Excitation of Energy Levels of Fissionable Nucleus Shape Isomers in the Doorway State in Reactions with Neutrons and Deuterons

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Abstract. Measurements were conducted for the fission neutron yields with fission fragments in the (d,pf) reactions at some excitation energies, where threshold neutrons were discovered. These data on the neutron yields in $^{233}$U(d,pfn) and $^{239}$Pu(d,pfn) reactions have been compared with the dependence of the average of fission neutrons $\nu_p(E_n)$ in the $^{233}$U(n,f) reaction as well as fission probability in the $^{239}$Pu(d,pf) reaction on excitation energy, which provides a better understanding of the nuclear fission process in a (d,pf) reaction and the $\nu_p(E_n)$ dependence on neutron energy.

INTRODUCTION

For the purpose of neutron yield study at $E^*$ near the fission barrier, we have measured the neutron yields with fission fragments and photons in the (d,pf) reactions at different excitation energies, for a variety of even-even nuclei. The study used a recharging Van de Graaff generator at the deuteron energy between 11.8 and 12.4 MeV. The experimental geometry is described in [1].

The measurements considered fast neutrons with $E_n > 0.5$ MeV and photons with $h\nu > 0.15$ MeV. A circuit was used for pulse separation from neutrons and photons.

FISSION NEUTRONS OF $^{233}$U(d,pf) AND $^{233}$U(n,f) REACTIONS

The studies of $^{233}$U(d,pf) reaction in [2,3] found significant resonances that occur in the subbarrier range of excitation energy.

Our measurements of the neutron yield in this reaction at $E_d = 11.8$ MeV are summarized in Fig. 1.

Obviously, when $E^* = 5.1\pm 5.7$ MeV, there is an increased yield of fission neutrons over the approximating linear dependence on $E^*$, and for $E^* > 9.5$ MeV, on the contrary, the neutron yield decreases, which correlates with a slight reduction of $\nu_p(E_n)$ in the $^{233}$U(n,f) reaction [4]. Thus, the former is the excitation energy range that fits the resonance positions in the $^{233}$U(n,f) reaction. We compare our observations against $\nu_p(E_n)$ data for the $^{233}$U(n,f) reaction.

As was shown in our study [5], the following expression can be used to approximate the $\nu_p(E^*)$ relationship for even-even fissionable nuclei of $^{234}$U, $^{235}$U and $^{239}$Pu:

$$\nu_p(E^*) = \nu^{sp} + (E^* - \Lambda)/\epsilon + \delta,$$

FIGURE 1. Fission neutron yield from $^{233}$U(d,pfn) and $^{233}$U(n,f) reactions.
where $E^* = \varepsilon_n + E_{kin}$; $\varepsilon_n$ is the neutron binding energy in a fissionable nucleus; $E_{kin}$ is neutron kinetic energy; $\Delta$ is some energy value to imply pairing energy; $\varepsilon$ is the average neutron binding energy in fission fragments, and $\delta$ is the possible correction for other relationships.

Evidently, this is a physically meaningful expression as it indicates the average of prompt fission neutrons as a function of level density.

Quite an interesting observation is $\nu_p$ decreasing at $E_n = 2.8 \pm 0.1$ MeV ($E^* = 9.6$ MeV). Such a decrease may be attributed to the excitation of lower rotational states in the second well (shape isomer) in a doorway state with nuclear fission to follow. Along with this, satisfying the following relationship is required:

$$E_n = m^*E_0 + I(I + 1)\hbar^2/2J,$$

where $m^*E_0$ is the ground-state energy of shape isomer, $J$ and $I$ are the moment of inertia and the spin of the rotational state-of-shape isomer, respectively.

Therefore, the interaction with a neutron at $E_n > 2.8$ MeV is where initially, in addition to the channel with compound nucleus generation, there are excited states of $^{233}{\text{U}}^*$ with a nearby neutron having low energy of relative motion, and this neutron is absorbed afterwards to produce isomeric states in the second well. Consequently, the $^{233}$U and neutron interaction in this case can be shown schematically as follows:

$$^{234}{\text{U}}^* \rightarrow f$$

$$^{233}\text{U} + n$$

$$^{233}{\text{U}}^* + n \rightarrow ^{234}{\text{U}}^* \rightarrow f$$

In the latter case for nuclear fission, the value of $\nu_p(E^*)$ should be expected to be smaller, which is because the level density is much lower for the shape isomer. If the contribution of this channel is estimated to be about 10%, then the $\nu_p$ change at $E_p = 2.8$ MeV in this fission case will actually be large and equal to $\Delta \nu_p \approx 0.7$, thus approaching 25% of the total $\nu_p$ value.

What would occur in the reaction with deuterons, except direct reaction and production of a compound nucleus $^{234}{\text{U}}^*$, is partial decay of the deuteron in the nuclear Coulomb field. Then, this is already a three-body reaction. Here, the energy spectrum of a third particle, which is a proton, should depend on the pattern of neutron and mather nucleus interaction (interaction Migdal-Watson). Also, there would be in this case a channel with shape isomer excitation. However, the energy of $2.8 + I(I + 1)\hbar^2/2J$ in the $^{233}$U(d,pf) reaction must be added with sufficient energy for splitting of the deuteron and a small value to account for center-of-mass motion.

Therefore, it is most likely that the resonances in the $^{233}$U(d,pf) reaction at $E^* \geq 5.12$ MeV $= 2.3$ MeV + $m^*/E$, should correspond to the initial excitation of the shape isomer rotational states, while the higher resonances are what account for the excitation of other shape isomer states. The lower excitation probability for such states (with high $I$) is offset by the fission barrier penetrability increasing with $E^*$.

