PRAMANA — journal of physics
© Indian Academy of Sciences
Vol. 75, No. 2
August 2010
pp. 317–331

Hybrid recoil mass analyzer at IUAC – First results using gas-filled mode and future plans

N MADHAVAN[1,*], S NATH[1], T VARUGHESE[1], J GEHLOT[1], A JHINGAN[1], P SUGATHAN[1], A K SINHA[2], R SINGH[3,7], K M VARIER[4], M C RADHAKRISHNA[5], E PRASAD[4], S KALKAL[3], G MOHANTO[1], J J DAS[6], RAKESH KUMAR[1], R P SINGH[1], S MURALITHAR[1], R K BHOWMIK[1], A ROY[1], RAJESH KUMAR[1], S K SUMAN[1], A MANDAL[1], T S DATTA[1], J CHACKO[1], A CHOUDHURY[1], U G NAIK[1], A J MALYADRI[1], M ARCHUNAN[1], J ZACHARIAS[1], S RAO[1], MUKESH KUMAR[1], P BARUA[1], E T SUBRAMANIAN[1], K RANI[1], B P AJITH KUMAR[1] and K S GOLDA[1]

[1]Inter University Accelerator Centre, Aruna Asaf Ali Marg, New Delhi 110 067, India
[2]UGC-DAE Consortium for Scientific Research, Kolkata Centre, Kolkata 700 098, India
[3]Department of Physics and Astrophysics, University of Delhi, New Delhi 110 007, India
[4]Department of Physics, Calicut University, Calicut 673 635, India
[5]Department of Physics, Bangalore University, Bengaluru 560 056, India
[6]Oak Ridge National Lab, USA
[7]Presently at AINST, Amity University, Noida 201 303, India
[*]Corresponding author. E-mail: madhavan@iuac.res.in

Abstract. Hybrid recoil mass analyzer (HYRA) is a unique, dual-mode spectrometer designed to carry out nuclear reaction and structure studies in heavy and medium-mass nuclei using gas-filled and vacuum modes, respectively and has the potential to address newer domains in nuclear physics accessible using high energy, heavy-ion beams from superconducting LINAC accelerator (being commissioned) and ECR-based high current injector system (planned) at IUAC. The first stage of HYRA is operational and initial experiments have been carried out using gas-filled mode for the detection of heavy evaporation residues and heavy quasielastic recoils in the direction of primary beam. Excellent primary beam rejection and transmission efficiency (comparable with other gas-filled separators) have been achieved using a smaller focal plane detection system. There are plans to couple HYRA to other detector arrays such as Indian national gamma array (INGA) and 4π spin spectrometer for ER tagged spectroscopic/spin distribution studies and for focal plane decay measurements.

Keywords. Fusion; heavy evaporation residues; gas-filled separator; recoil mass spectrometer; momentum achromat.

PACS Nos **25.70.-z; 27.80.+w; 29.30.-h**

1. Introduction

Hybrid recoil mass analyzer (HYRA) [1] is a dual mode, dual stage spectrometer/separator with its first stage capable of operating in gas-filled mode in normal kinematics (to access heavy nuclei around 200 amu mass 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). This unique device is being set up in the second beam hall, downstream of the superconducting linear accelerator [2], that is being commissioned at Inter University Accelerator Centre (formerly Nuclear Science Centre). The project is funded by the Department of Science and Technology (DST), Government of India and carried out in collaboration with university faculty and scientists from other institutions.

The need for HYRA and electromagnetic configuration and ion-optics of various modes of HYRA are briefly introduced in §2, the current status and the features of HYRA are summarized in §3, first results from gas-filled mode operation of HYRA for effective primary beam rejection and efficient selection of fusion-evaporation residues or target-like elastic recoils in the direction of beam are elaborated in §4 and §5 outlines the future plans with HYRA set-up.

2. Electromagnetic configuration of HYRA

The energy of beams from the 15 UD pelletron accelerator [3] at IUAC is planned to be further increased by injecting them into the superconducting LINAC accelerator consisting of three modules of eight niobium-based superconducting resonators each. The LINAC, when fully commissioned, will be able to almost double the energy of heavy-ion beams delivered by pelletron accelerator. The energy gain would allow us to surpass the Coulomb barrier for many projectile–target combinations involving heavier beams up to nickel in symmetric reactions and targets up to lead in normal kinematics. The increased energy would also allow us to access nuclei, near proton drip line, of mass up to and around 100 amu in inverse kinematics. The low cross-sections for the formation and survival of such nuclei also demand higher intensity beams which are planned to be achieved using an alternative high current injector (HCI) [4] to the LINAC accelerator, consisting of high-T_{c} superconductor-based electron cyclotron resonance (ECR) source followed by radiofrequency quadrupole (RFQ), drift tube LINAC (DTL) and low-β resonators to match the β-acceptance of superconducting LINAC accelerator. Of these, the ECR source, first of its kind and named PKDELIS (pantecknik-delhi-ionsource), has been fabricated and is being thoroughly tested for producing highly charged heavy ions, scaled-down prototype each of RFQ and DTL are undergoing detailed tests for field configuration and power/cooling requirements and design of niobium-based low-β resonators are underway. Thus, a significant number of nuclei in very heavy mass regions and in light and medium mass region around $N \sim Z$ can be effectively populated through fusion-evaporation reactions with the accelerator augmentation mentioned above. Needless to say, such evaporation residues (ERs) are kinematically forward focussed in a narrow cone. A spectrometer/separator that has very good efficiency and primary beam rejection along the beam direction (0°) enabling determination of mass number (A) and atomic number (Z) of the selected nuclei is essential for ER cross-section measurements, isomeric decay measurements and spectroscopy of weakly populated nuclei, by suppression of background through ER channel selection. In order to effectively address these requirements, the HYRA has been designed, fabricated and is being commissioned at IUAC with the capability of being utilized in stand-alone mode or in conjunction with Indian national gamma array (INGA) (http://www.iuac.ernet.in/research/nuclear_physics/INGA/INGA_main.html). The design of HYRA is not only unique but is planned to have larger acceptances and rigidities than the earlier recoil mass spectrometer, heavy ion reaction analyzer (HIRA) [5] set up in beam hall I, two decades ago, for studies using pelletron beams.

