Homi Bhabha and his legacies with specific reference to nuclear and high-energy physics research in independent India

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Homi J. Bhabha occupies a unique place in the history of India – an outstanding scientist, an institution builder and a visionary. He recognized early the immense potential of nuclear technologies for the public good and went on to establish infrastructure and a robust human resource pipeline, not only to support nuclear physics research but also to develop and deploy nuclear technologies for both power and non-power applications in the country. It is an irony of fate that we lost him in an air crash too early in his life and too early in the history of independent India. It is heartening to note that despite this tragic event, the country has moved forward along the course charted by Bhabha and enters the 21st century with confidence and with an aspiration to become part of the developed world, not only scientifically and technologically but also economically and socially. In this article, we share some glimpses of India's journey in nuclear physics research since independence.

Keywords: Accelerators, gamma-ray detector, high-energy physics, nuclear technology.

Prologue

INDIA has always had a tradition of scientific enquiry. Even when the country was under colonial rule, there were instances of path-breaking scientific contributions by Indian scientists working in the country. Who can forget J. C. Bose, P. C. Ray, C. V. Raman, M. N. Saha, S. N. Bose and many others? Institutional support by way of Government funding had to, however, wait till India became an independent democratic republic.

Homi Bhabha occupies a unique place in the history of nuclear science and technology in independent India (Figure 1). The country's remarkably confident foray into nuclear physics research and nuclear technologies can be traced back to a letter of Bhabha to Sir Dorab of Tata Trust nearly 75 years ago, where he pointed out that 'the lack of proper conditions and intelligent financial support hampers the development of science in India at the pace which the talent in the country would warrant'[1]. In a remarkably prescient statement, Bhabha had added that 'when nuclear energy has been successfully applied for power production in say a couple of decades from now, India will not have to look for its experts abroad but will find them ready at hand in India'. Both these observations were to prove prophetic and led not only to the founding of the Tata Institute of Fundamental Research on 1 June 1945, in Bombay, but also laid the foundation for 'nuclear' India.

Even though Bhabha was still in his thirties, the visionary in him could also see the enormous potential of nuclear science and technology for the public good. While the rest of the world was standing in awe at the enormous destructive power of the atom, India moved on with its development agenda. The Atomic Energy Establishment, Trombay (AEET) came into existence in 1954. Bhabha also presided over the First International Conference on the Peaceful Uses of Atomic Energy in Geneva in 1955 and played a crucial role in the formation of the International Atomic Energy Agency (IAEA) in Vienna, Austria, in 1957 with a primary objective to 'accelerate and enlarge the contribution of atomic energy to peace, health, and prosperity throughout the world'. Recognizing that the biggest challenge that developing countries like India would face in realizing their dreams was trained human resources, Bhabha

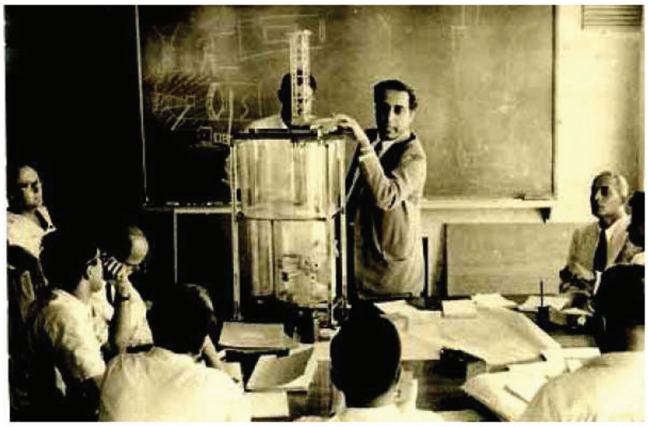

Figure 1. Homi Bhabha in discussion with colleagues.

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*For correspondence. (e-mail: srivastava.dinesh.kumar@gmail.com) also started in 1957, the AEET Training School that would identify promising youngsters with potential, train them and enable them to perform at their best, as covered in a separate article in this Special Section. The Department of Atomic Energy (DAE) also started a yearly Symposium on Nuclear and Solid State Physics around the same time to give a platform for young researchers from across the country, to discuss the results of their investigations with their peers in the field and benefit from interactions with them. These meetings were to blossom into separate symposia for nuclear physics, high-energy physics and solid-state physics, and become a model for symposia in other fields of research as well as a place to discuss plans for new facilities, special schools and theme meetings. These meetings also provided a venue to spot promising students in our educational institutions.

TIFR went on to excel in several areas of research such as mathematics, theoretical physics, experimental nuclear physics, reactor physics and several other emerging areas of research. A one-million-volt Cockcroft–Walton cascade accelerator was installed in TIFR in 1953 for research. AEET initiated several ambitious projects such as the design and construction of the swimming pool reactor APSARA in 1956, the 40 MW experimental reactor CIRUS in 1960, a zero-energy (100 W) reactor ZERLINA for the study of reactor lattices in 1961 and the installation of a 5.5 MV Van de Graaff accelerator in 1962 to strengthen nuclear physics research.

It should also be mentioned that the early decades after independence were also a period of acute resource constraints and foreign exchange was scarce. It is to the credit of the scientists that they could carry out competitive research even with limited resources. The authors remember the statements from their seniors that when they wanted specialized equipment like photomultiplier tubes or electronic vacuum tubes, their first stop was the famed ‘Chor Bazaar’ dealing in scraps in Bombay where the World War II rejects were available for sale.

Even with the limited facilities and resources, the contributions to nuclear research during these years have been noteworthy. For example, using the thermal neutron beamlines in the APSARA and CIRUS reactors, detailed studies of secondary radiations emitted in thermal neutron-induced fission of U-235 were first reported by the Trombay fission group[2]. Direct experimental evidence for pre-scission neutrons was first obtained in these studies. Similarly, experimental evidence for fission accompanied by the pre-scission emission of one or more light charged particles in thermal neutron-induced fission of U-235 was first reported by the Trombay fission group[3]. Similarly, extensive studies of elastic scattering of protons by nuclei were carried out by the Trombay Van de Graaf group leading to nucleon–nucleus optical model potentials at low energies[4]. In a unique experiment, a correlation between fission fragment mass asymmetry and angular anisotropy in fast neutron-induced fission of U-235 was also first reported using the Trombay Van de Graaf accelerator[5]. Such a correlation has strong implications for the dynamics of nuclear fission. The Trombay group was also the first to suggest nucleon exchanges between nascent fission fragments to explain the asymmetric mass distributions in low energy fission of heavy nuclei[3]. Direct experimental evidence for nucleon exchange between nuclei in proximity came several years later in accelerator experiments[3].

