PHYSICAL REVIEW C VOLUME 19, NUMBER 1 JANUARY 1979

Energy levels of ^{250}Cf populated in the β^- decay of ^{250}Bk

C. W. Reich, R. G. Helmer, and R. J. Gehrke
Idaho National Engineering Laboratory, EG&G Idaho, Inc., Idaho Falls, Idaho 83401
(Received 15 May 1978)

The level scheme of doubly even $^{250}_{98}$Cf$_{152}$ has been studied from the β^- decay of ^{250}Bk. γ-ray energy and intensity measurements were made using Ge(Li) and Si(Li) detectors. Analysis of γ-singles and γ-γ coincidence data has revealed the existence of ~ 46 γ-ray transitions. Approximately 40 of these, accounting for $\gtrsim 99.97\%$ of the observed γ-ray intensity, have been incorporated into a level scheme for ^{250}Cf consisting of 17 excited states with excitation energies up to 1695 keV. The following states, whose I^π values and energies (in keV) are well known from other experiments, are observed: the $0^+(0)$, $2^+(42.73)$, and $4^+(141.89)$ members of the ground-state band; the $2^-(871.56)$, $3^-(905.85)$, and $4^-(952.0)$ members of the $K^\pi = 2^-$ octupole band; and the $2^+(1031.85)$ and $3^+(1071.38)$ members of the γ-vibrational band. In addition, evidence is presented which permits the following I, K^π assignments to be made with reasonable confidence (the corresponding level energies—in keV—are given in parentheses): $1,1^-(1175.5)$; $2,2^+(1244.50)$; $2,0^+(1296.64)$; $2,2^+(1657.99)$; and $3,2^+(1695.2)$. The half-life of ^{250}Bk has been remeasured and a value of 192.7 ± 0.3 m obtained. The absolute intensities (in photons/100 ^{250}Bk β^- decays) of the prominent 989- and (1028 ± 1031)-keV γ rays have been measured using a 4π β-γ coincidence system and values of 45.0 ± 0.8 and 40.6 ± 0.7, respectively, have been obtained.

[RADIOACTIVITY ^{250}Bk from ^{254}Es α decay; measured $E\gamma$, $I\gamma$, γ-γ, $4\pi\beta$-γ, $T_{1/2}$; ^{250}Cf deduced levels, J, π, $\log ft$. Ge(Li) and Si(Li) detectors, chemical separation.]

I. INTRODUCTION

Until recently, relatively little information has been available on the level scheme of ^{250}Cf. As summarized in the Nuclear Data Sheets,[1] the ground-state band up through the $I^\pi = 6^+$ member and the 2^+ and 3^+ members of the γ-vibrational band are considered firmly established. This information was derived from studies of the β^- decay of ^{250}Bk,[2,3] the *EC* decay of the 2.1-h and 8.6-h isomers of ^{250}Es (Ref. 4) and the α decay of ^{254}Fm.[5]

Recently, information on the properties of a $K^\pi = 2^-$ octupole band and two-quasiparticle bands with K^π values ranging from 4^- through 6^- has been obtained from studies of the single-nucleon transfer reactions ^{249}Cf(d,p) and ^{249}Bk(α,t).[6] In particular, these studies established the existence of appreciable mixing between two-neutron and two-proton configurations with $K^\pi = 5^-$ and provided information concerning the two-quasiparticle makeup of the 2^- octupole band. Additional data on these same energy levels in ^{250}Cf have been obtained from a recent study[7] of the decay of the 8.6-h ($I^\pi = 6^+$) isomer of ^{250}Es.

With regard to the ^{250}Bk decay, in an early study[2] the half-life and Q_β value were measured, in addition to the energies and intensities of the more prominent β and γ transitions. Subsequently, the γ-ray spectrum of ^{250}Bk was measured[3] using a Ge(Li) spectrometer. From this study, a determination was made of the magnitude of the band-mixing parameter z_γ characterizing the mixing of the ground-state and the γ-vibrational bands. Some additional information on the ^{250}Cf levels observed in the ^{250}Bk decay has been given in an unpublished report.[8]

In this paper, the results of a study of the ^{250}Bk decay, carried out to provide a more complete picture of the ^{250}Cf energy-level structure, are presented. We have measured the γ-ray singles and γ-γ coincidence spectra, the ^{250}Bk half-life, and 4π β-γ coincidence relationships to obtain absolute intensity values (photons/decay) for the γ radiation. During the course of these measurements, a report appeared[9] describing the results of a study of the ^{250}Bk decay. The results of our study disagree in many significant respects with those given in Ref. 9.

