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Spectroscopy of fission fragments using prompt-delayed coincidence technique

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Abstract. The time-stamp structure of the digital data acquisition system of the Indian National Gamma Array (INGA) has been utilized to carry out prompt-delayed coincidence technique for the spectroscopic study of fission fragments. This technique was found to be useful to determine the states above the long-lived isomer (with half-life up to $\sim$5 μs), present in the fission fragments. The angular correlation of γ-rays, emitted by the fission fragments, has also been used in the present INGA geometry to determine the spins of the de-exciting states.

Keywords. Prompt-delayed coincidence; angular correlation.

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1. Introduction

The physics focus of INGA is to investigate the emergent properties of nuclear many-body system under varying rotational stress. These experimental investigations help in learning the symmetry of nuclear mean-field and its variation with angular momentum. A variety of high-spin phenomena related with the rotation of triaxial shapes [1,2], magnetic/antimagnetic rotations [3,4], shell model excitation [5,6], high-*K* isomers [7], octupole collectivity in heavy nuclei [8] and shape evolution with angular momentum have been investigated in the current experimental campaign of INGA. Most of the isotopes studied in these experiments were neutron deficient and populated with heavy-ion-induced fusion evaporation reactions. One of the frontiers in nuclear structure research is the investigation of high-spin states of stable and neutron-rich nuclei [9]. This will answer how the collective modes observed in neutron-deficient isotopes mentioned above get modified with changing isospin. Also, different effective interactions used in shell model need to be tested by comparing the results of these calculations with the measured high-spin states of neutron-rich nuclei. The effect of these interactions on the evolution of the single-particle energies at large isospin needs to be studied to determine the universal effective interaction in different regions of the nuclear landscape. So, the study of high-spin states in stable and neutron-rich isotopes has a wide scope in expanding our knowledge in terms of both single-particle excitations and collective phenomena. Here, we present some of the preliminary results of fission fragment spectroscopic studies with the existing INGA set-up using the ^{7}Li + ^{232}Th reaction.

This paper has been organized into four sections. In §2, the experimental details and analysis procedure have been given. Section 3 describes the techniques developed for the present geometry to determine the spin of the excited states of the fission fragments and to identify the states above the isomer and §4 presents the summary.

2. Experimental details and analysis procedure

^{7}Li beam at 38 MeV energy, provided by the TIFR–BARC Pelletron Linac Facility (PLF), was used to bombard a 12 mg/cm^{2} self-supporting ^{232}Th target. The excited compound nucleus, ^{239}Np, thus formed having a low fission barrier breaks into fission fragments after the emission of few neutrons. The fission fragments de-excite by emitting γ-rays. The γ-rays thus emitted were detected using the INGA spectrometer. The spectrometer contained 19 Compton-suppressed HPGe clover detectors. Three detectors, each was arranged in the rings at 40°, 65°, 115°, 140° and 157°, and four were arranged at 90° with respect to the beam direction as shown in figure 1. In addition to the Compton suppression due to vetoing of Compton scattered events by the BGO detector [10], the four Ge crystals packed in each clover detector help in generating the addback spectrum [11] leading to a further reduction in the Compton background. A fast digital data acquisition system (DDAQ) based on Pixie-16 modules of XIA LLC [12] was used to record two- and higher-fold coincidence events in the list mode form along with the time-stamp. For energy calibration and determination of relative photopeak efficiency of the array, a mixed source of ^{133}Ba and ^{152}Eu was used.

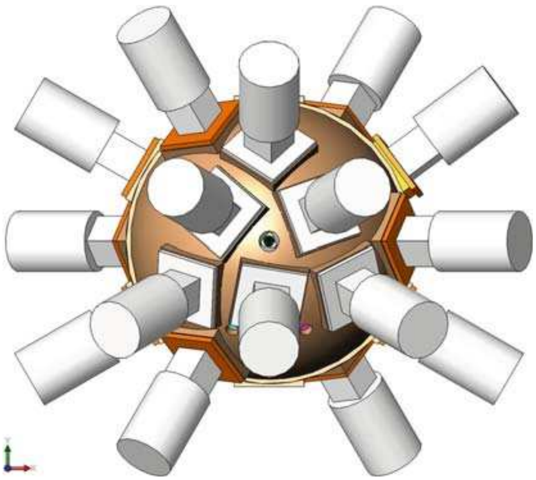

Figure 1. Schematic representation showing the position of the Compton-suppressed clover detectors in the INGA using Solidworks software.

