# NUCLEAR HORIZONS

(A Bulletin of the Indian Nuclear Physics Association)

**ADVANCING FUNDAMENTAL AND APPLIED NUCLEAR SCIENCE FOR A SELF-RELIANT INDIA**

**Volume 1 | Issue 2 | Year 2026**

## Aligned with Atmanirbhar Bharat



**The release of the inaugural issue of Nuclear Horizons by the Vice Chancellor Prof. A. K. Chaturvedi, BHU, Varanasi.**

PUBLISHED BY

**INDIAN NUCLEAR PHYSICS ASSOCIATION (INPA)**

JUNE 2026

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The Indian Nuclear Physics Association (INPA) gratefully acknowledges the guidance and support of the Advisory Committee. Their expertise will strengthen research, education, collaboration, and outreach in nuclear science, and help position INPA as a national platform of excellence.

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# President's Address



**Dear Colleagues and Friends,**

It gives me immense pleasure to address you through the second issue of our bulletin *"Nuclear Horizons"*. The journey of the Indian Nuclear Physics Association (INPA) has begun with great enthusiasm and a strong sense of purpose. Following the inauguration of INPA at Banaras Hindu University and the release of the inaugural issue of *Nuclear Horizons* by the Hon'ble Vice-Chancellor of BHU, Prof. A. K. Chaturvedi, we moved ahead with the formal registration of INPA as a society.

A major part of this important work was spearheaded by our dear colleague Prof. B. P. Singh, who carried out the responsibilities with exceptional dedication, commitment, and urgency. We were delighted to receive the certificate of registration of INPA on 2 May 2026, marking a significant milestone in the history of our association.

Soon thereafter, Prof. B. P. Singh proceeded on medical leave for a heart surgery. In a deeply unfortunate turn of events, he could not recover from complications following the surgery and passed away on 31 May 2026. His untimely demise is an irreparable loss to the entire nuclear physics community and a major setback for INPA in its formative phase. For many of us, it is also a profound personal loss. Through this issue, we remember Prof. B. P. Singh with deep respect and affection and pay our heartfelt tribute to his invaluable contributions and his vision for INPA.

We have made sincere efforts to carry forward the responsibilities entrusted to us and to fill the immense void created by his absence. This is indeed a challenging task, as Prof. Singh had been playing multiple crucial roles in shaping the activities of INPA. As an immediate step, we have appointed Prof. Soumya Bagchi, IIT Dhanbad, as the new Chief Editor of *Nuclear Horizons*. We have also welcomed Dr. Aniruddha Dey, JINR Dubna, as a new member of the Editorial Board. We extend our warm welcome to both of them.

The Editorial Board will continue to expand and strengthen the scope and reach of *Nuclear Horizons*. We envision the bulletin as an important platform for communication, collaboration, and knowledge exchange among the nuclear physics community in India and beyond. The Editorial Board has also initiated a monthly seminar series entitled **"INPA Young Scientist Colloquium"**, where outstanding research contributions by young scientists will be highlighted and shared with the wider community.

The Executive Committee has recently taken important steps towards strengthening the organizational structure of INPA. Prof. Manoj Kumar Sharma, University of Lucknow, has been elected as the new Executive Secretary of INPA. Manoj is a dynamic young scientist whose enthusiasm and commitment will greatly contribute to the growth of INPA and the advancement of nuclear physics in India. We have also elected Prof. M. Balasubramaniam, Coimbatore, as a member of the Executive Committee. We warmly welcome both of them and look forward to their valuable contributions.

This issue of *Nuclear Horizons* contains a rich collection of articles covering the history, science, technology, and applications of nuclear science, along with several inspiring contributions from young researchers. The messages from Prof. R. Prasad and Prof. S. Kailas provide valuable guidance and encouragement to the community. The article of Prof. Amit Roy provides a timely reminder of setting up the right goals for the future. The article by Prof. R. Prasad and Prof. B.P. Singh cover the rich heritage of nuclear physics research at Aligarh.

The special article remembering Dr. Raja Ramanna, based on the book authored by Prof. D. K. Srivastava and Prof. V. S. Ramamurthy, brings forward many lesser-known aspects of his remarkable life and contributions. The feature articles by eminent nuclear scientists provide stimulating and insightful reading. The article on the role of symmetries in nuclei by Prof. B. K. Agrawal and collaborators highlights an important theme in contemporary nuclear physics. The account of the criticality achievement of the PFBR by Prof. G. Vaidyanathan presents an inspiring story of scientific and technological accomplishment.

We are also pleased to feature the emerging initiatives in nuclear science education and research at a university in Nagpur led by Prof. R. Pandey, Vice-Chancellor, and Prof. Uday Majumdar. The laboratory focus in this issue highlights VECC, Kolkata, through an informative article by Prof. Parnika Das. We have also included thesis summaries of two young researchers and two excellent contributions from young scientists working in colleges.

The focus article on nuclear technology, dealing with targeted alpha therapy, is a significant contribution by Prof. B. P. Singh, Dr. M. Shuaib, and Mr. Aquib Siddique. INPA sincerely thanks all the authors for their valuable contributions and the Editorial Board for their dedicated efforts in bringing out this issue successfully.

At present, we are working towards establishing an efficient distribution network so that *Nuclear Horizons* reaches all members in a timely manner. Initially, a limited number of printed copies will be circulated among authors and selected institutions to enhance visibility and outreach. This process is still evolving, and we hope to streamline it further in the coming months. It is encouraging that more than 500 colleagues from across the country have already joined the INPA community. We are committed to building an organization that serves all its members effectively and meaningfully.

Looking ahead, INPA plans to constitute several working groups to identify and develop future programmes. These groups will focus on preparing educational resources, developing course materials, designing laboratory courses for colleges and universities, and formulating strategies for future nuclear physics facilities in line with the recommendations of the Vision-2035 document. Creating awareness about nuclear science and its applications among students, educators, and the public will remain one of our important objectives.

I sincerely thank all members of the Executive Committee and the Editorial Board of INPA for their wholehearted support and dedication. I look forward to the valuable suggestions and continued support of all the members in our collective endeavour to strengthen nuclear physics in India.

**With warm regards,**



**(A. K. Jain)**

# From the Chief Editor's Desk



It is my privilege and pleasure to present the **Second Issue of *Nuclear Horizons***, the official bulletin of the Indian Nuclear Physics Association (INPA). This issue is being released on the occasion of the **Symposium on Particle–Gamma Coincidence Techniques in Nuclear Science (SPaGCoNS 2026)**, to be held from **13 to 15 July 2026**, a vibrant scientific gathering that brings together researchers, faculty members, students, and young scientists from across the country. Such meetings provide invaluable opportunities for scientific exchange, collaboration, and the generation of new ideas that continue to advance our discipline.

**SPaGCoNS 2026** focuses on an area of growing importance in contemporary nuclear physics. Particle–gamma coincidence measurements have become a powerful experimental tool for investigating nuclear structure, reaction mechanisms, nuclear astrophysics, and the properties of exotic nuclei. The symposium provides a forum to discuss recent scientific results, advances in detector technologies and instrumentation, emerging applications of machine-learning techniques, and future opportunities in experimental nuclear physics. It also offers an opportunity to assess the present status of particle–gamma coincidence measurements in India and to deliberate on future directions for experimental research, detector development, and facility development.

The publication of the first issue of *Nuclear Horizons* marked an important milestone in the journey of INPA. It reflected the collective aspirations of a community that recognized the need for a common platform to strengthen interactions, share concerns, and work together to advance nuclear physics in India. The encouraging response received from colleagues across universities, research institutes, and national laboratories has reaffirmed the relevance of this initiative and strengthened our resolve to carry it forward.

Scientific progress depends not only on research facilities and resources but also on a strong and connected community. Opportunities to exchange ideas, discuss challenges, and learn from one another are essential for the growth of any scientific discipline. INPA was established with this spirit in mind, and it is encouraging to see increasing participation from researchers, teachers, students, and young scientists in its activities.

Meetings such as **SPaGCoNS** play an important role in bringing the community together. They provide a platform for sharing research, initiating collaborations, and encouraging interactions across institutions and generations of scientists. For students and young researchers in particular, such gatherings offer valuable opportunities to learn, interact, and become part of the wider nuclear physics community. The symposium also brings together experts working on detector systems, electronics, data-acquisition techniques, and related applications, thereby encouraging discussions that

extend beyond individual experiments and contribute to the broader development of experimental nuclear physics in the country.

*Nuclear Horizons* seeks to contribute to this effort. More than a bulletin, it is intended to be a forum for sharing the achievements, activities, and aspirations of the Indian nuclear physics community. By documenting scientific events, highlighting community initiatives, and providing a space for discussion, the bulletin aims to strengthen communication within the community and foster a sense of collective purpose.

The **Mega Science Vision–2035 (Nuclear Physics)** document provides an important roadmap for the future development of our field. Achieving its goals will require sustained effort, collaboration, and active participation from the entire community. INPA can contribute to this process by promoting dialogue, encouraging cooperation, and serving as a platform that brings together nuclear physicists from across the country.

I take this opportunity to sincerely thank the contributors, reviewers, members of the Editorial Board, and all colleagues whose efforts have made this issue possible. Their support and dedication continue to strengthen both *Nuclear Horizons* and INPA.

**I invite all members of the community, including scientists, educators, researchers, and students, to actively participate in INPA activities and contribute to its mission. Together, through collaboration, mentorship, and shared commitment, we can strengthen our community and help shape the future of nuclear physics in India.**

**Dr. Soumya Bagchi**
**Associate Professor at IIT ISM Dhanbad**
**Chief Editor of INPA**

# Tribute to Prof. B. P. Singh



The Indian Nuclear Physics Association (INPA) records with profound grief and deep sorrow the untimely demise of Prof. B. P. Singh, Senior Professor, Department of Physics, Aligarh Muslim University, who passed away on 31 May 2026 at the age of 61 following complications arising from heart surgery.

The entire nuclear physics community is deeply shocked and saddened by the sudden loss of an outstanding scientist, distinguished academic, and cherished colleague. Prof. Singh was among the most dynamic and accomplished experimental nuclear physicists of India. Through his pioneering research, particularly in the field of incomplete fusion reactions, he made significant and internationally recognized contributions to nuclear physics and earned the respect and admiration of the scientific community across the world.

Prof. Singh played a pivotal role in the establishment of the Indian Nuclear Physics Association. As its founding General Secretary, he worked with exceptional dedication and commitment to ensure that all statutory and organizational formalities of the Association were completed successfully. Despite facing serious health challenges, he remained steadfast in his responsibilities and took great care to see that the inaugural issue of the INPA bulletin, *Nuclear Horizons*, was published before proceeding for medical treatment. His vision, energy, and tireless efforts laid a strong foundation for the growth and future of the Association.

An inspiring teacher and mentor, Prof. Singh guided and nurtured generations of students at the master and doctoral levels. His passion for teaching, commitment to academic excellence, and unwavering support for young researchers have left an enduring legacy that will continue to inspire the scientific community for years to come.

In his passing, the nation has lost an eminent scientist, the academic community a distinguished scholar, and INPA one of its principal architects and most dedicated leaders. His contributions to scientific research, higher education, and institution-building will be remembered with deep gratitude and admiration.

The members of the Indian Nuclear Physics Association convey their heartfelt condolences to the bereaved family, colleagues, students, and friends of Prof. B. P. Singh. His sudden and untimely departure has come as a profound shock to his wife, son, parents, brothers, and the entire extended family. At this moment of immense grief and sorrow, the members of INPA stand in solidarity with the bereaved family and assure them of their full support and sincere goodwill.

We pray that the family finds the strength and courage to bear this irreparable loss and that the cherished memories of Prof. Singh's life and achievements provide them comfort in the days ahead. We also pray to the God Almighty for the eternal peace of the departed soul.

(Prof. A.K. Jain)
President, INPA
On behalf of the executive and members of INPA

Dated 3 June 2026

# Messages from Senior Nuclear Physicists



**Professor R. Prasad**
*Retd. Professor, Experimental Nuclear Physics*
*Ex-Dean Faculty of Science & Chair, Department of Physics*
*Aligarh Muslim University, ALIGARH-202002, INDIA*

## MESSAGE

I extend my warm greetings to colleagues, students, and the entire nuclear physics community on the formation of the Indian Nuclear Physics Association (INPA). Many of us have devoted our lives to experimental nuclear physics. This moment carries special meaning to all of us. It feels like the beginning of a renewed journey.

Nuclear physics has always been more than an academic discipline. It strengthens our understanding of the atomic nucleus while quietly serving society, in healthcare, energy, agriculture, industry, and environmental studies. I am sure, in the coming decades, nuclear science and its applications will play an even greater role in addressing national and global challenges.

The recent news of criticality of the Prototype Fast Breeder Reactor (PFBR) at Kalpakkam is a proud milestone for India. It reflects decades of sustained effort by our scientists and engineers and stands as a testament to indigenous capability and scientific perseverance. Such achievements inspire confidence in the strength of our scientific community.

To young students, I would say, this is an exciting time to enter nuclear physics. It is a field where theory meets experiment, and curiosity meets real-world impact. Working with radiation detectors, particle accelerators, and instrumentation teaches patience, precision, and scientific honesty. An experimental nuclear physicist is like a detective who tries to decipher the properties of a nucleus from the study of its debris in a nuclear collision. Modern nuclear experiments require collaborative work, that strengthens the noble human qualities of being generous, curious, appreciative, flexible, inspiring, motivated, respectful and a good human being. These are the values that shape not only a researcher but responsible scientist as well.

I recall the early days of experimental nuclear physics, way back in 1960s, at the Physics Department, AMU Aligarh, when facilities were limited but enthusiasm was abundant. Instruments were built by hand, experiments were designed from scratch, and learning happened through doing. Even the first neutron generator was ingeniously built withing the university system at Aligarh. That culture of experimental innovation created generations of capable physicists. Reviving this spirit in our universities is essential today.

Over the years, nuclear physics activities in many universities have weakened. This is mainly due to limited resources and shrinking nuclear physics related experimental programmes. The formation of INPA therefore comes at the right time. By strengthening collaboration between universities and national laboratories, supporting experimental training, and encouraging young participation, INPA for sure will help restore the vibrancy of nuclear physics in India.

I sincerely hope that this association becomes a platform where experience guides youth, collaboration replaces isolation. Further, the experimentation regains its central place in education and research. The future of nuclear physics lies not only in understanding the atomic nucleus, but in nurturing the next generation who will carry this science forward.

With best wishes to all members and students embarking on this shared scientific journey.



**Swaminathan Kailas**
*INSA Hon. Scientist*
*UM-DAE Centre for Excellence in Basic Sciences*

## Renaissance of Nuclear Physics

It is very timely that INPA has come into existence to take nuclear physics programmes to greater heights through our collective wisdom and efforts. In this context, I would like to flag 3 issues which require the attention/action of our community. More than 50 years back, Nuclear Physics discipline was occupying a pre-eminent place amongst the frontier areas of Physics research in the country, in terms of world-renowned experts, both in experimental and theoretical nuclear physics. Thanks to them, the nuclear physics research was flourishing. Over the years we have lost this lead and other disciplines like condensed matter physics, high energy physics and astrophysics have overtaken us. One of the yardsticks for judging this is through the number of faculty members in teaching institutes. The nuclear physics specialists in academic institutes are miserably low when compared to the faculty members from other disciplines. The number of nuclear physics faculty members in the premier academic institutes like IITs, IISERs and Central Universities put together will not be more than 20! With the result nuclear physics is being taught by non – nuclear physicists in some of these institutes. This is worrisome and INPA should take steps to improve this situation by discussing with funding agencies like DST, DAE and UGC and raise this alarming situation with the education minister. There should be at least one nuclear physics faculty member in each of these institutes to teach not only the subject but also to attract young students to this field. In my opinion, this is the most urgent matter which is affecting the growth of our community.

Even though faculty strength has grown marginally, it is reassuring to note that the number of research scholars in nuclear physics has grown significantly. This was clearly evident in the recently concluded DAE nuclear physics symposium held at Jalandur. To make out field more attractive to young students, we have to create new facilities in terms of accelerators and detector instrumentation which should be world class. We as a community should ensure that the upcoming facilities become operational as planned in time. I have been advocating formation of national steering committee for monitoring the progress of upcoming major facilities at VECC, Kolkata and BARC, Vizag in particular. It is essential to have this committee in place with members from IUAC, RRCAT, VECC, SINP, TIFR and BARC, the major accelerator centers in the country. In fact, all of them should become stake holders of these mega facilities and involve faculty and students from academic institutes and collectively work towards successful completion of the planned major accelerator facilities without time overrun. While we wait for the major RIB facilities to become operational, in the short run every effort should be made to develop low energy RIBs in the existing facilities. One successful effort was made from IUAC who developed 7Be for users more than 20 years back.

Another aspect of nuclear physics which we have to exploit and popularize is the successful application of nuclear physics data, tools used for nuclear physics research and nuclear techniques used widely in Nuclear power programme, Healthcare, Agriculture, Industry, Archeology, Material science and National security etc. We can organize a theme meeting on this topic of application of nuclear physics to society to spread the awareness in the community (also through outreach programmes) and make nuclear physics research more visible than what it is today. As a result, Nuclear Physics research scholars will also come to know about job opportunities in various fields in addition to nuclear physics. INPA can associate with IPA, IPS and INS to organize this theme meeting.

Nuclear physics research is indeed growing in the country and this is borne out by 500 research papers presented in the last nuclear physics symposium. INGA facility is one outstanding example to show case that how collectively we can succeed in building a world class facility. Similar effort should be made for early completion of upcoming major accelerator facilities. I am optimistic that nuclear physics research will grow to greater heights in the country and will be more visible to physicists at large if we can bring out the central role of nuclear physics in unifying different branches of physics at large and its rich connection to other physics disciplines like astro- and high energy physics in particular. The facilitating role of INPA in achieving this goal need not be overemphasized.

NUCLEAR HORIZONS: A Bulletin of Indian Nuclear Physics Association

# Nuclear Physics in India: Past Lessons, Future Opportunities

**Amit Roy**
*Former Director, Inter-University Accelerator Centre, New Delhi,*
*Ex-Raja Ramanna Fellow, Variable Energy Cyclotron Centre, Kolkata*
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Study of Nuclear Physics started in India in the very early stages of development of this field soon after the discovery of the nucleus by Ernest Rutherford. In 1923, D.M. Bose and S.K. Ghosh built a cloud chamber and photographed the tracks of a-particles from polonium in helium and also that of electrons from helium. Bose with Biva Choudhury photographed meson tracks in emulsions at high altitudes. Bose's student Shyamadas Chatterjee observed spontaneous fission of Uranium with the ionization chamber built by him immediately following the discovery of fission.

Nuclear Physics studies in India were given a strong phillip by M.N. Saha who initiated building a cyclotron accelerator at Kolkata and H.J. Bhabha who set up a Phillips Cockroft-Walton generator at Mumbai in the 1950s with emphasis on experiments being done with instruments built in-house.

Cockroft-Walton generators for neutron induced reaction cross section measurements were installed at Bose Institute, SINP, Aligarh and Waltair. The first reactor, APSARA started functioning in 1956 and the CIRUS reactor was commissioned in July 1960 providing a copious source of neutrons as well as radioisotopes for nuclear decay studies. The 5.5 MV van de Graaff accelerator was set up at BARC and a 7.5 MeV cyclotron was set up at Chandigarh. A vibrant community of experimental and theoretical nuclear research grew in the universities and the institutes during the 1960s.

Only towards the end of 1970s the first large particle accelerator built in the country, the K140 Variable Energy Cyclotron at Kolkata got the first beam in 1977 and in the 1980s two large Pelletron accelerators were bought and commissioned in this period, first at Tata Institute of Fundamental research in 1989 and the second at Inter-University Accelerator Centre (earlier Nuclear Science Centre) in 1991 rejuvenating nuclear physics research in India.

During the late 1980s and early 2000, superconducting linear accelerators were added to boost the beam energies obtained from the Pelletron accelerators at Mumbai and Delhi.

Many major experimental facilities and detector systems for nuclear studies were added in the past couple of decades. These are Indian National Gamma Array, Recoil Mass Spectrometers, Neutron arrays, Multi-layered Charged Particle arrays, Position sensitive detector arrays, Spin Spectrometers. High speed Data Acquisition systems and High-performance Computing facilities were developed at the Kolkata, Mumbai and Delhi centers.

Major advances were made by Indian researchers in studies of structure of nuclei (interplay of single particle and collective modes, behavior at high excitation energy, spin and isospin), nuclear reaction dynamics (different facets of direct, compound and pre-compound reactions, fusion and fission reactions, nucleosynthesis process).

Indian researchers are also participating in international projects at CERN, BNL, GANIL, RIKEN, FAIR The Indian researchers were supported by DAE and DST jointly, building some sections of the detectors and signal processing electronics. A very successful collaboration of large number of nuclear physicists from universities and institutes, the Indian National Gamma Array collaboration (INGA) worked beautifully moving between Delhi, Kolata and Mumbai accelerator facilities.

Following the establishment of SRF technology in the centers at Delhi, Indore, Mumbai and Kolkata, a collaboration was established between Indian Laboratories (BARC, RRCAT, VECC, IUAC) and Fermilab for joint development of a high-power high-energy proton accelerator. This collaboration has facilitated the development of a project for 1 GeV high power proton accelerator by DAE laboratories that has among its goals, utilization of Th, transmutation of fission products, production of radioisotopes, spallation neutron source and medical therapy.

New accelerator facilities that have recently started operations are, the Superconducting Cyclotron at VECC, Facility for Research in Experimental Nuclear Astrophysics (FRENA) at SINP, High Current Injector at IUAC. The initial phase of Advanced National facility for Unstable and Rare Ion Beams (ANURIB) has also been in operation.

Overall, the research conducted using these facilities in India resulted in many significant contributions to the understanding of nuclear interactions as well as nuclear structure. A large number of students got trained creating a reasonably large pool of experts, who can contribute to development of science and technology in the country.

During this process of pursuit of fundamental studies many of the tools required for nuclear science were developed. This process generated considerable technical expertise in the associated technologies. Many of these tools and techniques are already in use for societal applications in our country.



***Prof. Amit Roy**, former Director of the Inter-University Accelerator Centre, New Delhi, is a distinguished nuclear physicist known for his contributions to experimental nuclear physics and detector development. He has played a key role in advancing accelerator-based research in India and mentoring young scientists in the field.*

# Incredible 75-Years of Experimental Nuclear Physics Research at Aligarh

## (Historical Perspective and Current Status)

**R. Prasad and B. P. Singh**

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**Introduction**

Experimental nuclear physics has been one of the most dynamic branches of modern science. It has continuously expanded our understanding of the atomic nucleus and the fundamental forces that govern nuclear matter. From the study of nuclear structure to exploring the nuclear reaction dynamics, the experimental investigations have immensely contributed to the basic science and technological advancement. Over the past seventy-five years or so, the Experimental Nuclear Physics group at the Department of Physics, Aligarh Muslim University (AMU), Aligarh, has contributed significantly to the subject.

**Early Development of Nuclear Physics at AMU**

The journey of nuclear physics research at AMU began during the formative years of independent India. This was a period marked by scientific optimism and national reconstruction. Visionary scientists at AMU recognized the importance of nuclear science for the future of the country. With limited resources but remarkable determination, they initiated experimental programs in nuclear reactions, nuclear structure, radiation measurements, related nuclear electronics and in-house detector development. These efforts laid a strong foundation for nuclear physics research at the university.

In its initial phase, research activities were mainly focused on understanding radioactive decay processes and nuclear properties using available laboratory-scale instrumentation. Experiments were carried out using the procured thermal neutron sources. Gradually, the department expanded its capabilities through systematic development of experimental infrastructure and academic training. Dedicated faculty members nurtured a culture of precision experimentation and scientific curiosity. Students were trained rigorously, not only in experimental techniques but also in fabricating instruments, like gas filled counters, amplifiers etc. These were required for the nuclear research, data analysis, and instrumentation, creating a vibrant research environment.

As the subject of nuclear science grew worldwide, the AMU nuclear physics group also moved forward. It built links with major research labs in India. Access to accelerator facilities opened new ways to study nuclear reactions. The group contributed to areas like study of nuclear structure, measurement of reaction cross-sections, detector development work, and radiation physics.

A strong focus has always been on experiments. Researchers built their own setups and improved detectors. They used new techniques to solve scientific problems. This work also trained many skilled experimental physicists. Many of them later worked in prestigious universities and national labs. Over the years, research work at AMU kept growing. A large number of Ph. D. theses and research papers came out of this effort. The tradition of good mentorship continues to guide young students. Today, the work has become more advanced. The members of the group use national and international accelerator facilities. Studies are done on heavy-ion reactions. These experiments help in understanding fusion,

reaction mechanisms, and nuclear properties. Overall, this 75-year journey shows steady growth and strong dedication. It reflects a move from simple beginnings to modern research. It is a story of continuous effort and scientific progress. For all this progress, the initial impetus was provided by none other than Prof. Piara Singh Gill [1,2].