In parallel, the radiochemists in Trombay were not only making valuable contributions to the study of transuranium nuclei, but also gained valuable experience in managing spent nuclear fuel and in harvesting specific nuclear isotopes for diverse applications.

Considering the long history of nuclear research in India even before independence with radioactive sources, cosmic rays and several low-energy accelerators and the early experimental programmes in TIFR and AEET, Bhabha organized a review of the emerging needs of the country in nuclear physics research in 1964 and recommended a cyclotron and a medium-energy tandem accelerator for heavy ions to be added to the list of experimental nuclear physics facilities in the country[6]. It is an irony of fate that in 1966, we lost Bhabha in a tragic plane crash while he was on his way to Vienna to attend a meeting of the IAEA’s Scientific Advisory Committee. It is to the credit of his successors, in particular Vikram Sarabhai, a visionary in his own right, that the activities conceived and initiated by Bhabha continued with little disruption.

The Variable Energy Cyclotron Centre, Kolkata

In line with the recommendations of the Bhabha Committee on future accelerators, formal approval for the construction of a 224 cm, K130 variable energy cyclotron at a newly created centre in Calcutta (Variable Energy Cyclotron Centre, VECC) came in 1968. While the design and construction of the cyclotron started almost immediately, poor infrastructure, frequent power failures and political disturbances in the state of West Bengal resulted in considerable delays in the progress of the project. The technology denial regime following India’s Peaceful Nuclear Explosion in 1974 also added to the travails of the scientists and engineers in completing the project. The cyclotron became operational on 16 June 1977, and started providing protons, deuterons and alpha particles of various energies for experiments. Since the beginning, VECC, though created as a project of DAE, has been functioning as a national facility open to all educational and research institutions in the country with active support from the Kolkata Centre of UGC–DAE Consortium for Scientific Research, which was established a little later.

Buoyed by the success of the construction and operation of the cyclotron (see Figure 2), VECC coupled an indigenously built electron cyclotron resonance ion source to the cyclotron and started providing heavy ions for experiments in 1999, considerably enhancing the energy and ion options beyond what the Penning Ion Gauge ion source, used earlier, could provide[7].

Shortly after the commissioning of the room-temperature cyclotron, VECC took up the design and construction of a superconducting cyclotron, which was to provide heavy ions of much higher masses and at much higher energies. The construction, assembly and commissioning of the K500 superconducting cyclotron (Figure 3) required extreme expertise in rolling and machining the main magnet and the pole pieces, and mastering the design and fabrication of superconducting coils, a complex radio frequency (RF) system, uninterrupted running of the large capacity liquid helium plant, etc. This remains one of the most commendable technological achievements of the country. To achieve this, VECC developed expertise in the winding of superconducting coils and indigenously developed the largest superconducting coil in India to provide the required magnetic field of 5.5 Tesla (55,000 Gauss), with a precision of a few Gauss. Cryogenics technology at liquid helium temperature got a big boost in the country by building and operating this magnet. The 100-tonne main magnet was also fabricated indigenously, as in the case of the room temperature cyclotron, by Heavy Engineering Corporation, Ranchi. An internal beam from the superconducting cyclotron was obtained in August 2009. The extraction of the external beam necessitated identifying and correcting a micro-misalignment between the main magnet and the superconducting coil. This correction proved to be a great challenge and a great learning opportunity, and the external beam was obtained on 30 December 2020 (ref. 8).

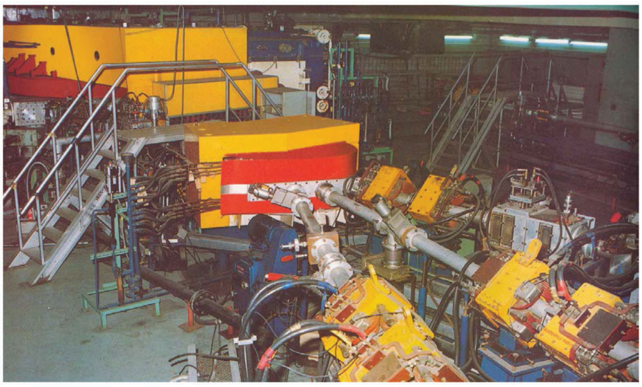


Figure 2. The variable energy cyclotron at Kolkata.

Figure 3. K-500 superconducting cyclotron at Kolkata.

It is known that stable nuclei constitute only a narrow band of about 300 nuclei in the neutron–proton space. While decades of nuclear reaction studies have opened up a large region adjoining the beta-stability line, our knowledge about the nuclei far off this line is highly fragmented and incomplete. On the other hand, as one moves away from the narrow band of beta-stable nuclei, one expects to see various interesting and exotic features and phenomena. Thus, for example, one could find nuclei with exotic shapes and sizes – a Li-11 nucleus swollen to the size of Pb-208, very unusual magic numbers, doubly magic nuclei like oxygen-24 and nickel-78, unusual shell structures, and life-times from a few years to the billionth of a second or less, as well as cluster radioactivity, and nuclei which played an important role in stellar nucleosynthesis.

Thus, nuclear reaction studies with radioactive ion beams open up entirely new and unexplored areas of research, far away from the stability line. Several radioactive ion beam facilities have been planned, built or are under construction globally[9]. VECC has taken long strides in this direction. Soon after the commissioning of the room temperature cyclotron, a programme to produce and transport radioactive nuclei to a low background area using a helium jet (isotope separation online, ISOL), and to study short-lived nuclei was taken up. This activity has now matured at VECC by re-ionizing, bunching, and then accelerating these short-lived nuclei successively through a radio frequency quadrupole (RFQ) and a set of linear accelerators to produce a low energy beam of radioactive nuclei (Figure 4). The nuclei are used to perform experiments in

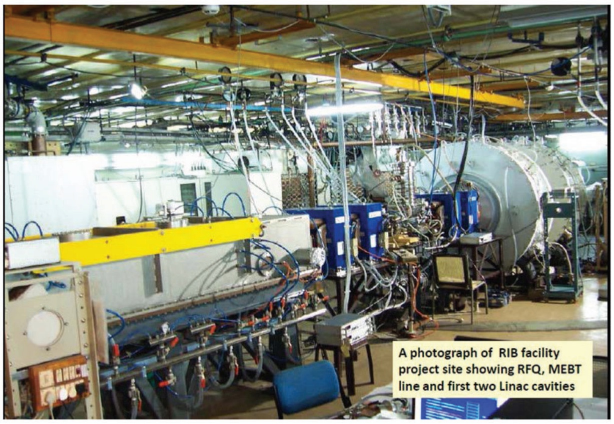


Figure 4. The Radioactive Ion Beam Facility at VECC, Kolkata.

nuclear physics and materials science. The entire design and fabrication of all the ionizing, accelerating, focusing and transporting components were done in-house.

