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In-beam γ-ray spectroscopy of ^{240}U using the (^{18}O,^{16}O) reaction

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In the two-neutron-transfer reaction of a 200-MeV ^{18}O beam with a ^{238}U target, deexcitation γ rays in a neutron-rich nucleus of ^{240}U were measured. The γ rays in ^{240}U were identified by taking coincidence with ^{16}O, using Si ΔE-E detectors. The kinetic energies of ^{16}O particles allowed us to select the excitation energies of ^{240}U below the neutron separation energy. The ground-state band and the $K^{\pi} = 0^{-}$ octupole band of ^{240}U were established up to 12^{+} and 9^{-}, respectively. The octupole-band head of ^{240}U is about a hundred keV higher than those of ^{236,238}U, suggesting that a secondary maximum of octupole correlations exists at $N = 144$–146 in U isotopes.

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Actinide nuclei can provide important information on nuclear collectivity. It is interesting to investigate how the quadrupole and hexadecapole deformations develop with neutron or proton numbers, and how the octupole correlations appear in these nuclei. Furthermore, these deformations as well as single-particle energies are important parameters for predicting the shell structure of superheavy nuclei. The present knowledge on nuclear structure of actinide nuclei is, however, based on studies of β-stable and proton-rich nuclei. Neutron-rich actinide nuclei have been scarcely studied because of experimental difficulty.

The multinucleon-transfer reaction is a promising tool for studying neutron-rich nuclei in heavy elements. In particular, the (^{18}O,^{16}O) reaction has a favorable Q value to yield a neutron-rich nucleus, because the mass excess (Δ) of ^{18}O is larger than that of the doubly magic ^{16}O by 4.0 MeV; ^{18}O is the only *stable* nucleus that has $\Delta(^{A}Z) - \Delta(^{A-2}Z) > 0$ in the isotopes lighter than zinc. A few γ-ray experiments have been performed using the (^{18}O,^{16}O) reaction. Hering *et al.* [1] employed this reaction near the Coulomb barrier and observed in-beam γ rays in the two-hole nucleus ^{206}Hg. Koenig *et al.* [2] measured deexcitation γ rays in ^{102}Mo and ^{106}Ru by identifying outgoing nuclei with a quadrupole-three-dipole magnetic spectrograph. Gerl *et al.* [3] observed γ rays in the ground-state band of ^{234}Th up to 10^{+} and showed the usefulness of this reaction for investigating actinide nuclei. The (^{18}O,^{16}O) reaction, however, has not been widely used for γ-ray spectroscopy. To measure in-beam γ rays through this reaction, it is important to select the reaction channel clearly and with high efficiency, because the cross section of the (^{18}O,^{16}O) reaction is much smaller than those of competing reactions such as Coulomb excitation and fusion-fission.

The ^{240}U nucleus has only two more neutrons than ^{238}U. However, there are only two reports of experiments on excited states in ^{240}U: an α-decay experiment of ^{244}Pu [4] and a (t, p) transfer reaction experiment [5]; the former measured the energy of α particles decaying to the first excited state, and the latter observed the 2^{+} and 4^{+} levels as well as energy levels higher than 1 MeV. γ rays in ^{240}U have never been measured. We have achieved γ-ray measurements of ^{240}U by selecting the reaction channel of (^{18}O,^{16}O) completely with Si ΔE-E detectors and observed the ground-state and octupole bands of ^{240}U.

The experiment was carried out at the Japan Atomic Energy Research Institute's tandem booster facility [6]. A natural uranium target, 4 mg/cm^2 in thickness, electrodeposited on a 3-μm aluminum foil was bombarded by a 200-MeV ^{18}O beam with 0.1 particle nA. The total dose was 1.3×10^{14} ions of ^{18}O. The target was thick enough to stop most residual nuclei.