In the present DDAQ, a single Compact PCI/PXI crate contains six Pixie-16 modules, two LVDS level translator modules and one controller. The crate is connected to the Windows PC via a MXI-4 PXI-PCI optical bridge. Each Pixie-16 card having 16 channels, serves four clover detectors. The preamplifier signals of the clover are digitized with a 100 MHz 12-bit flash analog-to-digital converter (FADC). One copy of the data stream generates a trigger by a fast filter once the output crosses the threshold. The fast trigger pulse is stretched to 100 ns and is used for multiplicity computation in the on-board FPGA. The fast triggers from the 16 channels of a Pixie-16 module are distributed to its adjacent modules through the PXI back-plane for generating global trigger after multiplicity computation. This trigger stretch length is kept as 10 μs to enable one to carry out prompt-delayed coincidence in the off-line analysis. The time-stamp will be latched and the event header information will be written for a channel if its fast trigger gets validated by the external trigger and not vetoed by channel veto signal. In case of a high-spin isomer, the γ-rays above the isomer will be registered within the prompt coincidence window kept at 100 ns, while the γ-rays of the cascade below the isomeric state can be detected up to next 10 μs.

'Multiparameter time-stamp-based coincidence search program (MARCOS)', a data sorting routine developed at TIFR, was used to sort the time-stamped data to generate one-dimensional histograms, E_γ–E_γ matrices and E_γ–E_γ–E_γ cubes. A set of 6.4×10^8 three- and higher-fold events were available for subsequent analysis. The RADWARE software package [13] was used for the analysis of matrices and cubes. A large number of isotopes were produced at high spins in this reaction and these were identified using E_γ–E_γ–E_γ cubes.

The total projection spectrum is shown in figure 2a. Various fission fragments have been produced in this experiment and a typical prompt coincidence spectrum of ^{100}Zr [14] is depicted in figure 2b. The spectrum has been obtained by gating on the lowest two

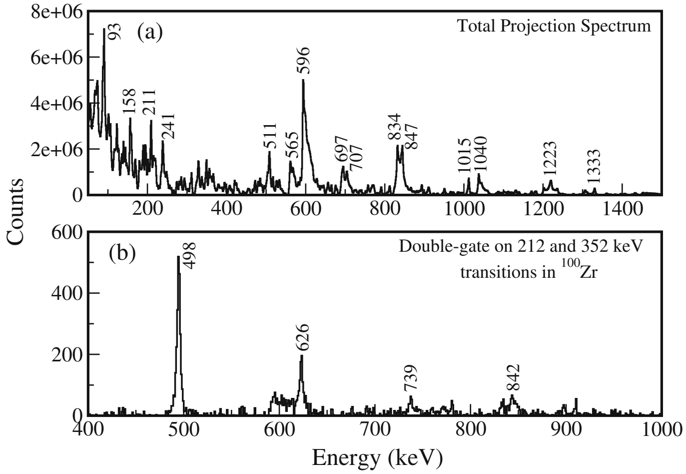

Figure 2. (**a**) Total projection spectrum. (**b**) The double-gated spectrum obtained by gating on 212 and 352 keV γ-ray transitions of ^{100}Zr (see [14] for the level scheme of ^{100}Zr).

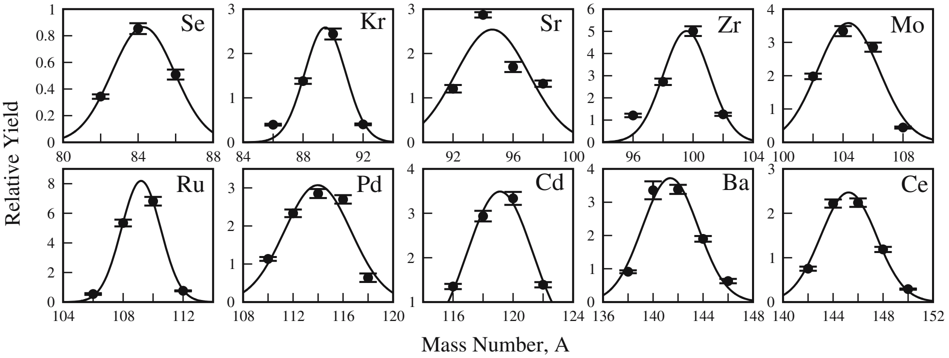

Figure 3. Total relative yields of some of the even–even isotopes. The data points were made to fit using a Gaussian function.

transitions with 212 keV ($2^+ \rightarrow 0^+$) and 352 keV ($4^+ \rightarrow 2^+$) energies. The 842 keV γ-ray decaying from the 12^+ state of ^{100}Zr is clearly identified in this gated spectrum.

