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α decay of ^{238}Cm and the new isotope ^{237}Cm

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Alpha decays of ^{237}Cm and ^{238}Cm have been studied using a gas-jet coupled on-line isotope separator. The new isotope ^{237}Cm has been identified through the detection of 6656 ± 10 keV α particles. The α energy of ^{238}Cm has been revised more precisely than the previous one. The α transition to the first excited 2^+ state in ^{234}Pu has also been observed. It was found that the 2^+ energy in ^{234}Pu is much higher than those in heavier Pu isotopes.

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Neutron-deficient Cm isotopes with a mass number smaller than 240 have been rarely studied because of small production cross sections, short half-lives of <3 h, and small α-decay branching ratios. The α decay of ^{238}Cm was studied in 1952 by Higgins [1] using the ^{239}Pu(α,5n)^{238}Cm reaction and a chemical separation technique. The 6.52(5) MeV α peak with a half-life of 2.3 h was observed, and the EC/α branching ratio of 240 ± 50 was estimated from the α decay rate and the disintegration rate measured by means of a windowless proportional counter. The EC decay of ^{239}Cm ($T_{1/2} \approx 2.9$ h) was also measured in the 1950s although these data were not published [2]. Since then, no experimental study had been reported for neutron-deficient Cm isotopes.

Recently, new attempts to study neutron-deficient Cm isotopes were carried out; the α decays of ^{233,234}Cm were newly identified using the velocity filter SHIP at GSI [3], and the EC decay of ^{239}Cm was measured with a chemical separation technique [4]. In this Brief Report, we have studied the α decays of ^{237}Cm and ^{238}Cm using an on-line isotope separator (ISOL). The ^{237}Cm is a new isotope whose decay properties have never been measured. For ^{238}Cm the α energy was reported but its accuracy is insufficient especially to establish excited states in the daughter nucleus, which could reveal collective properties of the nuclei in this region. The ISOL is very powerful to study EC and α decays of short-lived actinide nuclei with small α-decay branching ratios as demonstrated in our previous articles [5–10]. The preliminary results of ^{237}Cm and ^{238}Cm were also reported in Refs. [5–7].

The nuclei ^{237}Cm and ^{238}Cm were produced by the ^{237}Np(^{6}Li, xn) reaction using the 20-MV tandem accelerator at the Japan Atomic Energy Agency (JAEA). A stack of 21 ^{237}Np targets set in a multiple-target chamber with 5-mm spacings was bombarded with a ^{6}Li beam of about 300 particle-nA intensity. Each target was electrodeposited on a 0.8-mg/cm^2 thick aluminum foil with an effective target thickness of about 100 μg/cm^2. The energy of the ^{6}Li beam was 52–59 MeV on targets for the production of ^{237}Cm and 41–48 MeV for ^{238}Cm. Reaction products recoiling out of the targets were stopped in He gas loaded with PbI_2 clusters and transported into an ion source of the ISOL with gas-jet stream through an 8-m long capillary. Atoms ionized in the surface ionization-type thermal ion source were accelerated with 30 kV and mass-separated with a resolution of $M/\Delta M \sim 800$. Details of the gas-jet coupled ISOL system are described in Ref. [5].

For ^{238}Cm, the separated ions were implanted into an aluminum-coated Mylar tape in a tape transport system that periodically moved the implanted sources to seven consecutive detector stations at 3000-s intervals. Each of the detector stations was equipped with a Si PIN photodiode detector (18×18 mm^2 active area) to detect α particles. The distance between the tape and the Si surface was 1.7 mm. The γ-ray measurement was also performed using a different experimental setup with a short coaxial Ge detector (ORTEC LOAX). For ^{237}Cm, the separated ions were directly implanted into a Si detector. This setup was used to identify α particles of ^{237}Cm. The half-life measurement for ^{237}Cm was also performed using the tape transport system, although we could not obtain enough statistics to extract its decay rate. The energy calibration of the Si detectors was carried out before and after the experiments using mass-separated ^{221}Fr and its α-decay daughters ^{217}At and ^{213}Po, which were implanted into the tape or the Si detector by the present ISOL system. The energy resolution of the Si detectors was 27–35 keV (FWHM) for the 7067-keV α particles. All the data were recorded event by event together with time information.