Outgoing nuclei were detected with four sets of Si ΔE-E detectors of 20 mm in diameter, and γ rays emitted by residual nuclei were measured by seven Ge detectors in coincidence with the outgoing nuclei. These four Si ΔE-E detectors were placed at 28° with respect to the beam direction, at a distance of 5 cm from the target. A ring-shaped plate was placed in front of the Si detectors so that particles scattered at less than 21° did not enter the Si detectors. Thus, the Si ΔE-E detectors covered the scattering angles between 21° and 35°, and the total solid angles were 0.4 sr. All the Si detectors were surface-barrier type made from an n-type Si wafer of 4 kΩ cm with ⟨100⟩ orientation. The thickness of the ΔE detector, thinned by an ELID (electrolytic in-process dressing)-grinding technique, was 83 μm. The uniformity of the thickness was achieved within ± 1 μm.

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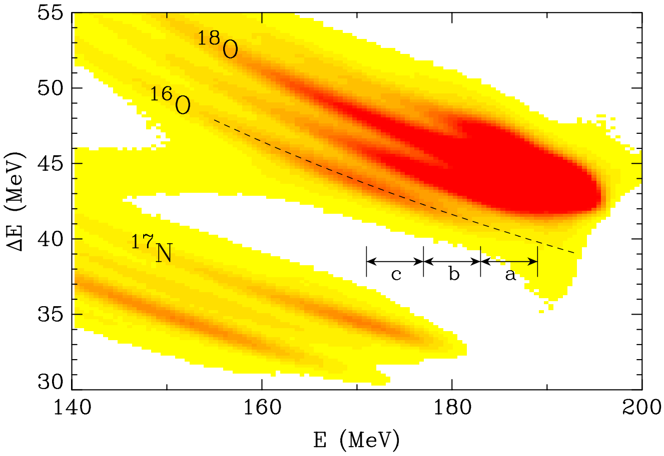

FIG. 1. (Color online) E-ΔE plot measured by a Si ΔE-E detector in the reaction of a 200-MeV ^{18}O beam with a ^{238}U target. Dashed line represents a calculated energy loss for ^{16}O particles. See the caption of Fig. 2 for the energy ranges of a, b, and c.

Four of the seven Ge detectors, with 60% relative efficiency, were arranged symmetrically in the plane perpendicular to the beam axis, at a distance of 6 cm from the target. Two of the Ge detectors and two of the Si ΔE-E detectors were placed in the vertical plane including the beam axis, and the other two Ge and Si detectors were placed in the horizontal plane. This setup allowed us to measure the anisotropy of γ rays emitted in the reaction plane to those out of the reaction plane. The other three Ge detectors, with 30–40% relative efficiency, were placed between the former Ge detectors. The absolute efficiency of the total Ge detectors was 9% and 2.5% for 0.2 and 1.33 MeV, respectively.

In the reaction employed, the grazing angle is 33° in the laboratory system, and the grazing angular momentum is $110\hbar$. The ^{16}O particle has a maximum kinetic energy when both of the ^{16}O and ^{240}U nuclei lie at the ground state. In this ground-state reaction, the incident energy of ^{16}O onto the Si detector becomes 189 MeV when the reaction occurs at the middle of the U target and the ^{16}O nucleus is scattered at 28°. A kinematic broadening is about 2 MeV; e.g., the ^{16}O particles scattered at 35° have a smaller energy than those scattered at 28° by 2 MeV. Ejectiles from the Al backing as well as N and O isotopes containing in the electrodeposited target do not disturb the identification of residual nuclei, because these ejectiles entering the Si detectors have smaller kinetic energies than scattered particles by U nuclei.

An E-ΔE plot obtained from the experiment is shown in Fig. 1. Outgoing nuclei were separated not only by the atomic number but also by the mass number. The energy signals of ΔE and E detectors were calibrated on the assumption that the peak with the highest intensity in the E-ΔE spectrum corresponds to elastically scattered particles entering the center of the Si detector. The dashed line in Fig. 1 represents a calculated energy loss for ^{16}O particles.

