Investigation on high spin states of trans-Lead nuclei

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Investigation of Nuclear structure of the neutron deficient Francium and other trans-Lead nuclei have attracted attention in recent times. The major interest from the nuclear structure point of view is the role of the high-j neutron and proton orbitals in generating novel modes of collectivity into the excited nucleus. There was almost no data available on some of the neutron deficient doubly-odd isotopes of Fr, At and odd isotopes of Po, Rn, Ra etc., except for a few low lying isomeric transitions. The major challenge involved in these studies is rather the poor yield of the nuclei of interest, produced with sufficient excitation energy and angular momenta. Utilization of highly efficient recoil tagging devices and also the use of large Germanium detector array with sufficient resolving power have made such studies possible. The high spin states and isomeric decay of some of these nuclei have been studied in recent times. In this talk, I shall review the present scenario in high spin spectroscopy of the trans-Lead nuclei, along with a flavour of the residue tagging techniques used. Then I shall present some of the results of our recent investigation of the high spin states of neutron deficient isotopes of Francium.

Introduction

Nuclear structure data are rather scanty or non-existent for the trans-Lead actinide nuclei till date. In fact, for most of the neutron deficient nuclei in this mass region, with a few protons outside $Z = 82$ closed proton shell and a number of neutron holes in the $N = 126$ neutron shell, their level schemes are to exhibit a competition between multi-particle proton excitations and neutron-hole excitations. The proton shell model space consists predominantly of $(1h_{9/2}, 1i_{13/2}, 2f_{7/2})$ states and the neutrons are promoted from the $(3p_{1/2}, 2f_{5/2}, 3p_{3/2})$ low spin orbitals to the $(2g_{9/2}, 1i_{13/2}, 1j_{15/2})$ high spin orbitals leading to the generation of high spin states. Only moderate configuration mixing and no additional collective motion are found to be adequate in explaining the levels in some of the nuclei. However, the high spin non-yrast states in many of the cases demand explanation based on novel modes of collectivity at very low deformation.

Abundance of low lying isomers with half lives ranging from nanoseconds to microseconds are found in these nuclei(eg. see Refs. [1, 2]). In most of these cases, isomers are rather caused by 1) the close proximity of levels, 2) slower tansitions of higher multipolarity, or 3) change of configurations between adjacent levels. These isomers make the spectroscopic investigations in these nuclei much more difficult to perform. Yet a systematic search and exploration of properties of the isomers are very important for a detailed and complete knowledge of nuclear structure.

A recent spectroscopic investigation[3] of the high spin states of $N = 119$ ^{206}Fr and ^{204}At nuclei reveals the existence of magnetic dipole transitions among the high spin states leading to the first observation of shears band in these nuclei. This is interpreted as due to the proximity of $N = 120$, which is considered as magic number for magnetic rotation[4, 5]. Placement of valence nucleons (protons and neutrons) in high-j orbitals in these nuclei is responsible for the shears band. This is one of the evidences of the existence of shears band in nuclei away from the $Z = 82$ benchmark observed in different neutron deficient Lead isotopes. Scope of further investigation on these neutron deficient trans-Lead nuclei seems to be abundant.

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A few spectroscopic studies of the high spin states have been carried out on neutron deficient Polonium, Radon and Radium isotopes[6, 7]. These nuclei are expected to have coexisting spherical, weakly deformed oblate and prolate ($\beta \leq \pm 0.1$) shapes competing with each other. However, apart from the existence of intruder bands, no conclusive evidence of deformation have been found in these nuclei. Most of these investigations were constrained by the existence of isomeric levels. However, for $N > 126$ nuclei, deformation were observed in even-A isotopes $^{218-222}$Rn, $^{222-228}$Ra and $^{228-234}$Th nuclei, where the high spins states were populated via multinucleon transfer reactions[8] up to spin as high as $28\hbar$. A systematic study of rotational alignments of the octupole bands in these isotopes manifests the role of octupole phonons and the onset of stable octupole deformation as function of rotational frequency. The Radon isotopes appear to be octupole vibrational over the wide range of spin excitations, but the other isotopes appear to be vibrational at low frequency, and tend to align along the rotational axis at high frequency creating a stable deformed shape. These and many other interesting phenomena can be addressed through experimental methods briefly reviewed as follows.