II. EXPERIMENTAL METHODS AND RESULTS

A. Source preparation

The ^{250}Bk activity was obtained as the daughter activity from the α decay of an ~ 0.02-μg source of ^{254}Es ($T_{1/2} = 275.7$ d). The source was acquired through the auspices of the Transplutonium Program Committee and was provided by ORNL. It initially contained the following relative activity levels, as determined by α-particle pulse analysis at ORNL: 276-d ^{254}Es (87.2%), 20-d ^{253}Es (12.7%), and 20-h ^{255}Fm (0.07%). A period of ~1 year elapsed between the receipt of the source and the initiation of the measurements. The content of the impurity activities ^{253}Es and ^{255}Fm was thus negligible. This was verified by careful examination of the γ-ray spectrum, which failed to reveal evidence for even the more prominent γ rays from these two activities and their daughters.

For the study of the higher-energy (> 0.5-MeV) region of the ^{250}Bk γ-ray spectrum and for the γ-γ coincidence studies, a source containing ^{254}Es and ^{250}Bk in secular equilibrium was used. For the study of the lower-energy (< 0.5-MeV) portion of the spectrum and for the 4π β-γ coincidence measurements, where the presence of the ^{254}Es can markedly interfere, the ^{250}Bk was milked from the Es. This was accomplished by oxidation of the Bk to the +4 oxidation state using $10M$ HNO_3-$0.1M$ $NaBrO_3$ and extracting into an equal volume of $0.1M$ HDEHP in heptane. Possible traces of entrained Es were eliminated by washing the HDEHP once with an equal volume of fresh $10M$ HNO_3-$0.1M$ $NaBrO_3$. The Bk was then back-extracted into $6M$ HNO_3 containing several drops of 30% H_2O_2. The Bk source was made relatively massless using successively anion-exchange and cation-exchange techniques.

B. Singles γ-ray measurements

The γ-ray singles spectra were measured on three separate 4096-channel Ge(Li) detector systems, each of which had an energy resolution of $\lesssim 2$ keV at 1 MeV. A typical γ-ray spectrum of the chemically purified ^{250}Bk source, emphasizing the energy region below ~1.1 MeV, is shown in Fig. 1. Because of the relatively short half-life (~3.2 h) of ^{250}Bk, four chemically purified sources were required to produce this spectrum, which represents ~24 h of counting. The high-energy portion ($E \gtrsim 1$ MeV) of the γ-ray spectrum from a ^{254}Es + ^{250}Bk source in secular equilibrium is shown in Fig. 2. A longer counting time (~90 h) was employed in order to increase the statistical quality of the data for the weak γ rays which occur in this region.

The energies of the more intense ^{250}Bk lines were determined from spectra containing these lines together with those from suitable calibration sources emitting γ rays whose energies are precisely known.[10-12] These measurements included two spectra calibrated above 1.1 MeV with sources of ^{182}Ta and ^{207}Bi, three spectra calibrated from 0.8–1.1 MeV with sources of ^{110}Ag^m and ^{207}Bi, and two spectra calibrated for the 99 and 160-keV γ rays with sources of ^{57}Co, ^{109}Cd, ^{139}Ce, ^{153}Gd, ^{203}Hg, ^{210}Pb, and ^{241}Am, in different combinations. In order to obtain a more precise value for the

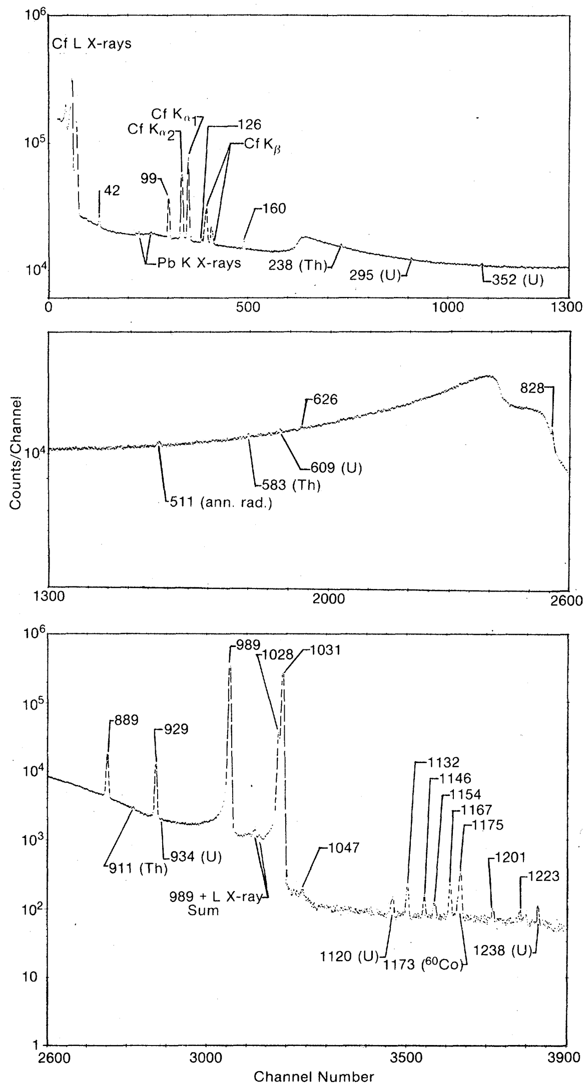

FIG. 1. Singles γ-ray spectrum of a chemically purified ^{250}Bk source, measured using a 55-cm^3 true-coaxial Ge(Li) detector at a source-detector distance of 3 cm. Sum peaks and peaks interpreted as background lines are labeled below the spectrum. The symbols U and Th, respectively, indicate that the associated peaks arise from the natural uranium and thorium backgrounds.

energy of the 42-keV γ ray, a separate calibration spectrum was measured using a 30 mm^2 × 3 mm Si(Li) detector.[13] With the energies of these prominent ^{250}Bk lines thus determined, these γ rays were then used as secondary standards to determine the energies of the weaker lines.

