Indian participation in NuSTAR experiments at FAIR

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Nuclei away from the valley of stability are characterized by unique properties including weak binding of outermost nucleons, changing shell structure, coupling between bound states and the particle continuum, diffuse neutron density distributions, formation of neutron skin and halo structures. The nuclear structure, astrophysics and reactions (NuSTAR) experiments aim to explore these aspects of nuclear structure at the extreme isospin using different experimental techniques. We propose to study the decay properties of the exotic nuclei with decay spectroscopy using stopped implanted ions set-up and precision measurements of very short-lived nuclei using an advanced trapping system for highly charged ions. Various nuclear reactions will be investigated using reactions with relativistic radioactive beams set-up, the new experimental storage rings and the high-resolution in-flight spectroscopy set-up. We plan to work for the design, optimization of the configurations, fabrication and commission of different detectors to detect gamma rays, neutrons, charged particles and heavy fragments. All these detectors will require fast and efficient signal processing in the above experiments.

Keywords: Dripline, exotic nuclei, fragmentation, fission, isospin.

Introduction and physics of NuSTAR

FINITE nucleus is a unique mesoscopic system composed of strongly interacting neutrons and protons. Study of its structure at varying temperature, angular momentum and isospin provides a new insight into the dynamics involved in the variety of emergent phenomena in this many-body system. The FAIR focuses on the production of beams of radioactive nuclei produced in fragmentation and fission processes. The nuclear structure, astrophysics and reactions (NuSTAR) collaboration at FAIR aims to use these radioactive ion beams (RIBs) in different experiments (http://www.gsi.de/fair/expriments/NUSTAR/index_e.html). The experiments involving RIBs at the present facilities are continuously changing the knowledge of nuclear properties and providing crucial information about the important nuclear reactions relevant for astrophysics. Measured quantities of nuclei at the extreme isospin will provide a new stringent test for the different theoretical frameworks capable of predicting nuclear properties and thereby improving their predictive power.

Figure 1 shows the nuclear landscape and scope of study of a wide variety of nuclear phenomena with RIBs, such as, neutron halo, neutron skin, changing shell structure with isospin, two-proton radioactivity, isoscalar pairing interactions and stability of super heavy nuclei. The isotopes marked as black are stable, the yellow region represents around 3000 radioactive nuclei which are produced in the laboratory and the green region represents the unexplored part of the landscape consisting of around 4000 radioactive nuclei which will be studied in future. NuSTAR experiments will be able to focus into the study of nuclei in this unexplored region of the landscape to obtain knowledge, which will help to obtain answers for some of the unsolved questions[1–4] about the nuclei.

- Where are the proton and neutron driplines situated?
- Where is the island of stability for the super heavy nuclei?
- How does the nuclear force change with isospin?
- What are the properties of open quantum system available near the neutron dripline where chemical potential is similar to the pairing gap?
- How does collectivity emerge from single particle motion of nucleons?
- How do we extract information about equation of state of asymmetric nuclear matter?
- What are the nuclei responsible for the astrophysical processes?

NuSTAR experiments and our participation

The superconducting fragment separator (Super-FRS) will be used for the separation and identification of RIBs using the in-flight technique following the fragmentation and fission processes. The separator has a large phase-space acceptance and is capable of handling high-intensity beams to be delivered by SIS100/300. Together with the increased beam intensity of the primary accelerator, the overall yield of exotic isotopes at the end of Super-FRS will increase by 2–3 orders of magnitude compared to the existing facilities. The RIBs identified at