The proposed fission pattern in the (d,pf) reaction is verified by the increasing yield of fission neutrons with fragments of the reaction $^{233}$U(d,pf) at the above values of excitation energy (see Fig. 1). Such an increase over the approximating dependence may be due to the emission of low-energy neutrons in the center-of-mass system of fissionable shape isomers, or threshold neutrons, which are caused by the kinematics amplification effect. Also, the shape isomer would get separated anyway, even without the neutron-binding energy involved.

For $E^* > 9.5$ MeV, the $^{233}$U (d,pf) reaction, similar to the $^{233}$U(n,f) reaction at $E_n = 2.8$ MeV, has fission occurring partially with the neutron to be absorbed by the shape isomer, thus showing a smaller yield of fission neutrons.

Also from Fig. 1, the decrease in the fission neutron yield of the $^{233}$U(d,pf) reaction at $E^* > 9.6$ MeV is evidently more significant (~15%) than for the neutron-induced fission of $^{233}$U (~3%). This appears to be associated with the higher population probability of isomeric states in (d,p) reactions.

### FISSION NEUTRONS FROM $^{239}$Pu(d,pfn) AND $^{239}$Pu(n,f) REACTIONS

The fission neutron yields of the $^{239}$Pu(d,pfn) reaction were measured at a deuteron energy of 12.4 MeV [6]. Here, a target was used that was made of plutonium oxide electrolytically deposited on a 1-μm thick aluminum foil. The best conditions were in the measurements using a thin absorber of lead with a thickness of 1.6 mm in front of the scintillation detector. This would provide absorption of the photons with $E \gamma \leq 0.25$ MeV, and therefore
improve the conditions for the separation of neutrons and photons.

As a remarkable detail found by the study, there are portions of increased neutron yield at $E^* = 5.3 \pm 0.1$ MeV and $5.85 \pm 6.35$ MeV over the approximating dependence, such as Eq. (1). The neutron yield reducing at $E^* = 6.75$ MeV is due to the neutron threshold in channel $^{239}$Pu + $n(\epsilon_n = 6.54$ MeV). Further reduction in the neutron yield is related to the generation of $^{239}$Pu with excitation energy at $E^* = 285.47$ keV, which can be proved by the increased yield of photons at $E^* = 6.7 \pm 0.1$ MeV.

Threshold effects upon the neutron yield may be interpreted as follows [7]. Thus, below the threshold, no neutrons can escape from the nucleus because of insufficient energy, so that their density goes down exponentially outside the reaction region. Hence, there is unlimited growth in the relative number of neutrons approaching the threshold from below. As they pass through the threshold point, the wave function has its exponential “tails” change into divergent waves, so that emission of free neutrons becomes possible. Therefore, the number of neutrons should be expected to grow in nuclear fission below the threshold, and above this to decrease.

The lower part of Fig. 2 shows experimental data from the study [8] that looked at energy dependence of the differential cross-section $d^2\sigma/d\Omega dE_p$ for generation of the $^{240}$Pu isomer in the $^{239}$Pu(d,p) reaction. The fit between the positions of proton peaks at $E^* = 5.2, 5.80$ and $6.25$ MeV and those of neutron peaks is what reinforces the statement about the peaks of neutron yield existing at $E^* = 5.3, 5.85$ and $6.35$ MeV. Such rises of the fission neutron yield come from the detection of threshold neutrons, with their yield increasing with fission fragments due to the kinematics amplification effect. The peak neutron yield of $^{239}$Pu(d,pfn) reaction at $E^* = 5.3 \pm 0.1$ MeV is correlated by a decrease in kinetic energy of the fission fragments in the $^{239}$Pu(d,p) reaction at $E^* = 5.2 \pm 0.1$ MeV [9], because the threshold neutrons carry out some part of the fission fragment kinetic energy [10].

Based on the findings about fission neutron yields in the $^{239}$Pu(d,pfn) reaction, one should expect irregularities in the $\nu_p(E_n)$ dependence at the neutron energy values $5.2-2.3 = 2.9$ MeV; $5.8-2.3 = 3.5$ MeV and $6.25-2.3 = 3.95$ MeV in the $^{239}$Pu(n,f) reaction. The ground state of the $^{240}$Pu shape isomer is most likely to be at $E^* = 4.897-2.3 = 2.597$ MeV. The most intensive peak in the proton spectrum of the $^{239}$Pu(d,p) reaction corresponds to this energy [11]. In this case positions of peaks in the $^{239}$Pu(d,p)$^{240}$Pu reaction, presented in Fig. 2, are determined by the energy of the vibration states measured in [12] by the $^{238}$U($\alpha$,2n)$^{240}$Pu reaction.

In [12], $4\pi$ gamma-detector measurements were used to establish the lower vibrational states of $^{240}$Pu with 785, 838 keV and 1300, 1397 keV energies in the $^{238}$U($\alpha$,2n) reaction, whose position is consistent with both ground-state energy of the $^{240}$Pu isomer and our neutron peak measurements, i.e., $2.597 + 2.3 + 0.81 = 5.7 \pm 0.1$ MeV and $2.597 + 2.3 + 1.35 = 6.3 \pm 0.1$ MeV, where $0.81 = (0.785 + 0.838)/2$, and $1.35 = (1.300 + 1.397)/2$.

Thus, there are threshold neutrons produced in a three-body channel, with their energies below the threshold of the primary channel of $^{239}$Pu + d $\rightarrow$ $^{240}$Pu + p reaction at $E' = 6.5$ MeV. And so, measuring neutron yields in the fission fragments’ direction can be useful to study the mechanism of deuteron and heavy nuclei interactions and improve the $\nu_p$ dependence for neutron-nuclei interactions.

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