5. RESEARCH ACTIVITIES

5.1 NUCLEAR PHYSICS

The Indian National Gamma Array (INGA) was installed at the new beam hall of IUAC in early January, 2008 and regular user experiments started from Feb 28. During the first Cycle of INGA operation (Feb 2008 – July 2008) fifteen user experiments were conducted. This was followed by three students' Ph.D. thesis experiments in Oct, 2008. Some of the interesting problems that were addressed during these experiments were (i) search for band termination in magnetic rotation band in A~140 region (ii) role of proton and neutron orbits in magnetic rotation for A ~ 137 nuclei (iii) high spin structure in ^{112}In and search for chiral bands (iv) spectroscopy of magnetic rotation bands near Z~64 N~82 shell closure (v) spectroscopy of neutron-rich nuclei near ^{132}Sn produced by heavy-ion induced fission (vi) spectroscopy of trans-lead nuclei $^{210-212}$Ra, $^{208-211}$Fr and (vii) study of octupole correlation in $^{239-241}$Pu, $^{237-240}$Np.

The gas-filled phase of the Hybrid Recoil Separator has been commissioned and the first set of user experiments carried out. Evaporation cross-section measurements for the reaction ^{16}O + ^{194}Pt were carried out near barrier energies. The gas-filled separator has an order of magnitude larger collection efficiency (~3%) compared to that in HIRA (~1%). Due to improved beam rejection, cross sections down to 50 μb level could be measured. A number of experiments were also carried out using HIRA to measure evaporation residue cross sections.

An experiment to measure the Coulomb excitation cross sections for ^{58}Ni + ^{112,116}Sn was carried out in collaboration with GSI group. The γ-rays from Coulomb excitation of Ni and Sn-isotopes were measured in coincidence with the forward scattered beam-like particles in a position sensitive detector. The measured B(E2) value for ^{112}Sn is larger than that of ^{116}Sn by a factor of 1.16 ± 0.02. This is consistent with the trend of larger experimental B(E2) ratios observed for ^{114}Sn and other lighter Sn isotopes compared to the theoretical prediction of a symmetric trend around N=66 midshell.

An experiment to investigate tetrahedral symmetry in nuclei was carried out by our group at LNL, Italy. The negative parity band in ^{156}Gd was excited by multiple E2 Coulomb excitation of the g.s. band followed by a single E3 transition. The feeding and decay pattern of this band is indicative of an octupole degree of freedom with a very weak quadrupole deformation that is consistent with the possibility of tertrahedral symmetry.

5.1.1 High spin states in ^{137}Pm

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The moderately deformed ($\beta_2 \sim 0.2$) nuclei in the mass A ~ 130 region, governed by $h_{11/2}$ intruder orbital, with Z ~ 60 - 65 have long been considered to be γ - soft. The degree of γ - deformation depends on the polarizing influence of the valence quasiparticles. The γ - softness and shape polarization make this region particularly interesting for shape driven effects. Coexistence of different shapes is one well known effect in this region, in which several different deformations of the nucleus may exist at nearly the same excitation energy and spin. The motivation of the present work is to investigate, understand and establish the level structure and nuclear phenomena at high spin and excitation energy in ^{137}Pm [1, 2] nucleus due to shape driving influence of the intruder orbital (*viz.* $h_{11/2}$). Preliminary results of the present investigations were reported earlier [3]

High spins states in the odd-Z ^{137}Pm nucleus were populated using the ^{109}Ag (^{32}S, 2p2n) ^{137}Pm reaction at an incident beam energy of 150 MeV. The ^{32}S beam was delivered by the 15-UD Pelletron accelerator at Inter University Accelerator Centre (IUAC), New Delhi. The de-exciting γ - rays were detected utilizing the Indian National Gamma Array (INGA) [4] which at the time of the experiment comprised of 18 Compton suppressed Clover detectors. The Clover detectors were arranged in five rings viz. 32°, 57°, 90°, 123° and 148° with respect to the beam direction. The total coverage of Ge crystals during the run was about 18% of 4π corresponding to a total photo-peak efficiency of ~ 3.75%. The distance between the target and the detector is ~ 24 cm. The isotopically enriched ^{109}Ag target was ~ 0.9 mg/cm^2 thick on an Au backing of thickness ~ 10 mg/cm^2. The data were collected in the list mode using the CAMAC-based MULTI-CRATE synchronization mode coupled with PC-LINUX environment. The energy and timing information from the clover detectors were processed using the indigenously developed (at IUAC) Clover modules and ADC's. A total of about 850 million two or higher fold coincidences were recorded.

The data were analyzed off-line using the analysis programs INGASORT, IUCSORT and CANDLE. The coincidence events were sorted into the conventional γ - γ symmetric as well as asymmetric matrices. The 4K ⊗ 4K matrices had an energy dispersion of 0.5 keV/channel. The level scheme of ^{137}Pm has been extended up to $J^{\pi} = 43/2^{-}$ and excitation energy of $E_x \cong 6$ MeV.

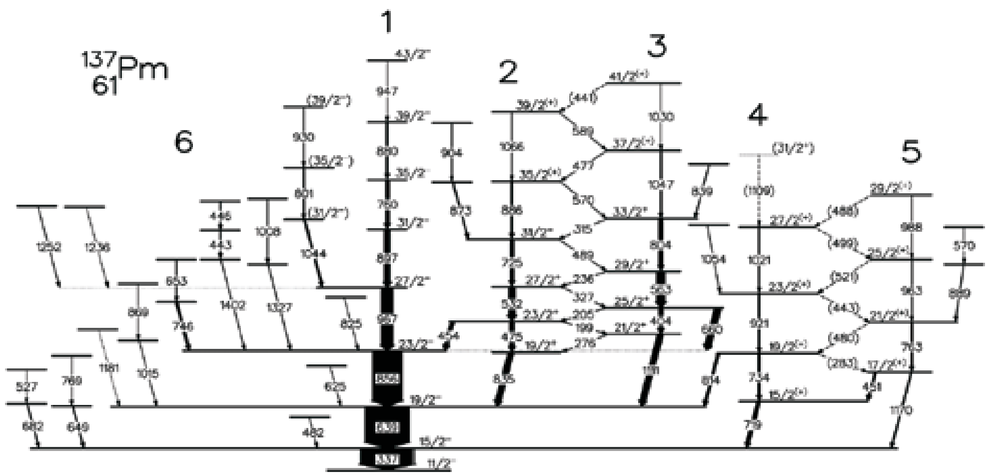

Fig. 1. The level scheme of ^{137}Pm deduced from the present work

A total of 42 new gamma-transitions (35 γ - transitions are confirmed whereas 7 γ - transitions are tentative) have been placed in the level scheme. The multipolarity assignments for most of the reported γ - transitions have been made using the observed coincidence angular anisotropy, R_{DCO}. The level scheme deduced in the present work is shown in Fig. 1. A representative partial gated sum spectrum of 897 and 967 keV transitions of Band 1 (yrast band) is shown in Fig. 2.

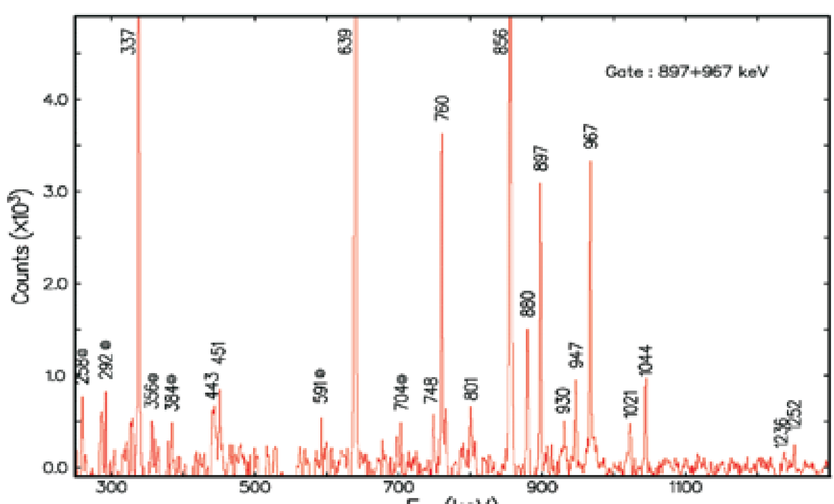

Fig. 2. Partial γ-γ coincidence gated sum spectrum of 897 and 967 keV transitions of Band 1 of ^{137}Pm. The peaks marked with '@' are contaminants from ^{137}Sm and ^{134}Nd.

In the odd-proton nuclei in this mass region the first proton crossing is blocked, which is also observed in the Cranked Shell Model (CSM) calculations for ^{137}Pm. The first neutron alignment and second proton alignment are expected to occur at almost same frequency. However in ^{137}Pm the gain in alignment $\Delta i \cong 8$ could be attributed to the second and third proton alignment. The protons favour a near-axial prolate shape ($\gamma \sim 0°$) where as the neutrons drive the nucleus towards oblate shape ($\gamma \sim -60°$). Though there is a signature of neutron alignment in ^{137}Pm, the sufficiently large prolate-oblate potential energy difference forbids the nucleus to change shape. The Total Routhian Surface (TRS) calculations with a Woods-Saxon potential and monopole pairing predict a near-prolate deformation of $\beta_2 \sim 0.20$ for this nucleus, evolving to a triaxial shape at higher frequency. In addition to the yrast sequence $[\pi(h_{11/2}) \otimes \pi(h_{11/2})^2]$, side-bands based on the configuration $\pi(g_{7/2}) \otimes \pi(h_{11/2})^2$ (Bands 2 and 3) and $\pi(d_{5/2}) \otimes \nu(h_{11/2})^2$ (Bands 4 and 5) have also been identified. The observations of inter-connecting transitions between Bands 2 and 3 confirm that these two bands are signature partners. Although the inter-connecting transitions between Bands 4 and 5 are weak, it appears that these two bands are also signature partners.

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5.1.2 Search for the role of proton and neutron orbits in Magnetic Rotation (A = 137 Nuclei)

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In the early 1990's, a new mode of nuclear excitation was discovered. A long and regular sequences of states of fixed parity I^{π}, $(I + 1)^{\pi}$, $(I + 2)^{\pi}$, . . . connected by strong $\Delta I = 1$, M1 transitions (with B(M1) values of several μ^2 prep) and relatively weak crossover E2 transitions were observed [1–4]. It was suggested by Frauendorf et al [3] that these sequences (bands) offer, in fact, a new type of nuclear rotation with an inertia not due to the asymmetry in mass distribution but almost entirely due to the highly asymmetric current distribution resulting from specific configurations of proton particles and neutron holes in high-j orbits. In this scenario, the presence of the slightly polarized (weakly deformed) core plays a crucial role [3]. It mediates effectively the repulsive pn particle-hole interaction tending to align the proton, j_π , and neutron, j_ν , intrinsic angular momentum in an almost perpendicular way, $j_\pi \perp j_\nu$, near the band-head in order to maximize the overlap in their density distribution with that of the core. Such a configuration is characterized by a large transverse magnetic moment ($\mu_\perp$) giving rise to strong dipole M1 radiation. Shears bands with different number of proton and neutron particles/holes may cross, similar to the band crossing observed for the normal rotational bands [5].

In mass region A=130, the MR Bands seen in ^{137}Pr [5] and ^{137}Nd [6] have the configuration $\pi h_{11/2}^{2} \otimes \nu h_{11/2}^{-1}$ and $\pi h_{11/2}^{1} \otimes \nu h_{11/2}^{-2}$ before band crossing, respectively. Clearly, one proton particle/neutron hole have exchanged their roles. This is an interesting situation. It would allow us to delineate the roles of proton/neutron in the phenomenon on the basis of lifetime measurements which would give us the B(M1) and B(E2) values. Thus, we planned to perform the experiment to study the high spin states and do the lifetime measurements using DSAM method.

In the present experiment, high spins states of ^{137}Nd and ^{137}Pr nuclei have been populated by using the ^{123}Sb (^{19}F, 5n, p4n) ^{137}Nd, ^{137}Pr reaction at an incident beam energy of 95 MeV. The ^{19}F beam was delivered by the 15-UD Pelletron accelerator at Inter University Accelerator Centre (IUAC), New Delhi. The de-exciting γ - rays were detected utilizing the Indian National Gamma Array (INGA) which at the time of the experiment comprised of 17 Compton suppressed Clover detectors. The target consisted of ~ 840 μg/cm^2 isotopically enriched ^{123}Sb on a gold backing of thickness 7 mg/cm^2. The efficiency and energy calibrations were carried out by using ^{133}Ba, ^{60}Co and ^{152}Eu radioactive sources. The data were collected in the list mode using the CAMAC-based MULTI-CRATE synchronization mode coupled with PC-LINUX environment. The energy and timing information from the clover detectors were processed using the indigenously developed (at IUAC) Clover modules and ADC's. A total of about 830 million two or higher fold coincidences were recorded. The data were analyzed off-line using the analysis programs CANDLE. The coincidence events were sorted into the conventional $E\gamma$ - $E\gamma$ symmetric as well as asymmetric matrices. The 4K × 4K matrices had an energy dispersion of 0.5 keV/channel. Typical sum gated gamma ray spectrum is shown in the following figure. Further analysis of the data is presently in progress.

The authors would like to thank all the participants of the joint national effort to set up the Clover Array (INGA), all the participants who helped during the experiment. The accelerator staff at IUAC, New Delhi. Financial support from the DST, DAE and MHRD is also gratefully acknowledged.

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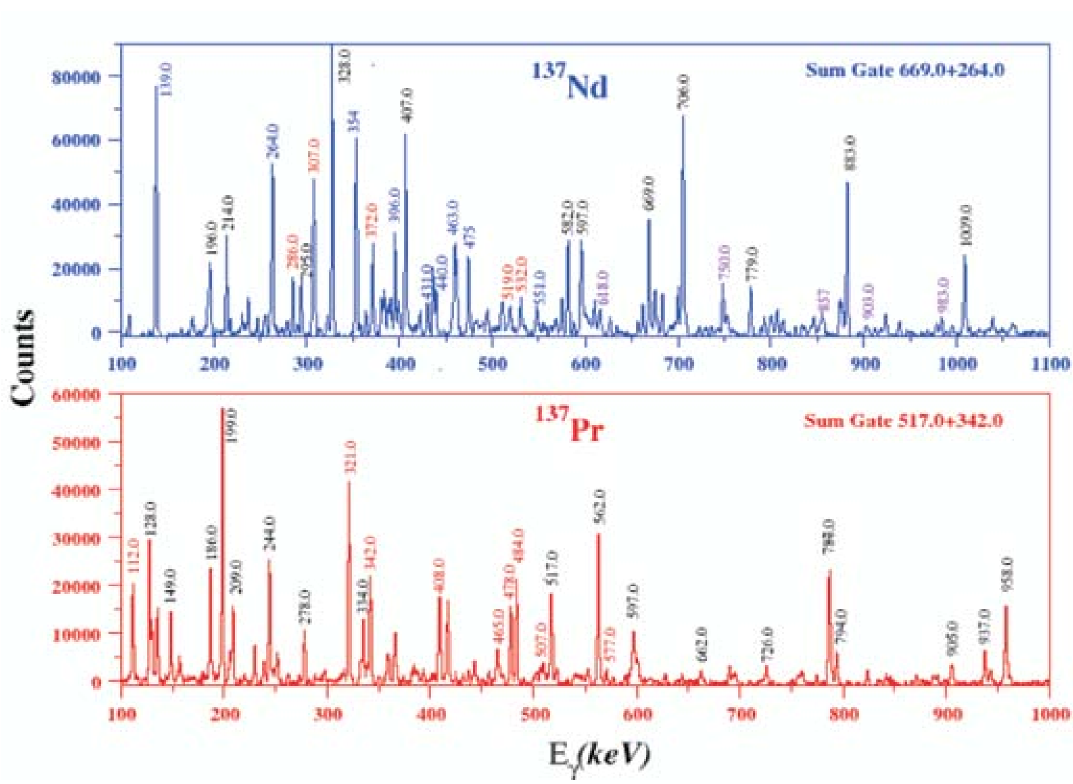

Fig. 1. The γ- γ coincidence gated sum spectrum of the 669 and 264 keV transitions shows the gamma-rays belong to the band in the current interest in ^{137}Nd in the first panel. The M1 transitions are shown with blue text where as E2 are shown with violet text and other strong transition are shown in black text . In the second panel, the γ - γ coincidence gated sum spectrum of the 517 and 342 keV transitions shows the gamma-rays belong to the band in the current interest in ^{137}Pr. The M1 transitions are shown with red text and other strong transition are shown in black text.

5.1.3 High spin states in ^{107}In

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Nuclei in the A~ 110 mass region have been studied for the search of magnetic rotation bands [1]. This mass region is also known to have anti-magnetic rotation band [2]. Low and intermediate spin states of odd A neutron deficient In isotopes have been studied in the framework of particle-core coupling model where $g_{9/2}$ proton hole is coupled with Sn core [3]. High spin states in indium isotopes have also been investigated and existence of magnetic rotation bands were confirmed [4]. It is promising to extend the work and look for high spin states in the isotopes close to ^{100}Sn.

An experiment to study the high spins states of ^{107}In was performed with INGA [5] at IUAC. High spin states in ^{107}In were populated using the ^{94}Mo (^{16}O, 2np)^{107}In reaction at an incident beam energy of 70MeV. The ^{16}O beam was delivered by the 15-UD Pelletron accelerator at Inter University Accelerator Centre (IUAC), New Delhi. At the time of the experiment INGA comprised of 17 Compton suppressed Clover detectors. The ^{94}Mo target of thickness ~ 0.9 mg/cm^2 with a backing of Au of thickness ~ 6.5 mg/cm^2 was made using the rolling technique, where foil of both the elements are rolled together. The data was collected in the list mode using the CAMAC-based MULTI-CRATE synchronization mode coupled with PC-LINUX environment. The energy and timing information from the clover detectors were processed using the indigenously developed (at IUAC) Clover modules and ADC's. A total of about 1000 million two or higher fold coincidence data was recorded.

The data is being analyzed off-line using the analysis programs INGASORT, RADWARE. The coincidence events were sorted into the conventional γ - γ symmetric as well as asymmetric matrices. Also a gamma gated matrix is made, where the gates are on strong transitions of ^{107}In. The 4K x 4K matrices had an energy dispersion of 0.5 keV/channel. In this report we wish to present the result of preliminary analysis. Figure 1 shows the line shapes of various transitions of negative parity states. Further analysis is going on.