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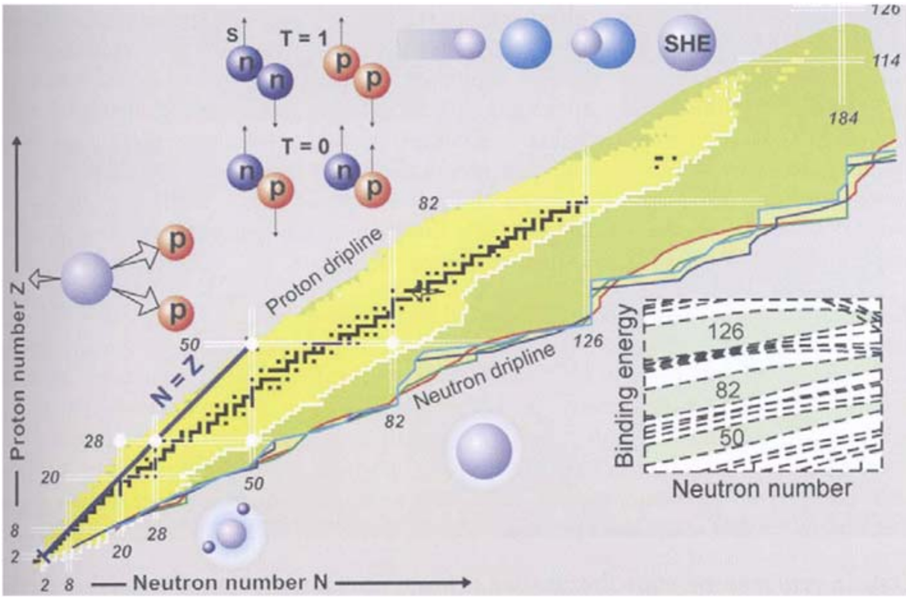

Figure 1. The nuclear landscape and the overview of different phenomena near the neutron and proton driplines.

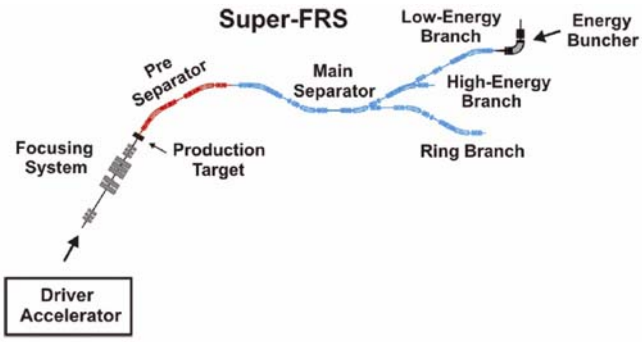

Figure 2. Schematic layout of the Super-FRS, the position of high-energy, low-energy and the ring branch that constitute the NuSTAR.

the Super-FRS will be transported to the three experimental areas, viz. the low-energy, high-energy and the ring branch as shown in Figure 2.

At the low-energy branch (LEB), the fragments will be slowed down to 50–100 MeV/u or completely stopped in a gas cell and then extracted for further experiments. Figure 3 gives an overview of the scientific programmes planned at LEB. At the decay spectroscopy (DESPEC) set-up, the different decay modes of short-lived nuclei from their ground or isomeric states will be informed. The RIBs with energy of few MeV/u will be stopped in an active stopper (layers of Si pixel detector). The active target will be surrounded by modular neutron and gamma detectors.

Reaction studies with short-lived isotopes at 3–100 MeV/u beam energy will be carried out in the high resolution in-flight spectroscopy (HISPEC) experimental set-up. Multiple as well as single step Coulomb excitations, direct reactions and fusion evaporation reactions on the secondary target will be studied with the advanced gamma tracking array (AGATA) coupled with other ancillary detectors for particle and recoil identification[5]. AGATA is a state-of-the-art 4π array of segmented high purity germanium detectors with high-efficiency and gamma-tracking capabilities.

HISPEC and DESPEC have much in common in terms of physics and instrumentation with the nuclear structure community within India. Some of the physics programmes which the groups from India would like to pursue at the HISPEC and DESPEC set-ups are mentioned below.

- Study of nuclei near predicted island of stability at $Z = 62$, $N = 100$ (ref. 6).
- Coulomb excitation experiments involving $N = Z$ nuclei to probe the isospin symmetry, exotic shapes and correlations.
- Multi-nucleon transfer to probe the pairing interactions in dilute nuclear matter.
- Shell structure near ^{132}Sn.
- Population of high spin states in fragmentation reaction.

The DESPEC and HISPEC set-ups have different subcomponents where groups from India have taken initiative and are planning to contribute. This makes India a major partner for the DESPEC/HISPEC collaboration. We propose to fabricate, characterize and operate a large part of the high-purity germanium detector array and modular neutron detectors of the DESPEC set-up. Based on the available Si technology within Indian laboratories and industry, we envisage to design the Si strip detectors for the different ancillary detectors to be used in different branches.

