Decay properties of $^{243}_{97}$Bk and $^{244}_{97}$Bk

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Electron capture decays of ^{243}Bk and ^{244}Bk have been studied by measuring the γ-ray spectra of mass-separated sources and level structures of ^{243}Cm and ^{244}Cm have been deduced. In ^{243}Cm, the electron capture population to the ground state, $1/2^+[631]$, and $1/2^+[620]$ Nilsson states have been observed. The octupole $K^\pi = 2^-$ band was identified in ^{244}Cm at 933.6 keV. In addition, spins and parities were deduced for several other states and two-quasiparticle configurations have been tentatively assigned to them.

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I. INTRODUCTION

Since it is usually difficult to determine the mass number of a new nuclide, it is, in most cases, identified by the excitation function of the nuclear reaction used for its production. The most definitive method for the characterization of a nuclide is to use a mass-separated source to determine its mass and use K x rays to define its atomic number. In electron capture decays, K x rays are produced and these are easily measured to characterize the element. But there are very few isotope separators available for the preparation of radioactive samples. At Argonne National Laboratory (ANL), there was such an electromagnetic isotope separator [1] which was used to mass-separate isotopes of actinide elements from the 1960s to 1980s. Samples of Bk were produced in the ANL cyclotron and were mass separated to identify ^{243}Bk and ^{244}Bk isotopes and study their radiations. In this article we describe these measurements and the energy levels deduced from these observations.

The nuclides ^{243}Bk and and ^{244}Bk decay by electron capture (EC) with half-lives of 4.5 ± 0.1 h [2] and 5.02 ± 0.03 h [3] and decay energies of 1508 ± 5 keV and 2262 ± 14 keV [4], respectively. Their decays were first studied by Chetham-Strode [5] who measured their γ-ray spectra with a NaI (Tl) crystal. Only two γ rays were assigned to the decay of ^{243}Bk, but several γ rays were identified in the ^{244}Bk decay. With the limited information, no decay schemes could be proposed. Later, these isotopes were produced via the ^{243}Am(α,xn) reaction by Ahmad [6] and their EC decays were investigated with a Ge(Li) detector. Several γ rays were assigned to the decay of ^{244}Bk but only two γ rays of 755 ± 2 keV and 946 ± 2 keV with relative intensities of 100 and ~80 were observed in ^{243}Bk EC decay. Since no conversion-electron spectrum was measured and no γ-γ coincidence experiments were performed, EC decay schemes were not proposed for these two nuclides.

In the 1970s, the nuclide ^{243}Bk was produced to measure the lifetime of the $1/2^+[631]$ state at 87.4 keV in ^{243}Cm [7]. The γ-ray spectrum was measured with a Ge(Li) spectrometer, but again no level scheme was postulated because no coincidence studies were performed. Recently, the EC decay of ^{244}Bk was studied by Sodaye *et al.* [3] who reported γ rays that agreed with the measurements of Ref. [6]. In this work, the ^{244}Bk source was produced by the ^{238}U(^{11}B,$5n$) reaction. The source contained fission fragment impurities that did not allow them to measure intensities of lower-energy γ rays. The impurities also gave a few false coincidences in the γ-γ coincidence measurement. Using these γ-γ coincidence data, level energies were derived but definite spin-parity assignments to ^{244}Cm levels were not made.

Mass-separated sources of ^{243}Bk and ^{244}Bk were produced by us in the 1970s and their γ-ray spectra were measured. Now that more information on the structures of actinide nuclei has become available, we examined the old data and proposed level schemes for ^{243}Cm and ^{244}Cm. In particular, a level at 840.9 keV in ^{243}Cm was assigned the $1/2^+[620]$ single-neutron configuration and the octupole $K^\pi = 2^-$ band was identified at 933.6 keV in ^{244}Cm. In this report we discuss the measurements and the respective level assignments.

II. SOURCE PREPARATION

The nuclides ^{243}Bk and ^{244}Bk were produced by irradiating an ^{241}Am target with α particles from the Argonne 152-cm cyclotron. Ion-exchange was used to isolate a chemically pure sample of Bk which was passed through the Argonne electromagnetic isotope separator [1] to provide isotopically pure sources of ^{243}Bk and ^{244}Bk. The details about the irradiation and the chemical separation of berkelium are given in Ref. [7].

III. EXPERIMENTAL METHODS AND RESULTS

γ-ray spectroscopy

The γ-ray spectra of mass-separated ^{243}Bk and ^{244}Bk sources were measured with a 25-cm^3 coaxial Ge(Li) spectrometer. Only one spectrum of ^{243}Bk was measured for 20 min because we were mainly interested in the decay of ^{244}Bk. The ^{243}Bk source also contained a small amount of ^{243}Cm, produced by the ^{241}Am(α,pn) reaction. Energies of γ rays in the ^{243}Cm decay were used for energy calibration. The source-to-detector distance for the ^{243}Bk spectrum was 1.5 cm and for the ^{244}Bk source it was 4.0 cm. γ rays are assigned to ^{243}Bk on the basis of the chemical and isotopic purity of

TABLE I. Energies and intensities of γ rays produced in ^{243}Bk EC decay.

