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Fission study of actinide nuclei using multi-nucleon transfer reactions

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Abstract

We have developed a set up to measure fission properties of excited compound nuclei populated by multi-nucleon transfer reactions. This approach has an advantage that we can study fission of neutron-rich nuclei which cannot be accessed by particle or charged-particle capture reactions. Unique feature in our setup is that we can produce fission data for many nuclei depending on different transfer channels. Also wide excitation energy range can be covered in this set up, allowing us to measure the excitation energy dependence of the fission properties. Preliminary data obtained in the $^{18}O + ^{238}U$ reaction will be presented.

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Keywords: Multi-nucleon transfer reaction, fission, fragment mass distribution ;

1. Introduction

Nuclear fission was found by irradiating uranium by neutrons. Fission can be also triggered by charged particles such as proton, α particle and heavy-ions. Gamma-ray and muon sources are also used for the fission

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study. Mass asymmetric fission was found already in the very beginning of the fission study. The phenomenon was not explained by the liquid-drop model of a nucleus, and it is essential to include the shell effects in fission. By exploring another region of the chart of nuclei, new phenomena in fission have been found. In the fission of heavy actinide nuclei, sharp transition from asymmetric to symmetric fission was found, suggesting the appearance of two ^{132}Sn-like clusters in the nucleus (Vandenbosch and Huizenga 1973). Existence of two fission modes was clearly observed in a systematic study of fission for actinide and pre-actinide nuclei using electro-magnetic induced fission (Schmidt 2000). Recently, mass asymmetric fission was observed in the low energy fission of proton-rich nucleus ^{180}Hg (Andreyev 2010), populated as a daughter by the β^+/EC-decay of ^{180}Tl.

At Japan Atomic Energy Agency, we started a campaign to study fission of actinide nuclei including those whose fission data do not exist. We use multi-nucleon transfer reaction to populate these nuclei (see Fig. 1). Advantage of this reaction is that we can produce many nuclei in one reaction depending on different transfer channels including neutron-rich nuclei which cannot be accessed by fusion reaction. Another unique feature is that the excitation energy of the fission system distributes widely, so that the excitation energy dependence of the fission properties can be obtained.

In this report, we describe the experimental setup. Some preliminary data for the fission fragment mass distributions obtained in the ^{18}O + ^{238}U reaction will be discussed.

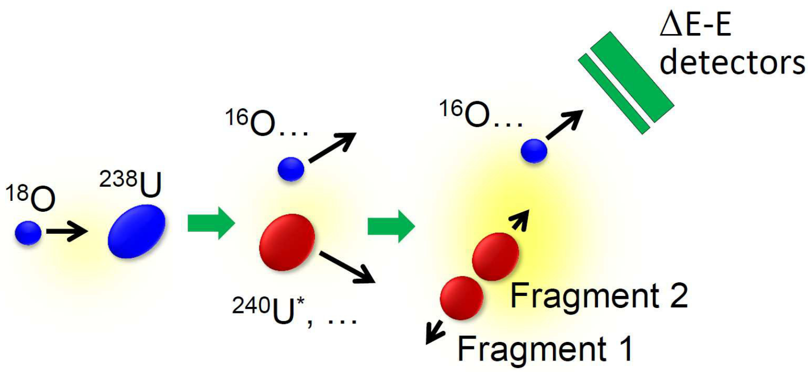

Fig. 1. Multi-nucleon transfer induced fission

2. Experimental Setup

Experiment was carried out at the JAEA tandem facility, Tokai, Japan. A thin ^{238}U target was irradiated by ^{18}O beams at energy of 157.5 MeV. The ^{238}U target was prepared by electrodeposition of natural $^{238}UO_2$ on a Ni backing of 90 μg/cm^2-thickness. Transfer channel was identified by detecting the projectile-like nucleus using a silicon ΔE-E detector array which was located to the forward direction of the target. Thickness of the ΔE detector was 75 μm. Twelve pieces of the ΔE detectors were used to form a ring shape around the beam axis to make an efficient collection of the projectile-like nuclei. The particles passing through the ΔE detector were detected by a silicon strip E detector (SSD) with thickness of 300 μm, and their energies (E_{res}) were determined. The E detector has an annular shape, and the detector covers the scattering angle from 17.2^o to

30.9° relative to the beam direction. The SSD has 16 annular strips within the active area, with which the scattering angle θ with respect to the beam can be defined.