HYRA is a two-stage spectrometer/separator with the first stage QQ-MD-Q-MD-QQ operable in momentum dispersive mode in gas-filled mode operation or as a momentum achromat in vacuum mode operation. The second stage consists of QQ-ED-MD-QQ which gives rise to mass dispersion by the cancellation of energy dispersion at a fixed focal point. Thus, the electromagnetic configuration of complete HYRA is Q1Q2-MD1-Q3-MD2-Q4Q5-Q6Q7-ED-MD3-Q8Q9. HYRA sets out to address (i) the reduced efficiency of HIRA in the formation of heavy nuclei with lighter projectiles by the choice of gas-filled mode operation of its first stage with large acceptances and magnetic rigidities and (ii) the reduced primary beam rejection of HIRA in the formation of medium mass nuclei in inverse kinematics by using both stages in vacuum mode and first stage as a momentum achromat similar to ORNL RMS [6] but with the use of only one electrostatic dipole. Several gas-filled separators such as DGFRS at Dubna (Russia) [7], RITU at JYFL (Finland) [8], GARIS at RIKEN (Japan) [9], BGS at BNL (USA) [10], etc. have been used effectively to detect heavy nuclei and the focal plane recoil decay for A and Z determination. HYRA differs from them in both design parameters and the possibility of using it in a higher purity (first stage completely gas-filled) or higher transmission efficiency (half of the first stage gas-filled) modes. The focal plane detector system and its support/alignment mechanism are made in such a way that it could be placed either beyond Q5 as at present or beyond MD1 (in the place of Q3 by reproducible, lateral movement of Q3 on precision rails). In the former case, the presence of two large dipole magnets in gas-filled mode will increase the rejection of primary/scattered beam as well as target-like particles at the focal plane thereby reducing the background in the focal plane detector while a reduction in transmission efficiency is unavoidable due to multiple scattering in the larger flight path in dilute gas. In the higher transmission efficiency mode, reasonable primary/scattered beam rejection can be achieved with only one dipole magnet MD1 in gas-filled mode and is especially attractive in reactions induced by lighter projectiles such as ^{12}C in very asymmetric reactions which result in much lower ER energies, larger energy spread and larger angular distribution around 0°.

3. Current status and design features of HYRA

All quadrupole magnets are room temperature, water-cooled magnets except Q1Q2 which is planned to be superconducting in order to increase the solid angle of acceptance. The first stage of HYRA has initially been set up (figure 1) using room-temperature quadrupole doublet for Q1Q2 and a quadrupole doublet of second stage in place of Q4Q5. The electromagnetic components (except the superconducting Q1Q2) and magnet power supplies of more than 300 A rating have been fabricated by M/s. Danfysik, Denmark. Elaborate testings of these components were carried out at Danfysik with the active participation of scientists and engineers from IUAC. Magnet power supplies (5 Nos.) of 300 A rating have been indigenously developed and commissioned. In addition, the readback and control system for all magnet power supplies use input gate output register (IGOR) modules developed indigenously.

The lower radius and higher radius sides of MD1 chamber are lined with tantalum with water-cooled copper backing to stop the primary beam in gas-filled mode and vacuum mode operation, respectively. The compact space between adjacent elements do not permit large vacuum pumps to be installed and hence these are connected to ports in magnet chamber brought out through holes, on either side, in the mid-plane of return yoke. The quadrupole Q3, between MD1 and MD2, is split into two halves with the intermediate space maintained for the insertion of slits or beam stoppers depending on the mode of operation. The entrance and exit of Q3 chamber are provided with welded bellows to allow the sideway movement of Q3 in a precise and reproducible manner on linear rails (figure 1). The space thus created will be used as focal plane position in gas-filled mode for better transmission efficiency of low velocity, heavy ERs as mentioned earlier.

The superconducting, superferric quadrupole doublet is being developed with the help from experts from MSU, USA. The yoke and poles have been machined, cryostat designed, fabricated and are awaiting the final weld. Prototype coils have been made with the new coil winding machine and the actual coils are required to be wound and tested prior to installing the magnets in the cryostat and carrying out the final weld.

The electrostatic dipole (ED) of the second stage has curved anode and cathode plates machined from solid titanium and is capable of reaching voltages of $+/-$ 300 kV across a gap of 12 cm. The power supplies are of Glassmann make and the external stacks are suspended above the ED chamber to increase the access of floor space around ED and a Faraday cage is provided around and in between the positive and negative power supplies for safety, similar to HIRA, our earlier spectrometer. The second stage elements are expected to be set up from mid-2010.

