Nuclear Physics Research in BARC

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Preamble

An overview of the Nuclear physics research programme pursued within BARC and other DAE institutions since inception and its subsequent growth is presented from the historical perspective. The diverse theoretical and experimental studies carried out by utilizing the research reactors and particle accelerators over the years have been described.The seminal contributions made in the area of fission physics in particular and nuclear reactions have been highlighted. Significant contributions made into the area of accelerator physics and nuclear instrumentation have been presented. Experiments performed in high energy physics through international facilities have also been described.

1. Introduction

Nuclear physics research programme in its early days was supervised and nurtured by Dr. Homi J. Bhabha under the umbrella of the India's atomic energy programme. Initial work done using the Cockcroft-Walton neutron generator at Tata Institute of Fundamental Research (TIFR) in early 1950's laid a good foundation in nuclear physics research. Dr. Bhabha provided strong, dynamic leadership in very early years, whereby two research reactors 1 MW APSARA reactor and 40 MW CIRUS reactor with assistance from UK and Canada, respectively, became operational at Trombay. These two facilities provided unique opportunities for carrying out the experimental nuclear physics research in the country. Dr. Raja Ramanna, who had earlier joined the faculty of TIFR, was called upon to take the leadership for the development of nuclear physics programme in the Atomic Energy Establishment, Trombay (AEET). Dr. Ramanna led the programme of utilization of research reactors for nuclear physics and other research purposes. He was also responsible for initiating programmes for the development of particle accelerators in the country as well as their utilization for nuclear physics research and other applications. At Trombay, an electrostatic accelerator (Van de Graaff Accelerator) was set up in the early 1960's. The Variable Energy Cyclotron (VEC) was commissioned at Kolkata in late 1970's. These provided new avenues for nuclear physics research in the country. Later with the installation of BARC-TIFR Pelletron accelerator in late nineteen eighties, the nuclear physics research has blossomed many folds leading to many types of developments in detector technology and electronics instrumentation.

The nuclear physics research using particle accelerators that provide charged particle beams and reactors with thermal neutrons enabled a wide variety of research for studying nuclear phenomena such as fission, nuclear reactions and nuclear structures of broad range of nuclei. A number of state-of-the-art detector arrays have been built for these investigations. In parallel, there has been considerable interest in the sub-nuclear and sub-nucleon phenomena which are explored at high energies, and are carried out by international collaboration using accelerator facilities abroad. All these research interests have also been supplemented by extensive theoretical studies. Of late, experimental setups involving measurements of antineutrinos from reactor and high energy cosmogenic particles have also been established. Nuclear Physics research is expanding broadly in three directions: Investigation of the nuclei away from the line of stability to map the nuclear landscape and studies relevant for nuclear astrophysics; shape evolution of the nucleus as a function of excitation energy and angular momentum; Study of nuclear matter at high energy and density. Besides these areas, the field of neutrino physics is receiving worldwide attention in recent years. The growth of nuclear physics research has been possible mainly due to the concurrent development of accelerators which delivered light and heavy ions, versatile detector set ups, high density electronics and state-of-the-art data acquisition system.

2. Reactor based Nuclear Physics studies in BARC

One of the early explorations in the field of nuclear physics studies in the country was the Nuclear Fission phenomenon using the research reactors. The Nuclear Fission process, which involves complex nuclear dynamics had been a subject of contemporary interest worldwide at the time of commissioning of APSARA and CIRUS reactors. Therefore, from the beginning of operation of these reactors, the reactor neutron beams were utilized to carry out extensive investigations in fission to understand the mechanism of the fission process. Studies were carried out with regard to the post-scission characteristics involving the radiations emitted in fission such as prompt neutrons, gamma rays, K-X-rays and long-range alpha particles (LRA) as well as the fission fragment mass and kinetic energy distributions and their inter-correlations. These studies yielded new and detailed information on both the static and dynamic aspects of the fission process.