Figure 2 shows an example of the projectile-like nuclei plotted on the ($\Delta E+E_{res}$, ΔE) plane. Oxygen isotopes are clearly separated as well as those of lighter-element isotopes. By choosing a specific channel, we can assign the transfer channel and the corresponding compound nucleus.

Fission fragments were detected using four multi-wire proportional counters (MWPCs). Each MWPC has an active area of 200×200 mm^2. The MWPC consists of the central cathode which is sandwiched by two wire planes. The wire planes were designed to detect the incident position of fission fragment. The MWPCs were operated with an isobutene gas of about 1.5 Torr. The operation gas was shielded by an aluminum-coated Mylar window of 2.0 µm thickness. Induced charge in the cathode was used to separate fission fragment from scattered particles and/or lighter ions. Distance between the target and center of the cathode was set at 224 mm. Time difference signal, ΔT, from the two facing MWPCs was recorded. Fission fragment masses were determined kinematically using ΔT and fission fragment directions.

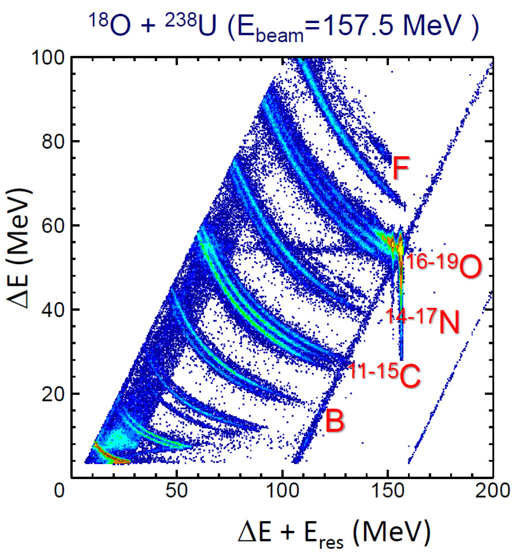

Fig. 2 Plot of the projectile nuclei on the ($\Delta E+E_{res}$, ΔE) plane obtained in the $^{18}O + ^{238}U$ reaction.

3. Experimental Results and Discussions

Results of the fission fragment mass distributions of the compound nucleus $^{239}U^*$ are shown in Fig. 3. The nucleus is populated by the $^{18}O + ^{238}U \rightarrow ^{17}O + ^{239}U^*$ reaction. In Fig. 3(a), fission events are plotted on the fragment mass and excitation energy of the compound nucleus. It is found that excitation energy (E^*) reaches to more than 50 MeV. It is evident that fission fragment yield is asymmetric at the low excitation energies, whereas symmetric fission dominates toward higher excitation energies. The excitation energy dependence of the fission yields is clearly seen in Fig.3 (b), where fission fragment yields are plotted in every $\Delta E^* = 10$ MeV interval. The peak to valley (P/V) ratio of the fission yield decreases at higher excitation energies. The present data is compared to the literature data (Simutkin 2014) obtained by the neutron-induced fission of ^{238}U. Mass asymmetry as well as P/V ratio agree with each other, indicating that present method using multi-nucleon transfer reaction can be used as a surrogate reaction to determine the fission fragment mass distributions.

The excitation energy achieved in the present experiment is limited by the thickness of the ΔE detector (75 μm in the present case). The spectrum in Fig.2 indicates that possible extension of the excitation energy should be possible by using a thinner ΔE detector.