The first stage can be used in momentum achromat mode for the production and selection of light unstable secondary beam from direct reactions involving inverse kinematics. The large-momentum dispersion produced by the first half at Q3 centre can be used to reject the primary beam using appropriate slit mechanism. The second half of the achromat then cancels the momentum dispersion at the focal plane. The quadrupole magnets help in focusing the particles of interest both at Q3 centre and at the focal plane in the horizontal, dispersive plane and to have parallel (at Q3 centre) and point focus at the focal plane in vertical, non-dispersive plane. This mode of operation has been tested with α-particles from ^{241}Am source. The source was mounted on a target ladder and a silicon detector of known area was mounted on a linear drive 10 cm downstream. This silicon detector was used to normalize the α-particle count rate for known solid angle of acceptance. MD1 and

MD2 fields, read using hall probes mounted in the homogeneous field area, were used for proper setting of dipole fields. Quadrupole fields were varied around values calculated using GIOS [11] ion-optical program to get the maximum count rate on the focal plane detector (50 mm × 50 mm, 300 μm thick resistive silicon detector). The normalized solid angle of acceptance was found to be about 28 mSr for this mode of operation which agreed with the simulated value of 25 mSr applicable to the current room temperature quadrupole doublet, Q1Q2. The transmission efficiency simulated through a slit of 10 mm (horizontal) × 50 mm (vertical) at the Q3 centre (nearly 65% of that with no slit) was also checked with α-source using a fixed-slit mechanism. This slit system is designed and fabricated so that multiple slits for more than one charge state of the unstable, secondary beam can also be used while rejecting the primary beam at Q3 mid-plane. Large, primary target foil mechanism with superimposed rotation and linear motion [12], developed for ^{7}Be secondary beam in HIRA spectrometer, has been adapted to HYRA target chamber too. A new, cryo-cooled gas target system has been fabricated as an alternative. This mode of operation is ready for tests with beam and we plan to take up the production of ^{6}He secondary beam as a first case. The energy of secondary beams in HYRA would be much higher than those possible with HIRA as there is no energy-limiting electrostatic dipole in the first stage of HYRA. However, for the same reason, the purity is expected to be less as only momentum analysis is possible in the first stage of HYRA.

The gas-filled mode operation of the first stage of HYRA, the first of its kind in the country, has been tested with the beam to study (i) the selectivity of evaporation residues or elastic recoils in the primary beam direction, (ii) beam and other background rejection in both the cases, (iii) transmission efficiency for evaporation residues, etc. and has also been used to measure fusion–evaporation cross-section around and below barrier in a student thesis experiment. The optimization and initial results in gas-filled mode operation are explained in the next section.

Figure 1. First stage of HYRA spectrometer used in gas-filled mode (particles enter from right).

4. Gas-filled mode operation

The target chamber is cylindrical with an inner diameter of 200 mm and a height of 305 mm. Option to have the entrance window foil either upstream of the target (within the chamber at a distance of 50 mm from the target) or downstream of the target for higher energy evaporation residues are provided. In measurements involving prompt γ-ray detection in coincidence with ERs, the window foil could be moved 300 mm upstream of the target to shield the HPGe detector from γ-rays emanating from the window foil using lead bricks. The gas used in the separator in gas-filled mode is helium at $\sim$1 Torr or less. The magnetic rigidity of MD1 and MD2, namely 2.25 Tm each (with a radius of 1.5 m and maximum magnetic field of 1.5 T) will allow the selection of superheavy nuclei once the LINAC and HCI are fully operational. Helium is introduced in the target chamber through a solenoid-based valve controlled by an MKS gas pressure controller which compares the set pressure value with that measured using a Baratron gauge. The active Baratron gauge is connected to MD1 chamber and it has been observed that the pressure in both MD1 and MD2 are the same due to large conductances. Helium is pumped out through MD1 roughing pump system. A continuous flow is maintained for the dynamic control of gas pressure.

The focal plane chamber (figure 2) consists of a large area (127 mm $\times$ 63 mm) polypropylene foil of 0.5 μm thickness followed by a multiwire proportional counter (MWPC) of 57 mm $\times$ 57 mm size consisting of three sets of wire frames forming the outer cathodes (x and y position sensitive) and inner anode. Position signals are taken from the two ends of x and y frames using delay-lines and the anode signal gives both the energy loss signal and start time for position

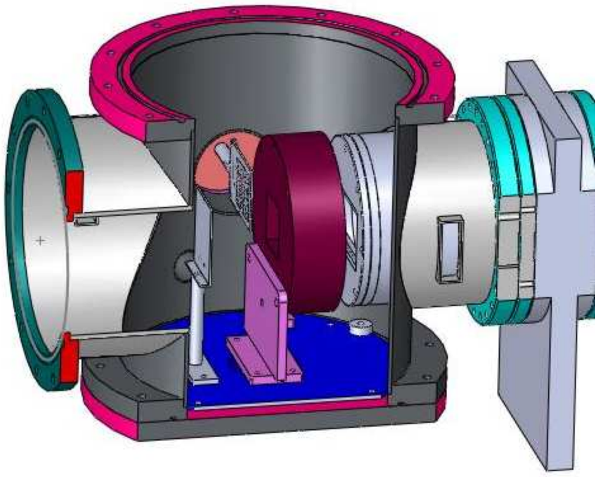

Figure 2. Schematic of focal plane detector system used in gas-filled mode of HYRA showing gate valve, window foil to separate helium and isobutane sections, MWPC detector, retractable shutter and silicon stop detector; residues enter from the right.