VECC has recently installed a 30 MeV, 500 micro-Ampere proton cyclotron for the production and supply of positron emission tomography (PET) and single photon emission computed tomography (SPECT) isotopes for medical diagnostics purposes, as well as isotopes such as those of iodine for cancer therapy. The cyclotron has special beamlines for the radiation damage studies of nuclear materials and for the testing of targets for accelerator-driven subcritical systems.

The BARC–TIFR Pelletron-LINAC Facility

The next major step in nuclear physics research in India was the creation of the Pelletron facility, MEHIA – a Medium Energy Heavy-Ion Accelerator, in TIFR in the late eighties (Figure 5). We have already mentioned that the 1964 Bhabha Committee had recommended the creation of such a facility. A 14 UD Pelletron accelerator was installed and formally inaugurated on 30 December 1988. Experiments started in right earnest with a general-purpose scattering chamber. In due course, more complex detector systems were also added. The facility was augmented with an indigenously developed superconducting LINAC booster not only to enhance the energy of the accelerated beams, but also to bunch the beam to enable time-of-flight measurements. The development of the superconducting LINAC is a major milestone in the accelerator technology in our country. It is to the credit of the scientists involved that most of the critical components of the LINAC booster were designed, developed and fabricated indigenously. Phase-I of the LINAC booster was commissioned on 22 September 2002, and the facility was dedicated to users on 28 November 2007, after the completion of Phase-II (ref. 10).

Inter-University Accelerator Centre, New Delhi

In order to give a boost to accelerator-based research in universities, an Inter-University Accelerator Centre (initially known as the Nuclear Science Centre) was established by the University Grants Commission in New Delhi in 1984. A 15UD Pelletron accelerator was set up at IUAC, which started delivering energetic beams of heavy ions to the users in 1991 (Figure 6). A superconducting LINAC booster was added to the main Pelletron in due course. The LINAC booster consists of three accelerating modules, each housing eight niobium quarter-wave resonators and an 8-tesla superconducting solenoid, a super buncher module and a re-buncher module housing one or two Quarter Wave Resonators (QWRs) respectively. Developed in collaboration with Argonne National Laboratory, USA, the complete LINAC booster became operational in 2012 (ref. 11).

Experimental facilities

It is known that the quality of nuclear research carried out in any accelerator laboratory depends as much on the beams available as on the detector systems for carrying out specific experiments. It is gratifying that the three accelerator laboratories in India put ample emphasis on state-of-the-art detector systems. Starting from simple scattering chambers and a few stand-alone detectors, the experimental facilities in all the accelerator laboratories have been augmented substantially over the years, both in size and sophistication (Figure 7).

Energetic nuclear collisions lead to a multiplicity of fragments and particles in the exit channel requiring detection and identification of all the reaction products enabling kinematic event reconstruction. Several detector arrays including delta E–E telescopes for particle identification have been designed and used by different groups. The Trombay group in particular has used novel ionization chambers with split electrodes to detect heavy nuclei

Figure 5. The BARC–TIFR Pelletron–LINAC facility, Mumbai with the three beam halls showing experimental facilities.

Figure 6. The 15 UD Pelletron–LINAC Facility at IUAC, New Delhi.

in the exit channel like fission fragments. In addition, several multi-wire proportional counters for the detection of heavy reaction products and fission fragments have been designed and fabricated indigenously.

To measure, event by event, the number and energy of neutrons emitted in a nuclear reaction, arrays of neutron detectors with time-of-flight measurements to discriminate gamma rays have also been set up. Similarly, charged particle detector arrays designed, developed and deployed in the country have proved extremely valuable.

A variety of gamma-ray detectors, both for high-resolution and high-energy measurements have been designed and built. The gamma ball or its equivalent with an array of high-resolution HPGe detectors with Compton suppression is the standard workhorse in all three accelerator facilities in India. These facilities have been used in various combinations for the study of nuclear reactions. While different detector systems have been designed and built by different groups for specific experiments, they are also made available to other users (Figure 8).

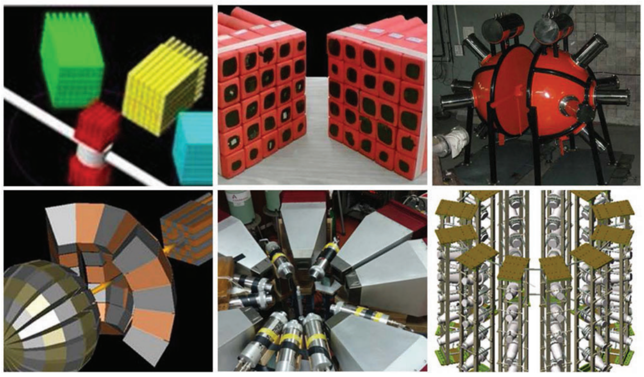
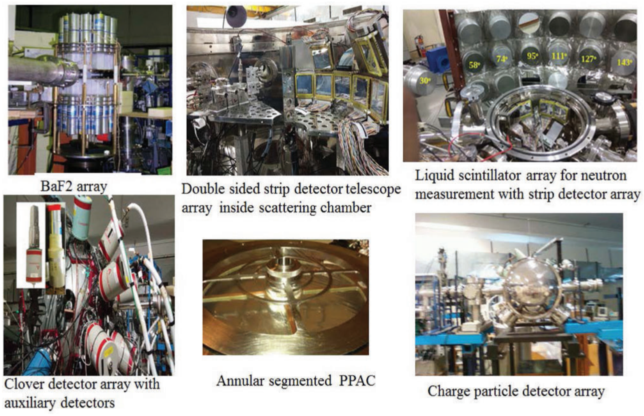


Figure 7. Some of the detector systems at VECC. Clockwise: LAMBDA (large area modular BaF2 detector array, schematic), GAMMA (gamma multiplicity filter array), neutron multiplicity detector, ChAKRA (high resolution charged particle detector array, schematic), VENTURE (array for nuclear fast timing and angular correlation studies) coupled to the VENUS array (for nuclear spectroscopy), and neutron time of flight array (schematic).



