obtained at 3.5 and 12 MeV may be regarded as strong evidence for the validity of the distorted-wave Born approximation for this reaction.

Finally, it may be thought that because the deuteron energy of 3.5 MeV is well below the Coulomb barrier the deuteron will never get close enough to the target to feel the short-ranged nuclear force. The results shown in Fig. 5, though, do not support this viewpoint because the effects of (1) eliminating the stripping that occurs in the nuclear interior and of, in addition, (2) setting the nuclear potentials equal to zero are seen to be large. This probably occurs because although the deuteron wave function is peaked outside the nucleus the proton wave function is peaked inside and the maximum stripping contribution occurs somewhere between. The Coulomb repulsion of the deuteron thus acts more to lower the cross section than to reduce the relative interior contribution.

V. CONCLUSIONS

Other than a small value of the deuteron imaginary potential, the present DWBA calculations for the $^{90}Zr(d,p)^{91}Zr$ reaction are in essential agreement with the predictions of higher energy proton and deuteron elastic scattering and deuteron stripping data. At low bombarding energies (below the Coulomb barrier), even very slight target contamination by light elements may lead to interfering reactions. When proper account is taken of such possible interference, it should be possible to employ stripping at low energies for the purpose of determining nuclear spins, parities, and spectroscopic factors in the same manner as this is done at higher energies.

ACKNOWLEDGMENT

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Decay of 25-Min Am^{246} and 1.8-Day Bk^{246}†

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The radiations associated with the β decay of 25-min Am^{246} and the electron-capture decay of 1.8-day Bk^{246} have been studied with γ-scintillation spectrometers, Ge(Li) detectors, and a Au-surface-barrier electron detector. Conversion-electron lines of the more intense Cm^{246} transitions have been observed and tentative multipole orders have been assigned. A decay scheme is presented on the basis of γ-ray energy and intensity data, γ-γ coincidence studies, and conversion-electron measurements. The Cm^{246} level diagram includes excited states at 43, 142, 843, 878, 1078, 1106 1126 (doublet), 1318, 1352, 1369, 1483, 1531, 1598, 1643, $\geq$1668, and $\geq$1739 keV. The levels at 843, 878, 1078, 1106, and 1126 (doublet) keV are all directly populated by both 25-min Am^{246} and 1.8-day Bk^{246}. The 1126-keV doublet level consists of the $I=3$ rotational member of a $K^{\pi}=1^-$ band based at 1078 keV and a 2^+ state that de-excites by essentially pure $E2$ transitions to the 0^+ and 2^+ members of the ground-state band. Consideration of the electron-capture decay information and available Nilsson orbitals leads to a spin and parity assignment of 2^- for 1.8-day Bk^{246}. The present work is in agreement with the previous 2^+ assignment for 25-min Am^{246}.

I. INTRODUCTION

DISCOVERY of the β emitters 11.2-day Pu^{246} and 25-min Am^{246} was reported by Engelkemeir *et al.* in 1955.[1] Isotopic identification of the two nuclides was based upon chemical (Z) and mass spectrometric (A) evidence. These investigators[1] studied a Pu^{246}-Am^{246} equilibrium source with a NaI(Tl) scintillation spectrometer and observed 18.5-, 43-, 103-, 175-, 220-, 795-, and 1069-keV γ rays.

Later, Smith *et al.*[2] studied the β-ray spectrum of a Pu^{246}-Am^{246} equilibrium source with a magnetic-lens β-ray spectrometer and reported the following Am^{246} β groups: 2.1 MeV, 7%; 1.60 MeV, 14%; 1.31 MeV, 79%. In addition, 51-, 65-, 74-, 94-, 114-, 127-, and 156-keV conversion-electron lines were observed.

Recently Stephens, Asaro, Fried, and Perlman[3] have used a high-resolution Ge(Li) detector to study the decay of Pu^{246} and Am^{246}. Their level scheme includes excited states in Cm^{246} at 43, 142, 842, 877, 1080, 1106, 1129, 1351, and 1368 keV with negative-parity assignments to all the states $\geq$842 keV.

Chetham-Strode[4] studied the γ-singles and γ-γ coincidence spectra of 1.8-day Bk^{246} with NaI(Tl) scintilla-

† Work performed under the auspices of the U. S. Atomic Energy Commission.

[1] D. Engelkemeir, P. R. Fields, S. Fried, G. L. Pyle, C. M. Stevens, L. B. Asprey, C. I. Browne, H. L. Smith, and R. W. Spence, J. Inorg. Nucl. Chem. 1, 345 (1955).

[2] H. L. Smith, C. I. Browne, D. C. Hoffman, J. P. Mize, and M. E. Bunker, J. Inorg. Nucl. Chem. 3, 93 (1956).

[3] F. S. Stephens, F. Asaro, S. Fried, and I. Perlman, Phys. Rev. Letters 15, 420 (1965).

[4] Alfred Chetham-Strode, Jr. thesis, University of California Radiation Laboratory Report UCRL-3322, 1956 (unpublished).

tion spectrometers and reported ≈250-, 800-, 980-, 1080-, and 1130-keV γ rays. His Bk^{246} decay scheme includes excited levels in Cm^{246} at 43, 142, 843, and 1130 keV.

In the present study, both 25-min Am^{246} and 1.8-day Bk^{246} have been studied with high-resolution Ge(Li) detectors and a Au-surface-barrier electron detector. The Am^{246} γ-ray spectrum was measured to 1900 keV. The highest energy γ ray detected was at 1738 keV and six higher energy states not previously reported have been proposed. Comparison of the Am^{246} and Bk^{246} decay modes has led to the assignment of a doublet level at 1126 keV and has provided some information concerning the configurations of lower levels.

II. EXPERIMENTAL: 25-MIN Am^{246}

A. Source Preparation

Pu^{246}, produced in underground nuclear explosions, was chemically separated from fission-product debris trapped in samples of fused earth. The fused material was pulverized and then dissolved in a boiling mixture of perchloric and hydrofluoric acids. The plutonium fraction was isolated by several cycles of coprecipitation with lanthanum fluoride and dissolution with boric and nitric acid solution. Two cycles of liquid-liquid extraction of the plutonium with di(2-ethylhexyl) orthophosphoric acid (HDEHP) in heptane from 4*M* nitric acid were followed by final purification with a standard anion resin column procedure.[2]

For Am^{246} electron studies, the plutonium fraction was similarly absorbed on an anion resin column. The Am^{246} was allowed to "grow in" for 60 min and was then rapidly eluted[2] with a small volume of concentrated hydrochloric acid. The eluate containing the Am^{246} was evaporated on a 0.5-mil Teflon film, resulting in a 3-mm-diam deposit that was essentially mass-free.

