
- Organizational and logistics constraints, e.g., an ITER-sized project execution requires larger organized setup and facility, including land, which are not yet planned.

Opportunities:

- Access to ITER by participation of Indian scientists in the scientific exploitation phase of ITER is equally open, as permanent staff as well as visiting researchers. Preparatory training of graduate students for ITER operation and exploitation should start now.
- Large pool of science and engineering students in the relevant fields can be introduced to fusion energy research by setting up small tokamak experiments in universities.
- Start of R&D and prototype construction of the relevant technologies where India is not delivering in-kind using access to knowledge available from ITER.
- Setting up a domestic program of equivalent dimension, gradually growing to a level comparable to other ITER member countries. This must include the construction of a midscale machine to address key areas not addressed in ITER.
- Leveraging goodwill from ITER for other international collaborations, including a possible establishment of a future fusion research facility (such as DEMO) in India.

Threats:

- Any constraints leading to India's withdrawal from ITER during the operation phase. A withdrawal would lead to loss of knowledge, which could only be acquired during the operation phase.
- ITER experiments not achieving key targets in fusion power, control and tritium breeding.
- Inability to retain trained personnel and expanding/transmitting knowledge and skills to the younger generation

- Delay in scaling up the domestic program will potentially leave little time to absorb all aspects of the complex subjects efficiently.

3.1.3 CBM, NuSTAR and PANDA experiments at FAIR

The international accelerator facility, FAIR, being built in Darmstadt, Germany, is one of the largest upcoming research projects worldwide [FAIR]. It will provide high-intensity beams of ions (from H to U), radioactive ions and antiprotons. These beams with unprecedented intensity and accuracy will generate new avenues for performing experiments in the fields of atomic physics, nuclear physics, hadron physics, nuclear matter physics, plasma physics, material physics and biophysics. Scientists from all over the world will be able to investigate various properties of matter under extreme conditions and gain new insights into the structure and origin of matter. FAIR will provide the opportunity to explore science at length scales ranging over 30 orders of magnitude, starting from the internal structure of the nucleons to the mysteries of astrophysical objects in the Universe, such as colliding neutron stars [Durante 2019]. The experiments at FAIR will have the potential to make path-breaking discoveries in these research fields.

Physics Questions:

FAIR will expand our knowledge in various scientific fields beyond the current frontiers [Durante 2019]. The four international collaborations, namely, anti-Proton ANnihilations at DArmstadt (PANDA) [Erni 2009], CBM [Friman 2011] [Ablyazimov 2017], NUclear STructure, Astrophysics and Reactions (NUSTAR) [Nilsson 2015] and Atomic, Plasma Physics and Applications (APPA) [Stöhlker 2015], will address the following:

- The role of the strong interaction in building the Universe and its evolution
- The phase diagram of QCD, in particular, at the high densities and its role in the core of neutron stars or in the mergers of neutron stars
- Tests of symmetries and predictions of the Standard Model of the electroweak theory, in particular, in the range of strong-field quantum electrodynamics and special relativity
- The properties of exotic nuclei and their role in the origin of the heavy elements in the Universe
- Applications in the areas of high-intensity radiations e.g., space science, radiology among others.

The Rare Ion Beams facility at FAIR will provide experimental data on exotic isotopes that are crucial for simulating the astrophysical r-process. This will help in obtaining stringent constraints that will allow for detailed analyses of merging neutron stars, which have been shown to be the sites of the r-process, thus solving one of the unsolved questions of the last century. With the reduced uncertainties in the nucleosynthesis studies, one can investigate the dynamics and properties of the environment on top of the freshly born neutron star. FAIR will also advance our understanding of the EOS of dense and hot matter. These measurements, along with the progress in multidimensional simulations, holds the prospect of exploiting gravitational wave signals from such events for searches of new physics. At high net-baryon density, restoration of chiral symmetry is an important area to be explored at FAIR.

Indian groups have expressed interest in contributing in CBM, NUSTAR, PANDA and APPA experiments in terms of the development, installation and running of the detector systems, development of the associated systems such as mechanical systems, electronics and readout, and the development and maintenance of the associated software and physics analyses.

Status of the FAIR Project in Germany:

The civil construction of the FAIR facility is in full swing at the site. For civil construction work, the entire FAIR area has been divided into two regions, i.e., north and south sites. Over the last one year, a major part of the construction of the main accelerator tunnel (SIS-100) in the north area has been completed, including the experiment hall for the CBM experiment, which is one of the major scientific pillars of FAIR. The 60 m wide and 20 m deep tunnels have been covered and the beam transportation line from the existing GSI to FAIR has also been built. The activities in the south site for beam transfer and production of secondary beams are in full swing. The entire civil construction work is expected to be completed by 2022 and the first experiments are expected to start in 2025. All accelerator equipment being built in India are scheduled to reach FAIR by 2022.

Indian Involvement:

On October 4th, 2010, India, with a commitment of 36 M€ (2005 cost book value) towards the construction cost (mostly in-kind), became one of the founder members of the FAIR GmbH at Darmstadt, Germany, the largest upcoming accelerator facility worldwide. A survey during the initial phase of Indian participation at FAIR among the interested groups in the country showed that about 40 groups (~15 from DAE) are interested to take part in these front-ranking experiments. In addition to performing experiments at FAIR, Indian in-kind contributions also include building accelerator equipment using advanced technology.

India's participation in FAIR is two-fold:

a. design, fabrication, installation and commissioning of advanced accelerator equipment for FAIR and

b. participation in the experimental program at FAIR, including development and fabrication of detector systems for the experiments

Physical Progress (India) Over the Last One Year:

There are two types of in-kind contributions i.e., accelerator and detectors. The status of the in-kind items identified so far is given below.

Power converters for the FAIR accelerator: About 650 ultrastable power converters are being designed and built by Electronics Corporation of India Limited, Hyderabad (ECIL-Hyderabad) for various rings of the FAIR accelerator. During the last one year, even at the time of the ongoing pandemic, the activities were in full swing. Up till now, 164 power converters have been shipped to FAIR from ECIL-Hyderabad. This essentially completes a large part of the converters for the normal conducting magnets of FAIR. One prototype has been built for the superconducting magnets and production will start in 2021.

Ultrahigh vacuum chambers: A total of 58 thin-wall ultrahigh vacuum (UHV) chambers (10^{-9} mbar) with up to seven ports for housing FAIR beam diagnostic equipment are to be built in India. Two prototype chambers built by a company in Bengaluru have been shipped and have passed tests at FAIR. The company has started the production of the remaining chambers. FAIR has sent a request to build 13 more chambers.

Beam stopper: A set of devices made of graphite/Cu with a provision of water cooling will be built in India for stopping the peak power of 23 KW from the high-intensity primary and secondary beam particles from FAIR in a very short time interval (100 ns). During the past several years, the Central mechanical Engineering Research Institute (CMERI)-CSIR, Durgapur in collaboration with GSI-Germany has completed the conceptual design report (CDR) and final design report (FDR) (both static and dynamic modes of operations) of the beam stoppers and associated equipment, and the process has been started to find manufacturers in the country.

Advanced detectors for FAIR experiments: The Indian research groups that are to perform experiments in FAIR have completed R&D on advanced radiation-hard, high-resolution detectors and electronics. During March-May 2020, Indian researchers participated in performing experiments in the phase-I program at FAIR remotely. Most of the operations such as the detector control, monitoring, data-taking were done remotely. The results were as per expectation, showing the performance by the India-made detectors at par with the detectors built by international teams. Indian teams are involved in building advanced gaseous detectors called GEM and low-resistivity RPCs, and the associated electronics. The prototype detectors have been successfully tested in the experiments at FAIR. The technical design reports (TDRs) have been approved by an expert committee of FAIR. R&D has been completed for all assigned detector types. Production process of these items has started.

DEGAS is a crucial detector system for the DESPEC experiments to study the most exotic nuclei that will be produced at NUSTAR/FAIR [DEGAS 2014]. TDR of DEGAS has been accepted by FAIR and the India-DEGAS proposal has been approved by the collaboration. The participating groups from India have made substantial and important progress in the design as well as validation of various prototypes related to their DEGAS proposal. Most importantly, the PHASE-I of DEGAS needs to be ready by 2022 for their use during the in-beam experiments scheduled at GSI/FAIR in 2022/2023. In order to further enhance the physics capability of the current DESPEC setup for high-energy heavy ions, a dedicated detector has been simulated, designed and fabricated. This Germanium double-sided strip detector (GeDSSD) enables the investigation of very low energy gamma rays as well as internal conversion electrons (ICE) populated by isomer decay, following a heavy ion implantation. This particular feature will enable future proposals in the heavy mass region to study very low-energy transitions, presently considered difficult. GSI Program Advisory Committee (PAC) has accepted the proposal and the testing of the detector will be done in 2022.

The mechanical housing of the detector, an aluminum cuboid chamber, has been machined. The electrode assembly, 21 aluminized mylar foil frames, has also been prepared. The integrated charge-sensitive preamplifier units are currently under fabrication. This detector is proposed to be commissioned at the exit of the fragment separator (FRS) for the initial phase of the NUSTAR campaigns from 2021–2022. The detector will be assembled and tested at IUAC, New Delhi before being shipped to GSI, Darmstadt.

1) The MONSTER array has been proposed for the measurement of the beta-decay properties of neutron-rich isotopes at the DESPEC experiment [MONSTER 2013].

Groups from India will build 42 similar liquid-scintillator-based neutron detectors for this array. The experiment "I240: Characterizing the MONSTER detector modules with beta-delayed neutrons from the decay of ^{85}As" was performed at the cyclotron accelerator facility at the University of Jyväskylä to test a part of the MONSTER array (48 detectors) and commissioning the electronics and data acquisition. Members from VECC, India played an important role in the setup and execution of the experiment.

The VECC Cryogenic Penning Trap group is a part of the Precision Measurements of very short-lived nuclei using an Advanced Trapping System for highly-charged ions (MATS) collaboration in FAIR. Penning traps will be used for high-precision mass measurements. Ions are trapped in a Penning trap using a strong magnetic field and a weak quadrupolar electrostatic potential [MATS 2009]. The most recent technique for measuring the mass of an ion in a Penning-trap is using the phase-imaging ion-cyclotron-resonance (PI-ICR) technique. In this method, the cyclotron frequency of the trapped ion is measured from the phases of the radial ion motions in the trap after a given period of excitation-free propagation. As the detection of the radial motion of the trapped ion is required, a position sensitive microchannel plate (MCP) is a key component for performing high-precision mass measurement of the ions using the PI-ICR technique. The VECC group will be providing the position-sensitive MCP detector and is responsible for the development of the related electronics. Expertise in Penning trap application will be used to integrate and develop the electronics for detecting the trapped ions using the PI-ICR technique. A technique has been also proposed for the Q-value measurement of the short-lived beta-unstable nuclei without using an additional semiconductor detector which might be used for electron-neutrino angular correlation studies.

Plans for the Next 15 Years and the Expected Major Outcomes:

- On-time delivery of the Indian in-kind accelerator equipment to FAIR in collaboration with Indian industries
- Complete R&D on the advanced detector and readout systems for the CBM and NUSTAR experiments. This will involve in-house tests and participating in experiments at the existing GSI facility, commonly known as Phase-0 experiments of FAIR
- Complete the review process towards the production of the systems. These international reviews will be at different stages such as CDR, engineering design report (EDR) and production readiness review (PRR).
- Start and complete the production of the detector systems and electronics for the abovementioned systems in which Indian groups have pledged to contribute during the first phase. This phase is anticipated to be completed by 2024, followed by the installation and commissioning so as to be ready for the beam in 2025.
- Start taking data from 2025 and continue for the next 10 years in phases of increasing the beam intensity and species. This is the phase in which all the collaborating institutes will participate in the experiments, data analysis and extraction of physics. There are regular discussions and reviews on the target physics observables by various experimental groups.
- It is expected that by 2022, we will be able to start discussions on our participation in the remaining two physics pillars of FAIR, i.e., PANDA and APPA. Even though APPA is expected to take data early, PANDA might get delayed due to delay in the relevant accelerator facilities. A series of reviews have taken place for this participation and the community can be brought together again to start the R&D followed by participation.
- We expect funding for these additional experiment participation by 2025 and begin participating in the experiments by 2027 followed by data-taking for the next 10 years.

The total number of Indian members in FAIR is currently about 80, with the median age in the range of 30–45 years. In the next 15 years, this number is projected to increase to about 150. The institutes/universities in the country that have shown interest in performing experiments at FAIR are given below.

Nuclear Structure and Reaction Studies:

Aligarh Muslim University, Aligarh; Bhabha Atomic Research Centre, Mumbai; Indian Institute of Technology, Bombay; Indian Institute of Technology, Kharagpur; Indian Institute of Technology, Roorkee; Inter University Accelerator Center, New Delhi; Gauhati University, Guwahati, Karnatak University, Dharwad; Punjab University, Chandigarh; Saha Institute of Nuclear Physics, Kolkata; Tata Institute of Fundamental Research, Mumbai; University of Calcutta, Kolkata; University of Delhi, New Delhi; and Variable Energy Cyclotron Center, Kolkata.

CBM Experiment:

Aligarh Muslim University, Aligarh; Banaras Hindu University, Varanasi; Bose Institute, Kolkata; Gauhati University, Guwahati; Indian Institute of Technology, Kharagpur; Institute of Physics, Bhubaneswar; National Institute of Science Education and Research, Bhubaneswar; North Bengal University, Siliguri; Panjab University, Chandigarh; University of Calcutta, Kolkata; University of Jammu, Jammu; University of Kashmir, Srinagar; and Variable Energy Cyclotron Center, Kolkata.

Hadron-structure Physics (PANDA collaboration):

Aligarh Muslim University, Aligarh; Bhabha Atomic Research Centre, Mumbai; Indian Institute of Technology, Bombay; Indian Institute of Technology, Guwahati; Indian Institute of Technology, Indore, Magadh University, MSU, Vadodara; National Institute of Technology, Jalandhar; Saha Institute of Nuclear Physics, Kolkata; South Gujarat University; Tata Institute of Fundamental Research, Mumbai; University of Pune, Pune; and Variable Energy Cyclotron Center, Kolkata.

Atomic Physics:

Bhabha Atomic Research Centre, Mumbai; Delhi University, Delhi; Inter-University Accelerator Centre, New Delhi; Saha Institute of Nuclear Physics, Kolkata; and Tata Institute of Fundamental Research, Mumbai.

The SWOT Analysis for the Project and its Future:

Strengths:

- Availability of unique high-intensity and high-quality beams of a wide range of nuclear species (p to U and RIBs)
- Possible involvement with the four science pillars (NUSTAR, CBM, PANDA and APPA)
- Wide-ranging industry participation

Weaknesses:

- Lack of human resource for performing meaningful experiments at FAIR
- Unless Indian participation is full and all-round, we might end up being fringe players. For central participation, induction of new manpower and training are crucial
- As the Indian participation at FAIR is mostly in-kind for the accelerator items, experimental funding is a cause of concern. For example, presently, no funding is available for participation in PANDA and APPA

Opportunities:

- Access to unexplored accelerated beams and their properties to have an opportunity for performing experiments with a new discovery potential
- This new generation of experimental facilities will allow us to work on the most advanced detectors, electronics and computing technologies
- Training in the most advanced science facility
- Transfer the knowledge and technology as and when required for inhouse uses

- Lead the activities at FAIR by working at key positions

Threat:

- Given the time-scale of building new facilities in the country, if we miss the opportunity to meaningfully participate in the FAIR facility, mainly based on our strength of being a member-state, we might miss the opportunity to make new discoveries in science. On the other hand, with less than optimum resources (manpower included), the participation might be suboptimum.

3.1.4 Indian National Gamma Array (INGA)

Nuclear models based on new theoretical concepts, combined with modern powerful computing resources and impressive advancement in experimental capabilities, have resulted in surprising as well as impactful discoveries in nuclear structure physics. The current focus in low-energy nuclear physics worldwide has been to investigate phenomena that occur at very low reaction cross-sections. In this context, the high-resolution gamma ray spectroscopy using HPGe detectors has played a leading role in discovering a variety of phenomena related with novel shapes, modes of excitations and new magic numbers in exotic nuclei.

To achieve this general goal, a 24-clover detector array with a total photopeak detection efficiency of ~5 %, named as the Indian National Gamma Array (INGA), was conceived, designed and assembled within the country. The first phase of INGA became operational in 2001 and became the first truly national collaboration between various institutes and universities. It has been instrumental in bringing a silent revolution in the frontline nuclear physics within the country.

The INGA grew, as it kept moving between the three accelerator centers at Delhi, Mumbai and Kolkata with more than 100 experiments performed using it to date. Some of the salient scientific achievements of the INGA campaigns can be summarized as follows:

- Lifetime measurements in subpicosecond range in magnetic and antimagnetic rotation
- Degenerate dipole bands in A = 110 and 130 regions in search for chiral rotation
- Shape evolution and coexistence in nuclei and the role of high-j orbitals
- Polarization measurements of gamma rays to establish transverse wobbling mode
- High-spin states in closed-shell nuclei for testing the shell model predictions and shape evolution
- Reaction dynamics study for fission and fusion processes

These studies have resulted in an impressive number of research papers (more than 130) in high-impact journals. More than 60 Ph.D. students have been involved in this project over the last 20 years. It has significantly added to the knowledge-base and the technical manpower in the country in the field of nuclear spectroscopy and reactions. Based on the quality of the data collected with INGA and the importance of the physics issues addressed in those published papers, INGA has established itself as one of the leading experimental facilities in nuclear structure physics research in the world [Jain 2001] [Muralithar 2010] [Bhattacharyya 2017].

It has also led to new technologies developed in-house such as the advanced INGA modules (analogue-based signal processing modules for Compton-suppressed clover detectors), time to digital converters (TDCs), DAQs, etc. The technology for annealing and repairing the electronic components of HPGe clovers was implemented within the country. Implementation of a modern digital DAQ coupled to INGA in the last experimental campaign improved the data-handling capability of the array to international standards. The international nuclear physics community has also shown a keen interest in the INGA program and many groups have already conducted experiments within the INGA collaboration.

The young and well-trained manpower from the INGA program is now ready to take on new challenges. To keep India in tune with the global developments in these fields, it is proposed to develop a high-resolution gamma detection facility with an array of HPGe detectors having a total photopeak efficiency up to 25 % for the accelerator centers within India. The array can be implanted in two phases in the next 10 years. In the first phase, about 36 Compton-suppressed clovers will be assembled together to make an 8 % array. This array should be implemented as a top priority in the next couple of years for the benefit of the community. Fast scintillators will be included in various geometries as per the experimental requirements. In the second phase, the forward detectors will be replaced by large-volume segmented HPGe detectors with tracking capability to improve the overall sensitivity of the array as well as enhancement of the photopeak efficiency. The gamma tracking detectors will be required for the nuclear structure experiments with inverse reactions from the new accelerators. This array can also be coupled with electromagnetic spectrometers as well as different ancillary detectors. Such a move will enable us to focus on landmark experiments with low cross-sections by using longer beam times, measurement of polarization of gamma rays and wide-range of timing measurements. The detailed nuclear structure problems that can be addressed with INGA have been described in section 1.2. The scientific themes and objectives of the three centers will be:

At IUAC: Research will focus on the structure of weakly-populated nuclei away from the line of beta stability by using the proposed clover array along with the Hybrid Recoil Mass Analyzer (HYRA). The topics to be studied with a high priority will be the spectroscopy of heavy nuclei, high-K isomers, and shape and fission isomers. Lifetime measurements of excited nuclear levels in the subnanosecond and subpicosecond range will be possible. The high-current injector program will provide a higher current and a wider range of isotopes for experiments in the near future.

At BARC-TIFR PLF Facility: The array will have the largest number of the clover detectors as well as ancillary detectors to study the exotic shapes using Coulomb excitation and lifetime measurements. Nuclear reactions relevant for nuclear astrophysics will be pursued. In addition, the geometry of the array is extremely favorable for lifetime measurements in the ps to 100 fs range, quadrupole moment measurements and angular correlation studies.