Energy (keV)	Relative intensity	Transition (initial level → final level)
87.4 ± 0.1	10.5 ± 0.9	$87.4 \rightarrow 0.0$
104.6 ± 0.1	197 ± 15	Cm $K_{\alpha 2}$
109.3 ± 0.1	294 ± 18	Cm $K_{\alpha 1}$
123.0 ± 0.1	97 ± 6	Cm $K_{\beta 1'}$
127.0 ± 0.1	35 ± 5	Cm $K_{\beta 2'}$
188.0 ± 0.2	1.2 ± 0.2	not assigned
255.7 ± 0.2	2.7 ± 0.4	$1024.2 \rightarrow 768.5$?
447.6 ± 0.2	5.1 ± 0.6	not assigned
632.5 ± 0.3	5.1 ± 1.0	$726.5 \rightarrow 94.2$?
692.7 ± 0.3	8.8 ± 0.9	$840.9 \rightarrow 148.9$
700.2 ± 0.3	11.5 ± 1.1	$870.9 \rightarrow 170.7$?
722.0 ± 0.2	42 ± 3	$870.9 \rightarrow 148.9$
732.1 ± 0.2	16 ± 1.4	not assigned
741.1 ± 0.2	23 ± 2	$890.0 \rightarrow 148.9$
753.4 ± 0.2	100(norm)	$840.9 \rightarrow 87.4$
776.7 ± 0.2	17 ± 1.6	$870.9 \rightarrow 94.2$
791.0 ± 0.2	13.4 ± 1.4	not assigned
840.9 ± 0.2	21 ± 2	$840.9 \rightarrow 0.0$
848.0 ± 0.2	14.5 ± 1.5	$890.0 \rightarrow 42.0$
870.9 ± 0.2	8.2 ± 0.9	$870.9 \rightarrow 0.0$
936.8 ± 0.2	5.9 ± 1.2	$1024.2 \rightarrow 87.4$?
944.9 ± 0.2	73 ± 6	$944.9 \rightarrow 0.0$?

the sample, and the fact that the strong γ rays observed in the present spectrum were also observed in Refs. [5,6]. Two spectra of the ^{244}Bk sample were measured 16 hours apart and each spectrum was collected for 300 minutes. γ rays were assigned to ^{244}Bk decay on the basis of the sample purity, their half-lives, and the fact that they were also observed in Refs. [3,6]. The 744.1- and 897.7-keV γ rays, assigned to the ^{244}Bk decay, also occur in the the β^--decay of the 10.1-h ^{244}Am [8]. However, these γ rays cannot be due to ^{244}Am because it cannot be produced by the ^{241}Am(α,xn) reaction used in this study. These two γ rays are assigned to ^{244}Bk decay because they decayed with its characteristic half-life of 5.0 h and they were also observed in Ref. [6]. In the present work, the γ-ray energies have been measured with higher precision than in Ref. [6], but the precision in γ-ray intensities is comparable to that in the previous two measurements. The data on ^{243}Bk and ^{244}Bk γ rays are given in Tables I and II, respectively. Also included in Table II are the intensities measured in Refs. [3,6]. The intensities of γ rays in both tables are given in relative units. Energies of γ rays not measured in the present work are taken from Ref. [3].

Absolute intensities of γ rays in ^{243}Cm in photons per EC decay were obtained in the following way. Using the γ-ray intensities in Table I and the level scheme of Fig. 1, the EC intensity to an excited state was obtained from intensity balances by taking the difference between the intensities of γ rays and conversion electrons depopulating that level and the intensities of γ rays and conversion electrons feeding that level. The Curium K x-ray intensity at each excited state was calculated from the EC intensity at that level and the theoretical K/total EC capture ratio. The sum of all K x-ray intensities at excited levels and K x-ray intensity due to internal conversion of γ-ray transitions were subtracted from the measured K x-ray intensity. This difference gave the K x-ray intensity at the ground state, which was multiplied with the theoretical total/K capture ratio to obtain the EC intensity. The sum of EC intensities to all ^{243}Cm levels was normalized to 100%. This gave a factor of 0.121, which should be multiplied to the relative γ-ray intensities in Table I to obtain absolute intensities. For the ^{244}Bk EC decay, the γ rays in Table II should be multiplied by 0.505 to obtain absolute intensities. This factor was obtained by normalizing the total intensities of all γ rays decaying to the ground-state band to 100%. We used all γ rays in this calculation—those that are placed in the level scheme of Fig. 2 and also those which could not be placed in the level scheme. The γ rays observed in our experiments were also reported in Ref. [3] and their energies and intensities are in agreement with our values. However, since our source was chemically and isotopically pure, its spectrum had less Compton background and hence we were able to identify weak low-energy γ rays. The spectrum in Ref. [3] has some additional weak γ rays that are not placed in our level scheme.