**Prof. P. S. Gill: Founder of Experimental Nuclear Physics at AMU**

Professor Gill was one of the founding figures of experimental nuclear physics research at AMU Aligarh. His scientific vision and leadership played a decisive role in establishing modern experimental physics at the university during the early decades of independent India. Born in a rural village in Punjab, Prof. Gill overcame severe financial and educational limitations to pursue higher studies abroad. Driven by determination, he travelled to the United States and completed his B.S. and M.A. degrees in Physics and Mathematics at the University of Southern California. He later joined the University of Chicago. At Chicago he carried out doctoral research under the Nobel Laureate Arthur Holly Compton, one of the pioneers of modern experimental physics.



**(Prof. Piara Singh Gill)**
**(1911–2002)**

Under the guidance of Prof. Aurthur Compton, Prof. Gill worked on cosmic ray physics. He performed precision measurements of cosmic ray intensity and latitude effects. His research work contributed to the early understanding of high-energy particles and gained international recognition in the post independent era. Prof. P. S. Gill was also a part of "Manhattan Project". This exposure to advanced experimental methods strongly shaped his scientific outlook and later influenced the development of research facilities in India.

In 1949, at the invitation of Prime Minister Jawaharlal Nehru and the then Vice-Chancellor Dr. Zakir Hussain (who later became the president of India), Prof. Gill joined Aligarh Muslim University as Professor and Head of the Department of Physics. This marked a turning point in the history of physics research at AMU. At AMU, he transformed a primarily teaching department into an active experimental research centre. He introduced modern postgraduate curricula aligned with global scientific developments. More importantly, he established laboratories for cosmic rays, nuclear physics, radiation detection, and electronic instrumentation. Much of the experimental equipment was designed and fabricated locally, creating strong technical expertise within the department.

Prof. Gill initiated systematic experimental nuclear physics work at AMU. He used Geiger–Müller counters, neutron detectors, nuclear emulsions, and electronic counting systems. He also established accelerator-based experiments through the installation of a Cockcroft–Walton accelerator. This placed AMU among the early centres of experimental nuclear physics in India. He also played an important role in setting up the Gulmarg High Altitude Research Observatory for cosmic ray studies. He trained many students who later contributed to nuclear physics programmes in India. Present experimental work at AMU, including heavy-ion studies at national accelerator facilities, builds on the foundation laid by Prof. Gill and Prof. Harnam Singh Hans. Their work established a strong culture of experimental research and instrumentation development at the university.

Early nuclear physics research work at AMU was focused on cosmic ray measurements and radiation detection using indigenously developed instruments. This established strong experimental and technical foundations. Over decades, the programme transformed from modest laboratory experiments into a nationally connected research effort, demonstrating sustained academic vision and contributing significantly to modern nuclear physics research and training.

It may not be out of place to mention that, in the years following India's independence, the country undertook a determined effort to build strong scientific institutions alongside national reconstruction. During this formative period, American physicist L. F. Curtiss visited India as a Fulbright scholar in 1951 and documented his observations in Physics Today (1952) [3]. This document presents an important historical perspective on the emergence of modern physics research in India. At AMU, Aligarh, Dr. Curtiss worked with Prof. P. S. Gill for a couple of months. Prof. Gill led the setting up of the cosmic ray laboratory at Gulmarg. It showed a strong push for building experimental facilities within the country, even with limited resources. The visit of Dr. Curtiss to many Indian universities reflected a clear effort to link science with national growth and self-reliance. In his Physics Today report, he has quoted that, "at AMU, he observed an environment marked by enthusiasm, ingenuity, and growing experimental ambition". International recognition provided encouragement to the young research community striving for global relevance.

In subsequent years, small experimental efforts evolved into organized nuclear physics programme. This was supported by locally developed instrumentation and expanding laboratory infrastructure. As India advanced in nuclear science, AMU strengthened collaborations with national research centres and trained students in modern experimental techniques. This period marked a transition from early promise to institutional consolidation. This helped in sustained nuclear physics research, establishing Aligarh as an enduring centre of experimental scientific tradition.

**Early Experimental Facilities and Cosmic Ray Studies**

A major early milestone at AMU was its work at the Gulmarg Cosmic Ray Observatory, set up under Prof. Piara Singh Gill. The high-altitude site was ideal for studying cosmic rays when accelerators were not available. These cosmic rays acted as natural high-energy particles. Gulmarg was developed as a centre for advanced experiments. It is worth mentioning that Giger Muller Counter, a detector essential for cosmic ray studies was fabricated for the first time in the country at the glass blowing section of the department under the supervision of researchers like Prof. S. P. Puri and others. Prof. Puri published a large number of research papers on the studies carried out using the counters.

AMU researchers designed detectors and carried out measurements of radiation detection. They used Geiger-Müller counters, neutron detectors, and coincidence circuits. Studies included cosmic ray intensity variations, absorption, air showers, and magnetic effects. Work with visiting scientists like L. F. Curtiss strengthened experimental methods and collaborations. The observatory at Gulmarg, served as an important training ground for students in instrumentation, electronics, and data analysis. It also built the experimental culture that later supported organized nuclear physics research at AMU.

**Expansion to Accelerator-Based Research**

Prof. Harnam Singh Hans played a key role in developing experimental nuclear physics at AMU. He joined Ph. D. in 1950

with Prof. P.S. Gill, an eminent Cosmic-ray Physicist at Aligarh Muslim University (AMU). He worked on development of instrument for measuring cosmic mesons. Later, he moved to Swarthmore (PA), USA (1953-56) to complete Ph.D. work dealing with experiments on the elastic and inelastic scattering of 3.7 MeV neutrons produced using 1 MV accelerator. He expanded the work from cosmic rays to accelerator-based studies using his training under Prof. Gill and experience in the USA.



**(Prof. Harnam Singh Hans)**
**(1922 -2014)**

After joining AMU in 1958, Prof. Hans led the construction of a Cockcroft–Walton accelerator-based neutron generator. The project of indigenous construction of the Cockcroft–Walton accelerator in the Department of Physics project was undertaken under the leadership of Prof. Gill and Prof. Hans. This facility was the first of its kind in an Indian university. With colleagues, he established facilities for neutron-induced studies and promoted indigenous instrumentation. He trained many students and encouraged independent scientific work. He also contributed to rebuilding a cyclotron at Panjab University and strengthened collaboration and research culture in India. His birth centenary was celebrated at the Central University of Himachal Pradesh, Dharamshala. The event highlighted his contributions to experimental nuclear physics, instrumentation, and research training in Indian universities.



**(Prof. Charanjit Singh Khurana)**

Dr. Charanjit Singh Khurana, as a Ph.D. student, played a key role in building a 150 kV Cockcroft–Walton type particle accelerator for 14 MeV neutron generation and carried out several measurements using neutrons. The construction and working details were published in the *Journal of Pure and Applied Physics* [4]. His Ph.D. thesis (1960) is still preserved in the accelerator laboratory of the Department of Physics. Prof. Khurana, later joined Punjabi University, Patiala. A typical layout of the 150 kV Cockcroft-Walton accelerator at AMU is presented in Figure 1.

Initially, Cockcroft-Walton accelerator was setup in the old Garage building of the department. After few years the building became in dilapidated state. The machine was then shifted to the new building. Resetting the accelerator in the new building and bringing it back to working condition, in record time, was all done by Prof. R. Prasad who was a research scholar in the department. A photograph of the neutron generator housed in the Accelerator lab of the department is given in Figure 2.

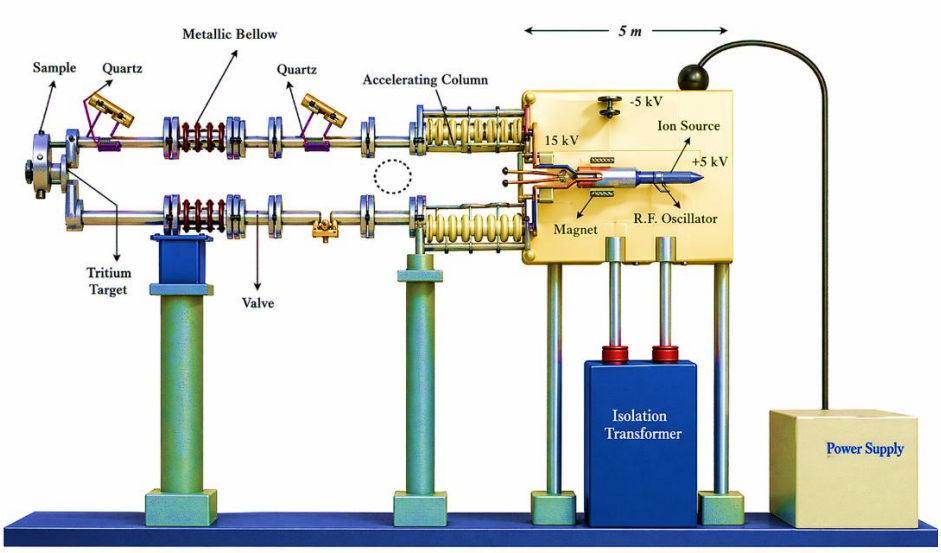



***Figure 1: A typical layout of the 150 kV Cockcroft-Walton accelerator at AMU***

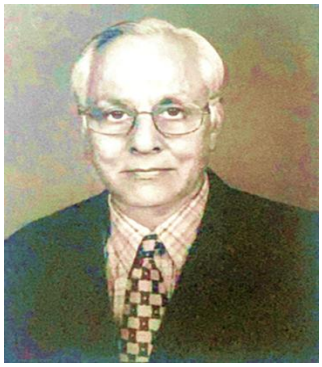


***Figure 2: A photograph of the neutron generator housed in the Accelerator lab of the department***

At a time when accelerator facilities were limited to national laboratories, its installation at a university reflected strong scientific vision and self-reliance. The Cockcroft–Walton accelerator was used to produce 14 MeV neutrons through the D(t,n) reaction. It was used extensively for measuring cross-sections for neutron induced reactions and to test the various aspects of the compound nucleus (CN) reaction mechanism. Most of these measurements were done using activation technique where radio-activities induced in neutron irradiated samples are followed to determine the strength of the activity.

In the absence of adequate instruments at that time, it was not possible to study reactions where induced activities were short lived, less than a minute or so. Special electronic circuits were designed and fabricated (by Prof. R. Prasad) to follow these short-lived activities and almost fifty reactions leading to short lived activities as small as 0.1 s were studied, most of them for the first time, filling the gap in experimental data. Reaction cross-sections for almost 150 reactions induced by 14 MeV neutrons were measured using the indigenous Cockcroft-Walton accelerator. Critical analysis and theoretical simulations of experimental data indicated that pre-compound emission of nuclear particles play an important role in nuclear reactions. It was a major development in nuclear research at that time. Some Ph.D. theses were also submitted on the topic. The facility also served as an important training platform and marked the beginning of sustained experimental nuclear physics work at AMU.

In parallel to these studies, early researches were carried out on the temperature dependence of Geiger-Müller counter characteristics.



**(Prof. R. Prasad)**

Measurements were performed using self-quenching gas mixtures such as argon-ether, argon-butane and argon-alcohol. The plateau behaviour was examined over a wide temperature range, providing insight into the stability and performance of GM counters under varying conditions.

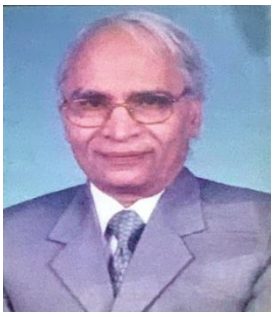
Prof. M. L. Sehgal carried out studies on thermal neutron cross-sections for isomer production. Experimental arrangements were developed for measuring gamma activity and decay curves. Half-lives and cross-sections for several reactions were determined, adding significantly to the available nuclear data.



**(Prof. M. L. Sehgal)**

Thermal neutron cross-section measurements were undertaken in collaboration with BARC by Dr. Sushil K. Mangal. Neutron activation techniques were employed to study isomer production and the dependence of nuclear level density on spin. Irradiations were carried out at the "swimming pool" reactor at Trombay for target nuclei ranging from $^{68}$Zn to $^{196}$Hg isotopes.

Prof. A. K. Chaubey also contributed significantly for the development of research in the physics department. Initially the neutron capture cross-section measurements were further extended by Prof. A. K. Chaubey. Experiments were conducted at 24 keV using an end-window beta counter and a NaI(Tl) spectrometer. The cross-sections were measured for a large number of reactions, yielding valuable nuclear data. Later he continued work on alpha-particle reactions and HI reactions.



**(Prof. A. K. Chaubey)**

Gamma-gamma angular correlation measurements, to investigate the spins of excited nuclear states, were carried out in the department by several researchers including, Profs. S. K. Mahendra, Krishn Mahesh, G. N. Rao, I. M. Govil and Rajendra Prasad. Studies were performed on various gamma cascades in radioactive nuclei. The systematic behaviour of E2 transitions in even-even nuclei was examined, providing information on transition probabilities and enhancement factors. Apart from that Dr. H. S. Hans carried out measurements of differential cross-sections for neutrons elastically scattered from zirconium and molybdenum at a mean energy of about 3.7 MeV. These measurements contributed to the understanding of neutron interaction processes.

**Growth Through National Collaborations (VECC Phase)**

The experimental nuclear physics group at AMU entered a mature phase with collaborative work at national labs, especially at VECC, Kolkata. Access to proton and alpha beams allowed advanced studies beyond the university.

Experiments were carried out to measure excitation functions (EF) and to study energy dependence of reaction cross sections. Various theoretical models were used to interpret the data. These included the Weisskopf-Ewing and Hauser-Feshbach statistical models for compound nucleus decay. Pre-equilibrium emission was treated using the exciton model and hybrid approaches. The calculations were carried out using standard nuclear reaction model codes based on quantum mechanical formalisms as well.

These studies helped separate the compound nucleus (CN) and pre-equilibrium (PE) reaction processes. Work was later expanded to study residue production, reaction channels, and angular momentum effects. Many faculty members and research scholars including Prof. M. Afzal Ansari, and Prof. I. A. Rizvi took part in experiments at VECC. This work produced large data set and led to many research publications. More than 150 reactions initiated by proton and alpha beams in light, medium and heavy targets were studied in this project. Stack-foil technique has been used to deduce excitation functions (EFs) for these reactions. Using the experimentally measured EFs, the results were compared with theoretical calculations based on CN and PE emission models. It was observed that these reactions proceed through an admixture of CN and PE processes. The PE fraction was estimated to study its dependence on different entrance channel parameters. One of the important results obtained from the variation of the PE fraction with excitation energy above the Coulomb barrier per surface nucleons, for targets in the mass range ≈55-197. The systematics developed indicated that mostly the surface nucleons take part in PE reactions.

The work done at AMU and collaborations with other researches strengthened AMU's scientific standing. They built a strong link with national laboratories. A large number of doctoral theses were completed. Many research papers were published on new measurements in reputed international journals on CN and PE emission studies. The work continues even today at VECC, Kolkata, now using mostly the heavy-ion beams. It connects earlier efforts of the group with present research. It also contributes to experimental nuclear science in India.

**Heavy-Ion Research and IUAC Programme**

The availability of the Pelletron accelerator at IUAC, New Delhi, marked a new phase. The AMU group became an active user of this facility. Experiments were done on heavy-ion reactions and angular momentum transfer studies. Focus was on complete and incomplete fusion. Excitation functions were measured using the stacked-foil technique. These gave cross-sections and reaction channels. Recoil range studies gave momentum transfer. Gamma-ray spectroscopy identified residues and their decay. Spin measurements studied angular momentum and deformation. These studies helped in understanding pre-equilibrium emission and reaction dynamics. The IUAC programme produced many Ph.D. theses and over 150 research papers in reputed international journals. It also provided skill to the students in modern accelerator-based research techniques.

**Key Research Contributions and Experimental Results**

One of the most important experimental programmes of the AMU nuclear physics group has been the systematic study of EFs in heavy-ion induced reactions (initiated by Prof. R. Prasad and Prof. B. P. Singh). The aim has been to understand the nuclear reaction dynamics in heavy-ion collisions, with a focus on complete fusion (CF) and breakup fusion (BUF) studies.



**(Prof. B. P. Singh)**

The measured EFs describe how reaction cross-sections vary with projectile energy and provide direct insight into reaction mechanisms. Using ion beam from pelletron accelerator, targets were irradiated over a wide energy range to examine the opening and competition of reaction channels populated via CF and ICF/BUF modes. High-resolution gamma-ray spectroscopy with HPGe detectors allowed precise identification of reaction residues and reliable cross-section determination. These studies enabled detailed investigation of compound nucleus formation and its dependence on angular momentum, mass asymmetry, nuclear deformation etc. In many HI reaction systems, measurements also revealed signatures of pre-equilibrium emission, highlighting non-equilibrium processes during early collision stages. Continuous comparison with theoretical models helped refine reaction calculations and improve understanding of nuclear equilibration. Over the years, these investigations produced valuable experimental data while training generations of students in advanced nuclear experimental techniques. At present we are an established group in the study of fusion and incomplete fusion reaction studies in heavy ion collisions. For the sake of completeness, some of the important results obtained are given here. Incomplete fusion strength functions in HI reactions for several projectiles were deduced and examined against the projectile α-Q value [5]. A clear trend emerges (see figure below), as loosely bound projectiles with less negative α-Q show larger ICF fractions, while strongly bound systems such as $^{14}$N exhibit minimal ICF. The behaviour persists across the studied relative velocities, with measurable ICF, even below 0.06c. These results point to the α-Q value as a key entrance-channel parameter governing breakup and incomplete fusion.

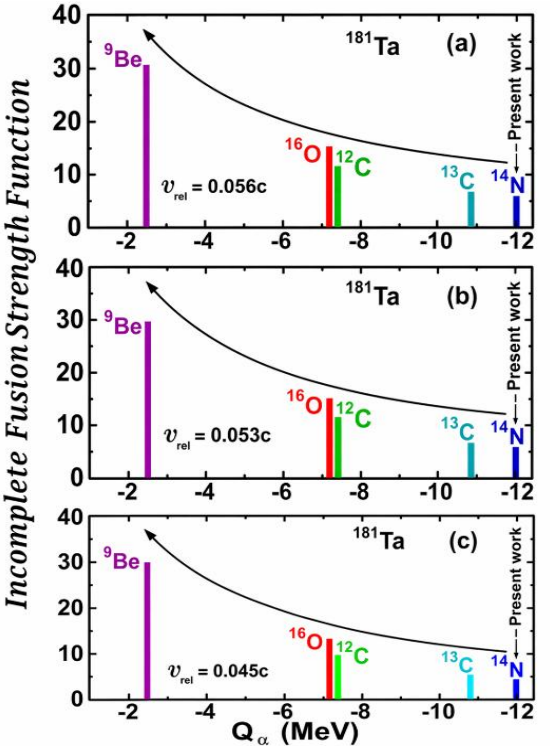



**Figure. 3: Incomplete fusion strength function as a function of projectile α-Q for reactions on $^{181}$Ta at different relative velocities**

Recoil range distribution (RRD) measurements constitute the most direct and irrefutable experimental technique used by the AMU nuclear physics group to probe reaction dynamics and momentum transfer in heavy-ion collisions. By analysing how reaction residues recoil into forward and backward thin catcher foils, researchers determine the extent of linear momentum transfer and identify underlying reaction mechanisms. Unlike EFs, the RRD studies reveal linear momentum transfer details and of how fusion occurs, enabling clear distinction between complete fusion, incomplete/breakup fusion processes. Combined with gamma-ray spectroscopy and activation techniques, these measurements provided crucial evidence

of reaction pathways, strengthening understanding of heavy-ion collision nuclear reaction dynamics.

The Coulomb effect studies helped conclude that as the projectile approaches the target, it may break up due to the Coulomb field. One fragment may then fuse with the target, leading to incomplete fusion of projectile. The breakup probability increases with the product $Z_P Z_T$. The data show a clear linear dependence of the $ICF$ fraction on $Z_P Z_T$. This Coulomb-driven trend provides a useful parameter for modeling $ICF$ at low energies and was observed here for the first time.

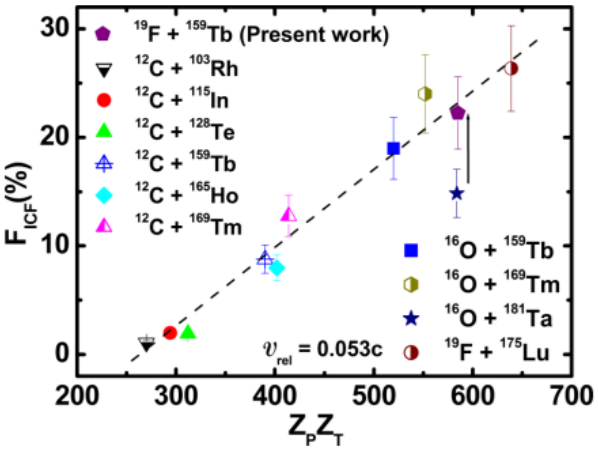



***Figure 4: The incomplete fusion fraction as a function of Coulomb factor***

The fusion data for the $^{14}$N-induced reaction [6] when compared with other systems, show a small suppression, with $F_{BU} \approx$ 0.945. The values follow a clear systematic trend, as seen in the figure 5. With a slight change in parameters, the data are well reproduced. The trend shows that the suppression is linked to the breakup threshold energy of the projectile. This indicates that projectile breakup plays an important role in reducing the fusion cross section.

In another important recent study, an attempt was made to verify the Bohr's independence hypothesis of CN theory in HI collisions at low energies. In this work, $^{18}$O + $^{159}$Tb and $^{12}$C + $^{165}$Ho systems, both

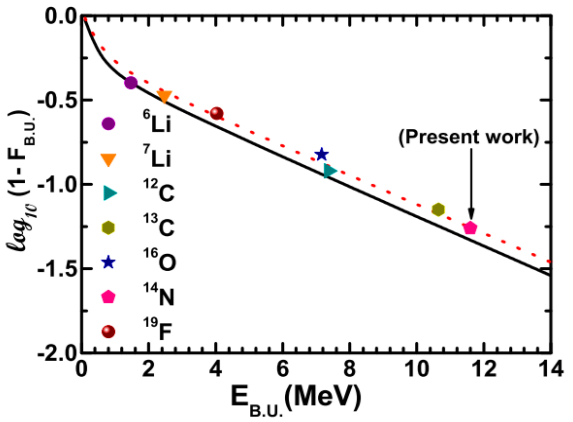



***Figure 5: The fusion data for the $^{14}$N-induced reaction shows suppression and follow a systematic trend, indicating that projectile breakup reduces the fusion cross section.***

forming $^{177}$Ta, were studied to test Bohr's hypothesis [7] The measured evaporation residue cross sections agree reasonably with statistical model (PACE4) predictions. At higher excitation energies, the results support the compound nucleus picture. At lower energies, deviations are seen, mainly due to differences in angular momentum as shown in figure below.

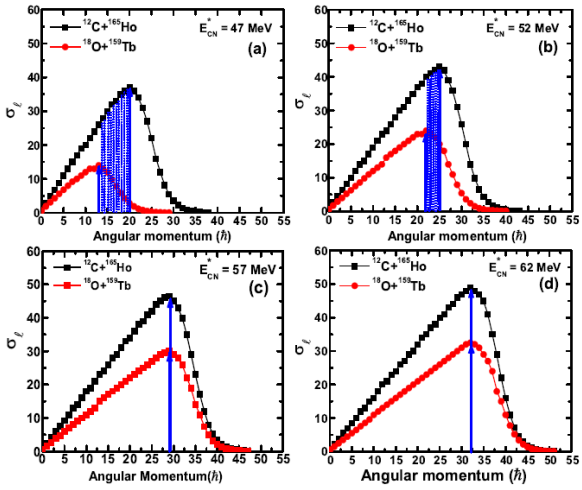



***Figure 6: Variation The fusion $\ell$-distribution for $^{18}$O+$^{159}$Tb and $^{12}$C+$^{165}$Ho systems at excitation energy (a) 47 MeV (b) 52 MeV (c) 57 MeV and (d) 62 MeV.***

In one of the important and recent investigations [8] the deduced ICF strength function is found to show a clear dependence on target deformation. For weakly deformed nuclei ($\beta_2 < 0.2$), the ICF fraction remains small, indicating dominance of complete fusion. As the

deformation increases, the ICF strength rises steadily and becomes significantly larger for strongly deformed targets. This behaviour is attributed to enhanced coupling and anisotropic nuclear potentials, which favour projectile breakup and peripheral interactions. Some deviations, such as in $^{124}$Sn, reflect underlying shell effects. Overall, the results highlight that target deformation plays an important role in governing incomplete fusion dynamics.