BaF2 array

Double sided strip detector telescope array inside scattering chamber

Liquid scintillator array for neutron measurement with strip detector array

Clover detector array with auxiliary detectors

Annular segmented PPAC

Charge particle detector array

Figure 8. Detection set-ups at Pelletron–LINAC facility, Mumbai.

IUAC has built a sophisticated hybrid recoil mass analyser (HyRA), a dual-mode, dual-stage spectrometer/separator with its first stage capable of operating in a gas-filled mode in normal kinematics (to access heavy nuclei surviving fission, around mass 200 amu and beyond), and both stages in vacuum mode in inverse kinematics (to access nuclei around $N \sim Z$ up to 100 amu mass and to provide light, secondary beams produced in direct reactions). It has also built, HIRA – a heavy-ion reaction analyser dedicated to the study of heavy ion-induced nuclear reaction dynamics (Figure 9).

As was mentioned earlier, the three major nuclear physics research facilities created in Kolkata, Mumbai and Delhi have also triggered one of the first large-scale collaborative efforts in nuclear research within the country. Supported by the Department of Science and Technology, INGA – the Indian National Gamma-detector Array, where gamma-ray and particle detectors from various laboratories (BARC, IUAC, IUC-DAE-CSR, SINP, TIFR) are pooled and rotated between the three main nuclear physics laboratories of the country is a unique initiative amongst Indian research institutions. The collaboration which started with a few detectors has now expanded to 24 Compton suppressed HPGe clover gamma-ray detectors to provide nearly 4-pi coverage, and is powered by high-speed data acquisition and analysis systems[12] (Figure 10).

Experimental programme highlights

It is known that charged particle beams from the medium-energy heavy-ion accelerator facilities of the type that India has established can address an important class of problems relating to nuclear reactions[7,10–12]. The dynamics of nuclear fusion, incomplete fusion, nuclear fission and fusion–fission reactions in heavy-ion collisions is one such area.

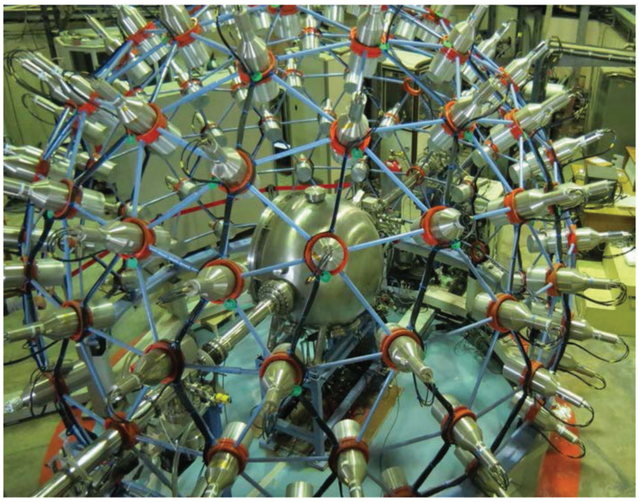


Figure 9. NAND: National Array of Neutron Detectors at IUAC, New Delhi.

Understanding processes of relevance for early nucleosynthesis, probing (cluster) structure of nuclei and their excited states, etc. are other areas of interest amenable to these energies. The class of investigations that have been carried out and are being carried out in the three facilities in India reflects this. The study of heavy ion-induced fission and fission-like reactions was one of the first investigations carried out at the Mumbai facility. Estimation of fission timescale from the measurement of pre-scission neutrons, light particles and γ-ray multiplicities, and study of quasi-fission have also been pursued.

Some of the other important findings in experimental nuclear physics include first observation of Jacobi shape transition in the vanadium-47 nucleus, where at large angular momentum the rotating nucleus changes shape abruptly from oblate to elongated triaxial; observation of coherent bremsstrahlung production of high-energy photons from fission fragments of heavy nuclei accelerating away from each other due to Coulomb repulsion, giant resonances built on excited states, determination of temperature dependence of the decay-width of giant dipole resonances and extraction of specific viscosity of nuclear fluid – and a demonstration that it is a near perfect fluid having close to the minimum possible viscosity, shape and spin dependence of level density of nuclei, first accurate measurement of the decay modes of the Hoyle state in carbon-12, the observation of de-excitation of Be-8 from its 4+ to 2+ state, the study of several short-lived nuclei produced in nuclear reactions, observation of vanishing of shell effects in the fission of nuclei as the excitation energy increases, a first observation of wobbling excitation of nuclei, several new bands in excited levels of nuclei, repeated observations of interplay of single particle and collective model description of nuclei, chiral bands and shape coexistence in nuclei, magnetic and anti-magnetic rotation of nuclei, spectroscopy of several isomeric states, etc. Sub-threshold and near-Coulomb barrier fusion, fusion–fission, incomplete fusion, dynamics of fission, detailed studies of entrance channel effects in fusion, emission of neutrons and gamma rays from various stages of fission, etc. have been extensively studied with the availability of a variety of beams at several energies and a vast array of particle and gamma-ray detectors. A particularly high point was the use of radioactive beryllium beam (Be-7) at IUAC, produced through p(Li-7, Be-7)n reaction and separated using HIRA for experimental studies.

An interesting study involved the use of surrogate reactions in various forms to get an indirect estimate of the neutron-induced fission reaction cross-sections for unstable actinides in Th–U and U–Pu fuel cycle, which are not accessible for direct experimental measurements.

Raja Ramanna Centre for Advanced Technology, Indore

The valuable experience in the construction and operation of the cyclotron at VECC and the confidence generated among accelerator physicists, engineers as well as industries in the field of accelerator technology led to the creation in the mid-1980s of a complex of electron storage rings Indus-1 (450 MeV) and Indus-2 (2.5 GeV), and a synchrotron radiation facility at the Raja Ramanna Centre for Advanced Technology (RRCAT) at Indore. Indus-1 has six beamlines providing synchrotron radiations ranging from far infrared to soft X-rays, while Indus-2 has provisions for close to 25 beamlines giving intense soft and hard X-rays for basic and applied research in condensed matter physics, materials science, biology, etc. Insertion devices (undulators, wigglers and wavelength shifters) have also been installed to provide radiation in different spectral ranges, with much higher brightness[13]. The facility hosts a vast variety of vibrant interdisciplinary research programmes by groups not only from the DAE institutions, but also from several universities and academic institutions (Figure 11).