IV. DISCUSSION

In the present experiment, as well as in previous studies, conversion coefficients of γ-ray transitions were not measured. In Ref. [3] a γ-γ coincidence measurement was made with a ^{244}Bk source but only limited information was obtained. Energies of levels in ^{243}Cm and ^{244}Cm were deduced from the sums and differences of γ-ray transition energies. Spins and parities of levels were derived on the basis of the ground-state spins and parities, branching ratios of γ rays, and log ft values of EC transitions. Energies of single-particle states

TABLE II. Energies and intensities of γ rays produced in ^{244}Bk EC decay. Energies of the highest three γ rays are taken from Ref. [3]. The 153.5-keV γ ray was seen in the coincidence spectrum (Ref. [3]) and its intensity was not measured.

Energy	Relative intensity			Transition
(keV)	present	Ahmad [6]	Sodaye [3]	(initial level → final level)
78.9 ± 0.2	5.5 ± 0.5			1374.3 → 1295.3
99.2 ± 0.2	3.3 ± 0.3			142.35 → 42.97
104.7 ± 0.1	71 ± 5	85 ± 10		Cm $K_{\alpha 2}$
109.3 ± 0.1	111 ± 5	130 ± 15		Cm $K_{\alpha 1}$
123.0 ± 0.1	34 ± 3	48 ± 6		Cm $K_{\beta 1'}$
127.1 ± 0.1	12 ± 1	20 ± 4		Cm $K_{\beta 2'}$
139.7 ± 0.1	0.8 ± 0.2			1151.1 → 1011.4
144.2 ± 0.1	7.5 ± 0.6	7.4 ± 0.4		1295.3 → 1151.1
153.5 ± 0.1				1374.3 → 1220.5
153.8 ± 0.1	3.7 ± 0.3	3.7 ± 0.4	5.4 ± 0.8	296.21 → 142.35
160.4 ± 0.2	0.5 ± 0.1			not assigned
176.8 ± 0.1	4.0 ± 0.3	4.2 ± 0.5	4.1 ± 0.4	1374.3 → 1197.5
187.5 ± 0.1	17.0 ± 1.5	16.5 ± 1.5	16.5 ± 0.5	1151.1 → 963.5
196.9 ± 0.2	0.6 ± 0.1			not assigned
209.5 ± 0.2	0.4 ± 0.1			Cm $K_{\alpha 2}$ + Cm $K_{\alpha 2}$ sum
217.5 ± 0.1	100 (norm)	100 (norm)	100 (norm)	1151.1 → 933.6
223.3 ± 0.1	2.9 ± 0.3			1374.3 → 1151.1
233.8 ± 0.1	2.3 ± 0.4	2.9 ± 0.4	1.8 ± 0.2	1197.5 → 963.5
322.0 ± 0.2	1.2 ± 0.2			217.5 + Cm $K_{\alpha 2}$ sum
326.9 ± 0.2	1.8 ± 0.3			217.5 + Cm $K_{\alpha 1}$ sum
334.0 ± 0.1	9.0 ± 1.0	10.0 ± 1.5	11.3 ± 0.4	1374.3 → 1040.2
411.0 ± 0.3	2.6 ± 0.3		4.0 ± 0.2	1784.7 → 1374.3
431.7 ± 0.3	1.8 ± 0.2		3.5 ± 0.3	
470.0 ± 0.3	1.5 ± 0.2		3.0 ± 0.2	1653.8 → 1183.5?
489.4 ± 0.3	16 ± 1.6	18 ± 2	14.0 ± 0.6	1784.7 → 1295.3
565.2 ± 0.2			1.8 ± 0.3	1784.7 → 1220.5?
607.8 ± 0.3	4.0 ± 0.4		2.9 ± 0.3	not assigned
624.8 ± 0.3	2.8 ± 0.3		1.3 ± 0.2	
642.4 ± 0.2	1.9 ± 0.2		1.8 ± 0.3	1653.8 → 1011.4
690.7 ± 0.3			0.4 ± 0.2	1653.8 → 963.5
744.1 ± 0.1	8.8 ± 0.7	8 ± 1		1040.2 → 296.21
846.7 ± 0.1			1.0 ± 0.2	not assigned
869.0 ± 0.2	5.5 ± 0.3	7 ± 1	5.6 ± 0.3	1011.4 → 142.35
890.6 ± 0.2	108 ± 10	114 ± 12	106.1 ± 3.7	933.6 → 42.97
897.7 ± 0.2	4.6 ± 0.5			1040.2 → 142.35
908.9 ± 0.3	3.0 ± 0.4	3.0 ± 0.5	3.0 ± 0.2	not assigned
920.5 ± 0.2	21 ± 2	22 ± 3	23.8 ± 0.9	963.5 → 42.97
944.4 ± 0.2	3 ± 1	∼ 3	–	not assigned
985.6 ± 0.2	5.0 ± 0.6	5 ± 1	2.5 ± 1.1	
1041.1 ± 0.3	3 ± 1	∼ 3	2.1 ± 0.2	1183.5 → 142.35?
1068.7 ± 0.3	1.3 ± 0.3			not assigned
1078.1 ± 0.3	1.1 ± 0.2			1220.5 → 142.35
1107.6 ± 0.5			2.4 ± 0.1	1151.1 → 42.97?
1138.0 ± 0.5		∼1.5	2.0 ± 0.2	not assigned
1140 ± 2		∼2		1183.5 → 42.97?
1152.8 ± 0.3	9.0 ± 0.9	9.5 ± 1.4	9.9 ± 0.3	1295.3 → 142.35
1173 ± 2		∼0.7	1.0 ± 0.1	not assigned
1177.5 ± 0.3	5.0 ± 0.9	5.0 ± 0.8	3.9 ± 0.2	1220.5 → 42.97
1205.3 ± 0.5		∼1	1.3 ± 0.2	not assigned
1212.1 ± 0.3	1.3 ± 0.2	∼1.3	1.3 ± 0.1	not assigned
1232.1 ± 0.3	3.5 ± 0.3	4.0 ± 0.8	1.5 ± 0.4	1374.3 → 142.35
1252.5 ± 0.5		3.0 ± 0.6	2.7 ± 0.1	1295.3 → 42.97
1331.6 ± 0.6		1.2 ± 0.2	2.1 ± 0.1	1374.3 → 42.97
1502.3 ± 0.7		∼3	1.2 ± 0.1	1644.8 → 142.35?