Experimental Methods

Spectroscopic investigation of trans-Lead actinide nuclei produced in fusion-evaporation reactions is severely constrained by the presence of a large fission background. While the ERs in the trans-Lead mass region, produced in the more asymmetric fusion evaporation reactions with light projectiles (beam energy $E < 8$ MeV/A), have low velocities ($v/c \ll 2\%$), the corresponding fission fragments produced having larger cross sections, would have relatively higher velocities ($v/c \sim 2 - 4\%$), and hence, the latter make the situation even worse in spectroscopic studies due to large Doppler broadening of the unwanted γ-rays contributing to the background. Due to above reason, the in-beam spectroscopy of these species at medium and high spin requires the use of a filter or tag in addition to a Germanium detector array for exclusive detection of the γ-rays from the ERs, separated from those of the fission products and other sources of background. This ER cross section quite often becomes very small (< 10 %) compared to fission, especially for $A > 200$ compound nuclei. Further, from the Monte Carlo simulation calculations using PACE, it can be seen that for forward kinematics and asymmetric target-projectile combination, the angular span of such heavy ER recoil is contained within a narrow forward angle. Therefore, the ER recoil filter should 1) detect and identify the ER, discriminated from the other in-beam products, 2) determine the angle of ER recoil, and 3) determine the kinetic energy of the ER.

Depending on the nature of the experiment and target-projectile combination, there are several methods used for recoil filter: (1) recoil mass separation and recoil decay tagging, using a gas-filled or vacuum mode mass separator, such as Recoil Ion Transport Unit (RITU)[9] at the University of Jyvaskyla, Finland and the Fragment Mass Analyzer (FMA)[10] at Argonne National Laboratory, USA, or a velocity filter like SHIP[11] at GSI, Germany; (2) detection of the ERs by time-of-flight and pulse height with a dedicated detection system[12]; (3) recoil detector placed near the target position, with good forward angle coverage, granularity, and capability to discriminate between the beam-like particles, fission fragments and ER recoils[13], (4) isomer tagging at the target position.

The Recoil Ion Transport Unit (RITU) is a magnetic separator for the heavy recoil ions which consists of the $QMQQ$ (where, Q = magnetic quadrupole, M = magnetic dipole) configuration with a total length of 4.8 m. The magnetic dipole, central to the separation of the recoils from the direct beam, is filled with light gas at low pressures (gas filled mode) which leads to charge state focusing effect, i.e. the ER ions of certain species follow the favoured trajectory determined by the average charge state of the ions in the

gas, irrespective of the charge states of the ions at the exit from the thin target. The effective solid angle acceptance is 10 msr at the forward angle. The salient features of the RITU are the ancillary detection facilities at the focal plane. Apart from the 43 element Ge detector array called JUROGAM placed at the target position, it consists of a versatile focal plane detector system GREAT[14], consisting of one Clover Ge detector for γ-ray measurements, a multiwire proportional counter (MWPC) detector and a pair of double sided silicon strip detectors (DSSSD) for recoil detection and implant decay measurements, an array of 28-element silicon PIN diodes for conversion electron detection, and a planar double sided Ge strip detector for X-rays and low energy γ-rays. The facilty also includes a conversion electron spectrometer SACRED[15], which consists of a superconducting solenoidal magnetic field for transport of conversion electrons and their subsequent detection in a highly segmented silicon detector. This facility is very important for the spectroscopy of trans-Lead and trans-Fermium nuclei, which is demonstrated in the observation of high multiplicity $M1$ conversion electron cascades of the rotational bands built on the high-K states of ^{254}No[16].

The fragment mass analyzer (FMA) is an 8.2 m long spectrometer with $\sim$ 8 msr acceptance, consisting of $QQEMEQQ$ (where, E = electric dipole deflector) configuration, which separates reaction products from the beam and disperses them according to their M/q ratio at the focal plane. The position of the residues at the focal plane is determined with a position-sensitive parallel-grid avalanche counter (PGAC). These residues are subsequently implanted in a thick DSSSD located behind the PGAC. This DSSSD is also used to measure the subsequent α-decay of the implanted recoils. The segmentation of the DSSSD provides effective spatial and time correlations between an implant and the subsequent α-decays. Trigger for valid events are generated when the PGAC detects in prompt coincidence with the DSSSD, or when a charged-particle decay is detected from the implant in the DSSSD. For the trigger events, the Ge detector array placed at the target position and the DSSSD parameters are recorded from which, the exclusive γ-spectra are generated. Despite the limitations on smaller solid angle coverage, these recoil analyzers have been effectively used in numerous experiments for their excellent separation and identification capability of the evaporation residues.