The Pu^{246}-Am^{246} equilibrium sources were also evaporated onto 0.5-mil Teflon films; these deposits, however, were ≈50 $\mu g/cm^2$ thick owing to the presence of Pu^{239} and a trace of iron.

B. Am^{246} Electron Spectra

The chemically separated Am^{246} sources described above were studied with a 2-mm×50-mm^2 Au-surface-barrier electron detector operated at 188°K (dry ice and acetone). A typical Am^{246} electron spectrum is shown in Fig. 1. Conversion-electron peaks lying above the β-ray distribution are identified with their associated transition energies (keV) and electron shell vacancies (*K*,*L*). In another measurement the electron distribution was recorded to 1.5 MeV; however, any additional conversion-electron lines that might have been present were too weak to be detected.

In a further electron study the intensity of the 800-keV *K*-conversion electron line was compared with the total Am^{246} β-ray intensity and with the 800-keV γ-ray

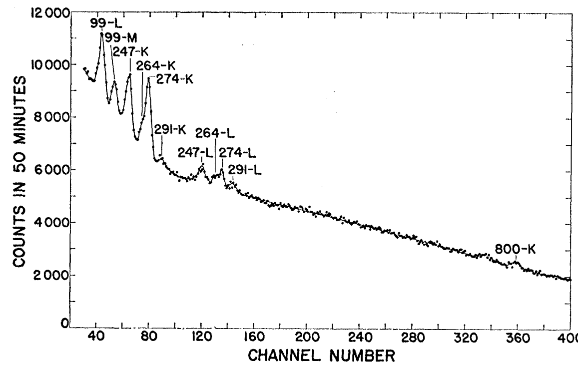

FIG. 1. Electron spectrum of chemically separated 25-minAm^{246}, measured with a 2-mm×50-mm^2 Au-surface-barrier detector. Electron lines are designated with their associated transition energy (keV) and electron shell vacancy.

intensity given in Table I. This crude measurement gave $4\pm3\times10^{-3}$ for the *K*-conversion coefficient of the 800-keV transition. Comparison of this value with the theoretical internal-conversion coefficients listed in Table II indicated that the multipolarity of this transition is *E*1. The coefficients listed in Table II were obtained by interpolation of the coefficients tabulated by Sliv and Band.[5]

On the assumption that the *E*1 multipolarity assignment for the 800-keV transition is correct, the *K*- and *L*-conversion coefficients associated with the other electron lines shown in Fig. 1 were calculated by comparing their intensities to the 800-keV *K*-conversion line which was now assigned its theoretical *K*-conversion coefficient (5.24×10^{-3}). These results are listed in Table I. The *K*-conversion coefficients of the γ transitions >800 keV, although listed in Table I, were actually calculated from a similar treatment of the Bk^{246} electron data which will be discussed later.

Analysis of the Am^{246} β-ray spectrum was not included in the present study since a detailed study of this spectrum using a magnetic spectrometer has been reported by Smith and co-workers.[2]

C. Am^{246} Gamma-Ray Spectra

The Am^{246} γ-ray spectrum was studied with both NaI(Tl) scintillation spectrometers and with a 2-mm ×1-cm^2 Ge(Li) detector. A typical spectrum taken with the latter is shown in Fig. 2. This spectrum represents a Pu^{246}-Am^{246} equilibrium source which contained ≈10^6 dis/min of Am^{246} at the start of the 1365-min counting period. All of the 180- and 224-keV peaks and a major portion of the *K* x rays are due to Pu^{246} decay. The remainder of the peaks are due to the Am^{246} decay.

Energy calibrations for Fig. 2 and all other γ-ray spectra measured in this work were based on Mn^{54},

[5] L. A. Sliv and I. M. Band, Leningrad Physico-Technical Institute Report, 1956 [English transl.: Reports 571CCKl and 581CCLl issued by Physics Department, University of Illinois, Urbana, Illinois (unpublished)].

TABLE I. Gamma-transition data for the beta decay of 25-min Am^{246}.

γ-ray energy (keV)	Relative photon intensity	K-conversion coefficient[a]	Assigned multipolarity	Estimated relative transition intensity	Observed in coincidence with L x rays	800-keV peak	≈1060-keV peak
235±4	≈0.2		...	≈0.7		+	
247±2	3.1	2.9±2.0	$M1$	10			+
264±4	≈0.2	≤3.8	$M1$	≈0.6			+
274±2	2.7	2.2±1.6	$M1$	7.3			+
291±2	≈0.3	1.5±1.2	$M1$	≈0.6			+
406±4	≈0.5	...	...	0.5			+
475±5	≤0.1	...	...	≤0.1		+	
651±4	≤0.5	...	...	≤0.5		+	
688±4	≤0.5	...	...	≤0.5		+	
720±4	≤1	...	...	≤1		+	
736±3	3.1	$\leq 10^{-2}$	$E1$	3.1	+		
755±4	≤1	...	...	≤1		+	
765±5	≤1	≤0.1	...	≤1		+	
800±2	77	5.24×10^{-3}	$E1$	77	+	+	
985±4	2.9	$\leq 8\times10^{-3}$	$E1$	2.9	+		
1035±3	44	$\leq 3\times10^{-3}$	$E1$	44	+		
1063±3	61	$\leq 3\times10^{-3}$	$E1$	61	+		
1078±2	100	$\leq 3\times10^{-3}$	$E1$	100	+ (weak)		
1083±4	≈7			≈7	+		
1126±3	2	$7\pm2\times10^{-3}$	$E2$	2			
1252±4	0.5			0.5			
1275±4	0.8			0.8			
1408±5	≤0.7			≤0.7			
1483±3	1.3			1.3			
1505±4	≤0.5			≤0.5			
1531±3	1.0			1.0			
1555±3	1.6			1.6			
1598±4	2.3			2.3			
1644±4	0.4			0.4			
1668±4	1.4			1.4			
1739±4	0.6			0.6			

[a] The K-conversion coefficients are based upon a presumed $E1$ assignment for the intense 800-keV transition with a value of 5.24×10^{-3} interpolated from the theoretical coefficients of Sliv and Band (Ref. 5).

