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Short Note

Identification of the new isotope ^{241}Bk

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Abstract. A new neutron-deficient berkelium isotope ^{241}Bk produced in the ^{239}Pu(^{6}Li, $4n$) reaction has been identified using a gas-jet coupled on-line isotope separator. Cm K and L X-rays associated with the EC decay of ^{241}Bk were observed in the mass-241 fraction, and three γ transitions were attributed to the EC decay of ^{241}Bk through X-γ coincidences. The half-life of ^{241}Bk was determined to be 4.6 ± 0.4 min which is 1/2–1/4 of that of theoretical predictions. The half-life value and the observed γ transitions can be consistently explained as a consequence of the allowed EC transition of $\pi 7/2^+[633] \rightarrow \nu 7/2^+[624]$.

PACS. 23.20.Lv Gamma transitions and level energies – 23.40.-s Beta decay; double beta decay; electron and muon capture – 27.90.+b $A \geq 220$

The decay of Bk nuclei has been studied scarcely. Only twelve Bk isotopes have been known so far [1]. One of the reasons is the small α-decay intensity. Measured or predicted α-decay intensities of neutron-deficient Bk isotopes $^{238\text{-}246}$Bk are of the order of 10^{-3} or less, which makes it difficult to study these nuclei through α-decay spectroscopy. The dominant decay mode of these nuclei is the electron capture (EC), and their production cross-sections are around the order of microbarn. Thus, to measure γ-rays following their EC decays, isolation and purification of the nuclei of interest from a large amount of other reaction products are indispensable.

The EC decay of $^{243\text{-}246}$Bk was studied in detail through γ-ray and conversion-electron spectroscopy [2–4] using a chemical separation plus off-line mass separation technique owing to their long half-lives of 4.5 h, 4.35 h, 4.94 d, and 1.80 d, respectively. The half-lives of more neutron-deficient Bk isotopes are shorter than 10 min, which makes experimental studies further difficult. The most neutron-deficient Bk isotope already known is ^{238}Bk ($T_{1/2}$ = 144 s) [5] and the second is ^{240}Bk (4.8 min) [6, 7], which were identified through the observation of the EC-delayed fission owing to the extremely high sensitivity of the detection of fission fragments. The ^{242}Bk was identified using a chemical-separation technique [8]. Cm K_α X-rays associated with the EC decay of Bk isotopes produced in the ^{235}U(^{11}B, xn) reaction were observed in the chemically purified Bk fraction, and a half-life of 7.0 min was derived for ^{242}Bk from its decay curve. The odd-mass ^{239,241}Bk were left unknown.

The half-life of ^{241}Bk was predicted by various theoretical calculations: 15 min [9], 19.9 min [10], 15.5 min [11], and 9.09 min [12]. These values are long enough for chemical separation. Thus, a few attempts to search for ^{241}Bk were made using chemical-separation techniques [8, 13]. Williams and Seaborg [8], they identified ^{242}Bk, tried to observe the EC decay of ^{241}Bk produced in the ^{235}U(^{10}B, $4n$) reaction under the same procedure in the ^{242}Bk experiment. They observed no activity with a half-life longer than 3 min and a cross-section larger than 2 μb. Hall *et al.* [13] also tried to observe the EC decay of ^{241}Bk in the ^{241}Am(^{4}He, $4n$) reaction. They observed Cm K_α X-rays associated with the EC decay of ^{242,243}Bk and deduced a new half-life value of 5.6 min for ^{242}Bk, but could not identify ^{241}Bk. These results suggest that the half-life of ^{241}Bk should be shorter than $\sim$ 5 min.

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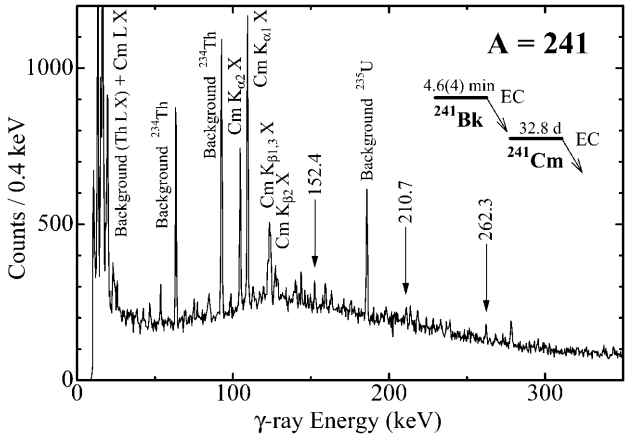

Fig. 1. Gamma-ray singles spectrum for the mass-241 fraction. Cm K and L X-rays and 152.4, 210.7, and 262.3 keV γ-rays are attributed to the EC decay of ^{241}Bk.