The goal of a velocity filter is charge state-independent velocity separation leading to very high rejection of beam background, especially for the asymmetric fusion evaporation reactions. The velocity filter SHIP[11] at GSI, Darmstadt, Germany has been used in many successful experiments including the discovery of new elements with $Z = 107 - 112$. Unlike a classical Wien filter, ship has separated electric and magnetic field elements, which improves efficiency and primary beam suppression. The overall configuration is $QQQEMMMMEQQQ$. However, for more symmetric type of reactions, the primary beam rejection is not as good.

Utilization of all the above recoil separator systems in the gamma spectroscopic studies are as follows. The recoiling heavy reaction products, on entry to the recoil separator, are separated from the beam particles and unwanted reaction products, such as transfer products, fission products etc., are implanted in a pixellated position-sensitive detector (eg. DSSSD) at the focal plane. The precise 2D position of entry to the focal plane and the corresponding time marker are often obtained from the MWPC type detector. The known flight time through the separator then allows a coincidence measurement to extract only prompt radiation in the correct time correlation with the detected recoil of interest. This is known as the recoil tagging (RT) technique. If the implanted nucleus undergoes decay, the emitted particles (α, β, or γ-rays) will be detected in the same position in the implantation detector or the adjacent detectors (as in GREAT) and the highly characteristic decay energy serves as a tag to identify the implanted nucleus on an event-by-event basis. This method is known as the recoil decay tagging (RDT) tech-

nique.

The above techniques are very useful for selecting extremely weak fusion-evaporation channels ($\sigma \leq 100\mu$b) in the spectroscopy of trans-Fermium nuclei, where very few reaction channels are open. The RT method is sufficient for channel selection in such situations. The α-decay of the implanted nuclei are used for confirmation of identification of the nuclei of interest. The RT method is severely constrained in situations, specially for lighter trans-Lead or trans-Fermium nuclei, where many reaction channels are open, and several α-emitting nuclei are produced. The nucleus of interest in such cases is selected by the RDT method, using the γ-recoil coincidence, exclusively selected by the recoil implant-chracteristic α-decay correlation within a time window spanning approximately three half-lives of the α emitting nucleus. Further details and the current status of spectroscopy of trans-Fermium nuclei using the above techniques can be found in Ref. [17] and the references therein.

The use of recoil analyzers as a tagging device is not very much suitable due to its small angular acceptance and hence, they have overall low ER detection efficiency in such a situation. A complmentary class of methods to the above recoil separation technique is the detection and tagging of the ERs and their decays near the target position. A recoil filter device (RFD) in the form of an annular array of secondary electron detectors and placed at 73 cm upstream from the target position spanning an angular zone of 2.7° to 12.1° from the beam axis[12] was used. The ERs, while passing through a thin aluminized mylar foil produce secondary electrons which are focussed, accelerated and detected by plastic scintillators. The ERs were separated from the beam-like particles and the fission fragments using the time-of-flight (TOF) taken with respect to the RF trigger from the accelerator, and the pulse height recorded. Recently, Reviol et al.[13] have successfully used a highly granular array HERCULES, consisting of 64 thin plastic (1 mg.cm^{-2}) scintillators coupled to photomultipliers and placed in annular configuration at 23–40 cm distance from the target. The angular coverage of the filter is from 3° to 19° from the beam axis. The residue detection method basically follows that originally demonstrated by Ajitanand et al.[18]. The heavier reaction products deposit energy inside the plastic scintillators and produce detectable signals. The ERs were discriminated against the other products using the same technique as in RFD. This device has been successfully used in the spectroscopy of high spin states of $^{205-207}$Fr and ^{204}At nuclei[3].

Another method employed for the ER tagging at the target position, specially when there are isomers, exploits the use of large Germanium detector array where the time difference ΔT spectra between the detectors and also between the beam pulse/RF trigger from the accelerator and the individual detectors are recorded[19]. Depending on the half lives of the isomers, ΔT windows can be selected to generate the gated γ-spectra from the $\gamma\gamma\Delta T$ cubes formed from the event-by-event data recorded. Time correlation with the beam pulse trigger is also used to clean up the spectra.