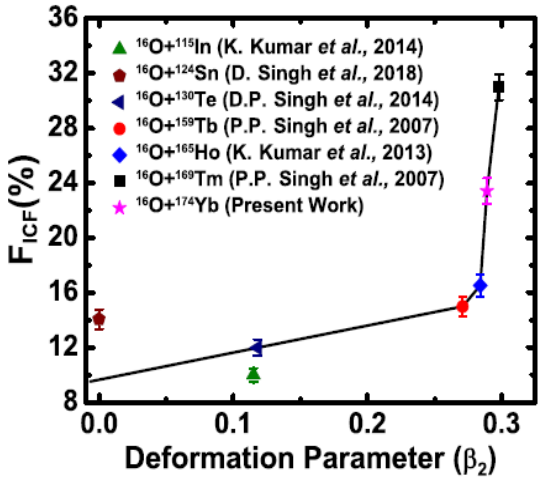



***Figure 7: Variation of the incomplete fusion strength function with the target deformation parameter for different reaction systems.***

In the study of $^{16}$O + $^{174}$Yb reaction [8], we have also identified a promising radionuclide, $^{186}$Pt, for possible theranostic use. Its decay properties and short half-life make it suitable for both imaging and therapy. It may complement platinum-based drugs by adding a radiation component to treatment. Other important nuclides observed include $^{185}$Ir, related to brachytherapy sources, $^{182}$Os with possible cytotoxic use, and $^{181}$Re, similar to $^{186}$Re used in therapy. These results show the relevance of such studies for nuclear medicine.

Angular distribution measurements of heavy residues have been an important experimental approach used by the AMU nuclear physics group to study heavy-ion reaction dynamics and momentum transfer. In these experiments, thick annular catcher foils were employed to collect recoiling residues over a defined angular range around the beam axis, enabling systematic measurement of emission patterns. Following irradiation, residues are trapped in the annular catchers. The residues were then identified through high-resolution gamma-ray spectroscopy using their characteristic γ-ray energies and decay half-lives.

The resulting angular yield distributions provided direct insight into reaction mechanisms. Symmetric distributions indicated compound nucleus formation and statistical equilibrium, while forward-peaked or asymmetric patterns revealed contributions from incomplete fusion, direct reactions, or pre-equilibrium processes. Thus, angular distribution studies are a powerful tool for distinguishing competing reaction pathways in heavy-ion collisions. When combined with EFs and RRD measurements, these experiments provided a comprehensive picture of momentum transfer, and fusion reaction dynamics near Coulomb barrier energies. The work significantly advanced understanding of nuclear reaction mechanisms, and produced a large number of research publications.

**Advanced Experimental Techniques**

Particle–gamma coincidence experiments have emerged in recent years as an important and advanced aspect of experimental nuclear physics research carried out by the AMU nuclear physics group. By detecting charged particles and γ-rays in coincidence, these studies establish direct correlations between reaction channels and populated nuclear states. Using the combined GDA-CPDA detector setup, charged particles were identified with high efficiency while γ-rays from excited residues were measured through Compton suppressed HPGe detector based high-resolution spectroscopy. Fast timing electronics

ensured true coincidence events, significantly reducing background and improving data selectivity.

A major outcome of these experiments has been the determination of spin distributions of reaction residues populated via CF or ICF processes. The representative results [9] clearly distinguished contributions from complete fusion and incomplete fusion mechanisms, offering strong experimental evidence of their coexistence near barrier energies. Such studies were carried out for several projectile-target combinations and at several energies. These studies have produced important scientific results like a narrow range of input angular momentum is involved in ICF reactions. On the other hand, in case of ICF reactions a broad range of angular momentum is found to be involved. Thus, angular momentum generation in residues due to CF and/or ICF reactions in heavy-ion collisions was studied.

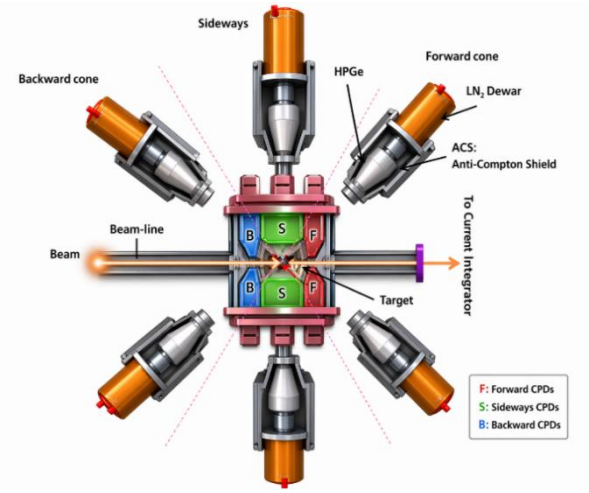



***Figure 8: The GDA-CPDA setup for particle gamma coincidence experiment at IUAC***

**Summary of Scientific Contributions**

From the brief description presented above, it may be observed that the AMU nuclear physics group has carried out exciting and impactful experimental studies. These studies revealed the fascinating reaction dynamics and behaviour of nuclei under heavy-ion bombardment. Through pioneering

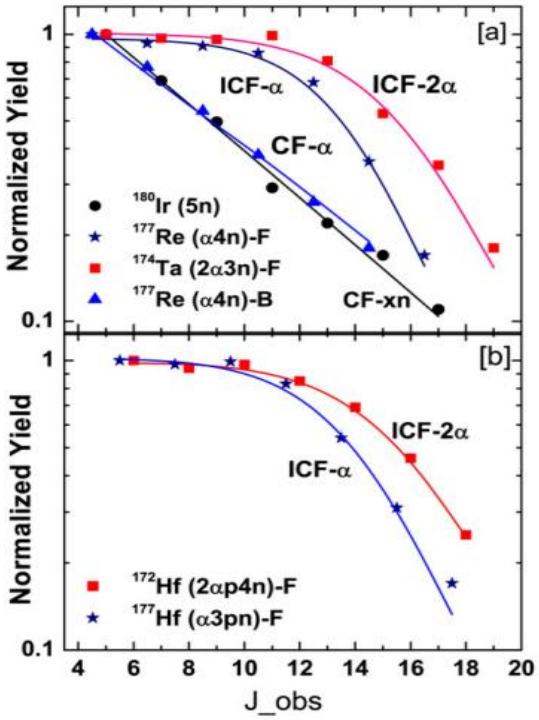



***Figure 9: Spin distributions for residues from xn (CF) and αxn/2αxn (CF/ICF) channels in 16O + 169Tm at ≈ 5.6 MeV/nucleon. ICF-α/2α denote incomplete fusion with α multiplicity, CF-α from backward α-gated spectra; F and B indicate forward and backward emission***

investigations of PE emission, low-energy fission dynamics, spin distribution measurements, and forward-to-backward yield ratios, the group uncovered how energy, momentum, and angular momentum evolve during nuclear reactions. Explorations in the Fermi energy regime through international collaborations, further highlighted the transition between reaction mechanisms. This significantly advanced the understanding of HI reaction dynamics and helped in strengthening vibrant experimental legacy. Presently, young researchers within the group, Dr. Mohd Shuaib, Dr. Shariq Asnain, Mr. Aquib Siddique, and Mr. Samveel Ansari, are actively contributing to research activities and laboratory development.

**Academic Leadership and Training Legacy**

Since the early 1950s, the Department of Physics at AMU has been a cradle of

experimental nuclear physics training in India. Guided by pioneers like Prof. P. S. Gill, Prof. H. S. Hans, Prof. M. L. Sehgal, Prof. C. S. Khurana, Prof. Rajeshwari Prasad, Prof. Ashok K. Chaubey, Prof. B. P. Singh, etc., generations of scholars gained hands-on expertise. This expertise later helped in strengthening universities, laboratories, and global nuclear research through sustained academic leadership. Apart from Prof. Gill and Prof. Sehgal, Prof. R. Prasad, Prof. A. K. Chaubey, Prof. Mohd. Afzal Ansari, and Prof. B. P. Singh also served as Chairpersons of the Department of Physics and contributed significantly to the overall growth of the nuclear physics in the department.

**Ph.D. Output and Research Impact**

Since 1950, the Experimental Nuclear Physics group at AMU has produced over 60 Ph.D. scholars in Experimental Nuclear Physics. This reflects a strong and sustained legacy of research, innovation, and academic excellence. These doctoral graduates have contributed significantly to the advancement of nuclear science through experimental investigations, teaching, and the development of research infrastructure. This has established the department as a consistent center for high-quality research training over several decades.

**Teaching and Laboratory Infrastructure**

Regarding present inhouse training facilities, the Experimental Nuclear Physics Laboratory of the Department of Physics represent one of the most comprehensive and effective teaching facilities at the postgraduate level in the Indian university system. The lab is designed to bridge theoretical learning with real experimental practice. The laboratory provides extensive hands-on training through a wide range of modern radiation detection and spectroscopy experiments that are used for all basic experiments on nuclear physics. Major equipment includes alpha, beta, and gamma spectroscopy systems, Geiger-Müller counting setups, Rutherford scattering set up, Compton scattering and internal conversion experiment set-ups, and X-ray fluorescence instrumentation. Through structured experiments and project-based work, such as detector characterization, radiation measurements, and instrument development, students gain practical expertise in nuclear electronics, data acquisition, and experimental analysis. This strong emphasis on learning by experimentation has made the laboratory a premier training ground. This has produced skilled experimentalists and establishing AMU as one of the leading centres for postgraduate teaching and training in experimental nuclear physics.

**Outreach and Societal Engagement**

Apart from the research activities, under the spirit of SSR, the group members organized many outreach and training programmes to connect nuclear science with society. Supported by DST, activities included workshops on nuclear instrumentation, radiation detection, and "Nuclear Science for Society," providing hands-on learning and promoting awareness of nuclear applications in healthcare, energy, and industry. These initiatives successfully bridged advanced research with education and public engagement. These activities helped in inspiring students and strengthening scientific awareness beyond the laboratory.

The members are actively involved in promoting science communication through popular articles aimed at connecting nuclear science with society. Guided by the theme "Science for Society and Sustainable Development," these writings explain nuclear applications in energy, healthcare, environment, and technology in simple language. Published in reputed magazines such as School Science (NCERT), Vigyan Setu, Vigyan Pragati, Down To Earth, and Science Reporter, the articles highlight topics like benefits of nuclear radiation, energy policy, nuclear batteries, and climate awareness. This sustained outreach is aimed at strengthening public

understanding, encouraged scientific temper, and inspired young learners toward science and sustainable development.

**Conferences and Academic Events**

The Experimental Nuclear Physics Group members at AMU have actively organized major conferences and academic events. A landmark early contribution was the DAE Symposium on Nuclear Physics (1989) hosted at the Physics Department, AMU Aligarh. This conference brought leading nuclear physicists together and established the university as an important centre for nuclear physics interaction. This tradition continued with the National Conference on Low Energy Nuclear Physics, focusing on fusion and reaction mechanisms near the Coulomb barrier. The National Conference on Recent Trends in Nuclear Physics (2016) highlighted modern experimental developments and interdisciplinary applications. The National Conference on Nuclear Structure and Nuclear Reactions (2020) emphasized links between nuclear structure and reaction dynamics, followed by the National Conference on Low Energy Nuclear Reaction Dynamics (2022) exploring fusion and breakup processes. Recently, the members if the group further expanded its global engagement by organizing the International Conference on Nuclear Structure and Nuclear Physics (September 2025). The international conference brought together national and international experts. A major focus was on development of nuclear reactors as well. In all, these events created vibrant platforms for scientific exchange and has strengthened the role of experimental nuclear physics group members at AMU in advancing nuclear physics research.

During Azadi Ka Amrit Mahotsav celebrations in the country, the group members showed strong and active participation. Faculty, research scholars, and students worked together. They organized lectures, outreach programmes, and awareness activities. The group members highlighted the link between nuclear science and social responsibility. Further, under the DST–STUTI programme, a series of training and awareness activities were conducted. Ten programmes of seven days each, spanning over one year were organized for students and teachers from different regions. The Nuclear Physics Laboratory was used extensively in these events. Participants got hands-on training on detectors, spectroscopy systems, and nuclear instruments. These efforts helped connect theory with experiment. The group members played a key role in outreach and training in nuclear science.

**Publications and Books**

Writing books, based on their experience and understanding, is expected from university faculty. Experimental Nuclear Physics faculty, at the Physics department, AMU has made significant contribution in this regard. Prof. S.P. Puri, way back around 1958, published a book on fabrication of G.M. counters. Later. Prof. H.S. Hans authored the textbook titled 'Nuclear Physics'' ISBN: 81-224-1320-X, published by New Age International (P) Limited. During the last 12 years or so, Prof. R. Prasad authored individually and jointly with Prof. B. P. Singh and Prof. Manoj K. Sharma seven books. All these books have been published by well-known international publishing houses, like the Cambridge University Press, Institute of Physics, London, Pearson Education, Springer Nature etc. Detail of these titles are given below for ready reference;

1. R. Prasad, *Understanding Medical Devices*, ISBN: 978-3-031-88629-4, Springer Nature, 2025.
2. R. Prasad, *Physics and Technology for Engineers*, ISBN: 978-3-031-32083-5, Springer Nature, 2023.
3. B. P. Singh, Manoj K. Sharma and R. Prasad, *Pre-equilibrium Emission in Nuclear Reactions*, ISBN: 978-0-7503-5077-8, Institute of Physics (IOP), London, 2022.
4. R. Prasad, *Analog and Digital Electronic Circuits*, ISBN: 978-3-030-65128-2, Springer Nature, 2021.

5. R. Prasad and B. P. Singh, *Fundamentals and Applications of Heavy Ion Collisions*, ISBN: 978-1-108-49911-8 (Hardback), Cambridge University Press, 2018.
6. R. Prasad, *Classical and Quantum Thermal Physics*, ISBN: 1107172888 (Hardback), Cambridge University Press, 2016.
7. R. Prasad, *Nuclear Physics*, ISBN: 978-93-325-2265-7, Pearson Education, 2014.

**Conclusion and Future Outlook**

Over the past seventy-five years, experimental nuclear physics at AMU has grown from modest beginnings into a strong and sustained programme of research. The contributions made over this period represent a significant and enduring input to the field. With new members joining and expanding the scope of work, the activity continues to evolve. The outlook remains positive, with a clear promise of further growth and meaningful contributions to nuclear physics in the years ahead.

Aligarh Muslim University, established in 1920, has been a leading centre of higher education in India. The Department of Physics has made strong contributions in experimental nuclear physics. Over the years, the department built good nuclear physics laboratory facilities and started collaborations with accelerator centres in the country and abroad. Work began with basic radiation experiments and later moved to advanced research studies in nuclear reactions and instrumentation.

The Nuclear Physics Group combined teaching with active research. Many students who later completed research are working in universities and laboratories within and outside the country. This long journey reflects steady growth and strong dedication. This has made AMU an important centre for experimental nuclear physics in India.

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***Prof. R. Prasad*** *has been a distinguished faculty member in the Department of Physics at Aligarh Muslim University (AMU), Aligarh. His research interests include nuclear reaction dynamics, heavy-ion collisions, and nuclear structure effects, and he has made significant contributions through numerous publications and books. He is highly regarded as an excellent teacher and mentor to young researchers.*

***Late Prof. B. P. Singh*** *was a Senior Professor in the Department of Physics at Aligarh Muslim University (AMU), Aligarh. His research focused on nuclear reaction dynamics, heavy-ion collisions, and pre-equilibrium processes, along with applications of nuclear physics in science and society. He was deeply committed to teaching, research, and promoting nuclear science education.*

# Nuclear Physics at IIT ISM Dhanbad

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The Nuclear Structure and Dynamics Group (NSDG) at IIT (ISM) Dhanbad studies the structure and dynamics of atomic nuclei through experiments, detector development, simulations, and data-driven analysis. Using accelerator facilities in India, Europe, and Japan, we investigate nuclear matter under a wide range of conditions, addressing questions related to nuclear structure, reaction dynamics, neutron-rich matter, and the origin of the elements in the universe.

One of the main research activities of our group is the study of Isoscalar Giant Resonances (ISGRs). ISGRs are fundamental collective excitation modes of atomic nuclei in which protons and neutrons oscillate coherently and in phase. These resonances provide important information on nuclear structure, bulk properties, such as incompressibility of nuclear matter. In particular, we study isoscalar electric giant resonances in highly deformed nuclei using an α-particle inelastic scattering experiment. We extract the strength distributions of various multipole modes and investigate how nuclear deformation affects their behaviour and characteristics.

Beyond the study of giant resonances, our research focuses on low-lying electric dipole (*E1*) excitations, particularly the Pygmy Dipole Resonance (PDR). The PDR appears near and below the neutron separation threshold ($S_n$) and is commonly interpreted as an oscillation of the excess neutrons at the nuclear surface against the nearly isospin-symmetric core. In contrast, the Giant Dipole Resonance (GDR) corresponds to a collective out-of-phase oscillation of protons against neutrons, concentrating most of the dipole strength at higher excitation energies. The

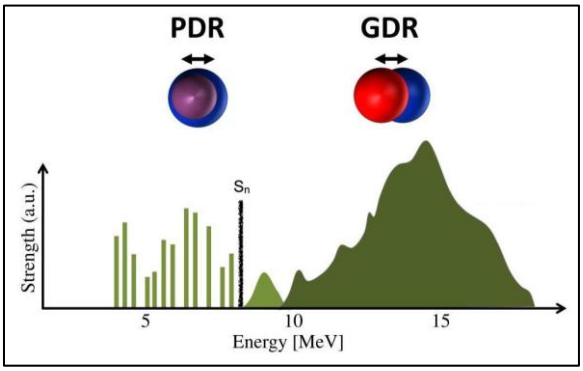
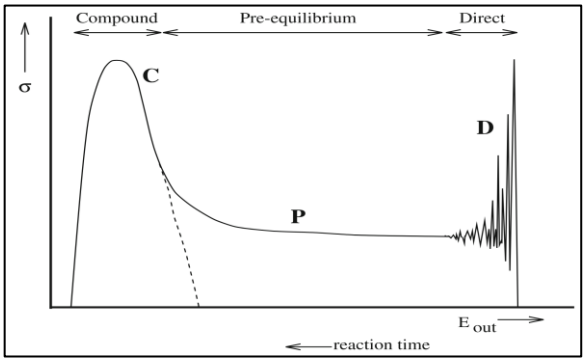


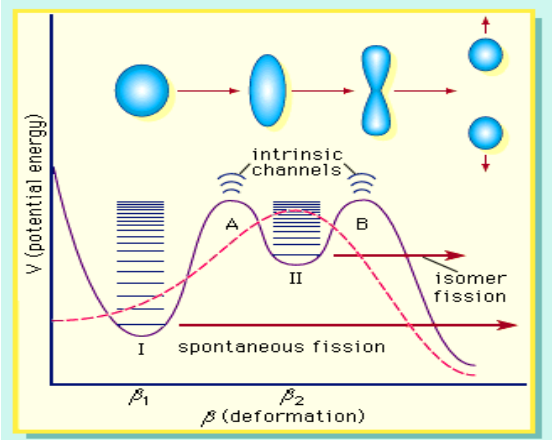

figure schematically illustrates the evolution of dipole strength from the weakly collective PDR region to the strongly collective GDR. Although the PDR carries only a small fraction of the total dipole strength, it provides valuable information on neutron-rich matter, nuclear symmetry energy, and astrophysical nucleosynthesis processes. We aim to populate the *E1* states through the nucleon transfer. Using particle–gamma coincidence spectroscopy, excited nuclear states can be selectively populated and identified, providing a sensitive probe of low-lying *E1* strength and proton–neutron dynamics. Through these measurements, we aim to investigate the distribution and nature of low-lying *E1* transitions and improve our understanding of dipole excitations in medium-mass nuclei.

Current work on nuclear reactions focuses on neutron emission in α-induced reactions on nuclei at the VECC K130 Cyclotron, Kolkata to understand the pre-equilibrium through emitted neutron detection. Experimental neutron energy spectra and angular distributions are analyzed and compared with TALYS calculations to investigate pre-equilibrium (PE) neutron emission. As PE reactions represent an intermediate stage between direct and compound nuclear (CN)

processes and remain one of the least understood reaction mechanisms, the present study aims to disentangle the PE and CN contributions and understand their interplay.




We also investigate fission isomers, which are long-lived, highly deformed metastable states in heavy nuclei. These states correspond to a secondary minimum in the nuclear potential energy surface and exhibit lifetimes significantly longer than those of typical excited states. A central focus of our current experimental program is the half-life analysis of the $^{236}$U fission isomer, based on data from a recent experiment at the GSI, Germany. We first establish particle identification from the observables like magnetic rigidity, time-of-flight, energy loss, and position information. The identified events are then searched for implantation–decay time correlations consistent with the fission isomer decay. The primary challenge is to demonstrate that the extracted time distribution reflects a genuine half-life measurement rather than background events, imperfect gates, or spurious correlations.



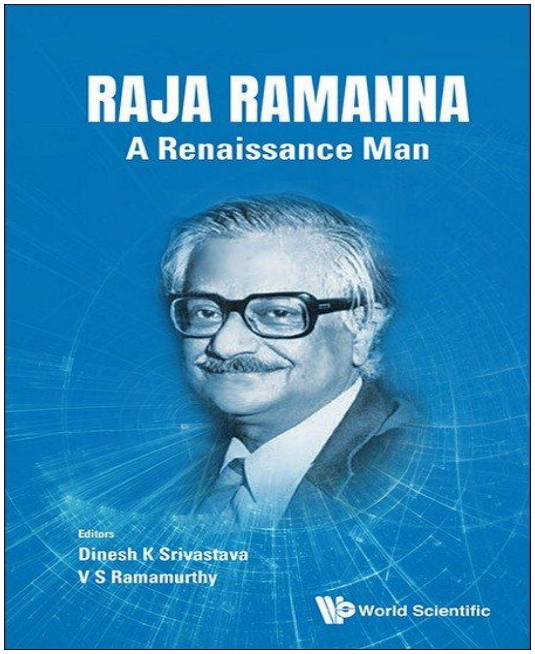

Complementing these experimental programs, our research also pursues machine-learning studies of nuclear systematics alongside work in detector characterization.

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***Dr. Soumya Bagchi*** *is an Associate Professor in the Department of Physics at IIT (ISM) Dhanbad. He is actively involved in teaching and guiding students, contributing to both academic research and the development of young scientists. He is also the Chief Editor of Nuclear Horizons.*

# The Resonance of a Renaissance: The Raja Ramanna Story

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We recently had the privilege of editing a book "Raja Ramanna: A Renaissance Man", containing memoirs from several of his colleagues from across the nation and fields [1]. Summarising the life and contribution of such a colossus in a short space is beyond us. We give here a gist, based on the views of some of the contributions to the volume.

**The Overture: Mysore, 1944**

The history of a nation is often written in the ink of chance encounters. In 1944, the city of Mysore was a place of royal elegance and intellectual ferment. There, a nineteen-year-old Raja Ramanna—a young man whose fingers were as comfortable on the ivory keys of a piano as they were with the equations of physics—was introduced to Dr. Homi J. Bhabha. He was already the visionary architect of India's atomic future, but he was also a man who lived at the intersection of European art and Eastern ambition. In Ramanna, he saw more than a student; he saw a mirror. This meeting determined the course of the next sixty years. When Ramanna joined the Tata Institute of Fundamental Research (TIFR) in 1949, with a Ph. D. in Nuclear Physics and Licentiate of the Royal Schools of Music (LRSM) Diploma, Bhabha's welcome was a manifesto in itself: Ramanna was granted two rooms—one for his nuclear experiments and one for his piano. This was the "Two-Room Protocol," a philosophy that suggested a scientist without culture was merely a technician. For Ramanna, physics would always be his profession, but music would be his yoga.

**The Explorer of Fission**

To capture the full measure of the man, one must look past the heavy steel of the reactors and into the subtle, stochastic world of his theoretical mind. Ramanna's personal research in nuclear fission was characterised by a rare, intuitive leap that predated much of the international consensus. He started the Trombay Fission Group and studied nuclear fission with them using neutrons from Apsara Reactor and later charged particles from Van de Graff generator. The group is still doing pioneering work, based on one premise-chase the anomalies to unravel physics. While the world was still grappling with the rigid mechanics of how a nucleus splits, he introduced the Stochastic Model of Fission. He envisioned the process not as a simple mechanical break, but as a random diffusion of nucleons between two nascent fragments—a "random walk" of matter at the subatomic level. This theory, which he later expanded into heavy-ion reactions with his colleagues, showcased a mind that was comfortable with the "unknowability" of nature. It was a quintessentially "Ramanna-esque" approach: a blend of high-level mathematics and a philosophical acceptance of chance, proving that he was never merely an administrator of science, but a deep-

thinking practitioner of its most difficult mysteries. It was decades before it was experimentally verified in deep inelastic collision of heavy nuclei.

