Fragment Mass Distribution of the ^{239}Pu(d, pf) Reaction at the Super-deformed β-vibrational Resonance

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We measured, for the first time, the mass distribution of ^{240}Pu fission fragments following the β-vibrational resonance, whose level is formed on the second minimum of the double-humped fission barrier. The distribution shows an asymmetric mass distribution similar to the one observed for thermal neutron-induced fission of ^{239}Pu and isomeric fission of ^{240}Pu. This indicates that the ^{240}Pu system following the β-vibrational resonance descends into a fission valley which is identical to the fission valley of the ^{240}Pu-isomer and ^{239}Pu(n_{th},f).

1. Introduction

For neutron-induced fission of ^{239}Pu, there is an old investigation on the mass division following the neutron capture resonance [1,2]. The results [2] show, in the abundance of ^{99}Mo and ^{115}Cd, that fission through the $J^{\pi} = 1^{+}$ state enhances the relative abundance of mass-asymmetric fission products (^{99}Mo) compared to fission through the the $J^{\pi} = 0^{+}$ state. This was interpreted in [3] as an effect of the collective motion at the saddle point that the octupole vibration of $K^{\pi} = 1^{+}$ with mirror asymmetry results in the enhanced mass asymmetry compared to the ground state of $K^{\pi} = 0^{+}$, namely the vibrational motion at the saddle point drives the system to the asymmetric fission mode (path). Supporting this interpretation, it would be natural to presume that when the β-vibration with $K^{\pi} = 0^{+}$ ispopulated at the middle stage of the fission process the resulting fission may have a symmetric fission component larger than the thermal neutron-induced fission due to vibrational motion with mirror symmetry. We can find the β-vibrational state on the second minimum of the double-humped fission barrier (super-deformed minimum : SD). This state is observed below the threshold energy in the form of an enhanced fission cross section due to resonance tunneling induced when the excitation energy (E_{ex}) of the compound nucleus matches the level [4,5,6,7].

We are interested in resonance fission through the β-vibrational state of $K^{\pi} = 0^{+}$ built on the SD which has a mass symmetric shape [8]. We expect for this specific case that near-symmetric fission would be enhanced. In this paper we measured the mass distribution of fission fragments by gating on the β-vibrational resonance. Our choice for this study was ^{240}Pu populated by ^{239}Pu(d,p) reaction. Plutonium-240 is one of the nuclei for which the properties of the β-vibrational state were extensively investigated. We have determined the excitation energy of ^{240}Pu by measuring protons using silicon detectors as in [4].

2. Experimental Methods

The experimental setup is shown schematically in Fig. 1. The reaction ^{239}Pu(d,pf) was used to study resonance fission of ^{240}Pu. The 13.5 MeV deuteron beam was supplied by the JAERI-tandem accelerator, and the typical beam current was 5 nA. The ^{239}Pu target was made by electrodeposition of $^{239}PuO_2(NO_3)_2$ on a 90 μg/cm^2 thick nickel foil, and the target thickness was 35 μg/cm^2.

The outgoing protons resulting from the (d,p) reaction were detected by a ΔE-E telescope which consisted of 300 μm (ΔE) and 1500 μm (E) thick silicon detectors. The telescope was set at 135^o relative to the beam direction with a solid angle of 45 msr. The protons were easily distinguished from deuterons and tritons on the Δ-E map, allowing the selection of neutron transfer events.

Two fission fragments were coincidentally detected by two silicon PIN diodes, which were equipped on both sides of the target with a similar aperture. The center of the PIN diodes were set at 90^o to the beam direction. The diodes which have an active area of 1000 mm^2, each, were masked by plates having a circular hole of 31.9 mm diameter, and each diode was viewed by the target at a solid angle of 1.25 sr.

3. Data Analysis

The energy resolutio ΔE-E telescope, namely the energy resolution for protons, was 55 keV(FWHM), which was determined by the elastic peak of the deuteron. The resolution includes the energy spread of about 30 keV arising from the kinetic effect. The proton energy was transformed to the excitation energy of ^{240}Pu using the mass table of Ref. [9] (The Q-value for the ground state nuclear transfer in ^{239}Pu(d,p)^{240}Pu is 4.31 MeV).

The calibration of the fission detectors is made by using the Schmidt formula [10] as follows. First, we constructed a pulse height spectrum, $S(X)$, by selecting the events in $6.0 < E_{ex} < 7.0$ MeV as in Fig.2. This spectrum is close to that for the thermal neutron-induced fission of ^{239}Pu, whose compound nucleus ^{240}Pu has an excitation energy of 6.53 MeV. The solid curve in Fig.2 is the result of decomposing the experimental data to two Gaussian distributions having the same area. The centroid of two Gaussian components, P_L and P_H, obtained in the fitting process were used to determine the calibration constants in the Schmidt formula,

$$E(X, m) = (a + a'm)X + b + b'm\,, \tag{1}$$

$$a = c_1 / (P_L - P_H)\,, \tag{2}$$

$$a' = c_2 / (P_L - P_H)\,, \tag{3}$$

$$b = d_1 - a P_L\,, \tag{4}$$

$$b' = d_2 - a' P_H . \qquad (5)$$

where E and m are the fragment kinetic energy and mass. We used the parameters (c_1, c_2, d_1, d_2) = (27.6654, 0.04106, 89.0064, 0.1362) for the ^{239}Pu(n$_{th}$,f) given by Neiler *et al.* [11].