γ-ray spectra of residual nuclei are shown in Figs. 2 and 3. The spectra in Figs. 2(a) and 3(a) were obtained by setting the gate on ^{16}O whose total energy E was between 189 and 183 MeV (referred to as a in Fig. 1). The decrement of kinetic energy of ^{16}O, (189 MeV) $- E$, corresponds to the excitation energy of ^{240}U by assuming that the ^{16}O nucleus is not excited. The neutron separation energy of ^{240}U is 5.9 MeV. Therefore, ^{240}U nuclei produced by the reaction for the 189–183 MeV range emit no neutrons. γ-ray spectra in Figs. 2(b) and 3(b) and Figs. 2(c) and 3(c) were obtained by the gates of ^{16}O with 183–177 MeV and 177–171 MeV (referred to as b and c in Fig. 1), respectively. The reactions for these energy ranges excite ^{240}U nuclei high enough to evaporate one and two neutrons, respectively. Thus, γ rays in ^{240}U, ^{239}U, and ^{238}U were observed distinctly in Figs. 2 and 3. The γ rays with the maximum yield at the 189–183 MeV ^{16}O gate were identified as those in ^{240}U. Note that contaminant γ rays appearing in Figs. 2(a) and 3(a) mainly come from Coulomb excitation of ^{238}U, because a small amount of channeling particles of ^{18}O intrude into the ^{16}O gate.

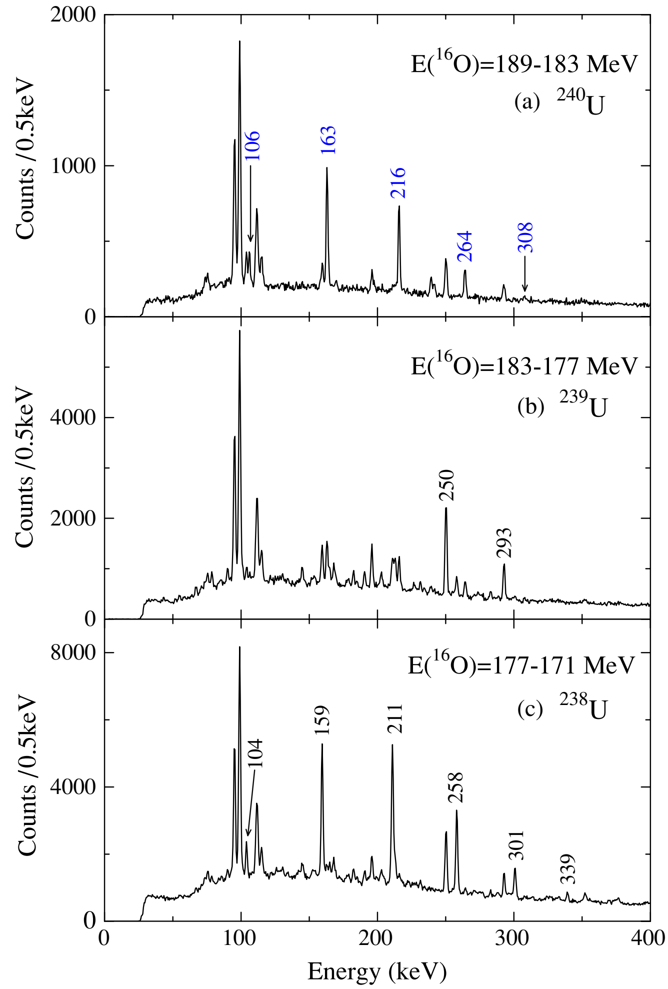

FIG. 2. (Color online) γ-ray spectra obtained by setting the gates on ^{16}O whose total energies are (a) 189-183, (b) 183-177, and (c) 177-171 MeV, respectively. These energy ranges are depicted in Fig. 1. γ peaks labeled by energies in the spectra of (a), (b), and (c) are the transitions in ^{240}U, ^{239}U, and ^{238}U, respectively.