Among the first studies to be carried out at Trombay was the measurement of angular distribution of prompt neutrons emitted in the thermal neutron induced fission of ^{235}U to determine the fraction of pre-scission neutrons. A new technique based on the gridded ionization chamber was employed to detect fragments in a 2π geometry measuring both kinetic energy and angle of the fission fragment with respect to electric field direction of the chamber, which was also chosen to be the direction of detection of the neutrons. The research work carried out by S. S. Kapoor and R. Ramanna using this novel technique could compete with the similar work being carried out elsewhere with higher flux reactors, mainly due to innovation in experimental techniques. The angle of the fission fragment with respect to the neutron direction was determined by employing the pulse height information of both the grid and the collector pulse associated with the detected fission fragment. The time-of-flight technique was used to measure prompt gamma intensities and prompt neutron energies at selected angles with respect to the direction of the fission fragments of selected energies. The experimental study of the early sixties on the emission of prompt gamma rays in the thermal neutron induced fission of ^{235}U using neutron beams from APSARA obtained the landmark experimental result that a significant angular momentum is generated in the fragments produced in the fission process. Studies with APSARA reactor neutron beams and later with CIRUS reactor beams obtained results on the neutron emission spectra and neutron-fragment angular correlations which yielded new information on the post-scission, pre-scission neutron multiplicities, effective temperatures and level densities as a function of the emitting fragment mass and total fragment kinetic energy. An important result obtained was that about 10% of the prompt neutrons were pre-scission neutrons and not emitted from the moving fragments. It was proposed that these "pre-scission neutrons" may be evaporated from the excited fissioning nucleus during the passage between the saddle and the scission stages of the fission process. This, however, required a rather long ($\sim10^{-19}$s) saddle-to-scission time. From the experimental heavy ion physics and also theoretical studies of nuclear dynamics including nuclear viscosity effects, it is now realized that such long saddle-to-scission time in fission are indeed possible. Fig.1 gives a view of the experimental set up used at APSARA reactor for these studies of the fission process.

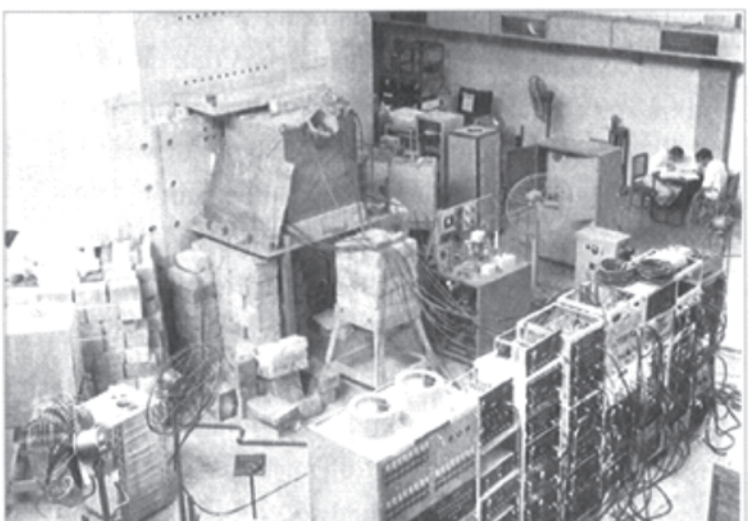

Fig.1: A view of the experimental arrangement for the study of the fission process used at the Apsara reactor

Further experimental research work in fission with CIRUS neutron beams aimed at the studies of the light charged particles emitted occasionally in fission which provides information directly on the static and dynamic state of the scission configuration and indirectly on the nature of large scale motion of nuclear matter from saddle-to-scission in the fission process. Some of these experiments involving rare modes of fission such as ternary and quaternary fission could be performed only because of the indigenous experimental techniques and multi-parameter data recording methods that were developed. Consequently, experimental data covering a number of correlations among parameters of interest in light charged particle accompanied ternary fission were obtained with the available neutron fluxes at the Trombay CIRUS reactor in an area of research which otherwise fell within the reach of only very high flux reactors. These experimental studies, which involved multi-parameter recording and computer analysis of the data provided important information on nuclear viscosity in the motion of fissioning nucleus from saddle-to-scission.

In the late sixties, a setup of high-resolution cooled Si (Li) detector spectrometers was built indigenously at a time when worldwide these were in the early stages of development. With these detector systems, a series of detailed studies of K-X-ray emission in fission were undertaken at Trombay, both in thermal neutron fission of ^{235}U and spontaneous fission of ^{252}Cf, which provided new insight on the de-excitation mechanism and regions of deformations of neutron rich fragment nuclei. Studies were started for the energy dispersive X-ray analysis of materials in the late sixties with these indigenously set up X-ray detectors, much before the advent of commercial systems using this technique.

In addition to the above-mentioned studies, APSARA, CIRUS and DHRUVA reactors have been extensively used to carry out basic and applied research work in the areas of nuclear fission using radiochemical, gamma spectrometric and solid-state nuclear track detector techniques. These include studies of mass, charge and kinetic energy distributions in the neutron induced fission of actinide nuclei such as ^{232}Th, ^{232}U, ^{233}U, ^{237}Np, ^{239}Pu, ^{241}Pu, ^{241}Am and ^{245}Cm. In these studies, in several cases, angular momenta of fission fragments were also determined via measurement of isomeric yield ratios. These studies have made significant contributions to our understanding of nuclear shell effects on the fission process.