The analysis of the γ-ray spectra to obtain peak positions and areas was carried out using the Gauss V program.[14] Corrections to the peak-position values for nonlinearities in the detector-amplifier-analyzer system[10,11] were made. A $1/\sigma^2$-weighted average of the results of the

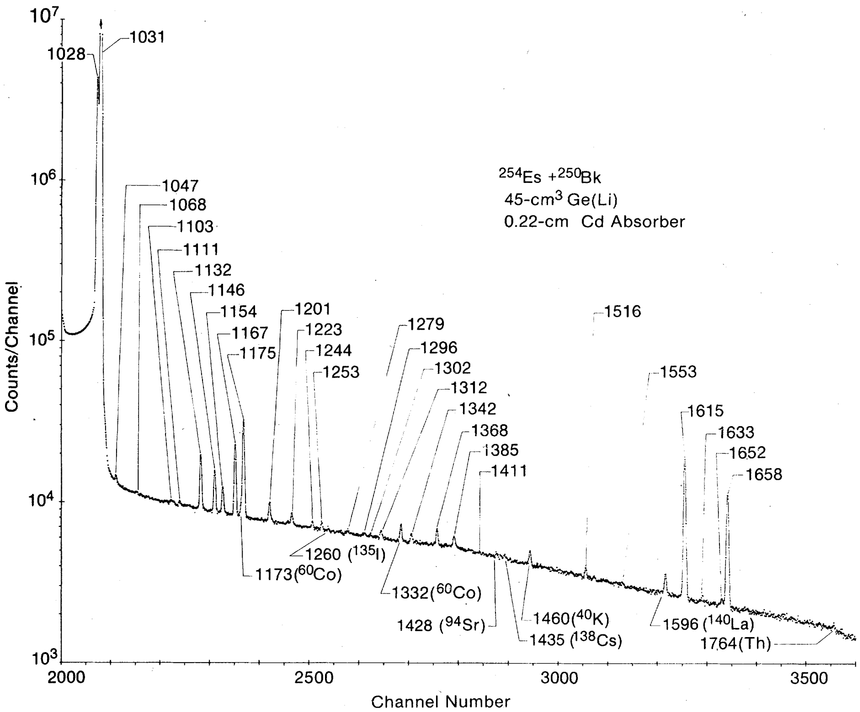

FIG. 2. High-energy region of the γ-ray spectrum of a ^{254}Es + ^{250}Bk source in secular equilibrium. The source-detector distance was 3 cm; and an ~ 0.22-cm thickness of Cd was interposed to reduce the effects of coincidence summing of these γ rays with the low-energy (< 0.2-MeV) radiation. The background lines are labeled as described in the caption to Fig. 1. The isotopic assignments of several of the weak peaks which can be associated with the decay of specific fission-product activities from the spontaneous fission of the ^{250}Cf daughter are also given.

analysis of a number of spectra (typically four) was made to provide a "best" set of energies for the ^{250}Bk γ rays. The uncertainties in these energy values were obtained by combining in quadrature those of the weighted averages with a reference error (13 ppm below 350 keV and 20 ppm above 350 keV).[11] Similarly, the relative γ-ray intensity values were determined from a weighted average of the results of the analysis of several spectra. The uncertainties resulting from this procedure represent only those of the respective peak areas. These were combined with the uncertainty in the efficiency vs energy curve to produce the overall uncertainties. The following uncertainty in the efficiency vs energy curve was used: <100 keV, 5%, 100–250 keV, 3%, and >250 keV, 1.5%.

The γ-ray energy and intensity data are summarized in Table I. Several additional weak γ rays are observed in the region above ~1 MeV which can be associated with the decay of specific fission-product activities, arising from the spontaneous-fission decay of the ^{250}Cf daughter in the sample. γ ray peaks associated with the decay of ^{135}I, ^{94}Sr, ^{138}Cs, and ^{140}La are labeled in Fig. 2. In addition, assignment of peaks at ~1525 keV to the decay of ^{146}Pr and ~1546, 2397, and 2542 keV to ^{142}La can tentatively be made. It should be borne in mind that some of the weaker of the γ rays in Table I not placed in the ^{250}Bk decay scheme may be associated with the decay of other fission-product activities.