Figure 1(a) shows an α-particle spectrum of the mass-237 fraction measured for 45 h. Three weak α peaks were observed at 5767(15), 6043(10), and 6656(10) keV in addition to a very intense peak of ^{237}Np that originates from the target material sputtered by the ^{6}Li beam. These α energies were determined with the maximum-likelihood method using an α peak shape of ^{217}At as a response function. The 5767- and 6043-keV peaks are attributed to the α decay of ^{236}Pu and ^{237}Am because

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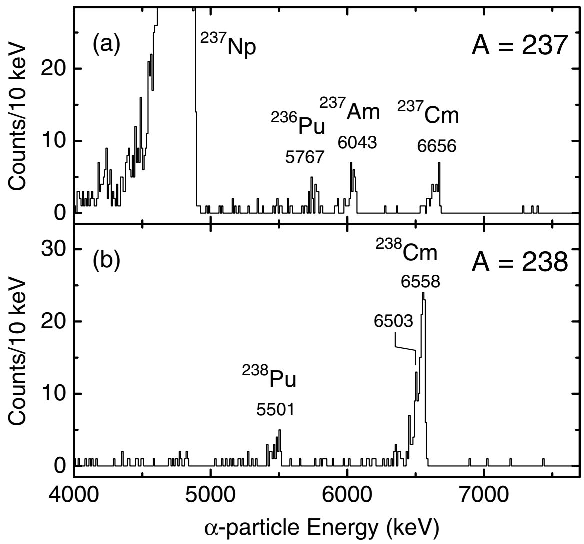

FIG. 1. α-particle spectra for the (a) mass-237 and (b) mass-238 fractions.

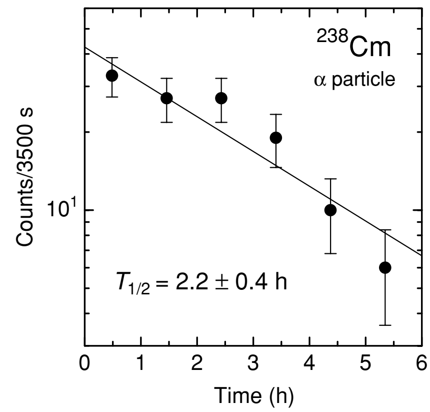

FIG. 2. Decay curve for the α particles of ^{238}Cm.

their energies are in excellent agreement with the literature values of 5767.66(8) and 6042(5) keV, respectively [11]. The appearance of ^{236}Pu in the mass-237 fraction results from the small contamination by adjacent mass fractions. Taking into account the mass resolution of the present ISOL system, about 0.2% of mass-separated ^{236}Pu may be observed in the mass-237 fraction [5]. To confirm the mass identification of the observed α peaks, the adjacent mass fractions of 236 and 238 were measured with the same experimental setup. The 6043- and 6656-keV α peaks were observed only in the mass-237 fraction, indicating that these transitions are attributable to the α decay of $A = 237$ nuclei. The present reaction can produce only $Z \leqslant 96$ nuclei, and α-decay energies of the $A = 237$ nuclei with $Z \leqslant 95$ are well known [11]. Therefore, the unknown α transition of 6656 keV is attributed to the α decay of the new isotope ^{237}Cm.

An α-particle spectrum of the mass-238 fraction is shown in Fig. 1(b). The measured α peaks at 5501(13) and 6558(10) keV are associated with the α decay of ^{238}Pu and ^{238}Cm, respectively. The half-life of ^{238}Cm was determined to be 2.2(4) h from the decay curve of the 6558-keV α particles as shown in Fig. 2. This value is in good agreement with the literature value of 2.3 h [1]. The α energy of ^{238}Cm was revised more precisely than the literature value of 6520(50) keV [1]. The 6558-keV α line is considered to be the transition between the ground states because ^{238}Cm is an even-even nucleus. In addition to this transition, another weak α component was found at 6503(11) keV by subtracting the single α component of 6558 keV from the measured spectrum; the α energy spectrum of ^{217}At was used as a response function for the single α transition. This α component is considered to be the transition to the first excited 2^+ state in ^{234}Pu. The energy difference between these α transitions was determined to be 55(7) keV, which revealed that the energy of the first excited 2^+ state in ^{234}Pu is 56(7) keV. The measured intensity of the 6503-keV α component was 14(3)% for total α intensity. This intensity is strongly affected by the coincidence summing effect between the 6503-keV α particles and following low-energy electrons. It is estimated that about 40% of the 6503-keV α intensity should be observed at higher energy than 6503 keV by more than 20 keV, which leads to the corrected α intensity of 23(6)% for the 6503-keV transition. This intensity is consistent with those of other Cm isotopes; the α decays of ^{240,242,244,246}Cm also show similar intensities of 29, 25, 24, and 18% for the transitions to the first excited 2^+ state, respectively [11].

In the atomic mass evaluations by Audi *et al.* [12], the Q_α value of 6805(216) keV was estimated for ^{237}Cm from systematic trends of atomic masses. This Q_α value corresponds to the α energy of 6690 keV for the transition between the ground states, which is in good agreement with the measured α energy of 6656 keV, although the level energy in ^{233}Pu populated by the 6656-keV α transition is not known. Energy systematics of the Nilsson orbitals in $N = 139$ and 141 isotones suggest that the ground-state configuration of ^{237}Cm$_{141}$ would be $5/2^+[633]$ as is the same as those in the isotones [9] and that the $5/2^+[633]$ state in ^{233}Pu$_{139}$ would be located at very low energy; it is the ground state in ^{229}Th$_{139}$ and