Co^{60}, Sn^{113}, Sb^{124}, Cs^{137}, La^{140}, Ho^{166m}, and Bi^{207} γ-ray energy standards that included the range 80 to 1692 keV.

Figure 2 differs from the previously published spectrum of Stephens and co-workers[3] in that the present spectrum extends to 1.9 MeV. Their spectrum includes an 834-keV peak that is not resolved in Fig. 2 because of the smaller Ge(Li) detector with the consequent higher ratio of Compton-scattered to full-energy events.

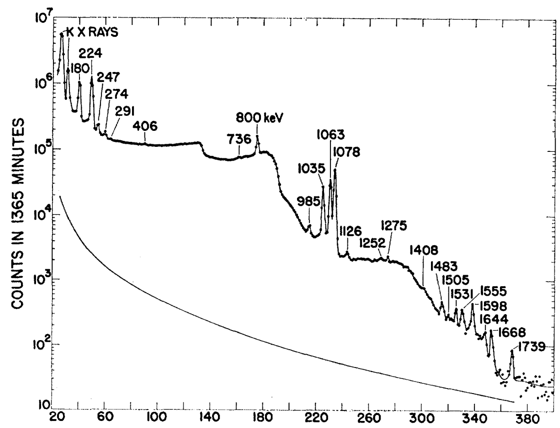

FIG. 2. Gamma-ray spectrum of a Pu^{246}-Am^{246} equilibrium source, measured with a 2-mm×1-cm^2 Ge(Li) detector. The lower curve gives the relative efficiency of the detector for full-energy peak detection. Most of the K x ray and all of the 181- and 224-keV peaks are due to the Pu^{246} decay.

The relative intensity of the 1083-keV photon listed in Table I was determined from a γ-ray spectrum measurement in which the energy scale of the 1100-keV

TABLE II. Theoretical internal-conversion coefficients[a] for γ transitions in curium.

Transition energy (keV)	Internal-conversion coefficient $E1$ α_K	$E1$ $\sum \alpha_L$	$E2$ α_K	$E2$ $\sum \alpha_L$	$M1$ α_K	$M1$ $\sum \alpha_L$
235	0.058	0.0140	0.115	0.30	2.23	0.48
247	0.052	0.0126	0.105	0.25	1.91	0.42
264	0.044	0.0108	0.096	0.19	1.57	0.34
274	0.042	0.0098	0.092	0.17	1.43	0.31
291	0.036	0.0084	0.082	0.13	1.19	0.26
736	0.006	0.0012	0.0169	0.0051	0.098	0.022
800	0.0052	0.0098	0.0148	0.0048	0.078	0.017
836	0.0048	0.00090	0.0136	0.0043	0.069	0.015
985	0.0036	0.00070	0.0130	0.0028	0.046	0.0090
1035	0.0034	0.00065	0.0097	0.0026	0.040	0.0076
1062	0.0032	0.00062	0.0091	0.0024	0.037	0.0070
1078	0.0031	0.00061	0.0090	0.0023	0.036	0.0067
1083	0.0031	0.00060	0.0089	0.0023	0.036	0.0065
1126	0.0029	0.00057	0.0083	0.0021	0.032	0.0057

[a] See Ref. 5.

region was expanded about 5 times over that shown in Fig. 2 with a biased amplifier.

A typical γ-ray spectrum taken with a Pu^{246}-Am^{246} equilibrium source located 10 cm from the crystal face of the 3-in.×3-in. NaI(Tl) scintillator unit is shown in Fig. 3. Regions B and C are the gate intervals for the γ-γ coincidence measurements shown in Fig. 4.

D. Am^{246} Coincidence Measurements

All coincidence measurements described in this work were made with a "slow" coincidence spectrometer with a resolving time $2\tau = 2\times10^{-7}$ sec. The γ-ray spectra were recorded with a 400-channel pulse-height analyzer. In all cases a 3-in.×3-in. NaI(Tl) scintillator unit covered with 1 cm of Lucite absorber was used as the "gate" detector and the 2-mm×1-cm^2 Ge(Li) unit served as the "analyzer" detector. Pu^{246}-Am^{246} equilibrium sources were interposed between the two detectors (180° coincidences) with the source 0.7 cm from the germanium crystal and ≤ 10 cm from the NaI(Tl) unit.

One series of γ-γ coincidence measurements is plotted in Fig. 4. Curve A is the singles spectrum measured with the germanium "analyzer" detector. Spectrum B is gated by γ-ray events in the energy interval 700 to 860 keV (see Fig. 3). The 180- and 224-keV peaks are due to Pu^{246} chance events, while the 247-, 264-, and 274-keV peaks are due to gates from Compton-scattered photons from the 1060-keV complex. The remaining γ-ray peaks are due to true coincidence relations with the 700- to 860-keV gate interval. Relative intensity measurements of the coincident γ rays indicated that a very-low intensity $\approx$800-keV γ ray is in coincidence with a high-intensity 800-keV γ ray.

Spectrum C is gated by γ-ray events in the energy range 900–1150 keV. Here again the 180-keV and most,

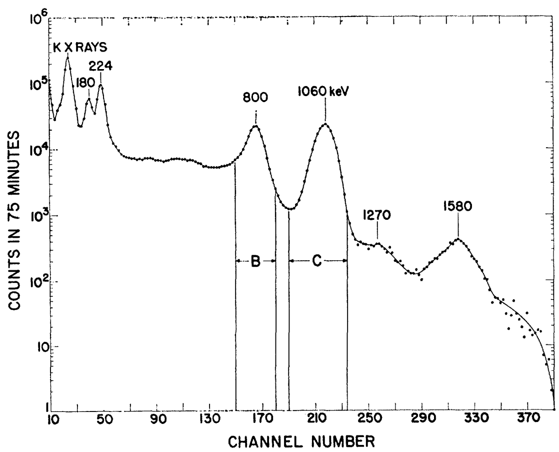

FIG. 3. Gamma-ray spectrum of a Pu^{246}-Am^{246} equilibrium source measured with a 3-in.×3-in. NaI(Tl) scintillation spectrometer. Source-crystal distance = 10 cm. Regions B and C are the gate intervals for γ-γ coincidence measurements shown in Fig. 4.