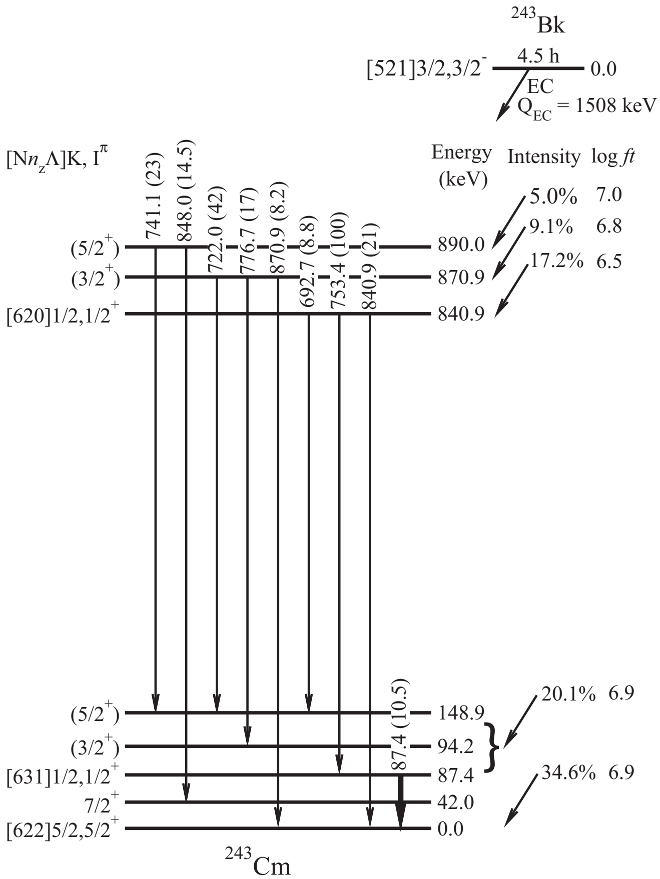

FIG. 1. Partial decay scheme of ^{243}Bk deduced from the present work. The 87.4-keV level was identified in Ref. [7]. γ-ray intensities are given in relative units and can be converted to photons per ^{243}Bk EC decay by multiplying them with 0.121. The total EC intensity in the figure does not add up to 100% because 4.7% belongs to γ rays, which are not placed in the level scheme and 9.3% belongs to a tentative 944.9-keV level, not shown in the figure.