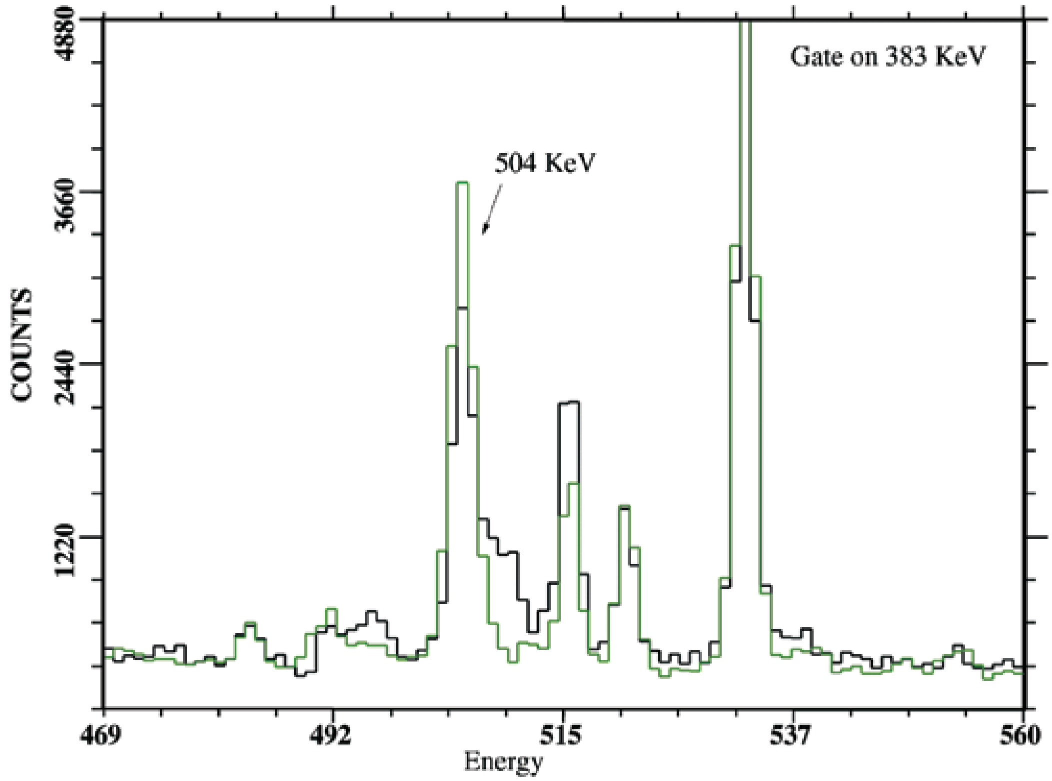

Fig. 1. The spectrum showing the lineshape in 504KeV transition of ^{107}In. Black spectrum corresponds to 32° while green corresponds to 90°.

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5.1.4 Lifetime measurement in ^{75}Kr using Doppler shift attenuation method

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The nuclei in the mass region near 70-80 have drawn considerable attention in recent past. The neutron deficient krypton isotopes at and near the N=Z line exhibit some of the best example of large quadrupole moment and shape coexistence. The previous investigation done by Skoda et al [1] shows that ^{75}Kr is strongly deformed in its ground state. Lifetime measurements for the lowest levels of the both positive as well as negative parity bands revealed large quadrupole deformation of about $\beta_2 \sim 0.4$. The motivation of the present work is to understand the nuclear shapes and nuclear phenomena at high spin and excitation energy in ^{75}Kr. Preliminary results of the present investigations are shown here.

High spins states of ^{75} Kr nucleus have been populated via the ^{50}Cr (^{28}Si, 2pn) ^{75}Kr reaction at an incident beam energy of 90 MeV. The ^{28}Si beam was delivered by the 15-UD Pelletron accelerator at Inter University Accelerator Centre (IUAC), New Delhi. The de-exciting γ- rays were detected utilizing the Indian National Gamma Array (INGA) [2] which at the time of the experiment comprised of 17 Compton suppressed Clover detectors. The target consisted of ~ 650 μg/cm^2 isotopically enriched ^{50}Cr on a gold of a 12 mg/cm^2 support. The data were collected in the list mode using the CAMAC-based MULTI-CRATE synchronization mode coupled with PC-LINUX environment. The energy and timing information from the clover detectors were processed using the indigenously developed (at IUAC) Clover modules and ADC's.

Initially, the excitation function was measured at various beam energies of 90-100 MeV. The 90 MeV beam energy was found to be optimum energy for the production of ^{75} Kr. A total of about 900 million two or higher fold coincidences were recorded. The data were analyzed off-line using the analysis programs CANDLE, INGASORT, DAMM and LINESHAPE. The coincidence events were sorted into the conventional $\gamma - \gamma$ symmetric as well as asymmetric matrices. The 4K ⊗ 4K matrices had an energy dispersion of 0.5 KeV/channel.

In the present experiment the lifetimes of the levels of 75Kr up to $33/2^+$ for positive parity and $27/2^-$ for negative parity bands have been measured using Doppler shift attenuation method. Lifetimes of levels were obtained from the analysis of line shapes in the detectors at 32 and 148 degree. Line shapes of the transition obtained were fitted with the program LINESHAPE developed by Wells et al. [3]. The observed lineshapes were obtained by gating below the transition of interest. Figure 1 shows the observed lineshapes and their simulated lineshapes for the 824 and 896 KeV transitions, in the positive parity band.

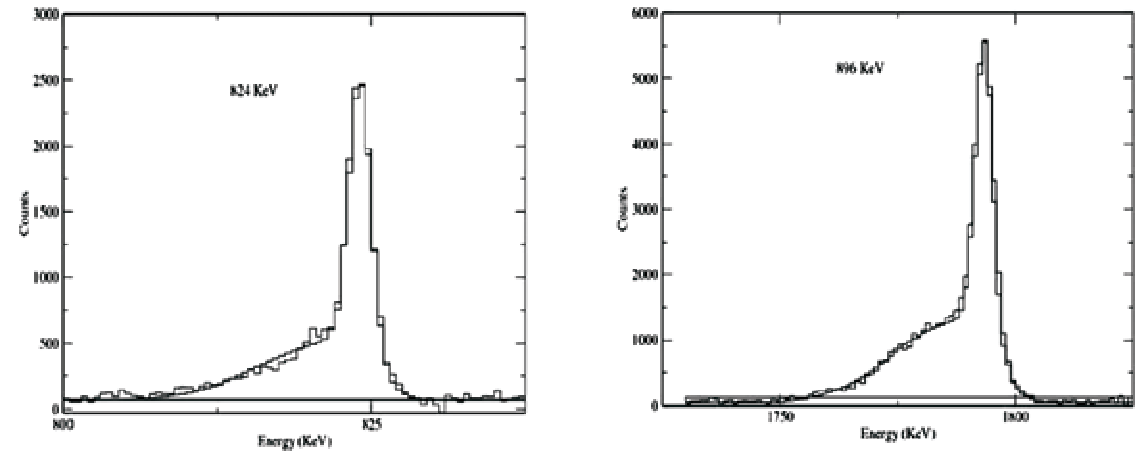

Fig. 1. Experimental and theoretical lineshapes for 824 KeV and 896 KeV transitions in the positive parity band of ^{75}Kr at θ =148^0

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5.1.5 High-Spin excitations in ^{99}Pd

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Transitional nuclei with Z < 50 and A ≈100 are characterized by a small quadrupole deformation and a gamma-soft potential at low and moderate angular momenta. The level structure of these nuclei provides an opportunity to investigate how single-particle motion coherently develops into collective effects, as nucleons are added to the closed shell. In recent years, various new interesting deformation generating mechanisms in spherical nuclei have been identified in theoretical interpretation of observed band structures in these nuclei [1]. The structure of these nuclei is characterized by valence hole-like protons in the high-Ω $g_{9/2}$ orbital below the Z ~ 50 gap and valence particle-like neutrons in the low-Ω $d_{5/2}$, $g_{7/2}$, $h_{11/2}$

orbitals above the N=50 gap. The simultaneous occupation of the $g_{9/2}$ proton holes and $h_{11/2}$ neutron particles could result in the observation of intriguing phenomenon such as magnetic, antimagnetic rotation and chiral structures. The ^{99}Pd (N=53 and Z=46) nucleus provides an opportunity of observing effects due to the presence of few neutrons above the closed N=50 closed shell. The low-lying levels of ^{99}Pd have been investigated from EC-β^+ decay of ^{99}Ag by Huyse *et al* [2]. Investigation via ^{96}Ru (α, p3n) and ^{96}Ru (^{6}Li, p2n) reactions has been performed by Dubuc *et al* [3]. Limited level scheme upto ~ 4 MeV excitation energy and $27/2^+$ spin was reported from this work. Two bands, built on the $\pi g_{7/2}$ and $\pi d_{5/2}$ single particle configurations, could be identified.

High spin states in ^{99}Pd nucleus were populated in fusion-evaporation reaction ^{75}As (^{28}Si, p3n) at E_{lab}= 120 MeV, and have been investigated through in-beam gamma-ray spectroscopic techniques. The ^{28}Si beam was delivered by the 15UD Pelletron accelerator at Inter University Accelerator Centre (IUAC), New Delhi. The ^{75}As target of thickness 3 mg/cm^2 rolled onto a 10 mg/cm^2 thick Pb backing was prepared by vacuum evaporation followed by rolling. The recoiling nuclei were stopped within target. The de-exciting γ-rays were detected using the Indian National Gamma Array-2008 equipped with 18 clover detectors mounted in five rings configuration [4]. This array has total photopeak efficiency of ~4%. The gamma-ray energy and efficiency calibration of clover detectors were performed using the ^{133}Ba and ^{152}Eu radioactive sources. A total of about 300 million triple or higher-fold coincidence events were recorded in the experiment. The data were sorted offline using INGASORT program [5] to produce symmetrised E_γ-E_γ matrices and E_γ-E_γ-E_γ cubes. RADWARE analysis package [6] was used to establish coincidence relationships and intensity for various gamma transitions. From the γ-γ coincidence data, the intensity, directional correlation of oriented states (DCO) ratio, and polarization asymmetry of different transitions were extracted and used for establishing the level scheme of ^{99}Pd. The partial level scheme of ^{99}Pd developed in the present work is shown in Fig. 1.

The level scheme of ^{99}Pd from the present work (fig. 1) is built on the ground state $I^\pi = 5/2^+$ and six bands labeled B1-B6 could be identified. The level scheme from the present work, established up to 9 MeV excitation energy and $49/2^+$ spin, has been significantly extended with addition of about 55 new transitions to those reported in the earlier work by Dubuc *et al [3].* The bands labeled B3, B4, B5 and B6 are being reported for the first time. The present level scheme preserves major features of the previous level scheme. The previously observed bands B1 and B2, have been assigned to be based on $\pi g_{7/2}$ and $\pi d_{5/2}$, respectively. The new band B6, with$11/2^-$ state at 2017 keV as bandhead, is based on $h_{11/2}$ orbital. It exhibits higher initial alignment ~6$\hbar$. The band B5 is due to γ vibration of the core coupled to the $\nu\pi g_{7/2}$ single particle configuration. The $9/2^+$ level at 1102 keV is possibly based on the $\nu g_{9/2}$. The excitation energy plots of the bands B1 and B2, and bands B3 and B4 exhibit similar trend and appear to be in continuation. It indicates that the shape-driving orbital in bands B3 and B4 are the same. The bands B3 and B4 are in continuation to the $\pi g_{7/2}$ band and exhibit large alignment gain ~6$\hbar$. Observation of low energy 431 ($49/2^+ \rightarrow 45/2^+$) transition at state is indicative of the

49/2$\hbar$ maximally aligned spin state with configuration as $(\pi g_{9/2})^{2n} \otimes \nu(g_{7/2})^{m} \otimes \nu(g_{7/2})^{k} \otimes \nu(d_{5/2})^{s}$. Various other states have been identified with configurations as variants of this configuration. As the $h_{11/2}$ and $d_{5/2}$ orbitals with $\Delta l = 3$ are near the Fermi surface, octupole collectivity is likely to be enhanced in this region. Signatures of octupole collectivity have been observed in Cs isotopes like ^{122}Cs and ^{141,143}Cs and also in the neighboring Xe and Ba isotopes, where the $\pi h_{11/2}$ and $\pi d_{5/2}$ orbitals play an important role. The signature for such effects are interleaved positive and negative-parity bands connected by enhanced $E1$ transitions. Such E1 transitions between the levels of $\nu h_{11/2}$ band (B6) to $\nu d_{5/2}$ band (B2) have been observed in the present work. This is because both neutron levels, arising from the same $h_{11/2}$ and $d_{5/2}$ orbitals ($\pi = -1$, $\Delta l = \Delta j = 3$), are near the Fermi surface. Nevertheless, the presence of these $E1$ transitions competing with highly collective $E2$ transitions is already a sign of large $B(E1)$ values.

The authors thank the collaboration of IUAC, New Delhi; TIFR, Mumbai; and IUAC-DAE-CSR and SINP, Kolkata, for establishing of INGA-2008. Financial support from UGC, New Delhi, under the Centre of Advanced Study Funds is duly acknowledged.

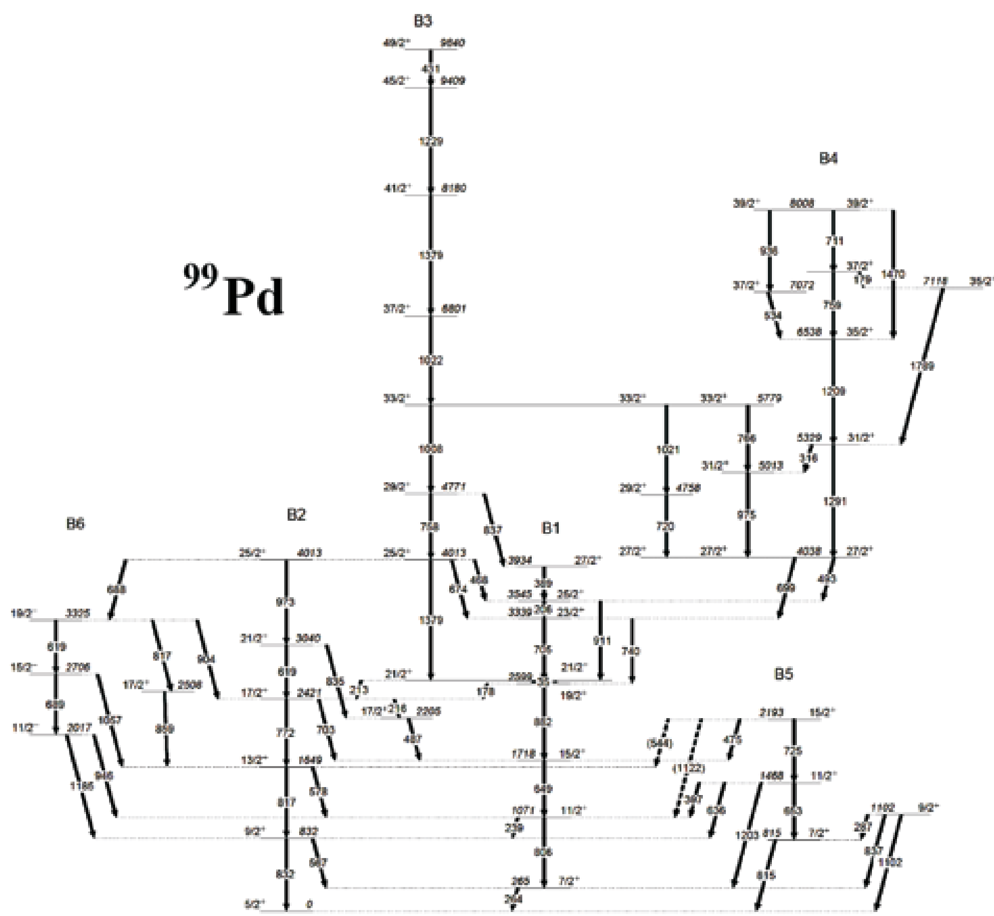

Fig. 1. Level scheme of ^{99}Pd

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5.1.6 High spin structure of ^{110}Ag and search for anti-magnetic rotation in ^{110}Cd

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Neutron rich nuclei in mass-100 region show an interesting interplay between tilted axis rotation (TAR) and principal axis rotation (PAR). It is due to the neutron(s) occupation in deformation driving low Ω orbital of $h_{11/2}$ and proton(s) in high Ω orbital of $g_{9/2}$. Such configurations open up the possibility of both TAR and PAR for these isotopes to generate angular momentum. As a result, interplay between TAR and PAR becomes possible and such interplay has already been identified in Ag isotopes. It has been observed that the lower spin states of the negative parity ground state band in odd-odd Ag isotopes ($^{104-108}$Ag) exhibit anomalous signature which vanishes beyond $I^{\pi}=13^{-}$. In ^{104}Ag this feature has been attributed to the alignment of two neutrons in $g_{7/2}$ orbital and this aligned band has been reported as M1 band [1]. It is interesting to investigate these Ag isotopes with increasing neutron number to address the question: whether TAR remains the favourable mode of excitation in heavier Ag isotopes or not?

The ^{110}Cd has been studied to look for a possible presence of AMR along the positive parity ground state band. It is interesting to note that only two such AMR bands have been reported till date and both of them were identified in ^{106}Cd and ^{108}Cd [2, 3]. Thus, it is important to search for AMR band in neighbouring Cd isotopes such as ^{110}Cd.

The high spin states of ^{110}Ag and ^{110}Cd were populated through the reaction ^{96}Zr (^{18}O, *xnypγ*) ^{110}Ag, ^{110}Cd using ^{18}O at 68 MeV at IUAC Pelletron, New Delhi. The gamma rays were detected with 18 Compton suppressed Clover detectors placed at five rings namely, 32^{o}, 57°, 90°, 123° and 148° [4]. A total of 1.2 billion triples or higher fold events were collected. The reaction cross-section ^{110}Ag is ~20 mb (only ~2 % of the total fusion evaporation cross section) which turns out to be 24 million 3-fold data. Data were sorted into γ-γ-γ and γ-γ matrices using Ingasort [5] and Radware package [6]. In addition to the symmetrised γ-γ matrix, the angle dependent matrices were build to carry out lineshape analysis to measure the level lifetime.

In a previous attempt, the high spin structure of ^{110}Ag was studied through fission induced spectroscopy. Thus, this is the first observation of high spin states of ^{110}Ag through fusion evaporation technique. The partial level scheme of ^{110}Ag is shown in fig.1 where the yrast band has been established upto $I^{\pi}=19^{-}$. The observed energy difference (E_I-E_{I-1}) in ^{110}Ag has been plotted in fig.2 as a function of level spin. It is apparent that there is a stark difference in the excitation mechanism in ^{110}Ag with respect to the other odd-odd Ag shown in fig.2. In ^{110}Ag, normal signature splitting appears at high spin followed by a signature inversion at clear presence of signature splitting at $I^{\pi}=13^{-}$. Similar signature inversion in odd-odd nuclei has been observed in number of nuclei ^{84}Y, ^{98}Rh, ^{154}Tb, and has been successfully described by Particle Rotor Model (PRM). These preliminary observations indicate that PAR outset TAR in ^{110}Ag [7]. It is well supported by the Total Routhian Surface (TRS) calculation which shows that the aligned configuration in ^{110}Ag is substantially deformed with respect to lighter odd-odd Ag isotopes.