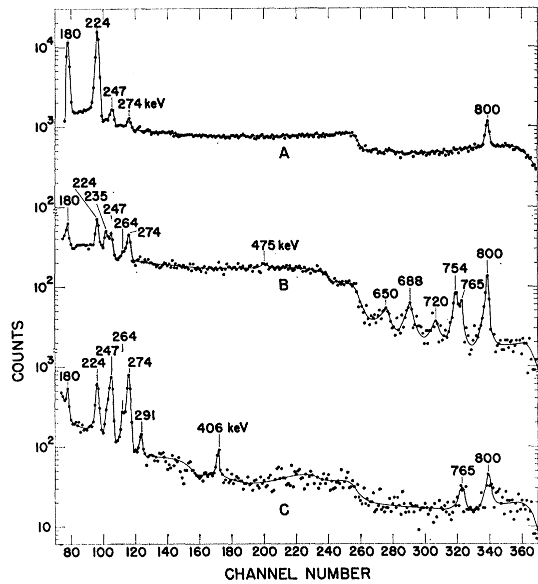

FIG. 4. Gamma-gamma coincidence spectra of a Pu^{246}-Am^{246} equilibrium source measured with a 2-mm×1-cm^2 Ge(Li) detector. Curve A shows the singles γ spectrum. Count length = 15 min. Curve B is the γ spectrum in coincidence with gate pulses from the 800-keV peak detected in the 3-in.×3-in. scintillator unit. Count length = 1500 min. Curve C is the γ spectrum in coincidence with gate pulses from the $\approx$1060-keV peak detected in the 3-in.×3-in unit. Count length = 2425 min.

if not all, of the 224-keV peaks are due to Pu^{246} chance events. The 765- and 800-keV prominences are presumed to be due to chance events and/or a small overlap of the "gate window" into the 800-keV photopeak distribution.

In another series of measurements, which is not shown, the γ-ray spectrum analyzed with the germanium detector was gated by L and K x rays which were detected in a $\frac{1}{4}$-in.×$1\frac{1}{2}$-in. NaI(Tl) crystal with a 5-mil beryllium window. The results of coincidence measurements are summarized in Table I.

III. EXPERIMENTAL: 1.8-DAY Bk^{246}

A. Source Preparation

Bk^{246} was produced by $Am^{243}(\alpha,n)$, by bombardment of 600 μg of Am^{243} with 45 μA h of 27-MeV α particles in the Los Alamos variable-energy cyclotron. Also present in the source was roughly twice as much 5-day Bk^{245} activity, formed by the $Am^{243}(\alpha,2n)$ reaction.

The berkelium fraction was chemically separated from fission products, α-induced activities from the target mount and target heavy elements (Am^{243},Np^{239}) by coprecipitation with lanthanum fluoride followed by oxidation-reduction cycles involving liquid-liquid extractions with HDEHP in heptane from 10M nitric-acid solutions, as described by Peppard *et al.*[6] The berkelium

[6] D. F. Peppard, G. W. Mason, J. L. Maier, and W. J. Driscoll, J. Inorg. Nucl. Chem. 4, 344 (1957).

and cerium activities were then separated from one another by elution from a cation-resin column with 20% ethanol-saturated hydrochloric acid solution.

The berkelium source was prepared by evaporating the final eluate onto 0.5-mil Teflon film as a 4-mm-diam spot. The source thickness was estimated to be ≈ 200 $\mu g/cm^2$ due to a trace of salts in the eluate. Source intensity at the time of the first count was $\approx 1.5\times 10^5$ dis/min.

B. Conversion-Electron Spectrum

The Bk^{246} conversion-electron spectrum measured with the 2-mm$\times$50-mm^2 Au-surface-barrier detector operated at 188°K is shown in Fig. 5. The spectrum below 500-keV electron energy is not shown since no detectable Bk^{246} lines were observed in this region. The electron lines in Fig. 5 are labeled with their associated transition energies (keV) and electron-shell vacancies. The electron lines are skewed on the high-energy side due to a small gain shift during the counting period. A measurement of the 5-day Bk^{245} electron spectrum after the 1.8-day Bk^{246} had decayed away showed that the highest energy electron line associated with Bk^{245} occurred at an energy of ≈ 400 keV.

K- and L-conversion coefficients for Bk^{246} transitions were calculated by comparing the relative intensities of the electron lines shown in Fig. 5. As previously discussed in the Am^{246} electron data, the 800-keV $E1$ transition was assigned a K-conversion coefficient $=5.24\times 10^{-3}$ and then conversion coefficients associated with the other Bk^{246} electron lines shown in Fig. 5 were calculated by comparing their intensities to that of the 800-K line and to the γ-ray intensities. These data are presented in Table III. Multipolarity assignments are suggested by comparison of the measured coefficients with the theoretical coefficients[5] listed in Table II.

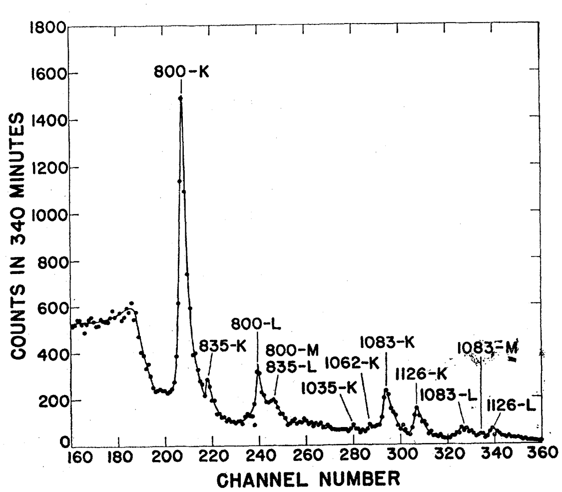

FIG. 5. Conversion-electron spectrum of Bk^{246} measured with the 2-mm$\times$50-mm^2 Au-surface-barrier detector. Electron lines are designated with their associated transition energy (keV) and electron shell vacancy.