Fission fragment masses, m_1 and m_2, were determined from the pulse height of both fragments, X_1 and X_2, by following the mass and momentum conservation law. An iteration procedure was used to numerically determine the mass number of the fission fragment. In this analysis, we determined the primary fragment mass, i.e. mass before neutron evaporation. This needs a number of neutron emission as a function of fragment mass, $\nu(m)$, for which data of Tsuchiya *et al.* [12] were used.

4. Experimental Results and Discussions

Figure 3 shows the proton-fission coincidence events plotted as a function of excitation energy of ^{240}Pu. The energy bin is set at 50 keV corresponding to the present resolution. The resonance peak is observed at 5.05 MeV. For excitation energies below the neutron binding energy (6.53 MeV), where neutron emission is energetically hindered and the γ-ray emission is the only decay mode competing with fission in the decay channel, the spectrum in Fig.3 is related to the 'fission probability' multiplied by the 'population probability' of the compound nucleus in the transfer reaction ^{239}Pu(d, p)^{240}Pu. The resonance energy of 5.05 MeV obtained in this work is close to that measured by Glassel *et al.* [6] and Hunyadi *et al* [7].

By measuring the ^{239}Pu(d,pf) reaction, fission events resulting from excitation energies near the first fission barrier height (E_A=5.80 MeV [4]) could be obtained. We show firstly in Fig.4(A) the mass yield curve following the excited compound nucleus of $6.0 > E_{ex} > 5.3$ MeV. The yield is normalized such that the sum of the yields becomes 200 %. The mass bin is set at 2.0 amu to gain statistics. This spectrum agrees with that for thermal neutron-induced fission of ^{239}Pu by Wagemans *et al.* (E_{ex} = 6.53 MeV) [13] shown by the solid curve. The data of [13] were obtained by measuring the kinetic energies of both fragments (2E method) by using silicon detectors similar to our experimental method.

Fission events through the vibrational resonance being characterized by their excitation energy between $4.78 < E_{ex} < 5.30$ MeV (see Fig.3) result in the mass yield in Fig.4 (B). We set the mass bin as 5 amu. Although the mass yield curve constructed by using only about 80 events has a large uncertainty, the asymmetric fission character is evident, and the yield agrees with that for ^{239}Pu(n$_{th}$,f) as well as the gross trend that the sharp rise in the near symmetric region when going from the heavy fragment mass m_H =125 amu to 135 amu and the gradual decrease in the far asymmetric region from m_H = 140 amu to 160 amu. The yield reaches the maximum at around m_H = 135 amu for all spectra shown in Fig.4. We have determined the average value of the heavy fragment mass as $\langle m_H \rangle = 140.2 \pm 2.8$ amu, where the error comes from the binning and the uncertainty arising from the energy calibration process. This agrees with the value 139.8±1.1 amu obtained from the spectra in Fig.4(A) within the error and with the value 139.7 amu for ^{239}Pu(n$_{th}$, f) [13]. The present data then lead to the conclusion that fission through the β-vibrational resonance does not show any significant enhancement in the symmetric mass division within the error.

We want to show in Fig.4(C) the mass yield for the fission of shape isomer in ^{240}Pu [14] (half-life is 3.8 ns [15]). This is localized in the SD of the double-humped fission barrier (2.25 MeV above the ground state) [7], and has the (J^{π}, K) value of (0^+, 0). Isomeric fission forms a good reference in the sense that the nuclear shape is the same as that experienced by the β-vibrational fission. Isomeric fission forms a mass distribution similar to that for ^{239}Pu(n_{th},f) and hence to the β-vibrational fission in Fig.4(B).

5. Conclusions

Motivated by the speculation that the β-vibration on the SD of the double-humped fission barrier would result in an enhancement of the symmetric mass components, the mass distribution of ^{240}Pu following the resonance tunneling originating from this level was measured for the first time. The obtained distribution shows an asymmetric mass division similar to the one for the thermal neutron-induced fission of ^{239}Pu and the isomeric fission of ^{240}Pu. This indicates that the system through β-vibrational resonance comes out in the asymmetric fission valley that the ^{240}Pu-isomer and ^{239}Pu(n_{th},f) descend.