C. Half-life measurement

The half-life of ^{250}Bk was measured using a 4π β-γ coincidence apparatus which employs a 4π gas-flow proportional chamber to detect the electrons and a 7.6×7.6 cm NaI(Tl) detector for the γ rays. Following the preamplifier and fast discriminator of each of these detectors are two parallel systems for pulse processing. The first system is a conventional 4π β-γ coincidence system with fixed pulse widths (~4 μs) for both β^- and γ channels. In this system, there is a constant dead time associated with each event. The second system is a new design developed especially for sources having high (> 10^5/s) disintegration rates. In this system the pulse widths are kept at a minimum and the associated dead times are measured. This is done with a gated internal 8 MHz clock.

The ^{250}Bk activity was followed for over twenty half-lives, counting the source for preset times (600 s) alternately with the fixed-pulse-width and the variable-pulse-width systems. The time between the end of one count and the start of the next was 300 s. Dead-time effects and background were taken into account, yielding corrected values for N_β, N_γ, and N_c (the β-chamber, γ-detector,

TABLE I. Summary of the energy and intensity data on the photons associated with the ^{250}Bk decay. Quantities in parentheses represent the uncertainties in the least significant figure (or figures) in the associated values. Quantities in square brackets represent tentative assignments.

γ-ray energy (keV)	γ-ray intensity[a]	Assignment	γ-ray energy (keV)	γ-ray intensity[a]	Assignment
...	...	*L* x rays	1103.33(10)	0.0020(3)	[1244 → 141]
42.740(15)	0.084(6)	42 → 0	1111.50(10)	0.0024(2)	[1253 → 141]
99.166(9)	0.285(15)	141 → 42	1132.804(30)	0.0430(22)	1175 → 42
109.84(1)	0.654(20)	Cf $K\alpha_2$	1146.674(30)	0.0280(14)	1189 → 42
115.03(1)	1.02(3)	Cf $K\alpha_1$	1154.765(30)	0.0159(8)	1296 → 141
119.4(3)	0.0015(5)[d]	1071 → 952	1167.247(31)	0.0614(31)	1209 → 42
126.01(3)	0.0140(12)	1031 → 905	1175.50(3)[c,f]	{0.078(5)[g]	1175 → 0
~129[c]	0.398(19)	Cf $K\beta_1'$		{0.015(3)	[1218 → 42]
~134[c]	0.152(14)	Cf $K\beta_2'$	1201.791(33)	0.0105(6)	1244 → 42
160.259(41)	0.0633(44)	1031 → 871	1223.922(36)	0.0062(4)	b
165.44(15)[d]	0.0030(4)[d]	1071 → 905	1244.416(71)	0.0029(2)	1244 → 0
199.72(20)[d]	0.0024(3)[d]	1071 → 871	1253.820(66)	0.0037(3)	1296 → 42
303.95(20)[d]	0.0051(5)[d]	1175 → 871	1279.21(23)	0.0018(2)	b
555.22(10)[d]	0.014(1)[d,e]	b	1296.54(13)	0.0015(2)	1296 → 0
586.43(7)	0.014(1)	1658 → 1071	1302.90(22)	0.0010(2)	b
626.11(4)	0.052(3)	1658 → 1031	1312.95(6)	0.0033(2)	b
786.26(14)	0.011(2)	1658 → 871	1342.87(8)	0.0042(3)	1385 → 42
828.812(25)	0.260(14)	871 → 42	1368.613(54)	0.0070(5)	1411 → 42
889.956(22)	3.40(5)	1031 → 141	1385.420(57)	0.0045(3)	1385 → 0
929.468(22)	2.74(4)	1071 → 141	1411.60(39)	0.0013(3)	[1411 → 0]
989.125(21)	100	1031 → 42	1516.22(7)	0.0027(2)	1658 → 141
1028.654(25)	10.9(3)	1071 → 42	1553.37(18)	0.0012(3)	1695 → 141
1031.852(21)	79.1(12)	1031 → 0	1615.295(40)	0.102(5)	1658 → 42
1047.514(53)	0.00503(36)	1189 → 141	1633.18(24)	0.0012(2)	b
1068.27(17)	0.0013(2)	[1209 → 141]	1652.40(10)	0.0022(2)	1695 → 42
1098.36(16)	0.0012(2)	b	1658.002(38)	0.0606(31)	1658 → 0

[a] To convert these relative values to absolute values (in % per decay) multiply by the factor 0.450 ± 0.008.

[b] Transition not placed in the proposed decay scheme.

[c] Observed peak contains more than one component.

[d] Energy and intensity determined from coincidence spectrum.

[e] Intensity obtained [relative to $I_\gamma(160)$] from the coincidence spectrum. If this transition directly feeds the 905-keV, 3^- or the 952-keV, 4^- state, this value must be further corrected for the branching of these states (see Sec. III of the text for further discussion).