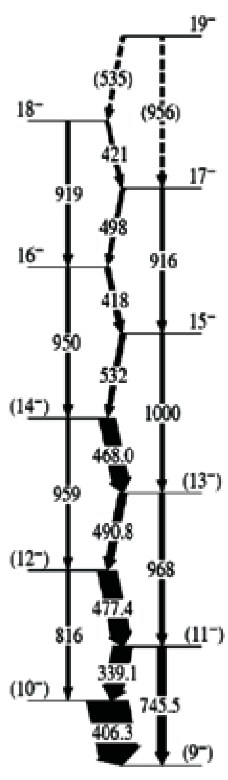

Fig.1 Partial Level scheme of the (-) ve parity ground state of ^{110}Ag

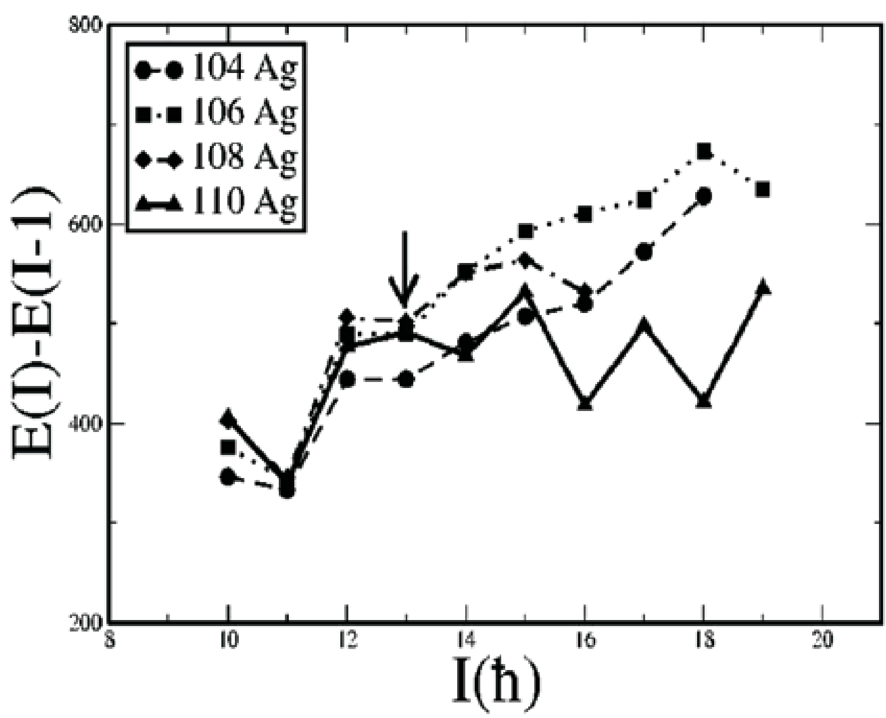

Fig.2. Energy difference (keV) vs. Spin (I) for the ground state band of ^{104,106,108,110}Ag

The ground state band of ^{110}Cd was established upto $I^\pi=28^+$ in the previous work which is found to be in good agreement with the present result. In ^{110}Cd, the neutron alignment takes place at $I^\pi = 10^+$ ($\omega \sim 0.35$) giving rise to the expected double Shears structure as observed in other two Cd isotopes mentioned above. However, the high spin behaviour of ^{110}Cd differs significantly with respect to ^{106}Cd and ^{108}Cd. In ^{110}Cd, an upbend in the aligned angular momentum beyond $I^\pi = 20^+$ ($\omega \sim 0.65$) has been noted while it remain almost constant in other two Cd isotopes [8]. It has been proposed that this behaviour may be attributed to the alignment of two more neutrons in $h_{11/2}$. Thus, it seems that angular momentum generation mechanism in the frequency domain of 0.60 to 0.75 MeV is different from than that of ^{106}Cd and ^{108}Cd. It is interesting to note that the experimentally measured B(E2) rates (through lifetime measurement) [8] indicates a falling behaviour and matches well with the theoretical calculation based on a semi-classical model assuming Shears mechanism. However, it is difficult to address both alignment behaviour and B(E2) rates through this model at same footing. An alternate description based on the band termination may also be considered to explain the observed features.

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5.1.7 Spectroscopy of Magnetic Bands in and around Z ~ 64 and N ~ 82 Shell Closures

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The first experimental evidence for sequences of strongly enhanced magnetic dipole (M1) transitions that follow a rotational I(I+1) dependence was found in Pb isotopes [1] [2]. These bands exhibited characteristics such as (a) strong M1 transitions (b) extremely weak E2 cross-over transitions (c) decreasing B(M1) strength. These bands originate when the symmetry of the nuclear system is broken by current distributions of few high-spin particles and holes outside a spherical or nearly spherical core. While substantial information on MR bands exist in Pb region, limited data is available on such phenomena in and around N ~ 82 and Z ~ 64, where the occurrence of $h_{11/2}$ neutron-hole and $h_{11/2}$, $g_{7/2}$ proton-particles favour magnetic bands in this region. Such investigations can give information on the core-polarisability effects and the influence of oblate and prolate deformation on magnetic rotation. Data on lifetimes are necessary to elucidate the underlying microscopic configurations, since multi-particle hole excitations in these nuclei could also present similar energy level systematics.

In nuclei with Z ~ 64 and N ~ 82, $\Delta J = 1$ magnetic sequences have been reported in ^{142,143}Gd, ^{141}Eu etc. Lifetime measurements have been performed for ^{142}Gd. However lifetime measurements in this region are limited and warrant further detailed investigation. Of particular interest is the M1 band from $J = 23^+$ to $J = 30^+$ in ^{146}Tb observed in our earlier INGA campaign which follows the angular momentum dependence expected from a magnetic-rotation mechanism [3].

The reaction ^{34}S+^{115}In was performed at beam energy of 140 MeV and the de-exciting gamma rays were detected by the INGA clover array [4] which had 18 clover detectors, 4 at 148^0, 4 at 123^0, 6 at 90^0 and 4 at 57^0. Conventional DSAM techniques were used to undertake lifetime measurements for the known magnetic sequences in the Z ~ 64 and N ~ 82 regions. The target was enriched ^{115}In 1.20mg/cm^2 thick with a gold backing of thickness 9.46mg/cm^2. ^{145,146}Tb, ^{145}Gd etc have been strongly populated in the reaction. Fig.1 shows a portion of 950 keV gated spectrum in ^{146}Tb. Several transitions of the M1 band of interest ($J = 23^+$ to $J = 30^+$) are visible in this part of the spectrum, viz. 413, 429, 465, 477 and 486 keV. As seen from the spectrum, 465 and 477 keV lines seem broadened compared to 409 and 526 keV that do not belong to the M1 band. This indicates the possibility of extracting the corresponding level lifetimes and the analysis is under progress. Asymmetric matrices with forward or backward detectors are being formed which will reveal the Doppler effects more clearly.

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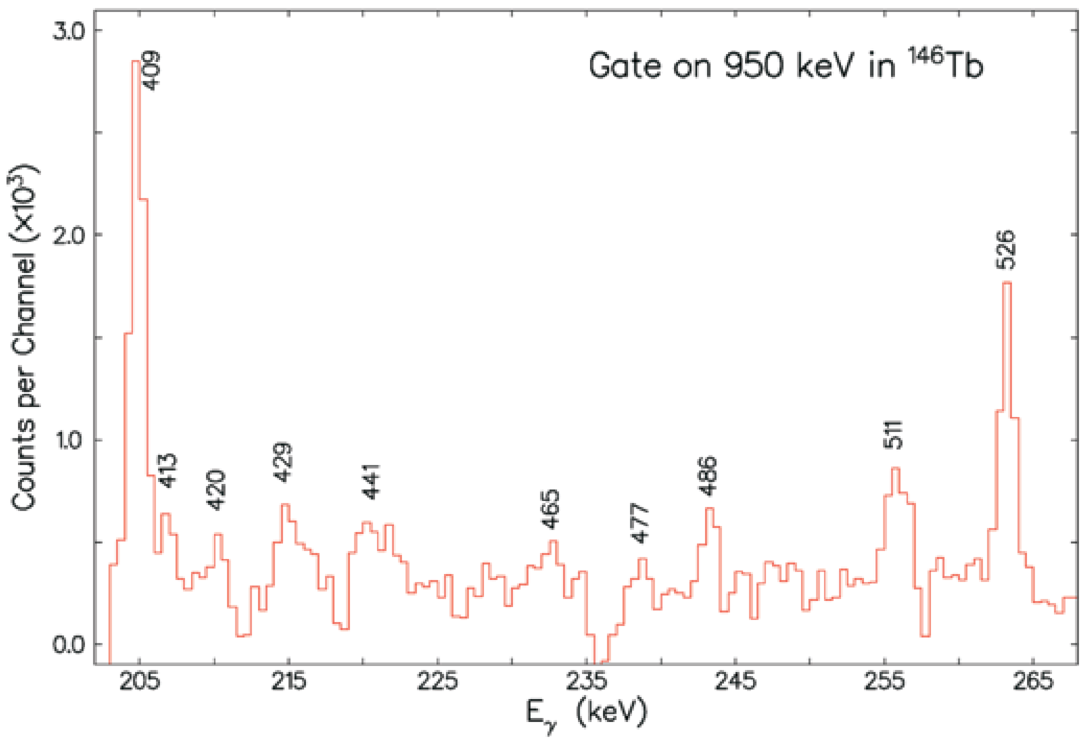

Fig. 1. Gate on 950 keV in ^{146}Tb

5.1.8 Investigation of High spin Structure of ^{112}In to Search for Multiple Chiral Bands

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Nuclei in the A ~ 110 region exhibit many exciting features involving regular band structures arising from the occupancy of the valance protons and neutrons in $g_{9/2}$ and $h_{11/2}$ orbitals, respectively. Such high-j orbitals are now well known for generation of rotation like sequences of M1 transitions called shears bands [1]. Another interesting aspect of nuclei in this mass region is the appearance of $\Delta I = 1$ doublet bands. These doublet bands have same parity and their levels with same spin are nearly degenerate in energy. On theoretical side, initially Tilted Axis Cranking (TAC) model gave the interpretation of chiral structures for these doublet bands built on the high-j orbitals of neutrons and protons [1]. In these pictures, the bands arise in nuclei having triaxial deformation leading to left- and right-handed systems, which differ by intrinsic chirality. When the chiral symmetry is broken in the intrinsic frame, its restoration in the laboratory frame is reflected in degenerate I = 1 bands from the doubling of states. Recent calculations using adiabatic and configuration-fixed constrained triaxial RMF approch show that the A~105 mass region may exhibit new phenomenon known as Multiple Chiral Doublets [2]. The above approach was applied to Rh, Ag and In isotopes. It is predicted that ^{112}In is one of the favorable examples which may have Multiple Chiral Doublet. To search for the multiple chiral bands, the decay properties of the excited states at high spin were investigated in an experiment with the present INGA array at IUAC, New Delhi.

The high spin states of ^{112}In were populated using ^{100}Mo(^{16}O,p3n) reaction at 80 MeV beam energy. The target consisted of isotopically enriched ^{100}Mo foil of 2.8 mg/cm^2 thickness rolled onto a 12 mg/cm^2 Pb backing. The master trigger for collecting the coincidence data was generated when atleast three Clover detectors fired in coincidence without any signal in their respective BGO anti-compton shields. This master trigger rate was kept around 3.5 kHz. Around 4×10^8 triple gamma coincidence events were sorted into a cube. Previously, only few excited states of ^{112}In were identified through ^{112}Cd(d,2n) and ^{110}Pd(^{6}Li,4n) reactions including low-lying isomers at 351 and 614 keV excitations with $T_{1/2}$ = 690 nsec and 2810 nsec, respectively [3]. Only 186.9 and 588.3 keV transitions have been placed above the 614 keV level in the previous work. The gamma spectrum obtained with simultaneous gate on 186.9 and 588.3 keV transitions is depicted in Fig. 1. Based on the intensity and DCO measurements, several new transitions (as marked in Fig 1) are arranged to extend the band structures up to spin $I=17\hbar$. Similarly, 319 keV transition was feeding the 7^+ isomer of ^{112}In in the previous work. New level structure has been extended up to $20\hbar$ in the positive parity band based on the 319 keV gated coincident spectrum.

The negative parity band has been compared with that of ^{110}In and ^{114}In isotopes [4] and prediction of the microscopic structures based on Projected Hartree-Fock (PHF) Model [5] in Fig. 2. The negative parity bands in these odd-odd nuclei have a similar behavior and the 2-quasiparticle configuration based on $\pi g_{9/2}$ and $\nu h_{11/2}$ give a reasonable description. Further analysis of the present experimental data is in progress to search for the multiple chiral bands in this nucleus.

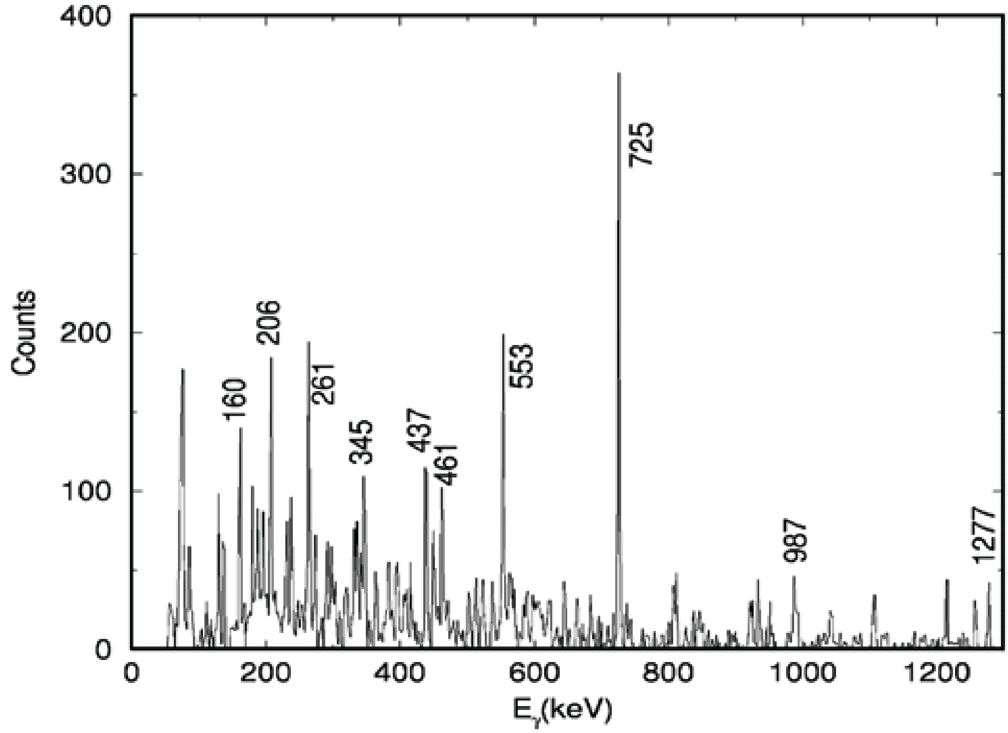

Fig. 1. The double gated (186.9 and 588.3 keV) spectrum of ^{112}In obtained in the present work

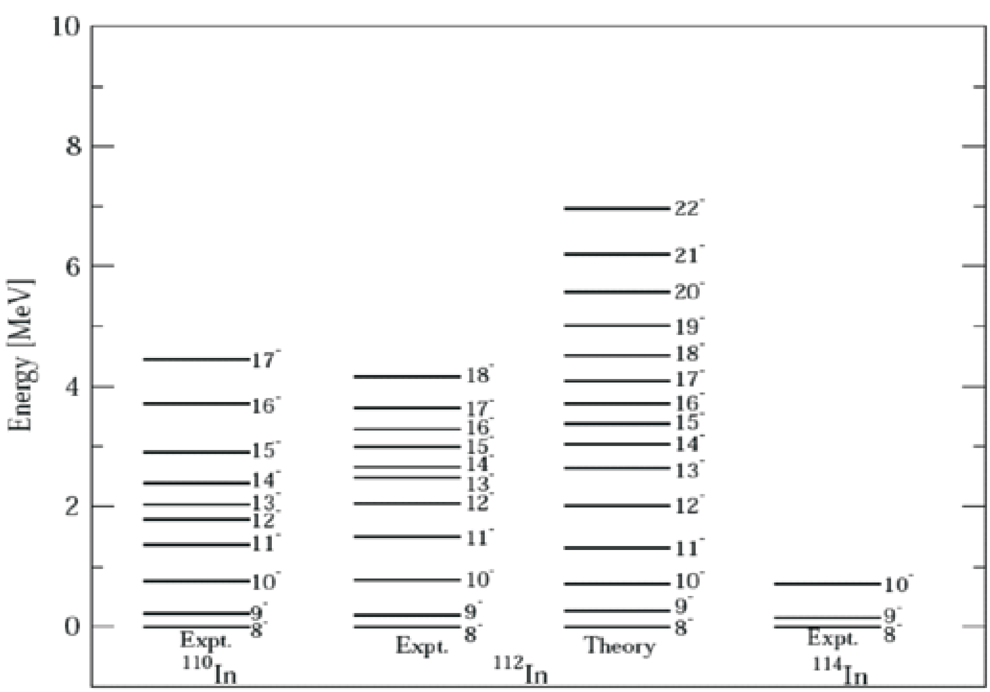

Fig. 2. Comparison of experimental negative parity bands in ^{110,112,114}In and PHF calculation

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5.1.9 Investigation of Positive Parity Degenerate Dipole Bands in ^{133}Ce

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The nuclei in the mass A~130 region show various intriguing phenomena. For these nuclei the proton Fermi surface lies low within the $h_{11/2}$ orbitals driving the nucleus to prolate shape, while the neutron Fermi surface lies near the middle of $h_{11/2}$ orbitals favouring an oblate shape [1]. Due to the opposite types of quadrupole deformations for proton and neutron mass distributions these nuclei develop shape instability. Depending upon the coupling of the angular momenta of valance neutrons and protons with that of the even-even core different types of excitations, namely, magnetic rotation, chiral twin bands and recently chopstick configurations are discussed in this region [2–4]. The twin degenerate dipole bands with similar energy staggering and electromagnetic strengths were explained with aplanar tilted rotation of the triaxial core along with the valence neutrons and protons aligned along the two extreme axes of the core. Recently, a truncated shell model calculation prescribes another angular momentum coupling scheme, namely the chop stick model, which predicts a series of degenerate dipole band structure in nuclei around A~130 region. A pair of dipole bands B2 and B3 have been identified with same parity in ^{133}Ce in our previous work [5]. To study the decay properties of these bands and measure their electromagnetic transition strengths, an experiment was carried out with the present INGA array at IUAC, New Delhi, to collect high statistics and high fold γ–coincidence data.

High spin states of ^{133}Ce were populated with $^{18}O + ^{120}Sn$ reaction at 87 MeV beam energy. The target consisted of isotopically enriched ^{120}Sn foil of 1.8 mg/cm^2 thickness rolled onto a 12 mg/cm^2 Au backing. The master trigger for collecting the coincidence data was generated when atleast three Clover detectors fired in coincidence without any signal in their respective BGO anti-compton shields. Around 5×10^8 triple gamma coincidence events were sorted into a cube. The transitions appearing in the coincidence for B2 and B3 bands are shown in double gated gamma spectra in Fig. 1.