At VECC: Along with light-ion beams, high-energy ^{20}Ne and ^{40}Ar beams are available. The cyclotrons will be exploited to perform horizontal spectroscopy by using α and proton beams from the K-130 cyclotron. The clover detectors, in conjunction with the ancillary fast-timing $CeBr_3$ scintillators, will be utilized to perform complete spectroscopy of nuclei. On the other hand, the energy domain of 7–8 MeV/A heavy-ion beams, including the inert species, such as ^{20}Ne, ^{40}Ar, etc., can produce neutron-rich nuclei using deep-inelastic reactions and fission.

The superconducting cyclotron (SCC) at VECC is getting ready to deliver much faster beams. Reactions induced by these energetic beams require precise Doppler corrections to identify the in-flight gamma rays emitted from the produced nuclei. This requires segmented HPGe detectors with better angular precision. Pulse-shape analysis using planar HPGe strip detectors has been carried out at TIFR, which will be useful for the next generation of HPGe detectors. In addition, preliminary work on the gamma ray tracking part will be initiated with the help of two 16-segmented clover HPGe detectors available at VECC.

To implement the proposed array, it is necessary to present a detailed project report of the first phase employing the Compton-suppressed clover HPGe detectors, with the funding requirements for new detectors, data acquisition system, as well as other required infrastructures. R&D related to the gamma-tracking detectors should be started at the earliest in parallel to the first phase implementation of the project.

The array, that has very good sensitivity for the detection of gamma rays with coincidence capabilities, can be used in different domains of physics. For example, it has direct relevance in nuclear astrophysics studies, measurements of electromagnetic moments relevant to the problems in condensed matter physics, as well as optimum reaction conditions for the production of radioisotopes required for nuclear medicine. The program also has the potential of springing new spin-offs such as application of digital DAQ (DDAQ) in medical imaging, homeland security, studies of neutron-rich nuclei, discovery of new isomers with applications in energy storage devices and the development of the next generation of nuclear power reactors. The data collection, storage and analysis techniques involved in INGA will contribute towards the science of large data.

The gamma detector facilities coupled with different ancillary detectors will be internationally competitive. This will make a strong base for the development of international collaborative efforts to pursue science using the national accelerators. In the case of special opportunities for performing outstanding physics programs, there should be a provision to plan experimental campaigns at international facilities abroad with ion beams not available within India. This can prove to be the stepping stone to prepare for the next generation of detector arrays. This is necessary to maintain the momentum of the low-energy nuclear physics community for carrying out world-class science in nuclear structure and reaction studies with the accelerator facilities within the country.

Collaborating Universities and Institutes:

Allahabad University (Allahabad), Amity University (Noida), Andhra University (Vishkhapatnam), Banaras Hindu University (Varanasi), Bengal Engineering and Science University (Kolkata), Bhabha Atomic Research Center

(Mumbai), Center for Excellence in Basic Sciences (Mumbai), Delhi University (New Delhi), Guru Ghasidas University (Bilaspur), Guru Nanak Dev University (Amritsar), Indian Institute of Technology (Roorkee), Indian Institute of Technology (Ropar), Indian Institute of Technology (Bombay), Indian Institute of Technology (Kharagpur), Institute of Physics (Bhubaneswar), Inter University Accelerator Center (New Delhi), MS University (Baroda), Panjab University (Chandigarh), Saha Institute of Nuclear Physics (Kolkata), Sambalpur University (Sambalpur), Tata Institute of Fundamental Research (Mumbai), UGC-DAE Consortium for Scientific Research (Kolkata), University of Mumbai (Mumbai), University of Calcutta (Kolkata), University of Kashmir (Srinagar), Variable Energy Cyclotron Center (Kolkata), Visva Bharati University (Santiniketan).

The current number of members in the INGA project is about 70, with the median age in the range of 30–45 years. This is projected to increase to about 150 in the next 15 years.

<u>The SWOT Analysis for the Project and its Future:</u>

Strengths:

- INGA facilitates the pursuit of contemporary nuclear physics at accelerator facilities within the country
- Trained manpower and young researchers in instrumentation
- Wide range of scope from fundamental physics to applications in different areas
- In-house developments of ancillary systems and software

Weaknesses:

- Specialized detectors that need high maintenance cost

Opportunities:

- Many technological spin-offs possible
- Training of highly skilled manpower in high-tech areas of detectors, computers, electronics and high vacuum apart from training in fundamental physics

Threats:

- Success is linked with the implementation of new accelerator programs
- Dependence of the involved technology on foreign companies
- Retaining young researchers in the field after completion of their Ph.Ds.

3.2 FUTURE PLANS OF CURRENT MEGA PROJECTS

3.2.1 EXPERIMENTS AT EIC

The study of nuclear physics at a fundamental level revolves around understanding the nucleus and its major constituents, the nucleons (protons and neutrons). Dedicated investigations in the past have revealed that nucleons consist of quarks that are bound together by gluons. The study of the quarks and gluons, their properties and their dynamics led to the development of QCD. The nucleus can be thought as the ultimate QCD molecule with a complex structure, and understanding the formation of nuclei in QCD is a long-term goal of nuclear science.

Unlike the theory of quantum electrodynamics (QED), where the force-mediator particle is the electrically neutral photon, the mediator in QCD, namely, the gluons, carry color charge. This specific property causes the gluons to self-interact among themselves leading to a less-explored territory of QCD matter where the gluons are abundant and have interesting features. This saturated gluon density regime has not been explored and a quantitative study of matter in this new regime can answer the outstanding questions about the inner structure of matter.

The future EIC facility is an experimental facility that will facilitate collisions of electrons with protons and heavy nuclei at higher energy and the resultant physics processes can probe regions of high gluon density. The science program is expected to start in the year 2032 and R&D for the detectors from 2021 [Accardi 2016] [Aschenauer 2019] [Khalek 2021].

EIC is a large-scale particle accelerator planned for construction at BNL, New York, USA. The current EIC design is based on the need to provide the kinematic reach well into the gluon-saturated region, which can be achieved by heavy-ion beams. The electron beams will provide the unmatched precision of the electromagnetic interaction as a probe, whereas nucleon beams will give information about the correlations of the sea quark and gluon distributions with nuclear spin. The EIC machine aims to produce beams of variable center-of-mass energies, ranging from 20 GeV to 140 GeV with high collision luminosity of 10^{34} $cm^2 s^{-1}$. It will exceed the capabilities of the HERA collider (the only electron-proton collider to date) by including polarized proton and light-ion beams, heavy-ion beams with wide energy variations and an increase in the beam luminosity to facilitate tomographic imaging of the nucleon structure.

The EIC will collide bright counter-circulating beams of electrons and ions and use large-scale complex detectors to identify specific physics processes whose precise measurements can yield unattainable insight into the structure of the nucleus. The EIC will provide access to the key aspects of nuclear structure in terms of answering the profound questions in the fundamental structure of matter broadly related to:

1. The distribution of the sea quarks and gluons, and their spins, in space and momentum inside the nucleon and the correlation of these distributions with the overall nucleon properties, such as the spin direction
2. The role of the orbital motion of the sea quarks and gluons in building the nucleon spin and the origin of the nucleon mass
3. The boundary that separates the saturated gluon density region from that of more dilute quark-gluon matter, and the change in the distributions of quarks and gluons as one crosses this boundary
4. The effect of the nuclear environment on the distribution of quarks and gluons and their interactions in the nuclei, the exploration of the transverse spatial distribution of gluons in comparison to that in the nucleon, and the response of the nuclear matter to a fast-moving color charge traversing through it.

Indian Participation:

Although the realization of the EIC is expected to evolve over time, Indian participation at this early stage is highly desirable for the following reasons:

(i) The participation in EIC will enable us to continue our pursuit in nuclear science research through the quest for understanding the unique gluon-dominated nature of visible matter in the Universe. The Indian research program should not miss on this fundamental quest of hadron physics.

(ii) The EIC requirements will push the accelerator and detector designs to the limits of current technology. The detector designing concepts contain assessments of the current state of the art in technologies, services, mechanical support and other components. It can therefore provide enormous platform for training the younger generation to be skilled scientists, engineers and technicians in cutting-edge technology that can have later societal applications in terms of application in medical sciences, indigenous development of technology, energy, etc.

(iii) It will inspire and attract new generations of young talented people in the pursuit of careers in science and technology.

The plans for Indian participation in EIC are driven by the existing rich experience and expertise gained from the participation in previous and ongoing international collaborations like such as ALICE, STAR, CMS and Belle II. There are three primary goals for the Indian scientists that are relevant to their participation in the EIC program:

1. To participate and contribute to the physics program of EIC. As the physics program would offer answers to a number of key questions in hadron physics, the long-term plan of Indian groups should be to focus primarily on the following studies:

Global properties and parton structure of hadrons: The study on this aspect would significantly deepen our understanding about the spin and mass of the nucleons and how these properties can be understood in terms of the partonic contributions. This can be realized by colliding polarized electrons and nucleons, with inclusive and semi-inclusive deep inelastic scattering (SIDIS) measurements. In the inclusive measurement, the scattered electron is detected, whereas in the latter, an additional hadron created in the collisions is to be detected and identified. The EIC will probe these parton distributions in a wide kinematical range not covered by any current or other future facilities.

The vibrant theoretical community in India has made remarkable advances in studying the motion of the confined partons in the fast-moving nucleon and the transverse momentum-dependent distributions (TMDs) of partons. These give the distribution of the quarks and gluons inside a nucleon in the 3D momentum space. There also is evidence of correlations between the parton momentum and spin, and the origin of such correlations are yet to be understood. As the TMDs are sensitive to these correlations, the measurement of TMDs via SIDIS processes (with polarized electron as well as nucleon beams at collider energies) would allow us to investigate the motion of the confined gluons and sea quarks that are inaccessible through any of the current facilities.

Multi-dimensional imaging of nuclei, nucleons and mesons: The measurement of SIDIS processes and other exclusive processes can give valuable information about the multidimensional quarks and gluon structure of nucleons, nuclei and light mesons. The appropriate choice of particular final states in the electron-proton scattering at EIC can probe the transverse spatial distribution of the gluons and sea quarks in the fast-moving proton with respect to the longitudinal momentum fraction, x, of the parton. This would be a complementary measurement to the transverse momentum distribution of quarks and gluons. Further, the tomographic high-precision images obtained from cross-sections and polarization asymmetries for exclusive processes will be able to reveal the generalized parton distributions (GPDs) that connect the concepts of parton densities and elastic form factors. The combined kinematic coverage of the EIC and the Common Muon and Proton Apparatus for Structure and Spectroscopy (COMPASS) experiment is essential for extracting the quark and gluon angular momentum contributions to the spin of the proton.

QCD at gluon saturation densities: The direct consequence of the gluon self-interaction in QCD predicts a saturation scale, Q_s, at which the nonlinear process of gluon recombination balances the gluon splitting process. Such a self-regulatory mechanism at this scale produces a new state of saturated soft gluonic matter known as the color glass condensate (CGC). EIC will be able to provide access to the saturation regime to investigate the effects of such a state in detail. The measurement of coherent diffraction and the energy dependence of the DIS cross-sections in the e-p and e-A collisions can help us to obtain evidence for the nonlinear QCD of gluon saturation. One can also look for the suppression of vector meson production in such collisions with respect to the e-p collisions at EIC as an evidence of gluon saturation.

Color charge in QCD matter: The suppression of high transverse momentum hadrons produced in heavy-ion collisions at relativistic energies was one of the smoking gun signatures of the existence of QGP. The observed suppression was attributed to the energy loss of the colored patrons traversing through the QGP medium. However, it was intriguing to observe a similar suppression pattern for heavy quarks as the energy loss due to medium-induced gluon radiation was expected to be less compared to the light quarks. The measurement of heavy flavor mesons and the detailed study of the difference in the multiplicity ratios between heavy flavor and light flavor mesons is expected to shed light on the hadronization mechanism.

2. To participate and contribute to detector research and development

The proposed new EIC poses a technical and intellectual challenge for the detector design to accommodate the long-term diverse physics goals envisaged by the program. Experimental measurements in multiple physics processes require precise measurement/reconstruction of the event and particle kinematics, which imposes stringent requirements on the detector acceptance and resolution. Specifically, one requires a full phase space detector system capable of identifying and reconstructing the energy and momentum of the final state particles with high precision.

Due to the asymmetric nature of collisions, different detector systems (hadron and electron end-cap, barrel detectors) see different momentum and particle-type distributions and their performance also varies between the detector regions. Therefore, one needs to combine the best/optimum detector technology for different regions of tracking, vertexing, particle identification and calorimetry.

The long-term plan would be to contribute towards the detector research and development, detector simulations, testing, quality assurance, commissioning, and operation of the silicon tracking and vertex detector and the particle identification detector.

A. Silicon tracking and vertex system and TPC tracking detector: The requirement of precision vertex and tracking has led to the MAPS technology to be the most suitable option. The Indian group would contribute towards the quality assurance studies of the sensors for the EIC vertexer and tracker in its design as well as final production phase and test the beam programs for characterization of the silicon system. This would also include in-kind labor contributions for detector R&D, testing, quality assurance, commissioning and operations, and developments related to the slow control system of the detector. For the TPC, one possibility being explored is micromegas detectors in addition to the GEMs.

B. Particle identification detector: The development of a new particle identification (PID) detector for EIC is of interest. Specifically, to contribute towards the development related to photodetector schemes, cascaded GEM/THGEM with reflective layers of photocathode.

C. Participation and contribution to EIC software developments: Indian groups are participating in the benchmarking and validation of the EIC software. There are four subgroups within the EIC software group in which the benchmarking and validation is ongoing. These are: Fun4All, Escalate, EIC smear and MC-Data Validation. A brief summary of the activities and long-term goals within each software subgroup would be the following:

Escalate: (i) Participate in Escalate framework development. Improve the reliability, performance and user experience, and implement new features within the framework. (ii) Create a common software environment for crosschecking and analyzing results from various simulation and reconstruction tools for EIC.

Fun4All: (i) Perform quality assurance of calorimeters (forward and barrel) and trackers. (ii) Characterize calorimeters and QA of tracking geometry. (iii) Test different input generators for actual physics signals with full detector simulations.

EIC-Smear: (i) Participate in the development of unit tests using catch2. (ii) Develop QA suites based on the requirements of various Physics working groups. (iii) Improve the existing and future detector concepts (e.g., BeAST, ePHENIX, JLEIC) and their GEANT counterparts. (iv) Develop a PID suite for the EIC.

MC-Data Validation: (i) Test and validate different Monte Carlo simulation tools for investigating and evaluating multiple types of phenomena or processes expected to influence the final observables at EIC. (ii) Use the Rivet framework for validating various physics analysis at EIC energies. (iii) Improvise on the existing Monte Carlo models to include effects of inclusive and semi-inclusive DIS processes.

4. Computational Resources: An important ingredient to our success in the EIC experiments is to have access to adequate high-performance computational resources. The following two areas would require computational resources.

Lattice QCD: A synergy between experimental and theoretical studies is essential to obtain a comprehensive understanding of the structure of nucleons. The lattice QCD methods provide a unique tool to study the properties of subatomic particles, including nucleons, from first principles with control systematics. It is envisaged to study the decomposition of the nucleon mass into various parts, namely, the quark condensate, quark energy, glue field energy and the trace anomaly. A related subject of interest is the calculation of the pressure distribution inside a composite subatomic particle. Similarly, precise studies might be carried out on the emergence of spin of a composite particle from a combination of various parts, namely, the quark spin contribution, gluon angular momentum contribution and the orbital motion of the quarks. Lattice QCD methods, along with machine learning tools, will be utilized to calculate various distribution functions, which, together with the experimental data, will enable us to obtain the tomography of a nucleon. More than 5 PFLOPS computing resources will be required to carry out these calculations.

Simulation and data analysis: Computational resources will also be required for data analysis including Monte Carlo simulations. Machine learning methods will also be utilized considering the large dataset, particularly to obtain different distribution functions (PDFs, GPDs and TMDs).

Collaborating universities and institutes:

Akal University, Aligarh Muslim University, Banaras Hindu University, Central University of Karnataka, Central University of Tamil Nadi, DAV College, Chandigarh, Goa University, Indian Institute of Science Education and Research – Berhampur, Indian Institute of Science Education and Research – Tirupati, Indian Institute of Technology – Bombay, Indian Institute of Technology – Delhi, Indian Institute of Technology – Indore, Indian Institute of Technology – Patna, Indian Institute of Technology – Madras, Institute of Physics – Bhubaneswar, Malaviya National

Institute of Technology – Jaipur, National Institute of Science Education and Research, Panjab University, Ramakrishna Mission Residential College – Kolkata, Tata Institute of Fundamental Research and University of Jammu.

The median age distribution of the current participants from India, who have shown interest and are working on EIC Physics is less than 35. Most of the group members are in their early career and see participation in the EIC project as their future post LHC-era. The distribution of various educational institutions are: 40% participation from universities and colleges, 30% from IIT and NIT, 20% from IISER and NISER and 10% from research institutes.

Strengths and opportunities:

Strengths:

- Large pool of young physicists, engineers and technicians with international expertise in data analysis and detector developments
- Active and effective participation in RHIC and LHC experiments with significant contribution in data analysis, software development etc.
- Successful development and installation of detectors in STAR and ALICE experiment
- Excellent collaboration between experimental and theoretical high energy communities.
- Availability of high-end computing facilities

Opportunities:

- Continue to participate and contribute to fundamental physics
- Attract and inspire the next generation to pursue research in basic sciences
- Develop a pool of highly skilled scientific and technical manpower
- Excellent opportunity to become world leaders in hadron physics
- Create job/fellowship opportunities for young researchers beyond 2030

3.2.2 Extreme Light Infrastructure – Nuclear Physics (ELI-NP)

ELI-NP, is an upcoming state-of-the-art laboratory dedicated to towards nuclear physics research with extreme electromagnetic fields. The photon-beam facility will host a high-power laser system (HPLS) including two 10 PW amplification arms along with a brilliant gamma-beam system (GBS) [Gales 2018]. The intense (~10^4 photons/s/eV), narrow band width (≥ 0.5 %), highly polarized (> 95 %) gamma-beam will be produced by Compton backscattering of laser photons off a relativistic electron beam and will allow precise photonuclear measurements in the energy range of 0.2–20 MeV.

A dedicated research program, including the diverse fields of nuclear photonics, has been planned and currently under development at ELI-NP [ELIWB 2011]. A few highlights of the program are stated below.

1. High-resolution photofission experiments in the actinide nuclei are aimed at including the investigation of the second and third potential minima of the multiple-humped fission barrier using transmission resonance spectroscopy [Choudhury 2017]. The kinetic energy, mass, atomic number and angular distribution of fission fragments will be measured with high-precision in these experiments. Measurements of the absolute photofission cross-sections with a higher precision will enable advanced investigations in this direction. In addition to binary fission, the high-intensity gamma beam will also enable the investigations of rare photofission events, such as triple fission, highly asymmetric fission, clusterization phenomenon, the predicted cold valleys of fission potential, etc., which are not well-explored yet. These goals will be achieved by state-of-the-art detecting systems consisting of fission chambers, gas-based ΔE-E detectors and THGEM array. It is important to note that the research within the HPLS experimental program, including the study of the fission-fusion reaction mechanism, will complement the abovementioned fission studies. Reactions of laser-driven actinide beams on deuterium targets will be useful in achieving this aim.
2. Nuclear resonance fluorescence (NRF) experiments are aimed to be carried out, which will enable us to recover several physical quantities that characterize the excited nuclear states in a completely model

independent way. In this case, the excitation energies, level widths, spin quantum numbers, parities and gamma-decay branching ratios are the important observables that can be measured. An advantage of these experiments is that the actinide region can be accessible for NRF studies with the available pencil beam at ELI-NP. One of the aims is to perform detailed high-precision and high-resolution investigations of the dipole strength distribution in the region of the pygmy dipole resonance (PDR). For such studies, an array of eight segmented clover HPGe detectors and additional four $LaBr_3$ detectors has been constructed.