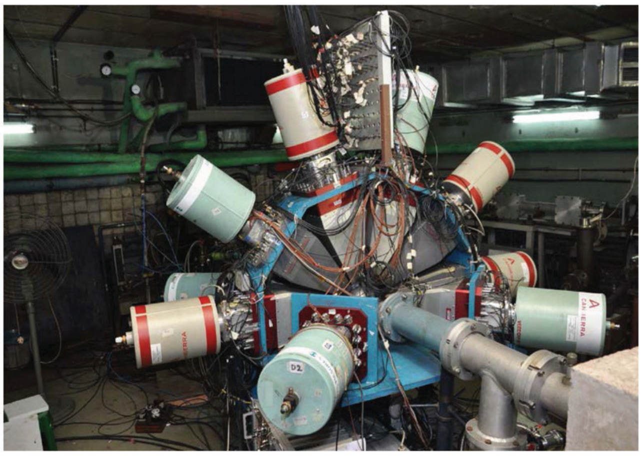


Figure 10. Indian National Gamma-Detector Array at VECC, Kolkata.

Figure 11. Angle-resolved photoelectron spectroscopy beamline at RRCAT, Indore.

As we will see later, RRCAT played a pivotal role in India's participation in CERN activities. It is also playing a leading role in India–Fermilab (USA) collaboration for the development of superconducting RF cavities for the high-current, high-energy proton accelerator for use with accelerator-driven subcritical systems and spallation neutron source, being undertaken jointly by BARC, IUAC, RRCAT and VECC.

Developments in electronic instrumentation and high-performance computing

As was mentioned earlier, the post-1974 technology denial also had an impact on the availability of state-of-the-art electronic instrumentation, including computers to DAE, while the requirements were increasing rapidly. The embargo against the core units of DAE was so severe and so strictly implemented that not only routine instruments were denied to DAE units, but even computers bought by other institutions in India were out-of-bounds for DAE scientists. It is to the credit of the Indian scientists and engineers who converted this challenge into an opportunity. For example, to meet the ever-increasing demand for the number-crunching power, BARC embarked on making the ANUPAM series of supercomputers. The first in this series was ANUPAM 860/4, giving a sustained speed of 30 Mega FLOPS, made in 1995 (ref. 14). Since then, successively proceeding through more massive and speedier parallelization, it has released several supercomputers in the ANUPAM series. The recently released Atulya delivers a whopping speed of 1.35 PFLOPS with 17,720 cores.

Homi Bhabha National Institute

Human resource development has remained one of the most important objectives of all the constituent units of DAE. To provide a vibrant platform 'to nurture in-depth capabilities in nuclear science and engineering and to serve as a catalyst to accelerate the pace of basic research and facilitate its translation into technology development and applications through academic programmes', the Homi Bhabha National Institute, Mumbai, was established in 2005 as a Deemed University, and it has started playing an important role in intense multidisciplinary basic and applied research, as described in a separate article in this issue (Grover *et al.*, pp. 441–450).

To share Indian nuclear expertise with other countries, particularly in the developing part of the world, the Global Centre for Nuclear Energy Partnership was started in Haryana in 2010. In addition to helping interested countries in capacity building in association with IAEA in the field of technology, human resource development, education and training, and giving momentum to research and development in areas important for nuclear energy, the Centre is also mandated to conduct research, design and development of nuclear systems that are intrinsically safe, secure, proliferation-resistant and sustainable.

India in international high-energy nuclear and particle physics research projects

As was mentioned earlier, India has a long tradition of experimental high-energy physics research. One of the first major efforts in experimental high-energy physics in India was by D. M. Bose and Bibha Chowdhuri, who exposed photographic emulsions to cosmic rays at high altitudes[15]. High-altitude cosmic-ray research has continued in TIFR since its inception. The TIFR group also went on to make the first observation of atmospheric neutrinos in the 2 km deep Kolar Gold Mines in a TIFR–Osaka–Durham Collaboration in 1965 (ref. 16). Vikram Sarabhai, who had earlier worked with Bhabha, established his own Institute, the Physical Research Laboratory, in Ahmedabad, to study cosmic rays using rockets – an effort that ultimately blossomed into the Indian Space Research Organization (ISRO). As high-energy physics research across the world migrated slowly to accelerators with increasing energies, high-energy physicists in India had no alternative but to collaborate with scientists and facilities abroad. Researchers in TIFR and several other universities in India started participating in particle physics experiments using nuclear emulsions and cloud-chamber photographs.

A few high-energy experimental physicists from TIFR started participating in experiments in CERN as early as the 1960s, essentially in their individual capacities. This matured to participation by groups, for example, in the case of the L3 collaboration for the study of the Z boson and W+W-physics. Interestingly, one of the TIFR scientists rose to become the spokesperson of the collaboration. Researchers at Delhi University had joined the E706 experiment in Fermilab to study direct photon production in the collision of protons and gluon structure–function.

In the late 1980s TIFR, Panjab University and Delhi University joined the D0 experiment at Fermilab, which lasted for close to 20 years, and led to the discovery of top quarks and set limits for the mass of the Higgs boson. It is currently in the news for providing the most accurate mass for W bosons, which if confirmed can provide a valuable hint for physics beyond the Standard Model.

In the late 1980s, a group from VECC along with scientists from several universities joined the CERN SPS/WA80 group to study high-energy, heavy-ion collisions by designing, fabricating and managing a photon multiplicity detector (PMD) for the study of quark–gluon plasma. It was a pre-shower photon multiplicity detector consisting of 7600 plastic scintillator pads that transported light generated in them as photons passed through a lead converter of a suitable thickness placed before them. The light was transported using wavelength-shifting fibres to a camera and used in the WA93 Experiment at CERN SPS to study

S–Au collisions. A much larger detector using 55,000 pads was employed to study Pb–Pb collisions at the WA98 Experiment (Figure 12). The PMD was redesigned for use in the ALICE experiment at the Large Hadron Collider (LHC) where the pads were replaced by honeycomb proportional counters (200,000 cells), and the STAR experiment at BNL RHIC using a similar design. The detectors led to the discovery of azimuthal flow in these collisions and limits of disoriented chiral condensate production, among other interesting results.