At the DHRUVA reactor, a multi- clover detector setup has been recently installed for carrying out nuclear spectroscopy studies of highly neutron rich fission fragments, far away from the beta stability line.

3. Accelerator based Nuclear Physics in BARC in the Early Years

One of the important aims of modern science has been to acquire a deeper understanding about the fundamental constituents of matter and the forces governing the natural phenomena. Most of our understanding of the structure of the atomic nucleus has come through the study of nuclear reactions caused by the energetic charged particles such as protons, deuterons, alpha particles and heavy ions. However, in order to penetrate the nucleus, the kinetic energy of these particles should be larger than the height of the Coulomb barrier caused by the repulsive force between the positively charged nucleus and the impinging charged particle. Particles of higher and higher energies are also needed to investigate the microscopic structure of matter on shorter and shorter wave-length scales. Hence, several types of particle accelerators have been developed and over the years, progress in nuclear and particle physics research has been intimately linked to the advances in accelerators in providing particle beams of different types and increasing energies. These accelerators which were developed for basic research in the various areas of atomic, nuclear and particle physics are also finding applications in various fields such as analytical science, medicine, industry etc.

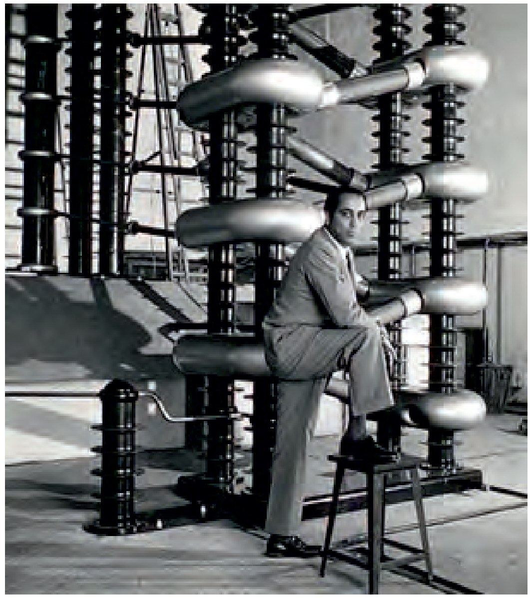

Fig. 2: 1 MV Cockcroft-Walton Accelerator (Cascade Generator) at TIFR,in 1953

Particle accelerators have always been the driving force of nuclear physics studies. While a few accelerators, notably a one Million-Volt Cockcroft Walton accelerator (Cascade Generator) at TIFR (Fig. 2), were operational in fifties and sixties at other places, the accelerator based nuclear physics research work took a significant leap in the sixties with the setting up of the 5.5 MV Van de Graaff accelerator at the Bhabha Atomic Research Centre (BARC) in 1962 (Fig. 3 (i)). This facility enabled pursuit of research in several areas of nuclear physics of contemporary interest. It should be mentioned that amongst others Drs A. S. Divatia, M. K. Mehta and N. Sarma had made pioneering contributions to nuclear physics research at the Van de Graaff in the early years.

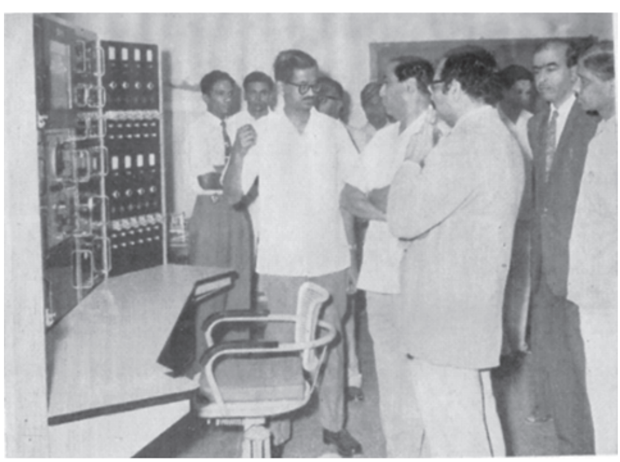

Fig. 3 (i): A photograph of Dr.Homi Bhabha with Dr. R. Ramanna at the time of the inauguration of 5.5 MV Van de Graaff Accelerator at Trombay. (Seen in the photograph from right to left: Dr. Athavale ,Dr. Jagadish Shankar, Dr. H. N. Sethna, Dr. A. S. Divatia, Dr. Homi Bhabha, Dr. Raja Ramanna, Dr. N. S. Thampi and Dr. Joseph John)

Charge independence of nuclear force in medium and heavy weight nuclei led to the observation of Isobaric Analogue States (IAS) and this was the topic in the forefront during the 1960's and 1970's. At Trombay, systematic studies were carried out to investigate IAS through (p, p), (p, n), (p, gamma) and (alpha, gamma) reactions on various targets ranging from ^{37}Cl to ^{80}Se. Using (p, n gamma) reactions as a probe, systematic measurements were carried out to determine the nuclear structure of bound states of medium-heavy nuclei. Proton optical model potentials were determined at sub-Coulomb energies for medium weight nuclei from a comprehensive analysis of proton reaction cross sections measured for A = 37 – 80. An efficient 4pi neutron counter was built for these investigations. Other studies include: (i) High precision proton elastic scattering from Pb to put a stringent limit on the strength of the long-range nuclear interaction. (ii) Alpha elastic scattering excitation functions in light nuclei up to A=40 to determine the excited states with large alpha parentage.