[f] In addition to two suggested γ rays from the ^{250}Bk decay, this peak contains a weak (~8%) contribution from the 1173.2-keV γ ray from ^{60}Co, present in the background. The listed energy value may be affected by the presence of this γ ray.

[g] Intensity of these two components obtained from comparison of singles and coincidence γ-ray spectra.

and coincidence counting rates, respectively). The level of the residual 13.1-y ^{250}Cf activity in the source was determined four days after the last half-life count was made. The half-life data were analyzed using a nonlinear least-squares fit with one exponential component. The data beyond ~32-h decay were not included in these fits because of their sensitivity to uncertainties in the background subtraction.

Half-life values were extracted from the β^- chamber data for both pulse-processing systems and from the computed disintegration-rate (N_0) data from the fixed dead-time system. The resulting three values were 193.15 ± 0.18, 192.67 ± 0.06, and 192.70 ± 0.10 m. These three sets of data included from 42 to 62 data points spanning 21 to 31 hours, and the reduced χ^2 values for the three fits were 0.5, 1.1, and 2.9, respectively.

The $1/\sigma^2$-weighted average of these three values is 192.71 ± 0.09 m. In addition to this statistical error, we assign a systematic error of 0.2 m, which is intended to include possible errors from the background subtraction and any rate-dependent β^- chamber effects. This yields the final result for the ^{250}Bk half-life:

$$T_{1/2}(^{250}\mathrm{Bk}) = 192.71 \pm 0.29 \text{ m} .$$

Our value for the ^{250}Bk half-life is in good agreement with the previously reported[2] value, 193.3 ± 0.3 m.

D. Absolute γ-ray intensities

We have measured the absolute intensities (photons/100 decays) of the 989- and the (1028+1031)-keV γ rays. This was done using 4π β-γ coincidence-counting techniques (see, e.g., Ref. 15). The conventional fixed-dead-time system was used to measure the sample disintegration rate and a 65-cm^3 closed-end coaxial Ge(Li) detector was used to determine the absolute γ-ray emission rates of the same source.

For these measurements the ^{250}Bk activity, chemically purified as described above, was deposited as a small droplet on thin conducting films of VYNS (a polyvinylchloride-acetate copolymer) and taken to dryness with a heat lamp. The VYNS films were typically 40 μg/cm^2 thick and had layers of Au 25 μg/cm^2 thick deposited on each side by vacuum evaporation. α counting for any residual activity (i.e., ^{250}Cf and ^{254}Es) after the ^{250}Bk decayed indicated that the chemical separation was quite good, with the ratio of the ^{250}Bk activity to that of ^{254}Es being $>3\times10^5$ at the end of the separation.

Three samples were measured in this experiment. Three somewhat different 4π β-γ coincidence techniques were used in order to provide some information about the internal consistency of the absolute-intensity data obtained. For the first sample, the 4π β-γ coincidence data were analyzed in the conventional manner. The β^-- and γ-ray counts were corrected for dead time and background and the coincidence counts were corrected for dead time, background, and random coincidences. The computed β-chamber efficiency (i.e., the ratio of coincidence and γ-ray counts) was 95.5%. The disintegration rate N_0 was then calculated from the relation $N_0=N_\beta N_\gamma/N_c$.[16]

For the second sample, the ratio N_c/N_γ was varied by placing thin aluminum absorbers over the source. In the analysis of this experiment $N_\beta N_\gamma/N_c$ is plotted as a function of N_c/N_γ and the disintegration rate N_0 is determined by extrapolation of the individual $N_\beta N_\gamma/N_c$ values to $N_c/N_\gamma=1$ (i.e., 100% chamber efficiency). This ratio, $N_\beta N_\gamma/N_c$, varied by only 2% for variations of N_c/N_γ from 64% to 94.4%. This indicates that for ^{250}Bk this extrapolation procedure provides a precise estimate of the source disintegration rate. (The small rate of change of efficiency with absorber thickness also provides justification for the simple approach used in the analysis of the data for the first sample.)

For the third sample, the ratio N_c/N_γ was varied by changing the chamber bias. The data were analyzed using the extrapolation technique as was done for the second sample. In this measurement the ratio $N_\beta N_\gamma/N_c$ varied by only 1% for variations of N_c/N_γ from 57% to 97%.

In each of the three experiments, the γ-ray emission rates for the 989- and the (1028+1031)-keV transitions were determined using a Ge(Li) detector. Since for these weak sources the statistical uncertainty in each of the γ-ray peaks was no better than ~2%, the 989/(1028+1031) intensity ratio measured in this experiment was adjusted (with the total intensity a constant) to correspond to the more precise data given in Table I. These adjustments were 0.0, 0.15, and 0.5% in the three cases.