By the mid-1990s, Utkal University, Punjab University and TIFR joined the Belle collaboration at KEK and it has continued with the Belle-II collaboration, with vastly improved capabilities to study rare decays of B and D mesons and tau leptons.

A group at BARC and some universities joined the PHENIX experiment at BNL RHIC and the CMS experiment (see later) at CERN LHC along with TIFR and several other universities. Scientists from the Saha Institute of Nuclear Physics, Kolkata, designed, fabricated, installed, validated and collected data, and analysed them from the second station of the ALICE di-muon spectrometer. Multiplex Analog Signal Processor (MANAS) chips, designed and produced in India, were installed in the ALICE detector. The total requirement (with spares) of 88,000 MANAS chips with a 16-channel readout for the muon spectrometer and 20,000 chips for PMD was also met by India. The TIFR group, following its success with the L3 experiment, joined the CMS collaboration and was soon joined by several other groups from various universities (Figure 13). The CMS experiment, along with the ATLAS experiment, led to the discovery of the Higgs boson in 2012. A remarkable contribution to this effort was the calculation of NNLO corrections to the total cross-section for Higgs boson production in hadron–hadron collisions, which played a key role in the precise determination of its mass[17]. The experiments are now focusing on decay modes of the Higgs boson, physics beyond the Standard Model, matter–antimatter asymmetry, dark matter candidates and sources of dark energy.

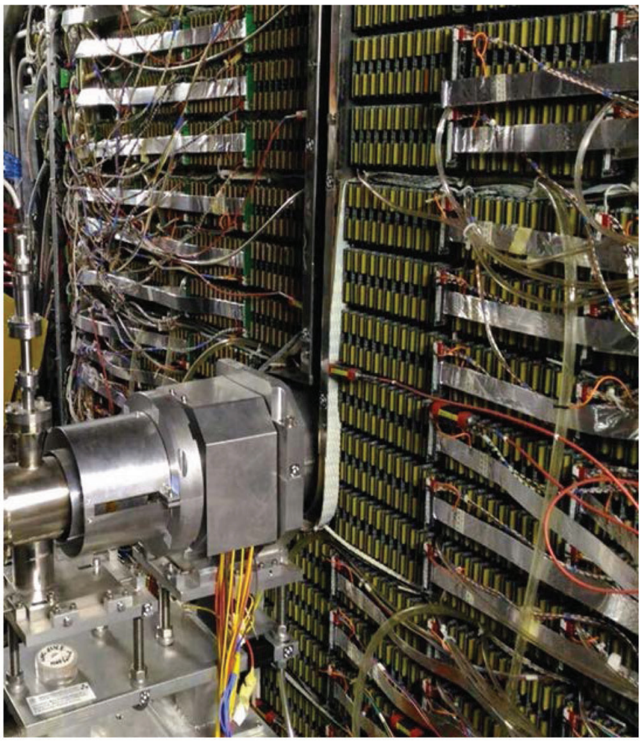


Figure 12. Photon multiplicity detector at ALICE – a Large Collider Ion Experiment at the Large Hadron Collider, CERN, Geneva.

As the Indian high-energy and particle-physics community prepared to participate in major experiments at LHC, CERN, the accelerator physics and technology community, led by RRCAT made under an India–CERN Cooperation Agreement signed in 1991, significant contributions to the construction of the LHC accelerator, both in the areas of design, development and supply of hardware accelerator components and software development and deployment in the LHC machine[18] (Figure 14).

The ALICE and CMS experiments have several detectors and collect a vast quantity of data (more than 100 Mbyte/sec

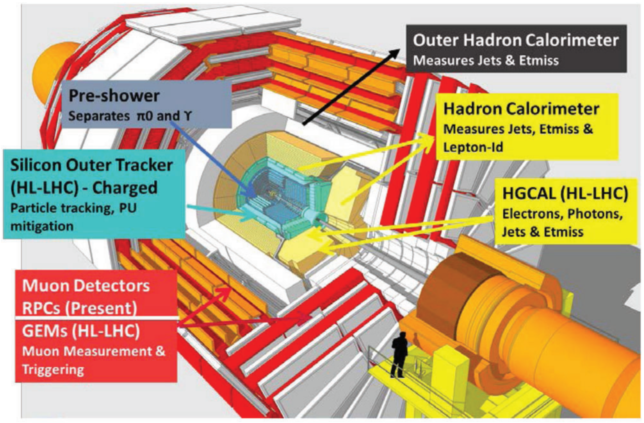


Figure 13. Main contributions to the CMS detector at CERN LHC from India.

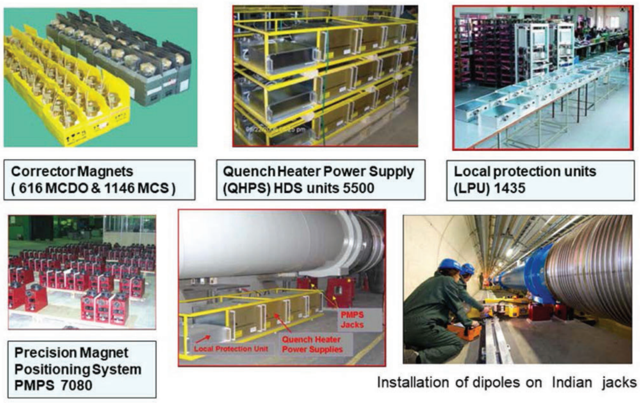


Figure 14. Main contributions of RRCAT Indore to CERN LHC.

and requiring 1.5 Peta-bytes of storage per year) which need to be analysed. Indian researchers from BARC, IGCAR, RRCAT and TIFR contributed to designing, developing and deploying software for the Worldwide Large Hadron Collider Grid (WLCG). The Tier-2 Grid computing facilities at VECC and TIFR, and Tier-3 computing facilities at participating institutions, connected by the 10 GBytes/sec National Knowledge Network have met the pledged resources and have operated with 96% uptime, thereby facilitating the running of jobs by ALICE, CMS and WLCG collaborations spread all over the world. The Tier-2 and Tier-3 Grid computing facilities are in the process of being further upgraded to meet the growing demands on computation, and data storage and transfers.