3. Experiments above the neutron threshold are also a part of the program which will address the open questions related to nuclear structure and astrophysical abundances of different nuclear species. The investigation of photodisintegration cross-sections for low-abundance nuclei which are relevant to the p-process nucleosynthesis is an example of such studies. Studies on gamma and neutron decays will be performed for the experimental investigation of the nuclear structure of the giant dipole resonances (GDR) as well as the PDR and the magnetic dipole resonance, which appear as the excess strength at the lower-energy tail of the GDR. These aims will be achieved using two dedicated setups comprising of 15 $LaBr_3$(Ce), 19 $CeBr_3$ scintillator detectors, and 33 liquid and 22 Li-glass scintillator detectors, and 28 ^{3}He tubes embedded in a polyethylene cube, respectively.

4. Charge-particle detection experiments aiming at forefront research in nuclear astrophysics are also included in the program. Several key astrophysics reactions have been considered for investigations. The time reversed reaction, namely, $^{12}C(\alpha, \gamma)^{16}O$, can be understood by investigating the $^{16}O(\gamma,\alpha)^{12}C$ reaction using the principle of detailed balance. Two experimental setups consisting of position-sensitive stripped Si detectors of two different types and a TPC will host such astrophysics problems. The gas in the TPC will simultaneously act as a target for the nuclear reaction as well as the medium for detection.

5. Intense positron beams will also be produced using the high-intensity gamma-beams. These beams will be utilized for material research and characterization. Structural and defect studies of metals, semi-conductors and insulators will also be carried out using the newly produced high-intensity beams of positrons.

6. Another important study includes the NRF analytical techniques and gamma-ray based radiography and tomography, for which dedicated setups comprising gamma-ray detectors is under development. The planned studies are mainly directed towards specific nuclear non-proliferation and waste-management applications and research in the direction of cultural heritage.

7. Along with this, research related to the production of radioisotopes for medical applications are aimed to be carried out using gamma-beams. An irradiation station has been designed for this purpose which is combined with a pneumatic transport system.

8. Ion Guide Isotope Separation On-Line (IGISOL) beam line is being designed, which will provide radioactive ion beams produced in photofission for the study of neutron-rich nuclei. A cryogenic stopping cell is being designed and a prototype setup is under construction for studies on the extraction of radioisotopes.

Proposal for Indian Contribution:

Nuclear photonics being an emerging field of research is of high interest among nuclear physicists around the globe. Since ELI-NP is an upcoming photon beam facility becoming operational in 2023, providing high power 10 PW laser as well as high-intensity, high-resolution polarized gamma beams can bring a breakthrough in the field of nuclear photonics overcoming the existing limitations in this field of research. It would be worthwhile for Indian researchers to get involved in this field of research and get benefited by the upcoming facility. Indian groups are already participating in several of the developmental works in ELI-NP. Researchers from India have submitted LOIs for experiments with the gamma beam facility at ELI-NP using the existing detectors. Following are the proposed plans.

1. ELI-NP has two setups for fission studies. One setup, called ELI-BIC, consists of an array of four twin Frisch-grid ionization chambers (FGIC), each coupled with eight ΔE-E telescopes for the complete study of the fission fragments along with the ternary fission process; a rare fission mode. For the detection of the latter, double-sided Si strip detectors (DSSDs) are employed. Currently, the fission chambers have single-disc anodes, which only provide information about the angular distribution of the fission fragments with respect to the symmetry axis in terms of polar angle, θ. It is very useful and important to construct a fission chamber with segmented anodes so as to get the full (polar angle θ and azimuthal angle φ) information about the

angular distribution of the fission fragments, and Indian researchers can contribute to this developmental work. The second setup consists of 12 THGEM detectors; a gas-based detecting system. This detecting system is currently based on analogue electronics. Digitizing the DAQ for this system can be an important contribution from India which can lead to advanced studies.

2. Nuclear Astrophysics: ELI-NP has two dedicated setups for the study of nuclear astrophysics. The first one is an array of double-sided Si strip (DSSD) detectors, called ELISSA, which are currently based on Analog electronics. These detectors will be used in (γ,p) or (γ,α) reactions to study the p-process. For advanced studies, digitization of the DAQ is of high importance and this is where India can contribute. The second setup is a gas-based detecting system using GEM technology and gas targets and 256 channel read-outs (ELI-TPC). It will be beneficial to use different gases inside and study different reactions. This needs simulations as well as developmental work.

3. ELI-NP has a dedicated array of neutron detectors, ELIGANT, for the study of neutrons above threshold. Calculations are being done in a way to maximize the coverage angle, but angular distribution is lost. Detectors to measure the angular distribution are important. Researchers at the High Intensity Gamma-ray Source (HIGS) and GANIL are working in this direction. Designing and constructing a modular setup would be very beneficial, like the Blowfish array, which is operational at HIGS, or one can use other technology, like using long plastic scintillators, which are read on both ends to achieve position sensitivity, an approach used at the Tonnerre neutron array at GANIL.

4. Complementary experiments using the Accelerator facilities in India can also be carried out with ELI-NP collaboration using neutron, proton, lithium and other beams populating the nuclei at different angular momenta and comparing them with photon induced reactions benefitting the study of the entrance channel effects.

5. It is desirable to have exchange programs between Indian Institutes and ELI-NP. Indian Institutes can invite people from ELI-NP and vise-versa to work in close collaboration for the advancement of the experimental setups and perform high-end photonuclear experiments. An Indo-European exchange program has been proposed by the European labs for hands-on training in nuclear photonics.

Timeline

ELI-NP 1PW laser and gamma beam facilities will become operational in 2022 and 2023, respectively. In India, the plan is to start with the designing activities for the gas-based TPC array and for the modular setup for neutron angular distribution studies in the first two years, after which the development activities will be carried out. Along with this, the digitization of the DAQ systems will call for the procurement of digitizers and developing the needed DAQ program. The development of the synchronization system between the digital and analog modules also needs to be developed. After the DAQ program, we plan to start with the designing and construction of the gas chamber with segmented anodes.

Around 10 research groups are interested to participate in this research program, with an overall number of 25 members at present and a median age in the 30-45 range. The projected number of members involved in the next 15 years is up to 45.

3.3 POTENTIAL NEW PROJECTS AND PARTICIPATION

This section describes two projects on which there has been a significant amount of activity in the country in the past few years. These projects do not come under the mega-science category at this stage, however they have the potential of expanding and becoming mega-projects in future. A very important aspect is that these projects are completely home-grown, and have, even in their current initial stages, led to the development of new detectors and related instrumentation.

3.3.1 Neutrinoless Double Beta Decay (TinTin)

The mass and nature of neutrinos play an important role in theories beyond the Standard Model of particle physics. Whether neutrino is its own antiparticle, as proposed by Majorana, is still an open question. At present, neutrinoless double beta decay ($0\nu\beta\beta$ /NDBD) is perhaps the only experiment that can reveal the true nature of the neutrino and provide information on the absolute effective neutrino mass. Given its significance, there is a widespread interest in the quest for $0\nu\beta\beta$ employing different techniques. In TIFR, a feasibility study to search for $0\nu\beta\beta$ in ^{124}Sn has been initiated for the TIN.TIN experiment (The INdia's TIN detector, www.tifr.res.in/~tintin) as a national collaborative effort (involving TIFR, BARC, VECC, IIT Ropar and others). It is envisaged that *TIN.TIN* will be housed at India based Neutrino Observatory (INO). The ^{124}Sn has moderate isotopic abundance ~5.8% and a reasonably high Q value of 2.28 MeV. Since the constancy of sum energy of two electrons defines the NDBD event, good energy resolution is of paramount importance. Cryogenic bolometers with excellent energy resolution and high sensitivity, are well suited for search of $0\nu\beta\beta$. Tin becomes superconducting below 3.7 K and at T<100 mK its specific heat has only lattice contributions and can thus be made into a high energy resolution bolometric detector.

A custom built cryogen free dilution refrigerator, CFDR-1200, with a high cooling power of 1.4 mW at 120 mK, has been installed at TIFR, to conduct initial R&D and build and study mK detector prototypes. For measurement of the temperature rise ~100 μK with high precision, neutron transmutation-doped (NTD) Ge sensors have been developed indigenously. The noise spectrum and the response to phonon pulses have been measured for a sapphire bolometer test setup with an indigenously developed NTD Ge sensor. The detailed noise characterization, investigation of various noise sources, and its mitigation to improve the performance of a cryogenic bolometer detector for the TIN.TIN experiment have been studied.

Understanding and minimizing the background is crucial for NDBD studies. The TIFR Low Background Experimental Setup (TiLES) with a special low-background HPGe has been set up at the sea-level at TIFR for radiation background studies. A two-detector setup for coincidence studies related to radiation background has also been set up with cryo-free low background detectors. TiLES has been extensively used for prequalification and selection of materials of the bolometer and for understanding the neutron- and muon-induced backgrounds. Further, radiative impurity studies in NTD Ge sensors, indigenously developed CsI and Ge crystals at BARC (for their possible application in the Dark matter experiment at INO, DINO), rock samples from INO and other possible tunnel sites are being carried out in TiLES. Further, the DBD of ^{94}Zr to the 2_1^+ excited state of ^{94}Mo at 871.1 keV was studied in TiLES, leading to a significantly improved half-life limit, $T_{1/2} > 2 \times 10^{20}$ y at 68 % confidence level. This is the first double beta decay experiment reported from India.

Future scope:

For experiments such as NDBD, a smaller underground Lab (typically 2 bays, each about 15 m wide, 15 m tall and 25 m long) with 500 to 1000 m rock overburden will suffice. Therefore, it is also possible to envisage a separate underground (UG) laboratory house the smaller experiments, such as NDBD version-0 experiment and other R&D/prototype experiments for dark matter or solar neutrinos. The possibility of joining other international NDBD collaborations can also be explored.

Manpower and Cost:

Setting up a dedicated UG facility can be initiated as a national effort and expanded to house international collaborative experiments in future. A few young faculty members (~5–6) trained and interested in rare decay studies (e.g., former INO training school students) and a few scientific and technical staff would be required to set up the necessary infrastructure. Involvement of IITs and IISERs will bring in requisite engineering and science expertise. An INO training school or equivalent is highly essential for attracting and training young researchers for such programs.

A dedicated tunnel near Aut, under the purview of the National Highway Authority in Himachal Pradesh is a possible site. Preliminary exploration has indicated good rock quality and ease of accessibility (in proximity to IIT Mandi and IIT Ropar). It should be mentioned that in addition to the cost of ton-scale experiment (which will depend on the isotope and cryogenic technology to be employed), tunnels (lab space with the associated safety features) together with the necessary infrastructure for the laboratory will cost about additional ₹ 60 cr.

3.3.2 Precision Neutrino Physics using reactors (ISMRAN)

Neutrinos and their antiparticles, antineutrinos, ($\bar{\nu}$), have unique features that make them quite a fascinating entity to probe the fundamental aspects of nature such as physics beyond the Standard Model, existence of a new type of neutrino via sterile neutrino searches, matter-matter asymmetry through the search of CP violation in the lepton sector, etc. Reactor neutrino experiments, where neutrino detection is performed via the inverse beta decay (IBD) process are at the forefront for answering some of these outstanding questions. Reactors are copious sources of electron-type antineutrinos arising from the undergoing fission process in their cores. The direct real-time measurements of antineutrinos using large-area detectors have a potential to provide the information on the power and operational status of the reactors and the fissile content of the reactor cores that is independent of reactor operation.

A vibrant physics program of neutrino physics, namely, The Indian Scintillator Matrix for Reactor Antineutrinos (ISMRAN) experiment using antineutrinos from the ~100 MW Dhruva reactor at BARC has been started in recent years. The ISMRAN is a large-area one-ton segmented plastic scintillator (PS) detector array with lead and boronated polyethylene shielding having a total weight of ~16 tons for realizing the goals of sterile oscillation searches and reactor monitoring purposes. Precision measurements carried out of the reactor antineutrino spectrum at these short baselines will be able to address the issue of anomalies in the antineutrino spectra and flux. In addition to the present location inside the Dhruva reactor hall, the enhanced ISMRAN detector is envisaged to perform measurements at other reactor sites having different core composition, such as the Prototype Fast Breeder Reactor (PFBR) at Kalpakkam or any other reactor site with accessibility of relatively small distances.

In the near future, it is planned to carry out measurements in the vicinity of reactors having higher power using the enhanced ISMRAN detector. The high-power reactor complex at Kudankulam with two operational reactors, having 3 GW thermal power each and more such units planned in the complex in near future, provides excellent opportunities for neutrino research. For example, it is being explored whether a near detector and a far detector weighing approximately 10 tons can be deployed at moderate distances from the reactor cores. These detector setups will be using either plastic scintillator or liquid scintillator material. The comparison of rate and spectra between the near and far detectors and the identically designed detectors will allow a near-complete cancellation of the correlated detector systematics. Very large size detectors of ~10 KT can be planned in the future for research into more ambitious physics goals of neutrino physics. Another related future proposal worth pursuing is the investigation of CENNS using neutrinos from a reactor. The CENNS process has been experimentally confirmed in recent times using neutrinos from stopped pion decay but it has not been demonstrated using reactor neutrinos yet. The measurement of CENNS in a reactor-based experiment is an active area of research and several experiments are being planned around the world towards this goal. Large-size cryogenic detector arrays with low energy thresholds and a highly efficient background suppression can be employed for reactor CENNS measurements.

For the deployment of very large detectors, it is desirable that the indigenous detector technology is available for fabrication. While some expertise exists in the country for the development of plastic scintillators, the capabilities of liquid scintillator fabrication, often, the preferred medium for large-scale reactor neutrino experiments, is non-existent in the country. It will be desirable to develop capabilities of gadolinium-doped liquid scintillators for IBD measurements, and possibly, the cryogenic detector arrays for the CENNS measurements. Further R&D of detectors with advanced materials capable of neutron detection, such as ^{6}LiF sheets or the Li-doped liquid scintillators will be helpful in designing the next-generation detectors for neutrino measurements, which might have cross benefits in other areas.

ISMRAN presents the first attempt in the country towards building capability, to perform research in a completely new exciting area of reactor nuclear physics [Netrakanti 2022]. Going into the future, a new generation of state-of-the-art neutrino physics measurements are possible due to the availability of high-power reactors at the Kudankulam site in close proximity in a single complex, which can be harnessed by building massive-sized detector setups.

3.3.2 Future Circular Collider (FCC)

Currently, plans are being made for the FCC in a 100 km tunnel at CERN. FCC will operate in the e^+e^- collider mode, pp collider mode and heavy-ion mode. The heavy-ion mode and electron-proton/ion modes are of interest to the nuclear physics community. The center-of-mass energy for the heavy-ion program (e.g., Pb–Pb) will be 39 TeV. At the same time, e–p collisions could occur at 3.5 TeV.

The main goals of the FCC relevant to nuclear physics include:

a. Study of QCD matter at the highest energy density and temperatures accessible in the laboratory. With a Bjorken x value of the order of 10^{-6}, FCC will provide access to an uncharted parton kinematic region. It could provide temperatures of the order of 1 GeV where the heavier charm quarks start to contribute as active thermal degrees of freedom to the QGP equation of state. With reasonable production rates of Z and W bosons and significant rates of highly-boosted top quarks, FCC can provide observables that bring unique insights to the mechanism of energy loss of partons in the dense QCD medium formed in heavy-ion collisions.

b. At FCC, the unprecedented ranges of Bjorken x and momentum transfer to partons Q will allow us to resolve the proton structure with very high accuracy and obtain a precise measurement of the strong coupling constant. In addition, the DIC-type measurements will allow the determination of the parton distribution functions with high accuracy. It will allow us to explore the parton dynamics in a kinematic range where the conjectured gluon saturation phenomenon is required to unitarize the high-energy cross-sections.

In future, there is expectation of participation of Indian scientists in experiments at FCC. The experiments at FCC will take place in a timeline beyond the current and planned experiments at LHC, RHIC, FAIR and EIC. The physics program at FCC will also be complimentary to those at LHC, RHIC, FAIR and EIC.

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4 BEYOND BASIC SCIENCE

Apart from addressing the questions about the fundamental nature of matter, nuclei and plasma, the field of nuclear physics has also been instrumental in giving rise to many applications. These are in the field of medical science, space missions, agriculture, archaeology, industry, environmental studies, etc. [Campajola 2016]. Several plasma-based products have been designed and commercialized worldwide for sterilization and decontamination. Recent progress in neutrino physics can now enable us to monitor our nuclear reactors in a completely independent manner. Most of these applications arose as a by-product of fundamental research and were not envisaged before they organically emerged. However, going forward, it is also important to keep an eye on what the possible by-products of the mega-science projects can be and encourage translational research that can allow a seamless connection between fundamental research and its applications.

The involvement of the Indian Nuclear Physics groups in mega projects have led to the development of detectors and read out systems of different kinds, starting from scintillator-based detectors in the WA93 and WA98 experiments to the gas-based proportional counters for STAR and ALICE experiments and the associated read-out electronics. Subsequent upgrades to the STAR and ALICE experiments and R&D for new experiments at FAIR have led to the development of novel detectors such as RPC and MPGDs. Several such detectors and readout system have also been developed for the India-based experiments. These developments have led to the participation of the Indian industry. Some of these detectors have significant societal applications, such as in medical imaging and muon tomography, as discussed in this chapter.

4.1 TECHNOLOGICAL APPLICATIONS

4.1.1 Space missions

Satellites provide information required for a wide range of applications. Satellite data is crucial for monitoring weather, communications and geological processes to plan agricultural development. The radiation environment present in space is a challenge to the satellite missions. This results in harsh operating conditions for the equipment and experimental setups mounted on the satellite. The space radiation hardness assurance problem for the microelectronics can be tested in laboratory experiments using ion-beam accelerators and radiation sources. From these ground-based experiments, the description of the different effects on the electronics chips occurring in space due to the ionizing dose of radiation and the displacement damage can be studied. Simulation of the space radiation environment and designing control experiments to study the effects of radiation on electronics components is a topic of immense interest. One important aspect is the development of a single-event setup for the radiation hardness assurance test, which will systematically study and evaluate the relevant parameters of a device during irradiation.

4.1.2 Reactor monitoring

Nuclear power reactors can be monitored using a detector that measures the electron antineutrino (~6×10^{20} $\overline{\nu}_e$ /GWe power) spectrum via the inverse beta decay reaction $\overline{\nu}_e \rightarrow e + n$. The $\overline{\nu}_e$ spectrum is different for fission fragments produced in the thermal-neutron-induced fission of ^{239}Pu and ^{235}U. Hence the quantities of these isotopes can be monitored remotely using a 1–2 ton detector placed outside the reactor building at a distance of 25–30 m from the reactor core.

The effort in this direction is currently being purposed under the ISMRAN project. A proof-of-principle detector using an array of 100 plastic scintillator (PS) bars of cross-section 10 cm × 10 cm, wrapped with Gd-coated foil, is being put together at the 100 MWth Dhruva reactor at BARC, Mumbai. Initial results with 16 PS detectors have been encouraging. After confirmatory tests with the full array at Dhruva, it will be moved to the Kudankulam Nuclear Power Plant which houses two 1 GWe light water nuclear reactors, or to the 500 MWe Prototype Fast Breeder Reactor at Kalpakkam. There is also the possibility of using a more efficient detector based on a Gd-doped liquid scintillator (LS) that will be developed as a part of the BARC-Heavy Water Board collaboration. Another possibility is to use a water-soluble LS, which is cheaper, and can be 3–4 times larger, leading to larger event rates. It should be mentioned here that such a detector could also be used for short baseline neutrino oscillation measurements, including a search for sterile neutrino mixing.

4.1.3 Nuclear waste management

Nuclear waste from reactors,and medical isotopes usage, is difficult to manage in contemporary society. Presence of long-lived radioisotopes in the nuclear waste poses bigger technological challenges for its storage. These wastes are made up of a number of materials and have a wide range of compositions. Since the last five decades, India has maintained an excellent record of safe management of radioactive waste. A considerable effort has been put in R&D toward developing new processes and techniques to manage radioactive waste, that include indigenous techniques for minimising and isolating the radionuclides efficiently in matrix form and most importantly extracting useful radionuclides from the waste for societal applications. These developmental activities have projected India as a front-runner in the world in radioactive waste management.