**The Evangelist of Nuclear Physics**

Beyond the laboratory, Ramanna acted as the great evangelist of nuclear physics, democratising a field that had once been the preserve of a few elite institutions. He saw the potential of the Indian youth as a vast, untapped energy source, much like the atoms he studied. Through the DAE Nuclear Physics Symposia, which he nurtured from their infancy in 1957, he physically moved the scientific conversation across the map—from Mumbai and Bengaluru to remote university centres in every corner of the country. He transformed these gatherings into a "Cricketing Culture" of science, where a student from a small-town college could stand before a giant of the field and be heard with respect. By building the BARC Training School, he ensured that India did not just have a nuclear programme, but a nuclear community.

He didn't just build machines; he built a self-sustaining intellectual ecosystem that allowed India to walk into the global arena of high-energy physics not as a spectator, but as an equal. He used this forum of Nuclear Physics Symposium to establish Indian Physics Association and generate consensus among researchers for large nuclear and accelerator facilities.

When asked for his advice on whether to move forward on a research collaboration proposal by a foreign laboratory, Dr Ramanna had enquired, 'How strong are we in the area?' When told that we were quite strong, he simply advised go ahead. His comment still reverberates in our corridors, ‘‘If we are very weak, we are likely to be exploited. On the other hand, if we are strong, the collaboration will make us stronger.’ This proved prophetic in the highly successful CERN and International Thermonuclear Experimental Reactor (ITER) Collaboration, and other international collaborations in Research which were to follow.

**The Architect of the Invisible: Building the Cyclotron**

By the early 1960s, the "Golden Age" of Indian science faced a fork in the road. The nation needed a high-energy particle accelerator. The global standard was to buy a "Tandem" machine from Western vendors. However, Ramanna, under Bhabha’s mentorship, pushed for a more radical path: building an Azimuthally Varying Field (AVF) Cyclotron indigenously.

To build a cyclotron is to dance with the limits of industrial tolerance. It required 260-tonne magnets where surfaces had to be machined to the precision of a human hair. The project was situated in a remote, swampy patch of Salt Lake City, Kolkata. In those early years, the site was a frontier; scientists fought off swarms of mosquitoes and local cobras by day and wrestled with unstable power grids by night.

When international "technology denial" regimes barred India from importing specialized copper conductors, Ramanna did not retreat. He turned the Variable Energy Cyclotron (VEC) into a national mission. He engaged HEC Ranchi to cast massive steel frames and BHEL Bhopal to innovate "epoxy-potted" coils that bypassed the need for banned materials. On June 16, 1977, when the first beam was accelerated, it was the "Silent Miracle" of Kolkata. It proved that the Indian spirit could not be choked by sanctions; it could only be provoked into invention. The cyclotron centre has gone on to set us a superconducting cyclotron, a medical cyclotron, and is working on a national facility for radioactive ion beams. It became training ground of generations of nuclear physicists, accelerator physicists, and engineers- several of whom moved to help establish the synchrotron radiation source at what is now Raja Ramanna Centre for Advanced Technology, Indore.

**The Desert’s Secret: Pokhran, 1974**

On May 18, 1974, the world’s geopolitical axis shifted. Under the white sands of the Thar Desert, the "Buddha Smiled." Ramanna was the mastermind of the Peaceful Nuclear Explosion (PNE), a project executed with such absolute

secrecy that even high-ranking officials were left in the dark.

When he returned to the Bhabha Atomic Research Centre (BARC) to a standing ovation that lasted until palms were bruised, Ramanna's response was a masterclass in humility. He didn't speak of glory or power. Instead, he spoke of the "capital items"—the cameras lost in the explosion pit—joking about how he would have to explain the loss to the government auditors. This was the Ramanna hallmark: the ability to carry the weight of a nuclear state on his shoulders while keeping the light-hearted wit of a scholar. He ensured that India's nuclear path was sovereign, fuelled by domestic uranium and heavy water, creating a "magnificent edifice" of national security, and avoided the trap of using enriched uranium for which we would have had to depend on imports.

**The Human Reactor: The Mentorship of Seven Thousand**

If the cyclotrons were his machines, the scientists were his soul. Ramanna understood that a laboratory is only as strong as its youngest researcher. He founded the BARC Training School, a democratic engine that moved science out of elite circles and into the hands of the common Indian.

He was a "Pole Star" for those who joined the DAE. He famously had a "hearty laugh" for the mistakes of the young, once authorising extra computing time for a student who had used up a month's quota in a single night. He was a leader who signed files on laboratory benches and rejected the "stifling clutches" of bureaucracy. By the time he completed his tenure, over 7,000 scientists and engineers had been mentored under his watch. His management creed was a simple, sacred trust: "Select the best, train them to the full, and trust them to deliver."

**The Harmony of the Atoms: The Scientific Philosopher**

Ramanna's mind was a bridge between centuries. While he managed nuclear reactors, he was also deep in the study of Gödel's Incompleteness Theorem and Heisenberg's Uncertainty Principle. To him, these were not just formulas; they were philosophical pillars that proved the "unknowability" of absolute reality.

He saw a deep symmetry between the periodic table and the Sanskrit alphabet. In 1974, the very year of the Pokhran test, he was finishing a translation of the Mukundamala, an ancient Bhakti poem. He argued that science, like art, required "Bhakti"—a total, selfless devotion to the task at hand. He was an "Indian von Humboldt," a polymath who could discuss the electronic structure of graphite in the morning and the nuance of a Vaisnavite text in the evening.

**The Lisztian Journey: A Patronage of the Keys**

In his final years in Bengaluru, the "Renaissance Man" found his most intimate expression through a teenage violinist, Anant Kamath. The man who had been the Scientific Advisor to the Defence Minister and a Member of Parliament spent his evenings as a simple piano accompanist.

His fingers, though slowed by arthritis, still sought the "tone colours" of Franz Liszt. He treated music as a laboratory, lingering on chords and stretching tempos to see how the sound would resonate in the room. He was a man who lived without "bridge phrases"—he never used his status to justify his presence. He was simply there for the music. His final public appearance at the Teen Murti Bhavan in 2003 was a rendition of Liszt's Bénédiction de Dieu dans la Solitude. It was a celestial performance, a premonition of his own return to the universe, where the "trio" of Ramanna, the piano, and Liszt became one.

**The Legacy: The Eternal Resonance**

Raja Ramanna passed away in September 2004, but his "vibration" remains the frequency of modern Indian science. He was the man who walked out of a burning plane (the 1966 crash he narrowly missed) and into a lifetime of nation-building.

He left behind a country that could build its own nuclear submarines, its own fighter jets (Tejas), and its own high-flux reactors (Dhruva). But more than the hardware, he left a "scientific temper"—a belief that India could stand as an equal on the global

stage. He proved that the pursuit of a nuclear weapon and the pursuit of a perfect sonata were part of the same human quest: to find order in the chaos and to leave the world a little more harmonious than we found it.

He helped Saha Institute of Nuclear Physics, Calcutta, Harishchandra Research Institute, Prayagraj, and Institute of Physics, Bhubaneswar, when they faced severe funding crisis and helped and guided Department of Science and Technology in its formative years. Under his guidance the Defence Research and Development Organisation became a formidable organisation. He established a unique institute like National Institute of Advanced Sciences at Bengaluru to bridge the gap between different disciplines of natural sciences, philosophy, and social sciences- a unique endeavour indeed.

The story of Raja Ramanna is the story of a Buddha who didn't just smile; he taught a nation how to build, how to think, and how to drink deep at the fountain of music and philosophy. It comes as no surprise that he named his autobiography, "Years of Pilgrimage" [2].

*We are grateful to Drs Ashok Kumar Jain and B. P. Singh for inviting us to write an article based on our book about Dr. Ramanna, for the newly founded Indian Nuclear Physics Association.*

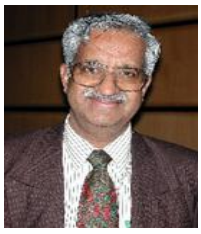
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***Professor D. K. Srivastava*** *is a distinguished Indian physicist and an INSA Senior Scientist at the National Institute of Advanced Studies (NIAS) in Bengaluru. He previously served as the Director of the Variable Energy Cyclotron Centre (VECC) in Kolkata.*



***Professor V. S. Ramamurthy*** *is a highly renowned Indian nuclear physicist who currently serves as an Emeritus Professor at the National Institute of Advanced Studies (NIAS) in Bengaluru. He has also served as the Secretary, Department of Science & Technology, and Director, Institute of Physics, Bhuvneshwar.*

NUCLEAR HORIZONS: A Bulletin of Indian Nuclear Physics Association

# Nuclear Structure Studies: From Fundamental Symmetries to Exotic Nuclei

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Fundamental symmetries form the backbone of modern nuclear physics, providing deep insights into the underlying laws governing nuclear interactions. Symmetries such as rotational invariance, isospin symmetry, gauge symmetry, and discrete symmetries like parity (P), charge conjugation (C), and time reversal (T) play a crucial role in shaping both the theoretical frameworks and experimental investigations. They not only simplify the complex many-body problem of the nucleus but also lead to conservation laws that guide our understanding of nuclear structure and reactions.

From a theoretical perspective, symmetries are essential in constructing nuclear models. Rotational symmetry leads to conservation of angular momentum and explains the occurrence of rotational bands in deformed nuclei. Isospin symmetry treats protons and neutrons as two states of the same particle, allowing unified descriptions of nuclear forces and mirror nuclei. Group-theoretical approaches, namely the Interacting Boson Model (IBM), exploit algebraic symmetries, U(6), SU(3) and O(6) to classify nuclear shapes and predict excitation spectra across entire regions of the nuclear chart. More advanced frameworks, such as chiral effective field theory ($\chi$EFT) and nuclear density functional theory (DFT), are built upon chiral symmetry, the approximate symmetry that connects nuclear forces to the underlying theory of quarks and gluons known as quantum chromodynamics (QCD). Chiral symmetry provides the mathematical scaffold that allows nuclear theorists to calculate forces between nucleons step by step, with reliable and improvable estimates of uncertainty built in; without it there would be no principled way to assign reliable error bars to nuclear structure calculations. Spontaneous symmetry breaking explains nuclear deformation, while explicit breaking, such as isospin violation due to electromagnetic interactions, provides important corrections to nuclear models and often reveals subtle effects pointing toward new physics.

On the experimental side, nuclear systems offer a unique laboratory to test fundamental symmetries with high precision. In 1936 Tuve, Heydenburg, and Hafstad measured proton–proton scattering at the Carnegie Institution and found, after correcting for Coulomb repulsion, that the nuclear force between two protons is identical to that between a neutron and a proton [1], the first direct experimental proof that the strong force respects isospin symmetry. Wigner formalised this result by showing that isospin groups nuclear levels into multiplets and explains the near-identical spectra of mirror nuclei such as $^{3}$H and $^{3}$He. Precision spectroscopy of nuclear energy levels and transitions continues to provide some of the most stringent tests of isospin symmetry and its breaking.

Parity conservation in nuclear reactions was taken for granted until Lee and Yang challenged it for the weak interaction. Wu and collaborators settled the question in 1957 by observing the $\beta$-decay of polarised $^{60}$Co: the emitted electrons showed a clear directional asymmetry with a parameter exceeding 0.7 [2],

proving that the weak interaction violates parity maximally. In 1964, Christenson, Cronin, Fitch, and Turlay observed a neutral particle, the long-lived kaon decaying in a way that should be forbidden if the combined symmetry of charge conjugation and parity were exact [3]. A deep result of quantum field theory, the CPT theorem, tells us that the combined operation of charge conjugation, parity, and time reversal must always be conserved, so this violation implies that time-reversal symmetry is broken as well. A direct nuclear check by von Witsch, Richter, and von Brentano compared the rates of the same nuclear collision run forwards and in reverse and found them equal to within about one percent [4]: the strong nuclear force respects time reversal to high precision even though the weak force does not. Physicists today search for a tiny misalignment between a nucleus's charge distribution and its spin axis, called an electric dipole moment which can only exist if both parity and time reversal are violated simultaneously. Isospin symmetry has its own subtler crack: since 1969, calculations of the energy difference between mirror nuclei have consistently underestimated measured values by about 7%, the Nolen–Schiffer anomaly. Cohen, Furnstahl, and Banerjee showed that part of this gap arises because the proton-neutron mass difference is itself modified inside nuclear matter through partial restoration of chiral symmetry [5], directly linking a macroscopic nuclear measurement to quark-level dynamics.

The interplay between symmetry and its breaking becomes most vivid when we move beyond the roughly 260 stable nuclei of the valley of stability to the approximately 3,000 nuclei known today and the perhaps 7,000 that theory predicts should exist before the nuclear force can no longer hold any more neutrons. Near stability, nuclear shell closures at the magic numbers N,Z = 2,8,20,28,50,82,126 arise from the symmetry of the nuclear mean field and the spin-orbit interaction; a nucleus with a magic number of protons or neutrons is unusually stable and nearly spherical, much like the chemical inertness of noble gases with closed electron shells. Modern radioactive ion beam (RIB) facilities have shown that these landmarks are not universal. The nucleus $^{31}$Na carries N = 20 neutrons, usually expected to be a magic number, yet measurements of its quadrupole moment reveal it to be strongly deformed: the N = 20 shell closure has dissolved, replaced by an island of inversion in which energy levels from the next major shell drop below their expected positions as the neutron-to-proton ratio increases, reshuffling the symmetry of the mean field. The same erosion afflicts N = 28 in $^{42}$Si, which is highly deformed, yet symmetry does not simply disappear; it reorganises. The measurements at RIKEN of the first excited state of $^{54}$Ca revealed a level pattern providing clear evidence that N = 34 has become a new magic number [6], absent anywhere near the valley of stability.

The most pronounced manifestation of symmetry reorganization is observed in weakly bound nuclei near the neutron and proton drip lines. As one moves toward the drip line, the binding energy of the outermost nucleons falls to just a few hundred keV, comparable to or smaller than typical nuclear excitation energies. At this point the familiar discrete energy levels of the bound nucleus begin to merge with the continuum of unbound scattering states. This continuum coupling violates the strict separation between bound and unbound degrees of freedom that underlies the conventional shell-model description, causing the effective symmetry of the nuclear mean field to break down and familiar magic-number gaps to dissolve. Entirely new structural phenomena emerge as a consequence. The nucleus $^{11}$Li is the textbook example: its two outermost neutrons are so loosely bound that they form a dilute quantum halo extending to a radius comparable to that of $^{208}$Pb, despite $^{11}$Li being nearly twenty times lighter. What makes this possible is a property called Borromean binding,

neither the pair $^{10}$Li nor a bare di-neutron is bound on its own, yet the three-body system $^{11}$Li holds together through quantum correlations with no classical analogue, a direct consequence of the way continuum coupling reshapes the effective symmetry of the potential. The halo nucleus $^{37}$Mg, identified at RIKEN in 2014 as the heaviest halo nucleus then known [7], provides a more recent example: the intruder orbital that drives the halo arises precisely because the N = 28 shell symmetry breaks down at extreme neutron excess, allowing a loosely bound p-wave state to spill outward. In the proton-rich mirror systems, the Thomas-Ehrman shift, an asymmetry in the energy levels of mirror-nuclei pairs caused by the different spatial extent of weakly bound proton states near the Coulomb barrier offers a experimental probe of how electromagnetic interactions and continuum coupling together break isospin symmetry in a regime simply unreachable with stable beams.

Symmetry principles continue to play a crucial role in understanding weakly bound nuclei, but their manifestation becomes more nuanced. While the underlying nuclear Hamiltonian remains invariant under rotations, isospin transformations, and parity operations, the proximity to particle emission thresholds enhances the effects of symmetry breaking and mixing. For example, parity inversion observed in certain neutron-rich nuclei reflects the delicate balance between shell structure and continuum coupling. Similarly, large neutron-proton asymmetry leads to modifications in isospin symmetry, influencing effective interactions and excitation modes. The most significant conceptual shift is the recognition that weakly bound nuclei are inherently open quantum systems. Unlike closed systems with discrete spectra, these nuclei exhibit coupling to decay channels, leading to resonance states with finite lifetimes and complex energies. This necessitates an extension of traditional quantum mechanics to include non-Hermitian formulations and generalized boundary conditions, fundamentally altering how symmetry and structure are understood. Together these systems demand theoretical frameworks that place bound and unbound states on an equal footing, opening a new chapter in how symmetry principles are incorporated into nuclear structure theory.

The role of symmetry extends well beyond exotic nuclei into some of the most consequential questions in physics and astrophysics. In astrophysics, the large reaction networks used to model how the heaviest elements are forged in neutron-star mergers must track thousands of nuclear species; a fundamental consequence of time-reversal symmetry requires every reaction and its reverse to stay in balance at thermal equilibrium, and networks that violate this accumulate errors of several percent in predicted elemental abundances [8]. The shell structure of exotic nuclei near the neutron drip line directly controls which reaction pathways are available and therefore which elements are synthesised. The extra energy cost of making nuclear matter neutron-rich, the nuclear symmetry energy determines neutron-star radii and stiffness, and was directly constrained by the gravitational-wave signal from a neutron-star merger in 2017, opening a route to nuclear physics in environments no laboratory can recreate. A rare process in which two neutrons inside a nucleus simultaneously become two protons emitting only electrons and nothing else would, if observed, establish that neutrinos are identical to their own antiparticles, with profound consequences for understanding why our universe contains more matter than antimatter; whether this occurs depends sensitively on proton-neutron correlations inside the nucleus, connecting symmetry studies to one of the deepest open questions in fundamental physics.

Fundamental symmetries serve as a unifying principle in nuclear physics, linking theoretical formulations with experimental observations. Their role

extends from simplifying complex nuclear interactions to enabling precision tests of the Standard Model and guiding the search for new physics. The evolution of symmetry in exotic nuclei, with familiar magic numbers dissolving and new ones emerging shows that the nuclear chart holds far more structure than the valley of stability suggests. By investigating when symmetries hold and how they break, nuclear physics offers insight into the governing interactions across scales, from the quark dynamics inside nucleons to the equation of state of neutron stars. Continued advances in both experimental techniques and theoretical methods promise to deepen our understanding of these symmetries and their implications for the structure of matter and the evolution of the universe. Further, the weakly bound nuclei serve as a bridge between nuclear structure, reaction dynamics, and astrophysics. They challenge established theoretical frameworks, reveal the limitations of traditional models, and offer a fertile ground for exploring the interplay between binding, symmetry, and continuum effects. Their study continues to deepen our understanding of quantum many-body systems under extreme conditions, making them a central focus of modern nuclear physics research.

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# India's Prototype Fast Breeder Reactor attains Criticality

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India's natural uranium reserves are modest. The first stage of India's nuclear power programme therefore involves use of natural uranium with heavy water moderator in PHWRs, which produce not only energy but also some fissile plutonium. The spent fuel from PHWRs contain small quantities of unutilized $^{235}U$, $^{239}Pu$ and large quantities of $^{238}U$. The recovered $^{239}Pu$ along with $^{238}U$ forms the fuel for the fast reactors.

Domestic natural uranium availability can sustain PHWRs power programme of ~10,000 MWe capacity, after which no further reactors can be fuelled, and the programme would be difficult to sustain. These reactors utilise only $^{235}U$ (0.7% in Natural Uranium rest 99.3% being $^{238}U$). While some conversion of $^{238}U$ to $^{239}Pu$ takes place in PHWRs, higher conversion rates are possible only in the fast Reactors. Hence the second stage involving fast breeder reactor became essential for India to effectively utilise the $^{238}U$ resources.

The second stage will use $^{239}Pu$ recovered from the reprocessed PHWR spent fuel along with depleted uranium, mostly containing $^{238}U$, in fast reactors. This will convert the fertile $^{238}U$ to fissile $^{239}Pu$. The capability of conversion of fertile $^{238}U$ or $^{232}Th$ depends on the number of neutrons produced in fission. This is denoted by factor $\eta$ which is the ratio of number of neutrons emitted per fission of a fissile nucleus. Besides one neutron to continue the fission chain, additional neutrons would be used for converting the fertile nuclei to fissile. This factor must be greater than 2, allowing for parasitic absorption of neutrons in other structural materials. Table 1 shows the value of $\eta$ for the different fissile nuclei and isotopes of interest.

***Table 1: $\eta$ values for different fuels***

| Neutron Energy | $^{235}U$ | $^{239}Pu$ | $^{233}U$ |
|---|---|---|---|
| 0.025ev | 2.44 | 2.87 | 2.48 |
| 100 Kev | 2.5 | 3.02 | 2.55 |

$^{239}Pu$ has highest $\eta$ in the fast neutron region while $^{233}U$ has the highest in the slow neutron region. Hence when Pu is used as the fissile material the reactor must be a fast reactor while with $^{233}U$ as the fissile material, thermal reactors would be the preferred choice. While the first few fast reactors would be converting $^{238}U$ to $^{239}Pu$, the latter fast reactors fuelled by $^{239}Pu$ would convert $^{232}Th$ to $^{233}U$.

The third stage will then use $^{233}U/^{232}Th$ combination in fast and/ or thermal breeders to fully exploit available Thorium to produce power. It must be borne in mind that India can generate up to 300 GWe with depleted uranium itself available from spent fuel of PHWR which may last for about 100 years. The third stage is still under development. Thorium utilisation is also important as India has considerable large thorium reserves. Indian priorities are, thus, quite unique. For its long-term energy security India has no option but to deploy nuclear power according to a strategy precisely tuned to its needs and resources. The three-stage nuclear power programme is depicted in Fig. 1.

In view of the fact that India is a non-signatory to the non -proliferation treaty which is discriminatory, the nuclear cooperation with other countries is practically nil. This has an advantage in the

long run, in that we develop our own design and construction capabilities and can be independent to chalk out the programme in the national interest.

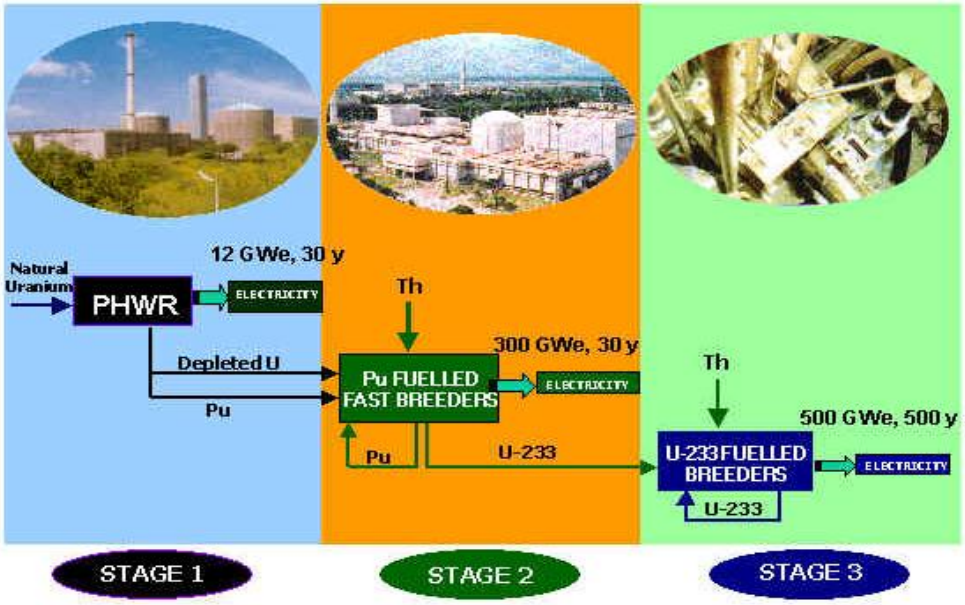



***Figure 1: India's Three Stage Nuclear Power Programme***

The first stage comprises the Pressurised heavy water reactors (PHWR) and the present Installed capacity of these reactors at present is 6780 MWe and construction activities are in progress for 3500 MWe (5*700 MWe). Besides PHWRs we have two light water reactor plants (imported from Russia) producing 2000 MWe at Kudankulam, Tamilnadu and construction of further four such units of 1000 MWe is in progress.

The second stage started with the design, construction and operation of the Fast Breeder Test Reactor (FBTR) (40MWt/13.2 MWe) at Kalpakkam in Tamilnadu. This reactor though based on the French reactor RAPSODIE design, incorporates a turbine generator circuit. Unlike PHWRs, wherein a moderator is used to slowdown the fast neutrons produced in fission to have greater fission probability, in fast reactors fission is with fast neutrons from breeding considerations and no moderator is used. In view of higher neutron energies with less fission probability more fissile inventory is needed for fast reactors.