In 1996, the Government of India also decided to take part in the construction of the LHC and to contribute to the CMS and ALICE experiments and the LHC Computing Grid with Tier-2 centres in Mumbai and Kolkata. The significant contribution of Indian researchers in accelerator technology, computing, detector fabrication, data-taking and analysis as well as the robust infrastructure and the large body of excellent researchers in the country earned the status of Observer for India to the CERN Council in 2002. India became an Associate Member of CERN on 16 January 2017.

Nuclear theory

Vibrant research in nuclear theory had also started early in the country, which saw several breakthroughs in nuclear structure and nuclear reaction studies. In the case of nuclear structure, pioneering results were obtained in the relation of particle–hole and particle–particle interactions, formulation of deformed shell model calculations, Hartree–Fock and projected Hartree–Fock calculations of the structure of nuclei, effect of two-body correlations, second-order effects in two body matrix-elements using separable non-local interactions, formulation of adiabatic, time-dependant Hartree–Fock theory, spectra and dynamics of complex nuclei, exploration of the consequences of the quark structure of nucleons on nuclear forces, structure of hypernuclei, theory of direct nuclear reactions, etc. Several of these works have found a place in textbooks on nuclear physics.

Some of the important directions in nuclear theoretical research in recent times include studies of nuclear and Coulomb break-up of light nuclei, studies in optical model for elastic scatterings of nucleons and light ions, consequences of saturating properties of nuclear forces, coupled reaction channel calculations, full finite range calculations of knock-out reactions – which resolved the several decades old discrepancy in spectroscopic factors, particle production in proton–proton interaction at an energy of a few GeV, role of symmetries in nuclear structure, interacting boson model and relativistic mean field theories applied to investigate nuclear structure, evidence for the seniority quantum number, study of isomeric states, ab initio and large-scale shell-model calculations of structure of nuclei, ab initio calculations of the structure of hyper nuclei, ab initio calculations of dynamics of fission along with emission of neutrons and gamma rays, nuclear matter properties, nuclear equation of state, determination of compressibility of nuclear matter and multi-fragmentation of nuclei, transition from the preponderance of one-body interaction to two-body interactions in nucleus–nucleus collisions with the rise in collision energy, and structure of halo nuclei and Borromean nuclei, etc.[7].

The theory groups in India have also made several pioneering contributions to the study of formation, evolution, signals and thermodynamic and hydrodynamic properties of quark–gluon plasma. These include prediction and explanation of radiation of thermal photons and dileptons from relativistic heavy-ion collisions as a signature of quark–gluon plasma, the first prediction of the elliptical and triangular flow of thermal photons emitted in these collisions – now verified experimentally at RHIC and LHC, pioneering results in the development of hydrodynamic flow in relativistic heavy-ion collisions, the first estimate of thermalization and energy loss of heavy quarks in quark–gluon plasma, the dynamics of particle production in proton–proton, proton–nucleus, and nucleus–nucleus collisions, calculation of thermodynamic properties of quark–gluon plasma using hard thermal loops, field theoretical calculations of thermodynamic properties of hadronic gas at high temperatures, lattice QCD calculations of hadronic masses and thermodynamic properties of quark matter at finite baryonic chemical potential – and possible location of the tri-critical point in phase space, etc.

The new India in the twenty-first century

The 1998 Pokhran II weapon test was a turning point in the history of India. As in the case of Pokhran I, Pokhran II also evoked severe scepticism in some quarters in India and abroad. Much to the surprise of the sceptics, Pokhran II was followed by a reassessment of India not only by USA, but also by all countries of the world. One may recall the establishment of the Indo–US Science and Technology Forum (IUSSTF) in March 2000, as an autonomous bilateral organization jointly funded by both the Governments to promote collaborations in science, technology, engineering and innovation through substantive interaction among government, academia and industry. The Indo-US civil nuclear agreement (the 123 Agreement) signed between USA and the Republic of India in 2008 was the next step in Indo–US relations. Following the Indo–US nuclear deal, our relations with the other countries also changed dramatically and led to India's rightful place on the international table of nuclear nations. India understandably entered the 21st century with a newfound confidence in all sectors, including nuclear research. It is interesting to note that the resource constraints of the early decades after independence and the technology denial later had the same impact – increase our resolve to stand on our own legs and increase our innovation skills. India has started participating as equal partner in several International Mega Science Projects like ITER (International Thermonuclear Experimental Reactor), SKA (Square Kilometer Array), TMT (Thirty Meter Telescope), LIGO (Laser Interferometer Gravitational-wave Observatory), etc.

India was one of the early partners to join (2010) the GSI Darmstadt Facility for Antiproton and Ion Research (FAIR) with a focus on basic investigations not only in the field of nuclear physics and atomic physics, but also in several other application-oriented studies in materials research, plasma physics, biophysics and nuclear medicine. India's contributions would include costs towards building the accelerator and also experimental facilities for the compressed baryonic matter experiment and nuclear structure, astrophysics and reactions experiment. As India is a part-owner of this facility – which will provide very intense beams of high-energy heavy-ions, radioactive ions and antiprotons, it provides a unique opportunity for our scientists to participate in experiments looking for the dense baryonic matter – as in the interior of neutron stars, understand the acquisition of mass by sub-nuclear particles, and study the nuclear structure and nuclear reactions in hitherto unexplored domains. Indian scientists are preparing to participate in the Compressed Baryonic Matter (CBM), Nuclear Structure and Reaction (NUSTAR) and antiProton ANnihilation at DArmstadt (PANDA) experiments.

These collaborations have nurtured generations of brilliant students who are working enthusiastically in a highly creative, competitive and frontier area of science and technology in a multinational, multicultural environment. For example, participation in the CERN activities has also led to exposure to an entirely new culture of doing science, where several thousand scientists and engineers work for decades to plan, build and perform experiments, analyse the data and examine every word of the manuscripts before they are finally communicated for publication. The Higgs boson discovery paper in 2012 had 5154 authors from across the world. The Indian connection to this path-breaking discovery does not end with Bose and the Bose–Einstein condensate. As was mentioned earlier, India is a partner in CERN with both cash and in-kind contributions. Many Indian institutions and scientists have been involved in the design, fabrication, carrying out the discovery experiment and analysis and interpretation of the results, as mentioned earlier.