As shown in Fig. 2(a), γ transitions in the ground-state band of ^{240}U were clearly observed. These γ rays were

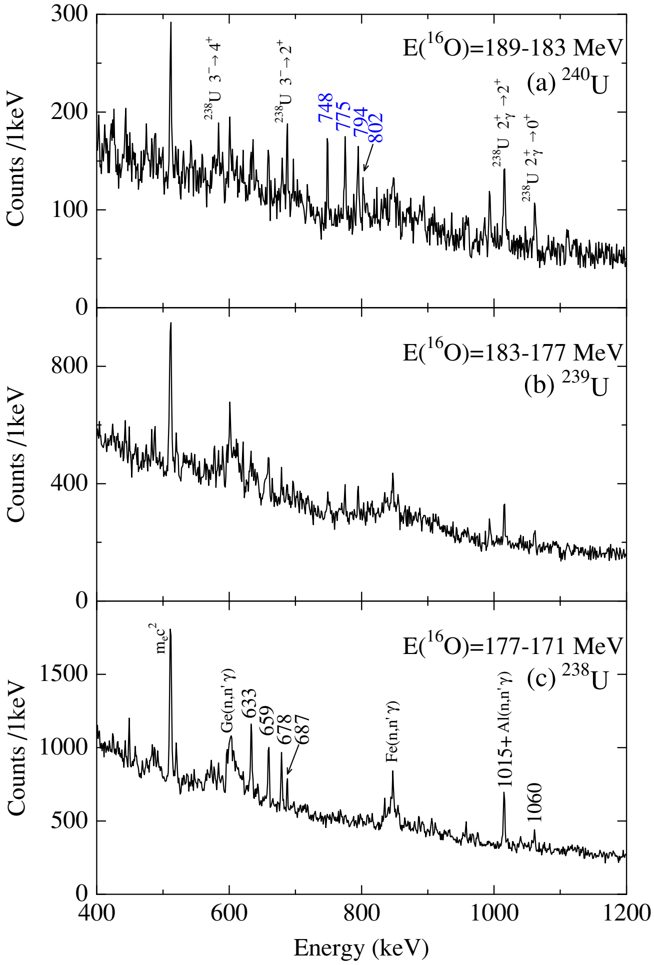

FIG. 3. (Color online) Same as Fig. 2, but for 400 keV $< E_\gamma <$ 1200 keV.

coincident with each other. Figure 4 shows the sum of γ-γ coincidence spectra gated on 163-, 216-, and 264-keV γ peaks; these spectra were obtained under the condition that the total energy of ^{16}O was between 189 and 180 MeV. The $2^+ \rightarrow 0^+$ γ ray of about 45 keV was not

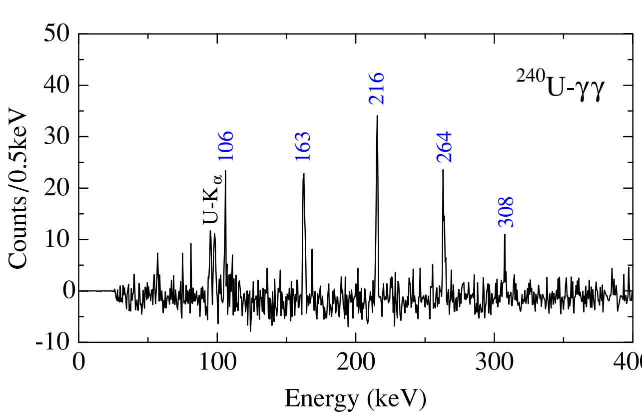

FIG. 4. (Color online) γ-γ coincidence spectrum for ground-state band transitions in ^{240}U, obtained by the sum of spectra in coincidence with 163-, 216-, and 264-keV γ rays.