Secondary beams of monoenergetic neutrons with energies ranging from keV to MeV were produced by energetic proton reactions on ^{7}Li and ^{3}H targets to study neutron induced reactions. In the fast neutron induced fission studies, the correlations between the fragment angular anisotropy and the fragment mass-asymmetry were measured at an excitation energy where multiple chance fission are absent to investigate the mechanism of the mass division in fission. In another study, anomalous behaviour of fission cross-section was observed when (p, f) cross-section measurements on ^{238}U were extended to deep sub-barrier energies. The low energy protons and alpha particles were also used for material modification and characterization studies as well as Proton Induced X-ray Emission (PIXE) studies of variety of samples for various practical applications. By the beginning of eighties, this machine was exploited to its fullest potential for nuclear physics research and applications.

In the nineties, this machine was dismantled and in its place in the same building utilizing the available infrastructure, a 6MV Folded Tandem Ion Accelerator (FOTIA) has been installed, as shown in Fig. 3 (ii). This accelerator is being used for low energy heavy-ion based research covering interdisciplinary fields.

Fig. 3 (ii): Accelerating column of FOTIA at Van de Graaff, Trombay

In order to extend nuclear physics research, the nuclear physics community planned for higher energy accelerators, which was realized through the indigenous development of VEC at Kolkata which became operational in 1977. This was followed by commissioning of Pelletron accelerator in late eighties. Availability of beams of alpha particles, deuterons and protons for a variety of nuclear reaction studies at VEC spurred the activities in diverse areas. Elastic and inelastic scattering, mass and charge distribution of fission fragments, reaction mechanism for emission of high energy gammas and formation of intermediate resonance structures in light nuclear system were some of the notable experiments that were studied utilizing the available alpha beams.

Recently, ion beams have been accelerated through superconducting cyclotron K500, developed in-house, at Variable energy Cyclotron Centre (VECC) . Presently, VECC has three functioning cyclotrons; K130, K500 and 30 MeV Medical cyclotron, and pursuing an upcoming project named as Advance National facility for Unstable Rare Ion Beam (ANURIB).

A 3MV high current accelerator FRENA (Facility for Research in Nuclear Astrophysics) at SINP, Kolkata, will enable the programme of nuclear reaction studies of Astrophysical interest.

4. Nuclear Physics using Pelletron – LINAC Facility (PLF)

In the eighties, a considerable interest had grown globally in the studies of nucleus-nucleus collisions at medium energies. At that time scientists from BARC and TIFR also initiated a proposal to set up a heavy ion accelerator facility in the country to pursue heavy ion-based physics research. A Medium Energy Heavy Ion Accelerator (MEHIA) was set up in the eighties under a collaborative project of BARC and TIFR at the campus of TIFR at Colaba in South Mumbai. The 14MV Pelletron accelerator in Mumbai was formally inaugurated on 30th December 1988 and marked an important milestone providing a big leap in nuclear physics research in India (Fig. 4 (i), (ii) and (iii)). This accelerator also facilitated research in atomic physics, condensed matter physics and interdisciplinary areas. The Pelletron LINAC facility, a joint venture between the BARC & TIFR, has been a major research centre for the heavy ion accelerator based research in India.