read-out. MWPC is followed by a retractable shutter which protects the downstream resistive silicon detector (50 mm × 50 mm size and 300 μm thick, Eurisys-make) during initial tuning of the separator. The silicon detector signals are taken from the four corners of the resistive side in order to derive the x and y positions and the back surface contact provides the energy deposited by the particles. Owing to the large capacitance, the energy resolution of this detector is not good enough for resolving α-particle energies of the nearby heavy residues. The data acquisition system CANDLE [13], developed at IUAC, is used in HYRA-related experiments and the data are acquired in a shielded cabin in the experimental hall.

In the gas-filled mode, the particles undergo charge changing collisions with the molecules of the gas and also lose energy in such collisions. Under optimum gas pressure and field setting, velocity and charge state focusing take place which cause the particles of interest to coalesce around the trajectory of a particle of some mean charge state. Extensive theoretical and experimental studies have been carried out at Dubna DGFRS [14] and elsewhere to empirically predict the mean charge state for various heavy ions. We use a simulation program developed in-house [15] which computes the mean charge state using empirical formula available in literature and also takes into account the energy loss in several steps of the gas medium. The magnetic field value of each dipole is computed using the average charge state and energy of the particle at the centre of that dipole. Multiple scattering effects on the efficiency reduction are ignored in this preliminary simulation.

The first system tried as calibration system is the fusion–evaporation reaction ^{16}O (Elab of 100 MeV) on ^{184}W (enriched target of 210 μg/cm^2 on thin carbon backing, with carbon facing the beam) leading to ^{200}Pb* compound nucleus (CN). This

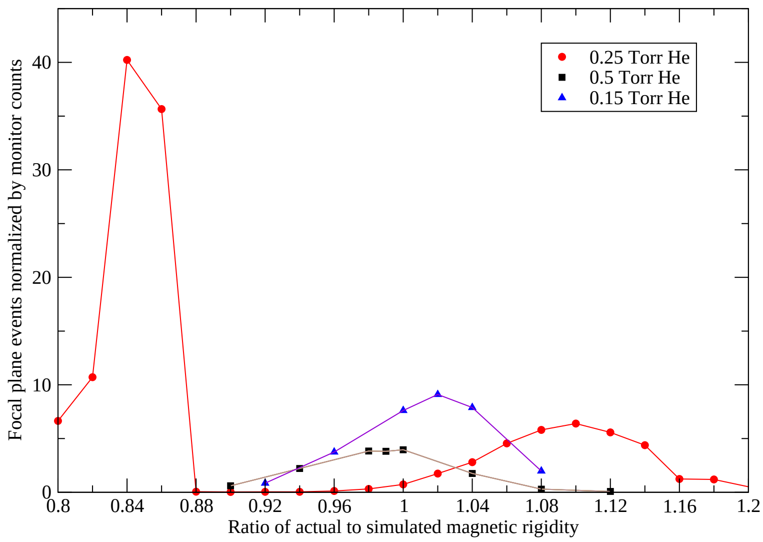

Figure 3. Normalized ER counts at the focal plane as a function of the ratio of actual to simulated magnetic rigidity for 0.5 Torr, 0.25 Torr and 0.15 Torr helium gas pressure settings in HYRA. Lines joining the points are to guide the eye.

system has been well studied [16] using the other spectrometer HIRA at IUAC. Two surface barrier (SB) detectors were mounted on either side of the beam direction, at ∼25°, for normalization purposes and for proper beam tuning. The beam was initially optimized on a quartz glass mounted on one of the four target ladder positions and viewed through the straight-through port in MD1 exit. Gas pressure was slowly varied and MD1 and MD2 fields were initially set to simulated values for each gas pressure setting. Quadrupole fields were tuned to get maximum ER transmission at the focal plane MWPC detector at the first gas pressure setting (i.e. at 0.25 Torr). Later, the fields of Q1 and Q2 were scaled by MD1 scaling factor, fields of Q4 and Q5 were scaled by MD2 scaling factor and Q3 field was scaled by the mean of MD1 and MD2 scaling factors for other gas pressure settings. In order to find out if the fields chosen for MD1 and MD2 were indeed correct, at each gas pressure a field variation of up to +/−10% in steps of 2% was carried out and data collected in each case. In subsequent gas pressures used, namely at 0.5 Torr and 0.15 Torr, the observed MD1 and MD2 settings agreed within 2% of simulated values validating the scaling procedure used (figure 3).

It was also observed that at 0.15 Torr, maximum transmission efficiency was obtained as shown in figure 3. The focal plane spectrum was very clean with only ERs reaching the detector and almost no beam-like particles. At 0.25 Torr, the fields were deliberately scaled down by large values till some traces of beam-like particles could be observed at almost 75% of the optimum value as shown in figure 3. This shows that the primary beam rejection is excellent for a wide range of MD settings. As the ERs (mainly ^{194}Pb and ^{195}Pb) do not undergo α-decay, the energy spectrum in the focal plane (figure 4a) consists of only ERs. The measured energy of ERs taking into account the pulse height defect (∼35%) agreed well with the estimated value.