These methods yield complementary information which may be combined to get a complete picture of the high spin states in such nuclei. For example, in a recoil separator experiment, nearly symmetric reactions and a thin target($\sim$ 0.3 mg.cm^{-2}) are required (due to the small angular acceptance of the device), whereas a residue detector is most efficient when an asymmetric reaction and thicker target (that causes large straggling but does not stop the ERs) is used. For the same reason, access to (αxn) evaporation channels is often not observed in a recoil separator experiment (since these residues receive a large recoil kick) but is easy to do so with a residue detector.

In recent years, it is demonstrated that the projectile fragmentation reactions at relativistic energies can produce a very high multiplicity of fragments spanning the neutron-rich to the neutron-deficient regions around the stability line. Using state-of-the-art fragment separators, like the Fragment Recoil Separator (FRS)[20] at GSI, Darmstadt, these nuclei

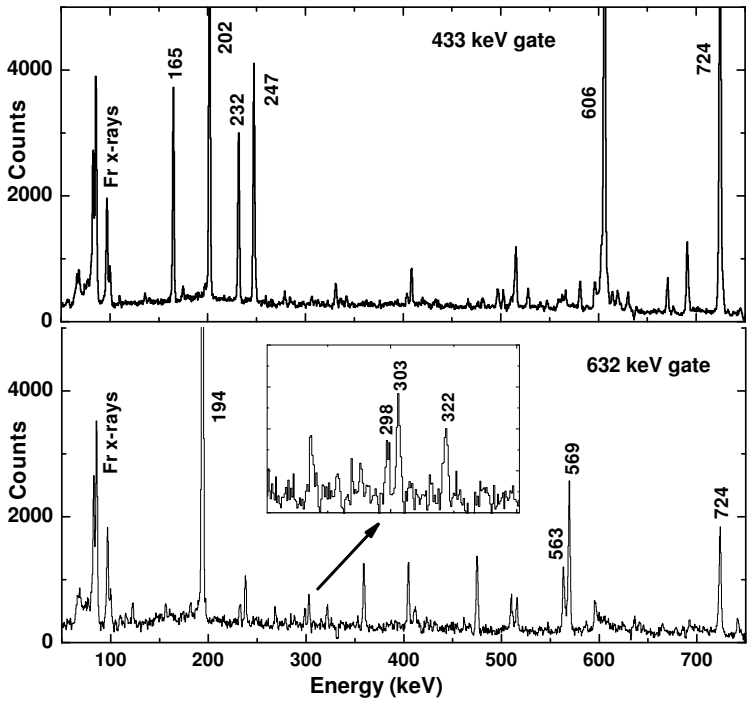

FIG. 1: A few gated spectra of the Fr isotopes. The 433 and 632 keV gates belong to ^{209}Fr and ^{208}Fr respectively. The inset in the lower box indicates some of the weaker transitions in ^{208}Fr.

are isolated, identified in-flight and their decay spectra observed at the focal plane. Since the TOF for such heavy fragments through the FRS is $\sim$ 300 ns, the nuclei, which have nanosecond isomers (half lives usually $\sim$ 100 ns or more) can only be studied by this technique. A huge number of heavy nuclei around Lead and trans-Lead regions were studied and their low lying levels up to the isomeric transitions are observed in the projectile fragmentation of ^{238}U[1] and ^{208}Pb[2]. However, the limitation of projectile fragmentation lies in that prompt gamma spectroscopy, or the spectroscopy of the levels above the isomers cannot be done by this method.