C. Bk^{246} Gamma-Ray Spectrum

A $Bk^{245,246}$ γ-ray singles spectrum measured with a 5-mm$\times$6-cm^2 Ge(Li) detector is shown in Fig. 6. The peaks ≥ 735 keV are associated with the electron-capture decay of Bk^{246} while all peaks below are associated with the electron-capture decay of Bk^{245}. The spectrum was measured to 1300 keV and no γ rays above 1126 were detected. If γ rays with energies >1126 do exist, their intensities must be ≤ 0.05 that of the 1126-keV γ ray. Four prominent sum peaks, due to curium K x rays summing with themselves and with strong γ rays, are labeled. The Bk^{246} γ-ray data are presented in Table III. The 1078-keV γ ray could not be resolved sufficiently from the 1083-keV γ ray to permit a measurement of its intensity. However, since the 1035-keV γ rays observed in decay of Am^{246} and Bk^{246} represented the same transitions in Cm^{246}, and the 1078-keV γ ray originated at the same level, its intensity in Bk^{246}

TABLE III. Gamma-transition data for the electron-capture decay of 1.8-day Bk^{246}.

γ-ray energy (keV)	Relative photon intensity	K-conversion coefficient[a]	Assigned multi-polarity	Estimated relative transition intensity
735	3.5	$\leq 10^{-2}$	$E1$	3.5
800	100.0	5.24×10^{-3} ($K/L\approx 5.2$)	$E1$	100.0
835	6.0	$4\pm 2\times 10^{-3}$	$E1$	6.0
985	≈ 0.6	$\leq 8\times 10^{-3}$	$E1$	≈ 0.6
1035	2.4	$\leq 3\times 10^{-3}$	$E1$	2.4
1063	5.6	$\leq 3\times 10^{-3}$	$E1$	5.6
1078	4.8	$\leq 3\times 10^{-3}$	$E1$	4.8
1083 (3^-)	1.0	$\leq 3\times 10^{-3}$	$E1$	1.0
1083 (2^+)	9.0	$8\pm 3\times 10^{-3}$ ($K/L\approx 3.9$)	$E2$	9.0
1126 (2^+)	7.3	$7\pm 2\times 10^{-3}$ ($K/L\approx 3.5$)	$E2$	7.3

[a] The K-conversion coefficients are based upon a presumed $E1$ multipole assignment for the intense 800-keV transition.

decay was computed from the 1078/1035 intensity ratio in Am^{246} decay, in which the 1083-keV transition is too weak to interfere significantly.

Although γ-γ coincidences were measured using two NaI(Tl) scintillator units, the results added no additional information concerning Cm^{246} transitions that had not already been determined from the Am^{246} coincidence measurements.

An estimate of the Bk^{246} electron-capture decay energy was provided by a γ–x-ray coincidence measurement in which the Bk^{246} x-ray region was gated by the complex 1090-keV peak that includes γ rays that de-excite the 1078-, 1106-, and 1126-keV Cm^{246} levels. The (L x-ray)/(K x-ray) intensity ratio was found to be 2.9. This value corrected for L and K fluoresence yields ($\bar{\omega}_L\approx 0.5$ and $\bar{\omega}_K=0.96$) and for L vacancies due to internal conversion in Cm^{246} yielded an electron-capture decay energy to the 1100-keV complex of ≈ 200 keV. This leads to a total electron-capture decay energy of ≈ 1300 keV for 1.8-day Bk^{246}.

Observation of the 800-keV γ ray for 10 days with the 3-in.×3-in. NaI(Tl) scintillator gave a 1.83±0.15-day half-life, in agreement with the 1.8-day half-life previously determined by Hulet[7] and by Chetham-Strode.[4]

IV. DISCUSSION

Decay schemes consistent with the measurements described above are shown in Fig. 7. In general, the assignments of energies and of spins and parities of the Cm^{246} levels up to 1369 keV agree with those made by Stephens *et al.*[3] from their study of Am^{246} decay. Since, however, the present work established the existence of higher levels from Am^{246} decay and provided additional information on the levels ≤ 1126 keV from Bk^{246} electron-capture decay, the assignments will be treated in more detail. Each of the levels ≤ 1126 keV assigned to Cm^{246} from Am^{246} decay was observed also in Bk^{246} decay, although relative populations differed.

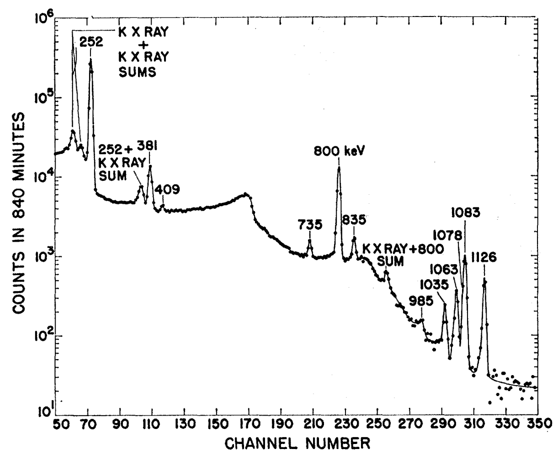

FIG. 6. Gamma-ray spectrum of $Bk^{245,246}$ measured with a 5-mm×6-cm^2 Ge(Li) detector. The 252-, 381-, and 409-keV peaks are due to Bk^{245} decay.

The Cm^{246} levels at 43 and 142 keV are the expected 2^+ and 4^+ members of the ground-state rotational band, previously observed both in Cf^{250} α decay,[8] and in Am^{246} β decay.[3] Higher members of the ground-state band were not observed.

Establishment of a 843-keV level in Cm^{246} was based on the following observations with Am^{246} sources.

(1) A strong 800-keV γ ray is observed in coincidence with L x rays but not with K x rays. This same γ ray is observed in Bk^{246} electron-capture decay; however, coincidence measurements involving K and L x-ray "gating" are complicated by the K- and L-electron capture to the Cm^{246} levels.

[7] E. K. Hulet, University of California Radiation Laboratory Report UCRL-2283, 1953 (unpublished).

[8] F. Asaro, S. G. Thompson, F. S. Stevens, Jr., and I. Perlman, University of California Radiation Laboratory Report UCRL-8369, 1958 (unpublished).