The road ahead

Nuclear physics research is a little more than a 100 years old. During these years, we have learnt a lot about nuclei – their ground state properties, the spectrum of their excited states, their interactions with other nuclei, the dynamics of nuclear fission, fusion, multifragmentation, etc. We have learnt to exploit the new knowledge for the public good in many ways. However, when we discuss nuclear physics research, we are always reminded of the famous quote 'Age cannot wither her, nor custom stale her infinite variety' from the play *Antony and Cleopatra* by William Shakespeare. Even today, what we have learnt so far about the nucleus is far from complete as its mysteries are so endlessly varied. For example, we know that stable nuclei constitute only a narrow band in the neutron–proton space. We have mentioned earlier that, while decades of nuclear reaction studies have opened up a large region adjoining the stability line, our knowledge about the nuclei far off the stability line is highly fragmented and incomplete. Nuclear reaction studies with radioactive beams open up entirely new and unexplored areas of research, far away from the stability line.

The availability of supercomputing facilities and developments in the understanding of free nucleon–nucleon interactions, three-body interactions, increasing important role of spin–orbit interactions and pioneering developments in nuclear theory are making it possible to perform ab initio study of the structure of nuclei, and the dynamics of nuclear reactions and fission. The theoretical studies are throwing up hitherto unexpected features of these processes, whose experimental verification is highly interesting. Radioactive ion beam facilities open this vast, varied and unexplored landscape of nuclei for us. Spurred by this, several countries have built or are building radioactive ion beam facilities using either production and on-line separation with post-acceleration of radioactive nuclei, or projectile fragmentation and separation of accelerated nuclei.

As we have already mentioned, VECC has been using the ISOL route to produce low-energy, short-lived radioactive ion beams with alpha particles from the K130 cyclotron. In parallel, the development of a 30–50 MeV electron beam using high-current continuous wave (CW) linear accelerators with superconducting RF cavities has also been taken up to produce energetic neutron-rich nuclei by fission of heavy nuclei. Based on these experiences, VECC has also proposed an Advanced National Facility for Unstable and Rare Isotope Beams (ANURIB). The project envisages a 50 MeV, 100 kW, superconducting CW electron LINAC-driven photo-fission target to produce radioactive nuclei, separate, ionize and accelerate them to up to 7 MeV/A using linear accelerators. ANURIB will thus give access to the entire possible landscape of nuclei, both neutron-rich and proton-rich, and provide not only new information on nuclei close to the drip-lines, but also deep insight into the nuclear equation of state, isospin dependence of nuclear forces and nuclear structure, and formation of elements in early universe and stars[19].

We would like to add that beams of neutron-rich nuclei can also be produced using neutron-induced fission of

U-235 at high flux reactors like DHRUVA and further accelerating these ions to a few MeV per nucleon levels. The fission fragments from recoil for a very thin target can be separated using an on-line mass-separator[20], or from a thick target using the well-developed techniques of diffusion and ionization, and further acceleration. These facilities have been in operation for decades, for example, in the Lohengin mass separator at Institut Laue-Langevin, Grenoble, France. Further acceleration of these radioactive ions to a few MeV per nucleon levels could open up an entirely new area of research with energetic ions of neutron-rich nuclei.

India was an early entrant in cosmic-ray research. From 1951 to 1992, the country had a programme to study neutrinos and muons in a facility located deep within what was then one of the largest active gold mines in the world, the Kolar Gold Fields. When the laboratory had to cease operations after the closure of the gold mine, efforts were made to identify and build a new place to continue these studies. After several rounds of national and international consultations, a proposal to set up an underground neutrino laboratory was formulated. Government approval for the same was also obtained. Unfortunately, the proposal is still stalled for political reasons. In the meantime, BARC has embarked on a vibrant programme of neutrino physics. The Indian Scintillator Matrix for Reactor Antineutrino (ISMRAN) is the first attempt in the country to study reactor neutrinos with the primary goals of sterile neutrino search and resolution of reactor antineutrino anomaly using the Dhruva reactor. A programme of neutrino measurements using coherent elastic neutrino–nucleus scattering has also been initiated at the newly upgraded APSARA-U reactor. These studies open up several other topics at the frontiers of physics research, such as measurements of neutrino electromagnetic properties, tests of non-standard interactions, coherence tests using neutrinos, etc.

Epilogue

When we look back at the struggles and travails of the nuclear physics, particle physics and accelerator physics community of the country, we cannot help but admire and wonder at their grit, determination and perseverance in the face of a shortage of funds, poor industrial infrastructure and technology, and even knowledge denials due to embargoes, for extended stretches during the period under discussion. Thus the indigenous construction of the variable energy cyclotron, superconducting cyclotron and the Radioactive Ion Beam Facility at Kolkata, the Indus-1 and Indus-2 synchrotron sources at Indore, the superconducting LINACs at BARC–TIFR Pelletron, Mumbai and at IUAC, New Delhi stand out as most remarkable achievements of the country. As mentioned above, this helped the accelerator physics and engineering community in the country to take up the challenging jobs of contributing to the construction of LHC at CERN, and the development of high-energy proton accelerators using superconducting RF cavities in collaboration with the Fermilab, for the spallation neutron source and the accelerator-driven subcritical systems being planned. These indigenous developments have led to a robust industrial infrastructure for precision technology in the country, which is now able to compete internationally and contribute extensively to FAIR, ITER, LIGO and other collaborations.

The extensive and sophisticated detector and data acquisition systems at the Kolkata, Mumbai and New Delhi centres for nuclear research were indigenously designed, developed and deployed. This has led to the nurturing and maturing of a vast pool of expert nuclear physicists – in the national laboratories, IITs and universities, who are contributing to the frontier areas of research. The detector systems designed, developed, fabricated and deployed at CERN and other international laboratories have enabled some of the most iconic fundamental discoveries of recent times, while we prepare to participate in experiments at FAIR, Darmstadt using similarly developed detectors and to take on bigger challenges.

The journey of the Indian nuclear physics and high-energy physics community, starting with detectors fabricated from components taken from a scrap market to developing internationally competitive facilities at home and contributing to international facilities – some of which India partially owns, is a journey of discovery and realization of our potential.

We have limited our discussions to nuclear physics, high-energy physics, and accelerators. The expertise developed though has contributed to several other fields, least of them being applications of nuclear techniques to medicine, agriculture, industry, water purification, waste disposal and use of nuclear radiation for the preservation of food and the country has continued to take rapid strides in taking fullest advantage of nuclear sciences. Several of these aspects are discussed in the companion articles in detail in this Special Section.

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