Recent INGA experiments on trans-Lead nuclei

In one of the recent attempts[22] at the spectroscopy of trans-Lead nuclei using INGA Clover detector array, we have performed the following experiment to produce $^{208-210}$Fr at the Inter-University Accelerator Centre (IUAC), New Delhi. The 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 nuclei of interest were produced as evaporation residues (ER) through (^{16}O, $xn\gamma$) reactions. Based on PACE calculations, $\sim$ 60 – 80 % of the fusion products at these bombarding energies undergo fission, which causes a huge

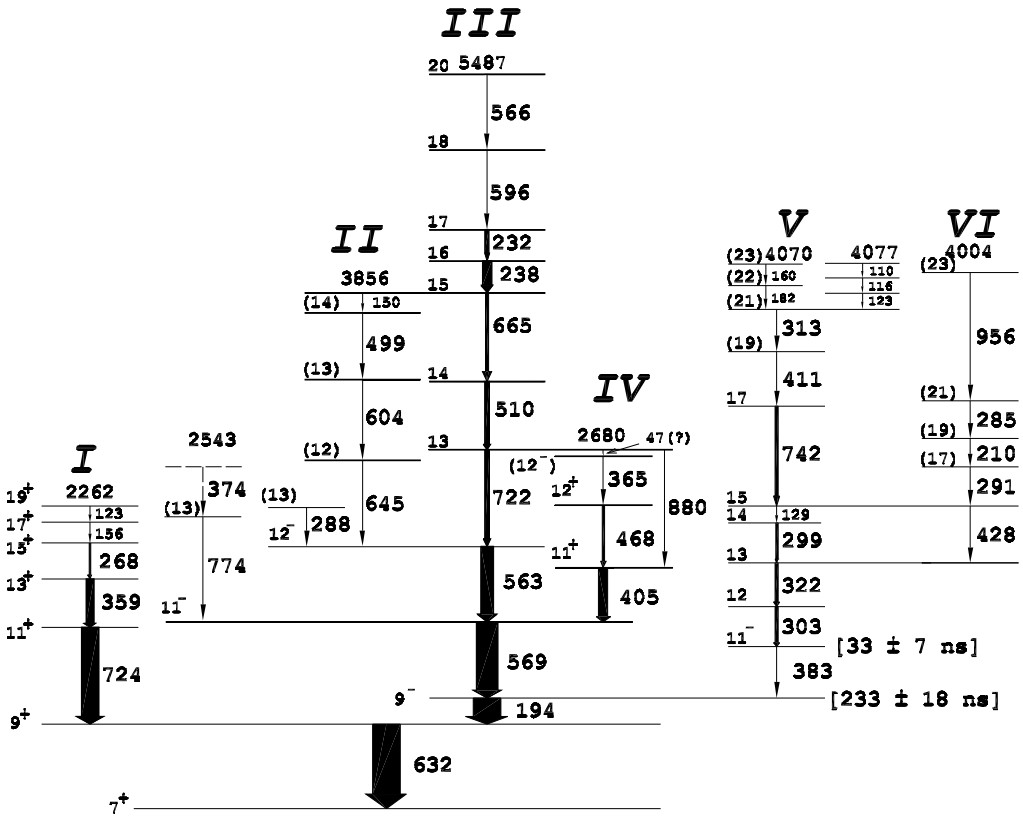

FIG. 2: Level scheme of ^{208}Fr based on our work. The spin-parity assignments are tentative, based on DCO ratio measurements.

background. Therefore, an effective filter to clean up the spectra, and / or good statistics are essential for extraction of meaningful results. We have followed the method of isomer tagging at the target position using the $\gamma\gamma\Delta T$ correlation as described above, exploiting the significantly large size of the Clover array. The γ-rays produced were detected by the Indian National Gamma Array (INGA) [21] consisting of 18 Compton suppressed Clover detectors placed around the target centre at the INGA-HYRA beam line. Necessary details of the experiment are described elsewhere[23].

Identification of the evaporation residues were done by a) excitation function measurements and comparison with statistical model predictions, and b) extrapolating the ER yields by tracking the offline decay yields of the daughter nuclei. Measurements by the two methods agree reasonably well and confirm the production of the nuclei of interest ($^{208-210}$Fr) during the experiment. The gamma rays assigned were validated by the X-ray gating on the K_α and K_β lines of Francium.

From the online data taken at 100 MeV beam energy, the francium X-ray gated $\gamma\gamma$ matrices, prompt and delayed $\gamma\gamma$ matrices and the γ-gated $\gamma\Delta T$ matrices were constructed. By gating on the 632 keV ground state transition and the intense 194 keV transition, the gamma rays belonging to ^{208}Fr were clearly established. The two transitions were known earlier from the projectile fragmentation reaction of ^{238}U beam at 900 MeV/u on ^{9}Be target at the FRS facility, where ^{208}Fr pro-