An important international effort is devoted to find a suitable solution to incinerate radioactive nuclear waste resulting from conventional power plants and from nuclear disarmament. Transmutation of long-lived radioactive waste can be carried out in an accelerator-driven system (ADS), where neutrons produced by an accelerator are directed at a blanket assembly containing the waste along with fissionable fuel. Following neutron capture, the heavy isotopes in the blanket assembly subsequently fission, producing energy in the process. ADSs could also be used to generate power from the abundant thorium element.

4.1.4 Nuclear Data Program

Detailed and accurate nuclear data are important not only for the advancement of basic research in nuclear physics but are also essential in different applications in the applied areas such as accelerator shield design, personal dosimetry, radiation safety, production of radioisotopes for medical applications, radiation damage studies, reactor safety, waste transmutation, homeland security, use of radiation in diagnosis and therapeutic application, archaeological applications, etc. The role of the Indian nuclear data program is not only to provide current, accurate and authoritative data for basic and applied research by means of compilation, evaluation, dissemination and archiving of extensive nuclear datasets, but also to generate specific, targeted and need-based nuclear data in India and address the gaps in the data.

India is involved in the network of nuclear structure and decay data (NSDD) evaluators as well as International Network of Nuclear Reaction Data Centers (NRDC) of the International Atomic Energy Agency (IAEA). VECC, Kolkata has been assigned as the India-NSDD Centre by the IAEA, whereas the EXFOR compilations in India are coordinated by BARC, Mumbai. This program has a nation-wide collaboration involving experts from IITs and universities. Enhanced support for human resources and research funds for nuclear data program will be essential for sustained activities in this field.

4.1.5 Muon Tomography

We are familiar with ordinary x-rays being used in standard radiography to provide images of organs, bones etc., in human bodies. Muon tomography provides an analogous method that utilizes the highly penetrative properties of cosmic-ray muons to explore inaccessible volumes, e.g., to obtain the depth of rock above an underground tunnel, contents of hollow vaults inside pyramids and volcanoes [Checchia 2016].

A cosmic muon, i.e., a charged particle, is decelerated and deflected due to multiple Coulomb scattering when passing through a target volume. The angle of deviation depends inversely on the muon momentum and directly on the ratio of the material thickness and the radiation length of the material (inverse of the linear scattering density). With the knowledge of the typical momentum distribution of cosmic muons, access to the nature of the material at a certain depth is possible by measuring the angle of deviation.

A typical detector for such studies would require

i. coverage over a large area and be cost-effective

ii. provide good angular resolution of the order of mrad

iii. stability in time and position

iv. good tracking performance

Some of the detectors such as RPCs, GEMs and detectors using plastic scintillators with multi-anode photomultiplier (MaPM) or silicon photomultiplier (SiPM) readout, that satisfy the abovementioned requirements are used in nuclear and high energy physics experiments.

A dedicated R&D program for muon tomography can have several applications such as (a) geological surveys (of mines, volcanoes, etc.), (b) transport control for detecting heavy metals in containers or trucks, (c) industrial applications such as detection of orphan sources in scrap metal, (d) archaeological inspections, (e) nuclear waste and spent fuel control, (f) monitoring of building stability and (g) glacier muon tomography, which is crucial for geology and global warming studies.

4.1.6 Archaeological research

The great potential of the combination of nuclear analysis and archaeological research in the Indian context can be explored with modern developments in nuclear spectroscopy. Nuclear physics techniques, ion beam accelerators and modern detectors find many applications for the analysis of archaeological artifacts. To be able to analyze archaeological artifacts, the microstructure of the matter has to be analyzed to estimate its age. These measurements require nondestructive techniques for carbon dating and analysis of the material, which are provided by the tools developed for nuclear spectroscopy. Improvement of instrumental sensitivity required for nuclear spectroscopy methods using neutron activation techniques, nuclear resonance analysis and accelerator mass spectroscopy (AMS) are critical in probing various problems in archaeological research. AMS facilities at IUAC – New Delhi, IOP – Bhubaneswar and Mumbai University will be important for archaeological research in India.

4.1.7 Industrial applications

Proton beams are often used for studying material degradation phenomena such as wear and corrosion of various mechanical components, which are common problem in industry and various technological areas. Measurement and quantification of wear and corrosion is often desired for quality control and assessment of reliability and durability of various mechanical parts and tools. Experiments to investigate the modification of material property due to an intense radiation environment, relevant for reactor components and ITER components, are being pursued at PLF, Mumbai as well as IUAC, Delhi. The wear rate of any iron-based material as well as Cr, Mn, Cu and V can be estimated using the thin layer activation (TLA) technique. Upon irradiation with a proton beam of suitable energy, iron-based and copper-based materials undergo the following nuclear reactions: ^{56}Fe(p,n)^{56}Co and ^{65}Cu(p,n)^{65}Zn, respectively. The activity of the product radioisotope changes as the component undergoes wear or corrosion. This reduced activity is measured and the wear/corrosion rate is estimated by the help of a calibration curve. Various engine parts include piston rings, cylinder liners, crankshaft bearing, valves or gear boxes and valve seats. Dedicated ion-beam facilities can be planned for industrial use to monitor the corrosion rate in various materials.

4.2 SOCIETAL APPLICATIONS

4.2.1 Medical

Nuclear physics techniques have brought a revolution in medical diagnostics and cancer therapy. Advances in nuclear medicine, imaging and treatment are inevitably tied to basic research in nuclear physics at all levels that include accelerators, detectors, understanding the interaction of radiation with matter, and creating complex statistical algorithms for identifying the relevant data.

Isotope Production for Medical Use:

Proton and electron accelerators, mainly developed for nuclear research, are widely in use for the production of important medical radionuclides. Research activities are also continuing on the high-precision determination and re-evaluation of cross-sections of the relevant nuclear reactions employed for the production of medical radionuclides, and in addition on the design and development of novel radiopharmaceuticals for targeted guided imaging and therapy in oncology. In our country, a medical cyclotron facility has recently been commissioned at VECC, Kolkata that is catering to the requirements of medical radioisotopes and radiopharmaceuticals used in positron emission tomography (PET) and single photon emission computed tomography (SPECT).

Hadron Therapy for Cancer Treatment:

Standard radiation therapy uses X-rays (photons) which deliver radiation to areas other than the tumor and affect healthy cells. However, proton beams can be adjusted to deliver most of the energy to the target point or tumor with minimal dose to the surrounding normal structures, thereby allowing an optimal radiation dose delivery with minimal side effects. The sites where particle therapy has been of maximum clinical benefit are pediatric cancers, bone and soft tissue tumors, prostate cancer, lung cancer and head and neck tumors.

Presently, only proton and carbon-ion therapy machines are commercially available in the world. In India, The Tata Memorial Centre (under DAE), is setting up a National Hadron Beam Facility (proton and carbon-ion). The installation of the proton beam therapy machine is almost complete. Presently, a private hospital in Chennai, Tamil Nadu, has this facility. More of such facilities will be required in the country to treat the large population of India. Developmental activities towards a hadron therapy machine capable of providing He, C, N, O and Ar ions are also desired by the medical community.

4.2.2 Agriculture

Nuclear applications in agriculture rely on the use of isotopes and radiation techniques to combat pests and diseases, increase crop production, ensure food safety and authenticity, and increase livestock production. Ionizing radiation has found use in mutation breeding for improving the crop quality by developing their genetic varieties. Worldwide, the most common physical mutagens for inducing mutagenesis are gamma rays. The widely used gamma sources for this purpose are ^{60}Co or ^{137}Cs. More recently, research activities have been initiated on using accelerated ion beams for this purpose. Compared to gamma rays, ion beams interact with the genetic materials with a very different mechanism. Since the energy transfer is high and linear with the energetic particles, they result in a different variety of mutations. The most commonly used ion beam is the proton beam for causing mutation breeding in the crops. Further R&D toward optimising ion-beams for mutagenesis will lead to a new direction in the improvement of various crops and work in this direction has tremendous scope in the field of agriculture. It will help farmers achieve desirable properties such as low harvesting time, higher yield and resistance to various diseases.

4.2.3 Environmental studies

Connecting nuclear science with the environment will be a growing challenge for the next decade. Changes in the environment will have wide-ranging consequences on mankind. Radioactive isotopes and modern nuclear techniques are being increasingly used to assess freshwater resources, oceanic ecosystems, atmospheric processes and biological systems. These can be used to improve agricultural practices. AMS remains a sensitive tool for some of these studies. These techniques also help in evaluating ecological impacts on the environment, particularly, for estimating natural and man-made pollution. The IAEA has programs for studying radionuclides in the environment including the soil, water, air, plants and animals. Understanding their behavior in the environment helps to model the distribution of these radionuclides following their accidental release by nuclear installations. Such studies provide crucial information to efficiently assess the risks and to take necessary steps toward remediation. In the atmosphere, radionuclides attach to aerosols. Measurement of radioisotopes in aerosols helps in predicting the movement of pollutants worldwide. A close collaboration between environmental laboratories and nuclear physics laboratories will have long-term benefits for the national environment program. Development of an atmospheric radiation monitor network with new-generation detectors will be highly necessary for such studies.

4.2.4 Plasma Program for People (P^3)

Several plasma-based products have been developed and commercialized worldwide for sterilization and decontamination, pollution control, enhanced seed germination, global warming mitigation, and many others. Examples of organizations outside India commercializing plasma-based products for societal applications are listed below:

- M/s Relyon Plasma GmbH, Germany: Piezo brush and plasma brush for plasma activation, sterilization, cleaning etc.
- M/s Adtec Healthcare, UK: Adtec Steriplas for wound treatment, plasma tact for disinfection
- M/s PlasmaTherm, USA: Versaline for PECVD coating, Vison420 for reactive ion etching
- M/s Surfx Technologies, USA: Atomflo 400 for surface cleaning, activation and adhesion
- M/s Thierry, USA: APC 500 for plasma cleaning and activation
- M/s Ionitech, Bulgaria: ION-25HWI plasma nitriding systems
- M/s Plasma Air Inc, USA: Plasma Air 7000 air purifiers
- M/s Flowrox, Finland: Flowrox plasma oxidizer for water purification
- Plasma Leap Technologies Limited, Ireland: Agriculture

IPR has been working proactively in collaboration with various organizations within India and abroad on the societal and industrial applications of plasma for more than three decades. In order to expand the applicability of the plasma technology further for society and industry, IPR has set up a Facilitation Centre for Industrial Plasma Technologies

(FCIPT) in GIDC Industrial estate, Sector 25, Gandhinagar, which will be dedicated to work on conceiving plasma technologies required in India. The FCIPT center has been working closely with various organizations, including industries, academics, public-sector undertakings, hospitals and research laboratories, to deliver various externally funded projects. The work involved development of systems and processes, feasibility studies, contract research and technology transfer to industries. In the last 15 years, IPR has completed more than 84 external projects worth ₹ 29.16 cr having third-party deliverables either in the form of novel systems, novel processes or scientific study reports, and is presently pursuing 35 ongoing projects worth ₹ 6.57 cr, through different funding bodies (DST, DAE, BRNS, Government of Gujarat) and by collaborating with more than 50 Indian institutions. In the past two decades or more, several plasma-based technologies have been developed at IPR, e.g., plasma nitriding, plasma pyrolysis, plasma nanosynthesis, etc. Many of these technologies (more than 20) have also been transferred and commercialized. More than 50 patents have been filed. Having built up a two-decade long track record of delivering technology products, IPR would like to aim at coming out with novel products at the world scale and optimization of existing systems. Hence, collaboration with domain experts in many areas is necessary.

It is proposed to have a national inter-disciplinary R&D program in plasma applications wherein close collaboration with domain experts in medical R&D and hospitals, agriculture, aerospace, waste management, textile, defense, space, industries, academia, etc. can be obtained. Answers to the open-ended questions raised above will be addressed and indigenous plasma technologies can be developed as import substitutes.

The following are the proposed present and potential future collaborators:

S.No.	Area	Present/Potential Partners
01	Waste remediation and Waste-to-Energy (WTE)	CSIR Labs (CSMCRI), BL Engineering, GPGESP Ltd., BARC Petro Industry, NRL – Assam, L&T/Ramky Ltd., GEMI, etc.
02	Bio-Medical and Health	C-CAMP, ICMR (NIRT), Civil Hospital – Ahmedabad, ACTREC-TMC, AIIMS – Delhi, IIT Gandhinagar, Nirma University, etc. ICMR labs, RML Hospital – Delhi, LV Prasad Eye Institute – Hyderabad, SMT Pvt. Ltd., etc.
03	Aerospace and defense	DRDO Labs (ARDE, TBRL), ATIRA – Ahmedabad, GFSU – Gandhinagar DRDO labs, ISRO labs, L&T Defense, Bharat Forge, Godrej Aerospace, etc.
04	Space technology	ISRO Labs (VSSC, SAC, URSC), SLT Ltd.
05	Agriculture and Dairy Industry	NDDB, NSS Pvt. Ltd., ICAR (IIMR), Anand Agriculture University, GB Pant University, etc. ICAR labs, IFFCO Ltd., Jain Irrigation Ltd., AMUL etc.
06	Environment (water and air)	IIT Gandhinagar CSIR labs, GEMI (GoG Lab), IOCL, IISC Bangalore, IITM, CPP
07	Energy Sector	IIT Gandhinagar, GP Green Energy Sys Pvt. Ltd. NTPC, SECIL, EIL
08	Nitriding works/CVD/Thin-film growth/ corrosion	IGCAR, HAL, DU, STAS NPL, NIIT, IITK, NAL, BARC
09	Textile	MANTRA, Reliance BITRA, IIT Madras, IIT Delhi
10	Nanotechnology	IIT Gandhinagar, IIAST

4.3 TECHNOLOGICAL CAPACITY BUILDING AND COLLABORATION WITH INDUSTRY

The questions addressed by the MSPs are some of the most important questions facing the world of science and appeals to the scientific curiosity of the researchers. These projects have the advantage that they network a wide range of expertise from a range of different disciplines. The involvement of India in these projects would be highly helped by large-scale industry participation within the country. At the same time, it would also offer a new pathway for exposing our young researchers in industry to a more holistic training involving state-of-the-art techniques. Indian industry has made several strides by large-scale manufacturing and supply of complex technology items meeting international standards, such as those required by CERN. In the coming years, with the participation in MSPs, the Indian industry has the possibility of rapid growth in the areas related to high-tech hardware and software products. The MSPs provide opportunities for the domestic industry to enter the international market for the supply products that include high-power RF amplifiers, superconducting magnets, high stability power supplies, RF electronics, control equipment, radiation-hard detectors, software, etc. Thus, the collaboration between the scientists and industry partners in MSPs will be mutually beneficial.

There are three major components in mega science research in nuclear physics: computing, accelerators and detectors. Participation in mega science experiments help in technology capacity building in each of these components. Capacity building can be categorized into two sectors: (a) due to contributions to international projects and (b) due to transfer of technology to other in-house projects.

Computing:

(A) Our participation in the Worldwide LHC Computing Grid (WLCG) program has led to the development of products, such as Grid View (which monitors the health of the computing resources), that are used in 38 countries. Indian scientists have been involved in the development of the Extra-Large Farm Management System (ELFMS), Large Hadron Era MONitoring system (LEMON) and Automated Installation System (QUATTOR), to mention a few. These projects were challenging and found immediate use in the development and deployment of the WLCG. Future participation and collaboration could lead to new challenging and technologically enriching projects such as data analytics, database services on-demand, cloud computing, cloud security and big data analysis. Further, through the LCG technology, which has a hierarchical structure of data dissemination, India was able to host two Tier 2 centers at VECC and TIFR, in addition to several Tier 3 centers.

(B) Detector simulation software tools, such as GEANT, and data analysis framework modules, such as ROOT, developed for mega science experiments have been adapted and are being used in in-house nuclear physics experiments extensively.

Accelerators:

(A) Indian scientists have been involved in the design of some of the major components of the LHC. These components were constructed by scientists and engineers through Indian industries. Some of these components include the superconducting corrector magnets, precision magnetic positioning system (PMPS) jacks, accelerator protection systems, quench detection electronics, vacuum system design for long beam transport lines, and cryogenic systems. About 100 engineers and physicists from RRCAT, BARC, VECC and IGCAR have assisted the above campaign at CERN successfully. All these led to technical capacity building. India is actively participating in the development of LINAC4 for the luminosity upgrade of the LHC and in the Compact Linear Collider (CLIC) test facility (CTF3) project that is related to the post-LHC electron-positron linear collider program.

(B) Indian industry has also made new strides by large-scale manufacturing and supply of high technology items meeting international standards to CERN. Items like PMPS jacks were made with the help of Avasarala, Bangalore and IGTR, Indore. QHPS and LPU units were made with the help of ECIL, Hyderabad. Superconducting corrector magnets were made with the help of Kirloskar Electric, Devas. As an example, success at CERN gave confidence and opened up opportunities for ECIL to participate in major international projects such as ITER, France and FAIR, Germany. ECIL is also setting up a state-of- the-art Power Electronics Lab with funding from DAE to meet the above challenges. The list of Indian industries involved is given in Annexure A.3.

Detectors and the Associated Components:

(A) Several industries within India have been involved in the hardware projects conducted by CERN-India collaborations. Some of these include: SCL – Chandigarh, ECIL, BEL, Avasarala Technologies Ltd., Indo German Tool Room, IGTR – Indore, Micropack Limited – Bengaluru, Shogini Technoarts – Pune and Gladstone Engineering Industries – Kolkata. The technology developed includes silicon and gas-based sensors. During the execution of activities assigned to ITER-INDIA, many contracts were signed with industries. This led to the development of large capacity vacuum vessels, water chillers, cooling towers and new material development. Annexure A.3 lists the names of the industries and the new developmental work done by them that has resulted in having global manufacturers for specialized jobs.

(B) The detector hardware technology and simulation tools developed in MSPs are being used for in-house experiments. Some of these are also being adapted for societal benefits, such as medical imaging. Skilled human resource, trained in the process, are getting employed in universities, institutes, R&D laboratories and industry.

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5 BUILDING THE ECOSYSTEM

A mature mega science policy must have internal mechanisms for initiating, approving, funding, facilitating and following up on mega science projects. These mechanisms should be fair, transparent and efficient. While India already has some of these mechanisms in place, certain improvements in the modalities of operation would help in building up a stronger base of technology, facilities and human resources, and consequently, in increasing the output of Indian scientists and at the same time allowing them to dream bigger. This chapter puts forth a few of such proposals, which include a single-window proposal submission forum, a clear phased approach to MSPs along the lines of the best practices worldwide, a Consultative Group for guiding the initiation of new ventures, as well as a Detector Development and Training Center for MSPs that will also connect to its applications and industry. The need for a combined outreach effort has been emphasized in this chapter. These proposals have emerged from discussions with the stakeholders and inputs from them about what changes they would find desirable.

5.1 FUNDING, MANAGEMENT AND EVALUATION STRUCTURES

MSPs are typically long-term projects involving multiple institutes, scientists, detectors, technologies and experimental facilities,acc and require significant resources. A successful MSP would need sustained funding over a long period.

Evolution of funding and management structures for MSPs in the country started with the India-CERN engagement in the mid-1990s and similar ideas were extended to other MSPs, nationally as well as internationally. The broad features of these structures are:

(a) Each MSP is a pan-India collaboration with an identified project leader.

(b) Each MSP's technical approval is done by a high-level apex committee co-chaired by the heads of all the funding agencies involved, scientific experts, financial authorities and other concerned officials of the funding agencies as members. Following this, the extant financial approval processes of the Government of India are followed.

(c) Each MSP has a scientific expert committee for overseeing the scientific and technical aspects of the project, recommendations of which are considered by the apex committee.

These structures have served the cause well and there has been a growth of MSPs in the country. However, over time, and with the increasing number and variety of MSPs, there is a need for minor modifications in the structures and processes to address the following issues:

(a) If a specific group of scientists is inclined to launch an MSP, there is currently no single identified forum that they can approach.

(b) Funding cycles are often much shorter than the appropriate activity-period in the life cycle of a project (i.e., design phase, construction phase, operation and maintenance phase, etc.), thus leading to funding uncertainties during the life-cycle of the project and the consequent undesirable effects on the project implementation.