All the components of FBTR were fabricated by Indian industries. FBTR went critical in 1985 and is operational. With the experience from FBTR, India ventured into a prototype fast breeder reactor (PFBR) of 1250 MWt/500 MWe. This reactor incorporates many safety features based on the international experiences. Fast reactors use either enriched uranium or Plutonium as the fuel. Since enrichment is a costly process and needs lot of R&D, Indian fast reactors use Pu as the fissile material. To have the highest cycle efficiency (Electrical power/ Thermal power), steam temperature needs to be high and hence sodium is used as the reactor coolant so that reactor outlet temperatures are ~500 deg. C and above.

However, sodium has high affinity to water and oxygen and hence the design has to ensure absence of leakage of water/air into the sodium. Large amount of operational experience has been gained in handling sodium at the Indira Gandhi Centre for Atomic Research at Kalpakkam since 1970.

To ensure that under no condition moderating materials get into the core (which can cause increase of power) another sodium circuit is interposed between the reactor coolant circuit and steam water systems. An Intermediate Heat exchanger (IHX) does the job of

transferring heat from reactor coolant to intermediate sodium which in turn transfers heat to water in the steam generators to produce superheated steam to run a turbine generator and produce electricity. Sufficient experience has indicated that water leaks into sodium in the steam generator can be easily detected (hydrogen concentration measurement) and any sodium leak event can be managed. Many sensors for incorporation in sodium systems have been successfully developed and implemented. One of the important sensors is the sodium ionization detector, which can detect nanograms/cc of sodium aerosols in air. And the other is the ultrasonic under sodium viewer to view objects under sodium. A schematic of the FBTR is shown in Fig 2. It can be seen that the reactor, the IHX and steam generator are linked by pipelines and requisite pumps.

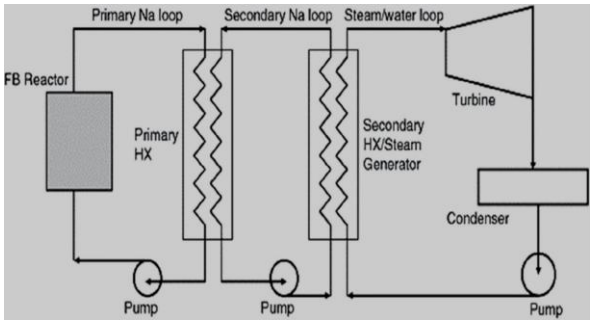



***Figure 3: Schematic of FBTR.***

PFBR incorporates experience in design of FBTR and other international reactors like Phenix, Super-Phenix in France (now Shutdown). The major change is that in PFBR the sodium pump pumping sodium into the reactor core and the IHX are placed in a larger vessel (main Vessel) surrounding the core which is located in the inner vessel (Fig.3). This minimizes the

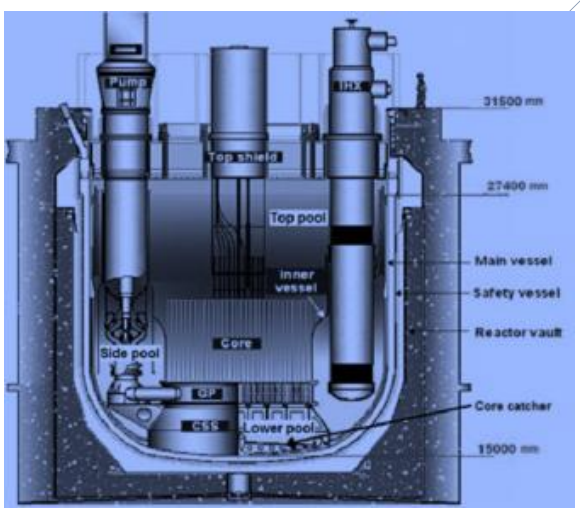



***Figure 2: Prototype Fast Breeder Reactor***

chance of sodium leakage as there are no pipes. It also provides a large sodium thermal capacity, which is helpful in slower rise of temperatures in case of any event.

In view of the large sizes of vessels and components a stage of technology development was introduced after FBTR towards the manufacturing of main vessel, steam generator and sodium pumps, besides materials development. Parallelly testing of components in sodium was carried out in the Engg. Dev. Laboratories at the Indira Gandhi Centre for Atomic Research, Kalpakkam. Steam generator being an important component a separate test facility for steam generator was built and it validated our design, manufacture, sensor development and in-service inspection tools.

The neutron flux at the core center varies from $1 \times 10^7$nv at shutdown to $8 \times 10^{15}$nv at nominal power (~1250 MWt). The neutron flux at detector location below the safety vessel is $1.34 \times 10^5$ nv at nominal power. The location of neutron detectors in a typical SFR is shown in Fig. 4.

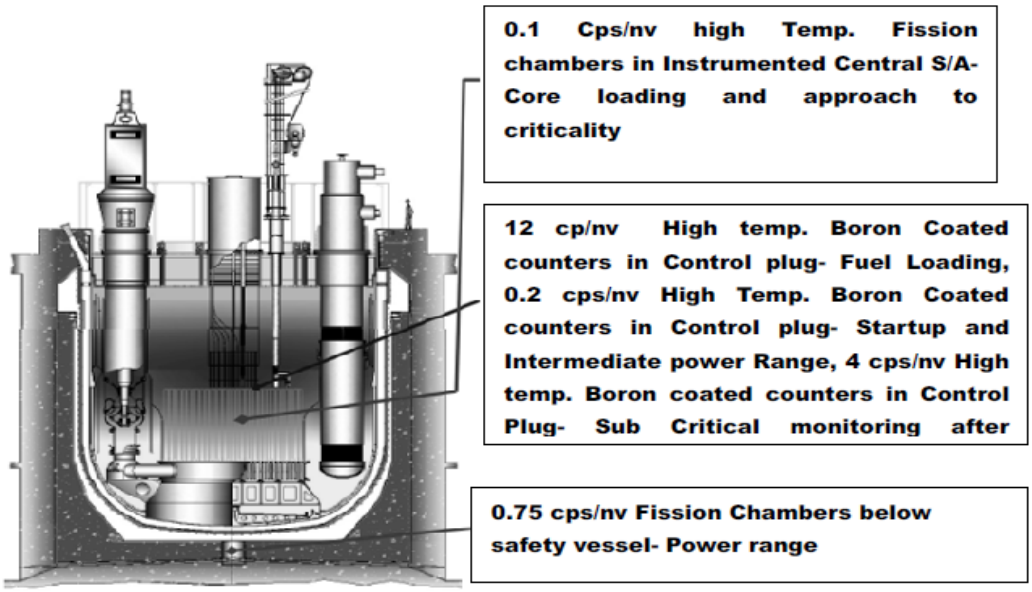



***Figure 4: Location of neutron detectors***

PFBR achieved its criticality on 6 April, 2026, indicating the presence of a continuous self-sustained chain reaction. All the neutron detectors developed indigenously behaved very well leading to smooth approach to criticality. The reactor power is ~ 100 KW now. Low power physics experiments are being carried out to measure the neutronic parameters and also verify proper operation of the neutronic and other sensors. The power will be raised slowly and various commissioning tests will be carried out to ensure that all components are delivering their requisite outputs.

At every stage right from design, site selection, start of construction, fuel loading and first approach to criticality, there is intense interaction and exchange of information with the committees of the Atomic Energy Regulatory Board (AERB). Only when AERB is convinced about safety aspects being followed, it will give clearance for the next step. It is a great achievement, though delayed for VIKSIT BHARATH. PFBR is our own reactor.

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# Capacity Building Initiatives in Nuclear Energy at Ramdeobaba University, Nagpur

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**Introduction**

In line with India's vision of achieving energy security and self-reliance through advanced nuclear technologies, there is a growing need to develop a highly skilled multidisciplinary workforce in the nuclear domain. Academic institutions play a vital role in creating strong educational, research, and innovation ecosystems to support this national mission. Recognizing this need, Ramdeobaba University (RBU), Nagpur, has initiated focused efforts toward capacity building in nuclear science and engineering through academic programmes, interdisciplinary initiatives, and proposed research activities.

**About Ramdeobaba University, Nagpur**

Ramdeobaba University (RBU), formerly known as Shri Ramdeobaba College of Engineering and Management (RCOEM), is a self-financed university approved by the Government of Maharashtra and the University Grants Commission (UGC), New Delhi. Established in 1984 under the aegis of Shri Ramdeobaba Sarvajanik Samiti, the institution is named after Saint Ramdeobaba, a revered 14th Century saint from Rajasthan known for his humanitarian values and social contributions.

Over four decades, the institution has evolved from an affiliated engineering college to an autonomous institute and finally attained the status of a full-fledged university in 2024. RBU has earned several prestigious recognitions including NAAC A+ Accreditation, Diamond Rating by QS I-Gauge, National Employability Awards, and strong performance in NIRF rankings.

Presently, the university has more than 7000 students and around 330 faculty members, including 162 Ph.D. holders and seven faculty members with post-doctoral qualifications. The institution consistently achieves excellent placements, with more than 90% students placed in core engineering and IT domains.

RBU has developed a vibrant innovation ecosystem through Centres of Excellence established with industries such as Microsystems with Intellisense, RCOEM-TATA-CIIIT,Energy research Centre and QCFI centre of excellence. Recently, RBU has initiated transformation into an AI-ready campus with advanced NVIDIA DGXB200 Next-gen GPU Centre, state of art Cyber Security and Digital Forensic Laboratory, Juniper Centre of Excellence and NetSim Simulator and Emulator laboratories. The university also operates the Section-8 company, RCOEM Technology Business Incubators Foundation, to nurture entrepreneurship and promote start-ups.

**Capacity Building Initiatives in Nuclear Energy at Ramdeobaba University**

Recognizing the growing importance of nuclear energy in India's future energy landscape, the university extended the activities of its Energy Research centre and initiated academic capacity-building activities in nuclear science and engineering. These initiatives aim to develop awareness, build foundational competencies, and foster interdisciplinary research interest among engineering students. The programmes are designed to introduce students to nuclear science fundamentals, develop understanding of nuclear systems, and prepare them for higher studies, research, and careers in the nuclear sector.

i) **Multidisciplinary Minor Track: Basics of Nuclear Systems**

This proposed academic track is designed as an introductory programme for engineering students from all branches.

This 12-credit multidisciplinary track has Four courses distributed across Semesters III, IV, VI, and VII. The track is open to students from all the engineering disciplines of Ramdeobaba University. This track will provide interdisciplinary exposure and help students appreciate the role of nuclear systems in sustainable development and national progress.

**ii) Minor Specialization in Nuclear Energy Systems**

In addition to the multidisciplinary track, RBU also proposes a more intensive Minor Specialization in Nuclear Energy Systems aimed at students interested in advanced learning and specialization.

This is an 18-credit specialization programme with four courses offered across Semesters III to VI and a Capstone project in Semester VII.

The programme will adopt a project-based and experiential learning approach with provisions for Internships, Laboratory exposure, Elective courses, Research-oriented mini projects and Industry and institutional interactions. Students successfully completing the programme will receive a Minor Specialization Certification in Nuclear Energy Systems, enhancing their academic profile and future employability in the nuclear sector.

**iii) Establishment of Nuclear Physics and Engineering Laboratory**

The proposed Nuclear Physics and Engineering Laboratory at Ramdeobaba University is envisioned as a multidisciplinary facility to support teaching, training, and subsequently the research in nuclear science and technology. The laboratory will provide hands-on exposure to fundamental concepts of radiation measurement, nuclear instrumentation, reactor systems, and radiation safety. The proposed setup includes basic instruments such as Geiger–Müller counters, scintillation detectors, radiation survey meters, dosimeters, NIM modules, digital oscilloscopes, and radioactive source demonstration kits. The laboratory will also support experiments related to nuclear electronics, detector characteristics, counting statistics, and shielding studies.

**iv) Envisaged Future Programmes in Nuclear Engineering**

As part of its long-term vision, Ramdeobaba University is also exploring the development of comprehensive undergraduate, postgraduate, and research programmes in Nuclear Engineering and allied domains. The proposed programs include B.Tech Programme in Nuclear Engineering, M.Tech Nuclear Energy Systems and Research and Doctoral Programmes.

Earlier, an MoU with Bhabha Atomic Research Centre led to a collaborative project on "Development of LED Based Dosimeters for Personal Monitoring." The project resulted in a patent, several SCI-indexed publications, and significant advancements in personal radiation monitoring systems. The collaboration strengthened research in radiation dosimetry, nuclear instrumentation, and academia–research laboratory interaction in the nuclear technology domain.

The proposed nuclear energy initiatives at Ramdeobaba University aim to strengthen India's advanced energy ecosystem through interdisciplinary education, research, innovation, and industry collaboration, fostering a skilled and future-ready workforce to support sustainable growth, technological self-reliance, and clean energy leadership.

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NUCLEAR HORIZONS: A Bulletin of Indian Nuclear Physics Association

# Variable Energy Cyclotron Centre (VECC): Recent Upgrades

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**Abstract:** *Development of state-of-the-art experimental facilities for exploring the enigmatic nuclei and understanding its properties has been one of the primary research objectives at **V**ariable **E**nergy **C**yclotron **C**entre (VECC). Along with research, social responsibility of taking the benefits of research to public led to the development of three major cyclotron facilities at this center. It is a rare achievement that sustained operations of all three cyclotron continues along with upgradion programs at VECC with a mission of performing high resolution, high precision experiments on frontier research topics. This article presents a brief discussion on upgradion carried at VECC to meet the centre's mission and vision.*

## Introduction

Indian accelerator programme was pioneered by Dr. Meghnad Saha and his dreams came true when city of Kolkata was blessed with first cyclotron of independent India. Recently, this city has been conferred a new name "City of Cyclotrons" by Dr. Bikash Sinha, a visionary for Nuclear Science community, in recognition of holding three major cyclotron facilities. The first cyclotron, a cyclotron operational at room temperature (K130), which is also called "first nocturnal cyclotron" was born in 1977, amid political turmoil and extreme power crisis. With no available technology infrastructure to meet the demand of a cyclotron, this accomplishment gave the scientists and engineers confidence to take up a more difficult challenge of building a superconducting cyclotron. A vivid description of struggles encountered in building these two cyclotrons can be found in two articles published in Statesman [1]. As main agenda of these two cyclotrons was research, along with facing new challenges in building cyclotrons, scientists and engineers were building state-of-the-art experimental facilities for utilization of available beams. Confidence built over years led to timely decision of developing **R**adioactive **I**on **B**eam (RIB) facility, which may be as a considered a current global scientific challenge. The centre was engaged in one hand with an intensive beam development programme with a focus on improvement on the beam quality, intensity and number of beam species, including RIB, on the other hand there was development of advanced detector systems for improving the experimental infrastructure with a motivation to widen the experimental horizon for the researchers. At one time, the scientists at VECC felt that the time has come when the fruits of arduous research should reach the society. So, medical cyclotron programme was taken up and "Cyclone 30" started production of isotopes for detection and diagnosis of cancer. With a goal of providing the best research environment and extend its benefits to society, center is evolving with continuous upgradation. All recent developments at these three cyclotron facilities for advancing nuclear research and application programmes will be discussed in this article.

## 1. Upgradation at Room Temperature Cyclotron (K130)

At birth in the year 1977, room temperature cyclotron was delivering only proton, deuteron and alpha beams and continued till 1996. Subsequently, heavy ion acceleration was facilitated and at present, RTC can provide a wide variety of

beams (proton ~7 to 15 MeV, deuteron ~14 to 25 MeV, alpha ~ 26 to 55 MeV and heavier ion beams ~ 7-10 MeV/A). A recent achievement in heavy ion is successful acceleration of Sulphur $10^{+}$ beam. There were three beam lines. The first beam line is used for irradiation-based experiments and typical beam current is 3μA. In the second and third beam line a variety of experiments are performed and a typical layout of detectors around the small scattering chamber is shown in Figure 1. A fourth beam line is dedicated for development of RIB facility.

As a part of upgradation programme, complex detector systems have been developed [2], however modular nature of these detectors facility has facilitated that a portion can be used for an experimental setup at any of the Cyclotrons at VECC.

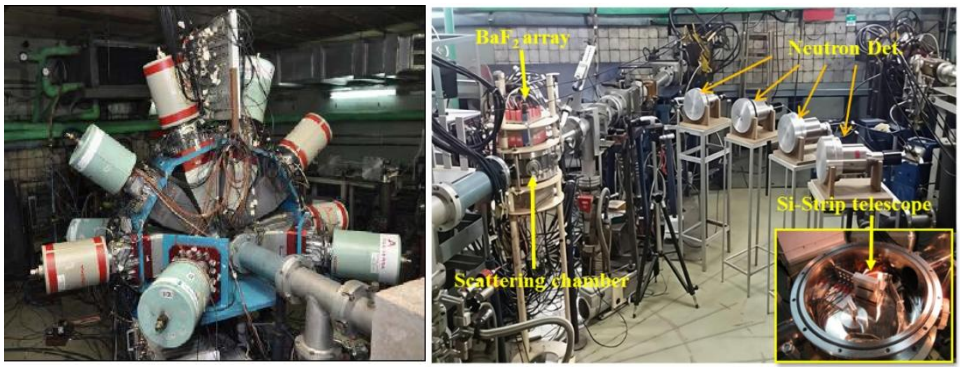



***Figure 1: (a) INGA array setup with CLOVER and LEPS detectors (b) Typical experimental setup comprising of BaF2 array, Neutron Detectors, Si-Strip telescope.***

## 2. RIB Facility and upgradation programme

RIB facility developed at VECC, uses the K130 cyclotron to produce radioactive isotopes, which are ionized by an ECR source and accelerated by an RFQ and three heavy-ion LINACs, delivering beams up to 1 MeV/u. Schematic layout is shown in Figure 2 and isotopes delivered till date are listed in Table 1.

***Table 1***

| RIB | Prod. route | T1/2 | I(pps) E(keV) before RFQ |
|---|---|---|---|
| $^{14}O$ | $^{14}N(p, n)$ | 71 s | $5.0 \times 10^{3}$ ; 10 keV |
| $^{42}K$ | $^{40}Ar(\alpha,pn)$ | 12.36 hr | $2.7 \times 10^{3}$ ; 5 keV |
| $^{43}K$ | $^{40}Ar(\alpha,p)$ | 22.3 hr | $1.2 \times 10^{5}$ ; 8 keV |
| $^{41}Ar$ | $^{40}Ar(\alpha,2pn)$ | 109 min | $1.3 \times 10^{3}$ ; 5 keV |
| $^{111}In$ | $^{nat}Ag(\alpha,xn)$ | 2.8 days | $1.6 \times 10^{5}$ ; 5 keV |
| $^{11}C$ (new) | $^{14}N(p, \alpha)$ | 20.4 min | $5.0 \times 10^{3}$ ; 10 keV |

With an experience in building RIB facility, a further upgradion has been planned under the **A**dvanced **N**ational **F**acility for **U**nstable and **R**are **I**on **B**eams (ANURIB) project [3], which intends to significantly enhance the intensity and energy of radioactive ion beams.

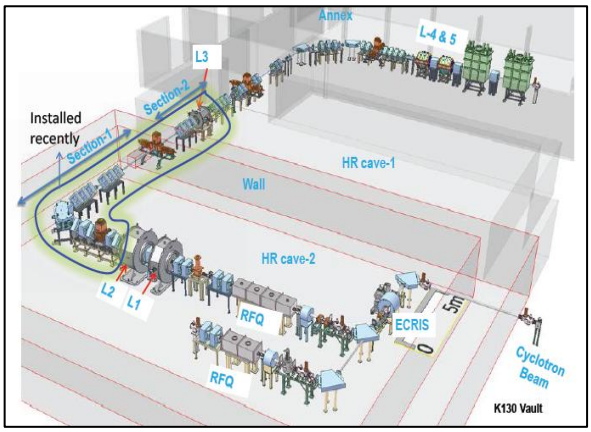



***Figure 2: Schematic layout of RIB Facility***

## 3. Upgradation of Detector Setups

### (a) Discrete Gamma Spectroscopy

Among the experiments performed at the RTC (K500) accelerator facility, the availability of INGA (Indian National

Gamma Array) consisting of Compton suppressed CLOVER detectors, enabled pioneering studies in nuclear structure physics at VECC. The first campaign with INGA at VECC, dates back to 2004-2006. The campaign completed recently, INGA setup consisted of total twelve Clover type HPGe detectors with option for placing 11 HPGe Compton suppressed CLOVER detectors and one LEPS detectors. INGA was augmented with a PIXIE-16 based digital data acquisition system provided by IUAC, Kolkata. Out of all the detectors placed in the INGA setup, VECC contributed upto eight Compton suppressed Clover HPGe detectors which is a part of VENUS (**V**ECC array for **NU**clear **S**pectroscopy) used as off-line gamma-spectroscopic studies. A typical INGA setup is shown in Fig 1(a).

**(b) Fast timing array for nuclear level life-time measurement ~pico-second**

Development of γ-γ fast timing Array, VENTURE (**VE**CC Array for **N**uclear fast **T**iming and ang**U**lar cor**RE**lation studies), comprising of 1inch x 1 inch $CeBr_3$ Detectors was initiated in 2011. A typical VENTURE configuration with CLOVER detectors coupled is shown in Figure 3.



***Figure 3: VENTURE array of eight 1" X 1" fast scintillator CeBr3 detectors, coupled to two Compton suppressed Clover HPGe detectors***

Nuclear level life-time with a precision of 5ps could be achieved using such a setup.

The array has been utilized for understanding different structure phenomenon across like (i) nuclear shape co-existence in A ~150 region, (ii) octupole correlations in A ~130 nuclei, (iii) double shell closure effect of Z = 50 and N = 82, (iv) Subshell closure at N = 40 etc. As a part of upgradation of this detector array, optimal design configuration has been completed with about 25 numbers of $\phi$=2 inch and length = 1inch detectors coupled to fast PMTs. The details can be found in Ref. [3].

**(c) 4π charged particle detector array (4π-CPDA)**

A large 4π array charge particle array for the studying the heavy ion reaction products at ~10-60 MeV/A beam energy has been designed, developed and characterized [4]. The array is divided into three portions with forward part built with 24 granular, high resolution charged particle telescopes, each of which is made by three layers [single sided silicon strip (ΔE) + double sided silicon strip (E/ΔE) + CsI(Tl)(E)] as shown in Figure 4. The backward part of the array consists of 112 CsI(Tl) detectors and the extreme forward part of the array is made up of 32 slow-fast plastic phoswich detectors. Part of this array is regularly used for experiments at both the cyclotrons at VECC. Precise estimation of the rare direct 3α decay of the Hoyle state of $^{12}C$ could be possible using a part of this detector array.

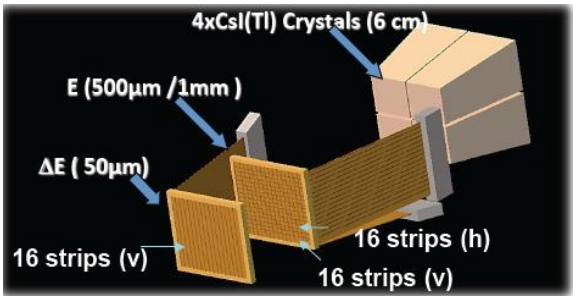



***Figure 4: Schematic of Three layer Charged particle telescope***

**(d) Neutron Detector Array**

Neutron being a particle with no charge, is difficult to detect but measurement of neutron multiplicity, time-of-flight

provides powerful means for determining the nuclear properties in excited conditions. Indigenous development of liquid scintillator (BC501A) based neutron detector was initiated for understanding (i) nuclear level density dependence on excitation energy, (ii) angular momentum,

(iii) iso-spin, (iv) collectivity, (v) shell effects etc. Modular detectors were developed for time-of-flight measurements, used in different configuration in experiments, led to deeper insights of characteristics of nuclei at extreme conditions. A typical experimental setup using these detectors in association with others detectors is shown in Figure 1(b). At present 50 neutron detectors are available at VECC and similar detectors are being fabricated as in-kind contribution to FAIR (**F**uture for **A**ntiproton and **I**on **R**esearch). In addition to liquid (BC501A) liquid, plastic (EJ-299-33A) scintillator based neutron detectors have been developed at VECC [5]. An exploration in going on development of **G**as **E**lectron **M**ultiplier (GEM) based neutron detector with the drift cathode of the detector was coated with 90% enriched B10 powder, with a motivation to develop novel kind of neutron detector.