Having found the optimum gas pressure and field settings for the calibration system, the user experiment involving a student from Calicut university, India was taken up to study ER excitation function in ^{16}O on ^{194}Pt leading to ^{210}Rn* compound nucleus. The main ERs in this reaction, ^{204}Rn and ^{205}Rn, have known α-decay branches. The energy spectrum for this system (figure 4b) clearly shows ERs of lower energy and α-decay from ERs of about 6.5 MeV. The target was replaced by aluminium foil, in the optimized settings, to quantify background involving only beam-like particles as no heavy products are expected in the reaction between ^{16}O and ^{27}Al. A primary beam rejection of better than 10^{12} was achieved even at a low gas pressure of 0.15 Torr (see figures 5a and 5b). The excellent cleanliness is also due to the fact that two large magnetic dipoles are used in gas-filled mode of HYRA. Fusion excitation function could be measured from nearly 25% above nominal Coulomb barrier down to about 10% below the barrier. At the lowest beam energy, pulsed beam with about 4 μs repetition period was used to study the time-of-flight (TOF) of the particles arriving at the focal plane to distinguish between ERs, target-like particles and beam-like particles. The beam-like particle contamination at ∼7% below barrier was found to be less than 5% of ER yield using the aluminium foil method mentioned earlier.

The transmission efficiency of ERs through HYRA was initially tried with γ coincidence method using a 23% relative efficiency HPGe detector mounted from below, at target site. However, the thick nickel entrance window foil (∼1.5 mg/cm^2)

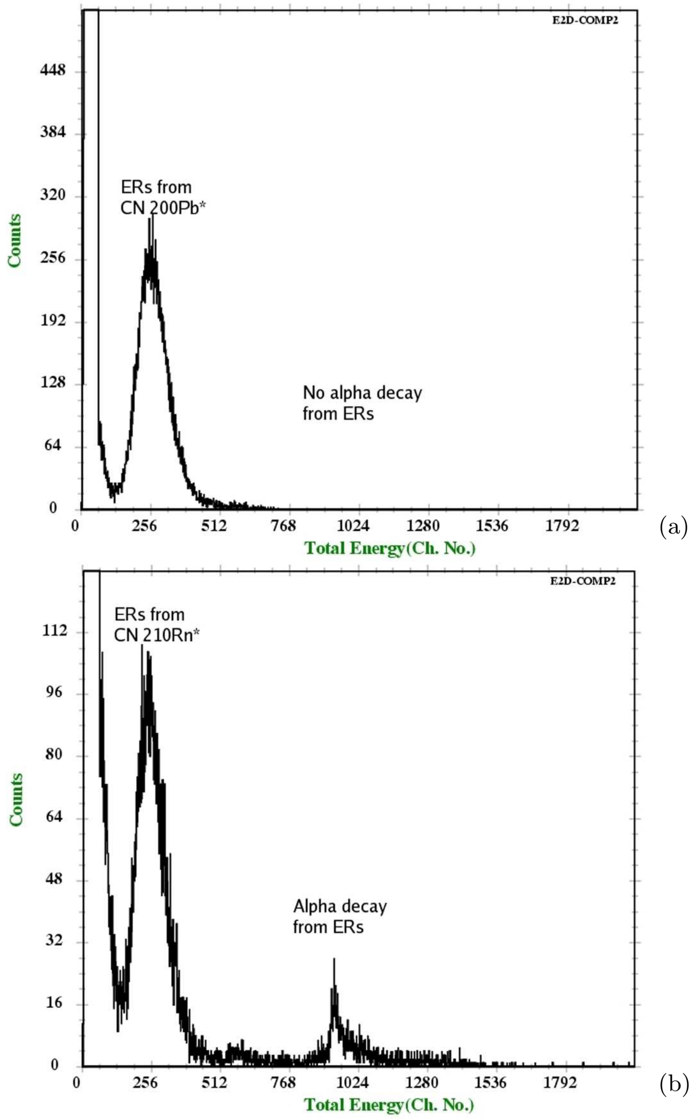

Figure 4. (**a**) Focal plane energy spectrum for ^{16}O on ^{184}W with only ERs of low energy seen (no α-decay is observed in the predominant ^{194,195}Pb residues). (**b**) Focal plane energy spectrum for ^{16}O on ^{194}Pt with ERs of low energy and α-decay of higher energy observed in the predominant ^{204,205}Rn residues.

mounted 5 cm upstream of the target gave rise to large γ background in the singles spectrum. The window foil was later moved to $\sim$30 cm upstream of the target so that the γ detector could be shielded from the γ-rays from the window foil with lead bricks placed between them. The transmission efficiency measured by taking the ratio of counts in ER-gated specific γ-ray to those in the same γ-ray