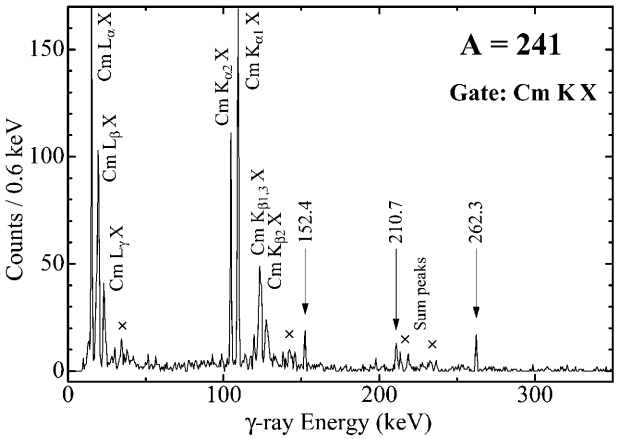

Fig. 2. Sum of γ-ray spectra in coincidence with Cm $K_{\alpha1}$, $K_{\alpha2}$, and $K_{\beta1}$ X-rays measured at the mass-241 fraction. Three γ lines indicated by arrows with their energies are attributed to the EC decay of ^{241}Bk. Crosses indicate coincidence summing peaks arising from Cm L X + L X, K_β X + L X, K_α X + K_α X, and K_α X + K_β X-rays.

In the present work, we employed an on-line isotope separator (ISOL) to identify ^{241}Bk. Using an ISOL, one can separate nuclei with a half-life longer than ∼1 s with unambiguous mass identification and obtain extremely low-contaminated γ sources. We have been studying the EC and α-decay of neutron-deficient $^{233\text{-}236}$Am and ^{237,238}Cm using the gas-jet coupled JAERI-ISOL [14–16]. The present work is an extension of this study to heavier actinide elements.

The nucleus ^{241}Bk was produced by the ^{239}Pu(^{6}Li, $4n$) reaction at the JAERI tandem accelerator facility. A stack of twenty-one ^{239}Pu targets set in a multiple-target chamber with 5 mm spacings was bombarded with a ^{6}Li beam of 200 particle-nA intensity. Each target was electrodeposited on a 0.9 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 34–42 MeV on targets. 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 a 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 $M/\Delta M \sim 800$. The separated ions were implanted into an aluminum-coated Mylar tape in a tape transport system, and periodically transported to a measuring position at 400 s intervals. The measuring position was equipped with a short coaxial Ge detector (ORTEC LOAX) and a 35% n-type Ge detector (ORTEC GAMMA-X) placed on both sides of the tape in a close geometry. The detectors were shielded with 100 mm thick lead bricks and 5 mm thick copper inner plates. Gamma-ray singles and γ-γ coincidence events were recorded event by event together with time information. The data were accumulated during 61 h. Energy calibration of the detectors were made using a ^{152}Eu source and also using background γ lines observed in the ^{241}Bk spectrum.

Figure 1 shows a γ-ray singles spectrum for the mass-241 fraction measured with the LOAX detector. Cm K X-rays associated with the EC decay of ^{241}Bk were clearly observed. Most of peaks in the spectrum arise from background γ-rays, and no γ-rays from the decay of ^{241}Cm and other isobars are seen in the spectrum owing to the long half-lives. Figure 2 shows a sum of γ-ray spectra in coincidence with Cm $K_{\alpha1}$, $K_{\alpha2}$, and $K_{\beta1}$ X-rays. Three γ lines with energies of 152.4(1), 210.7(1), and 262.3(2) keV were clearly observed in the spectrum, indicating that they are associated with the EC decay of ^{241}Bk. These γ-rays are also seen in the singles spectrum and in coincidence with Cm L_α X-rays. Coincidence relationships among these γ-rays are not clear owing to less statistics. Relative intensities of 152.4, 210.7, and 262.3 keV γ-rays were deduced to be 6(2), 6(2), and 10(3), respectively, from the singles spectrum. However, these values are tentative because the coincidence summing effect cannot be corrected for without knowledge of the decay scheme.

The half-life of ^{241}Bk was derived from the decay curves of Cm $K_{\alpha1}$, $K_{\alpha2}$, and L_α X-rays as shown in fig. 3. The Cm L_α X-rays are observed in the singles spectrum as a doublet peak with background Th L_β X-rays. Thus, the projection spectrum of the γ-γ coincidence matrix was used to obtain its decay curve because almost all the background peaks disappear in the projection spectrum. The half-lives of Cm $K_{\alpha1}$ and $K_{\alpha2}$ X-rays were deduced through both the analyses. By taking a weighted average, the half-life of ^{241}Bk was determined to be 4.6 ± 0.4 min.