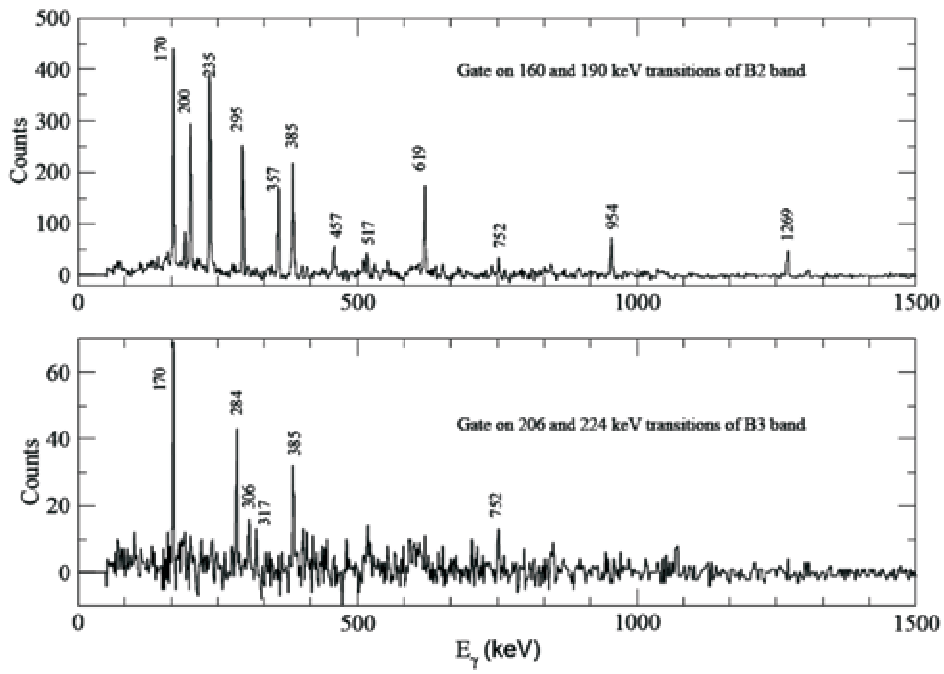

Fig. 1. The double gated spectra of ^{133}Ce obtained in the present work

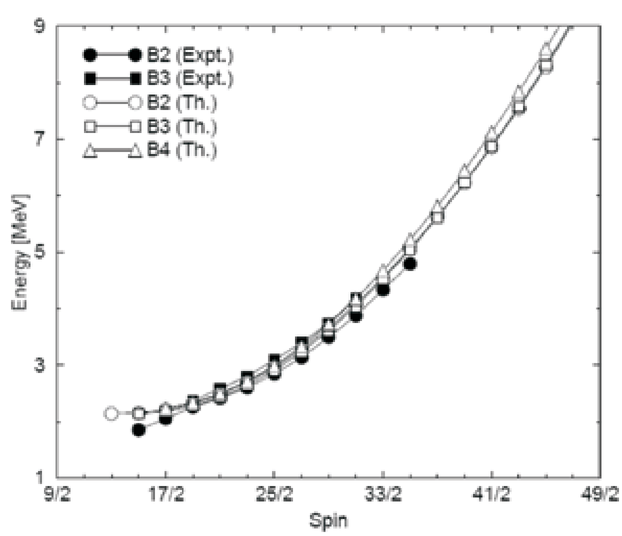

Fig. 2. Comparison of theoretical and experimental positive parity degenerated dipoles bands

The microscopic structures of these two positive parity dipoles bands have been analyzed with Projected Hartree-Fock (PHF) Model [6]. In the calculation these bands are obtained by occupying the odd neutron to $h_{11/2}$ orbitals and odd protons to $g_{7/2}$ and $h_{11/2}$ orbitals (3-quasiparticle configuration). In HF iteration, proton orbits, $\Omega = 1/2^-$ to $5/2^-$, originated mainly from $h_{11/2}$, are within 162 keV energy different just above the proton Fermi surface. By exciting the valance proton to these orbits we have obtained three nearly degenerated bands with K= $13/2^+$, $15/2^+$ and $17/2^+$. The calculated excitation energies of $J^\pi = 21/2^+$ states of all the bands are 2.484, 2.436 and 2.498 MeV showing considerable degeneracy among these bands. Comparisons of theoretical and experimental spectra are shown in Fig. 2.

Analysis of the present experimental data is going on. It will be interesting to verify the predictions of the nearly degenerate dipole bands on the basis of PHF calculations from the collected high fold gamma coincidence data.

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5.1.10 Lifetime Measurements of Excited States of ^{124}Ba and ^{123}Cs Using DSAM Technique

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Transitional nuclei between spherical and strongly deformed regions of the nuclear chart are usually soft with respect to deformation changes. Shape changes, including triaxiality, can be induced by the excitation of nucleons into specific deformation-driving orbitals. In the mass region around A = 125, both protons and neutrons can occupy the unique-parity $h_{11/2}$ intruder orbitals which play an important role in driving the nuclear shape. The proton Fermi surface lies in the lower part of the $h_{11/2}$ subshell, which favors prolate shape, whereas the neutron Fermi surface lies in the middle or upper part of the $h_{11/2}$ subshell, which favors oblate shape. Thus, a coexistence of different shapes is expected in these nuclei because of opposite shape-driving forces of protons and neutrons in $h_{11/2}$ orbitals. Total routhian surface (TRS) calculations show that the alignment of protons and neutrons drives the nuclei towards triaxiality with different values of γ[1,2]. Small positive values around $\gamma \approx 0°$ are favored after the proton alignment whereas negative γ values, around γ = -30°, are preferred due to the neutron alignment.

Low energy excitations in these nuclei are dominated by collective rotation with moderate deformation. However, it has been found that the rotational bands lose collectivity at higher spin, and single-particle alignments are favored as an efficient way to generate angular momentum. The band terminates when all the single-particle angular momenta involved are aligned along the rotation axis. Higher-spin states can then be generated only by breaking the core. These features have been recently observed in Xe[3], Cs[4], and Ba[5] isotopes. Lifetime measurement of noncollective states observed at high spin in ^{124}Ba and ^{123}Cs nucleus can verify the phenomenon of collective to noncollective transition observed in this mass region.

The excited states of ^{124}Ba and ^{123}Cs nucleus were populated using the reaction ^{96}Zr(^{32}S, 4n)^{124}Ba and ^{96}Zr(^{32}S, p4n) ^{123}Cs. The ^{32}S beam with an energy of 140 MeV was provided by the 15UD Pelletron accelerator at IUAC(New Delhi). The target used was 1mg/cm^2 enriched ^{96}Zr deposited on 10mg/cm^2 lead backing. Gamma ray coincidence events were measured with the Indian National Gamma Array (INGA) spectrometer which consisted of Eighteen Compton suppressed Clover detectors. The data were acquired with a condition of Ge-fold coincidence$\geq$3 using CANDLE, an acquisition system developed at IUAC. In order to analyze the experimental data, the entire list mode data were first calibrated using Eu source, and then sorted into 4k×4k matrices using the software INGASORT. One-dimensional spectra were extracted from these matrices for the "LINESHAPE" analysis. The figure shows a couple of representative spectra showing experimental shapes obtained from the present experiment.

The detailed line shape analysis is in progress.

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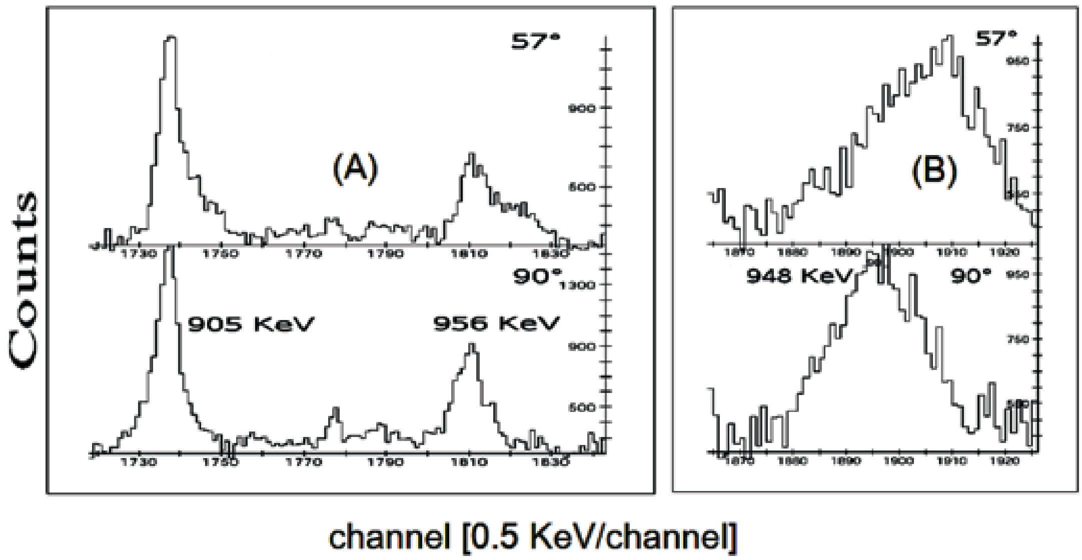

Fig.1. Experimental shape of (A) 905 KeV and 956 KeV transitions of ^{123}Cs, and (B) 948 KeV transition of ^{124}Ba as seen in spectra of forward(57°) and 90° detectors. The spectrum of 90° detector shows the position of unshifted peak

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5.1.11 Spectroscopy of N~Z, A = 25-30, Nuclei

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The modifications of the well established shell-closures as one approaches the proton and neutron drip lines has been the focus of several investigations in the recent past. Ozawa et.al [1] observed an enhancement of magicity with decreasing proton number for N=16 isotones. These isotones lie between the valley of stability and the neutron drip line and belong to a highly transient region for nuclear structure. The effective single particle energies and their relative ordering vary with distance from the valley of stability, resulting in sub-shell gaps that are different from those for stable nuclei. For N~16 isotones, the level structure is expected to be dominated by $1d_{5/2}$ and $2s_{1/2}$ orbitals. These orbitals are in close proximity and are well separated from the $1d_{3/2}$ orbital. Small localized changes in the $1d_{5/2}$ -$2s_{1/2}$ splitting can dramatically alter the properties of even the low-lying states in these nuclei. Hence it is important to investigate systematically the level structure of N ~ Z nuclei in and around N ~ 16. Further, the competition between the iso-vector (T = 1) and iso-scalar (T = 0) proton-neutron (p-n) correlations in N = Z nuclei can be investigated sensitively from the observed level structure of N ~ Z nuclei in the A ~ 30 region as the two are comparable in this region.

We have attempted to study these nuclei utilizing the fusion-evaporation reaction ^{16}O +^{18}O @ 34 MeV using the INGA array at IUAC, New Delhi. The array had 18 clovers with 3 at 148^0, 3 at 123^0, 5 at 90^0, 4 at 57^0 and 3 at 32^0 . The target was Tantalum Oxide (Ta_2O_5) with 50mg/cm^2 of Ta and 1.6mg/cm^2 of ^{18}O thickness. The Master Gate was taken from the OR of two-fold and three-fold triggers. The accepted rate was ~ 3 KHz. The beam current varied between 20 and 30 nA. Preliminary data analysis indicates ^{30}P, ^{32}P, ^{32}S, ^{29}Si etc to be the strongly populated nuclei. Several new gamma transitions were found in these nuclei and are being placed in the level schemes. Fig. 1. shows a representative gated spectrum where the gate is on 78 keV transition to the ground state of ^{32}P. The new assigned γ-rays are marked with a star. The data are being analyzed using IUCSORT and RADWARE programs. The use of clover detectors has facilitated angular correlation and linear polarization measurements which together will be crucial for unique spin-parity determination. Large basis shell model calculations are in progress to understand the underlying nuclear structure.

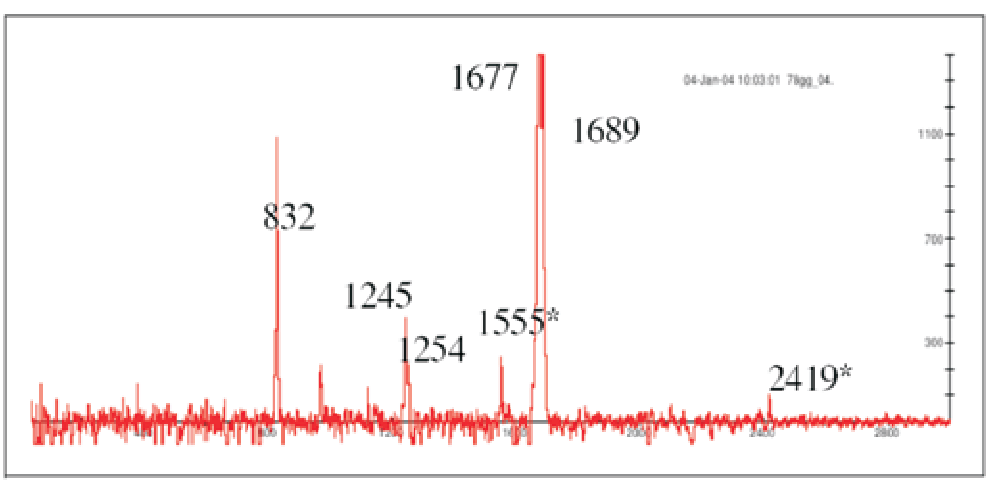

Fig. 1. 78 keV gated spectrum in ^{32}P nuclei.

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5.1.12 Investigation of high spin states and isomer decay in doubly odd ^{208}Fr

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Nuclear structure of the excited states of neutron deficient Francium (Fr) and other trans-Lead nuclei have attracted attention in recent times[1,2]. Use of highly effective recoil tagging devices and also the large Germanium Clover detector array with sufficient resolving power have made such studies possible. Though the high spin states and isomeric decay of a few odd-*A* nuclei have been studied in recent times[1], there is almost no data on the doubly odd isotopes ^{208,210}Fr, except for isomeric decay of only two low-lying transitions of ^{208}Fr produced via projectile fragmentation reaction: ^{238}U(^{9}Be,X) at 900 MeV/u bombarding energy [2]. However, a detailed study of the high spin states of ^{212}Fr has already been done [3]. High spin states of these nuclei are interpreted as single particle configurations arising from the $(1h_{9/2},2f_{7/2},1i_{13/2})$ protons and $(3p_{1/2},2f_{5/2},3p_{3/2},1i_{13/2})$ neutrons. One of the major interests in the spectroscopic investigation of these nuclei is the role played by the $i_{13/2}$ state in creating isomeric levels which decay through transitions of higher multipolarity, or are hindered by the close proximity of levels below. A systematic study of these nuclei will reveal many other interesting features like the interplay of the single particle and the collective degrees of freedom in generating high angular momenta, collectivity, if any, in these nuclei at higher spins, and possibly many more.

The experiment to produce ^{208}Fr was carried out at the Inter-University Accelerator Centre (IUAC), New Delhi. The evaporation Fr isotopes were produced by bombarding a 3.5 mg/cm^2 self-supporting Gold (99.95% purity) target with ^{16}O beam at 88, 94 and 100 MeV. The gamma-rays produced were detected by the Indian National Gamma Array (INGA) consisting of 18 Compton suppressed Clover detectors placed around the target centre [4] at the INGA-HYRA beam line. Altogether 3.2×10^{8} two-fold and 4.8×10^{7} three-fold coincidences were recorded in ~50 hours at 100 MeV beam energy, and ~20% of the above numbers were recorded at 88 and 94 MeV. The data were collected using the CANDLE data acquisition system [5], and were analyzed off-line using both CANDLE and INGASORT [6] analysis software. A representative gated spectrum of the Fr isotopes is shown in the Fig.1. All the assignments of gamma transitions to Fr isotopes were validated by x-ray gating on all the Fr K_α and K_β lines.

One of the major challenge in this experiment is that the same pair of low lying transitions at 194 keV and 632 keV were observed and assigned to both ^{209}Fr[1] and ^{208}Fr[2]. While the former measurement was done using fusion-evaporation reaction and a gas filled recoil analyser, the later one had made extensive use of the FRS at GSI, Germany, coupled with energy loss measurement by ionization chamber to achieve clean isotope separation for the trans-lead nuclei. In order to resolve the problem, we have done 1) excitation function study at the 3 bombarding energies, 2) beam-off yield and decay half lives measurement, and 3) gated time difference analysis to obtain the isomers and measure their half lives.

Based on our analysis of excitation function data and the off-beam yield and decay half lives measurements [7], which are found to be mutually consistent and agree with the PACE calculations, we can conclude that both the 194 keV and 632 keV transitions belong to ^{208}Fr. A time difference spectrum, obtained from the TDC data, gated by the coincident transitions from above and below the isomer level, is shown in the Fig. 2. Half life of the 194 keV isomeric transition, obtained from the fitted curve, is (213 ± 16) ns, while the measured half life of the 194 keV isomeric transition, assigned to ^{209}Fr was (446 ± 14) ns [1]. The half life obtained from our data is consistent with the estimated half life of ~ 200 ns for the 194 keV isomeric transition in ^{208}Fr obtained from the projectile fragmentation data [2]. This result points to the fact that the 194 keV and 632 keV transitions belong to ^{208}Fr, which is consistent with our conclusions based on the other methods of analysis mentioned above. Detailed analysis for the complete level scheme of ^{208}Fr is in progress.

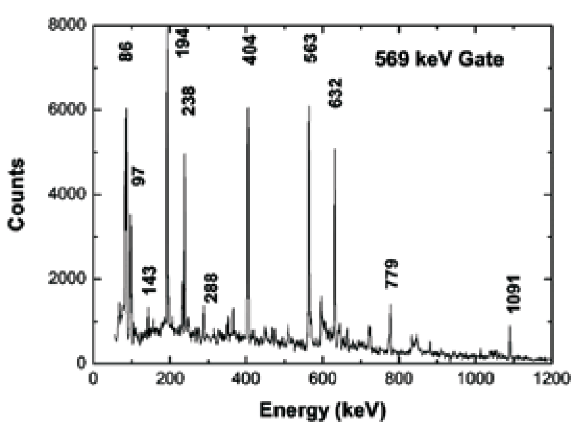

Fig.1. The 569 keV gated spectra

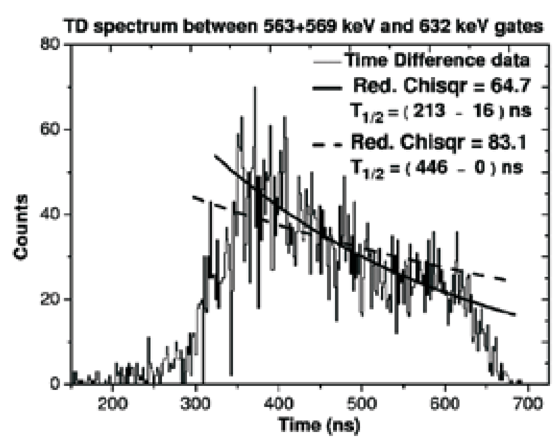

Fig.2. Time difference spectrum and the fitted curve for extracting half life

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5.1.13 Low-spin structure of ^{239}Np nucleus populated in incomplete fusion reaction

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In-beam gamma spectroscopy of trans-uranium nuclei is a challenging task due to practical difficulty in production of these nuclei and presence of large background due to fission fragments. In heavy mass region fusion-evaporation cross section is very small compared to that of fission yields. Due to this reason, to study heavier nuclei alternate mechanism were needed to populate the excited states in heavy actinide nuclei beyond the Th-U region. Level structure of a few nuclei in this region of *chart of nuclides* were studied using non-conventional mechanisms such as (1) unsafe coulomb excitation, (2) multi-nucleon transfer reactions and (3) deep-inelastic process. In all these methods require higher energies and heavier beams that are not available at present in India.