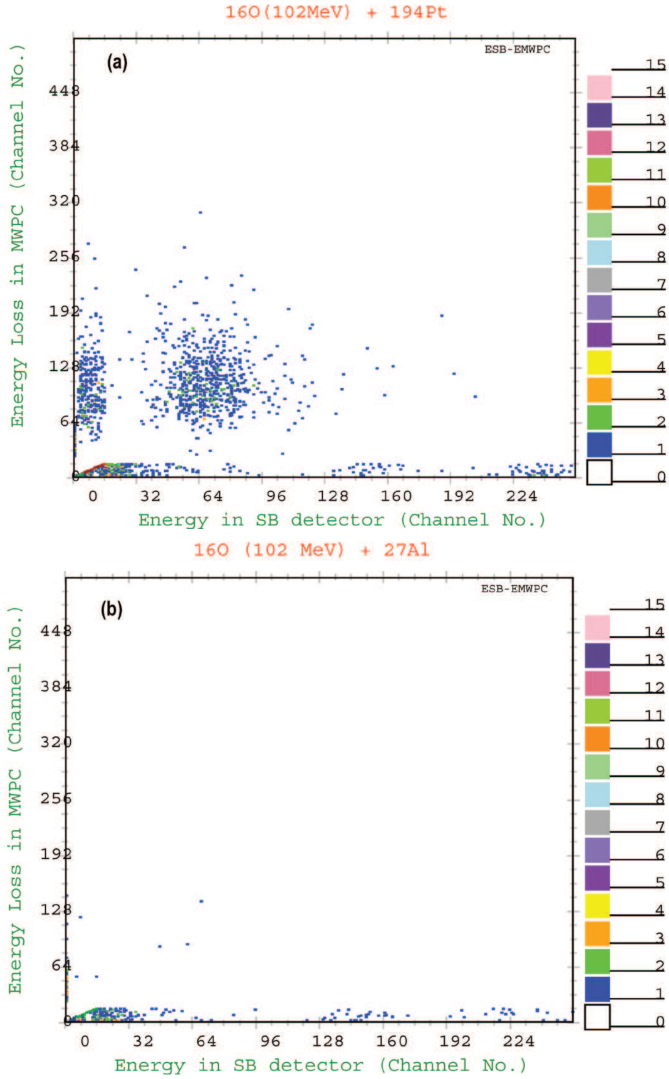

Figure 5. (**a**) ERs shown in total energy vs. energy loss spectrum for ^{16}O on ^{194}Pt target at 102 MeV beam energy with the gas-filled mode parameters optimized for heavy Rn evaporation residues. (**b**) Beam background (negligible), shown in total energy vs. energy loss spectrum for ^{16}O on ^{27}Al target, reaching focal plane with HYRA gas-filled mode parameters optimized for heavy Rn evaporation residues, at the same beam energy and for the same time as in (a).

in singles spectrum was scaled to near position of window foil by ER-to-monitor ratio and found to be 2.6% at 100 MeV beam energy. This scaling was required as the fusion excitation function was carried out with window foil in near position and as the window foil was moved away, multiple scattering effects led to angular

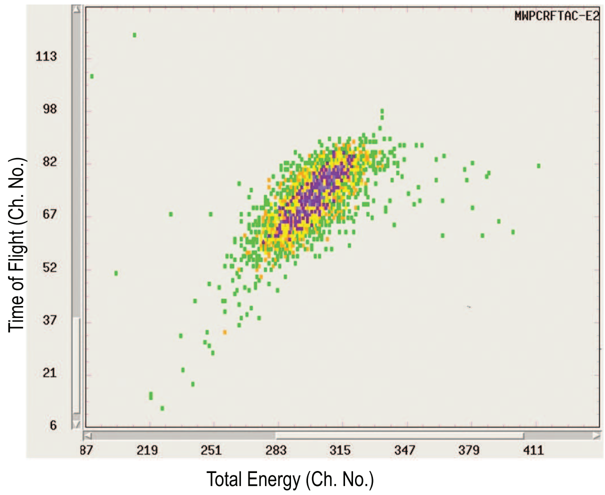

Figure 6. Forward moving elastic recoils from ^{48}Ti on $^{\rm nat}$Pb at an energy below barrier selected using gas-filled mode of HYRA as seen in total energy vs. time-of-flight spectrum.

straggling and thereby a reduction in transmission of ERs. In future, we plan to have a thinner carbon foil to overcome this problem. The efficiency extracted using measured cross-section of ERs for the same system using HIRA spectrometer and normalized ER yields in MWPC detector at HYRA focal plane after correcting for angular acceptances is $\sim$2.5% which agrees with value from γ coincidence method. The transmission efficiency of Dubna gas-filled separator has been tabulated for several projectile–target combinations in [14], for a focal plane detector area of 120 mm $\times$ 40 mm. Taking into account the kinematic factor as ER energy multiplied by projectile-to-target mass ratio and HYRA focal plane detector area which is lesser by 33%, the efficiency extracted for ^{16}O + ^{184}W using HYRA is comparable with that of Dubna gas-filled separator. The higher transmission mode and/or the ultimate use of superconducting Q1Q2 will enhance the transmission efficiency of HYRA gas-filled mode. The transmission efficiency up to MWPC (57 mm $\times$ 57 mm area) is almost 30% more than that up to silicon detector (50 mm $\times$ 50 mm area) which scales with area of the detector. In future, we plan to use a larger MWPC and two silicon detectors placed side-by-side.