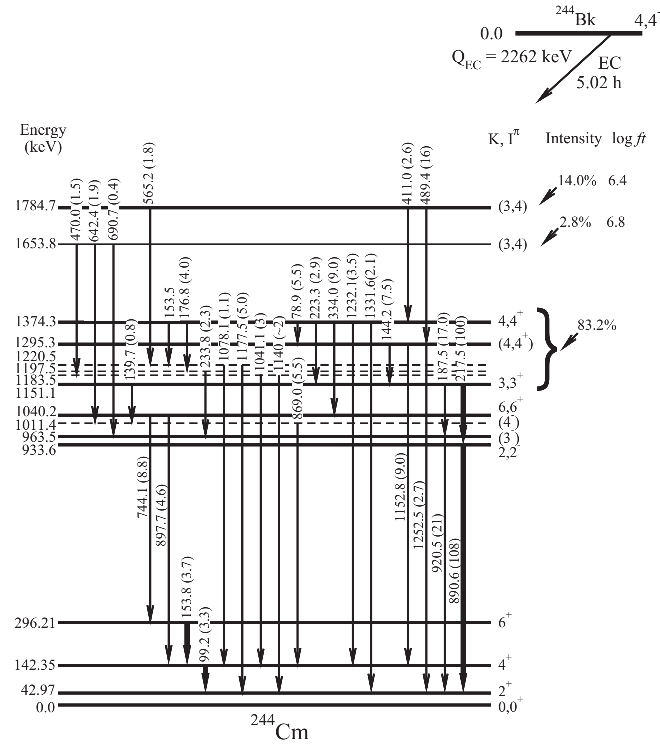

FIG. 2. Partial decay scheme of ^{244}Bk deduced from the present data. The labels shown on the right side of the levels denote the projection K of the total angular momentum I on the nuclear symmetry axis and the parity of the level π. The 6^+ state at 1040.2 keV was known previously [8]. γ-ray intensities are given in relative units and can be converted to photons per ^{244}Bk EC decay by multiplying them with 0.505. The 1151.1-keV state is given the two-quasiparticle configuration assignment of $\{5/2^+[622]\nu;1/2^+[631]\nu\}_{3+}$. The energies of the members of the ground-state band are taken from Ref. [15]. Levels placed on weaker evidence are shown as dashed lines.

and log ft values, published in Ref. [9], have been used to deduce one-quasiparticle configurations in ^{243}Cm and two-quasiparticle configurations in ^{244}Cm. Measurements using proton and neutron transfer reactions have shown that in ^{250}Cf two-proton and two-neutron configurations with $K^\pi = 5^-$ mix [10] and there is a strong transition between them [11]. In ^{244}Cm two states at 1295.3 and 1374.3 keV are assigned $K^\pi = 4^+$ with two-neutron and two-proton configurations, and a strong γ ray is observed between them indicating mixing between the two states.

A. ^{243}Bk EC decay scheme

The ground state of ^{243}Cm has been assigned to the $5/2^+[622]$ Nilsson state on the basis of its α decay to ^{239}Pu [2]. Only one level at 87.4 keV was identified in ^{243}Cm in the ^{243}Bk EC decay study and it was assigned to the $1/2^+[631]$ Nilsson state [7] on the basis of the measured $E2$ multipolarity of the 87.4-keV transition. In the present work, we observe the 87.4-keV γ ray and other high-energy γ rays. Because the spectrum was collected for a short time (20 min), only strong γ rays could be identified. The observed high-energy γ rays establish a level at 840.9 keV whose spin-parity has been deduced as $1/2^+$ on the basis of its decay pattern and given an assignment of $1/2^+[620]$. This state was also observed in the ^{244}Cm(d,t) reaction [12] with the expected cross section. The assignment is further supported by the similarity of the decay pattern of this state to the decay of the 755.15-keV level in the isotone ^{241}Pu [13] and the decay of the 741.0-keV level in ^{245}Cm [14] which have been well established as $1/2^+[620]$ Nilsson state. Levels at 870.9 and 890.0 keV have been tentatively assigned to the $3/2$ and $5/2$ members of the $1/2^+[620]$ band on the basis of the similarity of the level spacings and decay pattern in the isotone ^{241}Pu. The decay scheme of ^{243}Bk is shown in Fig. 1. From the level energies in Fig. 1, we calculate the decoupling parameter $a = -0.657 \pm 0.004$ and the rotational constant of 6.60 ± 0.02 keV for the $1/2^+[631]$ band and $+0.447 \pm 0.005$ and 6.91 ± 0.02 keV for the $1/2^+[620]$ band. These values are in good agreement with the values of -0.543 and 6.747 keV for the $1/2^+[631]$ band and $+0.493$ and 6.461 keV for the $1/2^+[620]$ band in ^{241}Pu [13].

For the absolute intensities of γ rays and EC population to ^{243}Cm levels, γ rays from Table I that were not placed in the level scheme were also included. The EC intensities and log

ft values deduced from the data in the present experiment are included in Fig. 1.

B. ^{244}Bk EC decay scheme

In Ref. [3], level energies in ^{244}Cm were derived from the measured γ-ray energies but their spins and parities and configurations could not be deduced because the conversion coefficients were not measured. Many levels in ^{244}Cm are known from β^- decays of the two ^{244}Am isomers [8,15]. The low-spin isomer populates low-spin states up to spin 2 $\hbar$ in ^{244}Cm and the high-spin isomer decays to a $K,I^\pi = 6,6^+$ state at 1040.2 keV which deexcites to the 6^+ and 4^+ members of the ^{244}Cm ground-state band. From this information and the EC decay of ^{244}Bk we can determine the range of spin values possible for the ^{244}Bk ground state.