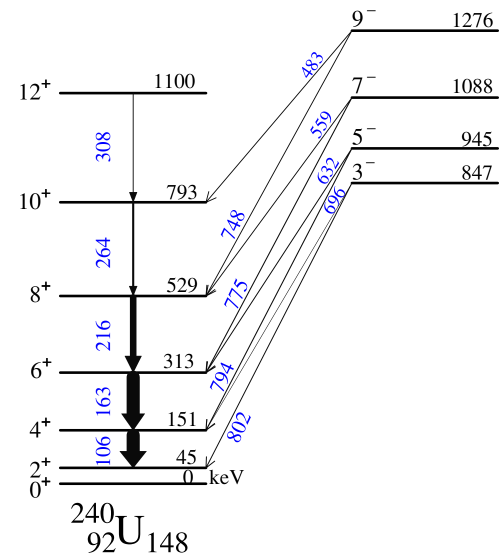

FIG. 5. (Color online) Level scheme of ^{240}U. The γ-ray and level energies are in units of keV. Energy of 45(1) keV for the 2^+ level was taken from Ref. [5].

observed owing to a large internal conversion coefficient ($\alpha_T \simeq 600$ [7]). In Fig. 3(a), a group of 748-, 775-, 794-, and 802-keV γ rays is noticeable and is very similar to that of 633-, 659-, 678-, and 687-keV γ rays of ^{238}U in Fig. 3(c). These γ rays in ^{238}U are interband transitions from the I^- states in the $K^\pi = 0^-$ octupole band to the $(I-1)^+$ states in the ground-state band. Therefore, we consider that those four transitions in ^{240}U are also $I^- \rightarrow (I-1)^+$ interband transitions. In addition to these transitions, $I^- \rightarrow (I+1)^+$ transitions in ^{240}U were observed. Among the interband transitions in ^{240}U, the 748-, 775-, 483-, and 559-keV γ rays were confirmed to be coincident with the ground-state band transitions, but the others were not because of low statistics.

A level scheme of ^{240}U is shown in Fig. 5, and the γ rays in ^{240}U are summarized in Table I. Intensities of γ rays were observed to depend slightly on the kinetic energy of ^{16}O; the 308-keV ($12^+ \rightarrow 10^+$) and 264-keV ($10^+ \rightarrow 8^+$) γ rays had larger intensities when ^{240}U was populated at higher excitation. The intensities in Table I were derived from the gate of ^{16}O with 189-180 MeV, using all the Ge and Si detectors. γ rays assigned to ^{240}U but not placed in the level scheme are also included in Table I.

Nuclei produced by heavy-ion transfer reactions are aligned perpendicular to the reaction plane defined by the beam axis and a Si ΔE-E detector. Therefore, γ rays emitted by these nuclei show in-plane to out-of-plane anisotropies depending on the types of transitions; e.g., I_γ(in-plane)/I_γ(out-of-plane) > 1 for a stretched quadrupole transition and <1 for a stretched dipole transition [8,9]. These intensity ratios are plotted in Fig. 6 for γ rays in ^{238,240}U. The transitions in the ground-state bands of ^{238,240}U showed quadrupole types, and the interband transitions were consistent with dipole ones.

Figure 7 shows moments of inertia J_0 for the ground-state bands of even-even heavy nuclei whose excitation energies

TABLE I. γ-ray energies and relative intensities in ^{240}U.

E_γ (keV)	I_γ	$I_\gamma(1+\alpha_T)^b$	$I_i \to I_f$
105.6(1)	8.5(8)	97(8)	$4^+ \to 2^+$
162.6(1)	37.2(20)	100(6)	$6^+ \to 4^+$
215.5(1)	31.3(13)	50(2)	$8^+ \to 6^+$
239.0(2)[a]	7.8(7)		
241.4(3)[a]	5.3(4)		
264.1(2)	13.3(9)	17(1)	$10^+ \to 8^+$
307.6(3)	2.8(7)	3(1)	$12^+ \to 10^+$
482.5(7)	2.5(8)		$9^- \to 10^+$
558.9(7)	1.9(9)		$7^- \to 8^+$
631.6(5)	5.1(10)		$5^- \to 6^+$
696.4(5)	4.4(10)		$3^- \to 4^+$
747.5(3)	7.1(10)		$9^- \to 8^+$
774.5(3)	7.9(11)		$7^- \to 6^+$
794.0(3)	8.1(12)		$5^- \to 4^+$
801.9(5)	5.2(10)		$3^- \to 2^+$
991.9(5)[a]	8.0(11)		

