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Fission fragment mass distributions via prompt γ-ray spectroscopy

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Abstract. The distribution of fragment masses formed in nuclear fission is one of the most striking features of the process. Such measurements are very important to understand the shape evolution of the nucleus from ground state to scission through intermediate saddle points. The fission fragment mass distributions, generally obtained via conventional methods (i.e., by measuring the energy and/or the velocity of the correlated fission fragments) are limited to a mass resolution of 4–5 units. On the other hand, by employing the γ-ray spectroscopy, it is possible to estimate the yield of individual fission fragments. In this work, determination of the fission fragment mass distribution by employing prompt γ-ray spectroscopy is described along with the recent results on ^{238}U(^{18}O, f) and ^{238}U(^{32}S, f) systems.

Keywords. Fission fragment mass distribution; γ–γ coincidence technique.

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1. Introduction

Nuclear fission is a complex process involving large-scale collective rearrangement of nuclear matter. The shape of the fissioning nucleus evolves in the multidimensional space of relative separation, neck opening, mass asymmetry and deformation of the fragments [1]. The fission fragment mass and charge distributions are decided during saddle-to-scission transition and are related to the scission configuration. Detailed studies on fission fragment mass, energy and charge distributions for a large variety of fissioning systems are important sources of information about the fission process. Conventionally, fission fragment mass distributions are studied by measuring the energy or velocity (time-of-flight technique, TOF) of the correlated fission fragments [2–4]. The main limitation of these measurements is that one cannot achieve a mass resolution better than 4–5 units. On the contrary, one can estimate the yield of individual nucleus from the de-excitation of its characteristic γ-ray. In the case of even–even nuclei the total intensity of its $2^+ \rightarrow 0^+$ ground-state transition provide the yield to a high degree of accuracy [5,6]. However, this technique/method in practical terms is very difficult with the singles data (γ-ray spectrums), as in fission a large number of nuclei are produced having a large number of γ-rays with overlapping energies. This problem has been overcome with the availablity of modern high efficiency Compton-suppressed HPGe detector arrays. Using the arrays the yield of individual fission fragment is extracted from the γ–γ (or higher fold) coincidence analysis of the prompt γ-ray spectroscopy (fission fragment spectroscopy) [7].

The fission fragment spectroscopy has been employed to study the level structures of a large number of neutron-rich nuclei. These nuclei are not easily accessible by conventional fusion evaporation reactions (which are best suited for high-spin studies). Spectroscopic studies of the neutron-rich nuclei from the spontaneous fission of ^{252}Cf [8–10] and ^{248}Cm [11,12] sources and heavy-ion-induced fusion–fission reactions [13–17] have enriched our knowledge on the evolution of nuclear shell structure. In addition to the isotopic yield distribution of fission fragments and structure studies, one can also extract information on the angular momenta of the fragments from these fission fragment spectroscopy measurements. The average angular momenta carried by the fission fragments are estimated from the relative intensities of the transitions in the ground band cascade as reported by Mukhopadhyay *et al* [18]. The angular momentum distribution of fission fragments provide information on the neck vibration at the scission point and is an important fission observable.

In this paper, the γ–γ coincidence technique to obtain the isotopic yield and fragment mass distribution is presented. We have employed the above method to obtain the isotopic yield and fission fragment mass distribution in the ^{238}U(^{18}O, f) reaction in an earlier investigation [7]. The experimental details of the work is presented in §2. The fission fragment mass distribution in the ^{238}U(^{18}O, f) reaction (obtained by employing the $\gamma-\gamma$ technique) [7] and mass distribution in ^{208}Pb(^{18}O, f) by Bogachev *et al* [19], lead to the observation of 'fine structure in fragment mass distribution' (see §3). More recently, we have carried out measurements for the ^{238}U(^{32}S, f) system at above and near-Coulomb barrier energies with an aim to study the evolution of fragment mass distribution as a function of excitation energy. The preliminary results are presented.

2. Experiment and data analysis

The ^{238}U(^{18}O, f) reaction was carried out at the 15UD IUAC Pelletron Accelerator Facility, New Delhi, bombarding the ^{18}O beam at an energy $E_{\text{lab}} = 100$ MeV on a self-supporting ^{238}U target of thickness $\sim$15 mg/cm^2 [7]. The thick target was used to stop at least one of the fragments in the target, to reduce the Doppler effect on the γ-ray energy. The γ-rays emitted in the reaction were detected using the Indian National Gamma Array (INGA) [20], comprising 18 Compton-suppressed Clover detectors at the time of measurement. The Compton-suppressed data were collected in an event-by-event mode with the minimum requirement of three-fold prompt γ-ray coincidence. The coincidence time gate for recording the data was set at $\sim$350 ns. The γ–γ matrix was constructed from the prompt γ-ray coincidence data. These γ–γ matrices were analysed using RADWARE software [21] to obtain independent yields of the fission fragments.