In the present work, a different mechanism *in-complete fusion* is used to populate Np-239 nuclei using 50 MeV ^{7}Li beam on Uranium target. From the systematics of incomplete fusion reactions involving weakly bound ^{9}Be and ^{6,7}Li beams it is evident that two-neutron evaporation followed by incomplete fusion provide cross sections that can be enough to perform in-beam gamma-spectroscopy of the heavy nuclei, however charged particle detector array could provide better channel selection mechanism.

Neptunium-239 nuclei were populated via the in-complete fusion reaction followed by two neutron evaporation reaction $^{238}U(^{7}Li,\alpha)^{241}Np^{*} \rightarrow 2n + ^{239}Np$. A beam of 50 MeV ^{7}Li beam was used to bombard a natural U self supporting target of 1 mg/cm^2 thickness. The de-exciting gamma-rays were detected by employing the Indian National Gamma Array (INGA) comprising of 18 compton suppressed Germanium Clover detectors. The clover detectors were arranged in four rings at 32^o, 57^o, 90^o and 123^o with respect to beam direction and all the detectors in the 5th ring at 148^o were removed from the array to avoid neutron damage. The total coverage of Ge crystals is about 20% of 4π corresponding to a total photo-peak efficiency of about 5%. The data was acquired requiring the 3-fold condition for some time and 2-fold data was collected for longer period to have more statistics. A total of 750 millions two or higher fold coincidences were recorded and most of which is due to fission fragments.

The online and off-beam data are analyzing using the analysis programs INGASORT, CANDLE, RADWARE. The coincidences were sorted in to the γ–γ matrices. The 4k x 4k matrices had an energy dispersion of 0.5KeV/channel. Spectroscopic information for the ^{239}Np nucleus is very limited. Sample spectrum of gated projection and total projection were compared in Figure-1 to show the quality of the data. In the preset study, trans-uranium nucleus ^{239}Np was populated via incomplete fusion reactions. In-beam spectroscopy is also possible in this method.

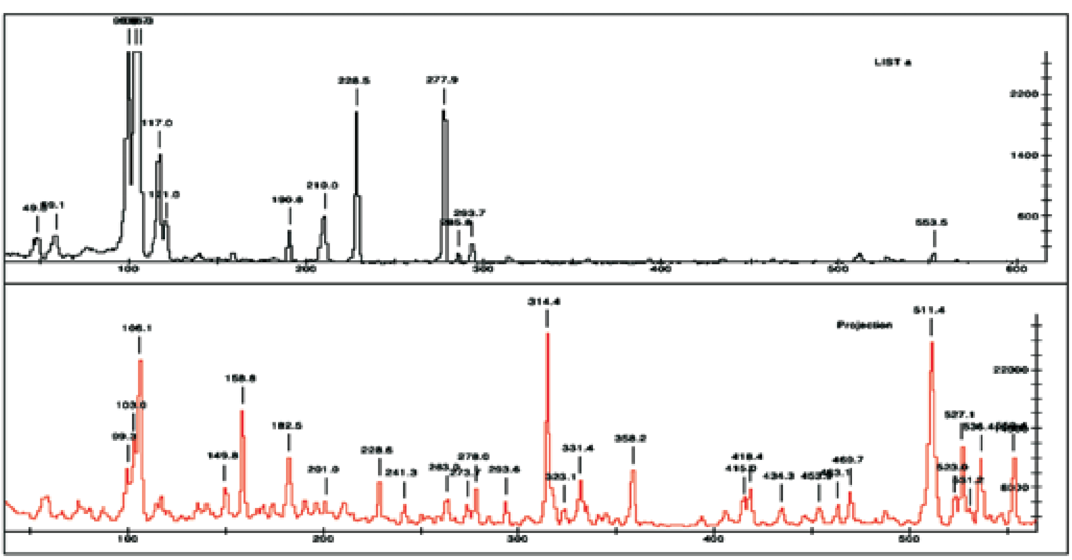

Fig. 1. Typical gated spectrum in the upper panel and total projection in the lower panel

5.1.14 Shears band in near-spherical ^{138}Ce

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In recent years, rotational like sequences of strongly enhanced magnetic dipole (M1) transitions have been observed in spherical or near-spherical nuclei with very small deformation and low quadrupole collectivity [1]. These new type of bands arises from a spontaneous symmetry breaking by anisotropic currents of a few high spin particles or holes[2] and are known to be excited due to the shears mechanism, developed between the proton and neutron high-j orbitals. The coupling of proton and neutron angular momentum vectors (j_π and j_ν) results in a large magnetic dipole moment (μ) at the bandhead. With the alignment of j_π and j_ν, the perpendicular component of the dipole moment ($\mu_\perp$) and therefore the B(M1) values decrease in a characteristic manner for such shears bands. Thus the measured values of B(M1) from the lifetime of the levels of such bands can give clear evidence of the presence of shears mechanism.

A ΔI=1 band has been observed in ^{138}Ce nucleus from our previous study [3], which was conjectured to be generated due to shears mechanism. Lifetime measurement of the levels of this band by DSAM technique has been performed with the Indian National Gamma Array (INGA), consisting of eighteen Clover detectors, placed in five rings around the target position. Five detectors were in the 90° ring, four were kept at 57° and three detectors in each of the 32°, 123° and 148° rings. The experiment was performed with 63 MeV ^{12}C beam from the 15UD pelletron at IUAC, New Delhi, with an enriched (99.99%) ^{130}Te target of thickness 800 $\mu g/cm^2$ backed by 4.8 mg/cm^2 ^{197}Au. The coincidence data were collected by eight channel 16 bit CAMAC ADCs using the data acquisition software CANDLE [4]. The data, sorted using the modified version of INGASORT [5], show the lineshapes for the γ-rays of the ΔI=1 band. Fig. 1 shows the lineshapes for forward and backward angles for the 475 keV and 665 keV γ-rays along with the fitting as obtained from a preliminary analysis using the LINESHAPE code[6]. The preliminary results also indicate a decreasing trend of inband B(M1) values. Further analysis is in progress. We propose [3] a four quasiparticle configuration of $(\pi g_{7/2}h_{11/2})(\nu h_{11/2})^{-2}$ for the band from the semi-empirical analysis, proposed by Clark and Machiavelli[7]. Tilted Axis Crancking (TAC) calculations [2,8] have been performed, which also support the proposed four quasiparticle configuration of the band. The calculation matches well with the experimental data considering the configuration $(\pi g_{7/2}h_{11/2})(\nu h_{11/2})^{-2}$, with $\beta_2 \sim 0.07$, $\gamma \sim 15^o$

and θ ~ 33°. In Fig.2 the experimental Spin (I) has been plotted with respect to the angular frequency (ω), which shows a good agreement with the TAC results. Further calculations are in progress.

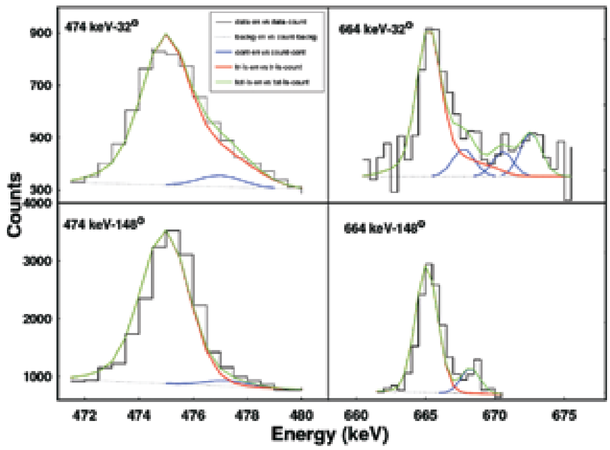

Fig. 1. Lineshapes of 475 keV and 665 keV

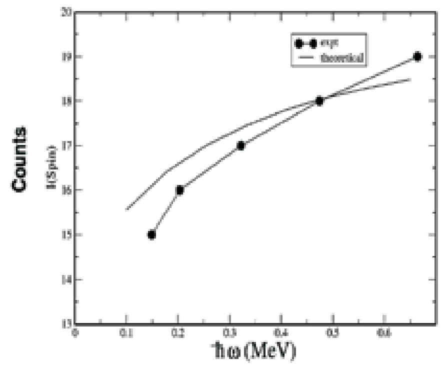

Fig. 2. Spin vs ω plot

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5.1.15 Spectroscopy of fission fragments produced in $^{18}O+^{238}U$ reaction

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The spectroscopic studies of fission fragments provide direct information on nuclear excited states, which is related to the shape and structure of the nucleus [1-3]. These exotic neutron-rich nuclei are not accessible otherwise in conventional fusion evaporation reactions. Search for new fission modes that will have influence on the mass distribution, has always been one of the highlights of the fission-spectroscopy studies and it still remains controversial [4,5]. To test the theoretical predictions of new physics that may be exhibited by neutron-rich nuclei, data are required over a wide range of isotopes [6]. In the present work we report the first results on the fission fragment spectroscopy using Indian National Gamma Array (INGA) to investigate the structure of the neutron-rich nuclei close to doubly magic ^{132}Sn and closed shell ^{162}Sm nuclei.

The experiment was carried out at 15UD IUAC Pelletron facility, New Delhi, using ^{18}O beam of energy 100 MeV. A self supporting ^{238}U target of thickness ~ 15 mg/cm^2 was used to stop at least one of the fragments in the target thereby reducing the Doppler broadening of the gamma ray spectrum of the fission fragments. The gamma rays emitted by the fission fragments were detected using INGA setup, which comprised of 18 Compton suppressed Clover detectors. As a preliminary run to check the feasibility of studying fission fragment spectroscopy, the experiment was performed for 3 days. The data was collected in three fold γ-ray coincidence, for which the event rate was 1.6K/sec by limiting the beam Current ~3 pnA. Symmetrized, two-dimensional matrix was constructed using RADWARE software to investigate the coincidence relationships between the gamma rays. As an example of the quality of the data, γ-energy spectrum gated on $2^+ \rightarrow 0^+$ transition in ^{128}Te is shown in Fig.1 and gamma rays up to $12^+ \rightarrow 10^+$ transition has been identified. We have identified several even-even neutron-rich isotopes of $^{90-100}$Sr, $^{96-102}$Zr, $^{100-106}$Mo, $^{102-110}$Ru, $^{110-116}$Pd, $^{116-122}$Cd, $^{118-126}$Sn, $^{124-136}$Te, $^{130-138}$Xe, $^{136-142}$Ba, $^{140-146}$Ce, $^{146-154}$Nd, $^{152-158}$Sm etc. from the γ-γ coincidence matrix.

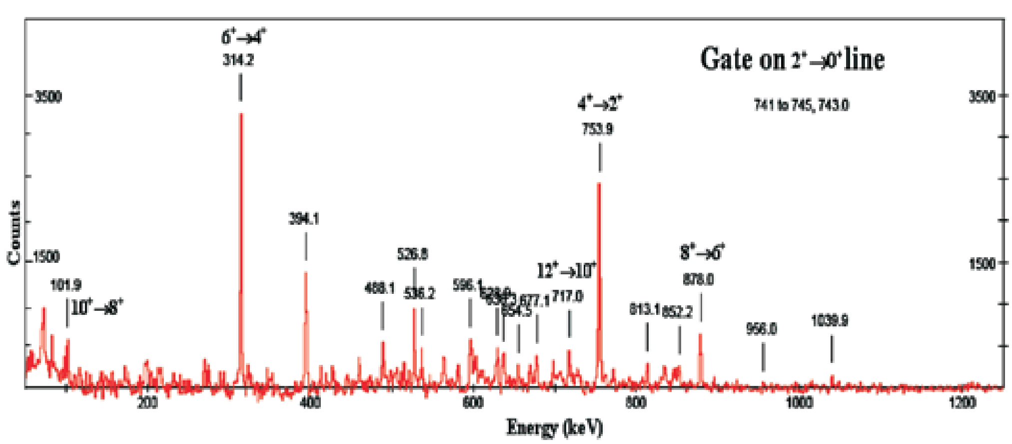

Fig.1. γ-ray energy spectrum of ^{128}Te with gate on $2^+ \rightarrow 0^+$ transition (E_γ=743 keV)

Yield distribution of fission fragments from spectroscopy studies: The yield of a particular fragment nucleus has been obtained from the coincidence of gamma rays of $2^+\rightarrow0^+$ and $4^+\rightarrow2^+$ transitions. From these measurements the yield distribution curve for various fission fragments has been obtained by plotting the yield of correlated even-even fission fragments produced in this reaction as shown in fig.2. From the yield distribution curve we have obtained the mass distribution of the fission fragments after adding the yield of various nuclei corresponding to a particular mass. It is observed that the distribution is symmetric and peaks at the half of the compound nuclear mass. These results will be important from the point of understanding the dynamical behaviour of the fission process.

In summary, we have shown that by employing the γ-γ coincidence technique it is possible to identify the individual fission fragment produced in heavy ion induced. We have obtained the mass distribution of the fission fragments from the mass yield of individual fragments. The present experiment has brought out the feasibility of studying the fission fragment spectroscopy using the INGA set up. Further investigation on fission spectroscopy using heavier beam with higher energies will be useful to obtain information on the fission dynamics and nuclear structure of ^{162}Sm and other neutron rich nuclei.

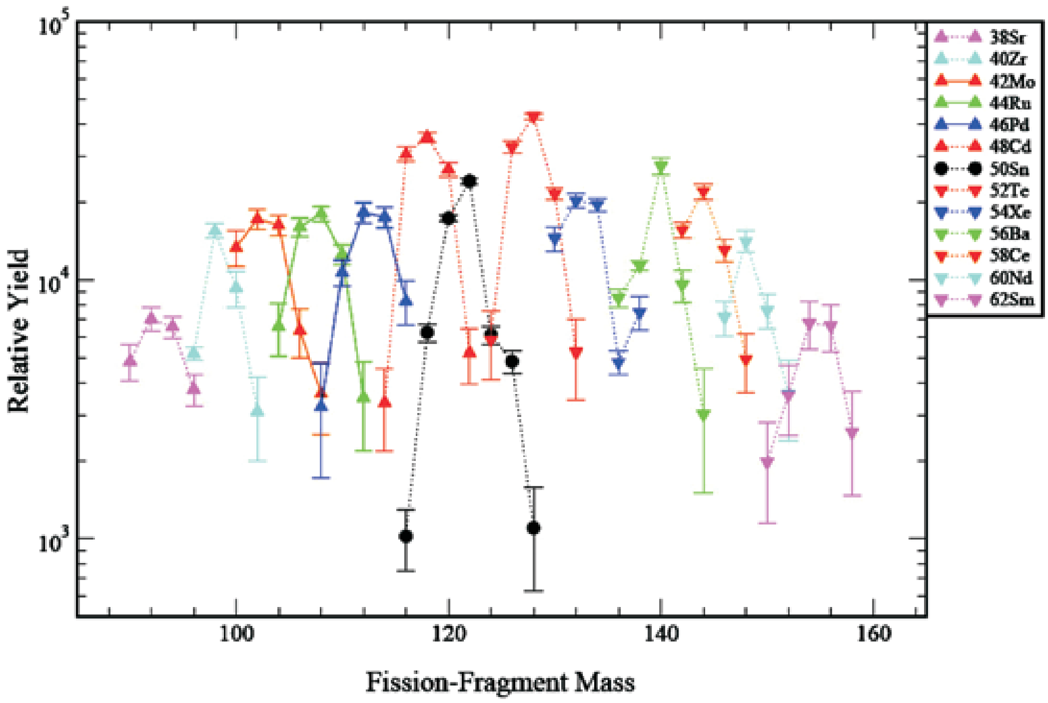

Fig.2. Relative yield distribution of various fission fragments produced in $^{18}O+^{238}U$ reaction

We acknowledge the support and help of pelletron operation staff and Electronics group of IUAC, New Delhi. We also thank Tarakeshwar, Gnaneswari, Dinesh Negi and Kumar Raju for their contribution in smooth running the experiment.

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5.1.16 Coulomb excitation of $^{112, 116}$Sn

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The B(E2) values calculated from shell model for the even tin isotopes $^{102-130}$Sn show a parabola-like trend as a function of mass number (Fig.1), which resembles the typical behaviour of a one-body even tensor operator across a shell in the seniority scheme[1]. Thus, for a seniority changing transition, the B(E2) values increase at first, peak at mid-shell and fall off thereafter with increasing A.

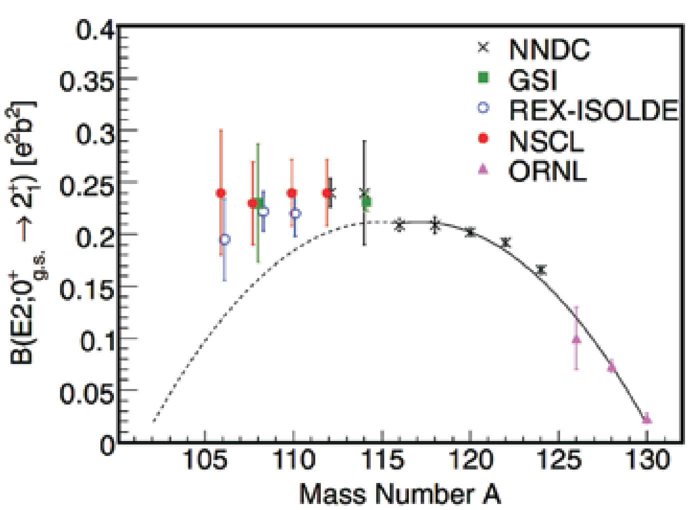

Fig. 1. Experimental B(E2 ↑) values in even-even Sn isotopes

Existing experimental data show an almost perfect agreement with this plot for tin isotopes heavier than A = 114[3,4], i.e. only if at least half of the major shell N = 50 - 82 is filled. In the case of lighter stable tin isotopes, which have a natural abundance of less than 1% , the publications for ^{112}Sn[5-7] and ^{114}Sn[8-10] yield higher B(E2) values than expected from shell model calculations, but so far, large experimental errors prohibit further theoretical interpretations. One main reason for these errors is that these experiments either have used partially enriched targets, so that the uncertainty stems from the impurity of the target, or used the recoil distance Doppler-shift (RDDS) method which adds sizable errors for lifetimes lower than 1ps.

In 2006, two Coulomb excitation experiments [11] were performed successfully at GSI which used ^{114,116}Sn projectiles and a ^{58}Ni target that significantly reduced the error in B(E2) for ^{114}Sn. The B(E2) value obtained for the unstable ^{108}Sn[2] in a RISING experiment is based on a B(E2) measurement relative to ^{112}Sn. Since the error in the available B(E2) measurements in ^{112}Sn is significant, a precise measurement in ^{112}Sn would also decrease the error of B(E2) value in ^{108}Sn. The aim of this experiment is to study the detailed structure of very rare stable ^{112}Sn isotope with an error of less than 3% (FWHM) for the B(E2) value, while ^{116}Sn serves as a calibration point.