Fig. 4 (i): Installation stages of Pelletron

Fig. 4 (ii): Ground breaking ceremony for Pelletron, in 1983

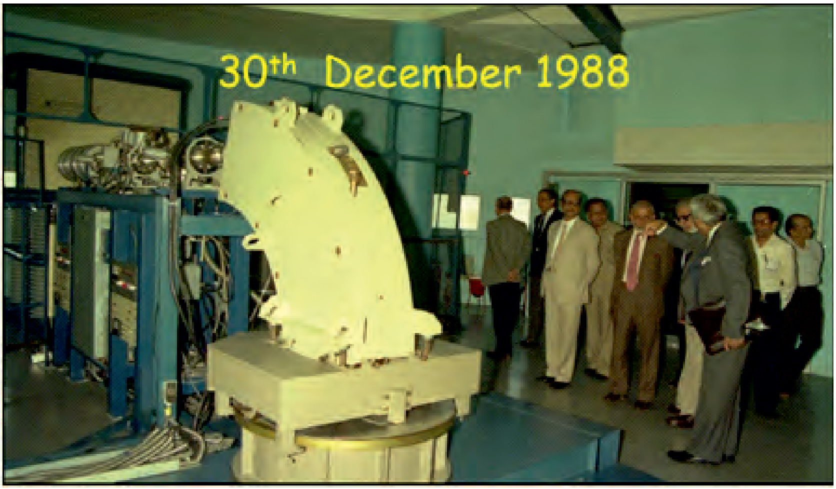

Fig. 4 (iii) Commissioning of 14UD Pelletron accelerator on 30th December 1988

This facility was further augmented with an indigenously developed superconducting LINAC booster to enhance the energy of the accelerated ion beams. The phase-I of LINAC booster was commissioned on 22nd September 2002 and the full facility was dedicated to users on 28th November 2007 after the completion of the phase-II. A variety of state-of-the-art experimental facilities have been developed at this centre to pursue frontier research in nuclear, atomic, condensed matter and multidisciplinary areas.

Over more than three decades, the Pelletron accelerator has been consistently working with very high efficiency, delivering a wide variety of ion beams ranging from proton to Iodine. A number of developmental activities have been carried out in-house to improve the performance of the accelerator, (Fig. 5 (i) and (ii)). While a majority of the researchers at this facility are scientists from BARC and TIFR, the experimental community includes researchers and students from VECC, SINP and universities within India and abroad. About 150 Ph.D. theses and about 750 publications in international refereed journals have resulted from the research activities at the PLF. These include a large number of publications in high impact international scientific journals.

Indigenous Multi-Cathode Sputter Negative Ion Source at Pelletron-Linac Facility

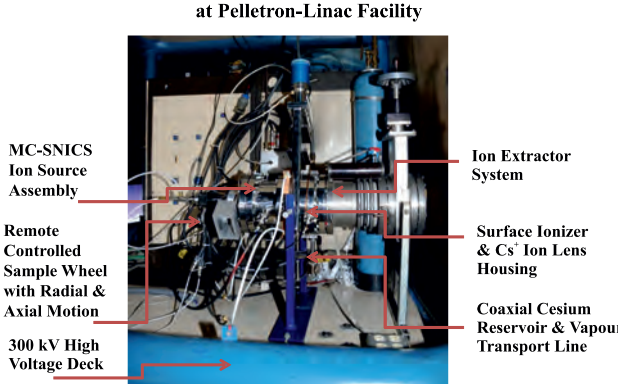

Fig. 5 (i): Multi-Cathode sputter negative ion source

Fig. 5 (ii): 6m High Current Irradiation Set Up at Pelletron

Major experimental facilities developed at PLF include (Fig. 6):

- Multipurpose scattering chamber having 150 cm diameter, with two independently rotatable arms permitting detector rotation and target ladder adjustment with remote control without beam interruption by using indigenously developed Programmable Logic Controller, to carry out experiments in charged particle spectroscopy and fission studies
- An array of Clover Detectors for discrete gamma ray spectroscopy along with auxiliary detectors
- Array of strip detectors for charge particle spectroscopy and study of cluster structure, and direct reactions
- $BaF_2/LaBr_3$ array for high energy gamma ray studies with BGO/Na(Tl) multiplicity filter
- Charged Particle Array based on pad (ΔE) and CsI(E) detectors
- Neutron Detectors Array of Liquid Scintillation detectors and Annular parallel plate avalanche counter having 12 segments with angular coverage from 5° to 11°, for Time-of-Flight Technique based compound nucleus residue tagging
- MWPC gas detectors for fission fragment mass and kinetic energy distribution
- High current proton irradiation facility and secondary neutron production through (p,n) reaction on Li, Be targets.
- A Versa Module Europa (VME)–based DAQ and advanced digital DAQ with analysis programmes

A versatile data acquisition and analysis package, LAMPS (Linux Advanced Multi Parameter System) has been one of the key indigenous developments responsible for pursuit of frontier research in nuclear physics.