(c) The process of newer groups/investigators joining a particular project, which is natural and even desirable in long-term projects like MSPs, often takes time.

(d) While periodic changes in the membership of the scientific expert committee overseeing an MSP are not only unavoidable, but also desirable, some essential continuity in the functioning and membership of the scientific expert committee is also important to avoid any information gap.

(e) Involvement of international experts in various expert committees has largely been absent. They could play a useful complementary role.

Keeping all these points in view, the Nuclear Physics community would like to suggest the following plan for funding and management of MSPs. In order to have transparency, accountability and efficiency in the process of funding and monitoring of existing and future mega projects, the following staged process is suggested:

Community Planning Exercise: MSPs need scientists from multiple institutions and with varied expertise to come together and work towards a common goal. Thus, a considerable amount of time is required for coordinating, planning and ultimately building the collaboration. Hence, it is recommended that for all fresh projects a Community Planning Exercise (CPE) is first undertaken. This can be done through presentation and discussion at an existing national-level meeting or at a specially-organized national-level meeting, with the goal of reaching out to a broader audience, including those working beyond the scope of the project. Such a process will ensure community participation, identification of the nodal person and building up an effective collaboration of interested scientists.

It is anticipated that in some cases, the proposing scientists might not be fully aware of the alternate facilities available, existing scientific expertise, or resources available in the country in the proposed field. In addition, they might also need some level of guidance while formulating a proposal. This aspect can be addressed by the formation of a Consultative Group, which will be composed of experienced members of the community and reconstituted every two years at a national-level meeting. This group might be approached by research groups with ideas that could potentially lead to mega projects. It will not be mandatory to approach the Consultative Group.

Submission of proposals: The funding for MSPs could come from multiple agencies and the participating scientists would be usually affiliated to institutes supported by a wide variety of agencies. Hence, it is desirable to have a single-window proposal submission forum. We propose that a Concept Proposal be submitted initially to a dedicated cell in the Office of the Principal Scientific Advisor (PSA) to the Government of India – Mega Science Nodal Unit in the Office of PSA (MSNU-PSA), or to a dedicated mega science proposal submission forum/board at the national level. This initial central point of contact should be able to identify the lead and partner funding agencies and forward the Concept Proposal to them for further consideration, including formulation of a Detailed Project Report, technical evaluation and funding. The status of the proposal should be communicated to the nodal person of the project. The national-level project submission forum or the lead funding agency should also include the possibility to host calls for proposals for participation in an MSP, if necessary.

Inter-Agency Committee: We propose that the lead funding agency set up an Inter-Agency Committee (IAC) for an MSP, co-chaired by the chiefs of the participating funding agencies, with scientific, technical, financial experts and representatives of the funding agencies as members. The IAC is expected to consider the Detailed Project Report and approve the recommendation of the Standing Review Committee (as detailed below) on the MSP.

Standing Review Committee: We propose that the lead funding agency set up a Standing Review Committee (SRC) for each mega science project, consisting of national and international experts and representatives of the funding agencies. This scientific committee would review the proposals at various stages (as mentioned below) within a timeline of 3-6 months from the date of submission of the project report. It will give recommendations for funding, and advise on course corrections, if needed. The SRC will be expected to monitor the project at least once every year and give its feedback to the project proponents. The recommendation of the SRC for the future of a project can be made based on the yearly reports on the progress towards achieving the goals. The report of the SRC in the penultimate year of the project should have special significance.

It is envisaged that the Detailed Project Report on a new or green-field MSP will be for one of the following three stages:

I. Fresh/Early Stage: For new or fresh MSPs, the proposers should typically complete the CPE and start with a Conceptual Design Plan (CDP). The CDP should, among other aspects, include the science goals of the project, a tentative list of potential contributions, a timeline, and funding required for R&D and prototyping of crucial components and statutory clearances, wherever required, leading to establishment of the feasibility of the project. It is like a letter of intent to have the mega project, with seed money to demonstrate the feasibility of the proposal. As mentioned above, first a Concept Proposal containing these aspects will be prepared and submitted to the single-window proposal submission forum in the O/o PSA or to a dedicated mega science proposal submission forum/board at the national level for its guidance. Further, all these aspects will be covered in greater detail in the DPR to be submitted later to the lead agency for a detailed evaluation by the SRC and the IAC, and the subsequent funding decisions.

II. Design, Construction and Commissioning Stage: MSPs could be in various stages of development, such as in the R&D stage or in the stage of construction and commissioning. Projects in such stages can submit their Preliminary Design Plan (PDP) if they are in the R&D stage, or a Technical Design Plan (TDP) if they are in the construction and commissioning stage. These stages would typically include funding proposals for large-scale production of components and/or funding required for the actual project, full-scale experiment/part of a large equipment in an experiment, their installation and, finally, commissioning of the facility. If these stages are a follow-up of a successful fresh/early stage of the same MSP, the proposers could directly formulate a DPR containing the PDP and/or the TDP and submit it to the lead agency for further evaluation by the SRC, IAC and the funding agencies. There might be no need to submit a Concept Proposal containing the essentials of the PDP and/or TDP to the single-window proposal submission forum in the O/o PSA or to a dedicated mega science proposal submission forum/board at the national-level once again. It is expected that the O/o PSA and the funding agencies will keep each other informed about various ongoing and proposed projects.

III. Operations, Upgrade and Maintenance Stage: MSPs will eventually enter a phase where the experiment will run for a long period to realize the science goals, sometimes requiring upgrades along the way based on the data collected. This stage will cater to running the facility successfully with maximum up-time and utilizing it for achieving the desired scientific and technological goals of the project.

This stage is normally referred to as the Operations and Maintenance Stage. The proposers would prepare an appropriate Operations and Maintenance Plan (OMP), containing details such as the science goals, milestones and funding required for continuing the project/experiment, including upgrades.

Given the different stages at which India has undertaken various MSPs so far, it is important to further qualify the funding stages mentioned above. The three-stage funding mentioned above will hold true for a new, or a green-field project, undertaken either in India or abroad. Proposals are also received for participation directly in stages II or III above when the basic conceptual design and feasibility studies have been completed by established groups elsewhere in the world. MSPs that are already in one of the advanced stages (II or III) should be designated as such and continue with the current monitoring mechanism, which will be equivalent to the SRC. In the case of new MSPs where scientists intend to directly participate in any of the two stages, II or III, they should first submit a Concept Proposal for participation in that stage to the single-window proposal submission forum in the O/o PSA or to a dedicated mega science proposal submission forum/board at the national level for guidance and then a DPR to the lead agency for further evaluation and funding through SRC and IAC.

Management Structure within an MSP: Management of a project at the end of investigators and institutions is expected to be through guidelines framed by the collaboration and approved by the SRC and IAC. The nodal/lead scientist of the MSP will be the contact person between the facility, experiment, funding agencies, SRC and IAC. It is expected that the budgetary provisions for the MSP will be distributed among the participating institutions as per the approved project sanction. Once the budget is approved, the relevant funds should directly flow to the institutions. This will allow adherence to proper financial rules such as submission of statements of expenditure and utilization certificates to the funding agencies directly, proper evaluation of the contribution of each institute to the project against their responsibilities, and help bring out the collaborative and complementary nature of the MSP.

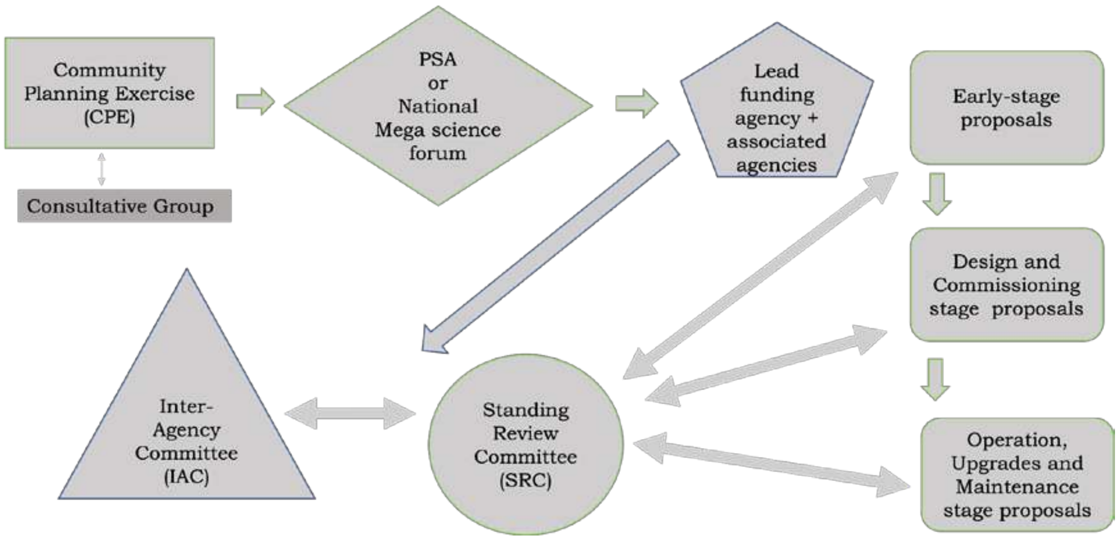

Figure 5: The proposed stages in funding, management and evaluation structures for fresh/early-stage MSPs.

5.2 INITIATIVES RELATED TO MEGA SCIENCE FOR NUCLEAR PHYSICS

For the further success of MSPs, several new initiatives related to funding need to be taken. Some of them are listed below.

(a) Bilateral Projects: Several funding agencies have the mandate to enter into Science, Technology and Innovation Agreements between India and other countries. For example, DST has bilateral cooperation with 83 countries. Such funding is usually for exchange visits, utilization of facilities abroad, joint workshops, etc. Typically, large-scale funding that is required for MSPs is not available through this route. However, international MSPs are important components of India's international relations. Several of such MSPs involve sharing of scientific resources and facilities in both the countries. The funding agencies on both sides come up with joint calls for the funding of scientific proposals. Such bilateral projects, even now, could act as seeding grounds for establishing contacts and developing a plan for an MSP. We recommend that for such purposes MSPs should be included in calls of proposals for bilateral projects. Not only will it strengthen our participation in global MSPs but will also allow projecting India's scientific excellence on the global research landscape as well as help in leveraging foreign alliances and partnerships to strengthen India's flagship national R&D programs.

(b) Participation of Industry in MSPs: MSPs, by their very nature, can improve the core capacity of a nation in knowledge-intensive and cutting-edge technologies by enhancing industrial partnerships. Benefits of such a partnership for the mega science community can include extensions of in-house research capabilities, alignment of efforts with viable technology options, direct and more immediate impact on technology and design infrastructure, and training students for industrial positions. Possible benefits for industry would include more research-intensive activities, investigations of high-risk ideas, increased efforts toward research for shortening the R&D cycles, training students for future employment and vetting of future hires.

Keeping these aspects in mind, we propose the following:

1. Allow industry to directly be part of the MSPs (preferably as partners right from the proposal stage). This can be through a call for proposal for industry participation and developing a methodology to qualify the participation.
2. Foster industry-university/institute collaboration by granting the involved industry the rights to use the results of the research at the project-end (subject to appropriate Intellectual Property Rights conditions that can be settled through appropriate memoranda of understanding).
3. Allow participation of engineers, scientists, or managers from a partner industry in the scientific meetings of the collaboration, to catalyze collaborative research in an effective manner.
4. Develop avenues for undergraduate students, Ph.D. scholars and postdoctoral fellows to gain experience by working in an industrial setting.
5. Provide support for a supplement to an existing grant for high-risk/high-gain research in order to develop a generic technology.

MSPs that are jointly designed and implemented by the university/institute and the industry engineers and scientists will encourage the principal investigators and their students to perform some of their research at the industrial sites. Researchers from industry and academia tend to complement each other and thus could form effective teams. Having multiple teams will provide expertise in materials, devices, characterization, measurements and other relevant areas that will exceed the capabilities of a single group. This mechanism will offer a special opportunity for industry, including small businesses, to enhance their research profile through their involvement in collaborative mega science projects. In several cases, the industry might need hand-holding to navigate through the process of product development for an MSP. This needs to be facilitated.

The modalities of including industries can start with the appointment of a liaison officer for an MSP, call for proposals, evaluation by an expert committee that will also work out the modalities of funding, management and monitoring.

(c) Transfer of Technology from Research Laboratory to Industry/Market: Some of the MSPs could lead to technological spin-offs, which, if developed further, could be of great national value. Further development of these technologies for niche applications would require separate funding. At the present time, there is no mechanism using which such projects can be supported. It is thus suggested that such projects also be received by MSNU-PSA or the special mega-science forum for initial evaluation and further directions regarding their source of funding.

(d) Building Infrastructure: Globally, the MSPs rely heavily on infrastructure and facilities for detector R&D, instrumentation, data acquisition, front-end electronics, high-performance computing, grid computing, etc. Physicists in the age group of 40 to 50 can be encouraged to propose and defend such long-gestation projects. At present, most institutes, especially universities, do not have many of these facilities. Empowering institutes/universities with such facilities will help in their effective participation in an MSP. Special funding should be allocated to all new institutes/universities to encourage setting-up laboratories and computing facilities to meet the requirements of an MSP. It is necessary to enhance the number, quality and service conditions of the technical support staff in the universities that support the MSPs. Further, as a training ground for human resource for MSPs, setting up smaller and appropriate accelerator facilities in universities and higher education institutions, such as IITs, IISERs and NISERs, for training and research will be useful.

(e) Increasing the Funding Base: Currently, most of the MSPs in nuclear physics are funded by DAE and DST. However, a large number of scientists participating in MSPs are from universities and institutes, which are funded by the Ministry of Education and UGC. In several MSPs, as they involve a number of innovative technologies, participation of large systems of national laboratories, such as CSIR, DRDO, etc., could be productive and desirable. Hence, it is suggested to increase the funding base for MSPs by including these other agencies too.

(f) Nuclear Science Society: We recommend the creation of an Indian Nuclear Science Society to advance, foster and spur the development and application of nuclear science, engineering and technology for addressing key scientific questions, and for the benefit of the society. It can be mandated to create and maintain a database of nuclear physicists, engineers, students, etc., as well as various scientific and technological outputs of the community in terms of publications, detector/product development, facilities, etc. It can also coordinate the annual meetings of the nuclear physics community, it can hold meetings for the presentation and discussion of scientific and technical ideas, and help to disseminate information related to nuclear science and technology using appropriate modes. The Society can also coordinate summer research programs for undergraduate and postgraduate students interested in nuclear and plasma physics in various institutes and universities of the country.

5.3 TRAINING AND RETAINING HUMAN RESOURCE

Nuclear physics experiments involve state-of-the-art instruments and detectors. Such equipment might not be available to students during their studies at the bachelor's and master's level. Early exposure to such devices can enhance the scope of nuclear physics teaching in universities and colleges. In view of this, digital labs can be developed in national laboratories, IITs, IISERs/NISER and some universities based on the available infrastructure there. These could supplement face-to-face instruction. Such laboratories could provide online tools where students could mimic an experiment. Students will also get the opportunity to mimic data collection, learn about data analysis and draw conclusions based on these. There can also be a provision to use robot-based control for some types of experiments that can enable the students to play with some of the hardware parameters of the experiments in the online mode.

The role of trained human resource for MSPs cannot be overstated. Not only do we need scientists interested in the science outcomes but also scientists and engineers capable of building the required instrumentation for experiments. This includes experts from fields as diverse as condensed matter physics, electronics, and mechanical and civil engineering.

Currently, there are more than 60 universities and research institutes that train nuclear physicists in India. It will be important to introduce modern Nuclear Physics courses even at the B.Sc. level with some rudimentary laboratory equipment to make younger students aware of the recent developments in the field. Overall, the number of students completing M.Sc. in India (with specializations related to Nuclear Physics) per year is about 350, whereas the number of PhDs is about 30 per year. India produces one of the largest numbers of engineers in the world every year. This strength of our country can be leveraged for the benefit of mega science activities.

While the current education system in the country focuses on training students in one particular discipline, it is important to widen the scope of their expertise, especially in areas related to the mega science activities that they will be a part of. Special training courses need to be organized regularly for this purpose. This can be coordinated by a National Training Centre, as described in the next section (Section 5.4). In addition, creating new modules at the undergraduate and post-graduate level in the relevant experimental and theoretical areas for both sets of students, as well as starting new M. Tech. courses in accelerator technology, control systems and communication electronics, that are taught as special topics in various universities will be essential for the manpower requirement of MSPs. In keeping with the National Education Policy (NEP) framework, for optimal effectiveness, suitable academic and training programs can be developed to impart the skills required, beyond the traditional subject silos.

However, in order to attract and retain the new generation of students, scientists and engineers in nuclear physics, there should be a clear visible long-term career-path for those aspiring to become a part of this community. Joint appointments between national laboratories and universities/IITs should be encouraged for intensifying the science related to MSPs. In this way, trained manpower will continue to be a part of the science community. At the same time, universities/IITs will have direct access to the science, technology, data and academic resources related to MSPs, which will be beneficial for training students in related subjects.

Working on Multiple Projects: With many MSPs around the world, it is often observed that research groups are involved in multiple projects. Indeed, research groups can have multiple expertise and interests, and it is also important for them to keep on working along different directions, given that research in a given direction, by its very nature, need not bear immediate fruit. Even among the MSPs, it is not certain which of the projects would finally see the light of the day. This uncertainty also motivates research groups to not put all their eggs in one basket, thus distributing their efforts in different directions. Indeed, for a healthy growth of the community and for training of students, it is important for scientists to be involved in more than one MSP at a given time that are at different stages of their life-cycle. For example, a scientist might be participating in the science/analysis of one project, and at the same time, be involved in the designing/commissioning/upgrade of another one. A downside of this is that this might lead to the dilution of efforts in any one project and a miscalculation of how much resource, of people, time and equipment, is actually available for any project.

Therefore, it is recommended that for all the MSPs that come under the umbrella of mega science funding, researchers involved should specify an estimate of the fraction of their time and resources that they can commit for each project. It is then expected that they will stick to their commitment. This will at least guarantee that no researcher has committed a total of more than 100 % of his/her time when all the MSPs under this umbrella are combined. In order to have a fair estimate of the human resource available, MSPs should also give an estimate of the full-time equivalent (FTE) scientists involved.

Centre for Nuclear Theory (CNT): It is envisioned that an inclusive and diverse research environment where scientists can focus on key frontier areas of the field, including those crucial to the success of the existing and future experimental and computational facilities is highly desirable. In this context, a CNT is proposed to be set up, initially in a virtual mode, and later, possibly in a physical mode at a suitable place. Some of the key goals of this Centre are expected to be (a) to create a pool of young nuclear physicists, nurture them so that they can go on to become capable researchers in leading universities, national laboratories and in the government as well as private sector, including technology companies, (b) to contribute to science education through graduate student research, summer schools, internships, scholarships, and co-sponsorship of national schools and workshops, (c) to build and strengthen international cooperation and collaboration in nuclear physics through cooperative programs and exchanges and (d) to encourage interdisciplinary research at the intersections of nuclear physics with related disciplines such as high-energy physics, astrophysics, atomic physics, condensed matter physics and quantum information science. This Centre will be along the lines of the Institute of Nuclear Theory (INT) at University of Washington in Seattle, Washington and European Centre for Theoretical Studies (ECT*) in nuclear physics and related areas.

5.4 A NATIONAL DETECTOR DEVELOPMENT AND TRAINING CENTRE

The science-training of students participating in MSPs of course takes place in their respective universities or research institutes. However, the required expertise in all areas relevant to a project, might not be available at a single place; this problem has been partly solved by the organization of training programs such as the SERB Schools. However, compared to the number of students who need these currently and the growing number of students expected with the increase in the number of MSPs, the number of students that can be trained in such schools is quite limited. In addition, instrumentation development is an important part of training of the students, the infrastructure for which is difficult to reproduce, transport, or set up at the different locations where such schools are organized. Furthermore, different teaching and examination schedules of different universities mean that it is also difficult to find a common time for students from all parts of the country.

