5. RESEARCH ACTIVITIES

5.1 NUCLEAR PHYSICS

We have now completed two years of operation of Indian National Gamma Array (INGA) at IUAC. During this period, more than thirty user experiments were conducted. The primary emphasis during this period has been into five different areas (i) loss of collectivity and band termination effects in mass 80 region (ii) magnetic and anti-magnetic rotation in mass 100 and mass 130 region (iii) high spin spectroscopy of transitional nuclei (A ~ 120) (iv) studies of shell model nuclei in the sd shell and near N ~ 50 shell closure and (v) spectroscopy of nuclei beyond Z=82. In most of the experiments, the existing level schemes have been extended and life times have been measured for selected bands for understanding their structure. Three of the experiments were aimed at identifying chiral partners in A ~ 100 region.

The Charged Particle Array in GDA has been used for studying spin distribution in incomplete fusion reactions. Strong localization of spin distribution near J ~ 8 has been observed for both *p* and α particles emitted in the forward direction.

The recoil separator HIRA has been successfully used to separate transfer channels from elastic scattering in the reactions $^{16}O + ^{90,94}Zr$ at near barrier energies. The objective was to investigate the role of shell closure on transfer probability.

The dynamics of fission for nuclei with moderate fissility has been studied through pre-scission neutron multiplicity as well as the mass distribution of fission fragments. The role of quasi-fission for heavier projectiles is clearly indicated by the above measurements.

5.1.1 Lifetime measurements in ^{123}Cs

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Nuclei which are lying between spherical and well-deformed region are generally known as transitional nuclei. The alignment of the valence nucleons outside the spherical ^{114}Sn core in the transitional nuclei of mass 125 region drives the nuclei into different shapes. The shape co-existence, which occurs in the excited nuclei are mainly due to the collective and noncollective excitations of the nucleons. The shape driving properties of the excited nucleons depends upon the position of its Fermi surface; the neutron Fermi surface which lies in the middle or upper part of the $h_{11/2}$ subshell, favors oblate shape, whereas, the proton Fermi surface, which lies in the lower part of the $h_{11/2}$ subshell, favors prolate shape. Total routhian surface (TRS) calculations show that the alignment of protons and neutrons drives the nuclei towards triaxiality with different values of γ, the triaxial parameter [1, 2]. Recent investigation in the neutron deficient isotope ^{123}Cs shows that the single-particle excitations take over the collective phenomenon at high spins which favors band termination [3]. The aim of the present work was to measure the mean lifetimes of the excited states in the bands, which can be useful in understanding the shape co-existence phenomenon. The Doppler Shift Attenuation Method (DSAM) technique has been used for the lifetime measurements.

The excited states of ^{123}Cs were populated in the ^{96}Zr (^{32}S, p4n) ^{123}Cs reaction. The ^{32}S beam of energy 140 MeV was provided by 15UD Pelletron accelerator at Inter University accelerator center, New Delhi. The target used was 1mg/cm^2 enriched ^{96}Zr deposited on lead backing of thickness 10 mg/cm^2. Gamma ray coincidence events were collected by the Indian National Gamma ray Array (INGA) spectrometer consisting of 17 Compton-suppressed clover detectors at the time of experiment [4]. The detectors were grouped into five rings at angles 57°, 32°, 90°, 123° and 148° with respect to the beam axis. The events were collected in the list mode by CANDLE [5], the data acquisition system with the condition of minimum three detectors in coincidence.

In the offline analysis, the data were calibrated for energy and efficiency by using ^{152}Eu source. The calibrated data were sorted into symmetric 4k x 4k matrix using INGASORT [6] for the intensity measurements. For the line-shape analysis, three asymmetric 4k x 4k matrices corresponding to detectors at angles 57°, 90° and 148° were formed. The extracted line-shapes at all the angles were fitted simultaneously with theoretical line shapes using the code LINESHAPE [7]. The theoretical line shape fitted with the experimental obtained line shape for the transitions of energy 868 keV and 905 keV for the angles 57°, 90° and 148° are shown in fig 1.

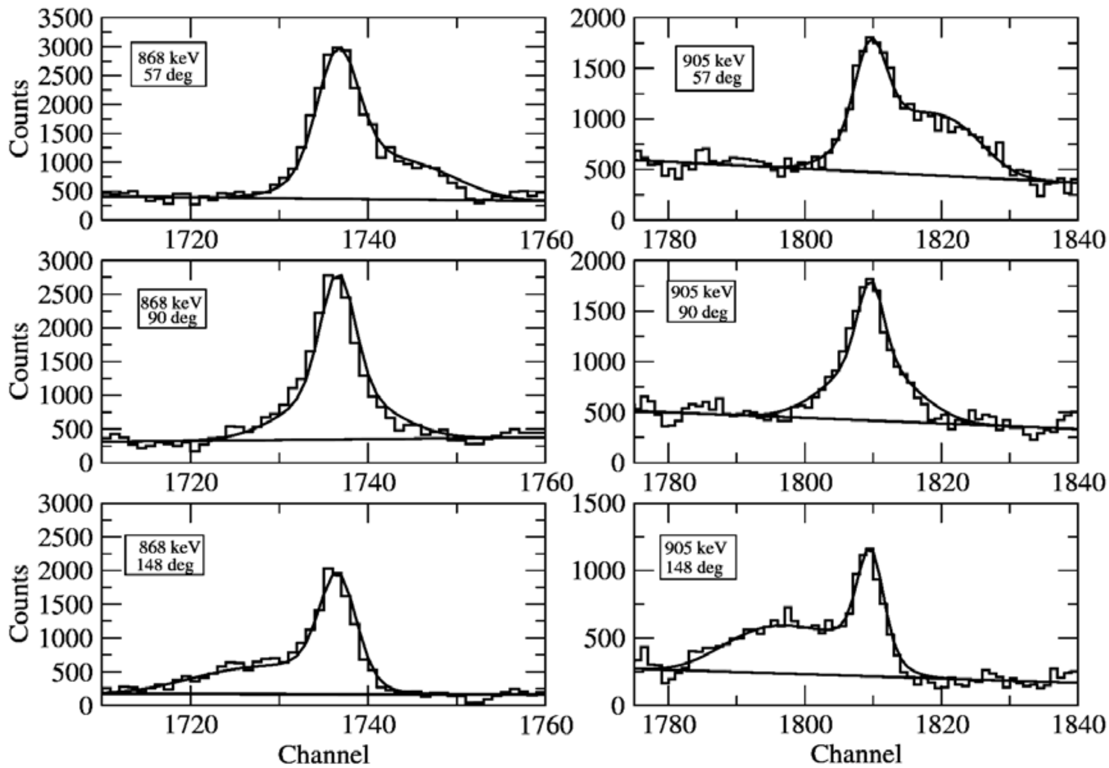

Fig. 1. Theoretical fitted line shape with the experimental data for the energies 868 and 905 keV

The obtained lifetimes for the transitions of negative parity band is tabulated.

Energy (keV)	Spin (ℏ)		Lifetime (τ) ps
	I_i	I_f	
1206	$51/2^-$	$47/2^-$	$0.92^{+0.03}_{-0.04}$
1113	$47/2^-$	$43/2^-$	$0.18^{+0.13}_{-0.13}$
1026	$43/2^-$	$39/2^-$	$0.24^{+0.17}_{-0.19}$
956	$39/2^-$	$35/2^-$	$0.43^{+0.04}_{-0.04}$
905	$35/2^-$	$31/2^-$	$0.31^{+0.05}_{-0.05}$
868	$31/2^-$	$27/2^-$	$0.32^{+0.09}_{-0.08}$
801	$27/2^-$	$23/2^-$	$0.69^{+0.31}_{-0.15}$

This work was supported by the Department of Science and Technology (DST/SR/S2/HEP-09/2005), New Delhi. The financial support from the MHRD, Govt. of India is also gratefully acknowledged. The authors would like to thank the Pelletron and Electronics group of IUAC for their kind support during the experiment.

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5.1.2 The question of dynamic chirality in nuclei: the case of ^{102}Rh

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A spontaneous breaking of chiral symmetry can take place for configurations where the angular momenta of the valence protons, valence neutrons and the core are mutually perpendicular [1]. Since chirality is a dichotomic symmetry, its spontaneous breaking leads to doublets of closely lying rotational bands of the same parity. Pairs of bands possibly due to the breaking of the chiral symmetry have been found in the mass A~130 region. The studies [2,3] suggest that the existence of the two crossing $\Delta I = 1$ bands with the same parity in ^{134}Pr should be attributed to a weak fluctuation dominated chirality combined with an intrinsic symmetry yet to be revealed. The goal of our experiment performed in June 2009 was to test the existence of dynamic chirality in the mass A ~ 100 region. Recent theoretical studies of the chiral phenomenon within the framework of the adiabatic and configuration-fixed constrained triaxial Relativistic Mean Field (RMF) approaches have been performed in order to investigate the triaxial shape coexistence and possible chiral doublet bands [4]. The nucleus ^{102}Rh according to the work of Meng et al. [4] is one of the candidates to present such a phenomenon.

Excited states in ^{102}Rh were populated using the 3n exit channel, of the reaction ^{11}B+^{94}Zr. The beam of ^{11}B, with energy of 36 MeV, was delivered by the 15-UD Pelletron accelerator of the Inter University Accelerator Centre (IUAC), Delhi. The target consisted of 0.9 mg/cm^2 ^{94}Zr onto 8 mg/cm^2 ^{197}Au backing. The de-exciting gamma rays were registered with the Indian National Gamma Array (INGA), which 15 Clover detectors were accommodated in 4π geometry [5]. Gain matching and efficiency calibration of the Ge detectors were performed using ^{152}Eu and ^{133}Ba radioactive sources.

In four days experiment we succeeded to collect data with an excellent statistics in order to investigate the level-scheme of ^{102}Rh as well as to perform polarization measurements and to measure lifetimes in the sub-picosecond region. The quality of the data is illustrated in Fig. 1. The Doppler-shifts corresponding to the forward and backward ring are nicely seen.

In order to determine a lifetime in a Doppler-Shift Attenuation Method measurement we need to know exactly the velocity histories of recoiling nuclei when they are slowing

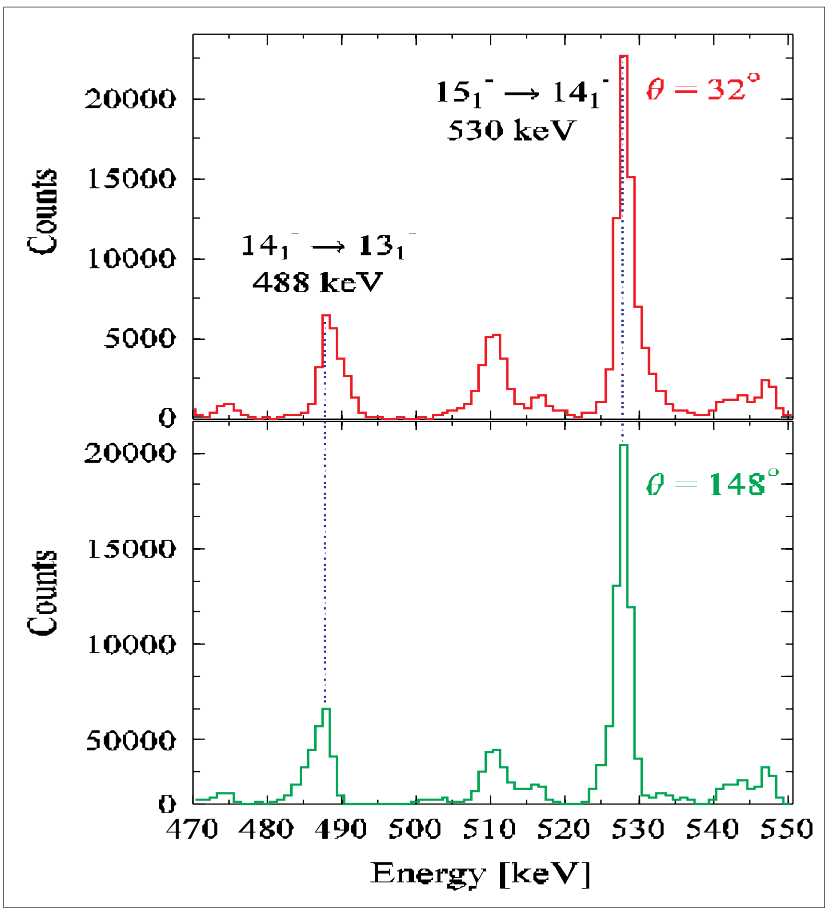

Fig. 1. Gated gamma-ray spectra of ^{102}Rh.

down in the target and stopper, until the moment they stop. For the Monte Carlo simulation of the slowing-down histories of the recoils we use a procedure described in [6]. According to the calculations performed, the mean velocity of the recoils was about 0.9 % of the velocity of light. Presently the data are under analysis.

In the upper panel the shifted and unshifted components of the $14_1^- \rightarrow 13_1^-$ and $15_1^- \rightarrow 14_1^-$ transitions are presented as measured by all detectors positioned at the forward angle of 32.0° with respect to the beam axis. In the bottom panel, the same transitions are presented but at the backward angle of 148°. The data clearly illustrate consistent Doppler-shifts for forward and backward detector rings.

We thank the accelerator crew of IUAC for excellent support. Two of us (D.T. & G. de A.) are grateful for the kind hospitality of the IUAC.

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5.1.3 Search for Anti-magnetic rotation in ^{105}Cd

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Since last few years, rotational like bands with strong M1 transitions have been observed in nearly spherical nuclei in A=80,110,135,190 mass regions [1]. Such Magnetic Rotation (MR) Bands arise due to anisotropic current distribution and are built on multi-quasi-particle configurations. This phenomenon has been well understood by Frauendorf's shears mechanism and the TAC approach [2]. Another interesting phenomenon called Anti-magnetic Rotation (AMR) has also been predicted to occur in the same mass regions as the MR. AMR bands are also built on multi-quasiparticle configuration, but here the coupling of the neutron and proton angular momentum vectors is different from that of MR. In the case of AMR, the spin vectors of high-*j* proton holes are in stretched mode and the neutron spin vector stands in the middle and is perpendicular to both of them. This is like two shears of MR type. There is no net magnetic dipole moment of the total system. The symmetry of the system demands that the AMR band levels differ in spin by 2ħ and are connected by weak E2 transitions due to weak nuclear deformation. Higher angular momentum states are generated by the closing of the two proton vector blades along the direction of total angular momentum. Hence there is rapid decrease of the B(E2) values and increase of $I^{(2)}$/B(E2) with increasing spin as the $I^{(2)}$ values remain nearly constant with spin. First evidence of AMR was reported in ^{106}Cd [3]. Other claims for AMR exist in ^{108}Cd [4], ^{109}Cd, ^{100}Pd.