Fig. 6: Experimental facilities set up at PLF a) 1.5m diameter Multipurpose scattering chamber for reaction studies b) High granularity large solid angle strip detector array for charge particle detection c) Liquid scintillator array for neutron measurements d) BaF_2 array for high energy gamma rays measurements e) CsI array for light charge particle detection f) MWPC detectors for fission measurements g) High efficiency, high resolution Indian National Gamma Array (IGNA) for gamma ray measurements

Research programmes in nuclear physics that have been pursued with the Pelletron facility include studies of (i) Fast rotating nuclei-their structure, spectroscopy, decay properties and dynamical behaviour; (ii) Nuclear scattering and reactions, elastic and inelastic scattering, few nucleon transfer reactions and strongly damped collisions; (iii) Heavy-ion fusion, sub-barrier fusion, fusion dynamics, compound nucleus formation and decay; (iv) Fission and fission-like reactions; (v) Spectroscopy of exotic nuclei far off the stability line; (vi) Giant Dipole Resonances (GDR); and (vii) Nuclear moments of excited states. Research programmes have also been undertaken in other areas such as (i) Atomic physics of highly charged ions (ii) Nuclear chemistry (iii) Condensed matter physics and (iv) Radiation damage studies with societal applications.

Similar to the BARC-TIFR Pelletron facility, a 15UD Pelletron - LINAC facility has been set up at IUAC (Inter University Accelerator Centre), New Delhi by University groups. The superconducting LINAC booster has been indigenously developed based on Nb resonator cavities. The accelerator facility is functioning very efficiently catering to various University institutions. DAE scientists from BARC, VECC, TIFR and SINP have been also using this facility to pursue nuclear physics research in a number of frontier areas. Nuclear Physics Division (NPD), BARC and IUAC (formerly called Nuclear Science Centre) continue to have mutually beneficial collaborations since inception, covering accelerator operations and effective utilization to the development of accelerator systems and experimental facilities. This facility has been further augmented by adding a high current positive ion injector to the LINAC booster.

At BARC-TIFR PLF, various application-oriented programmes such as radioisotopes production, radiation damage studies (space bound devices, yield improvement in wheat and rice seeds), secondary neutron production for cross-section measurements, radiation dosimetry studies, ion irradiation in semiconductor crystals for photoconductive Tera Hz emitters, Accelerator Mass Spectrometry, and production of track-etch membranes, are also pursued. Experimental facilities are attached to dedicated beamlines installed in the Cascade beam hall for Pelletron energies and two new LINAC beam halls I and II for both Pelletron and LINAC boosted energies.

Nuclear Physics Research highlights from PLF

Various interesting results and new findings have resulted from the research programmes undertaken at Pelletron accelerator facility and some are mentioned below:

Trombay group has long tradition in fission research. Many pioneering contributions related to the damping of shell effects and dynamical aspect of nuclear reaction have been made in the past. Fission fragment angular distributions around Coulomb barrier have shown enhancement in angular anisotropy, leading to conclusion that the potential energy surface governs the fission path in mass equilibration in fission process. Recently, by carrying out experiments and systematic analysis of the available experimental data from Pelletron LINAC Facility, the origin of newly observed asymmetric fission in pre-actinide nuclei (near Pb/ Bi) has been identified. The results provided the evidence for the general dominance of proton shells in low-energy fission. A rare fission mode from neutron rich ^{257}Md nucleus at high excitation energy has been observed in another study.

In the past few years, nuclear reaction studies with weakly bound stable nuclei (^{6,7}Li, ^{9}Be) to study role of coupling to low lying continuum on elastic scattering and fusion has been one of the main activities at PLF. The new findings include, clear evidence for the two-step process, transfer followed by breakup, origin of large alpha production, different resonant states arising due to different cluster structure configurations to name a few.

A novel sensitive and selective technique has been developed at PLF, for measuring ultra-low cross-sections by performing KX-γ–ray coincidence of the decay radiations within a low background setup. Using this method, the fusion cross-section up to nano-barn (10^{-33} cm^2) has been measured which is the lowest cross-section ever measured in heavy ion induced fusion at deep sub-barrier energies. These results have given a new direction to the present understanding of the fusion hindrance at low energies.

The cluster structure studies have been pursued at PLF through resonant capture, resonant breakup, knock out and direct reactions. The precise measurement of the radiative transition probability at different energies, has provided crucial evidence for the 2α-dumbbell-like structure of ^{8}Be nucleus.

Nuclear level density is another area where a lot of measurements have been performed to study influence of angular momentum, isospin, pairing, collective enhancement, shell effect etc. The extent of shell effect and it's washing out with excitation energy as theoretically formulated earlier by Trombay group, was confirmed by experimental measurement of nuclear level density in ^{208}Pb region.

In recent years, the surrogate reaction methods in various forms have been employed to get indirect estimate of neutron induced fission reaction cross sections of many compound nuclear systems in actinide region, which are not accessible for direct experimental measurements. The surrogate reaction methods have been successfully employed to determine ^{233,234}Pa(n,f), ^{236,239,240}Np(n,f) and ^{238,241}Pu(n,f) compound nuclear cross-sections in the equivalent neutron energy range around 10 to 20 MeV.