A crucial requirement of the Nuclear Physics community, which will take care of the issues mentioned above, is the establishment of a Detector Development and Training Centre (DDTC) having clear scientific goals, preferably at one of the places which are the hubs of activities in nuclear physics. It should be open to all the scientists and engineers involved in MSPs. Such a center should ideally stand on its own, supported financially by DAE and also DST, and not be connected with any of the existing institutions, making it an entirely inter-institutional center. It could have a limited number of permanent staff, including scientists, engineers and postdoctoral researchers.

As the experience of MSPs from all over the world confirms, postdoctoral researchers are the pillars of any such project. These are trained individuals who do not have a permanent academic position and associated duties such as teaching. A Centre like this would allow them to dedicate themselves full-time to an MSP, work in an environment where they have adequate facilities as well as exposure (due to the programs suggested below) and prove themselves.

There should be a Visitors' Program under which members of MSPs, who might be faculty members or scientific staff from various universities and institutes, can come and carry out their developmental work here. This will obviate the need for replicating major instrumentation in all participating institutions. It should be emphasized that this is not meant to be a replacement for the individual laboratories built in universities/institutes; indeed, the presence of such local laboratories is crucial for the growth of science and training of students in all parts of the country. The individual institutions will continue to have their own small-scale laboratories at their individual places. However, major instrumentation development specifically meant for MSPs, which might not be possible in a single institution, can take place at the proposed centralized location.

The same DDTC can also conduct specialized courses for students throughout the year. This will mean that more students can participate in these courses and can also be directly trained on the equipment that is already available there. Courses specially designed for industry partners can also be conducted at the same location. This Centre should also have an ongoing internship program for students doing their Bachelor's or Master's in engineering and allied disciplines. This would thus become a hub for MSP-related R&D and education.

For the success of such a Centre, it is important that visits to the Centre by faculty or staff from universities/institutes are recognized by their parent institutions as official duty and they are given some flexibility in their regular duties. This is often done for faculty/scientists involved in mega science experiments when they visit the location of the experiment. However, this needs to be extended even for detector development and specialized teaching at the proposed Centre.

It is envisaged that such a Centre will also be useful for High Energy Physics, which has many science issues, instrumentation techniques and technologies in common with the Nuclear Physics community. Indeed, a Centre with similar aims, Inter-Institutional Centre for High Energy Physics (IICHEP), is already planned to be built as a part of the INO MSP. A few more such centers will help in expanding the reach and impact of MSP activities in nuclear physics.

5.5 OUTREACH

Science in schools and colleges exposes students to examples of clear and rational thinking, methodologies of scientific inquiry such as experimentation, data collection, classification, hypothesis formation and use of logic. This, in turn, aids in understanding of other spheres of activity in life. Further, it is expected that modern society will inculcate scientific temper among its citizens, to let them appreciate the truths of the natural world and links with natural phenomena — and perhaps this is the major motivation for science outreach. In order to spread the spirit of scientific temper, science outreach activities are being organized by several institutions in India. Most of them now have flagship events that have been enormously successful with large turnouts. There are forms of outreach that target a specific audience. For example, refresher training workshops for high-school teachers and college lecturers are conducted under Vigyan Pratibha, the rationale being that these lecturers will, in turn, pass what they have learned onto their students. All such outreach activities have a typical format: talks, discussion sessions, activities and demonstrations for those in attendance. This typically goes on for a few days at the maximum.

The rapid progress in terms of scientific discoveries and technological innovations in mega science could lead to an ever-growing disparity between the understanding that the scientific community will enjoy and the knowledge that the public will manage to grasp. It will be important to bridge this gap, given that fundamental scientific research is increasingly dependent on public funding, and it is crucial for scientists to convey the importance and excitement of their work to the public at large. Since MSPs require relatively large funding over long periods of time, serious thought should be invested into 'how' to devise the most effective way to impart greater public understanding of mega science. Further, scientists need to think whether and how the public, especially younger minds, can have access to the big data emanating from the MSPs. A recent attempt at mega science outreach was made through the Vigyan Samagam programs at various science museums in the country. One has to build on this success and prepare dedicated programs for science outreach. It will be useful to undertake outreach programs by forming a consortium with MSPs in other related fields.

A collaboration among various MSPs will allow maximizing the impact of education and outreach efforts related to these projects. The collaboration can be in the form of networks of scientists, researchers, science educators, explainers and communication specialists active across the country in conveying the science of MSPs to the public at large. Some of the programs can include:

1. Masterclass: Allow school and college students to access data from various MSPs, analyze them and learn aspects of frontier science. Such classes should be held in various parts of the country at different times of the year.
2. Access and sharing of outreach resources: Provide a platform for sharing the wealth of already available and new resources, methods and scientific tools, in the form of an easily accessible database. Networks of various MSPs will allow for the following aspects:
   a. rapid communication of both local and global outreach events
   b. periodic meetings among the MSP participants providing a means to share expertise, examine feedback, analyze the impact and optimize methodologies
   c. expanding the global reach of all scientists engaged in the outreach. Collaboration should endeavor to achieve the widest possible distribution of outreach and educational materials for public use.
3. Foster the acceptance and value of the scientific method and evidence-based decision-making in society. Large-scale global research projects and the scientific breakthroughs that often accompany such projects teach our world the benefits of worldwide cooperation in science and beyond.

The programs should also aim at achieving proper gender balance, both in organizing the programs and reaching their beneficiaries.

One proposed collaboration would be along the lines of the International Particle Physics Outreach Group (IPPOG) that has originated at CERN. IPPOG is a global network of scientists, researchers, science educators and communication specialists active across the globe in outreach activities related to particle physics, whose mission is to maximize the impact of education and outreach efforts, and stimulate the younger generation to pursue careers in science, technology, engineering and mathematics. It is a collaboration between laboratories of 32 countries. Its missions are (a) sustainable development of particle physics outreach and (b) improving outreach standards worldwide. Two of its most successful programs are (a) Particle Physics Masterclass and (b) CERN's Beamlines 4 Schools. A similar program should be designed collectively by the leaders of various MSPs in the country.

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6 SYNERGIES WITH OTHER MEGA SCIENCE AREAS

Different areas of science are interconnected and the MSPs are no exception to this. The area of Nuclear Physics has clear overlaps with those of High Energy Physics, Astronomy and Astrophysics, and Accelerator Physics. Some of the mega projects themselves would be carried out with a collaboration among these areas. Coordination among the Working Groups for this Mega Science Vision exercise is also extremely crucial. This chapter points out the areas of overlap in order to ensure that the issues in the overlapping magisteria are discussed by the relevant communities.

The synergies with the High Energy Physics community are along the lines of overlapping science goals, very similar detector systems, read-out electronics systems and computing, whereas those with Astronomy and Astrophysics are dominantly in the areas of complimentary science topics and computing. Since most of the nuclear physics MSPs are facility dependent, they have strong connections and interests in the developments in the area of Accelerator-based Science and Technology. R&D on detectors, electronics and computing have a lot of common and overlapping areas for nuclear physics and high energy physics. In fact, exchange of knowledge between the two groups often takes place. On the other hand, developments in accelerator-based science and technology are crucial and play an important role to meet the goals of the mega science programs in nuclear as well as high energy physics.

6.1 HIGH ENERGY PHYSICS

There are three main areas of overlap with high energy physics: (a) direct dark matter search, (b) heavy-ion physics using the multipurpose detector at CMS in LHC and (iii) neutrino physics.

In the area of dark matter physics, the fundamental physics question is: what are the constituents of dark matter (DM) and are they different than normal matter? The two promising potential candidates are (a) weakly-interacting massive particles (WIMPs) and (b) axion-like particles (ALPs). Searches for DM are being carried out via two directions: (a) direct search (elastic scattering of DM with detector nuclei) and (b) indirect search (accelerators, neutrinos, gamma rays, positron from WIMP annihilations). Category (a) uses nuclear physics whereas category (b) uses high-energy physics techniques. Direct detection experiments search for elastic scattering of a WIMP from a target nucleus. Experiments of this type must be located in deep underground laboratories to avoid the effects of cosmic-ray interactions that produce energetic neutrons that could mimic WIMPs. The experiments must also shield the detectors from the decay products of radioactivity in the environment and in the materials of the experiment itself. State-of-the-art detectors and innovative ways to control and understand the background to DM search are the main challenges. Indian groups are involved in national as well as international efforts to address these physics problems, both programs being complementary to each other. (i) Indian groups are a part of the Super Cryogenic Dark Matter Search- Sudbury Neutrino Observatory Lab (SuperCDMS-SNOLAB) [Agnese 2014] and PICO experiments, which are some of the most sensitive experiments in the world to search for low-mass DM candidates. The current efforts include R&D on detectors which will provide the best signal to background discrimination as well as increased DM signal detection capability. (ii) Learning from this experience of working in international collaboration, a DM search experiment is proposed to be set up at the Jaduguda Underground Science Laboratory (JUSL) in India. The JUSL project will be the first step towards setting up a full-fledged DM experiment at Indian Neutrino Observatory (DINO). DINO is expected to have two phases. In the first phase, a mini-DINO experiment with a 1 kg active mass detector is expected to operate and in the second phase, a 1-ton-scale experiment is planned. The discovery of DM candidates is one of the key open questions in science, there must be Indian participation in this area of fundamental science. Details of these projects will be found in the High Energy Physics MSV2035 document.

In the area of heavy-ion physics, the overlap is via the physics program of the Compact Muon Solenoid (CMS) experiment. CMS is a multi-purpose detector at LHC for measuring muons, photons, jets and charged tracks from lead-lead collisions at a high rate over a very large rapidity range. It has capabilities to use soft as well as hard probes such as multiplicity, low and high transverse-momentum spectra of charged particles, photons, jets and quarkonia to study QCD at very high temperatures, high energy densities, very low x physics, dijet correlations and ultra-peripheral collisions. CMS, as a generic detector for heavy ions, has contributed to the above measurements with Indian contributions and it will continue to be an active physics program for the experiment at LHC. The prime goal of this research program is to test the fundamental theory of strong interactions (QCD) in the extreme conditions of temperature, density and parton momentum fraction by colliding nuclei at TeV energies.

Neutrino physics is at the boundary of nuclear physics and high energy physics. The topics discussed in sec. 1.3 in this document (neutrinoless double beta decay, reactor neutrino monitoring, sterile neutrino search, low-energy solar neutrino physics and neutrino-nuclear interactions) are of crucial importance and interest to high energy physics. However, the knowledge of nuclear structure and spectroscopy, as well as the experimental techniques required, need the expertise of the nuclear physics community. Therefore, it is envisaged that these projects will be led and executed by nuclear physicists. These are therefore included in this Nuclear Physics document.

The computational aspects of Nuclear Physics and High Energy Physics MSPs have a large overlap. Therefore, the computing requirements of these two disciplines have been combined together and presented in this document.

6.2 ASTRONOMY AND ASTROPHYSICS

Advances in nuclear physics along with astronomical observations and astrophysical modelling will provide new insights on the secrets of the evolution of the Universe. The quest is to explore the structure and the dynamics of different astrophysical objects and to identify and understand the processes of their origin. Such studies are expected to address the following key science questions:

- Which are the fundamental nuclear reactions that drive the evolution of the Universe?
- How does stellar nucleosynthesis evolve with time?
- How does matter behave under extreme conditions? Can multi-messenger observations provide access to conditions not reached at present laboratories?

This is truly an interdisciplinary subject entering into a new era due to the upcoming facilities in astronomy, nuclear and particle physics. The detection of a binary neutron star (BNS) merger on August 17, 2017 dubbed as GW170817, has strong impact on the advancement of the field of nuclear astrophysics. The electromagnetic counterpart of it was powered by r-process radioactive nuclei synthesized in the neutron-rich matter ejected in the BNS merger. This was the first confirmation of the nucleosynthesis of heavy nuclei beyond the nucleosynthesis in massive stars that undergo core collapse supernovae. Both low energy and high energy nuclear physics laboratory experiments will make a strong contribution in advancing the frontier knowledge in this subject. Science and technology interactions of MSPs of nuclear physics and astronomy will strengthen the mega science program and new directions might emerge. Here, we discuss some of the overlapping science issues.

The hurdles that often limit the desired progress in nuclear astrophysics are the uncertainties in the requisite nuclear-physics ingredients, thereby highlighting the importance of continuous efforts directed towards improving the knowledge of the same. A significant contribution to these uncertainties arises due to the difficulty in determining the nuclear ingredients directly in the laboratory under the conditions prevalent in the astrophysical environment. This makes nuclear modelling indispensable, which should, however, be based on reliable and realistic frameworks and be constrained and guided by experimental data as much as possible. For instance, astrophysical modelling of rates of stellar reactions are required in the nucleosynthesis networks for estimating the abundances of different elements. These require several inputs from experimental observations, such as those involving measurements of light charged particles (protons and alphas) and neutrons. Some of the reactions of interest involving charged particles i.e., transfer and capture processes, can be carried out at the accelerator facilities within India. In addition, a large fraction of the nuclei crucially involved in the astrophysical evolution of the universe are often short-lived isotopes lying away from the line of stability with unusual neutron-to-proton ratio. The Rare Ion Beam facility, with the simultaneous development of novel techniques and instrumentation, is required to probe the properties of many of these short-lived isotopes relevant for astrophysics. The FAIR facility will allow access to many of these short-lived nuclei, especially those relevant for the r-process of neutron capture, for the first time, thereby pushing the frontiers of knowledge deeper into the yet unexplored territories of the nuclear chart. This aspect has a large overlap with the Thirty Meter Telescope (TMT) project. TMT with its high sensitivity and spatial resolution can probe stellar populations towards the center of the Milky Way. These studies will open up new frontiers in the field of galactic archeology. One example of the overlapping science is: what is the origin of the r-process elements? Despite its critical role in producing elements beyond the iron peak (particularly in metal-poor environments) and its spectacular display in the first gravitational wave neutron star merger event, our theoretical understanding remains rudimentary. Fortunately, theoretical yields for the r-process can be greatly improved via a combination of vast spectroscopic samples and multi-messenger followup in astronomy. This problem has extremely wide-ranging implications, from understanding the first stars and supernovae to understanding the gross properties of high-redshift galaxies. The nuclear physics measurements for short-lived isotopes from FAIR will give valuable inputs in this subject.

Another ongoing quest is directed towards finding a reliable EOS of a neutron star at zero and elevated temperatures. Such estimations are crucial for understanding the observations that characterize the dynamical neutron star phenomena, such as inspiral of binary neutron stars, now detected by means of gravitational waves and the subsequent mergers detected by multi-messenger electromagnetic signals. Another field of interest is the neutron star seismology. The EoS is also vital for investigating the signatures of neutron star-black hole and neutron star-neutron star mergers at present and upcoming gravitational wave observatories, including LIGO, Virgo, GEO, KAGRA, LIGO-India, LISA and other spaced-based observatories, as well with the use of pulsar timing arrays. The proposed Square- Kilometer Array (SKA), of which India is a major collaborator, will be a discovery instrument for neutron star science. Further details on these activities will be a part of the Astronomy and Astrophysics MSV2035 document.

Neutron stars also offer a rich testing ground for microscopic theories of cold hadronic matter at high energy densities, such as QCD, that study the transition of matter to a new phase of quarks and gluons. As a result, they provide a complementary approach to probing such dense matter as already reported in ultra-relativistic heavy-ion collision experiments at the LHC, RHIC and FAIR. In addition, recent discoveries of maximally massive stable neutron stars with mass close to twice the solar mass present a direct challenge to theoretical models incorporating microscopic interactions of dense nuclear matter, as they are often speculated to be suitable candidates for quark-matter cores.

It is also expected that the gravitational-wave signals that would arise from the mergers of a neutron star with another neutron star or a black hole system would provide valuable information about the merger dynamics. This would, in turn, shed light on some of the fundamental properties of the neutron star, such as its compactness, in a model-independent manner since the peak frequency in the signal would be directly correlated with the radius of a cold neutron star.

To summarize, in the near future, the community will get the opportunity to unravel many mysteries related to matter subjected to extreme conditions in astrophysical environments, made possible by the trifecta of novel astronomical observation, advanced astrophysical modelling and laboratory experiments in nuclear physics across a wide energy scale.

6.3 ACCELERATOR-BASED SCIENCE AND TECHNOLOGY

The Low-energy Nuclear Physics and Nuclear Astrophysics community will require studies with probes ranging from stable and radioactive nuclei, to photons, neutrons and electrons. The stable-ion beam facilities at Mumbai (BARC-TIFR PLF at TIFR), Delhi (Pelletron-LINAC at IUAC) and Kolkata (cyclotron at VECC) have been crucial for carrying out frontier research in low-energy nuclear physics. These national accelerator facilities have helped in expanding experimental research activities in the country. Many young researchers got trained in experimental research with the state-of-the-art instrumentation. It is absolutely essential to upgrade these accelerators so that the community can continue to perform competitive nuclear physics research in these three accelerator centers. In this respect, heavy-ion accelerator augmentation is in progress with the new accelerating tubes for the pelletron and replacement of Pb-based superconducting RF cavities by Nb cavities at the BARC-TIFR PLF facility. Work is in progress at IUAC to develop a high-current injector (HCI) for the superconducting LINAC. VECC is engaged in the pre-project activity for constructing a full-fledged RIB facility, called the Advanced National facility for Unstable Rare Isotope Beams (ANURIB), which is aimed to be a facility for applied and nuclear research using rare isotope beams. RIB will be produced via the photofission and fusion-evaporation reaction routes using an electron and a proton driver, respectively. A new class of nuclear physics experiments can also be initiated with the availability of high-power lasers and a combination of devices with accelerator technology. Together with facility enhancements, a much-needed capacity-building of skilled scientists and engineers will be greatly facilitated.

A high-current low-energy accelerator has recently been installed at SINP, which will provide new avenues for nuclear astrophysics. An underground accelerator will be extremely useful for nuclear astrophysics. A proposal has been prepared to build a low-energy accelerator facility based on a single ended 5 MV Van de Graaff accelerator for doing carbon dating, measuring cross-sections of astrophysical interest and generation of neutrons for various applications.

Now, it is also time for the community to take our scientific endeavor to the next level and build a facility for rare-ion beams that will open up a large avenue for new discoveries. In this direction, two accelerators have been envisioned, which will provide radioactive-ion beams and high-current ion beams from proton to U.

Proton driver-based RIB:

Phase wise development of a proton accelerator has already started for the 1 GeV ADSS project that will be constructed at Vishakhapatnam. As a part of it, 3 MeV proton beam with 300 μA current has been achieved at the LEHIPA facility. This accelerator is planned to be used as the driver accelerator for RIB, once it reaches 50 MeV of proton energy. The post accelerator can be connected to two separate ECR ion sources for multiplying the charge state of the stable and radioactive ions, respectively.

High-intensity Ion Beam Facility:

Developing a new high-intensity ion beam facility, which can provide energies at and above the Coulomb barrier, is considered to be one of the important issues of the nuclear physics community. The facility should be capable of accelerating ions from proton to U and deliver high-intensity beams (μA current) at the target position. One of the possible configurations will be a LINAC, which can provide high-intensity beams from H to U with energy up to 10–20 MeV/u. A combination of high-intensity stable-ion beams and an ISOL or an in-flight separator equipped with a gas catcher technique can provide intense and exotic beams of low-energy radioactive ions.

Small-size and low-energy accelerator facilities can be established, operated and maintained on a typical university campus. These accelerator facilities can cater to a number of areas of basic and applied research and can provide a platform for training of academic and technical support manpower in the field of accelerators, accelerator-based research and accelerator-based techniques.