For nuclei in A~110 region (Z~50), proton hole(s) in high-Ω $g_{9/2}$ orbitals coupled to $\mathbf{j}_\pi$ and low-Ω $h_{11/2}$, $g_{7/2}$ neutrons to $\mathbf{j}_\nu$ with small nuclear deformation ($\beta \leq 0.15$) play an important role in the interpretation of the phenomenon of AMR. We are interested to look for AMR in ^{105}Cd. Previous spectroscopy of ^{105}Cd [5, 6] reveals that the negative parity Yrast band (Band 3 [6]) in this nucleus is built upon a single $\nu h_{11/2}$ neutron. The first band crossing is observed at a rotational frequency of ~0.44 MeV. This has been interpreted as most likely due to alignment of $\nu g_{7/2}$ neutrons. It is expected that the increase in spin beyond $I=23/2^-$ is due to alignment of a pair of $g_{9/2}$ proton hole vectors (shears mechanism) with a small contribution from the weakly deformed core. To study this, we have performed an experiment with the Indian National Gamma Array (INGA) at Inter University Accelerator Centre (IUAC) to measure the lifetime of these states using Doppler Shift Attenuation Method (DSAM) technique.

Excited states of ^{105}Cd nuclei have been populated by using the ^{94}Zr(^{16}O, 5n) ^{105}Cd reaction at a beam energy of 93 MeV delivered by the 15-UD Pelletron accelerator at IUAC, New Delhi. The target consisted of ~1.35 mg/cm^2 isotopically enriched ^{94}Zr on ^{197}Au backing of thickness 8.86 mg/cm^2. The emitted γ - rays were detected utilizing the INGA setup consisting of 14 Compton suppressed Clover detectors arranged in five rings viz. 32°, 57°, 90°, 123° and 148° with respect to the beam direction. Both 2-fold and 3-fold coincidence data were acquired in list mode form using CANDLE, an acquisition system developed at IUAC. The coincidence events were sorted into Eγ – Eγ symmetric as well as asymmetric matrices after gain matching in the offline analysis by using the INGASORT program.

The negative parity yrast band of ^{105}Cd (in which we predict AMR) was established up to $I^{\pi} = 47/2^{-}$ in the previous works [5,6], which is found to be in good agreement with the present result. This is shown in fig.1. Three new lines viz. 825, 1057 and 1285 keV were observed and interpreted as side feeding transitions to $19/2^{-}$ level.

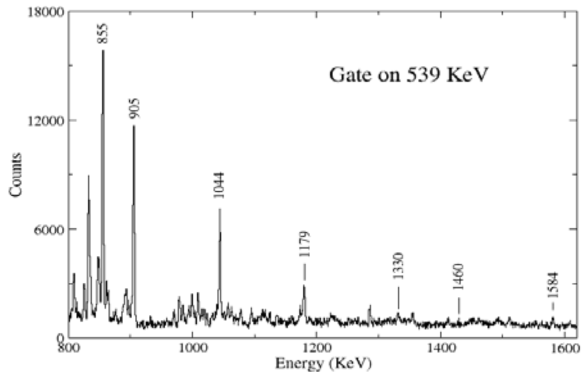

Fig. 1. Coincident γ-ray spectrum of the yrast band of ^{105}Cd well populated upto spin $47/2^{-}$

LINESHAPE program is being used to deduce the lifetime of the levels in the negative parity yrast band. 539 keV gated spectrum, for detectors at extreme forward (32° w.r.t. beam direction) and extreme backward (148° w.r.t. beam direction) angles has been used for lineshape fitting. Preliminary lineshape fitting for the 1180 keV peak has been shown in fig.2.

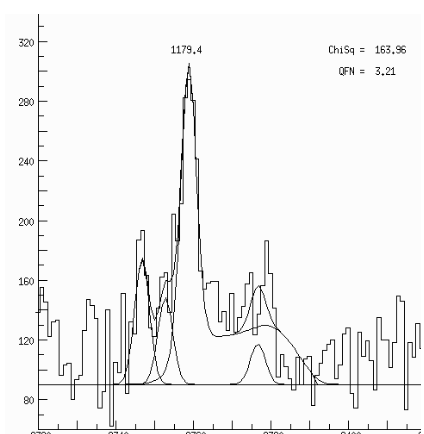

Fig. 2(a) 1180 keV peak for detectors at 32° w.r.t. the beam direction in 539 keV gated spectrum.

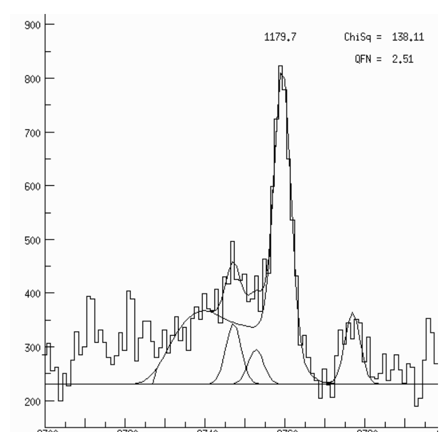

Fig. 2(b) 1180 keV peak for detectors at 148° w.r.t. the beam direction in 539 keV gated spectrum.

Further analysis of the data is currently in progress.

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

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5.1.4 Structure of ^{169}W

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The very neutron-deficient nuclei in the mass 170 region are expected to be rather soft with respect to β and γ vibration and the polarizing effect of the last nucleon becomes very important. In recent years evidence for stable triaxial shape has been investigated and established in several odd-A Lu nuclei in the form of wobbling bands [1]. TSD bands have also been observed in Hf isotopes but wobbling nature has not been confirmed. So far no experimental evidence for such bands has been found in odd-odd nuclei. The rotational bands in this mass region exhibit various features like multi-quasiparticle excitation based on both low and high K values, signature splitting, band inversion etc [2]. The present experiment has been performed to look for the connecting transitions, extend the already observed bands and to observe wobbling, if possible.

A ^{141}Pr target of thickness 1.8 mg/cm^2 with a gold backing of 6.8 mg/cm^2 was bombarded with a 155 MeV ^{32}S beam obtained from IUAC Pelletron. The beam current was 0.6 pnA on the target. The two-fold coincidence data were detected in the list mode using the INGA array comprising of 13 Compton suppressed clover detectors. For data acquisition the electronics comprising of the IUAC Clover modules [3] and the software CANDLE [4] were used. The data analysis is being performed with the program INGASORT [5].

From the preliminary analysis it is evident that the isotopes populated with considerable yield are ^{169}Re, ^{168,169}W, and ^{168}Re with a relatively small population. This is in conformity with the PACE4 calculations. The sum spectrum generated by putting gates on the 209, 368, 487,576 and 631 keV transitions of the yrast positive- parity band [6] in ^{169}W is shown in Fig.1a. Also included in the figure are the spectra generated by adding the 415 and 465 keV transitions belonging to the (-,+1/2) band (band 1, Ref. [6]). As evident from the figure, the present coincidence data are in conformity with the earlier results [6]. From the figure it is evident that the two bands are strongly interconnected.

The absolute energy values of the reported bands [Ref.6] are not known. Even the relative positions of the two bands were not established as the connecting transitions between the two bands were not observed. The gated spectra obtained in the present experiment (Fig.1a and b) show two new transitions at 344 and 919 keV which possibly connect the ($29/2^-$) state (band 1, Ref. [6]) with the $29/2^+$ and $25/2^+$ states of the yrast band respectively (Fig.2).

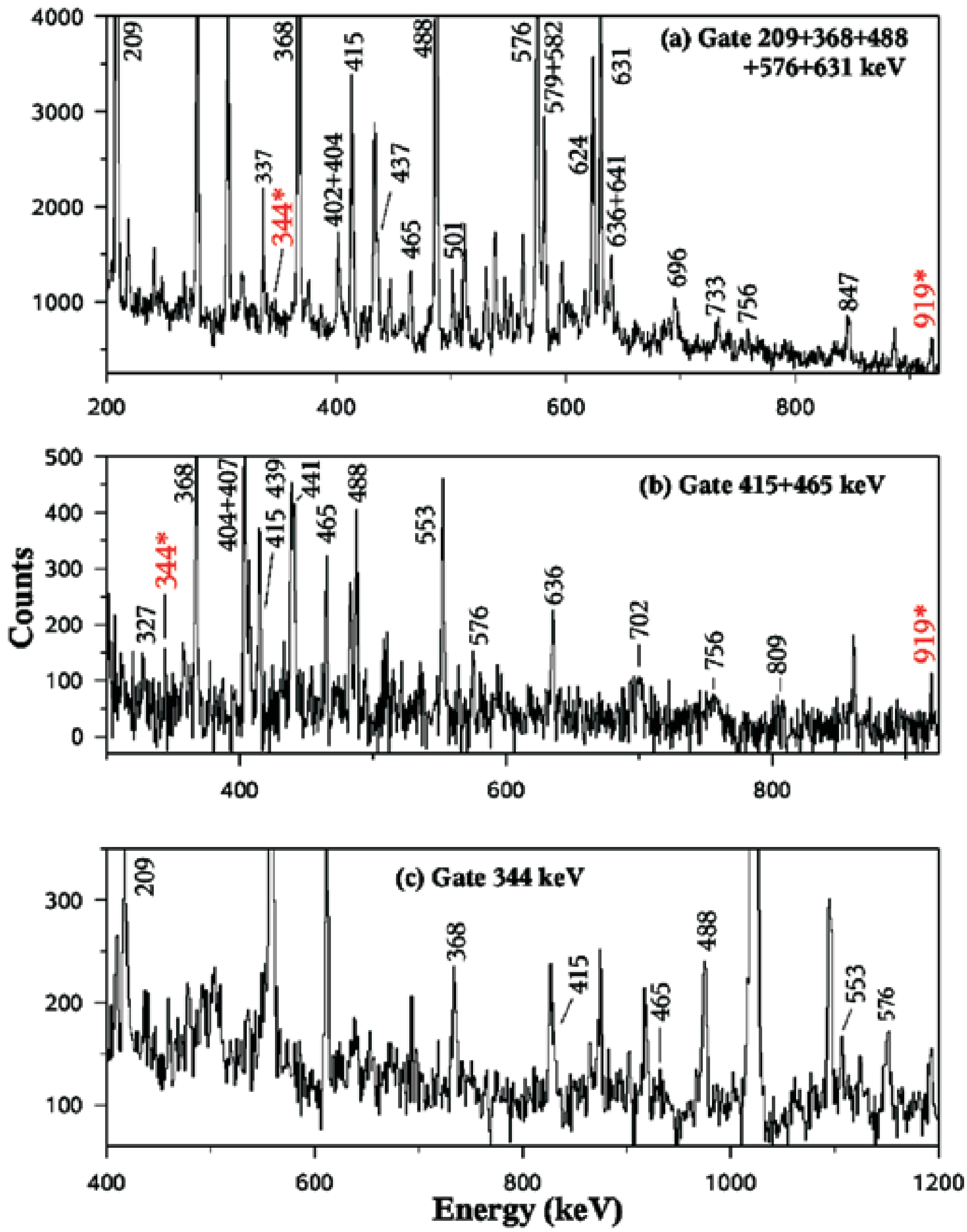

Fig.1. Gated spectra form the experiment

To establish the present observation, the spectra obtained by gating the new 344 keV line have been shown in Fig 1c. The gate clearly shows the various transitions belonging two both bands (Fig. 2). It is to be noted that the 919 keV gate (not shown) shows lines up to 488 keV further confirming the placement of the two new lines. The relative intensities for the 465, 553 and 636 keV lines normalized with respect to the 415 keV gamma- ray belonging to band 1 (Fig.2) obtained in 209 keV gate of the yrast positive-parity band is in agreement with the corresponding values obtained in the gate generated by adding the 439 and 442 keV transitions belonging to band 1 (Fig. 2) giving additional support to our result.

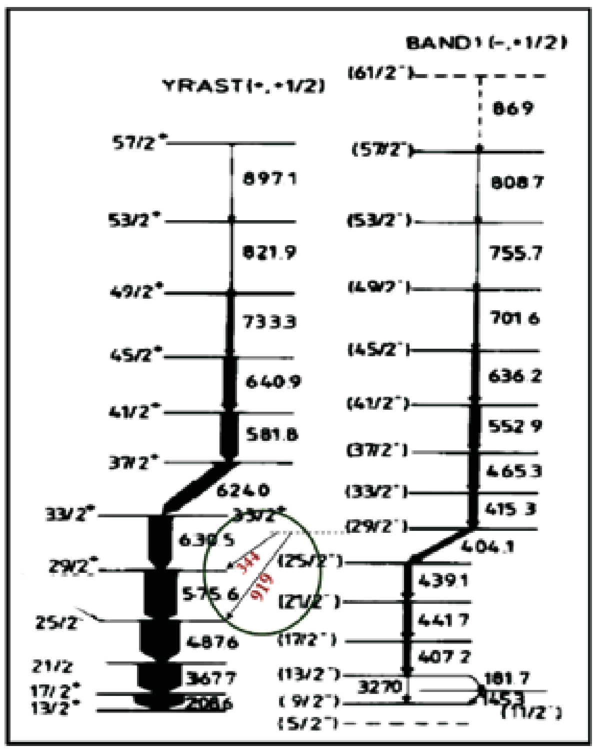

Fig. 2. The partial level scheme showing the new connecting transitions

These two new transitions 344 and 919 keV may fix the relative positions of the two bands. Further data analysis is in progress. DCO and DSAM analysis shall be performed to measure the spin-parity and lifetimes of the excited states wherever possible.