3. Results and discussion

As mentioned in §1, the yield of an even–even fragment can be estimated from the intensity of its $2^+ \rightarrow 0^+$ ground-state transition, to a high degree of accuracy ($\sim$ 90–95%) [5,6]. The independent yields of even–even fragments were determined from the coincidence between the γ-rays of $2^+ \rightarrow 0^+$ and $4^+ \rightarrow 2^+$ ground-state transitions. In case of nuclei with side feeding, the intensity of the $2^+ \rightarrow 0^+$ transition was obtained by putting gates on all transitions which feed the 2^+ ground state directly. The yield distribution of correlated fragments (Sr–Sm, Zr–Nd, Mo–Ce, Ru–Ba, Pd–Xe, Cd–Te and Sn–Sn isotopes) produced in the ^{238}U(^{18}O, f) reaction show a bell-shape distribution, as shown in figure 1.

The fission fragment mass distribution was obtained by adding the yields of various nuclei corresponding to a particular mass. The mass distribution was found to be

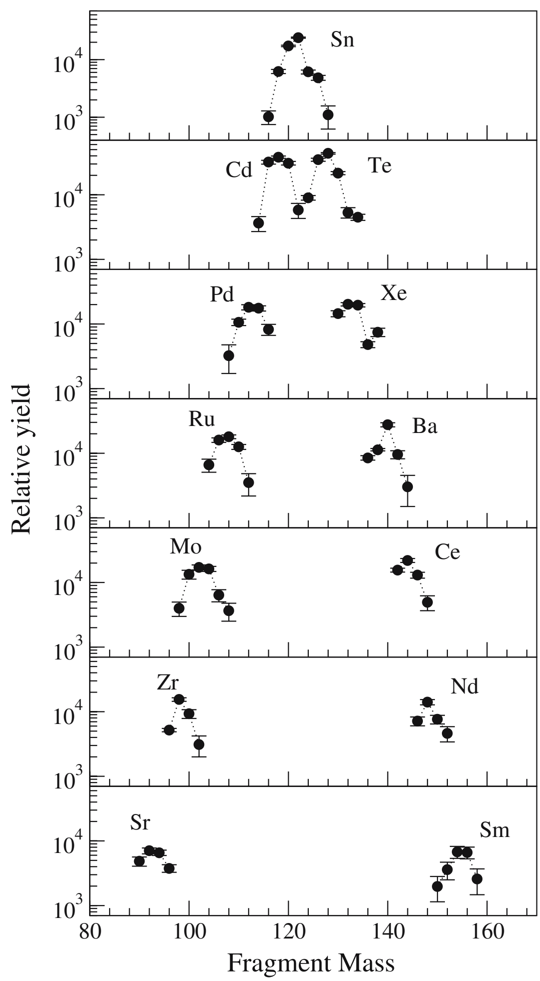

Figure 1. Relative yield distribution of various fission fragments produced in the ^{238}U(^{18}O, f) reaction [7]. The dotted lines are to guide the eye.

symmetric around $A = 124$, corresponding to an average of eight neutrons evaporated from the compound nucleus (CN) and the excited fission fragments. The mass distribution with an overall width of $\sigma_M = 20.5$ a.m.u., is in good agreement with the systematics obtained by employing the time-of-flight technique [4]. However, the interesting observation made from the work [7] was the presence of 'fine structure dips' in the mass distribution, corresponding to fragment masses $A = 112$, 124 and 136, where the yield was significantly reduced. Bogachev *et al* who had earlier reported similar structures in the mass distribution of ^{208}Pb(^{18}O, f) reaction [19], attributed them with the lack of odd–even and odd–odd isotope yields. The mass distributions of ^{238}U(^{18}O, f) [7] and ^{208}Pb(^{18}O, f) reactions [19] are shown in figure 2 for comparison. It is observed that irrespective of the compound system, the dips in the fragment mass yields occur for $A = 124$ and 136 and their complementary fragments. From the fragment yield analysis it was observed that these 'fine structures' in mass distribution are related to the shell closure of the secondary fragment at $Z = 50$ and $N = 82$ shells, where the yields are depleted. Both the experiments [7,19] gave clear indication of nuclear structure effects in the fission fragment mass distribution persisting at a high excitation energy where the shell effects are expected to be washed out. The 'fine structure' in the mass distribution can also be interpreted in terms of a new phenomenon 'shape inhibition' of close shell fragments at the scission point. This leads to a higher barrier for the splits in which one or both partners have closed shell configurations [7].