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ANNEXURES

ANNEXURE A.1:

TIMELINES OF MAJOR PROJECTS (TENTATIVE)

<table>
<tr><th>Prog./ year</th><th>2021</th><th>2022</th><th>2023</th><th>2024</th><th>2025</th><th>2026</th><th>2027</th><th>2028</th><th>2029</th><th>2030</th><th>2031</th><th>2032</th><th>2033</th><th>2034</th><th>2035</th></tr>
<tr><td>STAR</td><td colspan="5">Science Utilization Phase</td><td colspan="5">Data available for physics analysis</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>ALICE</td><td colspan="10">Science Utilization Phase</td><td colspan="5">Next generation heavy-ion experiment (ALICE 3)</td></tr>
<tr><td>FAIR</td><td colspan="5">Construction and Commissioning Phase</td><td colspan="10">Science Utilization Phase</td></tr>
<tr><td>EIC</td><td colspan="4">Detector Design and R&D Phase</td><td colspan="7">Construction and Commissioning Phase</td><td colspan="4">Science Utilization Phase</td></tr>
<tr><td>INGA</td><td colspan="15">Science Utilization Phase</td></tr>
<tr><td>ITER-India</td><td colspan="14">Construction and Commissioning Phase</td><td>Science Utilization Phase</td></tr>
<tr><td>ELI-NP</td><td colspan="5">Construction and Commissioning Phase</td><td colspan="10">Science and Utilization Phase</td></tr>
<tr><td>Tin.Tin</td><td colspan="4">Planning and Conceptual Phase</td><td colspan="2">Detector Design and R&D Phase</td><td colspan="2">Construction and Commissioning Phase</td><td colspan="7">Science and Utilization Phase</td></tr>
<tr><td>ISMRAN</td><td>Construction and commissioning phase</td><td colspan="6">Science Utilization Phase</td><td colspan="8"></td></tr>
</table>

ANNEXURE A.2:

FUNDING REQUIREMENTS: A TENTATIVE ESTIMATE

	Current/ Last project sanctioned annual budget in ₹ cr	2020-25		2025-30		2030-35	
		FTE scientists	Funding in ₹ cr (p.a)	FTE scientists	Funding in ₹ cr (p.a)	FTE scientists	Funding in ₹ cr (p.a)
Projects							
ALICE + STAR	15	100	19	150	20	150	15
CERN Associate Membership# (50 %)	40	##	40	##	40	##	40
FAIR (Experiment)	45 (for 2 years)	70	8	120	30	170	30
FAIR Accelerator O&M Cost		##	115	##	70	##	70
Experiments @EIC	N.A	45	10	90	25	130	30
INGA	N.A	70	10	110	40	150	60
ELI-NP	N.A	10	3	15	5	25	10
Utilization of International Low Energy Nuclear Physics Facility	N.A	30	5	50	7	60	10
Plasma Related Systems	N.A	148	237	43	461	43	424
P3	N.A	20	20	20	20	20	20
Other new ideas incl. Tin.Tin & ISMRAN)	N.A		50		70		100
Facilities							
National Detector Development and Training Centre	N. A.	20	10		30		10
HPC (NP+HEP)	(ILGTI+ Grid)	350	200	450	240	550	300
HPC (Plasma)	N.A.	150	75	150	100	150	150
Grand Total			802		1158		1269

ITER Funding Requirements:

In addition to the above projects and facilities, we separately give below the funding requirements for the ITER (International Thermonuclear Experimental Reactor) project, as it is a mega technology project. The ITER requirements have not been included in the "prioritized landscape" detailed on the next three pages.

	Current sanctioned annual budget in ₹ cr	2020-25		2025-30		2030-35	
		Number of users	Funding in ₹ cr (p.a)	Number of users	Funding in ₹ cr (p.a)	Number of users	Funding in ₹ cr (p.a)
ITER	625	130	2228	150	400	200	400

(The monetary estimates are based on 2020 as the Base Year. The figures quoted above have the inherent inflationary and FE rate uncertainties.)

The other 50% has been accounted for in the MSV-2035-High Energy Physics document.

It involves not only the scientists who are direct collaborators, but also a large number of students and industry personnel indirectly involved, whose number is hard to quantify.

A PRIORITIZED LANDSCAPE: 2020-2025

Modest Growth Scenario (All amounts in Rs crore p.a.)	Rs. (Cr)	Aspirational Growth Scenario (All amounts in Rs crore p.a.)	Rs. (Cr)
Total Required Funding (p.a.)	385	Total Required Funding (p.a.)	802
Ongoing projects	192	Ongoing projects	192
High-temperature QCD	59	High-temperature QCD	59
(1) ALICE	19	(1) ALICE	19
(2) CERN Associate Membership	40	(2) CERN Associate Membership	40
Nuclear structure, reactions, high-density QCD	133	Nuclear structure, reactions, high-density QCD	133
(1) FAIR	123	(1) FAIR	123
(2) INGA	10	(2) INGA	10
Plasma		Plasma	
(1) ITER #		(1) ITER #	
New projects / activities	193	New projects / activities	610
High-temperature QCD	10	High-temperature QCD	10
(1) Experiments @ EIC	10	(1) Experiments @ EIC	10
Nuclear structure, reactions, high-density QCD	8	Nuclear structure, reactions, high-density QCD	8
(1) ELI-NP	3	(1) ELI-NP	3
(2) Consortium for Int'l facilities	5	(2) Consortium for Int'l facilities	5
Plasma	80	Plasma	257
(1) Plasma-related systems	60	(1) Plasma-related systems	237
(2) Plasma Programme for People (P^3)	20	(2) Plasma Programme for People (P^3)	20
Eco-System Building Activities	80	Eco-System Building Activities	285
(1) Detector Development Centre (NDDTC)	10	(1) Detector Development Centre (NDDTC)	10
(2) HPC-NP&HEP	50	(2) HPC-NP&HEP	200
(3) HPC-plasma	20	(3) HPC-plasma	75
Other new ideas (incl. Tin.Tin, ISMRAN, DLS)	15	Other new ideas (incl. Tin.Tin, ISMRAN, DLS)	50
The projects above are based on the foundations built through past scientific investments and are geared towards a thorough understanding of the complex structure of nuclei under extreme conditions, reactions dynamics in different energy ranges and properties of nuclear matter under conditions close to different astrophysical scenarios. These are science questions that are globally recognized and are required to be addressed in the coming decade. For details of these projects, see Sec. 3.1.1 (STAR+ALICE), 3.1.3 (FAIR), 3.1.4 (INGA), 3.2.1 (EIC), 3.2.2 (ELI-NP), 2.7 (Plasma-related systems), 4.2.4 (P^3), 3.3.1 (Tin.Tin), 3.3.2 (ISMRAN), 5.4 (NDDTC), 2.6 (HPC)		In order to become a global scientific leader in the area of nuclear physics, the country should invest in creation of adequate infrastructure, technological capacity-building, and a vibrant ecosystem for research and industry participation. This scientific investment would also help in creating a robust knowledge base, achieving self-reliance, and lead to multiple societal applications in the fields of agriculture, medicine, environment, security, etc. For details of these projects, see Sec. 3.1.1 (STAR+ALICE), 3.1.3 (FAIR), 3.1.4 (INGA), 3.2.1 (EIC), 3.2.2 (ELI-NP), 2.7 (Plasma-related systems), 4.2.4 (P^3), 3.3.1 (Tin.Tin), 3.3.2 (ISMRAN), 1.3.3 (DLS), 5.4 (NDDTC), 2.6 (HPC)	

Since ITER is a mega technology project to generate energy from a large fusion reactor, its funding has not been included in the Prioritized Landscape.

A PRIORITIZED LANDSCAPE: 2025-2030

Modest Growth Scenario (All amounts in Rs crore p.a.)	Rs. (Cr)	Aspirational Growth Scenario (All amounts in Rs crore p.a.)	Rs. (Cr)
Total Required Funding (p.a.)	703	Total Required Funding (p.a.)	1158
Ongoing projects	180	Ongoing projects	200
High-temperature QCD	60	High-temperature QCD	60
(1) ALICE	20	(1) ALICE	20
(2) CERN Associate Membership	40	(2) CERN Associateship Membership	40
Nuclear structure, reactions, high-density QCD	120	Nuclear structure, reactions, high-density QCD	140
(1) FAIR	100	(1) FAIR	100
(2) INGA	20	(2) INGA	40
Plasma		Plasma	
(1) ITER #		(1) ITER #	
New projects / activities	523	New projects / activities	958
High-temperature QCD	25	High-temperature QCD	25
(1) Experiments @ EIC	25	(1) Experiments @ EIC	25
Nuclear structure, reactions, high-density QCD	12	Nuclear structure, reactions, high-density QCD	12
(1) ELI-NP	5	(1) ELI-NP	5
(2) Consortium for Int'l facilities	7	(2) Consortium for Int'l facilities	7
Plasma	251	Plasma	481
(1) Plasma-related systems	231	(1) Plasma-related systems	461
(2) Plasma Programme for People (P^3)	20	(2) Plasma Programme for People (P^3)	20
Eco-System Building Activities	200	Eco-System Building Activities	370
(1) Detector Development Centre (NDDTC)	30	(1) Detector Development Centre (NDDTC)	30
(2) HPC-NP&HEP	120	(2) HPC-NP&HEP	240
(3) HPC-plasma	50	(3) HPC-plasma	100
Other new ideas (incl. Tin.Tin, ISMRAN, DLS)	35	Other new ideas (incl. Tin.Tin, ISMRAN, DLS)	70
The projects above are based on the foundations built through past scientific investments and are geared towards a thorough understanding of the complex structure of nuclei under extreme conditions, reactions dynamics in different energy ranges and properties of nuclear matter under conditions close to different astrophysical scenarios. These are science questions that are globally recognized and are required to be addressed in the coming decade.		In order to become a global scientific leader in the area of nuclear physics, the country should invest in creation of adequate infrastructure, technological capacity-building, and a vibrant ecosystem for research and industry participation. This scientific investment would also help in creating a robust knowledge base, achieving self-reliance, and lead to multiple societal applications in the fields of agriculture, medicine, environment, security, etc.	
For details of these projects, see Sec. 3.1.1 (STAR+ALICE), 3.1.3 (FAIR), 3.1.4 (INGA), 3.2.1 (EIC), 3.2.2 (ELI-NP), 2.7 (Plasma-related systems), 4.2.4 (P^3), 3.3.1 (Tin.Tin), 3.3.2 (ISMRAN), 5.4 (NDDTC), 2.6 (HPC)		For details of these projects, see Sec. 3.1.1 (STAR+ALICE), 3.1.3 (FAIR), 3.1.4 (INGA), 3.2.1 (EIC), 3.2.2 (ELI-NP), 2.7 (Plasma-related systems), 4.2.4 (P^3), 3.3.1 (Tin.Tin), 3.3.2 (ISMRAN), 1.3.3 (DLS), 5.4 (NDDTC), 2.6 (HPC)	

Since ITER is a mega technology project to generate energy from a large fusion reactor, its funding has not been included in the Prioritized Landscape.

A PRIORITIZED LANDSCAPE: 2030-2035

Modest Growth Scenario (All amounts in Rs crore p.a.)	Rs. (Cr)	Aspirational Growth Scenario (All amounts in Rs crore p.a.)	Rs. (Cr)
Total Required Funding (p.a.)	752	Total Required Funding (p.a.)	1269
<u>Ongoing projects</u>	<u>185</u>	<u>Ongoing projects</u>	<u>215</u>
High-temperature QCD	55	High-temperature QCD	55
(1) ALICE	15	(1) ALICE	15
(2) CERN Associate Membership	40	(2) CERN Associate Membership	40
Nuclear structure, reactions, high-density QCD	130	Nuclear structure, reactions, high-density QCD	160
(1) FAIR	100	(1) FAIR	100
(2) INGA	30	(2) INGA	60
Plasma		Plasma	
(1) ITER #		(1) ITER #	
<u>New projects / activities</u>	<u>567</u>	<u>New projects / activities</u>	<u>1054</u>
High-temperature QCD	30	High-temperature QCD	30
(1) Experiments @ EIC	30	(1) Experiments @ EIC	30
Nuclear structure, reactions, high-density QCD	20	Nuclear structure, reactions, high-density QCD	20
(1) ELI-NP	10	(1) ELI-NP	10
(2) Consortium for Int'l facilities	10	(2) Consortium for Int'l facilities	10
Plasma	232	Plasma	444
(1) Plasma-related systems	212	(1) Plasma-related systems	424
(2) Plasma Programme for People (P^3)	20	(2) Plasma Programme for People (P^3)	20
Eco-System Building Activities	235	Eco-System Building Activities	460
(1) Detector Development Centre (NDDTC)	10	(1) Detector Development Centre (NDDTC)	10
(2) HPC-NP&HEP	150	(2) HPC-NP&HEP	300
(3) HPC-plasma	75	(3) HPC-plasma	150
Other new ideas (incl. Tin.Tin, ISMRAN, DLS)	50	Other new ideas (incl. Tin.Tin, ISMRAN, DLS)	100
The projects above are based on the foundations built through past scientific investments and are geared towards a thorough understanding of the complex structure of nuclei under extreme conditions, reactions dynamics in different energy ranges and properties of nuclear matter under conditions close to different astrophysical scenarios. These are science questions that are globally recognized and are required to be addressed in the coming decade. For details of these projects, see Sec. 3.1.1 (STAR+ALICE), 3.1.3 (FAIR), 3.1.4 (INGA), 3.2.1 (EIC), 3.2.2 (ELI-NP), 2.7 (Plasma-related systems), 4.2.4 (P^3), 3.3.1 (Tin.Tin), 3.3.2 (ISMRAN), 5.4 (NDDTC), 2.6 (HPC)		In order to become a global scientific leader in the area of nuclear physics, the country should invest in creation of adequate infrastructure, technological capacity-building, and a vibrant ecosystem for research and industry participation. This scientific investment would also help in creating a robust knowledge base, achieving self-reliance, and lead to multiple societal applications in the fields of agriculture, medicine, environment, security, etc. For details of these projects, see Sec. 3.1.1 (STAR+ALICE), 3.1.3 (FAIR), 3.1.4 (INGA), 3.2.1 (EIC), 3.2.2 (ELI-NP), 2.7 (Plasma-related systems), 4.2.4 (P^3), 3.3.1 (Tin.Tin), 3.3.2 (ISMRAN), 1.3.3 (DLS), 5.4 (NDDTC), 2.6 (HPC)	

Since ITER is a mega technology project to generate energy from a large fusion reactor, its funding has not been included in the Prioritized Landscape.

ANNEXURE A.3:

INDUSTRY PARTICIPATION IN MSP'S

Several industries within India have been involved in the hardware projects or product development for mega science nuclear and plasma physics experiments in India as well as abroad. A selected list of industry participation in such projects is given in the tables below.

Table A.1: Industry participation in MSPs in nuclear physics

Industry	Nature of contribution	Project	Remarks
Gladstone Engineering Industries, Kolkata	Fabrication of honeycomb structures for Photon Multiplicity Detector (PMD) modules	ALICE and STAR	Cost-efficient product for a multi-channel detector
Micropack Private Limited, Bengaluru	Readout Printed Circuit Boards (PCB) for PMD, GEM foil	ALICE and CMS	New capacity for MPGDs and PCB for multichannel detectors
Hi_Q Electronics Pvt. Ltd., Bengaluru	Readout PCBs for muon station	ALICE	Cost-effective PCBs for gas-based detectors
SCL-ISRO, Chandigarh	Fabrication of MANAS ASIC	ALICE	New capacity developed for frond end electronics
Shogini Technoarts, Pune	Readout PCB	ALICE	Cost-effective PCBs
Graphite India Ltd., Bangalore	Fabrication and supply of a high-density graphite component of the front absorber of the ALICE muon system	ALICE	High quality product of international standards
BEL, Bangalore	Silicon sensors, Si-preshower	ALICE and CMS	Capacity building in silicon detector technology
Focustech Ltd., Gurgaon	CROCUS assembly	ALICE	New product line created
Steel Authority of India, Ranchi	Fabrication and supply of non-magnetic stainless-steel ingot for the front absorber of ALICE muon system.	ALICE	High quality product of international standards
FlexTech Ltd., Hyderabad	Fabrication of rigid and flexible PCBs for the Muon chambers of the 2nd tracking station	ALICE	High quality and cost-efficient product
Magnacon Pvt. Ltd., Kolkata	Machining of PEEK GF- 30 for the frames of the muon chambers	ALICE	High precision techniques
Narendra & Narendra, Howrah	Machining of stainless-steel ingots	ALICE	New product line developed

IGTR, Indore	Accelerator Equipment	CERN Accelerator	High quality products of international standards
Avasarala Industries, Bengaluru	Accelerator equipment	CERN Accelerator	High quality products of international standards
ECIL, Hyderabad	Accelerator equipment	CERN Accelerator	High quality products of international standards
EXCEL Instruments	Beam line devices	BARC-TIFR PLF, Mumbai	Vendor is now developing vacuum systems for many universities in India
SMP Enterprises, Pune	Vacuum and slit components	BARC-TIFR PLF, Mumbai	Capacity building for high quality product
Fillunger	Vacuum and slit components	BARC-TIFR PLF, Mumbai	High quality and cost-efficient product
Dewang Electronic	Electronics	BARC-TIFR PLF, Mumbai	Capacity building for high quality product
Vacuum techniques	Vacuum components	BARC-TIFR PLF, Mumbai	Capacity building for high quality product
Kamal Engineering	Ion pumps and power supply	BARC-TIFR PLF, Mumbai	Technology developed in BARC was transferred
ECIL	Crate, units	BARC-TIFR PLF, Mumbai	High quality and cost-efficient product
Bharat electronics	RF electronics	BARC-TIFR PLF, Mumbai	High quality and cost-efficient product
VK Industries	Nb cavity	BARC-TIFR PLF, Mumbai	Capacity building for high quality product
HIND HIVAC	Scattering chamber	BARC-TIFR PLF, Mumbai	High quality and cost-efficient product
Bit Mapper	DAQ	EXOGAM, GANIL	High quality products of international standards
Sai Sri Precision Engineering	Precision Mechanics	NUSTAR, FAIR	High quality products of international standards
Eta Plast	INGA Stand	INGA	Capacity building for high quality product
Design Tech	Structural analysis	NUSTAR, FAIR	High quality and cost-efficient product
Vacuum Techniques, Bengaluru	RF Linac and HV/UHV components	VEC-RIB	High quality products of international standards
Gauss Magnetics, Kalyani	Permanent Magnets	VEC-RIB	Capacity building for high quality product
Fourvac, Pune	HV chambers	VEC-RIB	Capacity building for high quality product
IClean, Hyderabad	Clean-room	VEC-RIB	Capacity building for high quality product

Inox CVA, Baroda	Vertical Cryostat	IIFC-VEC	Capacity building for high quality product
Heavy-engg, Ranchi	Magnet components	SCC-VEC	Capacity building for high quality product
Patel Ind., Pune	SC Coil winding machine	SCC-VEC	Capacity building for high quality product
SAMEER, Mumbai	RF Amplifiers	VEC-RIB	High quality products of international standards
ECIL, Hyderabad	Solid State RF Amplifier (BARC Tech)	IIFC-BARC	High quality products of international standards

Table A.2: Knowledge intangibles gained by Indian industries in new products/technologies while working for ITER deliverables complying with international norms of performance, quality, reliability, safety and environmental standards.

Name of Industry	Relevant Contract	New Developments	Remarks
M/s L&T, Hazira	Manufacturing of ITER Cryostat	• Very large Vacuum Vessel (~30 m diameter and ~30 m height) with strict tolerances (0.33 %). • Thick plate welding (200 mm) with distortion control. • Compliance to French Nuclear Safety requirements. • Novel nondestructive testing technique for weld qualification.	First heavy nuclear component supplied to Europe, creating potential for positioning M/s L&T as a nuclear components manufacturer at the global level.
M/s Kiroloskar Chillers Pvt. Ltd.	Subcontracted by L&T, Chennai for chillers required for the ITER cooling water system contract	• Largest capacity (4 MW) chillers developed in India	Enhanced capacity product line compliant to European norm.
M/s Paharpur Cooling Towers Ltd.	Subcontracted by L&T, Chennai for cooling towers for ITER cooling water system contract	• Largest capacity (510 MW) cooling towers developed in India	New capacity of FRP fin cooling tower compliant to European norms.
M/s L&T, Chennai	ITER cooling water system	• Designed according to European regulatory compliance • Unique pipe-in-pipe concept developed for buried pipe spools without trench.	Potentially cost-efficient design solution for large process plants.
M/s Inox India Ltd., Vadodara	ITER Cryolines and Warm-lines	• Multi-process (up to six) pipe cryogenic transfer line • Novel decoupling system for seismic (SL-2 event) installation	New product line and additional facility/capacity created. The seismic decoupling technology has been patented.
NFTDC, Hyderabad	Material development for neutral beam technologies	• High strength, weld-able copper alloy (CuCrZr) with precision control of ingredients for high-temperature use	Novel process developed, potentially useful for high-temperature components.
M/s Precihole Machine tools, Pune	Subcontracted by NFTDC	• Deep drilled (1.8 m) with less than 500 μ drift in copper alloy.	Potential capacity for manufacturing of precision equipment created.
M/s Asaco, Hyderabad	Subcontracted by NFTDC	• Dis-similar and similar metal welded joints using electron beam welding.	