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5.1.5 Study of high-spin structure of the nuclei around Z = 82 shell closure

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The neutron deficient nuclei near Z = 82 region are known for rich variety of structural phenomena and interesting shape properties. It has been found that the heavier bismuth and thallium nuclei with A > 200 are spherical and the lighter nuclei with A < 194 have rotational bands indicating deformation [1 - 3]. The excitation energies of the proton intruder levels, $\pi s_{1/2}$ for Bi and $\pi h_{9/2}$ for Tl nuclei, have been observed to decrease with the decrease in neutron number as these intruder proton levels have shape driving effect towards oblate deformation. On the other hand the neutron orbitals near the Fermi level have prolate driving effect. In this region a new kind of excitation phenomena namely, magnetic rotational band has also been observed [4 – 5]. Recently some indication of onset of deformation at N = 112 has been found from the theoretical and experimental investigation of ^{195}Bi [6]. A small deformed (prolate) shell gap at N = 112 apparently triggers this onset of deformation. It is interesting to study the effect of this two opposite shape driving effects in an odd-odd nucleus. Moreover, the $\Delta L = 3$, $\Delta J = 3$ levels $\nu f_{7/2}$ and $\nu i_{13/2}$ are accessible to the odd-neutron in light Bi isotopes. So

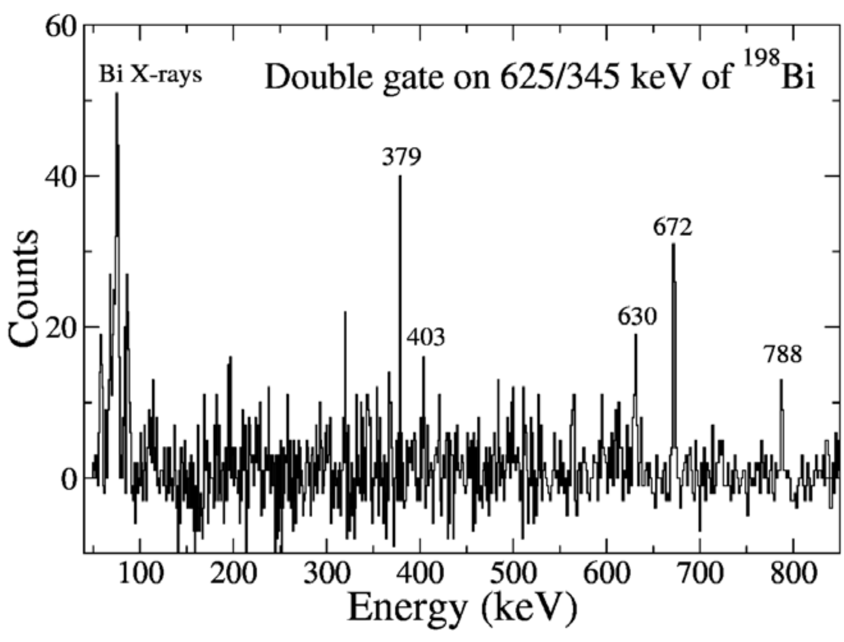

Fig.1. Double gated spectrum projected from cube is shown with gates on known transitions in ^{198}Bi

the octupole correlation is expected to be enhanced and its effect in stabilizing the shape of these nuclei can be studied. It is also interesting to study magnetic rotational bands for nearly spherical Bi nuclei. The present in-beam gamma spectroscopic investigations are planned to probe for the above-mentioned structural features in the Bi and Tl nuclei having atomic number on either side of Z = 82 shell closure.

Excited states of the ^{195,197,198,199}Bi and ^{194}Tl have been populated via the fusion-evaporation reactions ^{nat}Re(^{16}O,xnypγ) at 112.5 MeV of beam energy from the 15-UD Pelletron at IUAC, New Delhi, India. The target was a thick (18.5 mg/cm^2) natural rhenium target. The isotopic ratio of ^{185}Re and ^{187}Re in the natural rhenium is 37:63. The γ-γ-γ data were taken in the list mode using INGA detector array consisted, at the time of the experiment, of 15 Compton suppressed clover HPGe. The data were sorted into γ-γ matrix and γ-γ-γ cube. A double gated spectrum projected from the cube is shown in Fig.1. The INGASORT and the RADWARE codes are being used for the analysis. New gamma transitions have been identified for ^{195,197,198,199}Bi and ^{194}Tl from the result of preliminary analysis. Further detailed analysis is in progress.

We would like to gratefully acknowledge the support provided by the Pelletron stuff. The untiring help of Dr. P. Sugathan during the course of the experiment is also gratefully acknowledged. Many fruitful discussions with Mr. N. Madhavan and Mr. A. Jhingan are acknowledged.

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5.1.6 Transition Rates in Mirror Nuclei ^{35}Ar and ^{35}Cl

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Mirror nuclei are a pair of nuclei where the number of protons and neutrons are interchanged. The study of differences between excitation energies of analogue states in mirror pairs (Mirror Energy Differences or MED) has been pursued to test the charge symmetry of nuclear force. A complementary way to test isospin symmetry is based on the investigation of the electromagnetic decay properties in mirror pairs [1].

Anomalous MED in sd shell nuclei, *viz*., ^{35}Cl and ^{35}Ar has been observed [2]. But so far the electromagnetic decay properties deduced from the level lifetimes in this mirror pair have not been compared. We have already studied ^{35}Cl and have estimated lifetimes of quite a few levels [3]. But for ^{35}Ar, lifetime information for none of the levels is available. In the present work, more precise measurements of the lifetimes of excited higher spin levels of ^{35}Cl have been done. Mixing ratios of a few gamma transitions in ^{35}Ar have been determined. These data along with the assumption of isospin symmetry will provide estimate of lifetimes of levels in ^{35}Ar necessary for planning future experiment.

High-spin states in ^{35}Cl and ^{35}Ar have been populated through ^{12}C+^{28}Si (110 MeV) reaction in the inverse kinematics. The target was ^{12}C (50 μg/cm^2) evaporated on ~ 18 mg/cm^2 Au backing. Gamma - gamma coincidence measurement has been done using the multi-detector array of thirteen Compton suppressed Clover detectors (INGA setup) at Inter University Accelerator Centre (IUAC), New Delhi. In the set up, the power supplies, INGA modules, 8 channel 13-bit CAMAC ADC-814 and the Multi CAMAC Crate data acquisition system CANDLE [4] were all developed at IUAC. The detectors were placed at 148^o (4), 123^o (2), 90^o (4), 57^o (2) and 32^o (1). Data analysis was done using the improved version of the analysis program INGASORT [5]. A typical gated spectrum (Fig. 1) generated by putting gate on the 1446 keV transition in ^{35}Ar shows the quality and quantity of data for this weakly populated (~ 20 mb) channel.

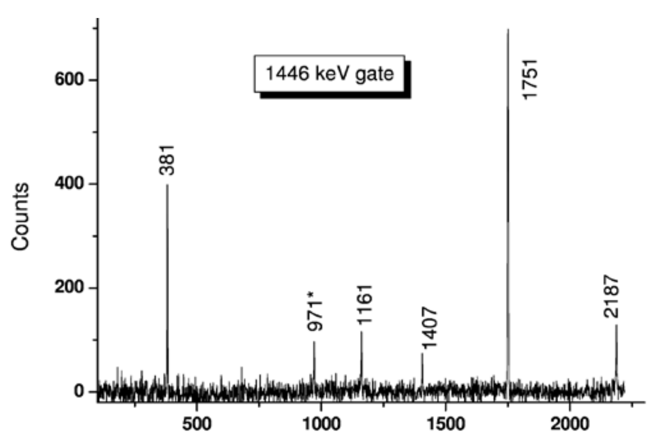

Fig.1. A typical gated spectrum for ^{35}Ar.

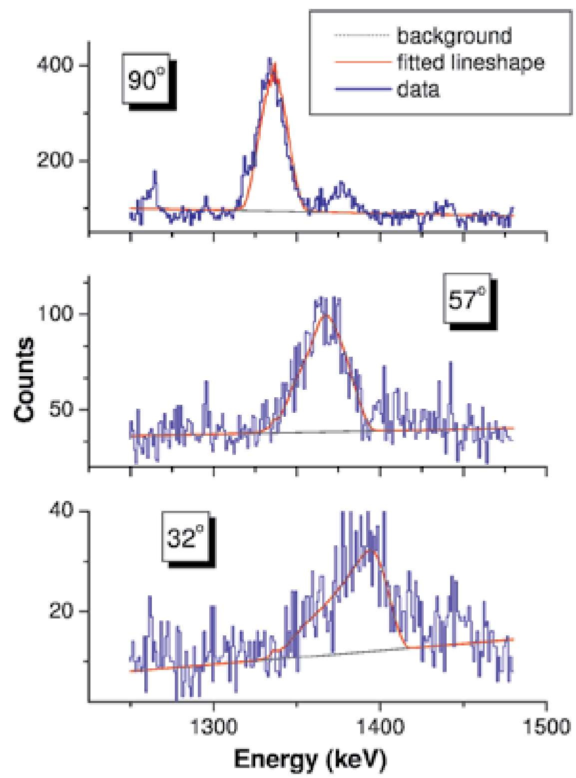

Fig. 2. Lineshapes (both experimental and fitted) for 1337 keV

Fig.2 shows lineshapes for a gamma ray (1337 keV) emitted from 10181 keV level (tentative spin is $19/2^+$) in ^{35}Cl at 90° and other forward angles. The spectra obtained at backward angles are not shown as they contained contaminant peaks. The preliminary estimation of the lifetime using the LINESHAPE [6] code is 0.18 ps. As the cross-section for

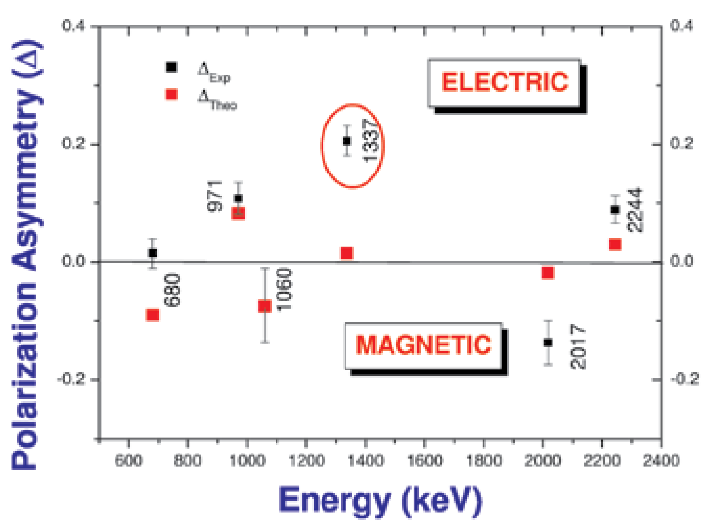

Fig. 3. Polarization asymmetry (both experimental and theoretical) for transitions of ^{35}Cl.

^{35}Ar was one order of magnitude lower than that for ^{35}Cl, data for ^{35}Ar were inadequate to get proper lineshape spectrum. But the DCO data and the singles data for angular distribution have been used to determine the multipolarities and mixing ratios δ of different transitions, which were not known so for. Polarisation measurements have also been done for the first time for ^{35}Ar. The polarisation data (Fig.3) for ^{35}Cl indicate a probable change of parity for the 10181 keV level. Detailed data analysis along with theoretical endeavors to understand the structure of this mirror pair is in progress.

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5.1.7 Evidence of Shear Band in ^{111}In

P. Banerjee[1], S. Ganguly[2], M.K. Pradhan[1], I. Ray[1], A. Goswami[1], M. Saha-Sarkar[1], S. Bhattacharya[1], A. Dey[1], H.P. Sharma[3], A. K. Mitra[1], A. Singh[5], M.K. Raju[6], N. Kaur[5], S. Muralithar[4], R.P. Singh[4], R. K. Bhowmik[4]

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Excited states of ^{111}In were populated in ^{100}Mo + ^{19}F at E = 105 MeV. Two high-*K* bands, built on $19/2^+$ and $27/2^+$ states and populated up to spins $(43/2^+)$ and $(33/2^+)$, respectively, are being presently studied in ^{111}In. The partial results for the first band are presented here. Figure 1 shows the partial level scheme for this band. No higher-lying state belonging to the band could be established from the present data. Mean lifetimes of four states in this band have been estimated for the first time from the DSA data. Representative DSA spectra along with the lineshapes (obtained using the code LINESHAPE) for the 371.3 and 535.4 keV γ-rays belonging to the band are also shown in Fig. 1. The lifetimes include the effects of both cascade as well as direct feedings to the states. Errors in the lifetime results include the statistical uncertainty in the data and the effect of an assumed 50% uncertainty in the side-feeding times

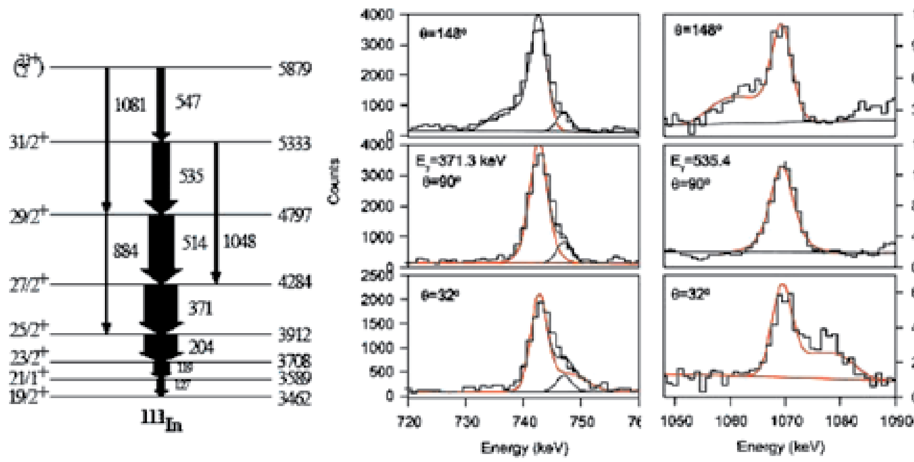

Fig. 1. Partial level scheme of ^{111}In (left) showing only in-band transitions and line shape fits to DSA data for the 371.3 and 535.4 keV transitions.

The band is proposed to have the configuration $\pi(g_{9/2})^{-1}(\nu h_{11/2})^{+2}$ involving no particle-hole excitation. The B(E2) values for the cross-over *E2* transitions correspond to a average quadrupole deformation of 0.05. The small deformation and the limited range of angular momentum for the states of the band are in support of this configuration. In addition B(M1) values decrease significantly from $2.7^{+0.56}_{-0.48}$ μ_N^2 for the $27/2^+ \rightarrow 25/2^+$ transition to 0.24±0.04 μ_N^2 for the $(33/2^+) \rightarrow 31/2^+$ γ-ray. The results favour the interpretation of the states as arising from shears mechanism.

5.1.8 Study of strongly deformed intruder band in ^{113}Sb

P. Banerjee[1], S. Ganguly[2], M.K. Pradhan[1], I. Ray[1], A. Goswami[1], M. Saha-Sarkar[1], S. Bhattacharya[1], A. Dey[1], H.P. Sharma[3], A. K. Mitra[1], A. Singh[5], M.K. Raju[6], N. Kaur[5], S. Muralithar[4], R.P. Singh[4], R. K. Bhowmik[4]

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Excited states of the Δ*I*=2 band built upon the 3.21 MeV state in ^{113}Sb have been populated up to $J^{\varpi}=67/2^-$ and an excitation energy of E_x=15.71 MeV in the reaction ^{100}Mo(^{19}F, 6n) at E = 105 MeV. Large Doppler shifts have been observed for all γ-rays depopulating states up to the $63/2^-$ state. A detailed analysis of the results is in progress. An earlier study of this band using the data from the INGA at the VECC, Kolkata, had provided lifetime results for states up to $43/2^-$. The present work will extend the lifetime information and provide a better understanding of the structure of the states belonging to this band.

Other nuclei populated in the work are ^{110}In and ^{111,112}Sn. The results will be analyzed shortly.

5.1.9 Search for chiral partner bands in ^{98}Tc

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Candidate chiral doublet bands are based on unique parity high-*j* particle-hole nucleon configurations. In the mass $A \sim 100$ region, such bands have been found in several of the odd-odd and odd-*A* Rh, Tc and Ag nuclei [1, 2]. For a deeper understanding of the phenomenon of chirality, it is important to map out the $A \sim 100$ region to search for signatures of this phenomena. The aim of the present experiment is to look for possible chiral candidate doublet bands in ^{98}Tc. TRS calculations for the -ve parity band based on the $\pi g_{9/2}^{-1} \otimes \nu h_{11/2}$ configuration in ^{98}Tc shows minima at $\beta_2 \sim 0.2$ and $\gamma \sim -29° - 27°$ are obtained depicting triaxial shape for the nucleus.