5. Nuclear collisions at high energies, Hadron Physics and Quark Gluon Plasma (QGP) and Studies

In parallel to experiments using home-based accelerators in MeV energy range, there has been considerable interest in the sub-nuclear or sub-nucleon phenomena which are explored at high energies. These interests have been pursued by extensive theoretical studies as well as by participating in the collaborations like COSY at Germany, PHENIX and STAR experiments at BNL, CMS and ALICE experiments at CERN, as well as India based mega projects like INO. Along with these, in-house detector laboratories and experiments involving high energy particles reaching Earth via cosmic particle interactions have been established. The collaborations enabled us to participate in frontline experiments and gain new knowledge in physics and technology.

Hadron physics

In NPD right from eighties, there have been noticeable theoretical studies on calculating production of hadronic states like eta, rho, omega, phi and delta in few GeV proton-nucleus collisions and investigate their role in nuclear dynamics. Experimental studies in these areas were carried out using multi GeV proton beams at Cooler Synchrotron (COSY) Germany. During 2002-2006, a large coverage plastic scintillator detector ENSTAR readout via optical fibres was built at NPD and was installed at COSY. The experiment hinted formation of eta-mesic nucleus in ^{24}Mg.

Nuclear collisions at high energies and Quark Gluon Plasma (QGP)

By late eighties, the standard model of particles was well established, all the three generations of leptons and quarks had been detected except the heaviest top quark which was discovered at Fermilab in 1995. The huge mass difference among these generations were understood in terms of mass generation mechanism in standard model formalism which predicted a new yet to be detected particle called Higgs boson. Another open problem was, although experimentally proven, that protons and neutrons are made of quarks, no experiment could detect a free quark. It is understood that after big bang, early universe at high temperature was in the phase of free quarks and gluons (QGP) along with all the other fundamental particles. It was soon proposed that such high temperatures could be created in lab by colliding two large nuclei at relativistic energies. The experiments with collisions of heavy nuclei started gaining momentum when gold ions with energy 14.6 AGeV were accelerated at BNL and soon Lead ions with energy 160 AGeV got accelerated at CERN. These were fixed target experiments and hence the required centre of mass energy remained small. A Relativistic Heavy Ion Collider (RHIC) which could collide gold beams of 100 AGeV energy each was planned at BNL. Soon after, a Large Hadron Collider (LHC) machine using existing LEP ring was planned at CERN.

The possibility of DAE institutions participating in these international experiments provided a renewed interest in physics activities in these areas. Significant work was done on aspects of the quark-hadron phase transitions, equation of state of the high temperature nuclear matter and chemical equilibration of matter in heavy ion collisions. The experimental probes of heavy ion collisions signal at high energies were modelled. STAR and PHENIX experiments at BNL started taking data on Au-Au collisions in 2001. The BARC group made hardware contribution for the muon arm of PHENIX detector and the VECC group made the Photon Multiplicity Detector (PMD) for the STAR detector. The analysis of data at VECC and BARC concentrated on study of probing the system with photons, muons, strange mesons and baryons produced in Au-Au collisions and study of QCD phase diagram. The formation of QGP was discovered in these studies for the first time.

CMS experiment at LHC studies both Higgs bosons as well as QGP matter in addition to various other aspects in standard model. The silicon sensors made for the pre-shower detector were developed in India with participation by BARC. BARC along with Panjab University made significant contribution in making RPC, a new type of large area gas detectors for muon identification. The VECC and SINP groups made significant contributions in photon and muon detection systems and their readout electronic hardware in the ALICE experiment at CERN. These experiments led to the discovery of Higgs particle and the robust signals of QGP, a phase which has fundamental importance to the early and the most eventful evolution of the universe.

The physics contributions include, observation of suppression of higher mass Upsilon states, detailed measurements of all quarkonia states and the detection of Z boson for the first time in heavy ion collisions. A series of systematic measurements of quarkonia states and their ratios in Pb-Pb collisions during (2011-2016) has helped establishing the colour screening behaviour of QGP. A systematic understanding of signals of QGP via experimental work is followed by theoretical modelling of the data.

In the area of muon detection, an experiment has been setup at Van de Graff laboratory to measure the angular distributions of cosmic muons and their interactions with matter. The energy deposition and excellent timing of scintillators is exploited to construct two dimensional tracks of muons and hence angles of muons. After establishing the method muons are used to study the interactions with matter.