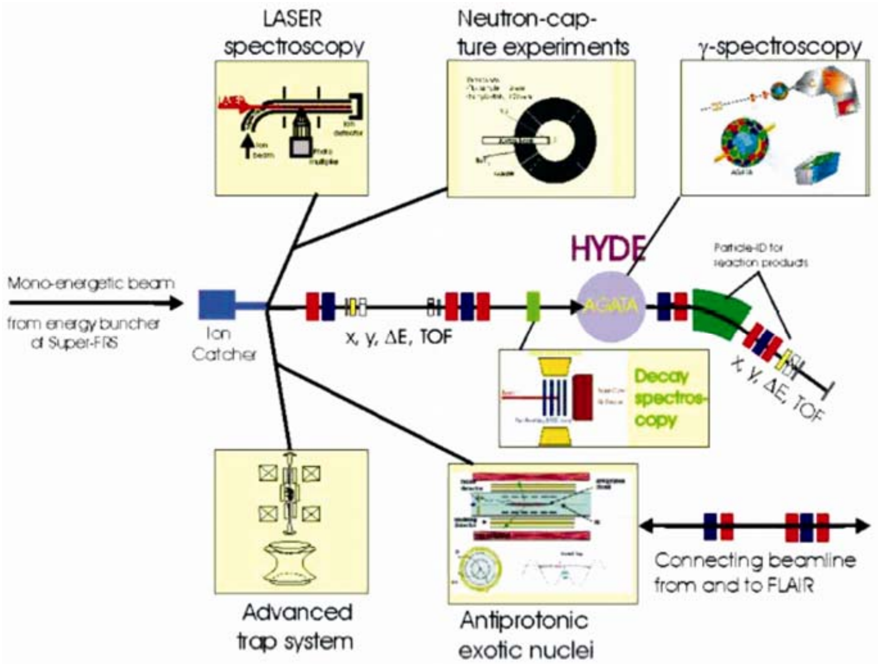

Figure 3. Physics programmes planned for LEB of the Super-FRS.

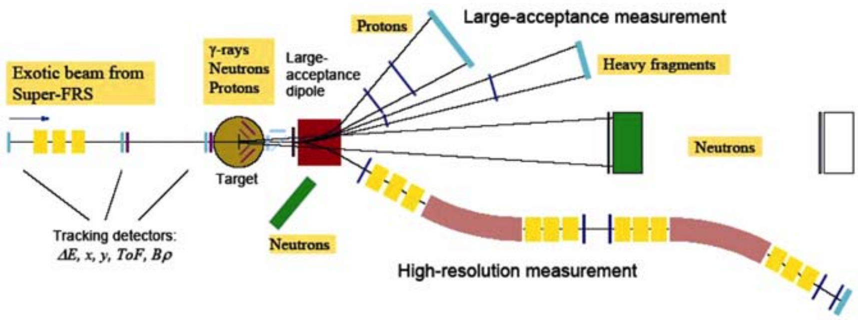

Figure 4. Schematic of the R^3B set-up for high-acceptance and high-resolution measurements for the study of RIBs through reactions at relativistic energy.

MATS experimental set-up aims for precision mass measurements using an advanced trapping system for highly-charged ions. Data with a relative precision of 10^{-9} on masses of exotic nuclei will provide a stringent test for different mass models, the test of standard model and alternative insight for the nuclear structure aspects, like shell closure and onset of deformation with changing neutron number. The Indian collaboration for MATS plans to measure the *Q*-values of beta unstable exotic nuclei by the determination of the energy of the recoiled nucleus. This proposal pertains to an addition of a combination of ion traps to the original MATS precision measurement programme of NuSTAR.

The high-energy cave houses the reactions with relativistic radioactive beams (R^3B) set-up which provides unique opportunities for kinematically complete measurements of reactions of the most exotic nuclei with high resolution at relativistic energy (see Figure 4). The incoming relativistic ions are tracked onto the secondary reaction target. A superconducting dipole magnet located downstream will, together with resistive plate chambers (RPCs), be used for ion identification and momentum analysis of charged fragments. The existing large area neutron detector (LAND) will be replaced with a new device to detect fast neutrons moving in the forward direction based on RPCs. A high-resolution spectrometer will be used at a later stage. The target will be surrounded by a silicon vertex detector and a highly granular calorimeter for gamma and charged particle detections. Quasi-free scattering of type (p, 2p) or (p, pn) of exotic nuclei in inverse scattering, Coulomb breakup, charge exchange reaction, elastic proton scattering, nuclear fission and fragmentation will be studied with this set-up by the groups from India.