High spin states in the odd-*Z* ^{98}Tc nucleus were populated using the ^{94}Zr (^{7}Li, 3n) ^{98}Tc reaction at an incident beam energy of 32 MeV. The ^{7}Li 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) [3] which at the time of the experiment comprised of 15 Compton suppressed Clover detectors. The Clover detectors were arranged in five rings *viz.* 32^0, 57^0, 90^0, 123^0 and 148^0 with respect to the beam direction. The total coverage of Ge crystals is about 25% of 4π corresponding to a total photo-peak efficiency of ~ 5%. The distance between the target and the detector is ~ 24 cm. The isotopically enriched ^{94}Zr target was ~ 4.4 mg/cm^2 thick. 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 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. From the preliminary analysis of our experimental data, the obtained level scheme (shown in Fig. 1) of ^{98}Tc has been extended up to $J^{\pi} = 19^{-}$ and excitation energy of $E_x \sim 6$ MeV with the addition of 50 new gamma-transitions. The partner band (band-B) and the connecting gamma-transitions from the partner band (B) to the yrast band (A) have been found for the first time, in addition to that reported earlier [4]. Similar decay pattern is also observed in odd-odd Rh and Tc nuclei. Gated sum spectrum of 402 and 984 keV transitions for band-A and band-B are shown in Fig. 2.

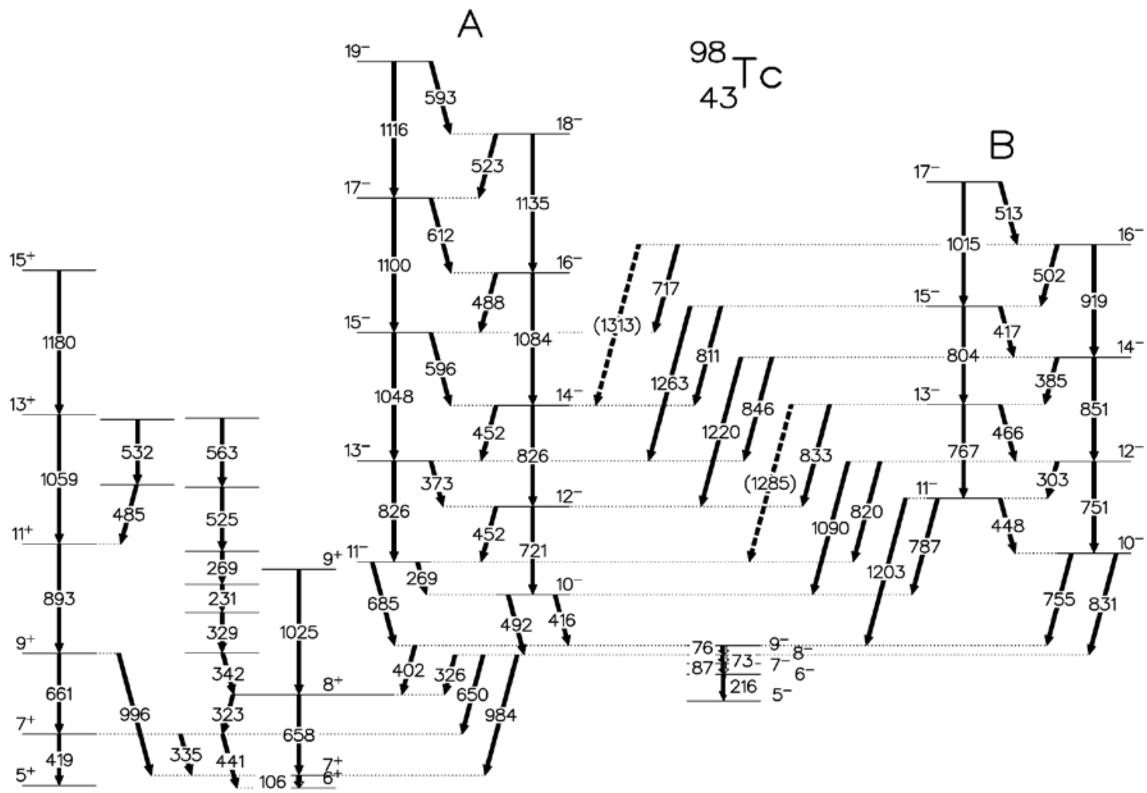

Fig. 1. Preliminary level scheme of ^{98}Tc deduced from the present work

The variation of excitation energy with spin for the doublet structure shows the energy degeneracy with increasing spin which is an indication of stable chiral geometry. Beyond the spin value 12ħ the staggering parameter S(I) = [E(I) – E(I – 1)]/2I show relatively smooth variation as a function of spin. A stringent test of chirality can only be from the B(M1) and B(E2) strengths for the doublet bands. Lifetime measurements are however required.

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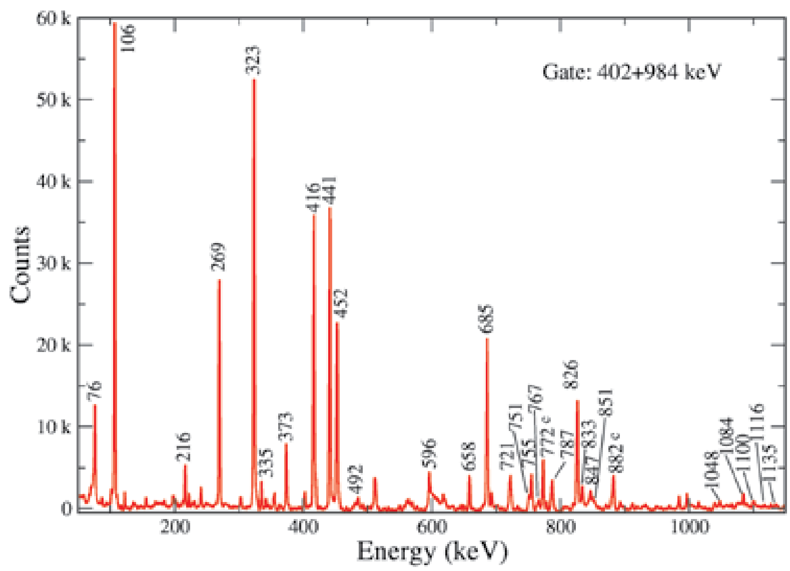

Fig. 2. Partial γ–γ coincidence gated sum spectrum of 402 and 984 keV transitions showing some of the gamma rays of band-A and band-B of ^{98}Tc.

5.1.10 In beam Spectroscopy of Negative Parity States in ^{135}Pr

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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 [1-3]. It was suggested by Frauendorf et al. [4-9] that these sequences (bands) offer a new type of nuclear rotation called magnetic rotation (MR). In special cases the band continues its MR character after the band crossing from one configuration to another (known as MR band crossing). In the mass A = 135 region, such crossing of MR bands have been explored by Priyanka et al. in ^{137}Pr nuclei [10]. Most favorable case in this mass region corresponds to the situation wherein the particles/holes occupy the $h_{11/2}$ orbit with 3qp configuration and have possibility for more than one 5qp configuration. The present experiment was performed to address this issue, to assign the spin and parity for negative states, and to measure the lifetimes using DSAM. We report here our results on the level structure of ^{135}Pr nuclei that has not been explored for MR earlier. The high spin spectroscopy of ^{135}Pr has been studied earlier by using 6 Ge detectors [11]. The level scheme is known to about 6 MeV of excitation energy and tentatively up to $22\hbar$ of angular momentum.

The high spin states in ^{135}Pr were populated by the reaction ^{123}Sb(^{16}O,4n)^{135}Pr using a ^{16}O beam of 82 MeV from the Pelletron accelerator of Inter University Accelerator Center (IUAC), New Delhi. The target consisted of a 800 μg/cm^2 ^{123}Sb with 10mg/cm^2 ^{197}Au backing. The γ-rays were detected using Indian National Gamma Array (INGA) during the second

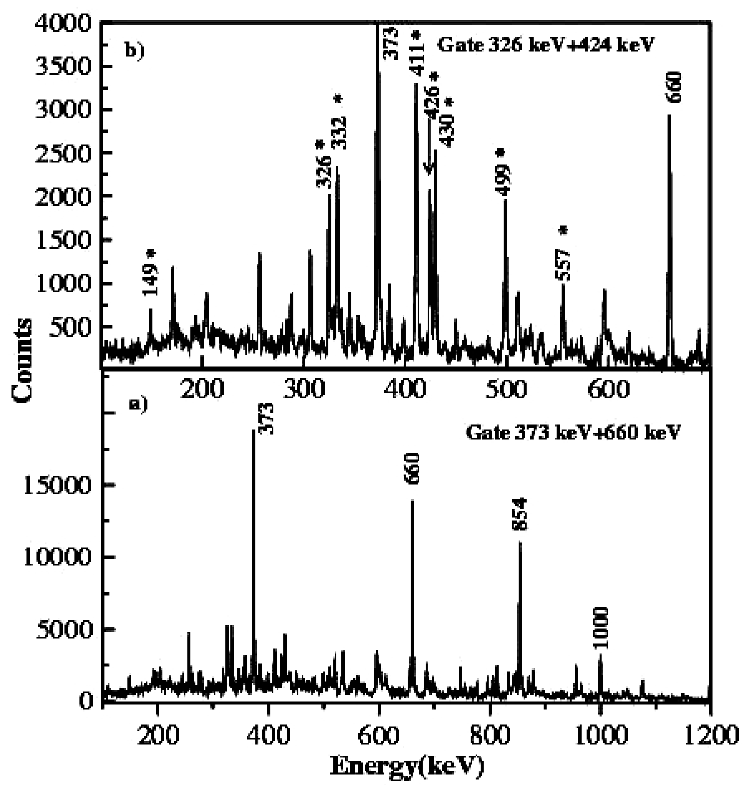

Fig. 1a) Sum (373 keV+660 keV) gate spectrum in the lower panel shows the γ- rays of the ground band & b) The sum (326 keV+424 keV) gate shown in the upper panel represents the γ- rays of the negative parity states.

campaign of INGA at IUAC. The array consisted of 15 Compton suppressed clover HPGe detectors placed at 148°, 123°, 90°, 57°, 32° with 4, 2, 4, 2 and 3 detectors respectively. The list mode data was taken in triple and higher fold. The excitation function was performed by taking the detector at 90° using 4 MeV step (lab. energy between 70-82 MeV). The data were sorted using INGASORT program to produce symmetrised E_γ -E_γ matrices. Relative efficiency calculations have been carried out. RADWARE analysis package is being used to establish coincidence and intensity relationships for various gamma transitions.

In the upper panel of Fig. 1, the sequence of 149 keV, 332 keV, 411 keV, 430 keV, 326 keV, 426 keV, 499 keV and 557 keV γ-rays (labeled by asterisk *). This sequence constitute a dipole band which has similar behavior as negative parity states in ^{137}Pr [10]. The Tilted Axis Calculations (TAC) will be helpful to understand the configuration of this band. Further data analysis and theoretical calculations are in progress.

All the members of INGA collaboration are gratefully acknowledged for setting up the array. The authors also gratefully acknowledge the support provided by the Pelletron staff at IUAC, New Delhi during the experiment. Financial support from the UGC-DAE-CSR Kolkata Center, India, at Department of Physics and Astrophysics, University of Delhi, is acknowledged.

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

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A few spectroscopic investigations on the proton rich lighter Francium isotopes have been made recently. While a complete study of the $^{205\text{-}207}$Fr nuclei[1], using Gammasphere and the HERCULES II array for filtering out the evaporation residues from the fission background, revealed the existence of shears band in ^{207}Fr, investigations on the $^{208\text{-}210}$Fr nuclei[2, 3] have resulted in contradictory conclusions. Spectroscopic studies made using the YRAST BALL array, comprising six Compton suppressed Clover HPGe detectors[2], coupled to the SASSYER recoil separator for selecting the evaporation residues had concluded that the pair of intense gamma rays of 632 keV (ground state transition) and 194 keV (isomeric transition) belong to ^{209}Fr. The half life of the isomeric transition was measured to be 446(14) ns. At the same time, another independent study of isomeric decay of proton rich nuclei produced by projectile fragmentation reaction of ^{238}U beam at 900 MeV/u on ^{9}Be target at the Fragment Recoil Separator (FRS) facility of GSI, Darmstadt, Germany had assigned the same pair of gamma rays to ^{208}Fr[3]. Half life of the 194 keV isomeric transition was reported to be ~ 200 ns, though the prompt transitions above the isomer could not be observed because of experimental constraints. However, during the final phase of data analysis, tentative assignment of levels and our new results on the isomeric decays of ^{208}Fr reported earlier [4], a report on the assignments of levels in ^{208}Fr was published by G. D. Dracoulis et al.[5]. The differences in our methods, the results of observations on the isomeric transitions, new transitions over and above those reported therein, and the basis for our assignments of the isomeric transitions to ^{208}Fr are subsequently reported[6].

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 at the INGA-HYRA beam line.

From the online data taken at 100 MeV beam energy, the γ-γ matrices, Francium X-ray gated γ-γ matrices, the prompt and the delayed γ-γ matrices and the γ-gated γ-ΔT matrices were constructed for establishing the level scheme and resolving the isomeric transitions. The observed γ-rays and their relative intensities match reasonably well with those obtained recently by Dracoulis et al.[5]. However, quite a few additional transitions were observed and included in the level scheme shown in Fig. 1. DCO analysis was also performed with the data taken at (90^o; 148^o) and (90^o; 123^o) angle pairs. Apart from one sequence of transitions (I) passing through 359 and 724 KeV, which directly feeds the 632 KeV first excited state, two major sequences (III and V) and three minor sequences (II, IV and VI) of transitions, which pass through the isomeric 826 KeV level, have been observed. Out of these, three sequences (II, III and IV) of transitions pass through the strong 569 KeV transition, and two (V and VI) through the sequence of 303 and 322 KeV transitions. About 25 new transitions, over and above those observed by Dracoulis et al.[5], were found. The half life of the 826 KeV isomeric level was extracted from γ-gated ΔT spectrum. Half life of 233(18) ns was obtained, which is consistent with the result quoted in Ref. [3]. A new isomeric level at 1209 KeV was also obtained for the first time in this experiment. Half life of the isomeric level was measured as: 33(7) ns[6]. Further details are being written up for publication of the results [7]. Interpretation of the results from the nuclear structure calculations is currently undertaken.