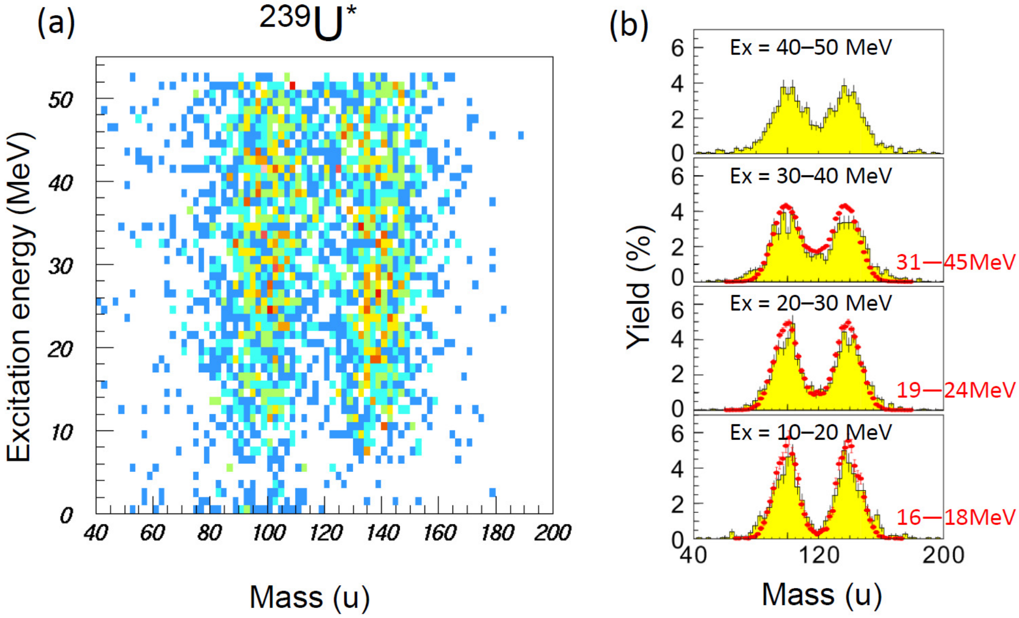

Fig. 3 (a) Fission fragment mass distribution of $^{239}U^*$ plotted on the mass and excitation energy. (b) Fission fragment yields obtained in the present experiment (histogram) are compared with the literature data shown by open circles. The literature data is taken from (Simutkin 2014) and the excitation energy range is marked in the right side of each panel.

Similar analysis was carried out for the different transfer channels. Figure 4 shows the fission fragment mass distribution for uranium isotopes $^{237,238,239,240}U^*$ and their excitation energy dependence, obtained by neutron-transfer channels. Mass yield data for the fission of $^{240}U^*$ was obtained for the first time. Transition from the asymmetric to symmetric fission is found for all the isotopes. Looking at the P/V ratio, it is evident that heavier isotopes have larger P/V values at excitation energy region of E^* >30 MeV when the spectra are compared at the same excitation energy. Possible explanation is that neutron-rich fissioning nucleus generates more neutron-rich heavy fragments, which is closer to the doubly-magic nucleus ^{132}Sn, thus the fission is more likely connected to the structure of ^{132}Sn. Such a system keeps shell structure even at high excitation energy.

Excitation energy dependence of the fission yield would have information on the damping of the shell. Recent model calculation uses an unexpectedly large shell damping energy E_D (Randrup 2013) to reproduce the measured fission fragment charge distribution than those obtained from the neutron resonance spacing

(Reisdorf 1981). Present experimental data covering wide excitation energy range would be useful to discuss the E_D value.

In this experiment, we could also obtain the fission data for heavier actinides than target nucleus. Preliminary data shows that fission data for more than 10 nuclei can be generated in this reaction. Another interesting and important feature in this experimental method is that the reaction plane, defined by the directions of scatted projectile-like nucleus and recoiled nucleus, can be fixed. This allows us to obtain angular distribution of emitted fission fragments, which is a function of spin J and its projection K on the symmetric axis of the fissioning system. Correlation between these variables and fission properties are under analysis.

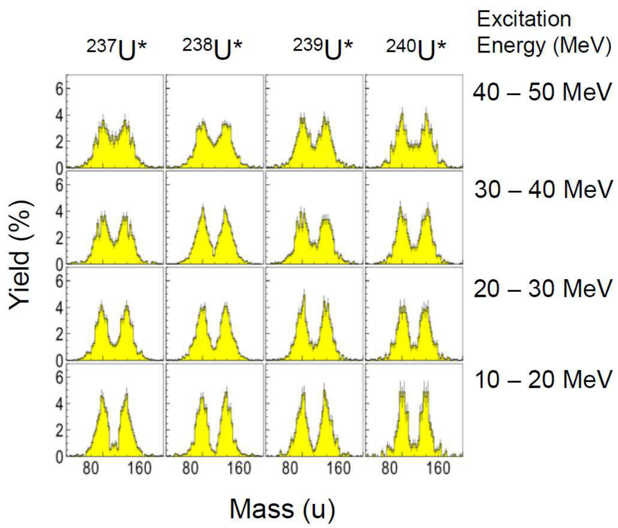

Fig. 4 Fission fragment mass distribution of $^{237,238,239,240}U^*$. Excitation energy range is shown.

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