C. ^{244}Bk ground state

In an electron capture decay, only EC transitions with $\Delta K = \Delta I = 0$ or 1 have a measurable EC population. Thus from the measured EC intensities and log ft values, we can determine the range of spin values for the ^{244}Bk ground state. In the present work we do not observe any of the γ rays seen in the decay of the low-spin ^{244}Am isomer [15], which suggests that the ground-state spin of ^{244}Bk is 3 $\hbar$ or higher. We observe the γ rays depopulating the 6^+ state at 1040.2 keV [8] with a very low EC intensity ($\leqslant$2.0%) indicating that it is not directly fed with high EC intensity. This limits the spin of the ^{244}Bk ground state to 4 $\hbar$ or lower. The ground states of the neighboring nuclei, ^{243}Cm and ^{243}Bk, are known to be the $5/2^+[622]\nu$ and the $3/2^-[521]\pi$ Nilsson states, respectively. Thus a possible assignment for the ^{244}Bk ground state is the $\{3/2^-[521]\pi;5/2^+[622]\nu\}_{4^-}$ configuration, and since it lies within the range of spin values deduced above, we assign this configuration to the ^{244}Bk ground state.

D. Spins and parities of ^{244}Cm levels

Although a γ-γ coincidence experiment was performed with a ^{244}Bk source in Ref. [3], it provides limited information for the postulation of energy levels in ^{244}Cm. However, some information about energy levels can be deduced because the energies of the members of the ^{244}Cm ground-state band are known and also some excited levels are known from the decay of ^{244}Am isomers. From the sums and differences of γ-ray transition energies, we deduce a level scheme, shown in Fig. 2, which is very similar to that proposed in Ref. [3]. Using the placements of transitions in the level scheme we determined the spin and parity of the levels.

From the transition (γ-ray and conversion electron) intensity balance, we can determine at which member of the ground-state band a high-energy γ ray terminates. Since, with the spin-parity of 4^- for the ^{244}Bk ground state, no direct EC population is expected to any member of the ground-state band, the intraband transitions in the ground-state band must be fed by higher-energy transitions. The intensities of the 153.8-keV ($6^+ \rightarrow 4^+$) and 99.2-keV ($4^+ \rightarrow 2^+$) transitions were calculated from the measured γ-ray intensities and their theoretical conversion coefficients [16] for $E2$ multipolarity. The measured intensity of the 153.8-keV ($E2$; 2.8) transition is 7.1% and it is fed by the known 744.1-keV ($M1+E2$; 0.10) transition with an intensity of 4.9%. In the parentheses, the transition multipolarity and the total conversion coefficient are given. The remaining 2.2% intensity could be due to the 153.5-keV transition observed in the coincidence data [3] and placed in the level scheme or due to other unobserved γ rays. The measured intensity of the 99.2-keV ($E2$; 19.4) transition is 34.0% and 20.0% of this intensity is fed by the 153.8- ($E2$; 2.8), 869.0-($E1$; 0.006), 897.7-($E2$; 0.017), 1041.1-($M1$; 0.049), 1078.1-($M1$; 0.045), 1152.8-($M1$; 0.037), and 1232.1-keV ($M1$; 0.031) transitions placed in the level scheme shown in Fig. 2. Thus, the remaining 14% of the 99.2-keV transition intensity is assumed to be fed by other high-energy γ rays. The γ rays listed in Table II that are not placed in the level scheme have a total intensity of 10.2% and the 920.5-keV ($E1$; 0.005) γ ray has an intensity of 10.7%.

Systematics and expected transition rates can be used to limit the spin and parity values. Any excited state in ^{244}Cm with spin-parity $0^+, 1^+, 2^+$, and 1^- will decay to the 0^+ ground state. Thus the absence of such transitions rules out these spin-parity values. The decay pattern of the members of the $K^\pi = 2^-$ band is known [14] in ^{246}Cm. A member of this band with even spin decays to the member of the ground-state band with the same spin and to no other member. On the other hand, a state with odd spin I of this band decays to the $I-1$ and $I+1$ members of the ground-state band with comparable intensities. We observe a strong transition of 890.6 keV with an intensity of 54.2% per ^{244}Bk EC decay, which cannot terminate at the 6^+ or 4^+ member of the ground-state band because of its high intensity. This transition decays either to the ground state or to the 2^+ member of the ground-state band. Any transition decaying to the ground state has usually an accompanying transition to the 2^+ member. Thus the 890.6-keV transition should connect a 933.6-keV level to the 2^+ member of the ground-state band. Since we do not observe a transition to either 0^+ or 4^+ member of the ground-state band, this level must have spin-parity 2^-, with $K^\pi = 2^-$. We interpret it as the 2^- octupole vibrational band head and its energy is in good agreement with the theoretical predictions of 960 [17] and 864 keV [18] for this band.