In the experiment carried out at IUAC, targets of ^{112}Sn & ^{116}Sn were bombarded with ^{58}Ni beam at 175 MeV. The targets were of thickness ~ 350 μg/cm^2 with more than 98% enrichment. The scattered beam and energetic recoils were detected in an annular PPAC subtending the angular range 15°- 45° in the forward direction. The cathode of the PPAC was subdivided into 20 segments for ϕ measurement. The anode of the PPAC was subdivided into annular strips of constant θ, and delay line readout from both ends was used to measure θ information. The γ-rays from coulomb excitation of ^{58}Ni and ^{112,116}Sn were detected in four clover detectors mounted at θ_γ ~ 135° with respect to the beam axis. The ϕ-angles for the clovers were ±55° and ±125° with respect to the vertical direction. A block diagram of the setup is shown in Fig 2.

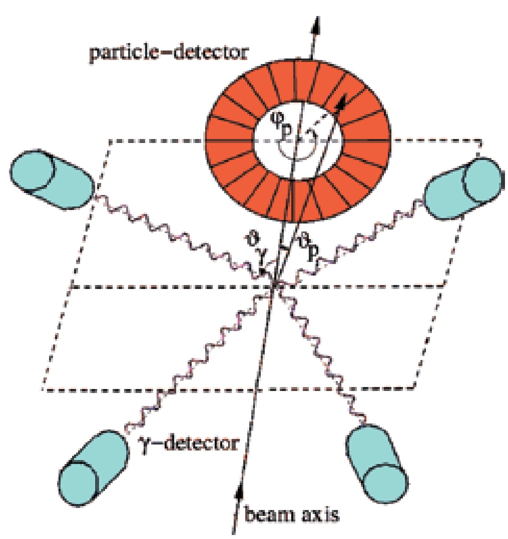

Fig. 2. Experimental setup for Coulomb excitation measurements

During the experiment, the 16 energies from the 4 clover detectors, four timing from the clovers, 20 timing signals from individual front PPAC detectors, and four signals from the two ends of the delay lines were recorded event by event. To avoid any systematic error due to instrumental drift, runs from ^{112}Sn and ^{116}Sn targets, each of ~ 3 hour duration, were interspersed alternatively. Energy and efficiency calibration run for the Clover detectors was carried out at the end of the experiment using a ^{152}Eu source.

The γ-spectrum from a clover detector in coincidence with the projectile-like fragments is shown in the bottom panel of Fig 3. From the measured scattering angle, the velocities of both projectile & target-like fragments could be calculated from two-body kinematics. The shifted energy is strongly dependent on the relative angle between the particle and gamma detector:

$$E_\gamma = E^o_\gamma \,[\, 1 + v/c \cos(\Theta_{p\gamma})]$$

with $\cos(\Theta_{p\gamma}) = \cos\theta_p \cos\theta_\gamma + \sin\theta_p \sin\theta_\gamma \cos(\phi_p-\phi_\gamma)$

From the measured ϕ_p dependence of the Doppler shift, the angles $(\theta_\gamma,\phi_\gamma)$ for each crystal of a Clover detector could be estimated for subsequent Doppler shift correction. The middle panel of Fig 3 shows the Doppler corrected spectrum for the ^{58}Ni peak at 1454 keV; the FWHM of ~ 13 keV arises primarily due to the finite acceptance angle of each crystal of the Clover detector. The slow-moving recoils lose, on the average, about ~20% of the energy in the target. The peak at ~ 1247 keV from the excitation of ^{112}Sn (FWHM ~ 7 keV) has been obtained after correcting for the reduced recoil velocity (top panel of Fig 3).

The ratio of counts under the Sn and Ni peaks is proportional to the B(E2↑) ratios for the excitation of 2^+ states of Sn and Ni. Because of the difference in p-γ angular correlations for the projectile and target, this ratio has a strong φ dependence. As a result, direct estimation of B(E2) of Sn from that of Ni has large systematic errors. The double ratio [σ(^{112}Sn)/σ(^{58}Ni)]/ [σ(^{116}Sn)/σ(^{58}Ni)] is, on the other hand, rather insensitive to the detection geometry and depends primarily on the B(E2) ratio for ^{112}Sn and ^{116}Sn respectively. The population of other excited states of Sn and subsequent feeding of the 2^+ state was estimated to be less than 1%.

From the weighted average of four measurements (using four clover detectors) The ratio ^{112}Sn/^{116}Sn for Coulomb excitation cross-section is given by:

$$\sigma(^{112}\mathrm{Sn})/\,\sigma(^{116}\mathrm{Sn}) = 1.304 \pm 0.024$$

After correcting for the difference in excitation energies 1257 and 1294 keV respectively for 2^+ states in ^{112,116}Sn and the difference in centre of mass energies, we get the ratio

$$[\ B(E2\uparrow)\ ^{112}Sn\ ] / [\ B(E2\uparrow)\ ^{116}Sn\ ] = 1.166 \pm 0.022$$

From the adopted B(E2 ↑) value of 0.209(6) e^2b^2 for ^{116}Sn [3], the corresponding value of ^{112}Sn is 0.243(7) e^2b^2. This is significantly higher than the value[12] obtained from DSAM measurements. The present measurements support the deviating trend of the lighter Sn isotopes [13] from the predictions of large basis shell model calculations.

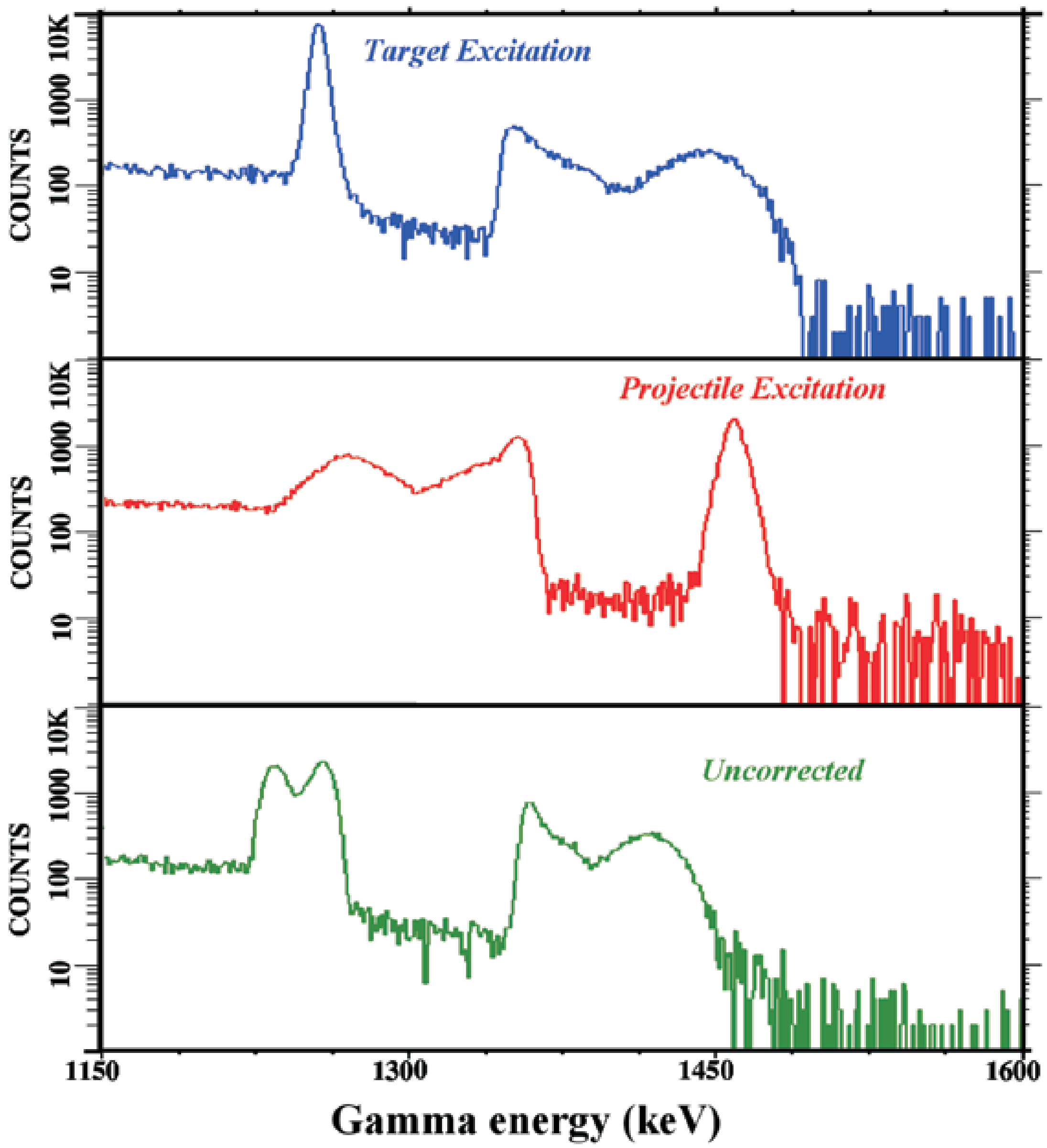

Fig. 3. γ-spectrum from a clover detector in coincidence with the projectile-like fragments in the particle detector is shown in the bottom panel. The middle and top panels show Doppler corrected spectra for ^{58}Ni and ^{112}Sn excitation.

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5.1.17 Investigation of tetrahedral symmetry in nuclei

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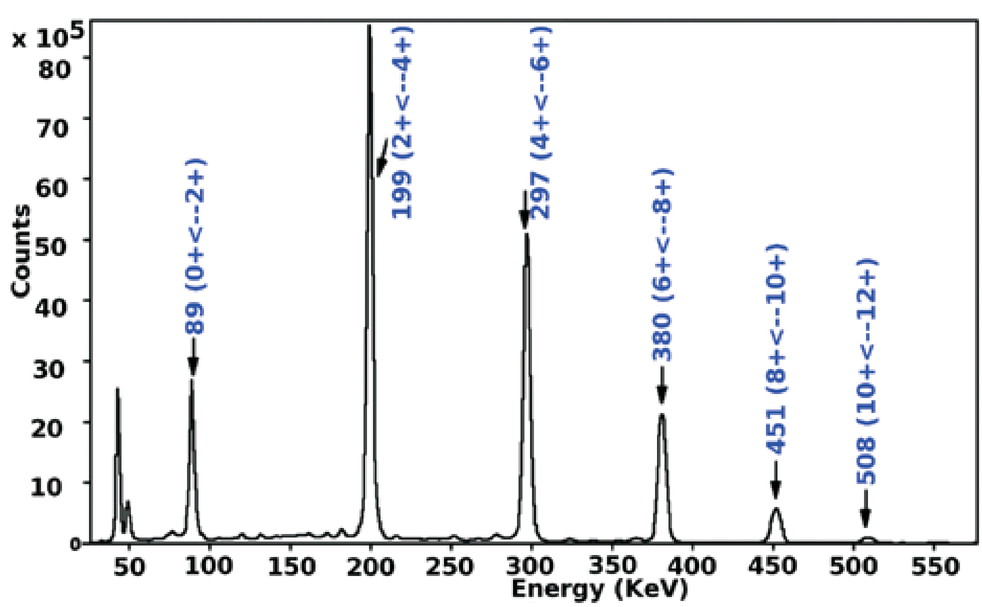
In recent years, number of theoretical studies [1-9] based on the nuclear mean field have predicted high rank symmetry leading to nuclei with a tetrahedral shape. With 48 symmetry elements, this shape would mean the most symmetric shape to be discovered so far. Because of this high level of symmetry the single nucleonic spectra possess unique properties. The most important one is that the nucleonic levels are divided into three families, one of which is composed of states with the four-fold degeneracy. Among the symmetry groups used in physics only the tetrahedral (and octahedral) ones imply the above special degeneracies - all the other point-groups symmetries lead to the well known double Kramers degeneracies. Strong tetrahedral symmetry effects are predicted in nuclei to occur at nucleon numbers around 16, 20, 32, 40, 56, 58, 70, 90, 94 [2]. However, it has not yet been identified in an unambiguous way in nuclei.

Dudek et al [9] had pointed out band structures in ^{156}Gd showing tentative signatures of possible tetrahedral symmetry. A joint collaboration experiment between Inter-University Accelerator Centre (IUAC), INFN Laboratori Nazionali di Legnaro, Legnaro(LNL), University of Lund (UL), Saha Institute of Nuclear Physics (SINP), Delhi University (DU) and the TetraNuc collaboration group (spokepersons: D. Curien and J. Dudek, IPHC-Strasbourg) was performed to investigate the structure of these bands. ^{58}Ni beam of 225 MeV was



delivered by the LNL tandem accelerator for safe Coulomb excitation of ^{156}Gd nuclei. The target thickness was about 1mg/cm^2. An annular double sided Si strip detector called LuSiA [10] from UL was used to detect the scattered nickel ions at the back angles; the angular range covered by LuSiA was about 138 to 170 degrees w.r.t. the beam direction. The gamma transitions were measured in coincidence with the scattered nickel ions using the gamma detector array GaSp [11] at LNL. Contemporarily two other experiments, one at IPN-Orsay and the other at JYFL-Jyvaskyla [12], have been performed by the Tetranuc collaboration to investigate tetrahedral symmetry in ^{156}Gd.

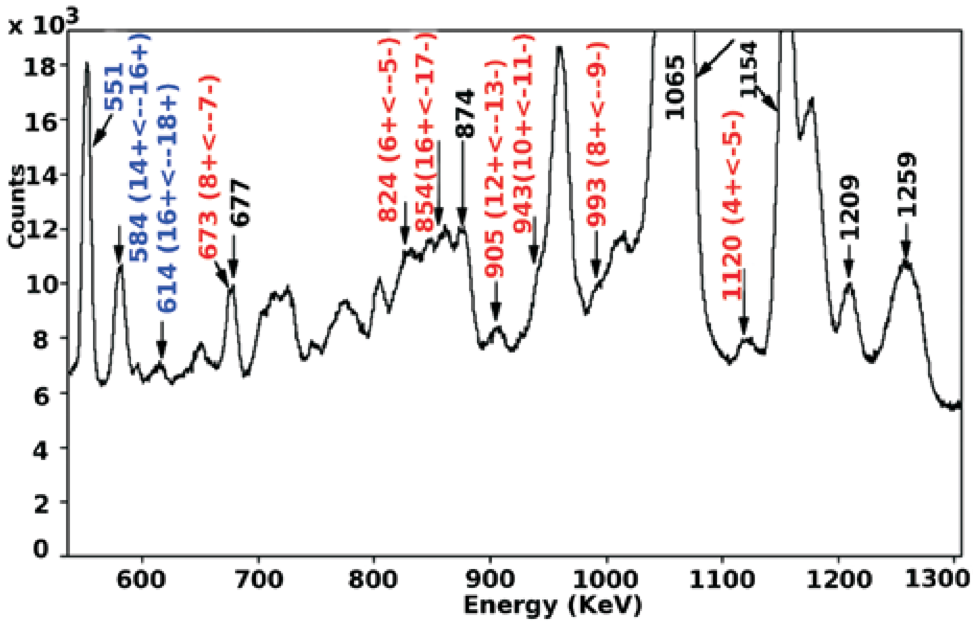


Fig. 1a, 1b. Total projection of the gamma in coincidence with scattered particle. Gsb transitions are indicated in blue and the inter-band transitions between the Gsb and the Npb are idicated in red

The projection from the matrix formed from the scattered particle - gamma coincidence is shown in figure 1a and 1b, after proper Doppler correction. Gamma transitions from the ground state band (gsb) at least up to $I^{\pi}=18^{+}\hbar$ are easily identifiable. This is higher in spin than reported in the previous Coulex experiment [13]. Many of the inter-band E1 linking transitions between gsb and the members of the negative parity odd and even spin bands are also indicated. These are the bands to be thoroughly investigated for tetrahedral symmetry and mainly the odd spin ones for which the missing E2's have been confirmed below spin 9^- [12]. Figure 2 shows a part of the gated spectrum from gamma-gamma matrix with gate on 380 KeV ($8^+ \rightarrow 6^+$) transition of the gsb. Some of the linking transitions from the negative parity band to the gsb with members of gsb are visible. They clearly show that this band of interest is fed up to at least spin of 17ħ. In multi-step Coulomb excitation, the feeding of these states could come only through multi-E2 transitions followed by a single E3 transition. The fact that the negative parity states are clearly fed indicated that the octupole degrees of freedom and though a possible tetrahedral symmetry, are clearly at work in this nucleus.

Detailed analysis is still in progress with the goals to obtain transition probabilities with good precision and also to determine the value of quadrupole moment for the above mentioned negative parity band.

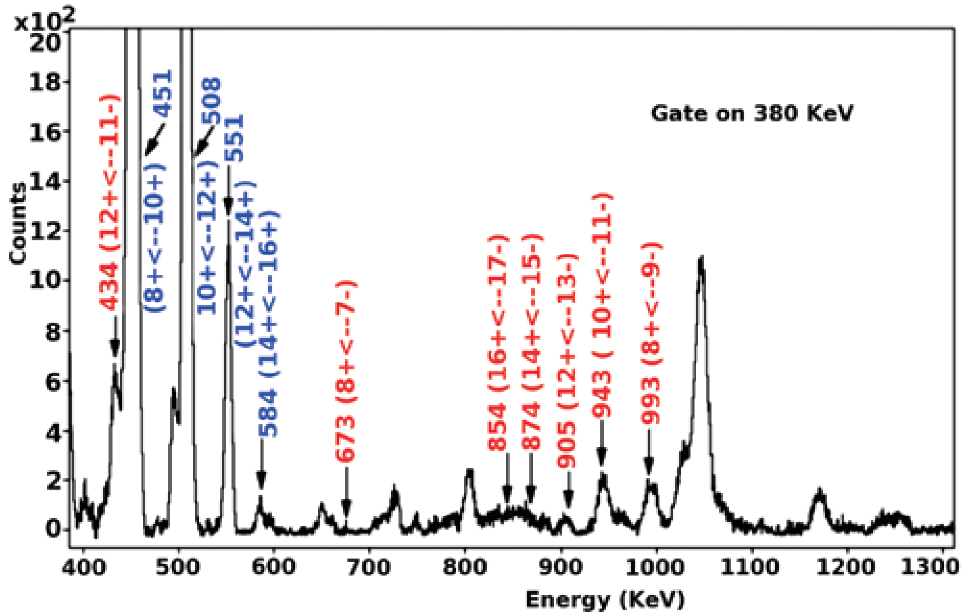


Fig. 2. Gamma spectra gated on the Gsb transition 380 KeV clearly showing the E1 interband transitions of interest in red and some members of Gsb in blue

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5.1.18 Measurement of fusion cross-section around the Coulomb barrier for $^{28}Si + ^{90,94}Zr$ systems

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Among the various degrees of freedom that influence the sub barrier fusion enhancement, the role of static deformation and quantal zero point motion [1,2,3] are well established but there are still ambiguities in the effect of transfer channels in sub barrier fusion enhancement [4,5]. Static deformation and zero point motion are very much dominant in enhancing sub barrier fusion cross section making it very difficult to disentangle the role played by transfer degree of freedom independently. Moreover when it is two particle transfer, transfer can take place either sequentially or simultaneously and this further makes it difficult to incorporate transfer channels in fusion cross section calculations theoretically.