The Indian collaboration is taking part in the design and testing of RPC detectors for NeuLAND. We propose to fabricate a large part of the RPC detectors and some of the associated electronics for the NeuLAND for R^3B and exotic nuclei studied in light ion induced reactions (EXL). Based on the expertise and technology available within India, there is a proposal to design and deliver the readout electronics for a subset of the CsI calorimeter in the R^3B programme.

The ring branch will consist of a collector and cooling ring (CR) and then the ions will be transferred to a new experimental storage ring (NESR). Using the storage ring as a device, the mass measurements of the ground and isomeric states would be possible for isotopes with very low yield. The cooled beams will allow to probe the low momentum transfer regime that carries crucial nuclear structure information through experiments of RIBs using the EXL at NESR.

Research on detectors and associated electronics

Experimental low-energy nuclear physics programmes have been developed around the accelerator centres at the Inter-University Accelerator Centre (IUAC), New Delhi, the TIFR–BARC Pelletron Linac Facility, Mumbai and the Variable Energy Cyclotron Centre (VECC), Kolkata. All the ongoing experiments based on the stable beams from these accelerators are based on a variety of radiation detectors to detect the gamma rays, light charged particle detectors, fission fragment detectors and neutron detectors. Various electronics modules for signal processing and digitization of the detector pulses have been developed by the different laboratories and used in the ongoing experiments.

High-resolution gamma ray spectroscopy has been a major experimental programme undertaken by several institutions and universities over the last two decades, culminating in the Indian National Gamma Array funded jointly by the Department of Science and Technology and the Department of Atomic Energy. NuSTAR–FAIR is a natural extension of this major Indian research activity. The planar Ge detectors having tracking and imaging capabilities are the next generation Ge detector systems[7] which are planned to be used at the DESPEC set-up (Figure 5). The characterization and pulse shape analysis of clover detector and $10X \times 10Y$ germanium strip detector at TIFR using digital signal processing set-up have been started. Figure 6 shows the pulse shapes obtained from clover detectors for timing analysis. Pulse-shape simulation and development of required software have been carried out at the Delhi University. We envisage to undertake the fabrication of some parts of the planar detectors and the associated electronics. A scanning table will be set up for the pulse-shape analysis of the planar detector.

Liquid organic scintillator based modular neutron detectors are fabricated at VECC, Kolkata and used for the in-beam experiments. The picture of the detectors and its time-of-flight (TOF) spectrum is shown in Figure 7. The Indian proposal is based on the existing expertise

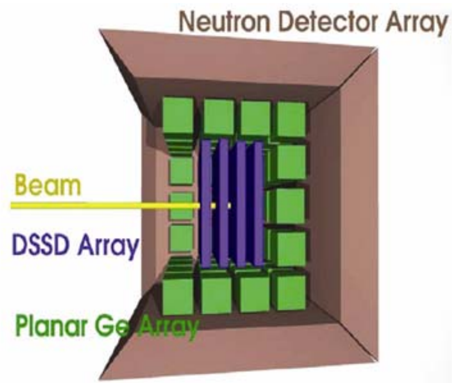

Figure 5. Experimental set-up of DESPEC showing the active target surrounded stack of planar HPGe strip detectors and neutron detectors.

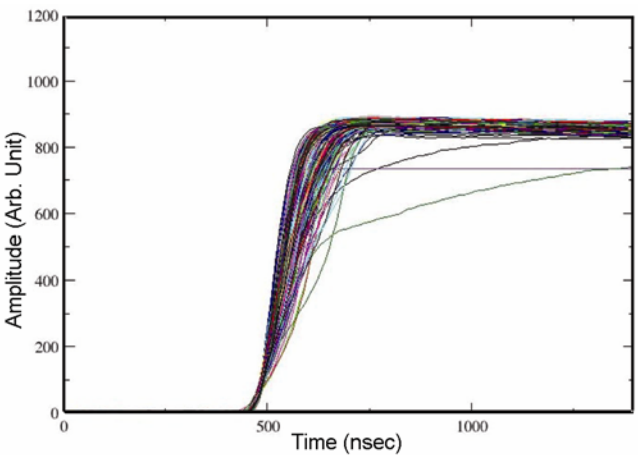

Figure 6. Analysis of the preamplifier traces of clover for characterization of timing properties.