[a]The transition is not placed in the level scheme.
[b]Total internal conversion coefficients α_T for $E2$ transitions were taken from Ref. [7].

were measured precisely [10–14]; here, the value of $\hbar^2/2J_0$, nearly $E_{2^+}/6$, is plotted against the neutron number. The J_0 value was derived from the fit of a kinetic moment of inertia $\mathcal{I}^{(1)}$ to the equation: $\mathcal{I}^{(1)} = J_0 + \omega^2 J_1$ using measured levels up to 12^+, where $\mathcal{I}^{(1)} = (2I-1)\hbar^2/E_\gamma$ and $\hbar\omega = E_\gamma/[\sqrt{I(I+1)} - \sqrt{(I-2)(I-1)}]$. The moment of inertia of ^{240}U is a little smaller than those of ^{234,236,238}U. As pointed out by Sobiczewski *et al.* [15], moments of inertia are sensitive to deformation with high multipolarity, β_4, β_6, etc., as well as β_2. It was shown from the precise Coulomb-excitation experiment [16] that the quadrupole deformation for ^{234,236,238}U and ^{238,240,242,244}Pu increases with neutron number while the hexadecapole deformation decreases with increasing neutron number. The calculation by Sobiczewski *et al.* [15] reproduced this tendency of β_2 and β_4 deformations in actinide nuclei and showed that the moment of inertia of ^{240}U becomes smaller than those of ^{234,236,238}U. This result agrees with the present data.

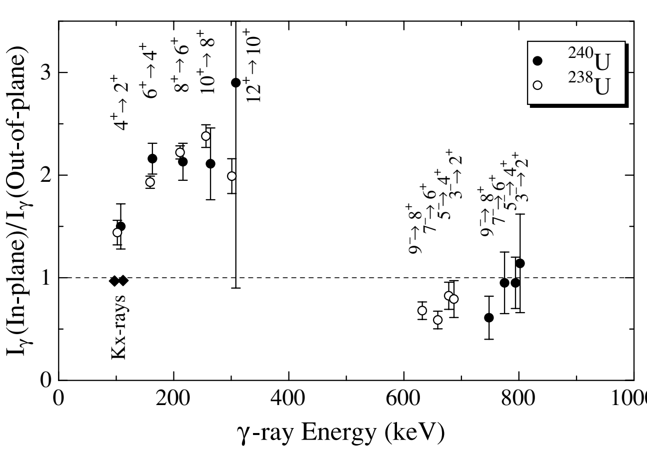

FIG. 6. In-plane to out-of-plane γ-ray anisotropies for transitions in ^{238,240}U.

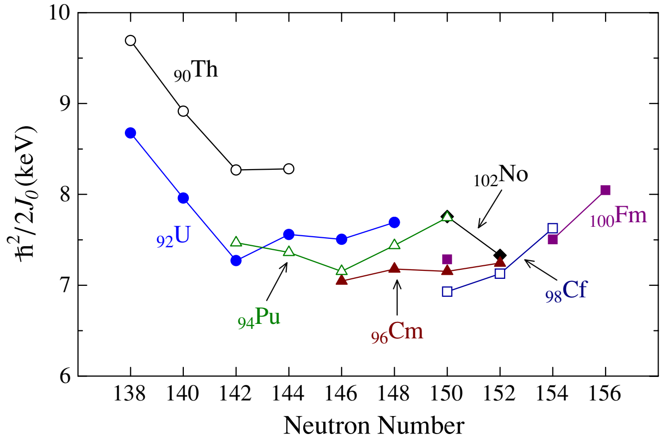

FIG. 7. (Color online) Systematics of moments of inertia J_0 for the ground-state bands of heavy nuclei. Value of $\hbar^2/2J_0$ was plotted against the neutron number.