To probe the role of transfer on the sub barrier fusion cross section enhancement, in the present experiment, we measured fusion excitation function for $^{28}Si + ^{90,94}Zr$ systems using Heavy Ion Reaction Analyser (HIRA) at IUAC [6]. The motivation behind choosing these systems was that ^{90}Zr and ^{94}Zr have almost same values of quadrupole and octupole deformations, but transfer Q values are positive up to four neutron transfer in the case of $^{28}Si + ^{94}Zr$. Hence, one can see the role of neutron transfer in sub barrier fusion enhancement. Pulsed beam of ^{28}Si was used and bombarded on enriched $^{90,94}Zr$ targets (97.65% and 96.07% purity, respectively) of 225 μg/cm^2 and 255 μg/cm^2 thicknesses prepared on 45μg/cm^2 carbon backing in target lab at IUAC. At the target chamber of HIRA, two silicon surface barrier detectors were mounted at ±25^o to monitor the beam and for normalization in the extraction of cross section. A carbon charge reset foil of 30μg/cm^2 thickness was used for charge state equilibration of Evaporation Residues (ERs) coming out of target. At the focal plane of HIRA, a Multi Wire Proportional Counter (MWPC) of active area 25 cm X 15 cm was used for the detection of ERs. Time of flight was defined for ERs reaching the focal plane with respect to RF used in bunching the beam to separate multiply scattered beam- like particles from the ERs at the focal plane. The fusion excitation function measurements were performed from 82 MeV to 120 MeV in steps of 2 MeV near the barrier and 3 to 5 MeV above the barrier (at 15 energies). This is ~15%

below to ~25% above the Coulomb barrier. The solid angle acceptance of HIRA was kept at 5 mSr for fusion excitation measurements. A raw spectrum of data taken is shown in Fig.1. From the spectrum, it is clearly visible that beam like particles are very well separated from the evaporation residues. A thorough scanning for the charge state of ERs coming out of reset foil, mass of ERs and energy of ERs was performed at 120 MeV for both systems.

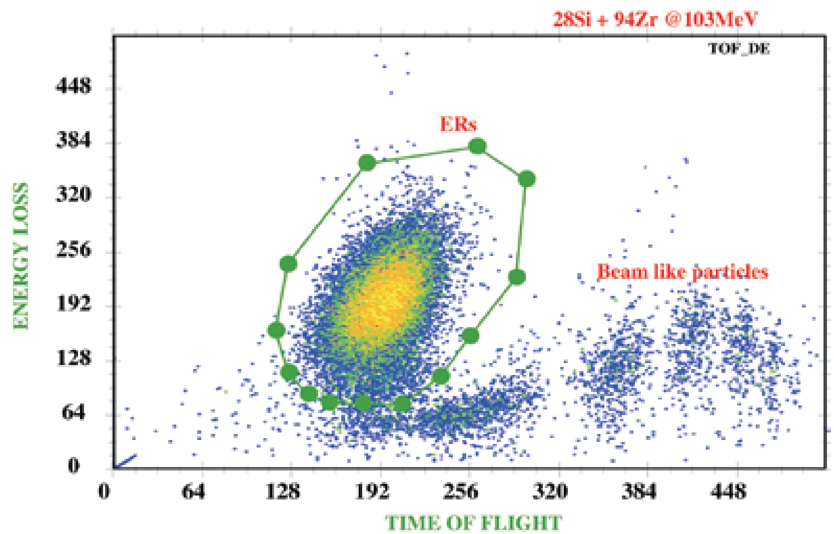

Fig.1. A raw spectrum showing Energy loss in MWPC vs time of flight

In order to have an idea of the behaviour of fusion cross-sections with projectile energy, ER yields divided by the square root of the products of the monitor yields is plotted. This quantity is plotted on the Y-axis and projectile energy on the X-axis in Fig. 2. These are raw data. Some more (efficiency related) corrections are being done.

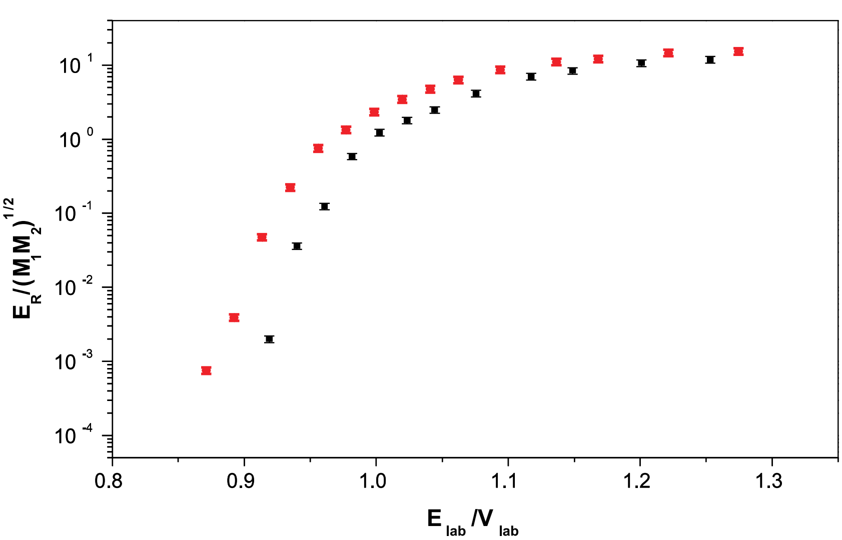

Fig.2. Comparison of fusion excitation function trend for both the systems. Red circles are for $^{28}Si+^{94}Zr$ whereas black circles are for $^{28}Si+^{90}Zr$

To measure HIRA efficiency for these systems, an HPGe detector was mounted vertically above the target chamber. Transmission efficiency for HIRA was measured for evaporation residues at 103 MeV of beam energy for $^{28}Si + ^{94}Zr$ system. As HPGe was kept very close to the target, gamma rays from ERs are Doppler broadened. In Fig. 3 shown below, HPGE_E-S stands for singles spectrum whereas HPGE-GTD stands for ER-RF-TAC peak gated HPGE spectrum. This efficiency will be used for making corrections in the fusion cross-sections.

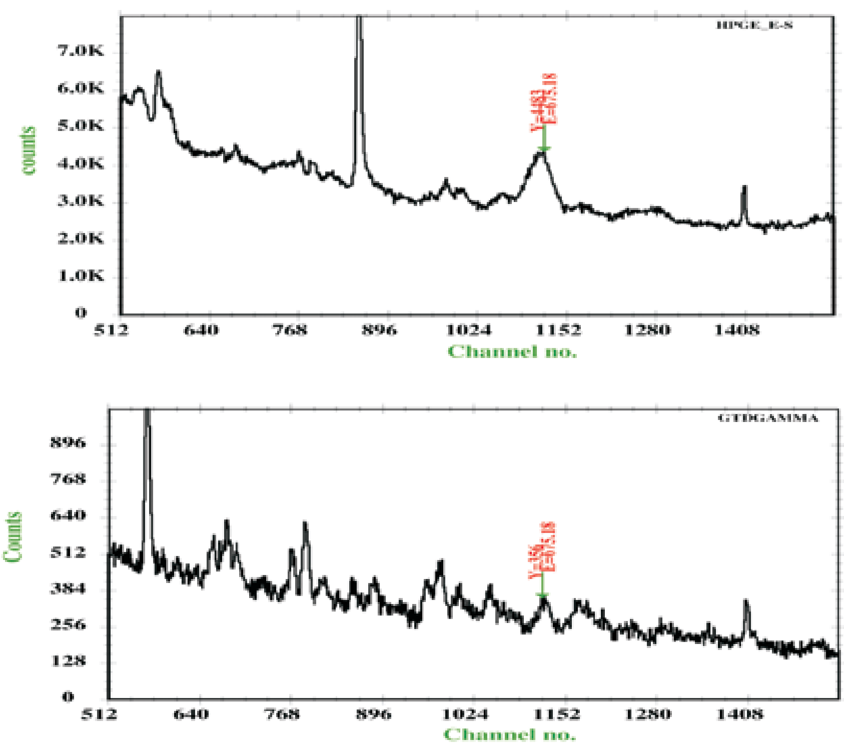

Fig.3. Gamma ray spectra: Singles spectrum (above) and coincidence (with ERs) spectrum (below)

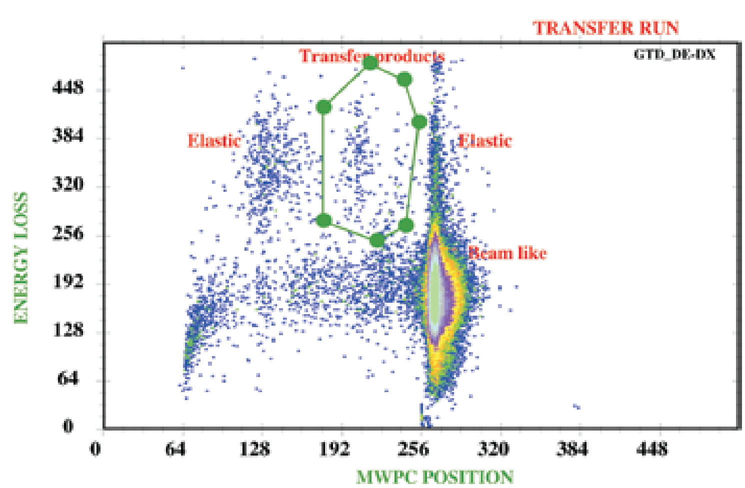

Fig. 4. A gated spectrum showing energy loss in MWPC vs. MWPC position

Angular distribution measurements were performed for ERs from 0° to 10° (w.r.t beam direction) in steps of 2° at 103 MeV beam energy with 1 mSr acceptance angle of HIRA. As $^{28}Si + ^{94}Zr$ shows positive Q values for neutron transfer channels, HIRA was briefly tuned for forward moving Zr – like recoils at 96 MeV beam energy. HIRA was kept at 15.8° (near grazing angle) for this short run. A gated raw spectrum is shown in fig. 4. Beam like particles and transfer products could be identified. We plan to take a transfer run in the near future. Detailed analysis of data for the two systems is in progress.

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5.1.19 Evaporation residue measurements for $^{16}O + ^{194}Pt$ reaction using Hybrid Recoil mass Analyzer (HYRA)

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Fusion-fission dynamics of heavy systems is a topic of considerable current interest. Measurements of evaporation residue (ER) cross section can reveal information about pre-saddle dissipation. It is also pointed out that ER cross section is a more sensitive probe [1] for understanding nuclear friction rather than neutron, proton and gamma multiplicities.

In this experimental program our plan is to measure the evaporation residue cross section, fission fragment angular distribution and mass distribution for two systems $^{16}O + ^{194}Pt$ and $^{24}Mg + ^{186}W$, both forming the same compound nucleus $^{210}Rn^*$ at similar excitation energies. It is well known that the entrance channel mass asymmetry (α) value with respect to Bussinaro – Gallone critical mass asymmetry value (α_{BG}) plays a very decisive role in the dynamics of fusion-fission process. It is theoretically predicted that systems with α value greater than α_{BG} will follow the compound nucleus path, while the systems with α value less than α_{BG} will preferably follow non-compound nucleus path during their long dynamic evolution. The α value for $^{16}O + ^{194}Pt$ reaction is 0.847 which is close to the α_{BG} value (0.838), but for $^{24}Mg + ^{186}W$ reaction, α value is much lower (0.771). We have already measured fission fragment mass distribution [2] for $^{16}O + ^{194}Pt$ system. We could not observe any non-compound nucleus processes in this reaction, suggesting that this system evolved through true compound nucleus formation. We are also interested in studying the effects of channels coupling in these two systems at near and below barrier energies, as both targets are deformed. In addition to this, in the case of $^{24}Mg + ^{186}W$ reaction, there are nucleon transfer channels with positive Q values, which can act as a doorway to fusion and can enhance the fusion cross section at near barrier energies. In the present experiment, we have measured evaporation residue cross sections for $^{210}Rn^{*}$ compound nucleus formed in $^{16}O + ^{194}Pt$ reaction at laboratory beam energies 73.7 (~ 10 % below the Coulomb barrier), 75.8, 79.9, 84.0, 88.1, 92.2, 96.3, 101.4 and 103.4 MeV (~25 % above the barrier).

Hybrid Recoil mass Analyzer (HYRA) [3] has been used for evaporation residue measurements in this experiment. HYRA was used in the gas filled mode. Table.1 shows the PACE calculation predictions for $^{16}O + ^{194}Pt$ reaction, for overlapping energies, above the Coulomb barrier. As fission is the dominant decay mode and ER cross section is much smaller, measuring the ER cross section using vacuum mode separator is very difficult. The gas filled separators, due to inherent charge state and velocity focusing, have very good transmission efficiency. Isotopically enriched ^{194}Pt target of thickness 300μg/cm^2 on 20μg/cm^2 carbon backing, was used in the experiment as the target. Besides ^{194}Pt target, ^{27}Al and ^{184}W targets were also mounted in the target ladder. Elastically scattered ^{16}O ions were detected in two silicon surface barrier detectors placed at ± 22° with respect to the beam direction. The detection of the ERs at the focal plane was challenging as the recoil energies of the evaporation residues were very small(at 73.7 MeV energy, the recoil energy of ^{206}Rn, after the target was about 4.6 MeV and after the poly-propylene foil at the focal plane it was about 1.5 MeV, at a helium gas pressure of 0.15 torr). The helium gas pressure in HYRA for such low energy ERs and the field settings were chosen from the calibration system $^{16}O + ^{184}W$ and using the simulation program [4] with proper scaling, where necessary. ^{27}Al target was used to check the beam like contamination at the focal plane. ERs were detected at the focal plane of HYRA using a multi wire proportional counter followed by a 2D Si surface barrier detector. The details of the facility and detector system are discussed by N. Madhavan et. al. elsewhere in this report.

Table. 1. PACE calculation for $^{16}O + ^{194}Pt$ reaction

Projectile energy (MeV)	ER Cross section (mb)	Fission Cross section (mb)
84.0	28	140
88.1	38	300
92.2	40	456
96.3	46	585
101.4	55	733
103.4	48	791

No appreciable beam-like or target-like particles were detected at focal plane for beam energies above the Coulomb barrier. At lowest energy, time of flight signal was used to separate the beam-like and target-like particles from ERs. Pulsed beam with pulse separation of 4μs was used to record the time of flight (TOF) of the slowly moving evaporation residues at 73.7 MeV. The start signal was taken from the focal plane MWPC anode and stop signal was the TWD. The logically "OR-"ed signal of two monitor detectors, MWPC anode and 2D surface barrier detector, was the master strobe for the data acquisition system. The ER ^{205}Rn undergoes alpha decay with a half life of 170 sec. This alpha decay was clearly observed in the 2D Si detector in this experiment. Fig.1. shows the evaporation residues in the two dimensional spectrum of energy loss in MWPC vs energy deposited in 2D detector and Fig.2. shows the TOF vs Energy loss in MWPC spectrum at 73.7 MeV beam energy.

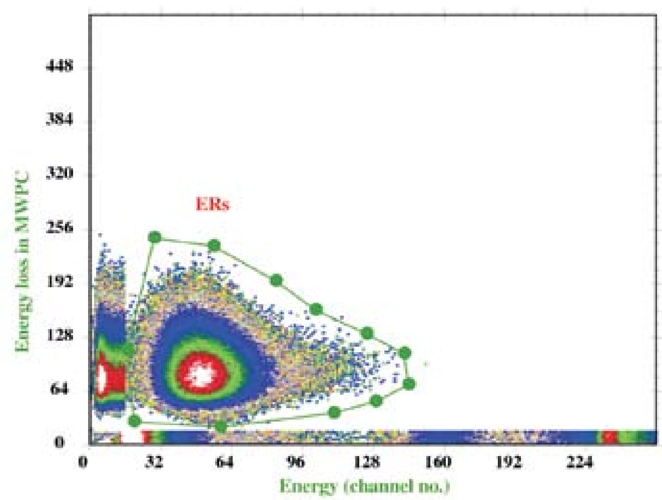

Fig.1. Evaporation residues in 2D spectrum of energy loss in MWPC vs energy deposited in 2D detector(ΔE vs E spectrum)

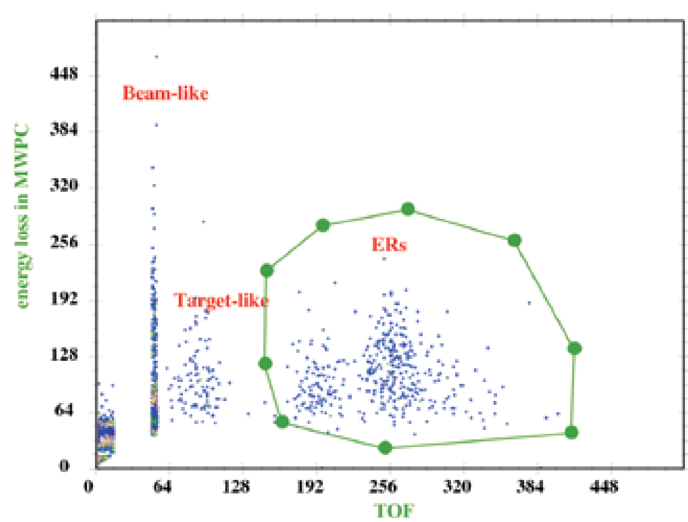

Fig.2. Evaporation residues are shown in TOF vs energy loss in MWPC spectrum with TWD, at 73.7 MeV beam energy

The trend of the normalized yields of evaporation residues is shown in fig.3. A separate experiment has been carried out for measurement of transmission efficiency in HYRA. Detailed analysis of the data is in progress.

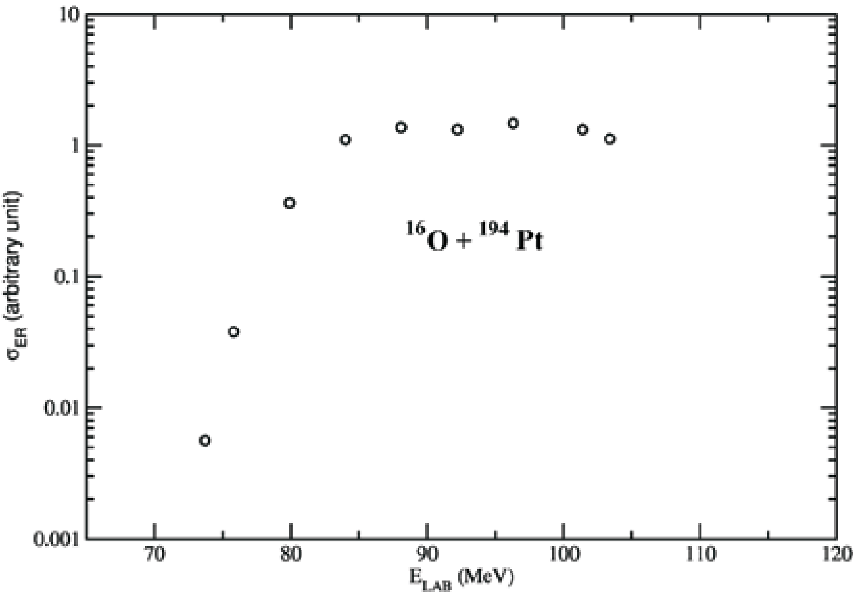

Fig.3. Evaporation residue cross section (arbitrary units) as a function of E_{LAB} for $^{16}O + ^{194}Pt$

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5.1.20 Study of Entrance channel effects in $^{215}Fr^*$

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Fission fragment angular distributions can be used as an effective tool for understanding fusion-fission dynamics. The standard theory of fission fragment angular distributions is based on the assumption that the fission fragments are emitted in the direction of nuclear symmetry axis and the properties governing their angular distributions are mostly determined at the fission saddle point [1]. The fragment anisotropy (A), which is defined as the ratio of the yield of fission fragments at 180^0 to that of 90^0, is a very sensitive probe to investigate the presence of non-compound nucleus fission processes such as quasifission(QF) and pre-equilibrium fission (PEF) in heavy-ion reactions [2].