The yield of a particular even–even isotope can be obtained from the intensities of $2^+ \rightarrow 0^+$ and $4^+ \rightarrow 2^+$ transitions [15,16]. The method of prompt coincidences of the γ-rays was used to measure the relative yields for a given pair of fission fragments. Different isotopes were identified using the E_γ–E_γ–E_γ cubes and known level schemes of these isotopes [17]. The intensities of the γ-ray transitions in different isotopes were corrected for the detection efficiency of the γ-rays involved in selection and used to extract the relative yields of the isotopes. The measured yield distributions of various even–even isotopes, $^{82-86}$Se, $^{86-92}$Kr, $^{92-98}$Sr, $^{96-102}$Zr, $^{102-108}$Mo, $^{106-112}$Ru, $^{110-118}$Pd, $^{116-122}$Cd, $^{138-146}$Ba and $^{142-150}$Ce are shown in figure 3. The data points were made to fit using the following Gaussian function:

$$\frac{C}{\sqrt{2\pi\sigma^2}} \times \exp\left(-\frac{(x - A_{\mathrm{P}})^2}{2\sigma^2}\right), \tag{1}$$

where the parameters C is a constant, σ and A_{P} denote width of the distribution and the most probable mass number of a given fission fragment, respectively.

3. Experimental results

For developing a level scheme of the fission fragments, the information on the spin and parity of their excited states needs to be obtained through measurement. In the fusion–fission experiment, the fission fragments are not aligned and so the angular correlation measurements of the de-exciting γ-rays were carried out to determine the spin of the excited states [18]. Here, the application of the angular correlation theory to the current INGA geometry is discussed. To determine the spin of the excited states, the coincidence rates of two successive γ-ray transitions were analysed as a function of the average relative angle (θ) between the two fired detectors. The INGA spectrometer had $C_2^{19} = 171$ combinations of two detectors, out of which only 37 involved different values of relative angle within 1°. The angular correlation functions at three different angles for several combinations of spin sequences, corresponding to typical multipole orders were calculated. It was found that the coincidence rate increases between 0° and 90° for the dipole–quadrupole cascades, whereas it decreases for the quadrupole–quadrupole or dipole–dipole cascades. To check the method for the present geometry, the angular correlations of transitions belonging to the standard radioactive sources and yrast cascades of the fission fragments having well-known multipole orders were analysed and the expected values were obtained in all the cases.

Figure 4 shows the angular correlation measurements performed for one of the fission fragments, ^{136}Xe [19]. The lowest two transitions 1313 keV ($2^+ \rightarrow 0^+$) and 381 keV ($4^+ \rightarrow 2^+$) were used in the measurements. Three angle-dependent matrices were created and a gate on the 1313 keV transition was applied to determine the intensity of the 381 keV transition. Similar measurements were carried out for ^{137}I [20]. The two transitions 554 keV ($9/2^+ \rightarrow 7/2^+$) and 400 keV ($13/2^+ \rightarrow 9/2^+$) were used to perform the correlation analysis. A gate was applied on the 554 keV transition to determine the intensity of the 400 keV transition from the three angle-dependent matrices. The results for ^{137}I are shown in figure 5. The data points were then made to fit using the following function:

$$W(\theta) = 1 + a_2 P_2(\cos\theta) + a_4 P_4(\cos\theta), \tag{2}$$

where a_2, a_4 are the angular correlation coefficients and $P_2(\cos\theta)$, $P_4(\cos\theta)$ are the Legendre polynomials. So, the spins of different transitions can be determined provided the statistics is good enough.

Some of the fission fragments have long-lived isomers and it becomes difficult to identify the γ-rays above the isomer. For this, the data sorting program MARCOS was modified to make prompt-delayed coincidence matrix. In this approach, the γ-ray transitions above the isomer, within a time window of 100 ns, was stored on one axis of the matrix (the prompt axis) and the delayed γ-ray transitions (transitions below the isomer) within a particular time window, depending on the half-life of the isomer, was stored on the other axis of the matrix (the delayed axis). The resultant matrix was subtracted for