6. Theoretical research highlights

Theoretical research forms an important and integral part to interpret and understand nuclear phenomena. Nuclei in their ground and excited states exhibit many structure changes due to the interplay of single particle and collective behaviour of nucleons. At very high energies, the underlying degrees of nucleons such as pions, quarks and gluons are exhibited in interactions producing variety of sub nuclear particles. All these aspects are investigated theoretically that provide rich information on the nuclear reactions and phenomena. In DAE, various groups at BARC, TIFR, VECC, SINP and IOP, Bhubaneswar have actively contributed in the theoretical studies. Some of the highlights of this vast field of work are enumerated below:

i The shell effects in the fission process leading to double hump fission barrier have been investigated. The washing out of shell effects with excitation energy or temperature was shown for the first time.

ii The asymmetric mass distribution in fission of actinide nuclei was explained to be due to stochastic Markov process by nucleon exchange of nucleons between newly formed fission fragments.

iii The evolution of nuclear shape, structure in the nuclear landscape was studied by nuclear shell model calculations.

iv Direct nuclear reactions such as stripping, pickup and knockout were investigated by optical model and DWBA analysis.

v Sub nucleonic degrees of freedom were studied to explain particle production at high energies.

vi The formation and evolution of QGP have been investigated in detail through hydrodynamic and statistical models.

vii The structure of neutron stars and supernovae have been studied by nuclear matter calculations.

viii Astrophysical processes in the formation of exotic proton and neutron rich nuclei are being studied.

Nuclear physics research is proceeding along new frontiers with the setting up of advanced accelerator facilities in India and abroad, throwing new challenges in experimental and theoretical areas.

7. Neutrino Physics with ISMRAN

Neutrinos are the second most abundant particle but remain elusive due to their feeble interaction. To study these particles, in recent years, a vibrant physics programme of neutrino physics studies has been started for the measurements of antineutrinos through inverse beta decay process at Dhruva reactor. For this purpose, a large area plastic scintillator ISMRAN (Indian Scintillator Matrix for Reactor Antineutrino) detector along with shielding was designed, fabricated and installed inside Dhruva reactor hall, as shown in Fig. 7. ISMRAN presents the first attempt in the country towards building the capability to perform research in a totally new exciting area of reactor neutrino physics with primary goals of sterile neutrino search and resolution of reactor antineutrino anomaly.

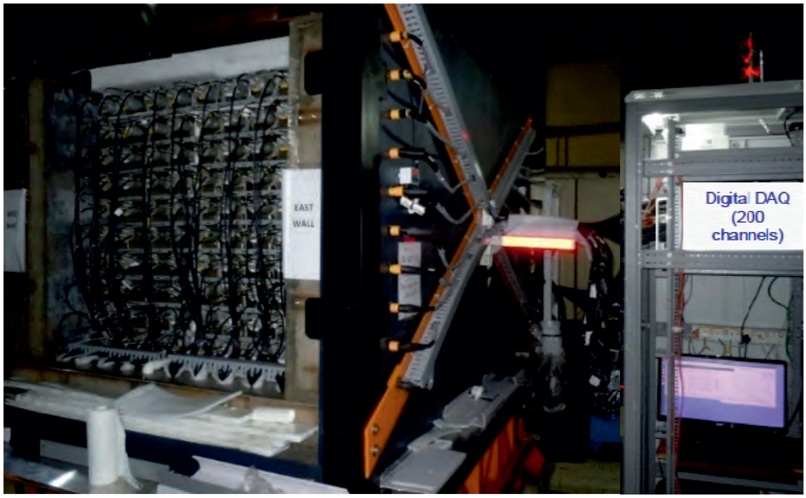

Fig. 7: ISMRAN detector installed inside Dhruva reactor hall for antineutrino measurements

8. Concluding Remarks

Nuclear physics research has been and continues to be an integral and core research area in the Department of Atomic Energy since beginning. In this article, an attempt has been made to give an overview of development of the nuclear physics in BARC which has been primarily driven by experiments utilizing the research reactors and particle accelerators. Development of theoretical and experimental reactor physics and the technological capability to design and construct research reactors as well as power reactors has been the foundation on which our experimental nuclear science programme rests. The neutron beams from the Trombay reactors were utilized for basic nuclear physics research in several areas, in particular fission physics, as well as for radioisotope production and applications. Accelerator-based research programmes have been pursued with the low energy accelerators as well as with medium energy, variable energy cyclotron and BARC-TIFR Pelletron LINAC Facility.

For future programme, the proton accelerator proposed for the ADSS (Accelerator Driven Subcritical Reactor System) at accelerator complex in Vizag, is planned to be used as the driver accelerator for RIB (Radioactive Ion Beam), once it reaches 40 MeV of proton energy, followed by a post-accelerator downstream. A 30 MeV electron accelerator is also planned at Vizag, producing RIB via photo-fission route. At BARC, a fast neutron facility is envisaged based on a high current ECR source enabling measurements of fission observables in the fast neutron region thereby contributing to the development of data driven models for fission which is being intensely pursued worldwide.

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