**(e) High energy γ-ray detector array**

The **LA**rge **M**odular **B**aF2 **D**etector **A**rray (LAMBDA), consisting of 162 large $BaF_2$ detectors (each of dimension 3.5 cm ×3.5 cm × 35 cm) has been developed to study the high energy gamma rays, coming from hot composite systems produced just after beam collision with target. In addition, 50-element $BaF_2$ γ-ray multiplicity filter array (each of dimension 3.5 cm×3.5 cm×5 cm) developed built is shown in set up shown in Fig 2(a). Experimental signatures obtained from the $BaF_2$ arrays have provided significant advancement in understanding (i) nuclear shape evolution, (ii) fluidity in nuclear matter, (iii) collective enhancement of nuclear level density, (iv) clustering etc.

**(f) Gas based detectors**

At VECC, different types of hybrid axial field ionization chambers have been built for the detection of complex fragments produced in nuclear reaction study. Detector configuration like (i) ΔE section of the detectors consists of 2 cm thickness of P-10 gas at typically 80–100mb pressure (equivalent to ~ 5 μm Si) and the E section is made up of large area Silicon detector. (ii) large area position sensitive multi-wire proportional counters (typical size ~ 20 cm × 6 cm, time resolution ≤ 1 ns, position resolution ~ 2mm), (iii) parallel plate avalanche counters (typical active area ~ 5 cm × 3.5 cm and time resolution ~ 0.7ns), has been built indigenously. Recent development in this type of detector is a thick GEM (Gas Electron Multiplier) based low pressure detector [7]. Detectors developed were extensively used for fission fragment study providing key insights in understanding (i) nuclear deformation effects, (ii) dissipative/stochastic dynamics, (iii) collective dynamics, effect of quasi-fission in super-heavy formation etc.

**(g) Cryogenic Penning Trap**

Mass measurement of nuclei is a unique technique where fundamental property of the nuclei is explored at ground state without excitation. With this objective and for β-decay studies, development of a Cryogenic Penning Trap Facility was initiated at VECC. Cryogenic Penning Trap was operated using detection circuit indigenously developed at VECC and a schematic is given in Figure 5. As part of detection circuit development for 4K operation, two pHEMT (High Electron Mobility Transistor) based tuned coupled amplifiers was developed and characterization results are reported [8]. The amplifier's performance remained unchanged even at a high magnetic field of 5T.

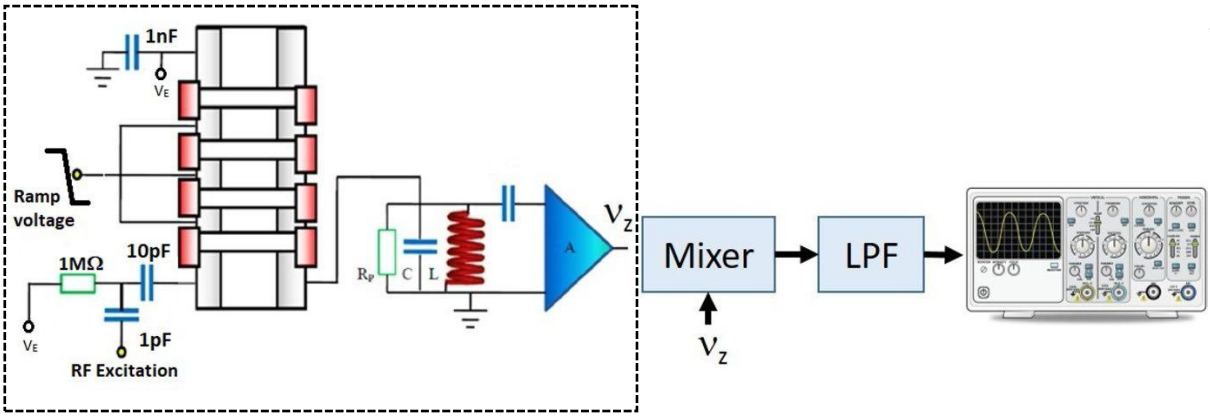



***Figure 5: Circuit for trapped particle detection using resonance absorption technique with indigenously developed cryogenic feedthrough, helical resonator and low noise amplifier in the inset.***

## 4. Upgradation at Superconducting Cyclotron: Beam and Detection facility

First external beam delivered from **S**uper **C**onducting **C**yclotron, SCC(K500) was ($^{14}$N) at E = (252.0 ± 1.0) MeV. Characterization through identification of various isotopes and precision beam energy measurements was performed in SHARC (**S**egmented, **H**orizontal **A**xis **R**eaction **C**hamber) scattering chamber using silicone surface barrier (Si-SB) detector telescope. When SCC(K500) started delivering $^{16}$O and $^{20}$Ne beams, isoscaling behavior was explored using part of 4π-CPDA array as described in section (c). Moreover, using detectors described in section (f), fission dynamics studies have been carried out. As Beam development efforts continued at SCC (K500), present several beam species are available (listed in Table-2).

**Table 2: Beam species at SCC(K500)**

| Ion | Beam Energy in MeV |
|---|---|
| $N^{4+}$ | 252, 269, 293 |
| $N^{5+}$ | 411 |
| $Ne^{6+}$ | 360, 379, 397, 416, 434 |
| $O^{5+}$ | 341, 362 |
| $Ar^{6+}$ | 200,204,216, |
| $Ar^{8+}$ | 720 |
| $Ar^{11+}$ | 740 |
| $Kr^{12+}$ | 420 |

## 5. Upgradation at Medical Cyclotron

The 30 MeV, Medical Cyclotron Facility became operational on September 18, 2018. Production and supply of Fluro-Deoxy-Glucose (FDG) radiopharmaceutical (by BRIT operated by VECC) has continued on regular basis since its inception. In addition, there is an ongoing search for production of new production route, chemical processing, improved methods which led to $^{68}$Ge/$^{68}$Ga Generator and Thallium-201 production.

## 6. Theoretical Studies supporting Experimental programme

VECC's experimental programme is strongly supported by in-house theory group members. Detailed research activities related of theory group at VECC is beyond the scope of this article. However, it needs to be mentioned that a numerical code named "VECLAN1D", developed by VECC theory group for analysis of data from nuclear physics experiments will be shortly available for public.

## Conclusion:

It is evident that VECC has supported and will continue with upgradation programme on all fronts to fulfill researcher's dream experiments and subsequently exploit application potential of research outcomes. It is expected that the experiments using facilities at VECC will

bring a more comprehensive understanding of the nuclei, which still remains mysterious and elusive and broaden societal application.

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NUCLEAR HORIZONS: A Bulletin of Indian Nuclear Physics Association

# Study of uncertainty quantification and parameter estimation through nuclear reactions

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Nuclear reaction data, involving nuclei throughout the nuclear chart and varying between a broad range of projectile energies, is needed for different applications in the use and further development of nuclear technologies. In many areas of nuclear physics, high-quality data with their uncertainties for nuclear reactions are crucial. Nuclear reaction cross sections, together with their covariance information, are crucial inputs which have a direct impact on the performance and efficiency of nuclear technologies. The importance of covariance analysis increases in the quest for more reliable and accurate nuclear reaction data in the field of neutrons and charged particles-induced reactions. Scientists and engineers require a database on nuclear reactions with complete experimental information and detailed uncertainty quantification for developing nuclear technologies and diminishing nuclear waste. In the literature, measurements have been made for neutron and alpha induced reaction cross sections. However, extensive information on these cross-section data is lacking, including experimental details and uncertainty quantification such as covariance and correlation matrices. Also, in many ranges of projectile energy, the data for cross section is missing, and discrepancies exist between different measurements for nuclear reaction cross section values in existing databases. The theoretical nuclear reaction models offer a systematic way to explain complexity of the nuclear reactions and involve the interactions of protons and neutrons within the nucleus. Uncertainty quantification is crucial for the reliability of the theoretical predictions and understand the inherent complexity of nuclear phenomena. By estimating model parameters along with their uncertainties, we can confirm the accuracy of these theoretical models, leading to a more refined interpretation of nuclear behavior. During my doctorate, a comprehensive study of neutron and alpha induced reactions was done, for which experiments were performed at two distinguished facilities, namely the Folded Tandem Ion Accelerator (FOTIA) at Bhabha Atomic Research Centre (BARC), Mumbai, India and the K-130 cyclotron at Variable Energy Cyclotron Centre (VECC), Kolkata, India.

At FOTIA, the neutrons with variable energies were produced by charged particle accelerator-based sources for neutron induced reaction studies. The neutrons were produced through $^{7}$Li(p,n)$^{7}$Be nuclear reaction having Q-value and threshold energy of -1.644 and 1.880 MeV, respectively. The proton beams of 3.0, 3.8 and 4.8 MeV were bombarded on the lithium target to produce different energies of neutrons. The neutron activation technique and subsequent $\gamma$-ray spectroscopy are preferred to measure the neutron induced reaction cross sections. The nuclear decay data properties from the ENSDF library were used for the analysis, and the cross sections were measured relative to well-known monitor reaction $^{115}$In(n, n$\gamma$)$^{115m}$In for the $^{58}$Ni(n,p)$^{58}$Co nuclear reaction [1]. The $^{58}$Ni(n,p)$^{58}$Co reaction is important because of the role of nickel isotopes in stellar nucleosynthesis as well as in the nuclear power reactors, where nickel containing materials are extensively used. This study has also carefully investigated the impact of uncertainties associated with the optical model parameters and level density parameters on nuclear reaction predictions for $^{58}$Ni(n,p)$^{58}$Co. The Monte Carlo method was used to provide an

understanding of the effects of these uncertainties on theoretical predictions. Beyond the realm of theoretical exploration, the $^{58}$Ni(n,p)$^{58}$Co reaction holds pivotal importance in advancing next generation nuclear reactors and accelerator driven systems within the field of nuclear technology. The accurate determination of reaction cross sections and their associated uncertainties, as presented in this study, provides crucial insights for optimizing the safety and efficiency of nuclear technology applications. Notably, the implications of this work extend into the field of medical applications, where $^{58}$Co, a product of the $^{58}$Ni(n,p)$^{58}$Co reaction, is widely employed in cancer treatment through radiotherapy. The accurate knowledge of reaction cross sections and their uncertainties become indispensable for optimizing production processes, ensuring a stable supply of medical isotopes, and upholding stringent standards of quality control in facilities dedicated to medical isotope production.

The K-130 cyclotron of VECC is utilized for experiments involving alpha induced nuclear reactions. In these experiments, the alpha particles were produced by helium gas through the PIG ion source, utilized for alpha induced reactions with various target materials. In the pursuit of advancing our understanding of nuclear reactions, a significant portion of this work is dedicated to the measurement and analysis of alpha particle-induced reactions on different target materials. The alpha induced reaction cross sections for $^{nat}$Zn, $^{nat}$Cu, $^{nat}$Mo, $^{nat}$Ag, and $^{nat}$Sn have been precisely measured, with a detailed covariance analysis [2-6]. The investigation extends to the production cross sections of important radioisotopes, namely $^{68}$Ge, $^{69}$Ge, $^{65}$Zn, and $^{67}$Ga, resulting from alpha induced nuclear reactions with $^{nat}$Zn. Excitation functions for $^{66}$Ga, $^{67}$Ga, $^{65}$Zn, and $^{64}$Cu radioisotopes, produced through alpha induced reactions on $^{nat}$Cu, have been comprehensively measured. Additionally, the excitation functions for the production of $^{103}$Ru, $^{97}$Ru, $^{95}$Ru, $^{96g}$Tc, $^{95g}$Tc, and $^{94g}$Tc from alpha induced reactions on $^{nat}$Mo have been measured. Further, alpha induced reactions on $^{nat}$Sn were measured, leading to the production of $^{119}$Te, $^{121}$Te, $^{122}$Sb, and $^{126}$Sb. The experimental methodology involved the stacked foil activation technique and subsequent off-line $\gamma$-ray spectroscopy in the incident alpha particle energy range of 10-50 MeV. The $\gamma$- ray activity generated by the produced radionuclides was measured using a high- purity germanium (HPGe) detector. The resulting nuclear reaction cross sections were compared with existing data in the EXFOR library, as well as with evaluated nuclear data from TENDL and theoretical predictions obtained through the TALYS nuclear reaction code. A detailed theoretical study was conducted through the TALYS nuclear reaction code using different level density models. Additionally, to evaluate the uncertainties linked to the experimental cross sections of nuclear reactions, a comprehensive covariance analysis was performed.

In this continued study of nuclear reactions, the focus shifts to the use of the Unscented Transform Kalman Filter technique [7]. The aim is to optimize the level density parameters and their correlation matrix for the $^{93}$Nb($\alpha$,2n)$^{95}$Tc and $^{93}$Nb($\alpha$,n)$^{96}$Tc reactions through the TALYS nuclear code. Since niobium plays an integral role in the construction of superconducting radio frequency (SRF) cavities for accelerators, this comparative study on niobium for experimental and theoretical aspects serves to enhance our understanding, directly influencing the design and performance of crucial SRF cavities in accelerator technologies.

This work serves as a comprehensive study of uncertainty quantification, measurement of nuclear reaction cross sections, and parameter estimation of theoretical nuclear models for both neutron and alpha induced reactions. The study includes experimental analysis as well as theoretical investigation of neutron

and alpha induced reaction cross sections. This work, at its core, represents a holistic and diverse approach for advancing our understanding of nuclear reactions, contributing to both theoretical frameworks and practical applications in the fields of nuclear physics and technology. Further details of the present work, including its methodology and implementation, are provided in Ref. [8].

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# Nuclear Structure Studies in the A ≈ 200 Mass Region: New Results from Polonium Isotopes

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The atomic nucleus is a fascinating many-body quantum system in which individual nucleons and collective degrees of freedom coexist and compete with each other. One of the most intriguing regions for exploring these phenomena lies near the doubly magic shell closure at Z = 82 and N = 126. Nuclei in this mass region exhibit a rich variety of structural features including shape coexistence, isomerism, configuration mixing, and the gradual emergence of collective behavior [1, 2]. Understanding how these different modes of excitation evolve is essential for developing a comprehensive picture of nuclear structure.

Among the nuclei in this region, neutron-deficient polonium isotopes provide an excellent laboratory for investigating the interplay between single-particle and collective excitations [3, 4]. With two protons outside the $Z$ = 82 shell closure, polonium nuclei are particularly sensitive to changes in shell structure and correlations among valence nucleons. High-$j$ orbitals such as $\pi h_{9/2}$ and $\nu i_{13/2}$ play a crucial role in shaping the properties of excited states, while the competition between proton and neutron excitations gives rise to complex level structures. Even-even nuclei such as $^{202}$Po provide insight into seniority-driven excitations, whereas odd-mass nuclei such as $^{201}$Po offer valuable information about single-particle behavior and configuration mixing.

To explore these questions, detailed spectroscopic investigations of $^{202}$Po and $^{201}$Po were carried out using in-beam $\gamma$-ray spectroscopy. The excited states were populated through the heavy-ion fusion–evaporation reactions $^{195}$Pt($^{12}$C,5n) and $^{195}$Pt($^{12}$C,6n). The experiments were performed at the 14-UD BARC-TIFR Pelletron LINAC facility, where de-exciting $\gamma$ rays were detected using an array of sixteen Compton-suppressed high-purity germanium (HPGe) clover detectors arranged at different angles with respect to the beam direction. The high efficiency and excellent energy resolution of the detector array enabled the construction of $\gamma$–$\gamma$ and $\gamma$–$\gamma$–$\gamma$ coincidence relationships, providing detailed information on the level structures of both nuclei. Directional correlation (DCO) ratios and polarization measurements (IPDCO) were employed to determine the spins, parities, and electromagnetic character of observed transitions [5,6]. Time-correlated $\gamma$-ray measurements were further utilized to determine the lifetimes of several isomeric states.

The investigations resulted in a significant extension of the level scheme of $^{202}$Po up to an excitation energy of approximately 8 MeV and a spin of 27$\hbar$. Fifty six new $\gamma$-ray transitions were identified, and previously known placements were revised [7]. One of the most important findings was the resolution of a long-standing ambiguity associated with the $8^+ \rightarrow 6^+$ transition. The very low energy of this transition explains the isomeric nature of the $8^+$ state and confirms its seniority-driven character. In addition, three new sequences of M1 transitions were identified at higher excitation energies, indicating the presence of more complex configurations involving both proton and neutron excitations. The observed level structure demonstrates the coexistence of positive- and negative-parity bands connected through multiple decay paths, reflecting strong configuration mixing and the gradual development of collectivity while

retaining significant single-particle characteristics.

The lifetime measurements provided another important window into the underlying nuclear structure. Using time-correlated $\gamma$-ray spectroscopy, the half-lives of several isomeric states in $^{202}$Po were determined by the decay-slope method employing the direct timing of High-Purity Germanium (HPGe) clover detectors. Figure 1 shows representative decay-slope fits for the proton-dominated $8^+$ and $11^-$ isomeric states, yielding improved half-lives of 114(5) ns and 83(6) ns, respectively. Lifetimes of several other isomeric states in $^{202}$Po were also measured, namely the $9^-$ [$T_{1/2}$ = 19(2) ns], $12^+$ [$T_{1/2}$ = 29(2) ns], and $15^-$ [$T_{1/2}$ = 17(2) ns] states, further enriching our understanding of the complex excitation patterns in this nucleus. The relatively long lifetime of the 8+ state originates from its predominantly seniority-driven $\pi(h_{9/2})2$ configuration and the hindered low-energy E2 decay, highlighting its single-particle character. In contrast, the enhanced B(E3) strength associated with the $11^-$ state points toward increasing collectivity and core polarization effects involving neutron excitations. Together, these measurements illustrate the delicate balance between single-particle and collective degrees of freedom in nuclei near the doubly magic $Z$ = 82 shell closure.

The neighboring odd-mass nucleus $^{201}$Po was also investigated in detail. Its level scheme was extended up to an excitation energy of about 4.5 MeV and a spin of 39/2, with 29 new $\gamma$-ray transitions identified and level assignments revised [9]. A major outcome of this study was the firm establishment of negative-parity states above the $13/2^+$ isomer through careful reassignment of key transitions and detailed coincidence analysis. Unlike the relatively regular structures observed in $^{202}$Po, the level scheme of $^{201}$Po exhibits significant fragmentation, which is indicative of strong configuration mixing and competing excitation mechanisms. The $\nu i_{13/2}$ orbital plays a dominant role in

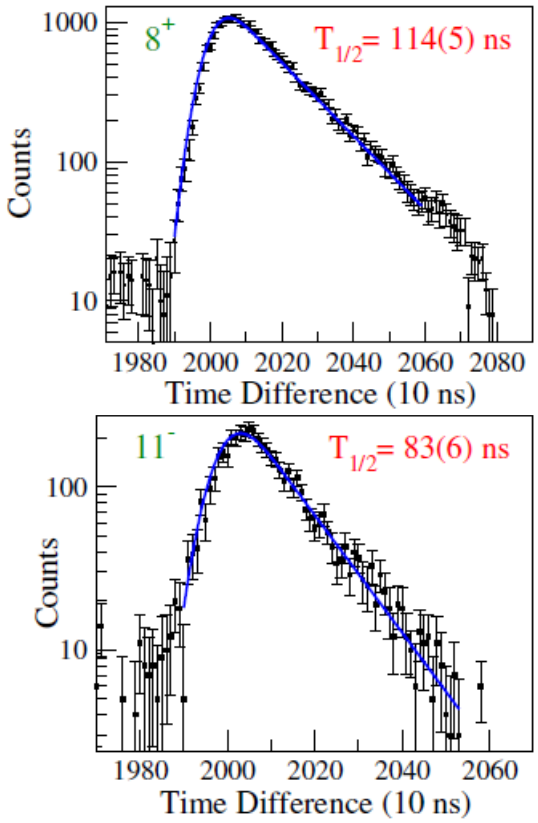



***Figure 1: Representative time-difference spectra and decay-slope fits for the (a) $8^+$ and (b) $11^-$ isomeric states in $^{202}$Po. The fitted distributions yield improved half-lives of $T_{1/2}(8^+)$ = 114(5) ns and $T_{1/2}(11^-)$ = 83(6) ns [8].***

generating high-spin states, and the observed decay patterns suggest that neutron excitations contribute significantly to the nuclear structure. This behavior contrasts with the comparatively proton-dominated configurations observed in $^{202}$Po and highlights the evolving balance between proton and neutron degrees of freedom in this region.

To interpret the experimental observations, large-scale shell-model calculations were performed. These calculations successfully reproduce the overall features of the observed level schemes and provide valuable insight into the microscopic structure of the nuclei. In $^{202}$Po, the calculations confirm the dominant $\pi h_{9/2}$ configuration of the 8+ isomer and demonstrate the increasing contribution of neutron excitations at higher spins. The absence of expected E2 decay branches in certain cases can be

understood in terms of configuration changes and reduced wave-function overlap. For $^{201}$Po, the calculations emphasize the importance of the $\nu i_{13/2}$ orbital and reveal strong fragmentation of wave functions arising from the mixing of multiple configurations. The good agreement between experimental data and theoretical predictions confirms that nuclei in this region exhibit a delicate balance between single-particle and collective behavior, with configuration mixing playing a central role.

The present investigations provide new insight into the evolution of nuclear structure near the $Z = 82$ shell closure. The significantly extended level schemes, identification of new transitions, and measurements of isomeric lifetimes reveal how shell effects persist while collective phenomena gradually emerge. The combined experimental and theoretical results contribute to a deeper understanding of high-spin behavior, isomerism, and shell evolution in heavy nuclei. These studies not only improve our knowledge of neutron-deficient polonium isotopes but also help refine theoretical models that aim to describe the complex interplay between individual nucleon motion and collective dynamics across the nuclear chart.

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# The Role of Nuclear Physics in Future Technologies

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Nuclear physics has long been a cornerstone of advanced technologies in fields such as clean and green energy production, radiotherapy, food irradiation, national security, and space. Its importance has expanded significantly due to the increasing global demand for sustainable green energy and the growing ambition of space exploration. Renewable energy sources produce clean energy but have limitations, such as lower efficiency and environmental impact, while conventional energy sources, such as fossil fuels, have a significant efficiency, but they have limitations related to resource depletion and environmental pollution. Nuclear energy is emerging as a reliable, low-carbon alternative, which is produced during nuclear fission and fusion. The nuclear reactors based on the nuclear fission reaction are well developed in many countries, while research on nuclear fusion reactors is ongoing. India operates 22 nuclear reactors, primarily utilizing Pressurized Heavy Water Reactors (PHWRs) and Light Water Reactors (LWRs). The total electrical power output capacity produced by these plants, following the conversion of thermal energy into electricity, is 6,780 MW(e) (Megawatt electrical) [1]. Conventional nuclear fission reactors (Pressurized Water Reactor (PWR), Boiling Water Reactor (BWR), and PHWR) are limited by high capital costs, long construction times, large space requirements, and massive, inflexible grid requirements, while Small Modular Reactor (SMR) [2] represent a new generation type of nuclear reactors that are smaller, compact design, more flexible, and inherently safer than traditional large-scale nuclear power plants. Their potential use beyond terrestrial applications plays a critical role in enabling long-duration deep space missions. The integration of nuclear physics principles into such advanced reactors (SMR) highlights its important role in shaping the future of both energy production and space technologies.

## Fundamentals of Nuclear Energy and Reactor Technology

Nuclear fission reaction in which a heavy nucleus, such as $^{235}U$, splits into smaller fragments, releasing energy of approximately 200 MeV per fission [3]. This energy is utilized to produce heat in the reactor core and then it is extracted from the core with the help of coolant materials. Finally, this tremendous heat is utilized to produce electricity through turbines and generators. The efficiency of this reactor depends on fuel composition, neutron flux, chain reactions, and heat extraction.

Neutron interactions, such as elastic, inelastic, and fission reactions, become critical to understand as neutrons sustain the chain reaction in a nuclear fission reactor. To understand these reactions, advanced computational codes are used for transport calculations. The Monte Carlo transport codes such as MCNP [4], Serpent [5], and OpenMC [6] are used to calculate the neutron flux distribution, criticality calculation, and radiation shielding design, ensuring stable and efficient operation. Moreover, thermal management systems and effective neutron and gamma shielding are essential for safety purposes.

The development and operation of conventional nuclear fission reactors involve several limitations and challenges, such as long construction times, high costs, the need for large land areas, and complex

reactor control systems. To address these limitations, an alternative is a small modular reactor.

## Small Modular Reactor: Design and Advantages

SMR [2] is an advanced nuclear fission reactor that can produce a clean energy source for electricity up to 10 MW(e), because of its compact size, making it ideal for remote industrial sites. Its components can be assembled in the company or factory and then transported to the site for installation, which significantly reduces the development period. SMR offers enhanced safety features through passive cooling systems based on gravity and convection principles; it can still function in the event of a power cut-off. This safety feature lowers the chance of accidents, making SMR more reliable, safer in mobile areas where maintenance and infrastructure may be limited, and suitable for harsh or challenging environments. Economically, developing SMR requires a lower investment compared to large-scale nuclear reactor. Another advantage is that it produces very low greenhouse gases emissions during operation, which helps in reducing pollution and global warming.