M/s Magod Laser Pvt Ltd., Pune	R&D under BRFST outreach	• Self-correcting Laser welded metal Lip seal joints for vacuum application	
M/s Vacuum Technique, Bangalore	Fabrication contract for diagnostic neutral beam R&D vessel, Prototype high voltage bushing, Tokamak cryopump housing	• Ultra-high vacuum (UHV) class vacuum vessels of 4.5 m diameter and 9 m length.	Capacity generated for manufacturing of large volume UHV class vacuum vessel and scientific equipment.
M/s Aditya High Vacuum, Ahmedabad	Development of High-power RF components for ICRF source: 12-inch transmission line 12-inch 3 dB combiner, (4 ports) 12-inch 3 port SPDT switch	• Import substitute for passive RF components	Capacity generated for manufacturing high-power RF components.
M/s India flex Engineering, Ahmedabad	Development of 12-inch assembly bellow for RF testing		
M/s V L Sons, Ahmedabad	Development of 12-inch 4-port directional coupler for RF testing		
M/s Creative Engineering, Ahmedabad	Development of 12-inch gas barrier for RF testing		
M/s Vikram Engineering works, Ahmedabad	Development of finger contact for stub RF testing		
M/s Nilyash Engineering, Pune	Development of finger contact for IC joint RF testing		
M/s Raut Uni-Tech Private Ltd, Dahanu	Development of 12-inch 6-port directional coupler for RF testing		
M/s ECIL, Hyderabad	Development of high-voltage power supplies	• 3 MW, dual output 27 kV/18 kV modular high-voltage power supply with fast dynamics. • 7.2 MW, 100 kV modular high-voltage power supply with fast dynamics. • Conformance of products to European regulations	New product line developed, potential for both domestic use as well as export.
M/s Transformers and Rectifiers India Ltd., Ahmedabad	Subcontract from M/s ECIL	• High power (MVA rated), 100 kV class multi-secondary (50 secondaries) oil-filled transformers conforming the European regulations	New product line developed, potential for both domestic use as well as export.
M/s Ames Impex Electricals Pvt Ltd., Ahmedabad	Subcontract from M/s ECIL	• High power (MVA rated) multi-secondary (50 secondaries) cast resin transformers	New product line developed, potential for both domestic use as well as export.
M/s Raychem, Pune	Development of cast resin transformer	• High power (MVA rated) multi-secondary (50 secondaries) cast resin transformers	New product line developed, potential for both domestic use as well as export.

M/s Amtech Electronics (India Pvt Ltd.), Gandhinagar	Subcontract from M/s ECIL	• Compact switch power supply modules up to 130 kW, compliant to European norms • 40 kW, 1 MHz modular solid-state RF generator • Fiber-optic trans-receiver form signals up to 300 kHz bandwidth, compliant to European norms	New products developed potential for both domestic use as well as export. Enhanced competence in meeting regulatory compliances.
M/s Agni Fibers Pvt Ltd., Baroda	High Voltage Structural Fabrication	• Large-size (4000 × 1500 × 4000 mm), Intra-woven FRP structures with HVDC isolation up to 140 kV DC	Competence for structures of special application
M/s Shell N Tubes, Pune		• 650/1500 mm coaxial transmission line of 140 kVDC class, for 10 MW electrical power besides RF transmission and hydraulic lines	Competence for structures of special application
M/s Hitachi Ltd., Delhi		• Development of large-size (800/600/55 mm) nanocrytalline magnetic cores for energy suppression	New product developed
M/s Technocables, Hyderabad		• Development of high-voltage coaxial cable with screen (33 kV class and RG220 versions)	New product developed
M/s Torrent cables Ltd., Nadiad		• Development of high-voltage short circuit switch (motorized) for 120 kV applications	New product developed

Notes:
1) Access to ITER documents created by contribution of all members over 30 years would be of immense value for domestic research and assigning any value to it might not be desirable or possible.
2) Data on actual revenue earned by industries from intangible gains from ITER participation is not available.

Participation of Indian industry in the global supply-chain system for MSPs

The participation of Indian industry as indicated in the tables above is through the collaborating institutions in the global mega projects. However, a globally competitive industry with large-scale manufacturing capacity can also participate directly as a supplier of complex technological items meeting international standards. Such a direct participation of Indian industry in MSPs is growing and the returns obtained by the industries have been increasing. While it is difficult to quantify the financial returns to industry in the absence of publicly available data, we point out below the examples of CERN and ITER-India, two of the mega projects with significant Indian investment.

Participation of Indian industry in the CERN projects

As a result of India's long-time collaboration with CERN programmes, and its well-recognized and valuable contributions to the construction of LHC as well as the CMS and ALICE detectors, India first acquired an Observer status, and then an Associate Member status, on the CERN Council. After India became an Associate Member, Indian industry could bid directly for CERN's tenders for supplying items to CERN *outside the ambit of the project-specific in-kind contributions*. The process is slowly picking up, with Indian industry getting into the CERN supply-chain system and competing with their European and global counterparts.

Since 2019, nearly 60 companies have participated in the CERN tendering process, out of which 15 have received offers/contracts. As of Jan 2023, about 90 companies have registered themselves with the CERN e-procurement website. Indian companies have mainly contributed in the areas of electrical engineering, information technology, electronics, cryogenic and vacuum equipment, mechanical engineering, raw materials and other industrial facilities. The products range from surgical masks during Covid times to complex PCBs and large argon storage tanks. A list of some Indian industry contributions to CERN is given below.

- Nearly 240 km of flexible low-voltage multicore copper cables were delivered by Polycab, Vadodara.
- Development, customization and migration of 9 CERN websites from Drupal ver.7 to Drupal ver.8 was carried out by Singsys, Lucknow.
- PCBs with complexities ranging from simple to very complex boards, with many layers, high frequencies and small vias by Micropack, Bangalore.
- Delivery of 57 vacuum vessels, 22 jumper vessels and 24 dish covers (total 103 units) were completed by Inox, Vadodara. They also delivered a cryogenic tank for liquid argon storage. Inox qualified for a large value contract for the supply of two cryogenic distribution lines for the HL-LHC project. However, they lost it in competitive bidding.
- SPS BTV optical line was fabricated and delivered by Macseal, Navi Mumbai.
- Precision machined components and elbows with flanges for SPS Cavities were supplied by Deccan Engineering Works, Nasik and IDEMI, Mumbai, respectively.
- Bellow expansion joints and flexible hoses for HL-LHC were delivered by Metallic Bellows, Chennai.
- Design, supply and installation of two modular ISO7 clean rooms for assembly and testing of the CMS HGCAL detector modules is being carried out by Cadillac Filters, Kolkata.

The overall value of offers/contracts received from CERN by Indian companies during 2019-2022 is nearly INR 60 crore.

Participation of Indian industry in the ITER Project

ITER-India is the domestic agency (special project) created under Institute for Plasma Research by DAE for the execution of the in-kind scope of the work as per the Joint Implementation agreement of ITER. The packages to be delivered as in-kind contribution to ITER are the cryostat, vacuum vessel in-wall shields, cryodistribution & cryolines, cooling water systems, Ion Cyclotron Resonant Heating (ICRH) and Current Drive (CD), Electron Cyclotron Resonant Heating (ECRH), diagnostics, power supplies for ICRH, ECRH, diagnostic neutral beam systems and neutral beam. The total expenditure incurred (till 31 March 2023) for delivering this in-kind scope is around INR 3600 cr. Out of this, nearly 60% contracts have been won by Indian industries.

Apart from delivering its in-kind scope, ITER-India has made efforts for direct involvement of Indian industries in ITER procurement. The efforts of ITER-India have created enough enthusiasm and momentum among Indian industries to bid for ITER works and has resulted in successful utilization of the opportunities of participation in ITER. Indian industry has been particularly successful in becoming a major part of the ITER Project Associates (IPAs: 153 Indian staff out of 246), a short-term Technical Service team providing expert engineering and management services for installation-related activities. After the introduction of a small team with active persuasion with both ITER and industries, these service industries have now successfully created their own niche by their high-quality service.

The Indian manufacturer of cryostats, following the success of its performance in earlier cryostats, has also won a multimillion Euro subcontract for final welding/assembly of the main vacuum vessel, after active dialogue with stakeholders. All possible avenues have been attempted to ensure that Indian industries participate and qualify in ITER bidding. In specific cases, when the qualification of a particular Indian industry within a short time is not possible, DAE organizations bid directly and get the work done through the Indian industry.

Among the Software Service companies, European Subsidiaries of Indian multinationals (e.g., M/s TCS, M/s HCL, etc.) too are actively participating in ITER activities and winning significant orders in the past few years. Starting with the nomination by ITER-India, these companies have been able to establish themselves quickly in the ITER environment.

A short summary of these additional benefits, by way of direct and indirect contracts from the larger ITER Project (i.e. outside the ITER-India Project commitments) and IPAs, is given in table below.

S. No.	Legal entity	Total Value of contracts (EUROs)
1.	Directly from ITER on Indian company	15,512,407
2.	Directly from ITER on European-subsidiary of Indian company	45,437,038
3.	Major Sub-Contracts on Indian company	27,000,000
	Total	87,949,445

(as on 31.12.2022)

Not included above is the remuneration of approx. 140 IPAs (on an average) from Indian Industry providing technical services at ITER since 2019. Their remuneration value is in the range of 7000-9000 Euros/month/person, implying a revenue of 12 to 15 M Euros per annum earned by the Indian industry.

Thus, the total value of contracts earned by Indian companies from the larger ITER Project (i.e. beyond the ITER-India Project commitments) is about Rs. 1000 cr. after conversion of currency.

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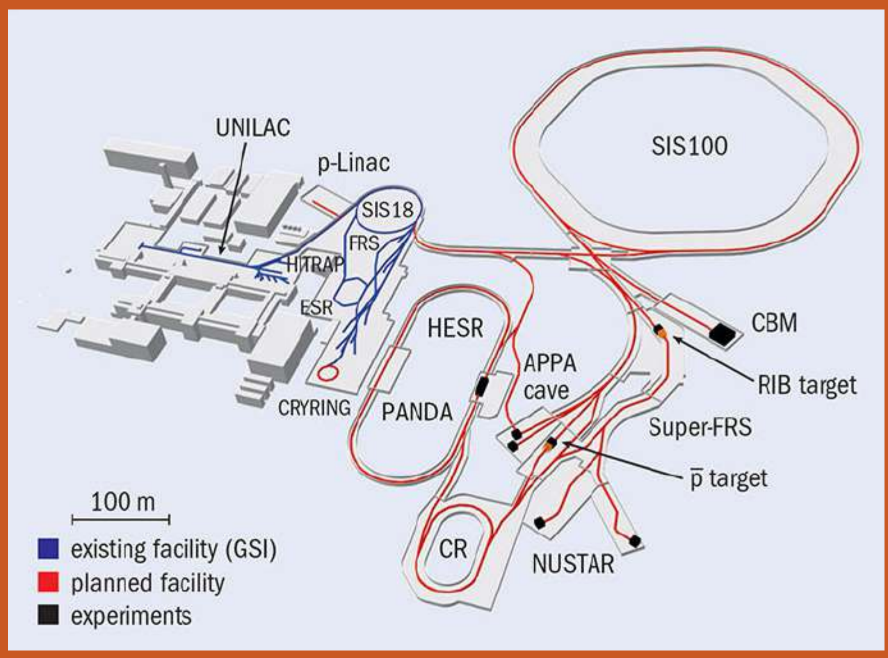
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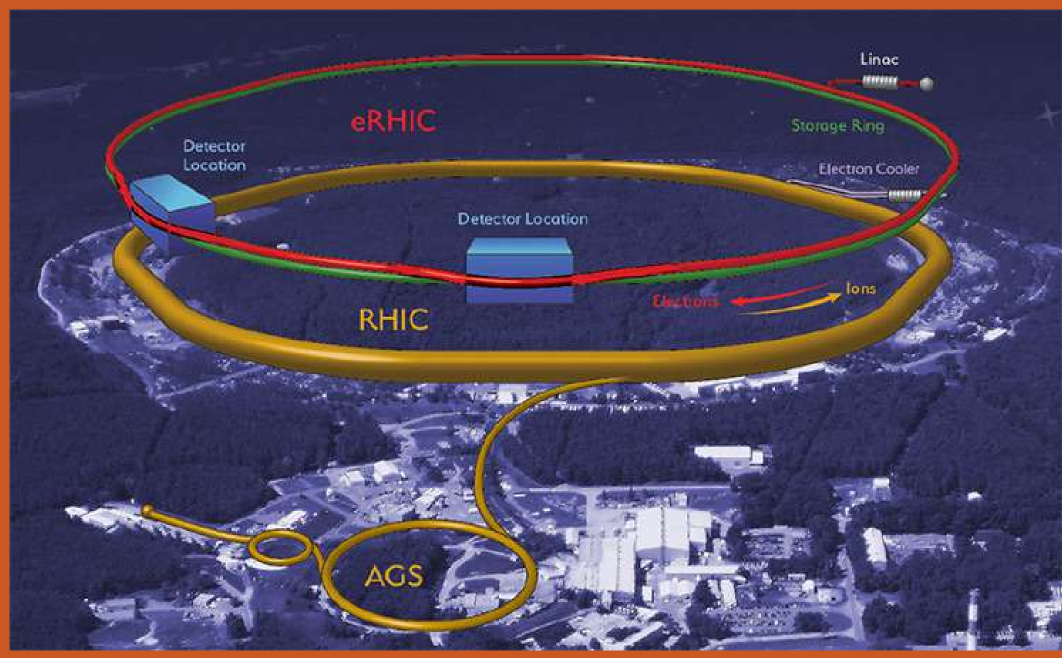
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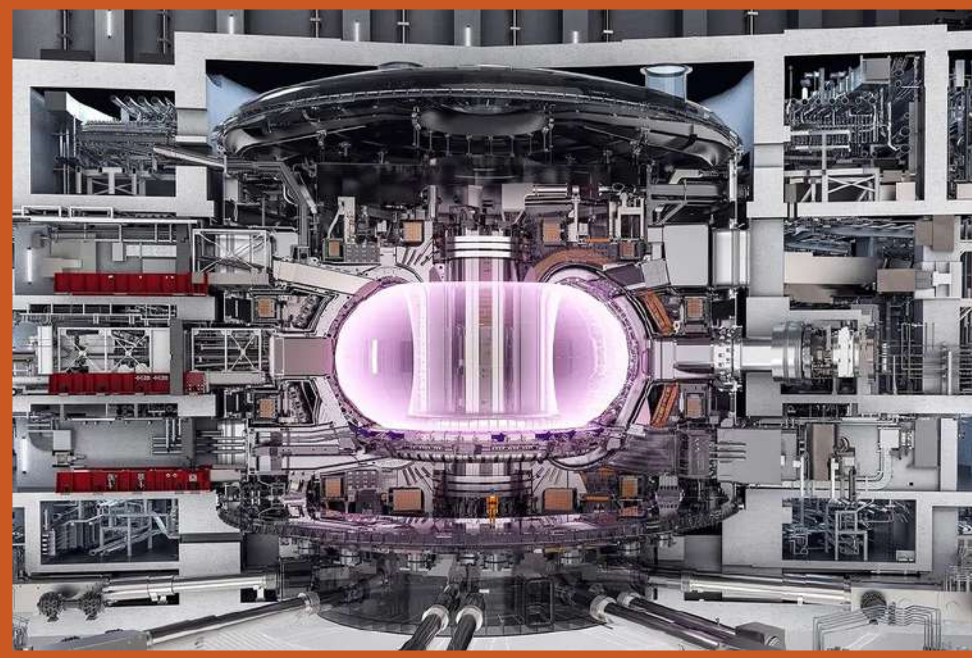

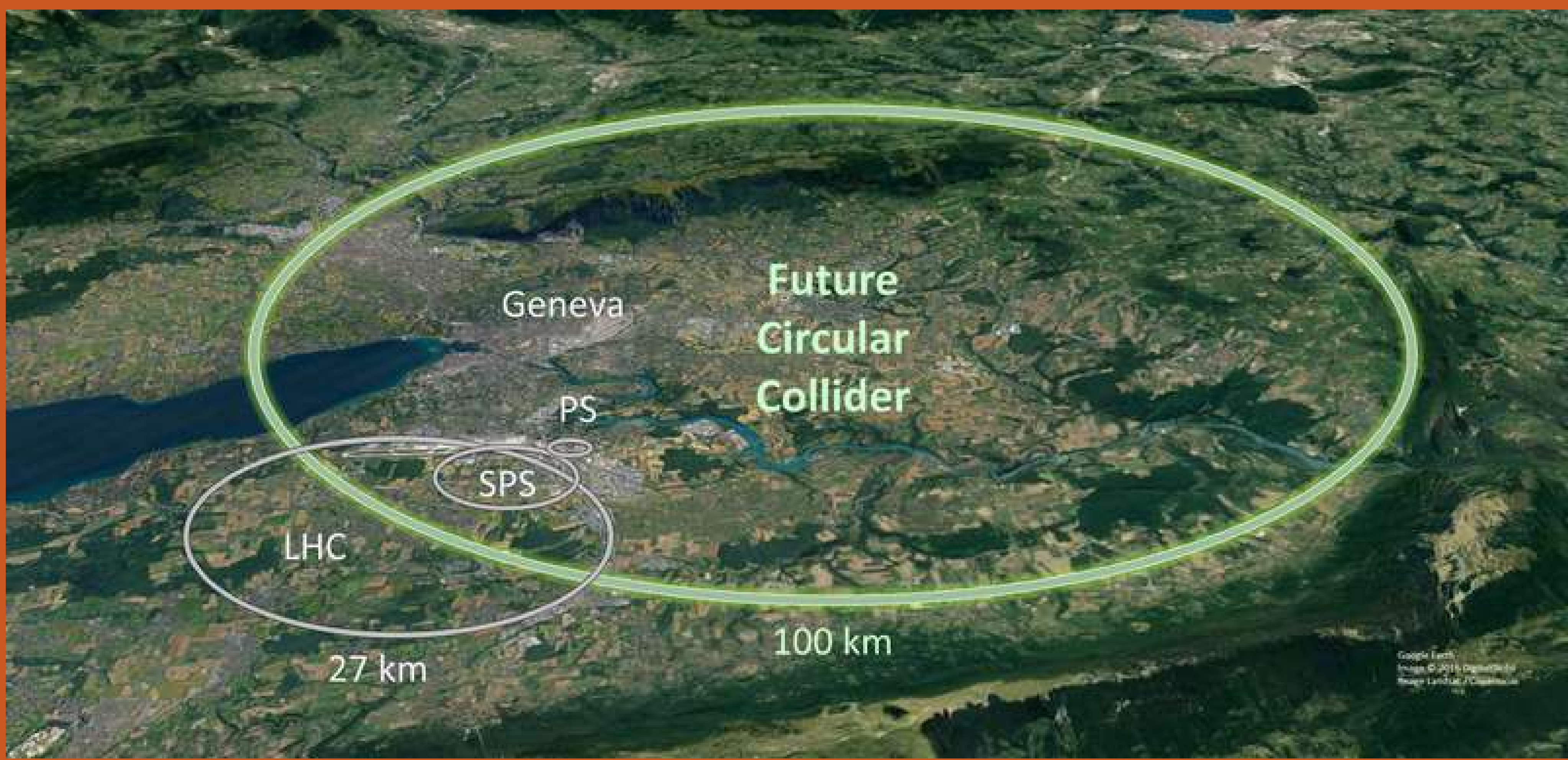
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