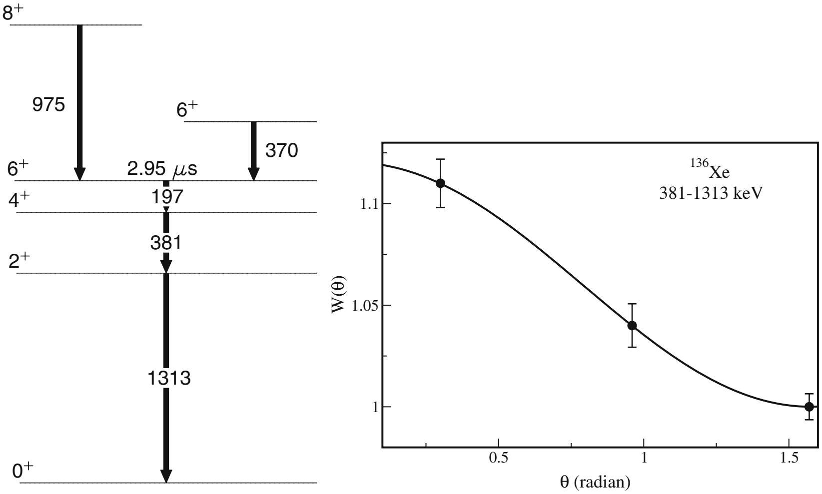

Figure 4. The level scheme of ^{136}Xe [19] and the angular correlation measurement for the 381 and 1313 keV γ-ray transitions.

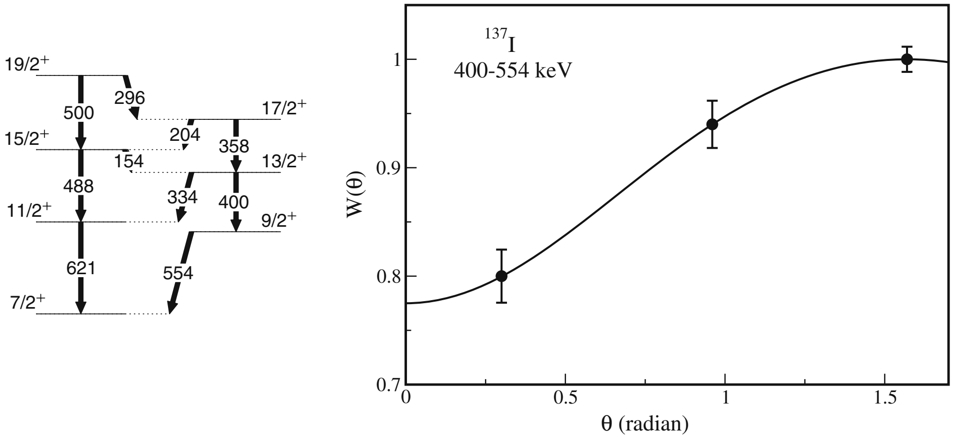

Figure 5. The level scheme of ^{137}I [20] and the angular correlation measurement for the 400 and 554 keV γ-ray transitions.

Compton background and then analysed using the RADWARE software. This technique was first applied to a particular isotope which has experimentally known excited states above the isomer. A gate was applied on the delayed axis and projected on the prompt axis of the matrix, resulting in a prompt spectrum containing all the γ-rays above the isomer after background subtraction. But, it might be possible that some of the γ-rays in the prompt spectrum are due to de-excitations from another fission fragment (a contaminant) having an isomer of similar half-life. To confirm the prompt γ-rays of the fission fragment we are interested in, a gate was applied on the prompt axis and projected on the delayed axis of the matrix. The resultant delayed spectrum, after background subtraction, must contain all the γ-rays below the isomer of that fission fragment. If, on the other hand, the delayed spectrum does not contain all the γ-rays below the isomer of the fission fragment, then it shows that the gating was done on a prompt γ-ray of the contaminant. So, this technique gives a unique identification of the states above the isomer of a particular fission fragment.

In ^{130}Te [21], a gate was applied on the 935 keV ($9^- \rightarrow 7^-$) prompt γ-ray transition and the 182, 331, 793 and 839 keV γ-ray transitions were observed in the delayed spectrum (figure 6a). Figure 6b shows the delayed spectrum containing the 182, 331, 793, 833 and 839 keV γ-ray transitions obtained by gating on the 718 keV ($12^+ \rightarrow 10^+$) prompt γ-ray transition. A gate was applied on the 793 keV ($4^+ \rightarrow 2^+$) delayed transition and all the prompt γ-ray transitions with 126, 299, 411, 458, 502, 654, 710, 718, 732 and 935 keV were observed (figure 6c).