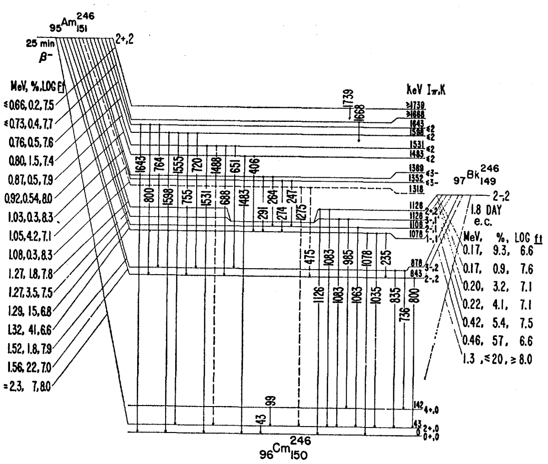

FIG. 7. Decay schemes for 25-min Am^{246} and 1.8-day Bk^{246}. Levels and transitions based upon scanty information are shown dashed.

(2) When β events >1.5 MeV were used as gates in a β-γ coincidence experiment, the resultant γ spectrum contained only a strong peak at 800 keV and weak peaks at 735 and 835 keV. The total β-disintegration energy of Am^{246} has been measured to be 2.4 MeV.[2]

(3) (L x-ray–L x-ray) coincidences were much less intense than (L x-ray–800-keV) coincidences. This result implies that the 800-keV transition populates the 43-keV level but not the 142-keV level.

The absence of 843-keV or 700-keV γ rays shows that the 843-keV level decays only to the 2^+ member of the ground-state band, and thus its spin and parity are most plausibly 2^- or 0^+. The K-conversion coefficient of the 800-keV transition is $4\pm3\times10^{-3}$; even within this rather large error limit, the only reasonable multipolarity is $E1$, and thus the $I^\pi=2^-$ assignment is indicated. Elimination of the 0^+ alternative is supported also by the absence of conversion electrons corresponding to the 843-keV ($0^+\rightarrow0^+$) monopole transition.

A level at 878 keV that is weakly populated by both Am^{246} and Bk^{246} is established from the results of the β-γ coincidence measurements just described under Observation 2 (735- and 835-keV γ rays are in coincidence with Am^{246} β events >1.5 MeV). Both of these γ rays are in coincidence with L x rays from Am^{246} decay. Although the 835-keV peak was not observed in the Am^{246} singles γ-ray spectrum (Fig. 2) due to the large underlying Compton distribution, it did stand out clearly in the Bk^{246} γ-ray spectrum (Fig. 6). The 735/835 relative intensity ratio taken from the Bk^{246} data (Table IV) was found to be 0.58. Stephens *et al.*[3] using a larger Ge(Li) detector, were able to measure this ratio 735/835=0.54 for Am^{246}. The K-conversion coefficients of the 735- and 835-keV transitions are consistent with $E1$ multipolarity assignments (Table III). Hence, the 878-keV state must have 3^- spin and parity.

The 843- and 878-keV levels on the basis of their

TABLE IV. Relative transition intensities for de-excitation of Cm^{246} levels.

Initial state (keV)	Final states (keV)	Relative transition intensities
878	142/43	0.58/1
1078	843/43/0	0.007/0.44/1
1126(3−)	142/43	0.70/1
1126(2+)	43/0	1/0.81
1352	1106/1078	1/0.73
1369	1106/1078	1/1
1483	1078/0	0.38/1
1531	878/843/0	$\approx$1/$\approx$0.5/1
1598	878/843/43/0	$\approx$0.43/$\approx$0.43/0.70/1
1643	878/843/43/0	$\approx$1/$\leq$1/ <2/0.4

$I^{\pi}=2^-$ and 3^- assignments and their energy spacing are presumed to be the first two members of a $K^{\pi}=2^-$ rotational band based at 843 keV. Stephens *et al.*[3] have discussed this band and emphasize that it must contain a significant amount of collective character to lie so low in Cm^{246}. The collective nature of this band is further indicated in the present work by the observation that both 25-min Am^{246} and 1.8-day Bk^{246} populate the 843-keV level with log*ft* values ≤ 7.0, although the inferred ground-state configurations of these two nuclei have no Nilsson orbitals[9,10] in common as discussed later in this section. Am^{246} and Bk^{246} would not be expected to decay with such small log*ft* values to any of the Cm^{246} $K^{\pi}=2^-$ pure two-quasiparticle states calculated on the basis of the pairing correlation model (Soloviev and Siklos).[11] These authors, however, do construct a collective $K^{\pi}=2^-$ band at ≈ 1.1 MeV that is an admixture of 3 different two quasiparticle configurations, and the 843-keV state may contain a considerable amplitude of this configuration.

The 1035-, 1063-, and 1078-keV γ transitions occur in both Am^{246} and Bk^{246} decay. The (L x-ray–1035-keV) and (L x-ray–1063-keV) coincidence rates measured with Am^{246} sources are consistent with the assumption that both of these γ rays populate the 43-keV level. The reduction in intensity of the 1078-keV peak in γ spectra gated by L x rays compared with singles γ-ray spectra, plus the 43-keV spacing (1078–1035), indicates that the 1078-keV γ ray represents a ground-state transition from a 1078-keV Cm^{246} level that also de-excites by the 1035-keV transition to the 43-keV state. Further evidence of a 1078-keV level is provided by the (800-keV γ) coincidence data with Am^{246} sources. The 235-keV γ ray in the coincidence spectrum (Fig. 4B) represents the energy difference between the 1078- and 843-keV levels. The fact that it was not observed in the Bk^{246} coincidence measurements is not surprising since the 1078-keV level is so weakly populated by Bk^{246}. The strong 1063-keV γ transition populates the 43-keV level, thus indicating a level at 1106 keV. The rather precise γ-ray energy measurements and coincidence data rule out any other γ-transitions de-exciting the 1106-keV level. The 1035-, 1063, and 1078-keV transitions all have $E1$ multipolarity (Table III); therefore, the 1078-keV level must be a $I^{\pi}=1^-$ state and the 1106-keV level must be 2^-.