Acknowledgments

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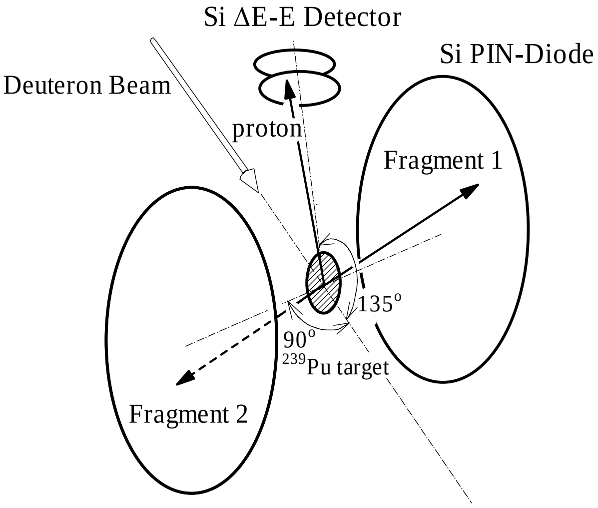

Fig. 1 Experimental setup for the fission fragment mass distribution in the ^{239}Pu(d,pf) reaction.

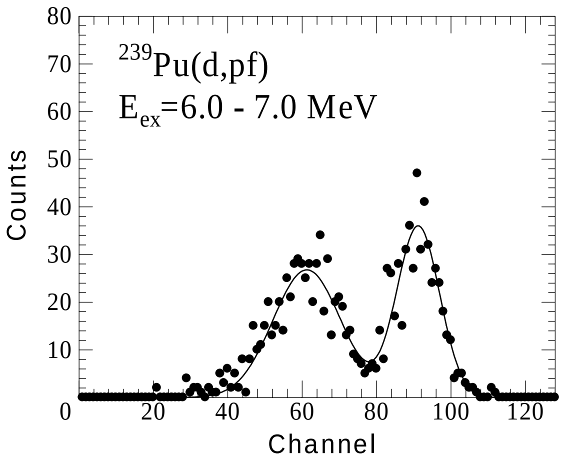

Fig. 2 Pulse height spectrum $S(X)$ of fission fragment obtained in the silicon PIN diode.
Curve is the result of the fitting of the spectrum to two Gaussian distributions with equal areas.

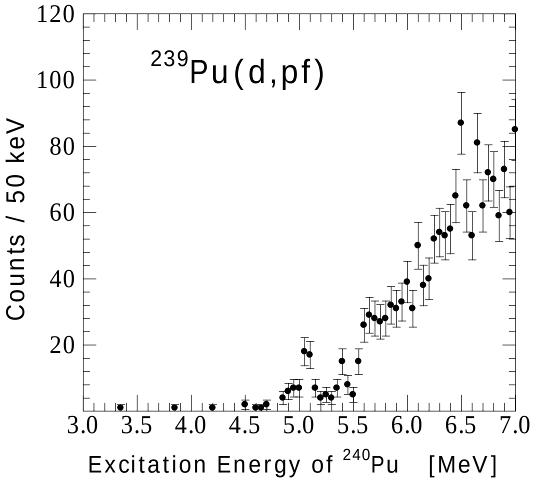

Fig. 3 Number of coincidence events between fission fragments and proton plotted as a function of excitation energy of ^{240}Pu.

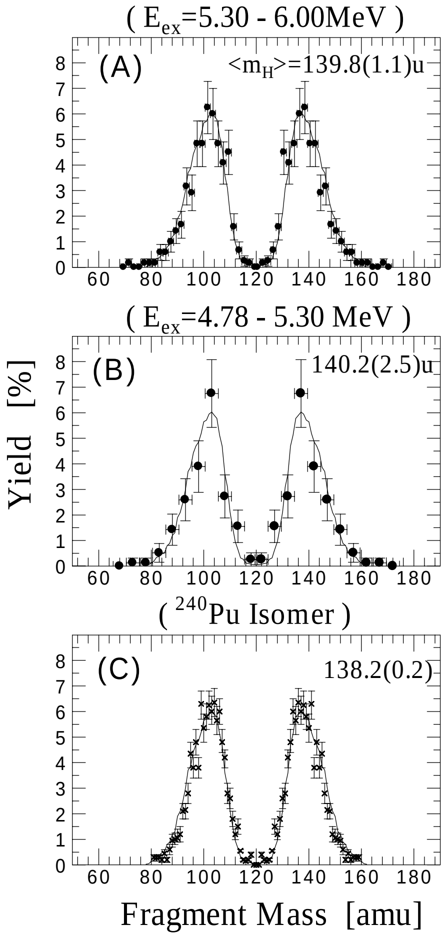

Fig. 4 Mass yield curves obtained for the ^{239}Pu(d, pf) reaction ((A) and (B)). These spectra are made by setting the excitation energy range as (A) 6.0 > E_{ex} > 5.3 MeV and (B) 5.30 > E_{ex} > 4.78 MeV. The average value for the heavy fragment mass $<m_{\mathrm{H}}>$ is shown in each section of the figure. The error shown in (A) and (B) comes from the binning and the uncertainty arising from the energy calibration process. Mass yield curve for the isomer fission [14] is shown in (C). Solid curve appearing in the every section is the data for ^{239}Pu(n$_{\mathrm{th}}$,f) [13].