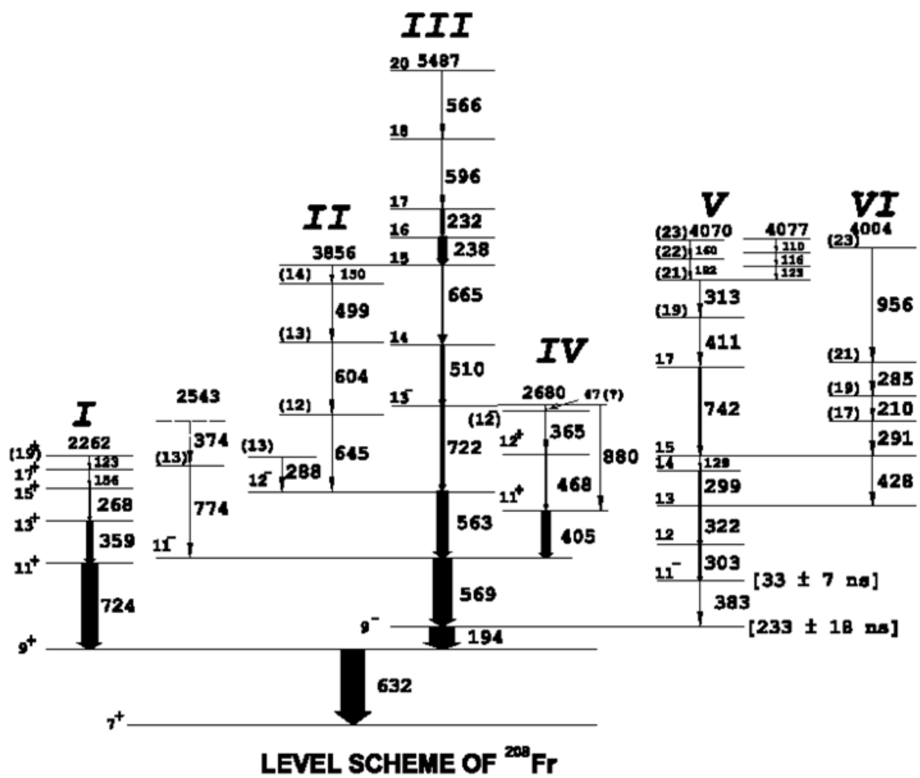

Fig 1. Tentative level scheme of ^{208}Fr.

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5.1.12 Lifetime Measurement in ^{139}Pr

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The transitional nucleus ^{139}Pr, with N=80 and Z=59, has valance quasiparticles of both kinds distributed over the same configuration space, viz., $1g_{7/2}$, $2d_{5/2}$, $2d_{3/2}$, $3s_{1/2}$ and $1h_{11/2}$. The spectroscopic study of this nucleus offers a good scope to observe a rich variety of inter-nucleonic interactions, especially those which involve the nucleons residing in the strongly shape driving π and ν intruder $h_{11/2}$ orbitals. The occurrence of yrast isomers is another feature for the nuclei in this region. The study of these isomers gives us the active configurations of the nuclear state, which, in turn, gives input to large basis shell model calculations. Earlier we have developed the level scheme of ^{139}Pr up to ~7.2 MeV excitation energy and 39/2 ħ spin [1]. In this work, we have conjectured the presence of some medium spin isomers in the level scheme. In a very recent experiment, Petrache et al. [2] has reported about the existence of a long lived isomer (~ 400 ns) at a very high spin (~ 20 ħ) in ^{140,139}Nd nuclei and collective deformed bands at higher excitation. A Cranked Nilsson Strutinsky (CNS) calculation for the ^{139}Pr nucleus predicts the existence of an isomer (~20 ħ) and triaxial bands at higher excitation energy. Therefore, in order to identify the isomer and to observe the aforesaid bands, we need to perform a pulsed beam experiment. This kind of experiment will not only help to observe the weakly populated triaxial bands but will give us the estimate of the lifetime of the yrast isomers present in the lower and medium spin regime, also.

The pulsed beam experiment using Indian National Gamma Array setup at IUAC has been carried out following the reaction ^{14}N(^{130}Te, 5n)^{139}Pr at 75 MeV beam energy. In this experiment a pulsed ^{14}N beam @4MHz was used and data was taken in such a manner that the prompt as well as delayed transitions could be studied in offline analysis. From the preliminary analysis, the TAC spectra corresponding to different transitions in ^{139}Pr have been generated using part of the data and after matching the extracted timing information of individual crystals of the Clover from their TDC.

From a preliminary analysis of the data indication of various lifetimes have been observed. Fig.1 represents the TAC spectrum corresponding to the 708.1 KeV transition of ^{139}Pr having a known lifetime of ~36 ns. Fig. 2 represents the 1330.7 KeV gated spectra belonging to the ^{139}Pr nucleus, in which indication of various new transitions have been observed. A detailed analysis of the data for measurements on lifetime and γ-γ coincidence is in progress.

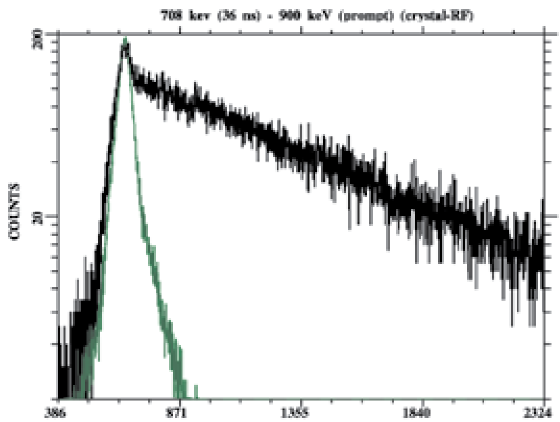

Fig. 1. Projection of RF-γ TAC in coincidence with 708 KeV (^{139}Pr). The corresponding projection for the prompt transition of 900 KeV is also shown for comparison.

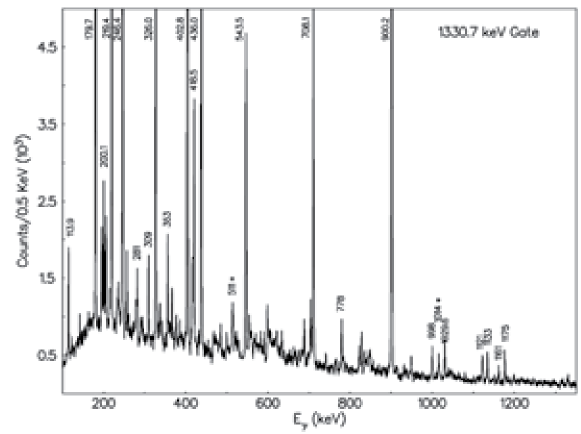

Fig. 2. Gated spectrum of 1330.7 KeV of ^{139}Pr.

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5.1.13 First observation of high excited states in ^{126}I

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The phenomena of chirality and decoupling were our main motivation towards studying the odd-odd nucleus ^{126}I. So far, in the literature the nucleus ^{126}I was produced using the reaction ^{126}Te(p, n)^{126}I and very low lying states have been reported [1]. In our earlier experiments, we identified many gamma transitions belonging to ^{126}I [2]. In the first measurement we identified the gamma lines belonging to ^{126}I populated through α-channel *via* incomplete fusion reaction. Second experiment was the excitation function measurement using ^{6,7}Li beams on ^{124}Sn target.

In July 2009, we populated the high spin states of ^{126}I with very good cross-section using the Indian National Gamma Array (INGA). The reaction used was ^{124}Sn (^{7}Li, 5n) ^{126}I at the beam energy of 50 MeV delivered by Pelletron accelerator at IUAC. The experimental set-up, called INGA, consisted of 15 clover detectors. A self-supporting target of thickness 2.7 mg/cm^2 was used. The excitation function measurement was performed to find the suitable beam energy for the population of ^{126}I. The other nuclei which were produced with good cross-section were ^{125}I, ^{127}I and ^{126}Te. The triple gamma coincidence data were collected at the rate of 3 kHz. The data were initially calibrated and gain matched. From the E_γ *vs* E_γ matrix, the projected spectra for various energy gates were generated. Figure 1 shows examples of projected spectra with gates on gamma transitions with energy values 325 keV and 866 keV. The partial decay scheme is shown in Fig. 2. Further data analysis is currently in progress.

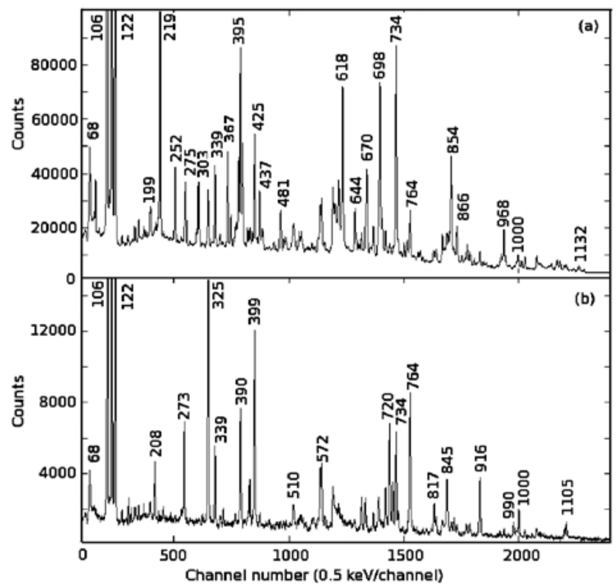

Fig. 1. Projected spectra with gates on (a) 325 keV & (b) 866 keV

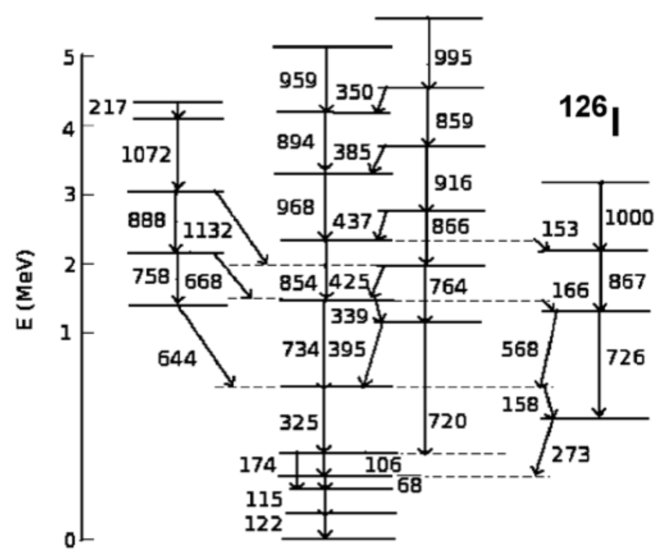

Fig. 2. Partial level scheme of ^{126}I

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5.1.14 Incomplete fusion dynamics in ^{16}O + ^{124}Sn system by spin distribution measurement

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In the past few decades, the study of incomplete fusion (ICF) dynamics of heavy ions has been the subject of interest at projectile energies above the Coulomb barrier [1-5] in nuclear physics. The first experimental evidence of ICF dynamics was given by Britt and Quinton [6], who observed the break-up of the incident projectiles like ^{12}C, ^{14}N and ^{16}O into alpha clusters in an interaction with the surface of the target nucleus at ≈10.5 MeV/nucleon bombarding energies. Later on, Galin et al. [7] carried out similar studies and observed PLFs in the forward cone and termed these reactions, leading to PLFs as "incomplete fusion" (ICF). These reactions were termed as incomplete fusion (ICF) reaction, in which a part of projectile behaves as a spectator and moves in the forward cone while the remainder fuses with the target nucleus, leading to transfer of a fraction of the incident momentum to the target nucleus. In the complete fusion (CF) process of the projectile with the target, the highly excited compound system decays by evaporating low energy nucleons and α-particles at the equilibrium stage. However, major advances in the study of ICF dynamics has taken place after the charged particle-γ coincidence measurements by Inamura *et al.* [8] for ^{14}N + ^{159}Tb system at beam energy ≈7 MeV/nucleons.

Several theoretical approaches have been proposed to explain ICF dynamics. The break-up fusion (BUF) model of Udagawa and Tamura [9] based on DWBA formalism explained ICF in terms of break-up of the projectile in the nuclear field (e.g. projectile ^{16}O may break-up into ^{12}C + ^{4}He and/or ^{8}Be + ^{8}Be) as it approaches to the nuclear field of target nucleus. It is assumed that either of the fragments may fuse with the target nucleus, while the remnant moves as a spectator and give rise the projectile like fragments (PLFs). The Sumrule model of Wilczynski et al. [10] assumes that the various ICF channels are localized in the angular momentum space above the critical angular momentum for the complete fusion of the projectile and target. Other models include promptly emitted particle (PEP) model [11], hot spot model [12], and multistep direct reaction model [13]. The existing models have been used to fit the experimental data above 10.5 MeV/nucleon energies. However, at energies less than 10 MeV/nucleon, no theoretical model is available to explain ICF process data satisfactorily.

Most of the ICF dynamics studies [14-17] by charged particle-gamma coincidence technique have been carried out with low-Z ($Z \leq 10$) projectile induced reactions on heavy targets ($A > 150$). These studies are mainly focused on γ- ray yield measurements in coincidence with emitted charged particles in forward cone. Observation of prompt γ-rays of the populated evaporation residues in coincidence with alpha particle(s) in forward cone provides an evidence of ICF. However, there are few studies at lower beam energies and with medium mass spherical target nuclei. In order to investigate the role of target and residual nucleus deformation on the spin population in incomplete fusion reaction, the present experiment has been undertaken. In order to understand the feeding pattern in different CF and/or ICF reaction channels, the direct feeding intensity of γ-rays have been deduced from the experimentally measured spin distributions of evaporation residues reported in ref [14].

The experiment has been performed at Inter-University Accelerator Centre (IUAC), New Delhi, India, employing charged particle-gamma coincidence technique. 15UD Pelletron Accelerator in the present experiment delivered $^{16}O^{+7}$ ion beam. The particle-gamma coincidence experiment has been performed with a view to study ICF dynamics by measuring spin distributions of the evaporation residues produced in $^{16}O + ^{124}Sn$ system at 100 MeV projectile energy. The Gamma Detector Array (GDA) is an assembly of 12 Compton suppressed, High Purity Germanium (HPGe) detectors at three different angles 45°, 99°, 153° with respect to the beam direction with the arrangement of 4 detectors at each of theses angle. The Charged Particle Detector Array (CPDA) is a group of 14 phoswich detectors. In the CPDA scattering chamber, seven CPD were placed on the top and seven in the bottom of the chamber. The 14 phoswich detectors of CPDA are divided in three angular zones. (i) 4 CPD in forward cone (10°-60°), (ii) 4 CPD in backward cone (120°-170°) and (iii) 6 CPD in sideways (60°-120°). Self-supporting enriched target ^{124}Sn (enrichment ≈97.2%) of thickness 2.0 mg/cm^2 was mounted at 45^0 with respect to the beam direction inside the CPDA chamber. The target was bombarded with the 100 MeV $^{16}O^{+7}$ beam with the beam current ≈20nA. Coincidences were demanded between particles (Z=1, 2) and the prompt γ-rays emitted from the evaporation residues during the interaction of ^{16}O with ^{124}Sn.