There is a strong transition of 217.5 keV with an intensity of 57.2% per ^{244}Bk EC decay which is the same as that of the 890.6-keV γ ray and these two γ rays are found to be in coincidence with each other [3]. In Ref. [3], the γ-ray spectrum gated by the 217.5-keV γ ray contains peaks at 995.6, 999.3, and 1014.6 keV. These are, most likely, 890.6-Cm K x-ray sum peaks, not transitions in ^{244}Cm. This spectrum contains only an 890.6-keV peak above 600 keV, indicating that this transition connects to the ground-state band. These observations point to a level at 1151.1 keV which decays to the $K^\pi = 2^-$ level at 933.6 keV. From the intensity balance, the multipolarity of the 217.5-keV transition is deduced to be $E1$ and hence the 1151.1-keV level should have spin-parity $1^+, 2^+$, or 3^+. Since the 1151.1-keV state does not decay to the groundvstate, it must have spin-parity 3^+. The 1107.6-keV γvray was seen in Ref. [3] and interpreted as the 1151.1 $\rightarrow$ 42.97 transition, but it is not observed in our work. The intensity of this peak indicates that it is most likely the 890.6 + 217.5 sum peak.

The 920.5-keV γ ray is in coincidence with the 187.5-keV γ ray and their intensities are almost equal. γ-ray transition intensity balance establishes the multipolarity of the 187.5-keV transition as $E1$. Since the $890.6 + 217.5$ sum is equal to the $920.5 + 187.5$ sum, the two cascades should start and terminate at the same levels, namely the 1151.1-keV level and the 42.97-keV, 2^+ member of the ground-state band. A 144.2-keV γ ray, shown in Fig. 2, is in coincidence with both the 217.5- and the 187.5-keV γ rays which indicates that 217.5- and 187.5-keV transitions deexcite the same level, namely the 1151.1-keV level. These observations suggest that the 920.5-keV γ ray deexcites a negative-parity level at 963.5 keV, which is fed from the 3^+, 1151.1-keV level by an 187.5-keV $E1$ transition. Hence the spin-parity of the 963.5-keV level should be 2^- or 3^-. This level fits as the 3^- member of the 933.6-keV band, but its decay only to the 2^+ member of the ground-state suggests 2^- spin-parity. We tentatively assigned a spin-parity of 3^- to this level because no 2^- state is expected in this energy region. The level at 1011.4 keV decays to the 4^+ member of the ground-state band and it is interpreted as the 4^- member of the octupole band.

The 1374.3-keV level decays to the 2^+ and 4^+ members of the ground-state band and to the 6^+ level at 1040.2 keV. Hence it must have a spin-parity of 4^+.

The decay of the 1295.3-keV state to the 2^+ and 4^+ members of the ground-state band and to the 3^+ level at 1151.1 keV restricts the spin of the state to 3 and 4. The fact that it does not decay to the 2^- state favors a 4^+ assignment.

The coincidence between the 1252.5- and the 489.4-keV γ rays indicates a level at 1784.7 keV. The decay pattern and the direct EC population suggest possible spin values of 3, 4, or 5. In the coincidence table in Ref. [3] there is a 233.8-keV γ ray which is in coincidence with the 920.5-keV γ ray only which indicates a level at 1197.5 keV. The coincidence data also show a 176.8-keV γ ray which is in coincidence with all γ rays deexciting the 1151.1-keV level. Thus this γ ray decays to the 1151.1-keV level or to its rotational member. An energy fit suggests this transition as the $1374.3 \rightarrow 1197.5$ transition. We interpret the 1197.5-keV level as the $I = 4$ member of the 3^+ band at 1151.1 keV.

In addition to the levels discussed above, we have weak evidence for 1653.8-, 1220.5-, and 1183.5-keV levels. The decay pattern of these states suggests the most likely spin of 3 or 4 $\hbar$ and they are included in Fig. 2.

E. EC intensities and log ft values

The EC intensity to a level is determined from the difference between the intensities of γ rays and conversion electrons depopulating that level and the intensities of γ rays and conversion electrons feeding that level. Conversion electron intensities were calculated from the measured γ-ray intensities and their theoretical conversion coefficients [16]. We used $E1$ multipolarity for the 217.5-, 187.5-, and 139.7-keV transitions, and $M1$ multipolarity for the 144.2-, 176.8-, and 223.3-keV transitions, which are based on the spin-parity assignments given in Fig. 2. However, since the level scheme is not complete and multipolarities of transitions have not been measured, it is not possible to determine accurate EC feeding intensities at each level.