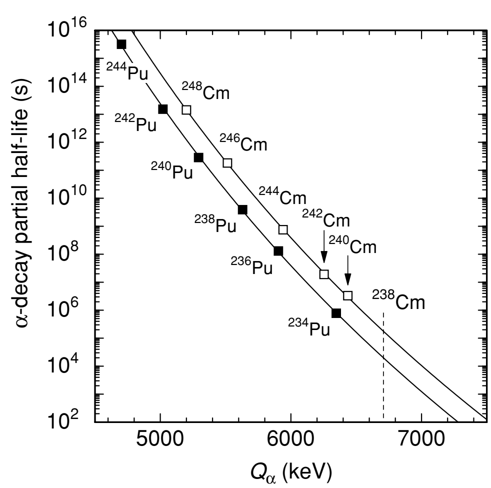

FIG. 3. α-decay partial half-lives of even-even Pu and Cm isotopes as a function of Q_α values corrected for the electron screening.

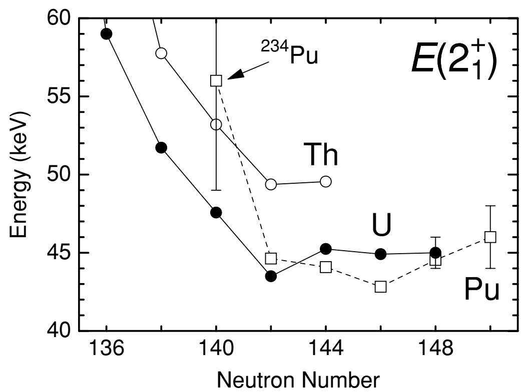

FIG. 4. Energies of the first excited 2^+ states in even-even Th, U, and Pu isotopes as a function of the neutron number.

at 1.7 keV in $^{227}Ra_{139}$ [11]. Thus, the 6656-keV α transition of ^{237}Cm would probably populate the low-energy level in ^{233}Pu.

The EC/α branching ratio of ^{238}Cm could not be determined in the present experiments, because very intense Pu K x rays associated with the EC and β^- decays of ^{238}Am and ^{238}Np prevented the observation of weak Am K x rays from the EC decay of ^{238}Cm. To estimate the EC/α branching ratio of ^{238}Cm, the partial half-life of the α transition is estimated from the semiempirical relationship between half-lives and Q_α values [8,13]. As shown in Fig. 3, experimental partial half-lives of the ground-state-to-ground-state α transitions in even-even isotopes are fitted well with the following equation: $\log T_{1/2} = aQ_\alpha^{-1/2} + b$, where a and b are fitted parameters and the Q_α value is corrected for the electron screening by adding $\Delta E_{SC} = (6.5 \times 10^{-2})Z^{7/5}$ keV [13]. For Cm ($Z = 96$) isotopes, $a = 4768$ and $b = -52.97$ are obtained. The partial half-life of the 6558-keV α transition is calculated to be 1.8×10^5 s, which leads to the EC/α branching ratio of 16 for ^{238}Cm. Higgins [1] reported the EC/α branching ratio of 240 ± 50 for ^{238}Cm. This value is much larger than the estimated one, as is also suggested in Ref. [14].

For the 6656-keV α transition in ^{237}Cm, the partial half-life of 6.6×10^4 s is estimated as well through the assumption that this α transition is a favored one with a hindrance factor of 1.0. A theoretical half-life of the EC decay of ^{237}Cm is 3.98 min [15]. Using these values and taking into account a large uncertainty of factor 2–3 for the theoretical half-life, the α branching of ^{237}Cm is estimated to be less than 1%.

Energies of the first excited 2^+ states in even-even Th, U, and Pu isotopes [11] are plotted in Fig. 4. The 2^+ energies of Th and U isotopes decrease with increasing neutron number and becomes almost constant in the $N \geqslant 142$ region. This trend is simply explained as the quadrupole deformation increases with the neutron number far away from the $N = 126$ closed shell and becomes the maximum around the midshell region. Although the 2^+ energy of ^{234}Pu deduced in the present work has a large uncertainty, this energy is apparently higher than those in heavier Pu isotopes, which is consistent with the trend of Th and U isotopes. On the other hand, it is also interesting to see the order of the 2^+ energies among Th, U, and Pu isotopes with the same neutron number. The present 2^+ energy of 56(7) keV seems higher than that of ^{232}U, but its accuracy is insufficient to clarify it. More precise determination of the 2^+ energy is desired to reveal collective properties of these actinide nuclei.

In conclusions, the new isotope ^{237}Cm has been identified, and the α energy of ^{238}Cm has been revised more precisely than the previous value, from 6520(50) keV to 6558(10) keV. The α transition to the first excited 2^+ state in ^{234}Pu has also been observed. The measured α energy of 6656(10) keV in ^{237}Cm is consistent with the Q_α value estimated from the systematic trends of atomic masses. The 2^+ energy in ^{234}Pu was found to be much higher than those in heavier Pu isotopes.

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