In the present experiment, two groups of α-particles are expected to be detected by forward angle (F) CPDs: (i) the fusion-evaporation (CF) α-particles of average energy $E_{\alpha\text{-}CF} \approx 17$ MeV and (ii) the ICF 'fast' α-particles of energy $E_{\alpha\text{-}ICF} \approx 25$MeV. In front of the each four forward angle CPDs, aluminum absorber of appropriate thickness was used to stop 'evaporation' α-particles as well as elastically scattered ^{16}O particles. As such only 'fast' or 'incompletely fused (ICF) α-particles' with energy greater than 17 MeV may be detected in the forward cone. The data analysis has been carried out off-line using software INGASORT.

Identification of the CF and ICF channels in forward and backward cone were achieved by looking into various gated spectra.

In the present work, to study the feeding pattern of different CF and/or ICF channels, the direct feeding intensity pattern of γ-rays for reaction channels ^{132}Ba(α4n), ^{131}Ba(α5n), ^{130}Xe(2α2n), ^{128}Xe(2α4n) and ^{131}Cs(αp4n) have been measured and plotted as a function of observed spin (J) displayed in Figs. 1(a)-(b). In Fig. 1(a) shows that, the feeding intensity for backward α-gated reaction channels ^{132}Ba(α4n), ^{131}Ba(α5n), ^{130}Xe(2α2n) and ^{131}Cs(αp4n), as expected for CF dynamics is showing sharp exponential rise towards low spin states, revealing strong feeding toward the bandhead, as expected from CF dynamics, where band is fed over a broad spin range. However, In Fig.1(b), the feeding intensity for forward α-gated reaction channels ^{132}Ba(α4n), ^{131}Ba(α5n), ^{130}Xe(2α2n), ^{128}Xe(2α4n) and ^{131}Cs(αp4n) shows an exponential rise up to certain J values and then found to decrease toward higher spin states; hence it is localized to narrow angular momentum window. This may be attributed to less feeding probability in ICF process caused by de-excitation of the residual nucleus.

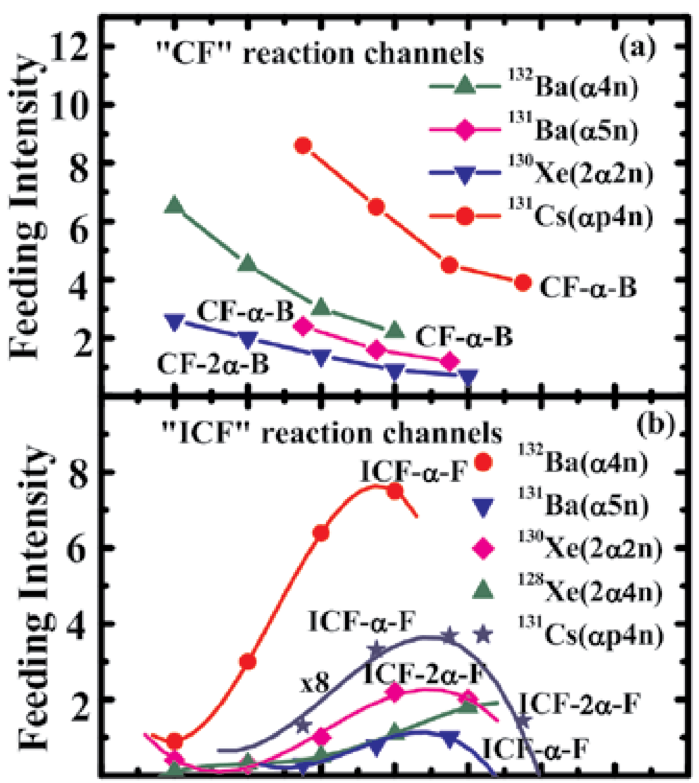

Fig. 1. Direct feeding intensities of γ-cascades of evaporation residues (ER) observed in (a) CF reaction channels (backward-α-gated for ERs ^{132}Ba, ^{131}Ba, ^{130}Xe and ^{131}Cs) (b) ICF reaction channels (forward-α-gated for ERs ^{132}Ba, ^{131}Ba, ^{130}Xe and ^{131}Cs)

On the basis of present investigations, it may be concluded that the experimentally measured spin distribution of ICF channels identified from forward α-gated spectra have been found distinctly different than that CF channels identified from backward α-gated spectra. The populations of low spin states are observed to be less fed in ICF channels, while in case of CF, significant feeding has been observed over the broad spin range. More experimental data are needed to gain a better insight into the reaction dynamics involved at projectile energies above the Coulomb barrier.

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5.1.15 Observation of Pre-equilibrium particle emission by measurement of yield ratio

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Heavy ion (HI) and light ion (LI) induced pre-equilibrium (PE) particle emission reactions has been the growing interest in nuclear physics for past few decades in intermediate energy region [1,2]. Fast light particles are observed in light and heavy ion induced reactions, indicated the existence of PE light particle emission process. In PE particle emission process, fast light energetic nuclear particles, like proton and neutron are emitted during the thermalization of composite system. The PE emission proceeds through two body residual interactions inside the compound system, after the initial interaction with the finite probability of particle emission after each collision. The PE emission may be considered as a bridge between two extreme reaction mechanisms. Presence of PE emissions at HI projectile energies slightly higher from Coulomb barrier has also been noticed [3]. There are some important features of PE particle emission process; (i) forward peaked angular distribution of energetic light nuclear particles, (ii) at higher energy region, slowly descending tail portion of excitation functions (EFs), (iii) in the exit reaction channels, the presence of relatively larger number of energetic light nuclear particles as compared to that emitted in equilibrium decay etc.

Some dynamical models have been proposed by several investigators to explain the PE-decay of highly excited composite system viz. geometry dependent hybrid (GDH) model, PE particle emission EXCITON model, inter-nuclear cascade (INC) model, and quasifree scattering (QFS) model. No theoretical model is available presently to explain the dependence of reactions on driving input angular momenta, entrance channel mass asymmetry and energy regime etc.

The particle-gamma coincidence experiment has been performed with a view to study the PE particle emission in the ^{16}O + ^{124}Sn system at 100 MeV beam energy during the complete fusion (CF) process. Earlier most of the PE particle emission studies have been carried out by excitation function measurement using activation technique, with LI induced reactions. However, there are few studies on PE particle emission on HI induced reactions with medium mass spherical target nuclei using particle gamma coincidence technique. In order to understand the PE particle emission reaction mechanism, an attempt has been made to deduced yield ratio (Y^F/Y^B) from the experimentally measured relative intensity of the prompt γ -rays transitions of evaporation residues ^{135}La and ^{133}La using particle gamma coincidence technique. In this paper, PE particle emission for two evaporation residues ^{135}La (p4n) and ^{133}La (p6n) have been observed by measurement yield ratio (Y^F/Y^B). To the best of our knowledge, this is the first time such measurements for this projectile-target system are being reported.

In-beam particle gamma coincidence experiment has been performed at Inter-University Accelerator Centre (IUAC), New Delhi, using Gamma Detector Array (GDA) along with Charged Particle Detector Array (CPDA) set-up. The experimental setup has been described earlier [4]. Self-supporting enriched target ^{124}Sn (enrichment ≈97.2%) of thickness 2.0 mg/cm^2 (prepared by rolling technique) was mounted at 45° with respect to the beam direction inside the CPDA chamber. The target ^{124}Sn was bombarded with the 100 MeV $^{16}O^{+7}$ beam with the beam current ≈20nA. Coincidences were demanded between particles (Z=1, 2) and the prompt γ-rays emitted from the evaporation residues during the interaction of ^{16}O with ^{124}Sn. In order to remove scattered beam, CPDs were covered with Al-absorbers of appropriate thickness. Gamma-ray spectra in coincidence with particle (p, α) and α-particle in forward cone, backward cone and side ways have been recorded. The data analyses have been carried out off-line using software INGASORT.

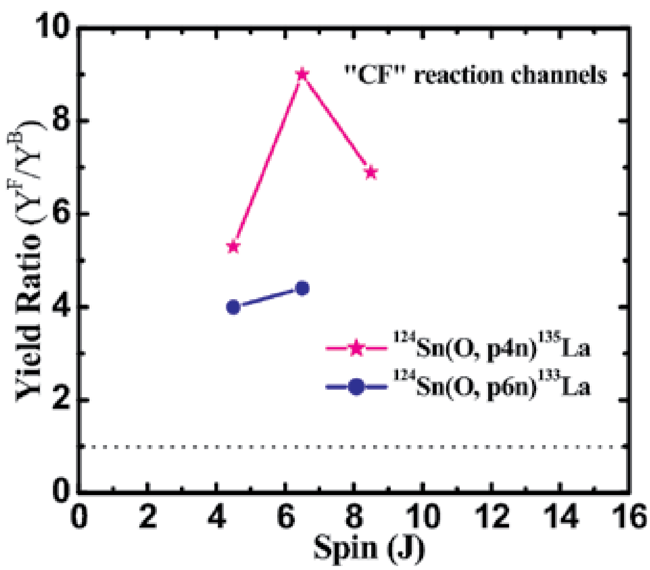

Fig. 1. Measured Yield Ratio (Y^F/Y^B) of gamma transitions for evaporation residues ^{135}La and ^{133}La.

In the present work, analysis of the experimental data has been performed in the following steps. In the first step of analysis we have separated PE contribution from ICF process using the subtraction method; (i) backward α-gated γ-ray spectra subtracted from backward particle-gated γ-ray spectra (ii) forward α-gated γ-ray spectra subtracted from forward particle-gated γ-ray spectra and (iii) sideways α-gated γ-ray spectra subtracted from sideways particle-gated γ-ray spectra. So, in this step a pure proton gated γ-ray spectra have been obtained. By projecting three different gating conditions (a) proton-backward (b) proton-forward (c) proton-90^0 on γ-ray energy spectra three types of proton gated spectra have been obtained. In the second step of analysis the evaporation residues have been identified their characteristic prompt γ-lines and confirmed by decay gamma lines in decay spectra. Area under the photo peak of characteristic prompt γ-ray transitions were used to determine the relative production yield of the different evaporation residues. The yield ratio defined as the ratio of yield in forward to backward direction i.e. Y^F/Y^B, have been measured for ^{135}La and ^{133}La produced through p4n and p6n channels of the ^{16}O + ^{124}Sn system and displayed in FIG. 1, as can be seen from this figure that the yield ratio (forward to backward yield) Y^F/Y^B is much higher than unity. It may be due to the significant PE contribution in these reaction channels. Thus the enhancement in Y^F/Y^B over unity may be attributed due to the PE emission along with the equilibrium (EQ) evaporation process of compound nucleus.

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5.1.16 g-Factor Measurement of $9/2^-$ Isomer in ^{129}Ba

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The nuclei in mass region A~130 shows coexistence of different nuclear shapes due to competition between proton and neutron $(h_{11/2})^2$ alignment. So the interest is mainly due to the presence of intruder orbits in this region. The quasi-particle energies of $\nu h_{11/2}$ and $\pi h_{11/2}$ as well as the energy needed to break $(h_{11/2})^2$ proton and neutron pairs are very similar [1]. This gives rise to two s-bands in many of these nuclei. Only for a few cases have the nature of particle alignment has been established through g-factor measurement. Theoretically, in the low mass region Ba isotopes (^{122}Ba -^{130}Ba), the alignment of proton precedes the alignment of neutron. This is consistent with the fact that Coriolis force responsible for particle alignment is more for low Ω-orbits. Since these nuclei posses prolate deformation in their g-band, protons lie in the low Ω-orbital. The magnetic moment measurement can help to identify its configuration. The half life of $9/2^-$ isomer in ^{129}Ba is well suited for g-factor measurements by time differential perturbed angular distribution (TDPAD) technique

The experiment was performed at 15UD Pelletron accelerator facility of the Inter University Accelerator Center (IUAC), New Delhi. The $9/2^-$ (~18 ns), 173 keV level of ^{129}Ba has been populated by the reaction ^{120}Sn (^{12}C, 5n) ^{129}Ba using 56 MeV pulsed ^{12}C ion beam having a pulse width of ~2 ns and repetition period of 250 ns. The external magnetic field of 7.5 kG (measured by Hall probe) perpendicular to the beam-detector plane was provided by C–type electromagnet. An isotopically enriched 600 μg/cm^2 ^{120}Sn evaporated on a 2 mg/cm^2 thick gold backing to stop recoils was used as a target. The spin rotation of the implanted ions in the gold backing modifies the angular distribution of the decay γ-rays and is normally observed in the time evolution of the ratio of counts at ± 45° to the beam. The data were collected in LIST mode with four parameters: the energy and time signals for both the $LaBr_3$ detectors. The acquired delayed timing data, following proper gain matching for energy and time, were sorted off-line into E_γ-t matrices corresponding to the two different detectors. The amplitude of the modulation is determined by the effective anisotropy contribution of 173.5 keV γ-rays transitions for $9/2^-$ state. From the measured value of the Larmor precession frequency $\omega_L = g.H.\mu_N/\hbar$, where H is the external applied magnetic field, the g-factor for $9/2^-$ state can be determined. Data analysis is in progress.

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5.1.17 Fission fragment mass ratio distribution measurements for ^{24}Mg + ^{186}W reaction at energies around the Coulomb barrier

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In recent years considerable effort has been made in the production of super heavy elements using heavy ion reactions. The major hurdle in the formation of a super heavy compound nucleus or evaporation residue is the presence of a non equilibrium process called quasifission [1, 2](QF). More recent observation of the unexpected presence of QF even in asymmetric reactions forming systems as light as Po, Ra and Th[3, 4], evoked considerable interest in this field. It is important to understand the dependence of QF on the entrance channel parameter of the fusing system, in a quantitative way. In this context, we have performed mass angle correlation studies of the binary fragments produced in ^{24}Mg + ^{186}W reaction forming the composite system ^{210}Rn.