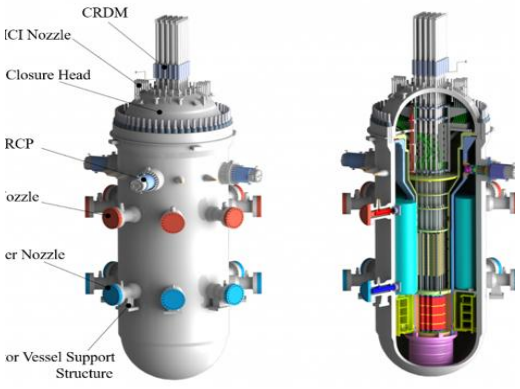



***Figure 1: Conceptual illustration of SMR system highlighting the compact reactor vessel and integrated safety-related components [7].***

## Applications in Space Exploration

The main challenge in space exploration is energy supply for prolonged space missions. Solar power is effective when sunlight is utilized, while it becomes less reliable in deep space or in shadowed regions in space. In that scenario, SMRs provide a consistent and long-lasting energy for successful space missions. In long-term space missions, SMRs can support high-power requirements such as life-support systems, scientific instruments, and in-situ resource utilization in missions. Moreover, establishing a sustainable human space mission on Mars would require continuous energy sources for habitat operations, communication systems, and resource processing. SMR can meet these demands with minimal maintenance, making them ideal for long-duration space missions. SMR, with its compact and robust design, is particularly well suited for these applications. In addition to electric power generation, nuclear physics plays a crucial role in advanced propulsion systems for space applications.

## Nuclear Propulsion Technologies

In the advanced propulsion systems, Nuclear Thermal Propulsion (NTP) and Nuclear Electric Propulsion (NEP) are two important concepts for future technologies that rely fundamentally on nuclear physics principles [8]. NTP systems utilize nuclear fission reactors to produce an enormous amount of heat. This heat helps to propel hydrogen gas through a nozzle at high speed; as a result, the force created by the escaping gas produces thrust, which moves the spacecraft forward. This method offers significantly higher efficiency than conventional chemical rockets but is suitable for shorter travel times. On the other hand, NEP systems convert nuclear energy into electricity to power ion or plasma thrusters, which accelerate charged particles and eject them at very high speeds, generating thrust that moves the spacecraft. Although NEP systems provide lower thrust compared to chemical rockets or NTP systems, they offer higher efficiency and are suitable for long-duration missions, especially deep-space exploration, where continuous and efficient propulsion is more important than acceleration.

## Challenges and Future Prospects

The deployment of SMRs and nuclear systems in space presents several technical challenges. Radiation shielding

remains a primary concern because hazardous space radiation environments, including galactic cosmic radiation (GCR), solar protons, and trapped radiation, can dominate exposure to high levels of radiation that can affect biological tissues and damage electronic systems. Additionally, managing heat dissipation in the vacuum of space requires innovative solutions for cooling techniques. Material degradation due to prolonged hazardous radiation exposure is another area of ongoing research. Advancements in nuclear materials, fuel cycles, and reactor design are addressing these challenges. The development of high-temperature fuels and radiation-resistant materials enhances the durability and efficiency of space reactors. Furthermore, improvements in passive safety systems and autonomous operation reduce the need for human intervention, which is crucial for remote missions. Looking ahead, the integration of nuclear technologies into space exploration is expected to play a pivotal role in enabling interplanetary travel and the establishment of extraterrestrial colonies. At the same time, SMRs hold significant promise for meeting Earth's growing energy demands sustainably.

## Conclusion

The continued evolution of nuclear physics is essential for addressing some of the most pressing challenges of modern technologies. Through research and innovations in technologies such as small modular reactors and nuclear propulsion systems, revolutionizing both energy production systems and space exploration is poised. By providing reliable, efficient, and sustainable power solutions, nuclear physics serves as a foundation for next-generation technologies, opening new frontiers for humanity both on Earth and beyond.

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## Declaration

AI tools were used only for language improvement and proofreading; the scientific content and analysis are entirely the authors' original work.



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# Strategic Role of Nuclear Physics in Advanced Energy and Scientific Infrastructure

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Nuclear physics is essential to modern science and technology for clean energy setups, advanced healthcare technologies, and big research facilities. The increasing demand for low-carbon energy sources and high-performance technologies has made nuclear science much more important. Understanding reaction dynamics that determine how particles interact is key to developing new technology. Near-barrier heavy-ion reactions gives important information about interaction potentials, barrier distributions, neutron-transfer processes, and nuclear deformation effects [1, 2]. Studies of fusion and quasi-elastic scattering help to learn more about tunnelling probabilities and reaction cross-sections, which are useful for advanced reactor systems, isotope production, and neutron use for better future fusion-energy systems. Doing this also helps us develop the materials that are resistant to radiation and accelerator-based systems.

The fusion cross-section is commonly expressed as,

$$\sigma(E) = \frac{\pi}{k^2}\sum_{l=0}^{\infty}(2l+1)T_l(E)$$

Here, $T_l(E)$ denotes the transmission probability over the barrier. These help us in the improvement of reactors and computer models of nuclear reactions [2, 3].

## Reaction Dynamics and Future Nuclear Technologies

Fusion and fission processes play an important role in building future energy systems, which involve holding plasma steady and the interaction of particles to produce more energy than is consumed. Experimental programs using tokamaks, stellarators, inertial confinement systems, and advanced magnetic confinement devices can't work without accurate nuclear reaction modeling and neutron transport analysis [3, 5].

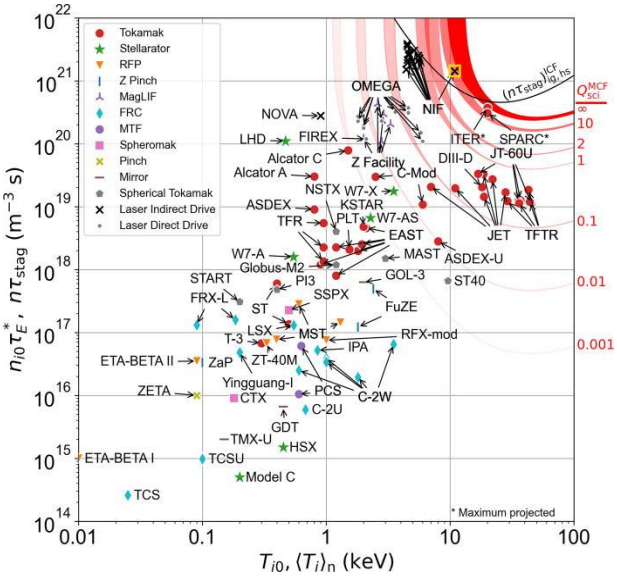



***Figure 1: Progress in controlled fusion systems with respect to Lawson criterion parameters for plasma confinement and fusion feasibility (adapted from Wurzel and Hsu, 2025 [5]).***

Recent growth in fusion projects demonstrates the progress towards using it for power by various global projects such as the International Thermonuclear Experimental Reactor (ITER), Joint European Torus (JET), Soonest/Smallest Possible ARC (SPARC), and National Ignition Facility (NIF) studied by the Lawson criterion [5]. The progress in these systems shows that nuclear science is capable of powering a clean energy future. India contributes to the core by providing

cryogenic systems, in-wall shielding, and superconducting technologies to ITER [4, 6], highlighting the growth of the nation in the nuclear field and its future plans.

Besides fusion and fission processes, nuclear physics plays a major role in radioisotope production, shielding of radiation, detector technologies, and accelerator-based applications such as reactors. Understanding the calculation of reaction cross-sections is key to the production of isotopes, which are further used in medical scans such as positron emission tomography (PET), targeted radiotherapy, and non-invasive checks for industrial safety [1, 2]. Modern computer models such as Fortran-based reaction codes and AI-assisted nuclear modeling approaches are now commonly used to predict the reaction results, to improve the reactor's performance, and to evaluate complex nuclear systems more efficiently [3, 5].

This article describes the connection between nuclear reactions and a new system that links measurable data, including fusion probabilities, barrier distributions, neutron transfer properties, and coupling effects, to growing areas of technology, such as advanced reactor systems. Nowadays, nuclear reactions are key to developing fusion energy, producing new isotopes, and building smart AI computer models, introducing advancements in future technologies. This approach strengthens the link between the core science of nuclear physics and future technology.

**Challenges, Sustainability, and Future Outlook**

While this technology has a lot of potential, it still faces major challenges such as management of waste by radioactive materials, safety of reactors, high infrastructure costs, risk of misuse of nuclear materials, and risks related to use of fusion at larger scale remain serious challenge to use nuclear energy globally [7, 8]. In many countries, nuclear energy policies are shaped on the basis of public support and its effect on the environment over a long time. However, ongoing improvements in computational nuclear physics, materials science, plasma modeling, and artificial intelligence are expected to enhance reactor safety, fuel efficiency, and accurate computer models. India is continuously making huge progress in the development of its own nuclear technology, with a focus on becoming energy independent by 2047. India reached historic milestone when its project Prototype Fast Breeder Reactor (PFBR) at Kalpakkam reached "criticality", and also India has mastered the design of its 700 MW Pressurised Heavy Water Reactors (PHWRs) pushing the nation to a great success towards its goal [6]. India's work on global collaborations such as ITER, FAIR, and JET, and its contributions to such major projects, reflect its growing commitment to building its own high-tech nuclear systems and to independence in science and energy. For future growth, nuclear physics needs to bring several areas of research together including reaction dynamics, advanced computer science, AI- powered nuclear simulations, and smart technological planning. With these advancements, India is ready for a fast takeoff in nuclear energy, and new scientific innovations will greatly help us to speed up the move to clean energy and help the country to lead the way in new technology for years to come.

**Conclusion**

Nuclear reaction dynamics is the basic science for many new technologies in future energy systems, modern medical treatments, and important research centres. Research on fusion reactions, quasi-elastic scattering, neutron transfer, and reaction cross-sections helps us to understand the science behind the reactor and accelerator technologies. By

combining AI with different computational models, we can enhance the accuracy of nuclear trials, which helps in improving the technology and reaching our energy targets. While nuclear powers still face challenges related to safety and waste, ongoing progress in nuclear research and new studies will help us build technology that lasts.

**Declaration**

The author declares that the work presented is original and not generated with AI tools.

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NUCLEAR HORIZONS: A Bulletin of Indian Nuclear Physics Association

# Targeted Alpha Therapy: The Next Generation of Precision Nuclear Therapy

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## 1. Introduction

Malignant diseases are increasing worldwide and have become a major global health concern. According to the World Health Organization (WHO), about 20 million new cases and nearly 9.7 million deaths were reported globally in 2022. These numbers are expected to rise in the coming decades. As per the Indian Council of Medical Research (ICMR) and National Centre for Disease Informatics and Research (NCDIR)-2022, India reports ≈1.5-1.6 million new cancer cases annually. This corresponds to approximately 8-9 lakh deaths each year. These trends highlight the urgent need for advanced and precise treatment strategies to benefit society [1].

Targeted alpha therapy (TAT) has emerged as one of the most advanced realizations of nuclear physics in modern medicine [2]. In TAT, the α-emitting radionuclides are chemically linked to biomolecules capable of recognizing tumour-specific biomarkers such as receptors, antigens, or metabolic pathways. After systemic administration, these radiopharmaceuticals these radiopharmaceuticals selectively accumulate in tumour tissues, converting each cancer cell into a localized radiation target while minimizing damage to healthy tissues.

The uniqueness of TAT arises from the physical characteristics of α-particles emitted from heavy nuclei. These particles deposit a very high amount of energy over extremely short distances. This energy deposition produces dense ionization and complex, often irreparable, DNA damage. The resulting lethal effects are confined to a few cell diameters. This makes TAT particularly effective against micro-metastases and minimal residual disease, which are major causes of cancer recurrence.

This work discusses the nuclear physics principles underlying TAT, including decay-chain characteristics, radiopharmaceutical design, and microdosimetric considerations. Recent clinical developments and emerging technological advances are also briefly reviewed, with special emphasis on India's growing contributions through radioisotope production and accelerator facilities such as facilities such as BARC (Bhabha Atomic Research Centre) and VECC (Variable Energy Cyclotron Centre). Future developments suggest that TAT is poised to play a significant role in precision oncology and personalized medicine.

## 2. Physics Principles and Linear Energy Transfer

The α-particle has a charge equal to $+2e$ and is the nucleus of helium atom. The α-particles are often regarded as the lightest heavy ions. The α-particle consists of two protons and two neutrons, with a binding energy of 28.3 MeV. This relatively high value explains why the α-particle is extremely stable. The heavy nuclei, are in general, found to be alpha emitters. Their relatively large mass typically $\approx 7300$ times that of an electron and $+2e$ charge produce strong Coulomb interactions with surrounding as they pass through matter. This interaction results in significant ionization along the trajectories of α-particles.

The energy loss of charged particles in matter is described by the stopping power

[3]. The stopping power is closely related to the linear energy transfer (LET), although the two are not strictly identical. and is given by standard Bethe-Bloch formula. The expression for LET is derived using the laws of conservation of energy and momentum, and is presented below;

$$LET \approx -\frac{dE}{dx} = \frac{4\pi e^2 z^2 N}{(4\pi\varepsilon)^2 m_e v^2}[\ln(\frac{2m_e v^2}{I})\text{-}\ln(1\text{-}\beta^2)]$$

Where, the terms used have their usual meanings, $dE/dx$ represents the differential energy loss per unit path length.

Typical LET values vary significantly for different types of radiation. Alpha particles have very high LET values, typically in the range of ≈50–100 keV/μm. This indicates that they deposit a large amount of energy over a very short distance. On the other hand, β-particles have relatively much lower LET values of ≈0.2 keV/μm. However, X-rays exhibit intermediate LET values of ≈2 keV/μm. Therefore, it may be observed that, α-particles deposit nearly two orders of magnitude more energy locally (in the surrounding volume) compared to low-LET radiation such as β-particles and X-rays. This makes α-particles highly effective for delivering localized energy. Such effective localised delivery is required in applications such as targeted alpha therapy (TAT).

Alpha particles with energies of ≈5 MeV or so, have very short range in biological tissues. Their range is typically ≈50-100 μm, and corresponds to only a few cell layers in human body. It means they travel only a few cells before stopping in the human body. During this short distance, α-particles produce strong and dense ionization along their track.

The decay behaviour of alpha emitters follows the Geiger-Nuttall law, which shows a correlation between the alpha-particle energy and the half-life of the nucleus. Mathematically, it is expressed as [4];

$$\log_{10}(T_{1/2}) = a + \frac{b}{\sqrt{E_\alpha}}$$

where, $T_{1/2}$ is the half-life, $E_\alpha$ is the α-particle energy, while $'a'$ and $'b'$ are constants for a given radioactive series. The relation shows that nuclei emitting higher-energy α-particles have shorter half-lives. This also reflects the quantum tunnelling mechanism of α-decay and help in the selection of suitable isotopes for targeted therapeutic applications.

The large energy deposition leads to severe biological damage. These damages are related to double-strand DNA breaks, chromosomal fragmentation, and complex clustered lesions. Such damages are generally difficult for the cell to repair automatically. As such, the repair mechanisms do not work and the cell undergoes apoptosis or mitotic death. For non-biology readers it may be mentioned that apoptosis is a natural, programmed process where a cell dies in a controlled way without harming surrounding tissue. However, the mitotic death is when a cell dies because it cannot complete mitosis properly, often due to DNA damage or division errors. Here, mitosis is the process by which a single cell divides to produce two genetically identical daughter cells. Another advantage is that the effectiveness of α-particle radiation does not depend strongly on oxygen concentration. This allows it to destroy cancer cells even in hypoxic regions of solid tumours where conventional or traditional radiation treatment is less effective.

The Figure 1, below shows a representative comparison of DNA damage caused by α-particles, β-particles, and Auger electrons through direct and indirect radiation mechanisms. The α-particles produce dense ionization tracks with very short ranges, depositing energy directly within DNA and causing complex, difficult-to-repair damage. This clearly demonstrates the high spatial precision of

targeted alpha therapy, where the effects remain confined to tumour cells.

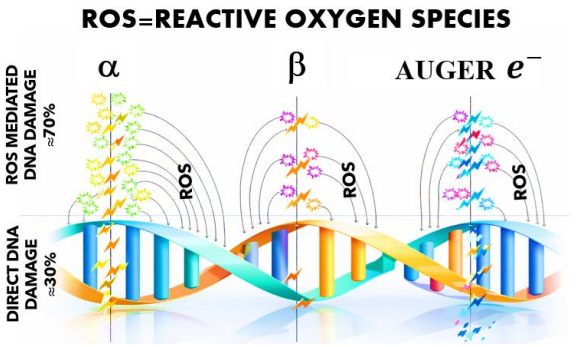



***Figure 1: Ionization density comparison for α-particles (dense), β-particles (sparse), and Auger electrons (localized clusters).***

In contrast, β-particles have longer range and lower LET, leading to more diffused and largely indirect damage via Reactive Oxygen Species (ROS). Auger electrons create highly localized damage at the nanometre scale when emitted close to DNA. Overall, the comparison highlights that TAT offers superior as well as spatial precision in radiation delivery.

### 3. Decay Sequence and Nuclear Considerations

The therapeutic effectiveness of TAT depends strongly on the radio-active decay characteristics of the radionuclides to be used. In targeted therapy, the radioactive atoms decay directly inside the biological systems. As such, properties of the α-emitter, viz., as half-life, decay mode, α-particle energy, and daughter products are important aspects. These properties determine both treatment efficiency and radiation safety. An ideal α-emitter must have an appropriate half-life (normally hours to days), emit multiple α-particles, produce minimal long-range γ-radiation, and most importantly form chemically stable complexes with biomolecules used for targeting cancer cells. Radioactive decay follows the exponential decay law; $N(t) = N_0 e^{-\lambda t}$. Where, $N_0$ is the initial number of nuclei, $N(t)$ is the number of nuclei remaining after time $t$, and $\lambda$ is the decay constant. The half-life ($T_{1/2}$) is related to the decay constant as; $T_{1/2} = \frac{\ln 2}{\lambda}$. The choice of radionuclide, therefore, requires matching the $T_{1/2}$ of α- emitter with biological targeting times so that maximum activity reaches the tumour inside the body before significant decay occurs.

The Actinium-225 $\left({}^{225}_{89}Ac\right)$, is one of the most promising radionuclides for TAT because it produces multiple alpha emissions within a decay chain. Its decay sequence is discussed for ready reference. The radioisotope ${}^{225}_{89}Ac$ undergoes α-decay to form francium-221 ${}^{221}_{87}Fr$. The reaction can be written as, ${}^{225}_{89}Ac \rightarrow {}^{221}_{87}Fr + \alpha$. It has a half-life of 9.92 days, which is well suited for medical applications. The emitted α-particle carries an energy of 5.83 MeV, initiating the therapeutic decay chain. The daughter nucleus ${}^{221}_{87}Fr$, further decays via α-emission as, ${}^{221}_{87}Fr \rightarrow {}^{217}_{85}At + \alpha$. The isotope ${}^{221}_{87}Fr$ $\left(T_{1/2} \approx 4.8\ m\right)$ releases 6.34 MeV α-particle, thus continue the sequence of high LET radiation deposition. This ${}^{217}_{85}At$ is extremely short-lived $\left(T_{1/2} \approx 0.033\ \text{s}\right)$ and decays almost instantaneously through α-emission as; ${}^{217}_{85}At \rightarrow {}^{213}_{83}Bi\left(T_{1/2} \approx 32\ \text{ms}\right) + \alpha\ (7.06\ \text{MeV})$ [5]. The above may be represented with a help of figure 2, in simplified way.

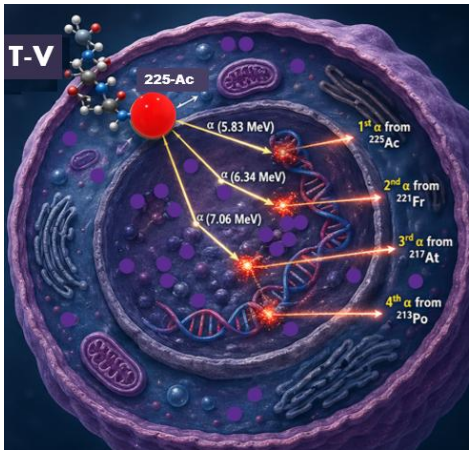



***Figure 2: This image illustrates the working mechanism of Targeted Alpha Therapy (TAT) using the radionuclide Actinium-225 inside a cancer cell. (T-V: Targeting Vector)***

The ${}^{213}_{83}Bi$ primarily undergoes $\beta^-$decay (98%) as; ${}^{213}_{83}Bi \rightarrow {}^{213}_{84}Po\left(T_{1/2} \approx 45.6\ \text{m}\right) + \beta^- + \bar{\nu}$. A small fraction (~2%) decays directly by α-emission to ${}^{209}_{81}Tl$, with $E_\alpha \approx$

5.87 MeV [5]. This step links α-emitting daughters to the final stages of the decay chain. The $^{213}_{84}Po$ decays extremely rapidly by α-emission $^{213}_{84}Po \rightarrow ^{209}_{82}Pb\left(T_{1/2} \approx 4.2\ \mu s\right) + \alpha\ (8.38\ \text{MeV})$. This is one of the most energetic alpha-particle in the chain. The $^{209}_{82}Pb$, then undergoes negative beta decay; $^{209}_{82}Pb\left(T_{1/2} \approx 3.25\ \text{h}\right) \rightarrow ^{209}_{82}Bi(stable) + \beta^- + \bar{\nu}$; producing stable bismuth as the final product. Through this sequential decay, a single $^{225}_{89}Ac$ nucleus produces four high-energy α-particles. Each of these α-particles deposits intense localized energy, which is the basis of its high therapeutic efficiency in the field of TAT.

It may, however, be mentioned that, during the α-decay, in order to conserve the momentum, the daughter nucleus of mass $M_D$, recoils with a reoil kinetic energy ($E_R$), given by [6];

$$E_R = \frac{m_\alpha}{M_D} E_\alpha$$

where, $m_\alpha$ and $E_\alpha$ are the mass and energy of α-particle respectively. For a typical α-particle energy of about 5.0 MeV, the value of $E_R$ is typically about ~100 keV or so. This value is much larger than chemical bonding energies which are typically of the order of a few eV or so. As such, the daughter nucleus may also break away from the targeting molecule or chelator. This allows the radioactive daughter nuclei to migrate towards the healthy organs as well. As such, to control this recoil effect remains one of the major challenges in TAT radiochemistry

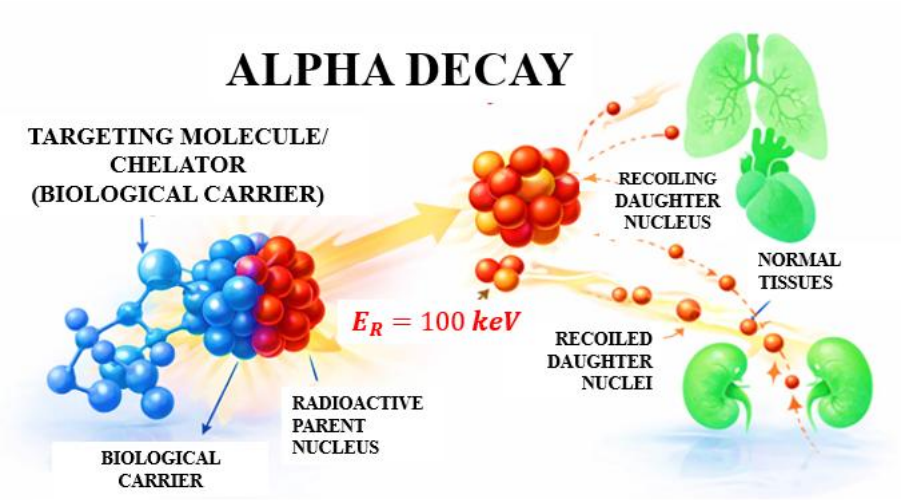



***Figure 2; Schematic illustration of α-decay recoil in TAT showing emission of the α-particle, daughter nucleus recoil, and possible migration of radioactive daughters to healthy organs.***

The figure 3, gives the pictorial representation of recoil effect during α-decay in TAT, using coloured coding. The blue structure represents the targeting molecule or chelator that carries the radioactive isotope to the tumour. The red-orange cluster shows the radioactive parent nucleus. The small orange particles moving outward are the emitted α-particles with energy $E_\alpha$. The larger cluster moving in the opposite direction represents the recoiling daughter nucleus with recoil energy $E_R \approx 100$ keV. As mentioned, this energy is much higher than chemical bond energies. The dashed paths indicate the escape and migration of daughter nuclei after bond breakage. The green colour organs in the figure, represent healthy tissues where these nuclei may accumulate. Yellow arrows indicate the direction of energy transfer and recoil direction. As such, even with precise targeting, heavy recoil nucleus may redistribute radioactive daughters and create off-target effects.