The half-life value of 4.6 min is reasonably reproduced by the allowed EC transition of $\pi 7/2^+[633] \rightarrow \nu 7/2^+[624]$. Alpha-decay studies of $^{243\text{-}249}$Es [17] suggested that the ground state of ^{239,241}Bk would have the $\pi 7/2^+[633]$ configuration, not the $\pi 3/2^-[521]$ one like ^{243,245}Bk. EC transitions from the $\pi 3/2^-[521]$ ground state to low-energy odd-Cm levels would have large log ft values because there are no Nilsson states whose asymptotic quantum numbers satisfy the selection rule of the allowed transition; only a few negative-parity states exist at low energy in $N \approx 141$–149 nuclei; $\nu 7/2^-[743]$, $\nu 5/2^-[752]$, etc. [1]. On the other

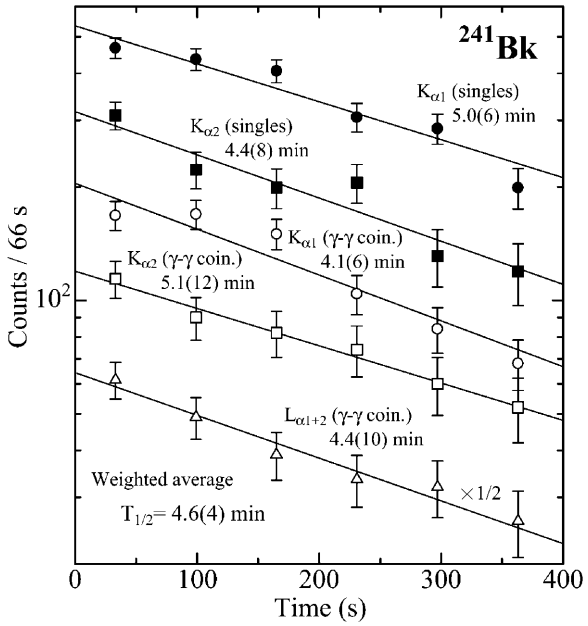

Fig. 3. Decay curves of Cm $K_{\alpha 1}$, $K_{\alpha 2}$, and $L_{\alpha 1+2}$ X-rays associated with the EC decay of ^{241}Bk. The decay curves were obtained through the analysis of γ-γ projection spectra as well as through singles ones.

hand, EC transitions from the $\pi 7/2^+[633]$ ground state can populate many positive-parity states, especially the unoccupied $\nu 7/2^+[624]$ state strongly. The $\log ft$ value of the $\pi 7/2^+[633] \rightarrow \nu 7/2^+[624]$ transition is expected to be about 5.0–5.5 like the $\nu 7/2^+[624] \rightarrow \pi 7/2^+[633]$ transition observed in the β^--decay of ^{243}Pu ($\log ft = 5.5$) and like the similar transition of $\pi 5/2^+[642] \rightarrow \nu 5/2^+[633]$ in ^{232,233}Np, ^{235}Pu, and ^{236}Am whose $\log ft$ values are 4.8–5.4 [1,16]. The $\nu 7/2^+[624]$ state in ^{241}Cm is expected to lie at ∼420 keV as discussed later. Taking this energy, $\log ft$ = 5.0–5.5, and $Q_{\rm EC}$ = 2400 keV [18], the partial half-life of this transition becomes 4.4–14 min [19], which is reasonable to explain the total half-life of 4.6 min.

The observed three γ transitions are also consistent with the above interpretation. The ground state of the N = 145 isotones ^{237}U, ^{239}Pu, and ^{241}Cm is known to be the $\nu 1/2^+[631]$ state [1], and the next Nilsson state $\nu 5/2^+[622]$ is located at 160 and 285 keV in ^{237}U and ^{239}Pu, respectively. The $\nu 7/2^+[624]$ state lies at 426 keV in ^{237}U and 512 keV in ^{239}Pu. If the EC decay of ^{241}Bk populates the $\nu 7/2^+[624]$ state strongly, the γ transition from the $\nu 7/2^+[624]$ state to the $\nu 5/2^+[622]$ one and the transitions from the $\nu 5/2^+[622]$ state to the $3/2^+$ and $5/2^+$ ones in the $\nu 1/2^+[631]$ band should be observed strongly like the decay patterns in ^{237}U and ^{239}Pu [1]. Expected energies and intensities of these three γ transitions are consistent with those of the observed 152.4, 262.3, and 210.7 keV γ-rays, respectively.

In conclusion, the new isotope ^{241}Bk has been identified using the ISOL. The half-life was determined to be 4.6 ± 0.4 min. The half-life value and the observed three γ transitions can be consistently explained as a consequence of the allowed EC transition of $\pi 7/2^+[633] \rightarrow \nu 7/2^+[624]$.

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