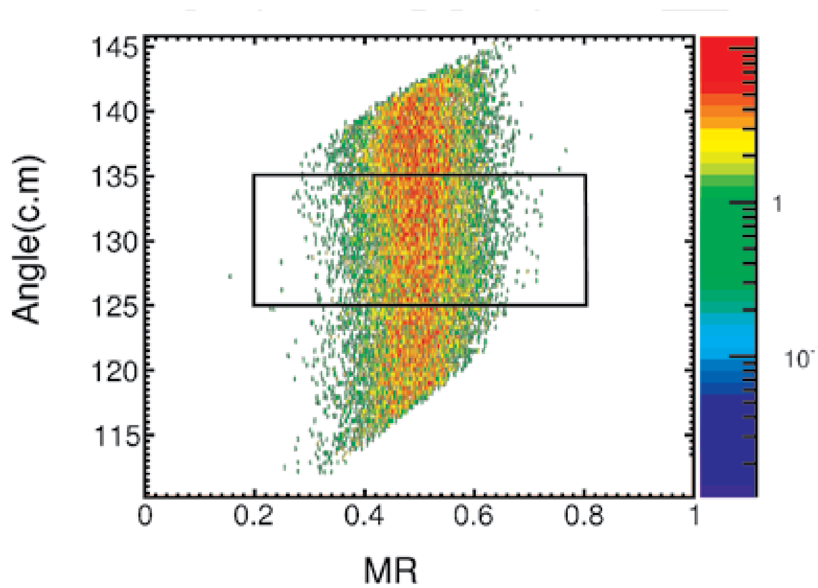

Fig. 1. Fragment mass ratio distribution versus centre of mass angle plot at projectile energy 118.9 MeV

The experiment was performed in the General Purpose Scattering Chamber. ^{24}Mg beam from Pelletron accelerator, in the energy range 111 MeV to 125 MeV, was used to bombard isotopically enriched (99.5%) ^{186}W target of thickness 110 μg/cm^2 (on 15 μg/cm^2 carbon backing). The fission fragments (FF) were detected in two large area position sensitive multi-wire proportional counters (MWPCs) of active area 20 cm × 10 cm, mounted on each arm of the chamber. The forward detector was centered at an angle θ = 38° and the backward detector was centered at θ = 113°. The nearest distance to the front detector from the target was 55.5 cm and that to the back detector was 40 cm. The gas detectors were operated at a gas pressure of 3.5 mbar of isobutane gas. Positions of fragments entering the detectors were obtained from the delay line read out of the wire planes. The position resolutions of the detectors were better than 1.5 mm FWHM. Two solid state detectors were mounted at ±10° with respect to the beam direction, to monitor the elastically scattered events which in turn, were used to keep the beam always at the centre of the target. The timing pulses from both anodes were processed through constant-fraction discriminators. The 'OR'ed signal of two MWPCs and two monitor detectors formed the master strobe of the data acquisition system. TDCs were used for individual MWPC signals with anode as start and four position signals as individual stops. Since the beam current was very low at the required energies for ^{24}Mg, dc beam was used in the experiment and the time difference method was used for obtaining the fragment mass ratio distribution. The basic assumption in time difference method is the presence of only full momentum transfer reactions, which is valid in the present measurements as the target used is not fissile, the probability of incomplete momentum transfer processes like transfer induced fission are absent. A TAC signal was formed by taking start signal from the anode of back detector and stop from the delayed anode signal from the front detector.

The calibrated position signals (X, Y) were converted to polar angles θ and Φ. From this and TOF information, masses of the fission fragments were determined, event by event, using the method given in ref. [5]. In order to avoid any biasing coming from the geometrical limitations of the detector system, a cut (125° to 135°) was used in the analysis for all the energy points studied.

^{16}O + ^{197}Au reaction, which is expected to undergo fission through pure compound nucleus formation, was used as the calibration system for obtaining the electronic time delay involved in the measurements. In the calibration run, MWPCs were kept at 90° in centre of mass frame, and the fragments were measured at 90 MeV beam energy. The electronic delay is calculated by imposing the condition that the mass ratio distribution is reflection symmetric about 0.5 at θ_{cm} = 90°. Fig. 1 shows the fragment mass ratio versus centre of mass angle at beam energy 118.9 MeV. No mass angle correlation has been observed in the entire energy region studied. The fragment mass ratio distributions can be represented by Gaussian function and the standard deviation represents the width of the mass ratio distribution. Fig. 2 shows the mass ratio distribution for all the fragments for the energy range studied.

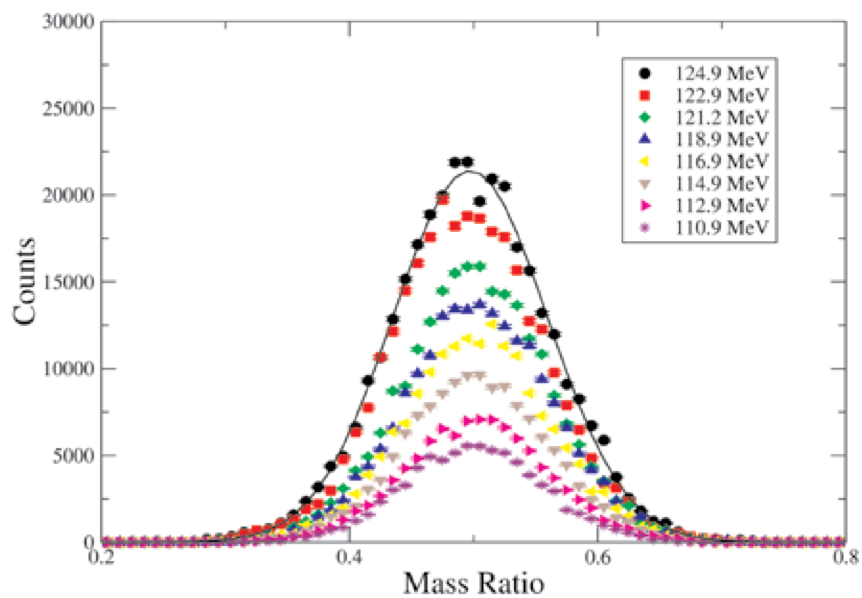

Fig. 2. Fragment mass ratio distribution for different beam energies. The solid line shows the Gaussian fit to the experimental mass ratio distribution at 124.9 MeV

Width of the fragment mass ratio distributions for ^{24}Mg + ^{186}W reaction is compared with our previous measurements on ^{16}O + ^{194}Pt reaction [6], forming the same compound system ^{210}Rn. It is observed that in the case of ^{24}Mg + ^{186}W reaction, mass widths are larger in comparison to that of ^{16}O + ^{194}Pt reaction. It is well known that in the case of compound nucleus fission, the mass variances of the fragments are linearly proportional to nuclear temperature and mean square angular momentum. Fig. 3 shows the mass width versus compound nucleus excitation energy for both reactions and the calculations assuming compound nucleus formation with the proportionality constants obtained from $^{16}O + ^{194}Pt$ reaction. The deviation from compound nucleus behavior for $^{24}Mg + ^{186}W$ reaction clearly suggests the onset of quasifission process in this reaction.

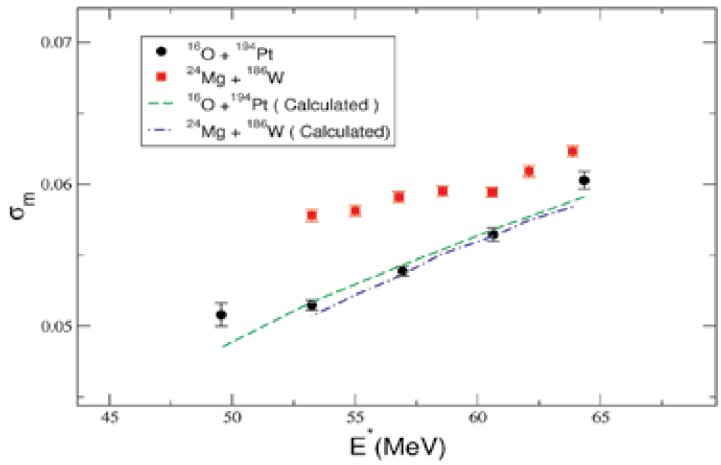

Fig. 3. Fragment mass ratio width versus compound nucleus excitation energy plot. Dashed and dot dashed lines are the theoretical predictions assuming compound nucleus formation for $^{16}O + ^{194}Pt$ reaction and $^{24}Mg + ^{186}W$ reaction.

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5.1.18 Multi-nucleon transfer reactions for $^{28}Si+^{90,94}Zr$ systems in sub and near barrier region

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The study of heavy ion transfer reactions serves a wide range of objectives like estimation of relative and absolute spectroscopic factors of nuclear levels, understanding correlations between nucleons, the transition from the quasi elastic to deep inelastic regime, dynamics of neck formation. In the sub-barrier region, multi-nucleon transfer reactions data are very scarce due to various technical difficulties faced [1-2]. The reaction products in these kinds of reactions are backward peaked (180^{o}) in centre of mass system and forward moving recoils are peaked at zero degree. Moreover, the energy of forward moving recoils as well as back scattered particles is less than 1 MeV/nucleon, so the detection of the particles in these kinds of reactions is very cumbersome. Hence, a recoil mass separator is very efficient device for carrying out these kinds of measurements. Here we report the results of measurements of multi - nucleon transfer for ^{28}Si + ^{90,94}Zr systems at near barrier energies. The studies revolve around the interplay of transfer reactions channels (mainly positive Q value multi neutron pick-up) and the fusion cross sections around the Coulomb barrier. We have already done fusion cross section measurements for these systems [3]. As ^{90}Zr has closed neutron shell, the effect of shell closure on neutron transfer can be studied. On the other hand, ^{94}Zr has four nucleons outside the closed shell, which allows us to investigate the effects of pairing correlation on multi-nucleon transfer mechanism.

The experiment was performed with pulsed ^{28}Si beam having a repetition rate of 1μs using Heavy Ion Reaction Analyzer (HIRA). The targets used were isotopically enriched ^{90,94}Zr (97.65% and 96.07% respectively) 280 μg/cm^2 foils prepared on 45 μg/cm^2 carbon backings in the target lab of IUAC [4]. In the target chamber of HIRA, two silicon surface barrier detectors were mounted at ±25^{o} to monitor the beam. To improve the beam rejection, HIRA was rotated to 6°. A silicon surface barrier detector of 20×20 mm^2 active area was mounted at back angle to set-up kinematic coincidence between forward moving target - like recoiling particles and back scattered projectile-like nuclei. The angle of this back detector was optimized by maximizing the coincidence counts. At the target chamber of HIRA, 14 elements BGO array was also mounted for gamma detection in coincidence with recoils. A carbon charge reset foil of 30 μg/cm^2 thickness was used for charge equilibration of recoiling particles coming out of the target. At the focal plane of HIRA, a Multi Wire Proportional Counter (MWPC) of 150 × 50 mm^2 active area followed by ionization chamber was used for the detection of recoiling particles. The measurements were performed from 83.3, 86.4, 89.5, 92.5 and 95.5 MeV (in laboratory frame E_{lab}) in steps of 3 MeV. The nominal Coulomb barriers for ^{28}Si+^{90,94}Zr are 95.76 and 94.15 MeV (E_{lab}) respectively. The solid angle of acceptance for HIRA was kept 5 mSr (6^{o}±2.28^{o}) for carrying out all these measurements.

A gated two dimensional spectra between the time of flight (TOF) vs. MWPC position for ^{28}Si + ^{94}Zr at 94 MeV is shown in Fig. 1. Transfer of up to 4-nucleon pick-up and one nucleon stripping can be noted in the figure. We could clearly resolve m/q ambiguity by time of flight. From the Q-value considerations it was found that pick-up channels were neutron transfer whereas stripping channels were proton transfer. An extreme low energy run was taken at 70 MeV (much below the Coulomb barrier so that transfer does not take place significantly) to determine the isotopic contents of the targets experimentally. The values so obtained were found to be consistent with the values provided by supplier. In Fig. 2, the transfer probability extracted vs. the distance parameter is plotted for $^{28}Si+^{94}Zr$ system. Fig. 3 shows the excitation energy spectrum for $^{28}Si + ^{94}Zr$ system. Theoretical calculations were performed using code GRAZING [5].

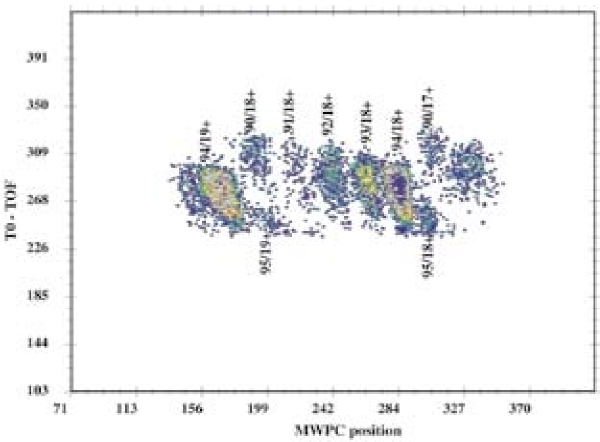

Fig. 1. A two-dimensional spectrum of ^{28}Si + ^{94}Zr at 94 MeV.

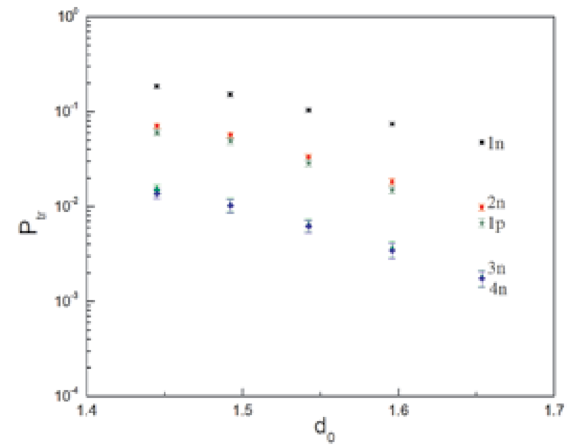

Fig. 2. P_{tr} vs. distance parameter (d_0) for $^{28}Si+^{94}Zr$.

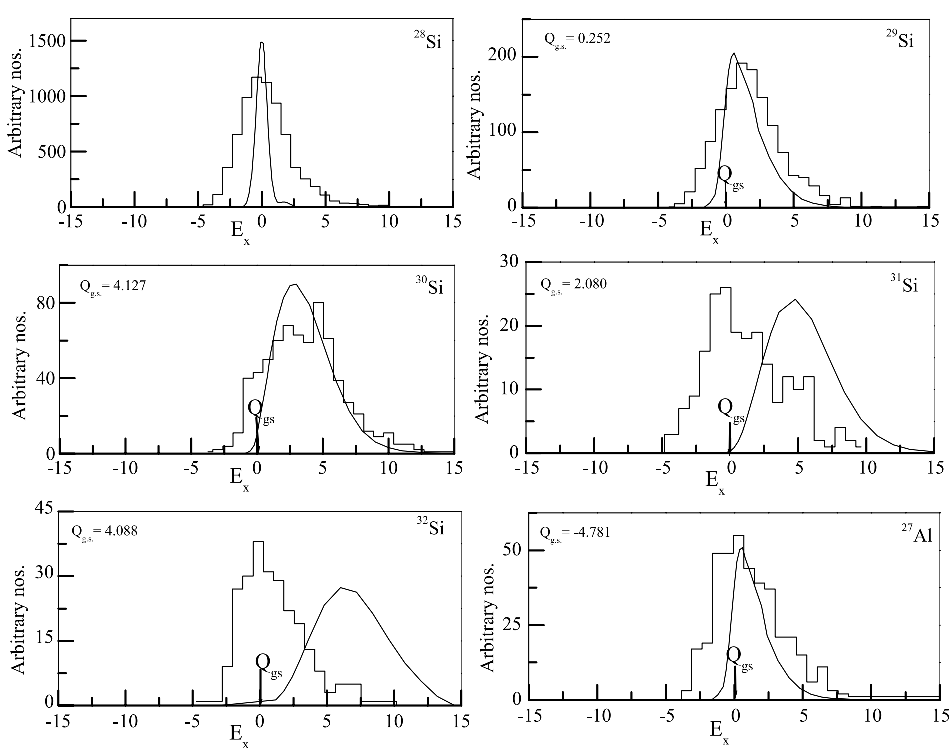

Fig. 3. Excitation energy distribution for $^{28}Si+^{94}Zr$ at 97 MeV. The step line shows the experimental and continuous line shows the excitation energy spectrum obtained by using code GRAZING.