The resulting absolute γ-ray intensity data are summarized in Table II. For each of the three samples the nonsystematic contribution to the uncertainty in the absolute-intensity value from the N_0 determination is 0.2–0.3%. Typical values of the uncertainties from the γ-ray counting considered in the individual values in columns 2, 3, and 4 of Table II are as follows: statistical error in the Ge(Li)-spectrum peak areas, 1–2%, source position, 0.25%, adjustment to precise relative intensities, 0–0.25%, and decay corrections, 0.08–0.50%. After averaging the three values, an uncertainty of 0.5% was added to account for the systematic error in the N_0 determination and an uncertainty of 1.5% was included to represent that of the Ge(Li) detector-efficiency curve. The latter is the dominant single error in the resultant absolute-intensity values.

E. γ-γ coincidence measurements

γ-γ coincidence measurements were made using a 55-cm^3 true-coaxial and a 50-cm^3 closed-end

TABLE II. Experimental results of absolute γ-ray intensity measurements for ^{250}Bk.

γ-ray branch	γ-ray emission probability				
E (keV)	1st sample	2nd sample	3rd sample	weighted average	adopted[a] value
989	0.450_4 (6_7)	0.456 (10)	0.446_4 (6_9)	0.449_9 (4_3)	0.450 (8)
1028+1031	0.405_4 (5_5)	0.410_4 (5_7)	0.401_8 (5_4)	0.405_7 (3_2)	0.406 (7)

[a] The quoted uncertainty was derived by combining in quadrature the uncertainty in the weighted average (see column 5) with systematic errors of 0.5% from the N_0 determination and 1.5% from the Ge(Li) photopeak efficiency.

Ge(Li) detector. The measurements were carried out in a 180° geometry. With the source mounted on the face of the true-coaxial detector, an absorber consisting of a 0.9-cm thick piece of Pb sandwiched between 0.05-cm thick sheets of Cd was placed between the source and the closed-end detector to reduce the effects of backscattering between the detectors. The timing of the system was determined by two constant-fraction timing-single-channel analyzers and a coincidence circuit whose resolving time 2τ was set nominally at 80 nsec for the majority of the measurements. In one detector, 4096-channel γ-ray spectra were recorded in coincidence with the output of a single-channel gate set on selected peaks in the other detector. Such spectra were taken for single-channel gates set on the L x rays and γ rays having the following energies: 42, 99, 828, 929, and 989 keV. (Because of the relatively low intensity of the 42-keV γ ray, the spectrum gated by it yielded information only on the strong γ-ray peaks near ~1 MeV.) For the gates involving the low-energy γ radiation ($\lesssim$100 keV) the true-coaxial detector, because of its higher low-energy detection efficiency, was used for the gating and the coincidence spectrum was recorded in the closed-end detector; for the higher-energy gates, where the lower-energy region of the coincidence spectrum is primarily of interest, the roles of the detectors were interchanged. In several cases, spectra coincident with regions above a peak were also measured in order to ascertain whether certain observed lines were coincident with the gating peak itself or with the background underlying it.

In the coincidence spectra, a number of weak transitions were observed which were not seen directly in the γ-ray singles spectrum. The energy and intensity values for these, listed in Table I, were based solely on analysis of these coincidence spectra.

Examples of the γ-γ coincidence spectra, those coincident with the 828-keV γ ray and with the Bk + Cf L x rays, are shown in Figs. 3 and 4, respectively. The observed coincidence relationships are summarized in Table III.

III. DECAY SCHEME

A. General considerations

The proposed decay scheme of ^{250}Bk, based on the results of the present study, is shown in Fig. 5. The 2^+ and 4^+ members of the ground-state band and the 2^+ and 3^+ members of the γ-vibrational band (at 1031 and 1071 keV, respectively) are well established from previous studies[1] and are typical features of the level scheme of a strongly deformed, doubly even nucleus. These have formed a framework within which the γ-γ coincidence data and γ-singles data have been interpreted. As noted in Table III, the placement of all the stronger transitions is verified by the coincidence results.

Because of the large L-shell conversion coefficients of the 42- and 99-keV transitions (and the absence of K-shell conversion) and their overall strength, the γ-ray spectrum gated by the L x-rays effectively represents that in coincidence with either the 42-keV γ ray or both the 42- and