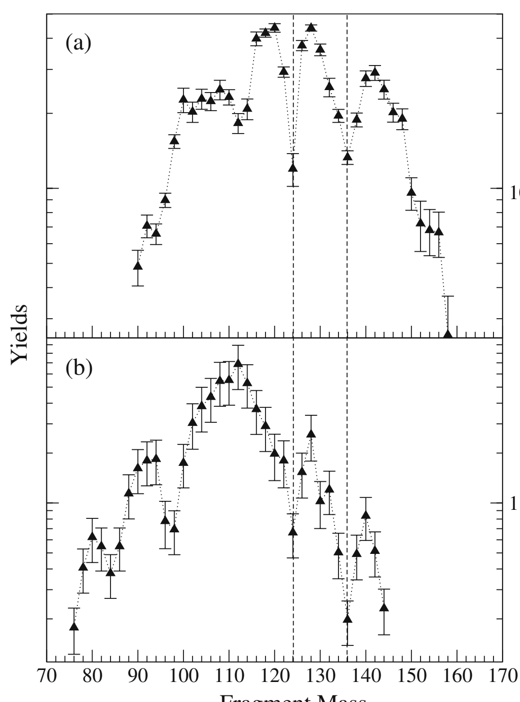

Figure 2. Fission fragment mass distributions obtained in (**a**) ^{238}U(^{18}O, f) [7] and (**b**) ^{208}Pb(^{18}O, f) reactions [19].

The results on mass distributions of ^{238}U(^{18}O, f) and ^{208}Pb(^{18}O, f) [7,19] provide important new insights in the fission process. More systematic experimental data are required to clearly understand the 'fine structure' in mass distributions. With this motivation, we have further carried out fission fragment spectroscopy of ^{238}U(^{32}S, f) and ^{238}U(^{12}C, f) reactions. The study of mass distributions as a function of $Z_P Z_T$ is interesting as the heavy-ion fusion–fission dynamics depends on the product ($Z_P Z_T$) which is expected to affect mass distributions. The measurements for the ^{238}U(^{32}S, f) system has been carried out at above and near Coulomb barrier energies. As the product $Z_P Z_T$ is higher for this system, the non-compound nuclear fission modes are expected to contribute more. A comparative study of mass distributions (with unit mass resolution) at above and below barrier energies will be interesting. Figure 3 shows the preliminary results on isotopic yield distribution for Xe and Te–Ba fragments in ^{238}U(^{32}S, f) at above and below barrier energies.

4. Summary and outlook

In summary, we described the determination of fission fragment mass distribution by employing γ–γ coincidence technique for the ^{238}U(^{18}O, f) system. The observed 'fine

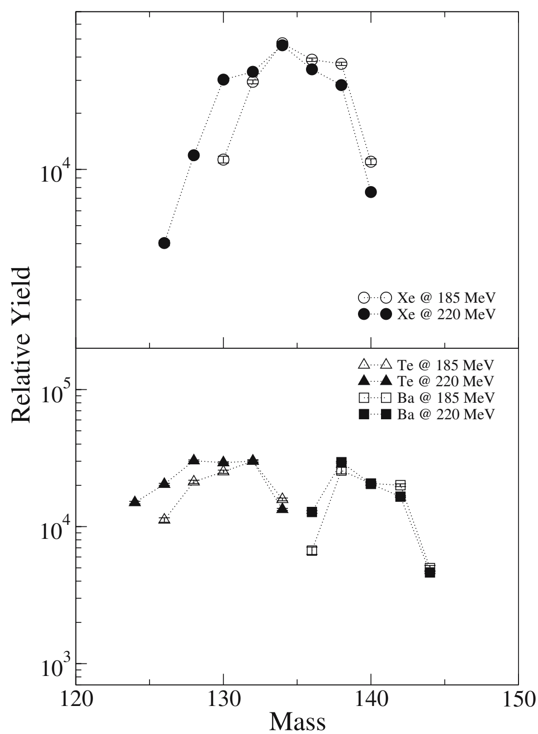

Figure 3. The isotopic yield distributions for Xe, Te and Ba for the ^{238}U(^{32}S, f) reaction at 220 and 185 MeV incident energies. The open symbols represent the isotopic yield obtained at 185 MeV and solid symbols represent the yields at 220 MeV.

structure in fragment mass distribution' has been understood in terms of 'shape inhibition' phenomena arising due to fragment shell effect. Further, we have shown some preliminary results on isotopic yield distribution for ^{238}U(^{32}S, f) at two different bombarding energies. A comparative study of fragment mass distribution at different bombarding energies can throw light on fusion–fission dynamics.

The γ-ray spectroscopy method gives unit mass resolution as compared to 4–5 units by the conventional methods of measuring mass distributions. This procedure can be applied for even–even isotopes, where the level schemes are usually well-known and the ground-state rotational band is clearly identified. In odd–odd and even–odd nuclei the decay paths are much more complicated and complete spectroscopic information is not available for some nuclei. Due to these reasons the yield of odd–odd and even–odd fragments cannot be determined. Also, in contrast to the TOF method (velocity measurement), the γ-ray spectroscopy method probes the fission fragment masses after the post-scission neutron emission (secondary fission fragments). However, the study of mass distribution as a function of $Z_P Z_T$ and comparative study of mass distribution as a function of bombarding energy via the γ-ray spectroscopy method will be considered important to study fusion–fission dynamics, owing to unit mass resolution.

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