Apart from the Actinium-225, several other α-emitters are widely investigated due to

their favourable α-decay properties. Like, the isotope $^{233}_{88}Ra(T_{1/2}\approx 11.4\ d)$ is an important α-emitting radionuclide. It undergoes a series of α-decays that enhance the delivered radiation dose. Chemically, radium behaves like calcium and therefore naturally accumulates in bone tissue. This property makes it highly effective for treating metastatic bone cancer. As such, it selectively targets diseased bone regions. The $^{233}_{88}Ra$ is generally produced from long-lived $^{227}_{89}Ac$ generators, where $^{227}_{89}Ac$ decays to form $^{233}_{88}Ra$, that allows its continuous extraction for medical applications.

The $^{211}_{85}At$ radioisotope ($T_{1/2} = 7.2$ h) also decays mainly through α-emission. Its chemistry is similar to iodine, which allows efficient labelling of antibodies and other biomolecules for targeted therapy [7,8]. Because of its short half-life, it is well suited for treatments requiring rapid delivery of radiation to tumour cells. The isotope $^{211}_{85}At$ is typically produced in cyclotrons through the nuclear reaction; $^{209}_{83}Bi(\alpha, 2n)^{211}_{85}At$. The optimum production of $^{211}_{85}At$ isotope is expected ≈26-32 MeV α-beam energy [9].

The $^{213}_{83}Bi$ is also important α-emitter, and is widely used in fast-targeting therapeutic applications. is not usually produced directly in accelerators. It is obtained from a radionuclide generator system, most commonly based on the decay of $^{225}_{89}Ac$. It is called a generator because it continuously produces a short-lived daughter isotope from a longer-lived parent. This allows repeated use without needing an accelerator each time.

In this system, $^{225}_{89}Ac$ (half-life of ≈10 days) is fixed on a column. As it decays, it produces $^{213}_{83}Bi$, which has a much shorter half-life of ≈46 minutes. Because actinium and bismuth have different chemical properties, $^{213}_{83}Bi$ can be separated easily using a suitable solvent. After each separation, more $^{213}_{83}Bi$ is formed from the remaining parent. In this way, the generator acts as a continuous and reusable source of $^{213}_{83}Bi$, which is very useful for medical applications like targeted alpha therapy. This helps in allowing on-site availability in hospitals for medical treatments. The short half-life of this isotope ensures rapid radiation dose delivery while limiting long-term radiation exposure.

The radioisotope $^{227}$Th has a relatively long half-life (≈18.7 d) and undergoes α-decay. It produces additional α-emitting daughter nucleus that enhance therapeutic effectiveness. The longer lifetime allows sufficient time for antibody-based targeting and accumulation in tumours. The $^{227}$Th is generally produced from the decay of $^{233}$U or through separation from $^{227}_{89}Ac$ parent sources. Its generator-based production makes it suitable for preparing targeted radiopharmaceuticals used in antibody-mediated cancer therapy.

From nuclear physics perspective, the effectiveness of TAT arises from a delicate balance between nuclear decay kinetics and biological delivery. On the one hand the radionuclides with suitable half-lives ensure efficient tumour targeting, while multiple α-emissions give extremely high localized energy deposition. However, to tackle recoil effects and daughter redistribution remain active areas of research. Understanding decay schemes, half-life matching, and nuclear energy release are therefore essential for designing safer and more effective α-emitting radiopharmaceuticals.

## Radiopharmaceutical Design

A targeted α-radiopharmaceutical is composed of three closely integrated components that work together to deliver highly localized therapeutic radiation to diseased tissues. The first component is the radionuclide. It provides the therapeutic α-radiation responsible for cell destruction. The choice of radionuclide depends mainly on the compatibility between its physical half-life and the biological targeting kinetics [8]. This ensures that radioactive decay occurs while the agent remains localized at the tumour site.

The second component is the chelator, a molecular cage designed to securely bind the metal radionuclide and prevent its release into healthy tissues. Commonly used chelators include DOTA and macropa derivatives, which are specifically engineered to provide high thermodynamic stability and strong metal coordination, thereby improving in-vivo safety and effectiveness. In fact, the macropa derivatives are special chelating molecules used to tightly bind large radioactive metals like actinium-225 ($^{225}$Ac). They form very stable complexes quickly and under mild conditions. This makes them useful in targeted alpha therapy where safe and strong attachment of the radionuclide to biomolecules is required.

The third component is the targeting ligand. This ligand acts as a biological carrier directing the radiopharmaceutical toward specific cells or receptors. These ligands may include monoclonal antibodies, peptides, small molecules, or receptor-specific binding agents. Each of these is selected according to the biological characteristics of the target disease.

Designing effective targeted alpha radiopharmaceuticals faces key challenges such as ensuring chemical stability against alpha-recoil, achieving selective tumour uptake, minimizing off-target effects, and maintaining favourable pharmacokinetics for rapid clearance from healthy tissues. Recent advances using nanoparticle-based encapsulation address these issues by retaining daughter radionuclides after α-decay, improving therapeutic efficiency and reducing unwanted radiation exposure.

## Microdosimetry and Biological Effect

The targeted alpha therapy (TAT) operates at microscopic spatial scales where conventional absorbed dose concepts become insufficient. The energy deposition must be treated statistically using microdosimetry. The specific energy delivered $(z)$ to a cell nucleus is given by the relation $z = \varepsilon/m$, where $'\varepsilon'$ represents the energy deposited by radiation and $'m'$ is the mass of the target volume (e.g., the cell nucleus). The α-particles deposit a very large amount of energy over extremely short distances. Thus, even a single α-particle passing through a cell nucleus can deposit several several hundred $keV$ of energy within the nucleus. This causes lethal DNA damage that leads to the cell destruction. This localized damage is reflected in the high Relative Biological Effectiveness (RBE) of α-radiation [10]. The RBE describes how efficiently a type of radiation produces biological damage compared to standard reference radiation. Standard reference radiation is typically taken as X-rays or γ-rays. The α-radiation typically shows RBE values of ≈3–7. This means a smaller number of α-particles is required to achieve the same biological damage effect as compared to photons or β-radiation. The α-particles lead to dense ionization along the track and causes complex DNA damage, to the tumour microenvironment.

## Clinical Applications

The Radium-223 $(^{223}_{88}Ra)$ therapy represents one of the first successful clinical applications of targeted alpha therapy [11]. It is used for the treatment of metastatic castration-resistant prostate cancer with bone metastases. This treatment is used for advanced prostate cancer that has spread to the bones. In some patients, the cancer continues to grow even after hormone therapy that lowers testosterone levels. Such cancer is called castration-resistant prostate cancer. The treatment helps target cancer cells present in the bones, reduces symptoms like pain, and helps control the disease progression. Since the radium chemically behaves like calcium, it naturally accumulates in areas of active bone formation, particularly at cancerous bone lesions. Once localized, it emits energetic α-particles that destroy nearby tumour cells only. This causes minimal damage to surrounding healthy tissue due to the short

range of alphas from natural alpha emitters.

The radioisotope $^{225}_{89}Ac$ based therapies have also gained significant attention in recent years. Specially in prostate cancer treatment using Prostate Specific Membrane Antigen (PSMA) targeted radiopharmaceuticals these isotopes are useful. These therapies attach radioactive $\alpha$-emitter $^{225}_{89}Ac$ to molecules that specifically bind to PSMA expressed on cancer cells. Many clinical studies have shown remarkable treatment responses, even in patients with advanced disease. These are the patients who no longer respond to conventional chemotherapy or beta-emitting radiotherapies. As such, the TAT provides strong therapeutic potential of alpha emitters.

The study by Kratochwil et al., [12] reported one of the first clinical applications of $^{225}_{89}Ac$-PSMA-617 targeted $\alpha$-therapy for metastatic Castration-Resistant Prostate Cancer (mCRPC). The treatment uses a PSMA targeting molecule to selectively deliver the $\alpha$-emitting isotope actinium (A=225) to prostate cancer cells. The study demonstrated significant tumour regression and strong reduction in PSA levels with manageable side effects. This highlights the promising therapeutic potential of TAT for patients resistant to conventional treatments.

The TAT is also being explored for several other cancers, including leukaemia, neuroendocrine tumours, glioblastoma, ovarian cancer, and micrometastatic disease. The TAT technique is particularly effective in cases where tumour deposits are small but widely distributed throughout the body. The short penetration depth and high biological effectiveness of alpha particles allow precise destruction of isolated cancer cells. At the same time, it limits systemic toxicity. This makes TAT a promising approach for treating difficult and disseminated cancers. The RIKEN Radioactive Ion Beam Factory is taking a leading role in the production of radioisotopes for application studies and in the search for new elements [13]. It also makes significant contributions to medical diagnosis and cancer treatment. Thus, nuclear physics is there to help the society at large.

## India's Perspective

India has a strong and growing infrastructure in nuclear science, radioisotope production, and radiopharmaceutical research, providing a solid foundation for targeted alpha therapy (TAT). A key contributor is the Bhabha Atomic Research Centre (BARC), Mumbai, which produces medical isotopes and develops radiopharmaceuticals using its research reactors, supporting programs in radiochemistry, isotope processing, and clinical translation [14].

Another major institution is the Variable Energy Cyclotron Centre (VECC), Kolkata, which focuses on accelerator-based isotope production, heavy-ion research, and nuclear reaction studies. India's largest medical cyclotron, Cyclone-30 at VECC, Kolkata, now produces high-energy beams for medical isotope production [15].

It produces Fluorine-18, which is used to make FDG, an important radiopharmaceutical for PET scans in cancer care. The facility also produces isotopes such as Germanium-68 and Palladium-103, and plans to produce Iodine-123 for medical use and research. This cyclotron helps produce affordable radioisotopes for patients across the country, especially in Eastern India. It also has potential for export of medical isotopes. From Indian perspective, the successful commissioning of Cyclone-30, shows the strong capability of Indian scientists and engineers in nuclear technology for societal benefit.

India's capabilities are set to expand further with a new medical cyclotron facility at NISER, Bhubaneswar. This facility is designed to accelerate protons and deuterons (≈18–30 MeV) for PET and therapeutic isotopes like $^{18}$F, $^{68}$Ga, $^{64}$Cu,

and $^{89}$Zr. Equipped with radiochemistry labs and target-processing systems. This facility will support interdisciplinary research, strengthening India's role in advanced nuclear medicine. Keeping in view the above, India is well positioned to expand indigenous production of medical isotopes. The growing cyclotron network, together with strong radiochemistry expertise, places the country in a favourable position. Thus, it will contribute, in a major way, to global alpha-therapy isotope supply chains as well at a later satge.

Apart from these centres, many independent researchers are actively involved in the field of theranostic studies. Beyond Targeted Alpha Therapy (TAT), several radioisotopes show strong theranostic potential in radionuclide therapy. Recently, the radio-isotope $^{186}$Pt has been suggested as a promising dual-use radionuclide for cancer imaging and treatment [16]. Its favourable decay characteristics, including electron capture (EC) and positron ($\beta^+$) emission, enable PET/SPECT imaging along with therapeutic radiation delivery to tumour sites. Moreover, its chemical similarity to established platinum-based chemotherapeutic drugs allows the combination of radiological and chemo-toxic effects. This makes it a potential candidate for precision oncology and personalized cancer management.

In the years to come, the developments in TAT are likely to focus on improving isotope availability, treatment precision, and better clinical outcomes. Accelerator-based production of $^{225}$At is being expanded to fulfil growing demand for such therapies. The artificial intelligent (AI) assisted dosimetry and personalized treatment planning are expected to optimize patient specific dose delivery. Further the new advances in nanocarriers are expected to safely transport radionuclides. Further, the combination of these therapies with immunotherapy are expected to enhance effectiveness. As such, the theranostic approaches combining diagnosis and therapy is likely to further improve patient management.

## 8. Conclusion

In view details mentioned above, it may be inferred that TAT represents one of the most compelling demonstrations of how basic nuclear physics principles can directly benefit human health. Combining molecular targeting with high LET radiation, the TAT can achieve excellent precision in cancer treatment. However, the challenges are still there in the field of dedicated isotope production, radiochemistry, and dosimetry. The present research, which includes contributions from India as well, suggests that TAT is going to become an important method in precision oncology.

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# INPA News & Announcements

**Membership updates, upcoming events, workshops, and collaboration initiatives**

## Release of *Nuclear Horizons* (Inaugural Issue) at BHU

The Indian Nuclear Physics Association (INPA) has been formally registered at Banaras Hindu University (BHU), marking a significant milestone for the nuclear physics community in India. The occasion was celebrated with the inauguration of the INPA Bulletin, "Nuclear Horizons," and the announcement of BHU as the host institution by Hon'ble Vice-Chancellor Prof. A.K. Chaturvedi.

INPA aims to provide a common platform for researchers, teachers, and students working in areas such as nuclear reactions, structure, heavy-ion physics, and instrumentation, fostering collaboration and academic exchange across institutions.

BHU, once a leading center for nuclear physics research under Prof. P. C. Sood, is expected to witness a revival of its rich scientific legacy through this initiative.

The event was attended by several distinguished academicians, including Prof. Ashok Kumar Jain, Prof. Bhanu Prakash Singh, Prof. Manoj Kumar Sharma, Prof. Manoj Sharma, Dr. Mohd. Shuaib, Prof. Ajay Kumar Tyagi, Dr. Rebecca, Dr. Vikas Kumar, and Dr. Somnath Nag.

Described as a promising beginning, INPA is expected to strengthen the nuclear physics community and inspire young researchers across the country.



# NEWS ITEMS

## Recognition of Prof. A. K. Jain with Springer Nature Editor of Distinction Awards

The Indian nuclear physics community is proud to note that Prof. A. K. Jain has been honoured with the prestigious *Springer Nature Editor of Distinction Awards* for his exemplary contributions to the journal *Pramana*. He has received both the *Editorial Contribution Award* and the *Author Service Award*, placing him among the top 20% of editors for excellence in managing the peer review process and ensuring timely and constructive editorial decisions. These recognitions highlight his dedication to maintaining high scientific standards, supporting authors, and strengthening the research community. This achievement is a matter of great pride for INPA and reflects Prof. Jain's continued commitment to advancing scientific scholarship and academic excellence.

## Forthcoming Conferences & Calls for Participation

# Symposium on Particle–Gamma Coincidence Techniques in Nuclear Science (SPaGCoNS 2026)

**13-15 July, 2026**

**IIT ISM Dhanbad, Jharkhand - 826004, India**

The Symposium on Particle–Gamma Coincidence Techniques in Nuclear Science (SPaGCoNS 2026) brings together researchers, students, and experts from India to discuss emerging trends, scientific challenges, and future directions in nuclear physics research. While the symposium is centered on particle–gamma coincidence measurements, its scope encompasses a broad range of topics, including nuclear structure, nuclear reactions and reaction mechanisms, nuclear astrophysics, radioactive ion beams, exotic nuclei, detector development, and modern experimental techniques.

Particle–gamma coincidence spectroscopy has become a powerful tool for addressing a variety of important questions in nuclear physics. By combining charged-particle and gamma-ray measurements, the technique provides unique access to nuclear excitation modes, decay pathways, and reaction dynamics. The scientific programme includes discussions on studies of pygmy dipole resonances, gamma-ray strength functions, nuclear level densities, octupole excitations, cluster structures in nuclei, transfer reactions, and detailed gamma-ray spectroscopy. Recent results obtained using the available experimental facilities at TIFR, Mumbai; IUAC, New Delhi; and VECC, Kolkata, will also be presented and discussed.

An important theme of the symposium is the current status and future prospects of particle–gamma coincidence measurements in India. Advanced integrated facilities of this kind are presently available in several countries, including Romania, Germany, South Africa, and the USA, whereas India does not yet possess a comparable full-scale setup. The symposium provides a forum to assess existing capabilities and discuss future detector developments, including advanced silicon detector systems and large-volume $LaBr_3$ or HPGe gamma-ray detector arrays, along with the associated electronics and data-acquisition systems required for comprehensive measurements.

Along with developments in experimental facilities and detector systems, the symposium will provide a platform for discussions on future scientific opportunities and experimental programmes in nuclear physics, including those that can benefit from particle–gamma coincidence measurements. Particular emphasis will be placed on identifying important physics questions, fostering collaborations among Indian institutions, and exploring advances in detector technologies, electronics, instrumentation, and machine-learning-based data analysis.

In addition to fundamental nuclear physics, the symposium will highlight applications of these techniques in nuclear medicine, including PET/SPECT imaging, dose calculations, and radiopharmaceutical development. Discussions will also address broader applications in nuclear waste management, quantum science, advanced radiation-detection technologies, and space-related instrumentation.

We hope that SPaGCoNS 2026 will provide a stimulating forum for scientific discussions, the exchange of ideas, and meaningful interactions among researchers, students, and experts working in nuclear physics and related disciplines while strengthening collaborations within the Indian nuclear physics community.

## HORIZONS IN NUCLEAR PHYSICS 2026
## 21-23 September, 2026
## Shiv Nadar Institution of Eminence, Delhi-NCR, India

The inaugural edition of a biennial international conference titled "Horizons in Nuclear Physics" will be held during September 21-23, 2026, at Shiv Nadar Institution of Eminence (SNIoE), Delhi-NCR. This conference will bring together researchers from around the country and across the world in the areas of nuclear structure and dynamics, nuclear astrophysics, societal applications of nuclear physics and other related areas. Details about the conference may be found on the conference website: https://nuclear.org.in/

The conference will feature about 35 invited talks by leading experts and 50 poster presentations by doctoral students and early postdoctoral researchers. To promote vibrant interactions during the conference, accommodation will be provided on the picturesque 285-acre SNIoE campus to all delegates; this will be at a nominal cost to students. All meals will be complimentary throughout the conference. Students and early postdoctoral fellows (within 2 years of PhD degree) should submit their expression of interest for poster presentation; research supervisors should separately send reference letters. Early submission of the expression of interest and the reference letter in support of the poster presentation is recommended since slots are limited. A maximum of 50 one-page abstracts will be accepted for poster presentation after screening by the committee. The best six will be awarded prizes and an opportunity for oral presentation. The proceedings of the conference, including invited talks and six best poster presentations, will be published in a SCI-indexed journal.

The deadline for abstract submission is July 31, 2026, and the last date for registration is August 14, 2026. Additional information, which may not be available on the conference website, may be obtained by writing to hinp@snu.edu.in. The conference organizers look forward to welcoming you in September 2026.

## National Conference on "Innovations in Nuclear Physics and its Application to Nuclear Power Generation 2026 (INP-NPG 2026)"
## 20-24 July, 2026
## ICFAI University, Tripura

The conference on "Innovations in Nuclear Physics and its Application to Nuclear Power Generation" brings together eminent scientists, academicians, and industry experts to discuss recent advances in nuclear science and its technological applications. The program begins with an inaugural address on the status of nuclear science and technology in India, followed by invited talks spanning key areas such as nuclear structure, nuclear reactions (fission and fusion), nuclear astrophysics, neutrino physics, and advanced experimental techniques including accelerators and instrumentation. A special focus is given to emerging domains like nuclear data and the application of artificial intelligence and machine learning in nuclear physics. The conference also highlights applied aspects through dedicated sessions on nuclear power generation and safety, addressing both technological developments and societal relevance. The event concludes with a summary session outlining major insights and future directions, aiming to foster collaboration and knowledge exchange within the nuclear science community.

## 6th International Conference on Application of RadiotraCers and Energetic Beams in Sciences (ARCEBS-27)

## 15-21 March, 2027

## Sinclairs Hotel, Chalsa, West Bengal, India

ARCEBS series of conferences are considered as benchmark conferences in accelerator applications in all discipline of sciences. The scope of the conference includes application of radiotracers and accelerated beams from basic sciences to human welfare. ARCEBS is concerned about Earth and Environment and therefore a special topic, accelerator applications in Earth and environmental science, has been included in the scope of the conference. The conference is a quadrennial event. The first conference was held in 2006 at Saha Institute of Nuclear Physics (SINP), Kolkata, India. The second, third and fourth conferences were also organised by SINP. The fifth conference was organised by the Sidho-Kanho-Birsha University Purulia, India. All the earlier conferences in the ARCEBS series were highly successful, breeding ground of new ideas and seeding new collaborations across the globe. The sixth conference, ARCEBS 2027, will be hosted by the oldest and one of the most prestigious universities of India, University of Calcutta.

# Editorial acknowledgements and concluding remarks

As we bring out the second issue of Nuclear Horizons, we take this opportunity to reflect on the continued momentum generated within the Indian nuclear physics community and to acknowledge the collective efforts that have contributed to this publication. Building upon the strong foundation laid in the inaugural issue, this edition further reinforces the shared vision of advancing nuclear science in India in alignment with national priorities and long-term strategic goals.

We continue to recognize the importance of the Mega Science Vision–2035: Nuclear Physics document released by the Office of the Principal Scientific Advisor, which remains a guiding framework for the community. Its emphasis on strengthening infrastructure, fostering collaboration, and promoting cutting-edge research continues to inspire discussions and contributions reflected in this issue.

We extend our sincere appreciation to the nuclear physics community across universities, research institutes, IITs, IISERs, and DAE laboratories for their sustained dedication and scientific contributions. The breadth of work in experimental and theoretical nuclear physics, accelerator science, detector development, nuclear astrophysics, and interdisciplinary applications continues to drive the field forward.

We are deeply grateful to all Professors, Scientists, Researchers, and contributors whose articles and insights have enriched this second issue. Their continued engagement highlights the growing strength and cohesion of the community.

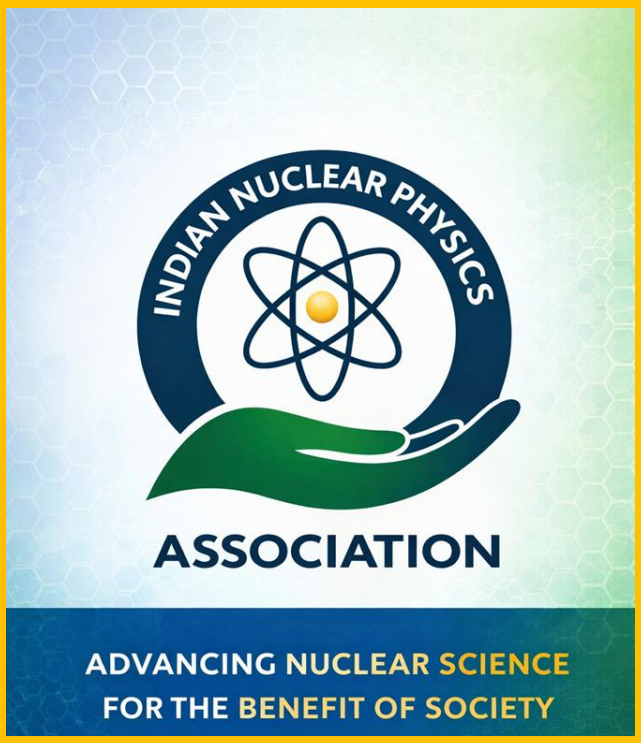
We also express our sincere thanks to the INPA Advisory Committee and Executive Committee members for their constant guidance, support, and encouragement in shaping this publication. We especially acknowledge the leadership of the President of INPA, Prof. A. K. Jain, whose efforts remain instrumental in fostering unity and direction within the community.

We also acknowledge the valuable contributions of reviewers and members who have provided critical inputs during the preparation of this issue. Their thoughtful feedback has helped maintain the quality and relevance of the bulletin while strengthening its role as a platform for academic exchange.

Looking ahead, the coming years present significant opportunities for growth and innovation. With sustained commitment to the Vision–2035 roadmap, India is well-positioned to enhance its capabilities and expand its global presence in nuclear physics research. The continued collaboration of researchers, educators, institutions, and policymakers will be essential in translating this vision into reality.

With this second issue, Nuclear Horizons continues its journey as a platform for dialogue, dissemination, and collaboration. We move forward with renewed enthusiasm and a shared commitment to strengthening India's nuclear science ecosystem, contributing to the broader vision of Atmanirbhar Bharat, and shaping the future trajectory toward Vision 2047.

**— Editorial Team, Nuclear Horizons**




**"Strengthening India's scientific future through excellence in nuclear physics research, education, and applications."**

**The Indian Nuclear Physics Association (INPA)**
is a national professional body dedicated to promoting research, education, and collaboration in nuclear physics and its applications for societal and strategic development.

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