The (L x-ray–985-keV) coincidence rate measured with the Am^{246} source is consistent with the assumption that the 985-keV γ transition populates the 142-keV level. (L x-ray–γ) coincidences also indicate that the 43-keV level is populated by a 1083-keV γ transition although the 1083-keV γ ray is very weak in the Am^{246} γ-ray singles spectrum. In addition, there was observed in the Am^{246} singles γ spectrum a weak 1126-keV peak which did not appear in the (L x-ray–γ) coincidence measurements. These observations, all with the Am^{246} sources, pointed to a single 2^+ level at 1126 keV, decaying to the 0^+, 2^+, and 4^+ members of the ground-state band with the relative intensities 0.4/1/0.3. Examination of the Bk^{246} γ spectrum, however, brought out a complicating feature: although the same three γ transitions were observed, their relative intensities were 0.73/1/0.06. This striking difference in intensity ratios implied the existence of two very close-lying Cm^{246} levels near 1126 keV.

The de-excitation modes of these two levels were disentangled by examination and comparison of the γ-ray relative intensity data from both Am^{246} and Bk^{246} together with the conversion electron data of Bk^{246}. In Bk^{246} a poorly resolved but discernible component of the 1078-keV γ ray contributes to the intensity of the 1083-keV peak. Resolution of this 1078-keV component has been discussed in Sec. IIIC. On the basis of model considerations it was assumed that the 1126-keV γ transition proceeds almost entirely from only one of the 1126-keV levels (which will be designated as 1126A), and essentially all of the 985-keV γ transition proceeds from the other (1126B). Allocation of the total 1083-keV γ intensity between the two (1126$\rightarrow$43)-keV transitions was based on solution of two simultaneous equations:

$$a\left[\frac{I_{1126}}{I_{1083}}\right]_{Am^{246}}+b\left[\frac{I_{985}}{I_{1083}}\right]_{Am^{246}}=1$$

and

$$a\left[\frac{I_{1126}}{I_{1083}}\right]_{Bk^{246}}+b\left[\frac{I_{985}}{I_{1083}}\right]_{Bk^{246}}=1\,.$$

The relative-intensity ratios in the four brackets are taken from Tables I and III. a is the relative intensity ratio of $1083\gamma/1126\gamma$ from level 1126A and b is the relative intensity ratio $1083\gamma/985\gamma$ from level 1126B. Solution of these equations establishes that $a=1.25$ and $b=1.5$.

With the decay modes of the two 1126-keV levels worked out above, the γ and conversion-electron

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[10] B. R. Mottelson and S. G. Nilsson, Phys. Rev. **99**, 1615 (1955).
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intensity data can be used to infer probable spins and parities. The conversion-electron data indicate $E1$ multipolarity for the 985-keV transition, which has been shown to proceed from level 1126B to the 4^+ member of the ground-state band. Level 1126B also de-excites by a 1083-keV transition to the 2^+ member of the ground band and therefore its spin and parity must be 3^-. The other level, 1126A, de-excites by 1083- and 1126-keV transitions to the 2^+ and 0^+ members of the ground band. The Bk^{246} conversion electron data indicate that these two transitions have $E2$ multipolarity. Level 1126A is therefore assigned as a 2^+ state.

Soloviev and Siklos[11] construct a $K^\pi=2^+$ collective state in Cm^{246} at 0.8 MeV which contains contributions from three different two-quasiparticle configurations, $nn[622]\uparrow-[620]\uparrow$, $nn[624]\downarrow-[622]\downarrow$ and $nn[622]\downarrow-[620]\uparrow$. However, two Nilsson orbitals which most plausibly make up the Am^{246} ground state, $pn[523]\downarrow-[734]\uparrow$ are not represented in this quasiparticle state and according to Gallagher and Soloviev[12] population of such a state by Am^{246} should be completely forbidden (change of two quasiparticles). Since 25-min Am^{246} decays to the 2^+ 1126-keV level in Cm^{246} with $\log ft=7.5$, the implication is that the Am^{246} ground state shown is admixed with other Nilsson states. Similar 2^+ states have been observed and discussed[13,14] in studies of Pu^{240} and Cf^{250} level structure.

The negative-parity states at 1078, 1106, and 1126 keV have the spin sequence 1, 2, 3. Stephens *et al.*[3] have discussed this triad and have suggested that these states comprise a $K^\pi=1^-$ band based at 1078 keV with the quasiparticle configuration $(nn,\ \frac{7}{2}^+[624]-\frac{9}{2}^-[734])_{1^-}$. Soloviev and Siklos[11] calculate the position of this band at 1.1 MeV. Although 25-min Am^{246} should decay to the intrinsic state by a first forbidden, unhindered β transition, it will later be seen that population of the intrinsic state by Bk^{246} would involve a $\Delta\Omega=3$ transition with an expected $\log ft>12$. That the actual $\log ft$ for this transition is ≤ 7.9 suggests that this band contains admixture from other states. The possibility of this band representing an octupole vibrational band is precluded by the 1, 2, 3 spin sequence, since octupole bands have a 1, 3, $5\cdots$ progression.

The Cm^{246} level at 1318 keV is shown dashed in Fig. 7 since the data supporting its position are somewhat scanty. It is proposed on the basis of energy matches: a 1275-keV peak in the Am^{246} γ singles spectrum (Fig. 2) and a 475-keV peak in the coincidence spectrum gated by 800-keV γ rays. Cm^{246} levels above 1126 keV are not measurably populated by 1.8-day Bk^{246} decay.

A close-lying pair of Cm^{246} levels at 1352 and 1369 keV is established on the basis of γ-γ coincidence spectra gated by the 1060-keV γ-ray complex and on rather precise energy and intensity measurements of the Am^{246} γ rays. The only intense γ rays in the complex 1060-keV γ peak [measured with NaI(Tl)] are the 1035-, 1063-, and 1078-keV peaks representing de-excitation of the 1078- and 1106-keV levels. The γ-ray energy measurements and the Am^{246} conversion-electron data indicate that the 1352-keV state de-excites by 247- and 274-keV $M1$ or $M1+E2$ transitions to the 1106- and 1078-keV levels. The 1369-keV state de-excites by 264- and 291-keV $M1$ or $M1+E2$ transitions also to the 1106- and 1078-keV states. The 1352- and 1369-keV levels are therefore established as negative-parity states.