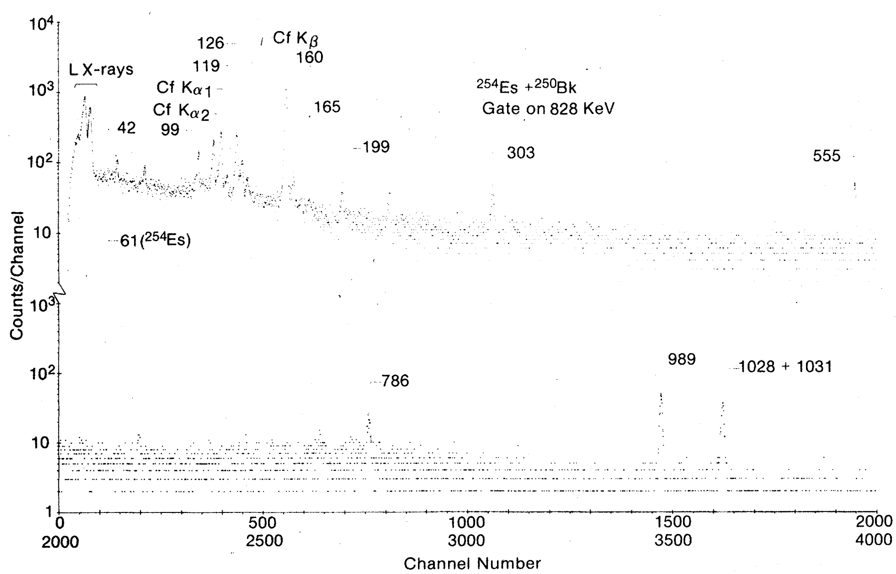

FIG. 3. γ-ray spectrum coincident with the 828-keV transition measured using a 55-cm^3 true-coaxial Ge(Li) detector. Contributions to this spectrum from random coincidences and from coincidences with the Compton distribution contained within the gating channel have not been removed.

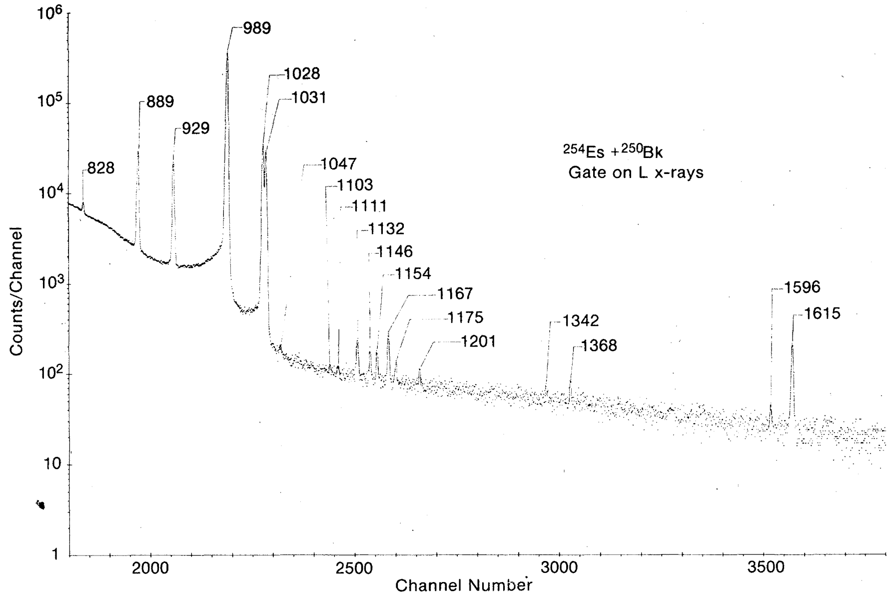

FIG. 4. Portion of the γ-ray spectrum in coincidence with the L x-ray region. The spectrum was measured on a 50-cm^3 closed-end Ge(Li) detector with a backscatter shield (0.9-cm Pb + 0.10-cm Cd) placed between source and detector. Contributions to the spectrum from random coincidences and from coincidences with the Compton distribution underlying the peaks in the gating channel have not been removed. As discussed in the text, the presence of the 1596-keV peak is currently unexplained.

99-keV γ rays. Thus, a selective enhancement (of roughly a factor of 2) in the L x-ray coincidence spectrum is expected for γ rays that feed the 141-keV rather than the 42-keV level.

In the spectrum coincident with the L x rays (see Fig. 4), peaks can be located corresponding to the 1103- and 1111-keV γ rays. Although the statistical quality of the data in this region of the coincidence spectrum is rather poor, the intensities of these "peaks", relative to those of near-lying γ rays known to feed the 42-keV level, appear to be larger (by a factor of roughly 2) than what is observed in the singles spectrum. We have thus tentatively placed these γ rays as transitions feeding the 141-keV level. This placement of the 1111-keV γ ray suggests the existence of a level at 1253.4 keV. Since this is the only evidence we have for the existence of this level, we have chosen not to show it in Fig. 5.

Evidence for the presence of at least two γ rays (in addition to the 1173-keV γ ray from the ^{60}Co background) in the 1175-keV peak is provided by the spectrum in coincidence with the L x rays (see Fig. 4). An 1175-keV γ ray is present in this spectrum, although its intensity, relative to those of the near-lying γ rays, is much smaller than in the singles spectrum (Fig. 2). This suggests that there is a transition feeding either the 42- or the 141-keV level in this peak, in addition to a ground-state transition. The absence of an 1175-keV transition in the spectrum coincident with the 99-keV γ indicates that this γ ray feeds the 42-keV level. The existence of a state at ~1218 keV is thus suggested. We have indicated on the level scheme that this state is only tentatively established, since we cannot exclude the possibility that this coincidence results from feeding of the 1175-keV level by a highly L-converted transition unobserved in this study and since no other γ rays are observed to feed or to depopulate this state. No appreciable displacement of the 1175-keV peak with respect to those of the near-lying γ rays is observed in the singles and coincidence spectra. Consequently, the "two" transitions are assumed here to have the same

TABLE III. Summary of γ-γ coincidence relationships. Parentheses indicate a tentative coincidence.