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5.1.19 Fission mass widths in ^{213}Fr

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Observations of the presence of quasifission (QF) in less fissile systems are a matter of intense research in recent years [1, 2]. Evidence of onset of quasi-fission even in asymmetric reactions forming less fissile systems appears to be a very puzzling phenomenon. Earlier dynamical models predict that the QF occurs when Z_PZ_T =1600. However recently QF has been observed with fusion of asymmetric systems like ^{19}F + ^{197}Au (Z_PZ_T = 632) [3]. The observation of QF with less asymmetric reactions has been attributed to the entrance channel effects of the interaction systems in which the entrance channel mass asymmetry (α) of the interacting systems is small when compared to the critical Businaro-Gallone mass asymmetry (α_{BG}). Later the same system was investigated through fission fragment angular distributions and there was no evidence of non compound nuclear fission (NCNF). It seems mass distribution of fragments produced in these reactions showed evidence of QF while their angular distributions showed no evidence of non-equilibrium fission. In one of our earlier work, we have studied fission fragment angular distributions for the system ^{18}O + ^{197}Au which is having entrance channel mass asymmetry very much similar to ^{19}F + ^{197}Au and observed that there is no evidence of NCNF[4]. Further, recent results show that the onset of quasi fission starts at nearly Z_PZ_T = 1000. It is important to understand the onset of QF as a function of fissility, Z_PZ_T value, entrance channel mass asymmetry and deformation of target and projectile. Since Fr is very much close to Ra, where reduction in ER cross sections and broader mass angle correlations were reported [3]. Therefore, it is expected that Fr will also behave similar to Ra. In this context we have carried out measurement on mass angle correlations and fission fragment angular distributions for the two systems $^{16}O + ^{197}Au$ and $^{27}Al + ^{186}W$ around the Coulomb barrier energies, leading to the same compound nucleus ^{213}Fr.

Beams of ^{16}O and ^{27}Al were bombarded on ^{197}Au, ^{186}W targets of thickness 150 and 110 μg/cm^2 respectively at different beam energies. Fission fragments were detected by two large area multi wire proportional counters (MWPC) placed at a distance of 40 and 55 cm on the rotatable arms inside the 1.5m diameter General Purpose Scattering Chamber (GPSC). These two detectors were kept at folding angles to detect the complementary fragments in coincidence. The detectors were rotated to cover the angular range of 80^0 to 180^0 in laboratory frame. Two Si surface barrier detectors of thickness 300 microns with a collimator of 1mm were placed at $\pm10^0$ to the beam direction, at a distance of 70 cm from the target. These detectors were used for normalization of the fission yields to obtain the absolute differential cross sections for angular distribution measurement and also for aligning the beam on the center of the target. The angular calibration of the MWPC's were done by taking elastic scattering data at an energy below the Coulomb barrier. We have used DC beam in this experiment and adopted the time difference method to extract the mass ratios assuming that only binary reaction is taking place [5]. The positions information of the fission fragments entering the detectors were obtained from the delay line read out of the MWPC wire planes. The central foil of both the MWPC's recorded the timing and energy loss signals. The position calibration (x,y) and solid angle of both the detectors

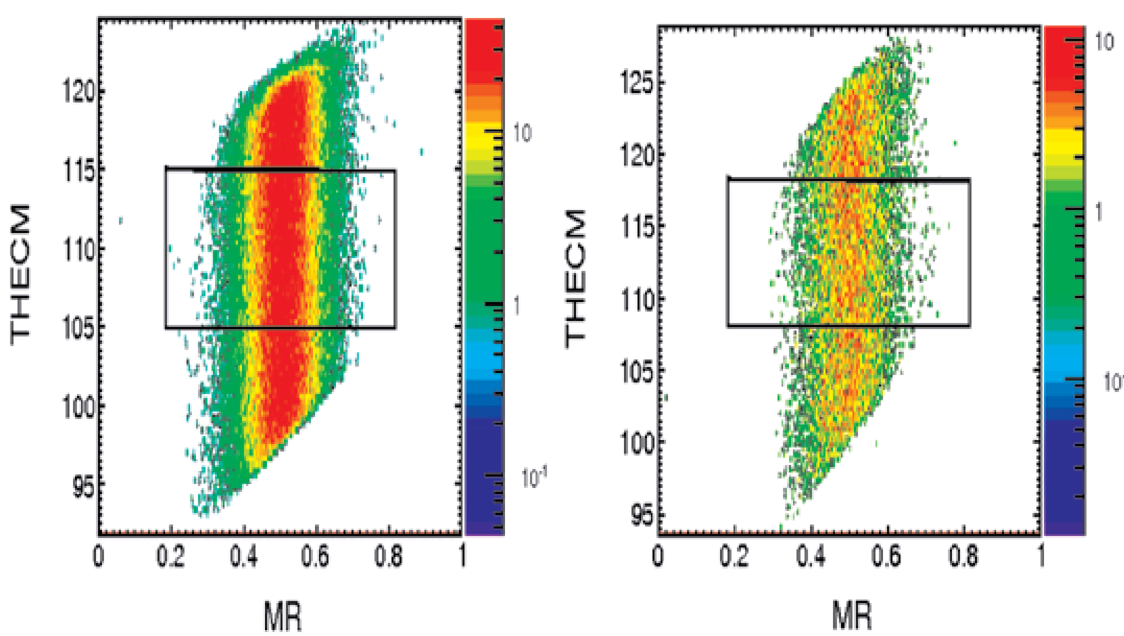

Fig. 1. The mass ratio vs centre of mass angle density plots for $^{16}O + ^{197}Au$ and $^{27}Al + ^{186}W$ at the same excitation energy E^* = 55.5 MeV.

were determined by taking elastic scattering data in singles mode below the Coulomb barrier. These (x,y) position information were later converted to (θ,φ) and the time of flight information was taken from the TAC signal, by taking start signal from the anode signal of back detector and stop from the delayed anode signal from the front detector. The velocities of the fission fragments were reconstructed by using the (θ,φ) information with the time of flight information. The time difference calibration for the studied systems was achieved by imposing the condition that the mass ratio distribution is reflection symmetric about $M_r = 0.5$ at $\theta_{c.m.} = 90^0$, a condition true for both the reactions. By application of proper kinematic transformations and conservation of linear momentum, the mass ratios (M_r) will be obtained. Data analysis is under progress, the experimentally extracted mass angle correlations for the two systems $^{16}O + ^{197}Au$ and $^{27}Al + ^{186}W$ at the same excitation energy E = 55.5 MeV are shown in the Fig.1

We acknowledge the financial assistance and Pelletron time given by IUAC, New Delhi.

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5.1.20 Neutron multiplicity measurements for $^{19}F + ^{194,198}Pt$ systems at high excitation energy to understand the role of shell closure in fission dynamics

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From the study of light particles emitted in heavy-ion induced fusion-fission reactions, the importance of dissipation in fusion-fission dynamics is well established. Experimental signature of large dissipation is observed through large excess in pre-fission neutrons, gamma ray multiplicities from compound nucleus giant dipole resonance (GDR), light charged particles and evaporation residue [1-4]. Dissipation has been observed at nuclear temperature between 1 and 2 MeV, with dissipation effect increasing with excitation energy. Back *et al.*[4] reported that in order to reproduce evaporation residue cross-sections for ^{224}Th and ^{216}Th nuclei, a larger dissipation strength was required for ^{224}Th compared to ^{216}Th. They have concluded that nuclear dissipation has possible relation with neutron closed shell N_C=126 [4]. It is to be noted that this conclusion was drawn from one observable sensitive to nuclear dissipation (i.e. evaporation residue). So it is desirable to do a consistent analysis for other observables like pre-scission neutron multiplicity, fission and ER cross section to establish the role of neutron shell closure in the dissipation strength. With this motivation in mind, we have performed a simultaneous analysis of neutron multiplicity, fission cross-section and evaporation residue cross-section for ^{19}F+$^{194,196,198}Pt$ (N_c = 126, 128, 130) systems at excitation energy range 50-100 MeV.

The experiment was done using pulsed beam of ^{19}F at energies 140.8 and 137.2 MeV delivered by Pelletron plus Ist module of LINAC of IUAC. ^{19}F beam was bombarded on ^{194}Pt and ^{198}Pt targets of thickness 530 μg/cm^2 and 1.45 mg/cm^2 respectively. Targets were located at centre of a thin walled spherical scattering chamber of 60 cm diameter. Fission fragments were detected by a pair of Multi-wire proportional counter (MWPC) (5" × 3") kept at fission fragment folding angle at distance of 24 cm from target position. Two silicon surface barrier detectors were also placed inside the chamber at ±16^o to beam direction out of reaction plane for normalization purpose.

24 Neutron detectors (NE213 and BC501) were kept at 2 meter distance from target, at different angles ranging from 30^o to 315^o around the target chamber. Out of these 24 detectors, 16 detectors (5" x 5") were kept in reaction plane and remaining 8 detectors (5" x 3") were kept at 15^o up and down out of reaction plane Hardware threshold of 0.5 MeV of neutron energy was applied using ^{137}Cs and ^{60}Co sources. In order to reduce gamma background, beam dump was extended 3m downstream from target and beam line was shielded with paraffin and lead bricks. The time width from the LINAC was continuously measured and it was found to be approximately 400 psec. The trigger of data acquisition was generated by Logical OR of cathode signal of two MWPC 'AND'ed with RF of the beam pulse. Neutron gamma discrimination was done using IUAC made Pulse Shape Discrimination module.

The neutron spectra detected in coincidence with fission fragments were fitted assuming the neutrons to be originating from three moving sources, i.e. compound nucleus evaporation (Pre-scission), and from each of the two fission fragments (Post-scission). The pre and post-scission contributions were assumed to be isotropic. Further, post-scission neutron multiplicity and temperatures are assumed to be same for both the fragments. Hence the total neutron multiplicity $M_{total} = M_{pre} + 2 * M_{post}$. The raw neutron TOF spectra are converted to energy spectra for all 16 in-plane detectors. Data were corrected for efficiency of neutron detectors. The efficiency was measured using ^{252}Cf source at appropriate geometry and comparing with a Monte Carlo simulation code MODEFF. In order to obtain pre-scission and post-scission contributions spectra of 16 detectors are fitted simultaneously for 32 different neutron-fission angle (Φ_{nf}) combinations, using Watt expression:

$$Y(E_n) = \sum_{i=1}^{3} \frac{M_n^i \sqrt{E_n}}{2(\pi T_i)^{3/2}} \times \exp\left[\frac{-(E_n - 2\sqrt{\varepsilon_i E_n} Cos\,\Phi_i + \varepsilon_i)}{T_i}\right]$$

where ε_i, T_i and M_n^i are energy per nucleon, temperature and multiplicity of neutron source *i*. E_n is lab energy of neutrons and Φ_i is neutron detection angle with respect to source *i*.

Neutron multiplicities were obtained by using T_{pre}, M_{pre}, M_{post} and T_{post} as free parameter. The values of the neutron multiplicities obtained from the above procedure for decay of ^{217}Fr and ^{213}Fr are given in Table [1] and fitting plots are shown in figure 1.

Table-1

CN	M_{pre}±err	$2M_{post}$±err	M_{total}±err
^{217}Fr (N_C=130)	5.5± 0.03	1.60±0.02	7.10±0.04
^{213}Fr (N_C=126)	4.71± 0.03	1.74±0.01	6.45±0.03

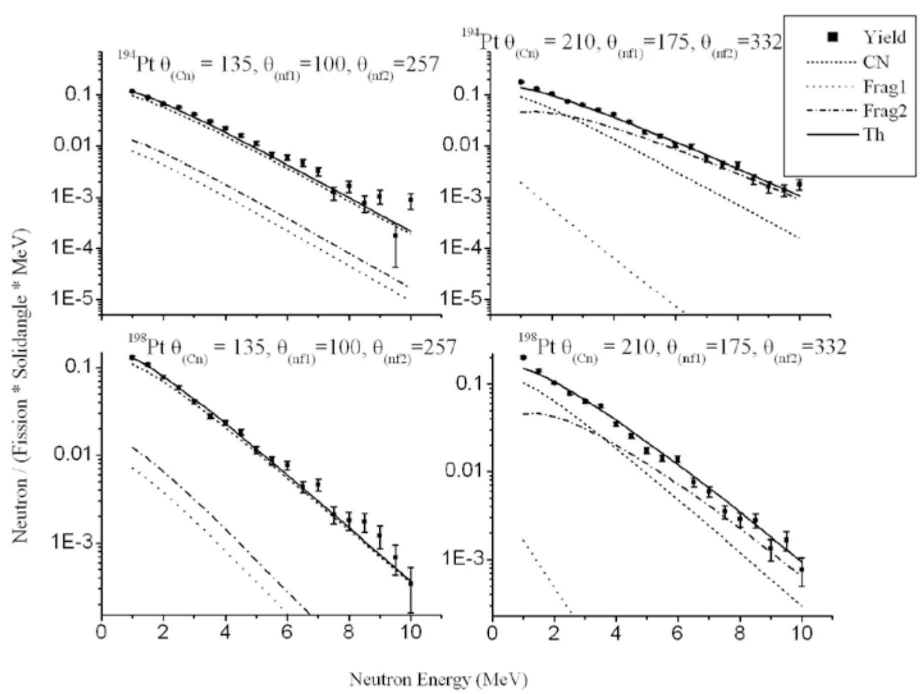

Fig. 1. Neutron multiplicity (filled circle) for the $^{19}F+^{194,198}Pt$ system at E_{ex}=92.2 MeV along with the fits for the pre-scission (short dash curve) and post-scission from one fragment (dot curve) and that from the other (dot dash curve). The solid curve represents the total contribution.

Total neutron multiplicity obtained for both the systems roughly matches with the systematic given by Hinde et al.[5] for a wide range of systems with various fissility and excitation energies.

The pre-scission neutron multiplicity for ^{217}Fr is larger compared to ^{213}Fr at similar excitation energy of 92.2 MeV. ^{217}Fr has four neutrons more compared to ^{213}Fr. Statistical model PACE2 calculation was performed with a reasonable value of parameters obtained from the fitting of the fission and ER excitation function for the systems under study [6].

The predicted pre-scission neutron multiplicity values for ^{217}Fr and ^{213}Fr, ignoring dissipation effects, are 1.03 and 0.70 respectively. According to Back et al. [4] neutron shell closed nuclei will have higher threshold for dissipation and one may expect less neutron multiplicity for shell closed nuclei. However, a detail consistent analysis including all observables sensitive to dissipation is warranted. Measurements of neutron multiplicity at few other energies, fission and ER cross sections are planned.

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