It has been reported earlier [3] that the entrance channel mass asymmetry plays an important role in fission anisotropies, if entrance channel mass asymmetry smaller than α_{BG} critical value the measured anisotropy values are much larger than the model predictions which can be interpreted as a signature of the occurrence of the pre-equilibrium fission in addition to the non-compound nucleus fission. The systems which are less symmetric in entrance channel than α_{BG} critical value the fission anisotropies are well explained by SSPM where the compound nucleus is formed by the evolution of the composite system. However at sub-barrier energies it is observed that the measured anisotropies for all the systems are anomalously large due to the channel couplings and due to the shift in the α_{BG} towards higher mass asymmetries [4]. It was also well established from the previous studies with actinide targets that the target deformation and the presence of ground state spin of target or projectile strongly influences the fission anisotropies [2, 4]. However, the observation of the unexpected presence of quasifission in reactions forming compound systems as light as ^{216}Ra [5] has become a matter of intense investigation recently. In this context we have carried out fission fragment angular distribution measurements for two systems ^{11}B + ^{204}Pb and ^{18}O + ^{197}Au leading to the same compound nucleus ^{215}Fr* and falling on either side of α_{BG} to investigate the entrance channel effects, of deformation and the ground state spin on fission anisotropies.

Beams of ^{11}B, ^{18}O from 15UD Pelletron of IUAC were bombarded on sandwiched ^{204}Pb target of thickness 250 μg/cm^2 and self supporting ^{197}Au targets of thickness 1.8 mg/cm^2 and 400 μg/cm^2 respectively. The beam energies used for ^{11}B, ^{18}O were 51 – 64 MeV and 78 – 97 MeV respectively. Four ΔE-E Silicon telescopes detectors consisting of 15 – 20 μm thick ΔE detectors and 300 – 3000 μm thick E detectors with a collimator of diameter 5 mm were used to detect fission fragments at a distance of 13 cms from the target in 1.5 m diameter scattering chamber. Two Si surface barrier detectors were placed at a distance of 70 cms at an angle of $\pm 10^0$ with the beam direction from the target ladder with a collimator of diameter 1 mm for the normalization of fission yields and estimation of the absolute differential cross sections. Fission yields were measured from 80^0 to 170^0 for each energy in laboratory frame. The signals from ΔE detectors were used to trigger the gate of ADC. Data at overlapping angles were taken in the telescope detectors for normalization of the solid angles.

The measured fission fragment angular distributions were transformed from laboratory to center of mass frame using Viola systematics for symmetric fission [6]. The differential cross sections of the elastic events into monitor detectors were used for normalization by assuming that all of this from Rutherford scattering. The angular distributions are fitted to Legendre polynomials up to second order to extract the anisotropies. The extracted fission anisotropies were compared with the predictions of transition state theory. The anisotropy values for the two systems with respect to SSPM calculations are shown in Fig. 1 as a function of E_{cm}.

The measured anisotropy values for the both systems found to be consistent with the SSPM predictions showing no effects from entrance channels, ground state spins and energy, this can be attributed to the high values of B_f/T so that the contribution from PEF is negligible (< 5%) in the energy range which we have studied. The effect of ground state spins of target or projectile is also not observed in the present systems as observed in case of reactions involving actinide targets.

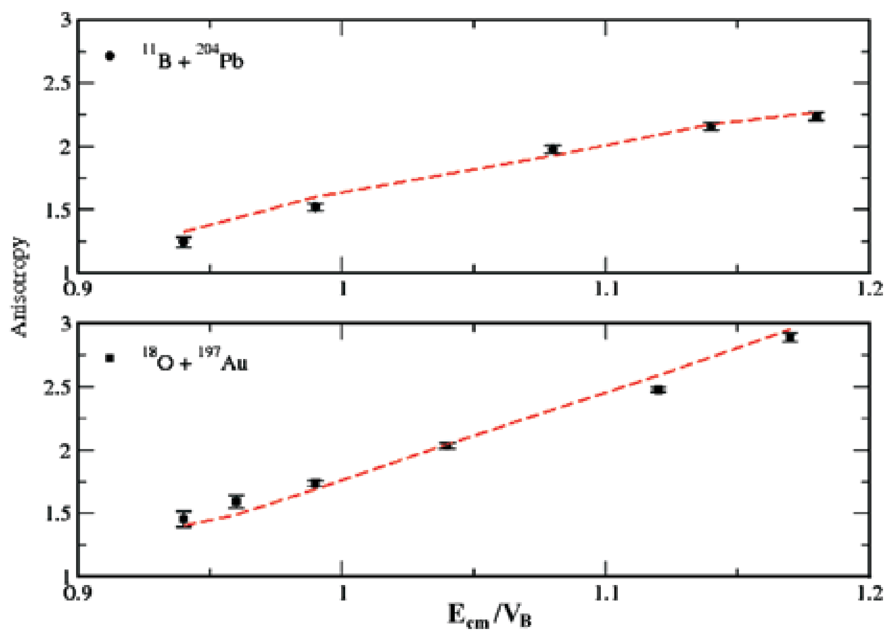

Fig. 1. Plot of experimental and calculated anisotropies (dotted line) in $^{11}B + ^{204}Pb$ and $^{18}O + ^{197}Au$ reactions

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5.1.21 Coincident detection of α particles and identification of reaction channels for $^{6}Li + ^{64}Ni$ at 26 MeV

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Extensive investigations are being pursued in recent years to understand the breakup modes of loosely bound stable projectiles not only because of their intrinsic interest but also because of their effect on other reaction processes especially at low energies around the Coulomb barrier. The dynamical effect of breakup of weakly bound projectiles has been shown to be completely different from those observed in the case of strongly bound systems [1]. Measurements of singles α yield in reactions involving $^{6,7}Li$, having strong α+d or α+t cluster structures, show significantly large cross section for alpha production but breakup model calculations failed to reproduce the magnitude of the α yield [2,3]. Exclusive coincidence measurement for the $^{7}Li + ^{65}Cu$ system [4] has shown that one neutron transfer followed by breakup, producing α as one of the outgoing particles, has a larger cross section compared to that of the breakup of ^{7}Li. Thus, to disentangle the contributions of breakup and breakup-like channels and to understand their effects on elastic or fusion processes involving weakly bound stable projectiles, it is important to perform exclusive measurements on different target masses. The relative importance of different breakup-like channels with changing target mass and decreasing bombarding energy needs to be investigated.

We performed an experiment at IUAC, New Delhi to detect α particles in coincidence with deuteron from breakup of ^{6}Li and with proton coming from unbound ^{5}Li produced by one neutron stripping of ^{6}Li for the system $^{6}Li + ^{64}Ni$ at 26 MeV. This is a part of our systematic investigation of the coupling effect of breakup like channels on the interaction potential describing the elastic scattering of $^{6}Li + ^{64}Ni$ [5]. Primary motivation was to obtain the angular distributions of (^{6}Li,$^{6}Li^{*}$) and (^{6}Li,^{5}Li) channels. A self supported ^{64}Ni target (enrichment ~ 99%, metallic) of thickness 376μg/cm^{2} was used and placed at an angle of 45^{o} to the beam axis. Two sets of coincident detectors were used. One set in the off-the-reaction plane configuration and consisted of a telescope (33μ ΔE and 300μ E detectors) and a single position sensitive detector (PSD) (1000μ). In order to measure the relative angle between the detected particles, the E-section of the telescope was also position sensitive. The other set was in the reaction plane and comprised of a normal telescope (50μ ΔE and 5000μ E detectors) and 16-channel Silicon strip detector. The normal telescope had a 5mm diameter collimator and the position sensitive detectors were fully exposed to cover the maximum solid angle. The centre-to-centre angular separation between the detectors for both the sets was ~ 20°.

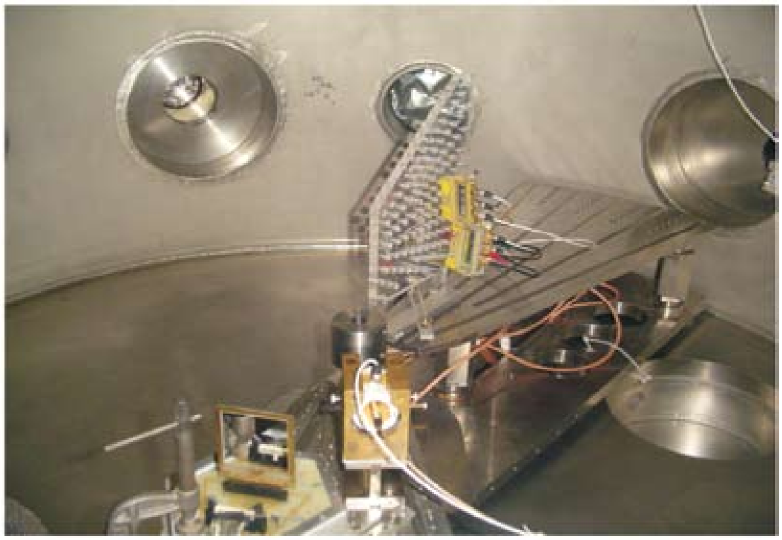

Fig.1. Chamber set up showing the detection arrangement for the experiment

Fig.1 shows the detection arrangement inside the General Purpose Scattering Chamber (diameter 1.5m) at IUAC. Fig. 2 shows the two-dimensional plot of the total energy from the telescope (x-axis) and the energy of PSD (y-axis) gated by the TAC signal between the two. The two kinematic loci correspond to the energy correlations between α & *d* from ^{6}Li* (2.18 MeV) and between α & *p* from unbound ^{5}Li. Detailed analysis using the analysis software FREEDOM is in progress.

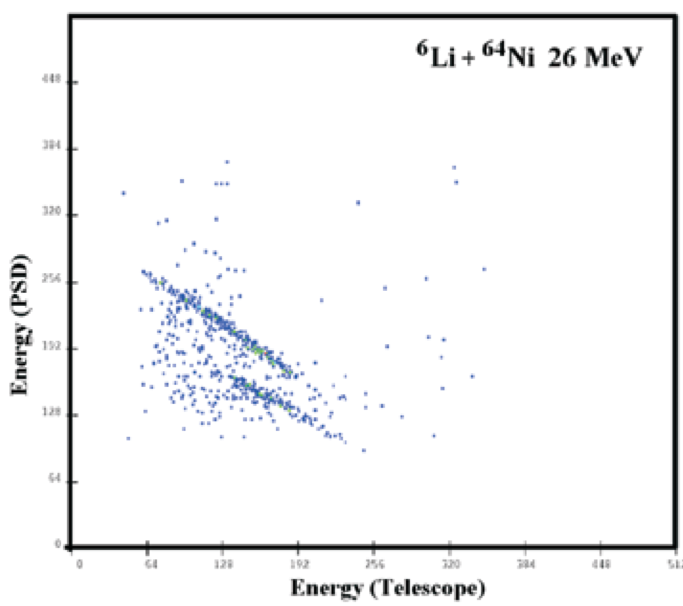

Fig. 2 Time gated two dimensional spectrum of $E_{telescope}$ vs. $E_{PSD\text{-}single}$

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5.1.22 Light particle emission in fusion reactions at high excitation energy and angular momentum

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Heavy-ion reactions involving medium mass nuclei (A<100) are dominated by fusion-evaporation process. The composite nuclei which are formed with large angular momenta and high excitation energies subsequently undergo decay through many open channels. In many of the recent experiments it was found that for the compound nuclei, populated through mass symmetric target-projectile combinations, the hardness of the high energy part of the light charged particle (proton, alpha) and neutron spectra show anomalous deviations from the shape of the evaporation spectra predicted by standard statistical model calculations, assuming the decay from an equilibrated compound nucleus [1-3]. On the other hand the spectra obtained from the corresponding compound nucleus populated through asymmetric combination of the target and projectile could be explained nicely through standard statistical model calculations [1-3]. The alpha and proton spectra were in general explained by re-scaling the Yrast line or spin dependent level density expression to restore the agreement of alpha particle spectra with the conventional statistical picture. Some authors have also shown that the use of structure dependent level density parameter ‘a’ with shell model corrections without considering the dynamical aspect of fusion can also explain the shape of the alpha and proton spectra [4]. In general it is also accepted that at high excitation energy, fusion hindrance do take place due to dynamical effects and fusion and fission time scales are altered by such effects. The analysis of vast amount of data obtained from the measurements of pre-scission neutron multiplicity, GDR gamma ray and evaporation residue clearly suggest that the time scale for fission process is hindered due to dynamical effects such as nuclear viscosity etc.[7-9]. Such hindrance can also take place for the fusion of the medium mass nuclei. In some of the analysis of the alpha, proton and neutron spectra [5-6] it was found that statistical model calculations performed using the ***l***- distribution (or l_{graz}) obtained by Bass-systematics under-predicts the alpha and proton spectra obtained through the fusion of mass symmetric entrance channel. However, these spectra were explained by using the l_{crit} value obtained from HICOL dynamical model calculations. The dynamical model predicted l_{crit} was found to be much less compared to the l_{graz} obtained through Bass-systematics. It was conjectured that in case of mass symmetric systems some of the higher partial waves are not fusing due to fusion hindrance. In all the above measurements some of the main limitations were, simultaneous analysis of all the observables like cross sections, spin distributions, evaporation residue(ER) gated proton, neutron and alpha spectra were never carried out. In order to address above problems in a better way, we have chosen a system with symmetric target projectile combinations and measured simultaneously the ER cross-sections and the ER-gated, proton, alpha and neutron spectrum.

125 MeV ^{28}Si beam was bombarded on a ^{45}Sc target of thickness 600 μg/cm^2 to populate the compound nucleus ^{73}Rb. ERs were separated from beam like particles and detected in the focal plane detectors of the Heavy Ion reaction analyzer (HIRA). ERs were also measured at different angle setting of the HIRA to take into account the recoil due to alpha particle emission. Charged particle spectra were obtained at different laboratory angles using a ΔE-E (25μm- 5mm) detector telescope. Neutron spectra were measured at one angle using a NE213 liquid Scintillator detector. Gamma and neutrons were separated both by time of flight and with also with pulse shape discrimination technique. Analysis of data is in progress.

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5.1.23 Studies using spherical shell model

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Nuclear shell model provides a microscopic and unified approach for studying both the single-particle and collective features in atomic nuclei. The other advantage of the shell model is that one can investigate the evolution of the nuclear properties as a function of excitation energy and angular momentum. An important advantage of shell model analysis compared to mean-field approximation is that most of the symmetries of the original many-body Hamiltonian are conserved and therefore, one does not need any additional efforts for restoring the correct symmetry of the states.

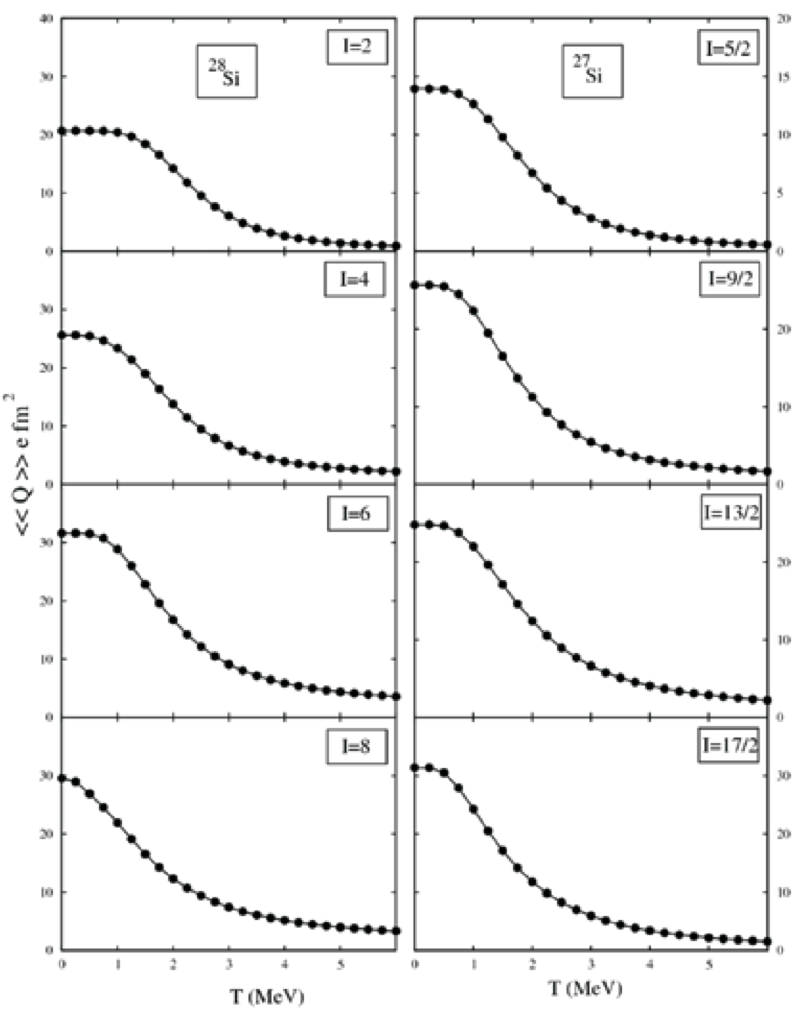

Fig. 1. Average quadrupole moments are plotted as function of temperature for various angular momentum states for ^{28}Si and ^{27}Si.

Recently, a completely new shell model program has been developed at IUAC [1]. The main advantage of this new code is that it completely works in the angular-momentum coupled representation and the Lanczos algorithm is implemented. In our earlier study [2] we have used this program to study the pairing correlations in sd-shell region for even-even, even-odd and odd-odd systems near N=Z and also for the asymmetric case of N=Z+4. Recently we have performed calculations for temperature and spin dependence of quadrupole deformation in the middle of the sd-shell. In figure 1, the variation of average quadrupole moment as a function of temperature is shown for fixed different values of spin for ^{28}Si and ^{27}Si. It can be seen that the quadrupole moment shows a transitional behavior and the transitional temperature also varies with angular momentum. These calculations were performed with the modest computational facility at Kashmir University and IUAC.

We would further like to extend these studies to larger model space and also take up interesting problems of intruder states, shape-coexistence and super-deformations in the fp-shell and mass ~ 80 regions. These studies would be soon feasible with the upcoming 'High Performance Computing' facility at IUAC.

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