Stephens *et al.*[3] have previously postulated that this pair forms a negative-parity band with $K^\pi=1^-$. The fact that these two levels do not de-excite directly to the ground-state band, however, suggests also a $K=2$ or 3 assignment for this pair, in which case $E1$ transitions to the ground band would be K forbidden. Soloviev and Siklos[11] have constructed a $K^\pi=2^-$ two-quasiparticle band at 1.4 MeV with the configuration $(nn,\ \frac{5}{2}^+[622]-\frac{9}{2}^-[734])_{2^-}$. As will become apparent after the Am^{246} spin and parity are discussed, beta decay from Am^{246} to this Cm^{246} state would be classified as first forbidden unhindered ($\log ft$ $6.0\rightarrow 7.5$).

Six levels ≥ 1483 keV are shown in Fig. 7. Although multipolarities of the transitions could not be determined due to lack of measurable conversion-electron lines, the levels are well established on the basis of γ-ray energy measurements and γ-γ coincidence studies with Pu^{246}-Am^{246} equilibrium sources. Measurement of the γ spectrum gated by the 800-keV group indicated that 650-, 688-, 720-, 754-, 765-, and 800-keV γ transitions populate the 843- and 878-keV levels in Cm^{246}. This information and the observation that a 491-keV γ transition populates either the 1078- or 1106-keV level were combined with the precise energy measurements of γ rays ≥ 1483 keV to form a consistent set of levels ≥ 1483 keV. (L x-ray–≥ 1483-keV) coincidences could not be measured due to lack of intensity. Levels are indicated at ≥ 1668 and ≥ 1739 keV solely since γ rays with these energies are seen in the Am^{246} γ-ray spectrum.

Spin assignments for the 1483-, 1531-, 1598-, and 1643-keV levels are limited to ≤ 2 since they apparently all de-excite at least partially to the 0^+ ground state.

Although the 291-keV γ transition is shown between the 1369- and 1078-keV levels, its placement between the 1643- and 1352-keV lines would also be consistent with the energy, intensity, and coincidence measurements. Placement of the 406-keV γ ray between the 1483- and 1078-keV levels is also nonunique. The coincidence and energy relations allow some 406-keV γ rays to result from de-excitation of the 1531-keV level ($1531\rightarrow 1126$); however, the intensity measurements favor the position shown. A portion of the strong 1598-keV transition can also result from de-excitation of the 1643-keV level to the 43-keV level.

Energies of the Am^{246} β transitions were calculated

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[13] M. E. Bunker, B. J. Dropesky, J. D. Knight, J. W. Starner, and B. Warren, Phys. Rev. **116**, 143 (1959).
[14] S. E. Vandenbosch, H. Diamond, R. K. Sjoblom, and P. R. Fields, Phys. Rev. **115**, 115 (1959).

by subtracting the appropriate Cm^{246} terminal level energy from the 2.41-MeV Am^{246} disintegration energy (Q_{β^-}) measured by Smith *et al.*[2] The β-transition intensities were obtained by assuming that 7% of the β transitions proceed to the ground-state band[2] and by allocating the remaining 93% on the basis of γ-transition intensities. The log*ft* values for the Am^{246} β transitions were determined from the Moszkowski nomograms.[15] The decay energy shown for Bk^{246}, ≈ 1300 keV, is based on the ≈ 200 keV electron-capture branches to the 1100-keV group. The decay energy estimated by Viola and Seaborg[16] is 1460 keV.

The $\leq 20\%$ electron-capture branch to the ground-state band was determined by comparing the γ-ray intensities from the ≥ 843-keV levels with the total number of disintegrations. The latter quantity was estimated by counting the Bk^{246} source in a NaI(Tl) well counter.

The electron-capture branches to the Cm^{246} levels ≥ 843 keV were obtained by assuming that 20% of the Bk^{246} electron-capture decays proceed to the ground-state band and by allocating the remaining 80% on the basis of γ-transition intensities.

Relative transition intensities for de-excitation of Cm^{246} levels are presented in Table IV. The intensities have not been converted to reduced probability ratios since it appears that considerable configuration mixing is occurring in the levels and in most cases final states involve different rotational bands.

With the establishment of I, π, and K assignments for the Cm^{246} levels up to 1126 keV the state assignments for 25-min Am^{246} and 1.8-day Bk^{246} can now be discussed.

Am^{246} β decays to 2^+, 1^-, 2^-, and 3^- states in Cm^{246} with log*ft* values ≤ 7.9; therefore, its spin must be $1 \leq I \leq 3$. If its spin and parity were 1^+ the β branching to the ground-state band would be expected to have log*ft* < 7 instead of 8. If $I^\pi = 1^-$ the log*ft* values to the 3^- levels at 878 and 1126 keV would probably be > 12 instead of ≈ 7.8. If I^π were 3^+ or 3^-, β population of the ground band would be almost negligible due to K forbiddenness ($\Delta K = 3$). A spin of 3 is also inconsistent with the log*ft* (6.6) for population of the 1^- state at 1078 keV. The most reasonable spin assignment for 25-min Am^{246} based upon the experimental data is 2; a unique parity assignment cannot be made. The log*ft* value (8.0) for the β branch to the ground band is perhaps a little low for the negative parity alternative. The configuration postulated by Stephens *et al.*[3] $(pn, \frac{5}{2}^-[523] - \frac{9}{2}^-[734])_{2^+}$ remains as the one most consistent with the present data.

The 1.8-day Bk^{246} also decays to 2^+, 1^-, 2^-, and 3^- states in Cm^{246} and here again the log*ft* values for the electron-capture branches to these states are consistent only with $I = 2$ and without a unique parity assignment.

In Bk^{246}, the lowest Nilsson orbital for the 97th proton is most likely $\frac{3}{2}^-[521]$ or possibly $\frac{7}{2}^+[633]$, and for the 149th neutron it should be $\frac{7}{2}^+[624]$. Coupling of the $[521]\uparrow$ proton with the $[624]\downarrow$ neutron according to the rules of Gallagher and Moszkowski[17] results in a spin and parity of 2^- with 5^- as an excited state. Combining the $[633]\uparrow$ proton with the $[624]\downarrow$ neutron would result in a 0^+ state. The experimental results favor the former, $(pn, \frac{3}{2}^-[521] - \frac{7}{2}^+[624])_{2^-}$.

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