Level scheme of $^{124-131}$Te isotopes are recently reported up to high spin using fusion–fission reactions from the triple coincidence data [21]. 10^+ seniority isomers are observed in ^{128,130,132}Te [21,22]. A knowledge of the high-spin states above these isomers will allow one to look for proton particle and neutron–hole excitations near the closed shell nuclei. In particular, no states were known above the 10^+ isomer with $T_{1/2} = 3.2\ \mu$s in ^{132}Te. Therefore, the previously mentioned prompt-delayed technique is used to extend the level structure above the 10^+ isomer. The spectrum indicates the presence of 901 and

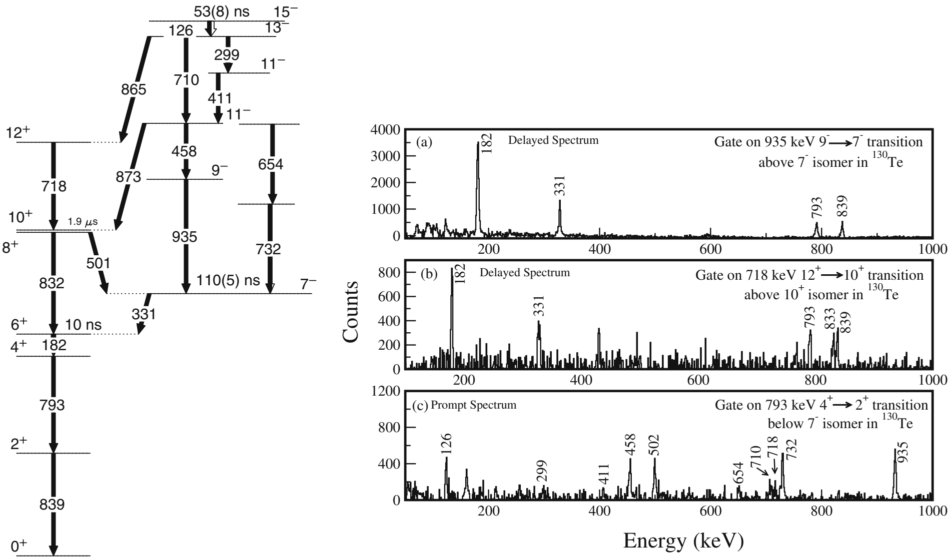

Figure 6. The level scheme of ^{130}Te [21] and the prompt-delayed coincidence spectra in ^{130}Te.

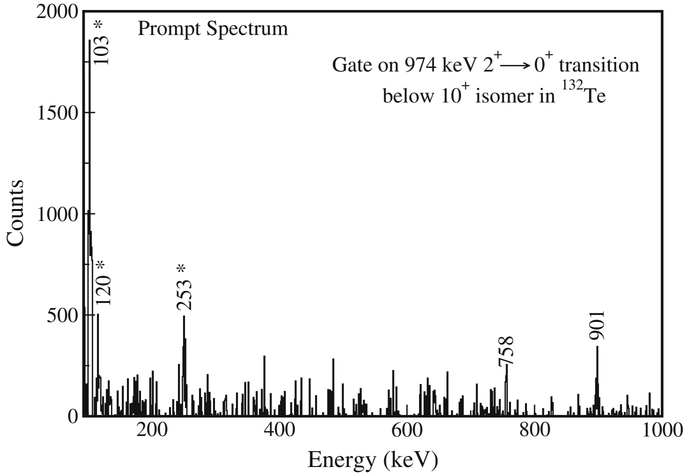

Figure 7. Prompt spectrum obtained by gating on 974 keV $2^+ \rightarrow 0^+$ transition in ^{132}Te which is below the 3.2 μs isomer at the 10^+ state [22]. The transitions marked with an * are due to de-excitations of ^{124}Sn having an isomer of similar half-life.

758 keV transitions above the 10^+ isomer (see figure 7). Further analysis of the data is in progress to look for new states above the known isomers present in the neutron-rich nuclei produced in the ^{7}Li-induced fusion–fission reaction.

4. Summary

^{7}Li + ^{232}Th fusion–fission reaction was performed to populate the neutron-rich isotopes and to study their structure at high spins. The yields of the different neutron-rich isotopes produced in this reaction were measured. The angular correlation measurements were performed to determine the spins of the excited states. The prompt-delayed coincidence technique was discussed in detail. The potential of this method to determine the states above the isomer was demonstrated. Further data analysis of the current experiment using this technique will provide additional information on high-spin states of neutron-rich fragments.

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