During the stability tests of the first superconducting LINAC module, the gas-filled mode was used to detect the forward moving target-like recoils in the ^{48}Ti + $^{\rm nat}$Pb target at 212 MeV beam energy (152 MeV using pelletron and additional energy of 60 MeV using the LINAC) in elastic backscattering below the nominal Coulomb barrier. This task of detecting the target-like recoils in the primary beam direction is impossible with vacuum mode magnetic separators and also extremely difficult using vacuum mode RMS such as HIRA. However, with the gas-filled mode of HYRA we could achieve a primary beam rejection of better than 10^{13}. The two-dimensional spectrum of energy vs. time-of-flight (with focal plane signal as start and RF from beam pulsing system as stop) shows the target-like recoils

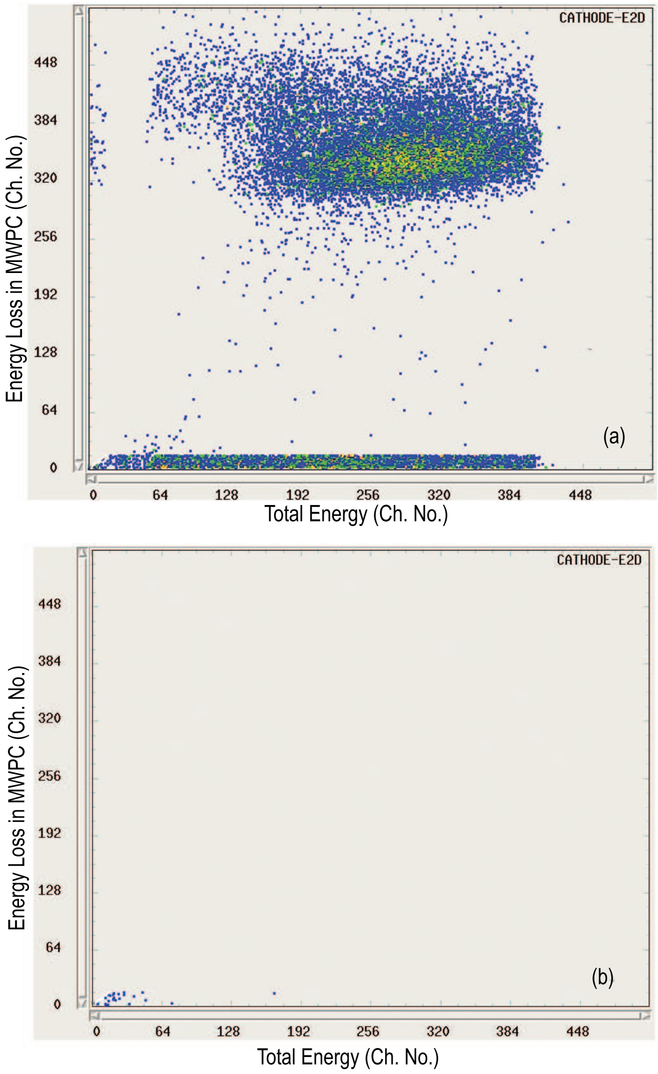

Figure 7. (**a**) Pb-like recoils shown in energy vs. energy loss spectrum for ^{48}Ti on (^{nat}Pb at 212 MeV beam energy selected at 0°) with HYRA gas-filled mode parameters set for the selection of forward moving recoils. (**b**) Beam background (negligible), shown in energy vs. energy loss spectrum for ^{48}Ti on ^{27}Al target, reaching the focal plane with HYRA gas-filled mode parameters set for Pb-like forward moving recoils, at the same beam energy and for the same time as in (a).

(figure 6). The spectra of total energy vs. energy loss in MWPC for ^{nat}Pb target and aluminium target of similar thicknesses and collected for the same period of time (figures 7a and 7b) shows effective primary beam rejection in this mode. The reproducibility of the transmission efficiency with changes in beam energy is to be

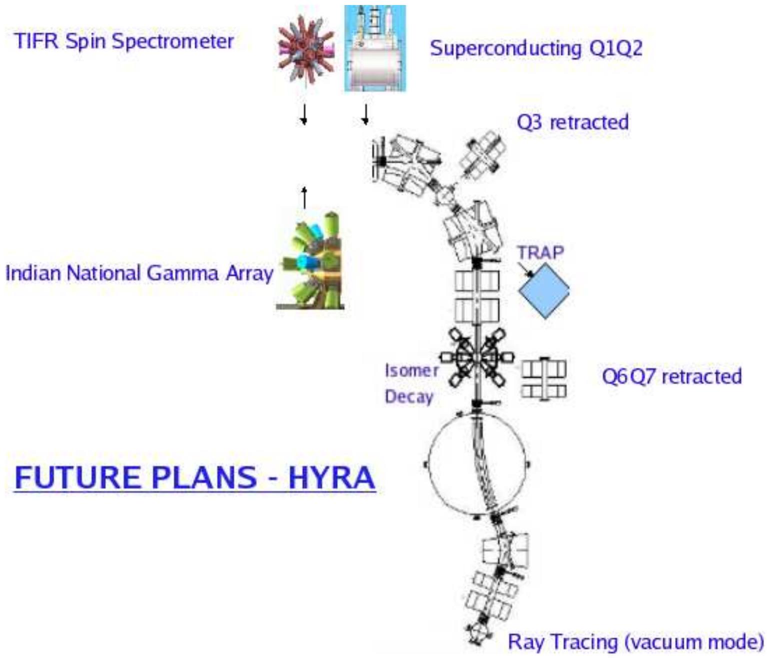

Figure 8. Schematic of both stages of HYRA with the various modes of operation and planned add-on facilities.

ensured in order to have faith in the scaling procedure for HYRA electromagnetic fields as per the modified energy and mean charge state. This was checked by reducing the beam energy by 15% and ensuring that the recoils reaching the focal plane normalized by monitor counts remained the same.