Absolute intensities of γ rays in ^{244}Bk EC decay have been determined by normalizing the total intensities of high-energy γ rays depopulating the excited levels to the ^{244}Cm ground-state band to 100%. We used the γ rays placed in the level scheme, as well as those that were not placed in the level scheme of Fig. 2. Because of the spin 4 $\hbar$ for the ^{244}Bk ground state, we assume there is no direct EC decay to the ground-state band. The high intensity of γ rays deexciting the 1151.1-keV level suggests that most of the EC decay occurs at the 1151.1-keV level or at higher levels. Since we do not observe any γ ray populating the 1784.7- and 1653.8-keV levels, the intensities of the transitions decaying these levels give the EC intensities. The EC intensities to the 1151.1-, 1295.3-, and 1374.3-keV levels were deduced using the level scheme in Fig. 2 and the assumed multipolarities of the γ-ray transitions. We find an intensity of 12.9% per ^{244}Bk EC decay for the 1151.1-keV level and a total of 68.0% for the 1295.3- and 1374.3-keV levels. The corresponding intensities and the log ft values are shown in Fig. 2.

The measured Cm K x-ray intensity of (115 ± 4)% per ^{244}Bk EC decay agrees with the Cm K x-ray intensity of (123 ± 8)% per ^{244}Bk EC decay deduced from the EC intensities to the ^{244}Cm levels and K conversion coefficients of γ-ray transitions. This provides further support for the proposed level scheme.

F. Two-quasiparticle state assignments

Energies of the two-quasiparticle states in ^{244}Cm can be estimated from the known energies of single-particle states near the Fermi surface in the adjacent odd-neutron and odd-proton nuclei. The lowest neutron states known in ^{243}Cm are the $5/2^+[622]$ (0 keV), $1/2^+[631]$ (87.4 keV), $7/2^+[624]$ (133 keV), and $1/2^+[620]$ (841 keV) and the lowest proton states identified in ^{243}Am are the $5/2^-[523]$ (0 keV), $5/2^+[642]$ (84.0 keV), $3/2^-[521]$ (267.0 keV), and $7/2^+[633]$ (465.7 keV).

The configuration $\{5/2^+[622]\nu;7/2^+[624]\nu\}_{6^+}$ in ^{244}Cm is already known at 1040.2 keV from the β^- decay study of the high-spin ^{244}Am isomer and its energy is reproduced by theoretical calculations [17]. The energy of the $\{1/2^+[631]\nu;7/2^+[624]\nu\}_{4^+,3^+}$ state is calculated [17] to be 1200 keV and the energy of the $\{5/2^+[622]\nu;1/2^+[631]\nu\}_{3^+,2^+}$ state should be similar (not calculated in Ref. [17]) because the $5/2^+[622]$ orbital is the ^{243}Cm ground state. Since the spin-parity of the 1151.1-keV level has been deduced as 3^+ and its energy is close to the calculated value, it is given the $\{5/2^+[622]\nu;1/2^+[631]\nu\}_{3^+}$ assignment.

The 4^+ states at 1295.3 and 1374.3 keV are most likely the $\{1/2^+[631]\nu;7/2^+[624]\nu\}_{4^+}$ and $\{3/2^-[521]\pi;5/2^-[523]\pi\}_{4^+}$ configurations. The 78.9-keV γ ray, observed in the present work, is interpreted as the $1374.3 \rightarrow 1295.3$ transition. The decay of the 1374.3-keV state to the 1295.3-keV level indicates that the two $K^\pi = 4^+$ two-proton and two-neutron states mix. Similar mixing was observed in the decay of the $K^\pi = 5^-$ two-proton state to the $K^\pi = 5^-$ two-neutron state in ^{250}Cf [10,11]. The higher EC intensity to the 1374.3-keV level favors the $\{3/2^-[521]\pi;5/2^-[523]\pi\}_{4^+}$ configuration assignment to this state and the $\{1/2^+[631]\nu;7/2^+[624]\nu\}_{4^+}$ configuration assignment to the 1295.3-keV level.

The low log ft values of the 1784.7- and 1653.8-keV levels indicate that one component of two-quasiparticle configurations for these levels should be the same as the one single-particle component in the ^{244}Bk ground-state configuration. Thus possible configurations for 1784.7- and 1653.8-keV levels, which are calculated to have similar energies, are $\{5/2^+[622]\nu;1/2^+[620]\nu\}_{3^+}$, $\{5/2^+[622]\nu;3/2^+[622]\nu\}_{4^+}$, and $\{3/2^-[521]\pi;5/2^+[642]\pi\}_{4^-}$. No assignments have been made to the weakly populated states at 1183.5 and 1220.5 keV.

G. Summary

γ-ray spectra of mass-separated ^{243}Bk and ^{244}Bk sources were measured with a high-resolution germanium spectrometer. The strong γ rays of these sources can be used for the identification of ^{243}Bk and ^{244}Bk isotopes. In ^{243}Cm, the $1/2^+[620]$ Nilsson orbital was identified and its energy provided information about the gap at the $N = 152$ neutron subshell. In ^{244}Cm, the octupole vibrational band $K^\pi = 2^-$ was identified at 933.6 keV. Several two-quasiparticle states were also observed in ^{244}Cm.

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