Figure 7. The neutron detectors developed at the Variable Energy Cyclotron Centre, Kolkata.

and available infrastructure for the fabrication of the part of the neutron detectors of the HISPEC/DESPEC set-up with liquid organic scintillators.

The Bharat Electronics (BEL) in collaboration with BARC has a proven track record of making Si single-sided strip detectors and Si pad detectors (see Figure 8). Also, more recently BEL in collaboration with TIFR has undertaken production of double sided strip detectors. These developments are essentially for international high-energy physics programmes and groups from India are working to adapt this technology to meet the requirements of NuSTAR. The spin-off from this additional R&D would also serve the experimental heavy-ion nuclear physics programmes in the country.

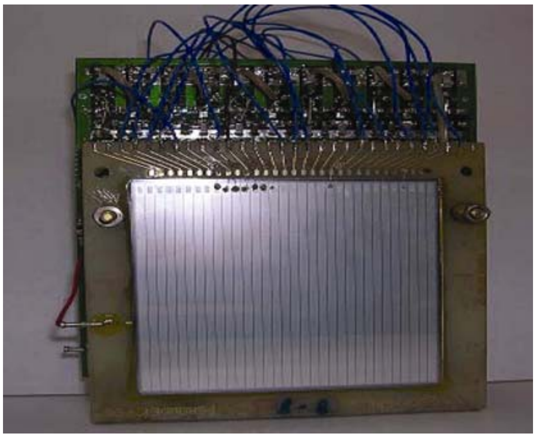

Figure 8. Si strip detectors developed by BEL–BARC collaboration and used for heavy fragment detection in fission experiments at TIFR–BARC pelletron facility.

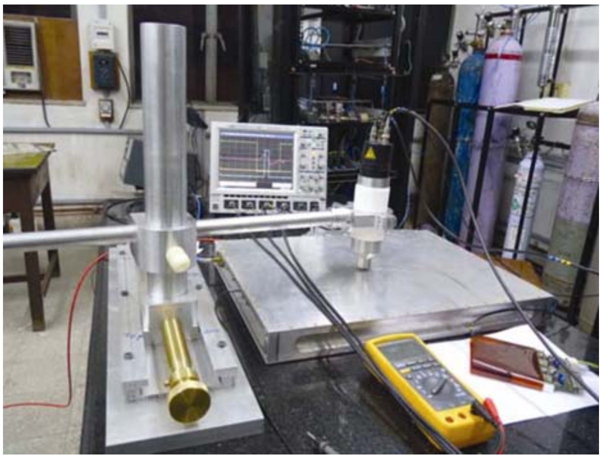

Figure 9. Test set-up at SINP for the multi-gap RPC.

Large-area RPC have been developed by several institutions for both national and international programmes involving extensive R&D over several years. Extensive R&D on the NeuLAND has been started in the Saha Institute of Nuclear Physics by the Indian collaboration. The testing of the newly fabricated multi-gap RPC and the associative sub-system is in progress (see Figure 9).

The development of high density readout electronics for different classes of detector arrays has been extensively pursued by the groups at TIFR, BARC and IUAC for both national and international programmes. The Electronics Division, BARC and Centre for Microelectronics, ECIL, in collaboration with these research groups, have developed several ASIC and DSP modules. Also, similar R&D has been going on in the Pelletron-Linac facility at TIFR. Based on this experience, the Indian collaboration expects to design and deliver the readout electronics for a subset of the CsI calorimeter in the R^3B programme.

Summary and discussion

Study of nuclei at extreme isospin using different experimental techniques will provide a new insight into the structure and dynamics of nuclei. The requirements of high resolution, better efficiency and fast detector-systems for different types of radiations and associated electronics will demand the exploration of a new technological domain. The spin-off from this activity would be relevant to development and planning of future experiments at the accelerator facilities within India and its application in other areas like medical imaging.

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