The octupole band of ^{240}U lies at higher energy than those of ^{236,238}U$_{144,146}$. Although the 1^- level in ^{240}U was not identified, we can estimate this level to be 793(2) keV from the moment of inertia obtained by the fit of the excitation energies of the 3^- to 9^- levels. Recently, Asai *et al.* [17] found by an electron capture decay study of ^{236}Am that the 1^- level in the octupole band of ^{236}Pu is higher in energy than those of ^{238,240}Pu$_{144,146}$. Figure 8 shows the excitation energies of the 1^- states in the $K^\pi = 0^-$ octupole bands of Ra, Th, U, and Pu isotopes [10]. The new data of ^{240}U and ^{236}Pu clearly established the existence of the second minima of the 1^- excitation energies at $N = 144$–146 in U and Pu isotopes.

The Ra-U nuclei with $N \sim 136$ are known to have large octupole correlations, and thus, the 1^- levels in these nuclei lie at very low excitation energies. Sheline and Riley [18] pointed out that large octupole correlations also appear at

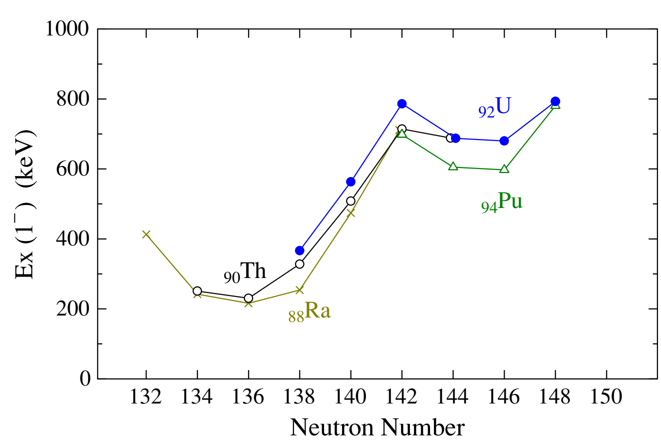

FIG. 8. (Color online) Excitation energies of the 1^- states in the $K^\pi = 0^-$ octupole bands of Ra, Th, U, and Pu isotopes. The 1^- level in ^{240}U was deduced from the moment of inertia obtained by the fit of the level energies from 3^- to 9^-.

$N = 144$–146 in U and Pu isotopes on the basis of the 1^- excitation energies and of the hindrance factors in α decays populating these states. We have confirmed their suggestion by establishing the second minima of the 1^- excitation energies. Wiedenhöver *et al.* [19] found that the Pu nuclei with $N = 144$–146 show the properties associated with stable octupole deformation, such as large electric dipole moments and level sequences of alternating spin and parity, at very high-spin states. These properties also confirmed the second maximum of octupole correlations in Pu. The particle-hole configurations of $\Delta l = 3$ and $\Delta\Omega = 0$ near the Fermi surface should play an important role for these correlations [19]. Detailed microscopic calculation is required to account for the second maxima of octupole correlations. On the other hand, Zamfir and Kusnezov [20] reproduced the energy levels in the $K^\pi = 0^-$ and 0^+ bands of U and Pu nuclei by an *spdf* interacting boson model, but no prediction was given for the levels in ^{240}U.

In conclusion, we have measured γ rays in ^{240}U produced by the (^{18}O, ^{16}O) reaction by taking coincidence with ^{16}O using the Si ΔE-E detectors. The excitation energies of ^{240}U nuclei were selected below the neutron separation energy by the measured kinetic energies of ^{16}O. The ^{240}U nucleus is one of the heaviest neutron-rich nuclei studied by in-beam γ-ray spectroscopy. The moment of inertia for the ground-state band of ^{240}U is consistent with the systematics of β_2 and β_4 deformations in actinide nuclei. The excitation energy of the 1^- state in the octupole band of ^{240}U suggests that a secondary maximum of octupole correlations exists at $N = 144$–146 in U isotopes. Using the present experimental technique and *radioactive* nuclear beams such as ^{20}O, it would be possible to study more neutron-rich nuclei in heavy elements.

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