5. Future plans

A larger MWPC and two silicon detectors (strip-detector type) are planned to be set up at the first-stage focal plane.

Nearly 12 experiments have been sanctioned using gas-filled mode of HYRA, most of which were the outcome of a workshop held at IUAC in May 2009. Most of them are for measuring the ER excitation function and spin distribution to understand fusion–fission dynamics in heavy systems. We plan to couple the 4π spin spectrometer [17] set up at TIFR, Mumbai with HYRA for carrying out these measurements and the support and alignment structure for the same is nearing completion. Experiments looking for isomer decay in $N \sim 126$ region are planned to be taken up subsequently using a clover detector mounted close to the focal plane silicon detector. Two other experiments involve exclusive GDR measurements and the look-out for pairing/clustering effects using vacuum, momentum-achromat mode of the first stage of HYRA. The germanium clover detectors of INGA array are expected to be at TIFR, Mumbai for a year and a half, after which they can be brought back to IUAC for ER-gated γ-spectroscopy in heavy nuclei with 16 clover detectors (8 each at 90° and backward angles) and few low-energy photon spectrometer (LEPS) detectors. The mechanism for mounting clover detectors at HYRA target site is ready. There is a plan to produce ^{6}He secondary beam in direct reactions involving inverse kinematics using the first stage in vacuum, momentum achromat mode and the necessary slit system to be used at Q3 centre has been fabricated and tested using α source.

The electrostatic dipole of the second stage has been tested for vacuum and high voltage. The second stage is expected to be completed in the second half of 2010 and a large two-dimensional MWPC followed by ionization detector and another MWPC (for ray tracing) will be set up at the focal plane of the second stage of HYRA. Experiments in medium mass nuclei in the vacuum mode of the complete HYRA and using inverse kinematics will be taken up after the completion and testing of second stage of HYRA. Provision for precise and reproducible sideways movement of Q6Q7 will help in switching over to focal plane decay measurements using gas-filled mode and vacuum mode operation of complete HYRA (figure 8).

In the long term, an ion trapping/cooling system behind the first stage of HYRA with heavy nuclei selected by MD1 in gas-filled mode and transported through the straight-thru port of MD2 will be ideal for mass measurements and/or decay measurements. Mass measurements of trans-uranium nuclei using the trap is still a nascent field with only one known successful set of measurements using SHIPTRAP carried out and reported recently [18].

6. Summary

First results using the gas-filled mode of HYRA, a unique dual stage, dual mode spectrometer, has been reported for the successful separation and detection of heavy evaporation residues and α decay from them and also heavy target-like elastic recoils in the direction of primary beam. Primary beam rejection extracted in both the cases have been excellent and better than 10^{12}. A reasonable transmission efficiency for heavy ERs has been achieved with relatively smaller focal plane detection system. The transmission efficiencies of target-like elastic recoils have been found to remain constant over a 15% change in primary beam energy. Plans, with priority, for the immediate future and long-term goals have been presented.

Acknowledgements

The authors are thankful to both Pelletron and LINAC accelerator and support staff for providing excellent quality beam for the tests and experiments. Continuous guidance and encouragement from Profs G K Mehta, V S Ramamurthy, S S Kapoor, S Kailas and other senior colleagues are gratefully acknowledged. The authors also thank the Department of Science and Technology, Government of India for funding the project and for continued support.

References

[1] N Madhavan *et al*, *Proc. DAE-BRNS Symp. Nucl. Phys.* **47A**, 50(2004)
[2] P N Prakash *et al*, *Pramana – J. Phys.* **59**, 849 (2002)
[3] G K Mehta and A P Patro, *Nucl. Instrum. Methods* **A268**, 334 (1988)
[4] D Kanjilal *et al*, *Rev. Sci. Instrum.* **77**, 03A317 (2006)
[5] A K Sinha, N Madhavan, J J Das, P Sugathan, D O Kataria, A P Patro and G K Mehta, *Nucl. Instrum. Methods* **A339**, 543 (1994)
[6] C J Gross *et al*, *Nucl. Instrum. Methods* **A450**, 12 (2000)
[7] Yu S Tsyganov, *J. Phys. G: Nucl. Part. Phys.* **25**, 937 (1999)
[8] M Leino *et al*, *Nucl. Instrum. Methods* **B99**, 653 (1995)
[9] K Morita *et al*, *Nucl. Instrum. Methods* **B70**, 220 (1992)
[10] K E Gregorich *et al*, *J. Nucl. Radiochem. Sci.* **1**, 1 (2000)
[11] H Wollnik, *Optics of charged particles* (Academic Press, Orlando, Florida, 1987) pp. 212–213
[12] T Varughese *et al*, *Nucl. Instrum. Methods* **A521**, 143 (2004)
[13] E T Subramaniam *et al*, *Rev. Sci. Instrum.* **77**, 096102 (2006)
[14] K Subotic *et al*, *Nucl. Instrum. Methods* **A481**, 71 (2002)
[15] S Nath and N Madhavan, *IUAC Annual Report* (2006–2007) Section 4.3.3, pp. 103–105
[16] P D Shidling *et al*, *Phys. Lett.* **B670**, 99 (2008)
[17] G Anil Kumar, I Mazumdar and D A Gothe, *Nucl. Sci. Symp. Conf. Record* 2008, NSS '08.IEEE
[18] M Block *et al*, *Hyperfine Interactions* **196(1–3)** February (2010)