Gate energy (keV)	Coincident γ-ray energies (keV)
L x rays [a]	626, 828, 889, 929, 989, 1028, 1047, (1068), 1103, 1111, 1132, 1146, 1154, 1167, 1175,[b] 1201, 1342, 1368, 1596,[c] 1615
99 [a]	889, 929, 1047, 1154
828	42, 119, 126, 160, 165, 199, 303, 555, 786
929	42, 99, 586
989	42, 626

[a] Because of the presence of a thick Pb backscatter shield between the source and the detector used to record the coincidence spectrum, information about the low-energy portion of the coincidence spectrum was not obtained.

[b] Only a portion of this peak is present in the coincidence spectrum.

[c] This γ ray is not included in Table I or the decay scheme; see text for comments.

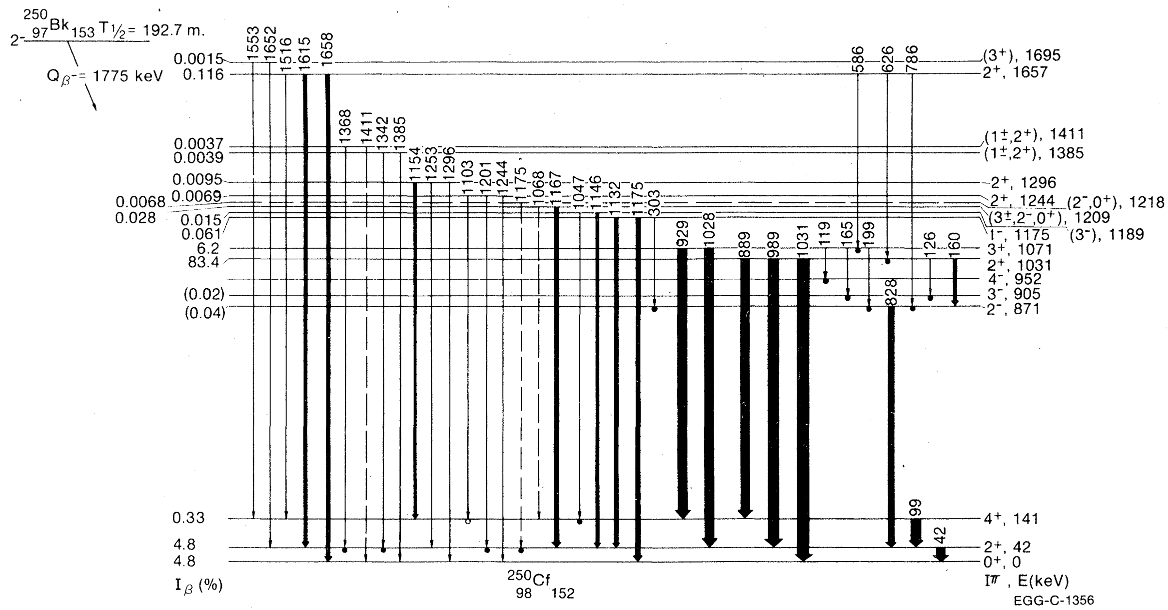

FIG. 5. Decay scheme proposed for ^{250}Bk from the results of this investigation. The log*ft* values of the β^- transitions and more precise values of the level energies are given in Table IV. Circles at the heads of arrows representing the γ-ray transitions indicate that the placement is based on coincidence information; filled circles indicate definite assignments and open circles indicate a tentative placement. The stronger transitions, indicated by the broader arrows, are all placed in accordance with the coincidence data; and no circles are shown for them. Tentatively placed γ rays and levels are shown as dashed lines.

energy, and the energy value given in Table I is that determined from analysis of the singles spectrum.

The 1596-keV peak observed in the singles spectrum results, at least in part, from the decay of ^{140}La, a product of the spontaneous fission of ^{250}Cf. The presence of a 1596-keV peak in the *L* x-ray coincidence spectrum (Fig. 4) may indicate that there is also such a transition in the ^{250}Bk decay (implying a possible level at 1638 keV). However, we have not included this γ ray in Table I or in the level scheme.

The 555-keV γ ray is in coincidence with the 828-keV γ (see Fig. 3). It can feed the 871-keV level either directly or through the 905- or the 952-keV levels (since the decay of these latter states proceeds primarily to the 871-keV level). Lacking other information we are unable to propose a unique placement for this γ ray.

A set of "best" level-energy values for the ^{250}Cf states was obtained from a least-squares fit of the γ-ray energies. In this fitting process, the γ-ray energies listed in Table I were used as input and those transitions were excluded whose placement in the level scheme was regarded as uncertain. The effect of nuclear recoil on the γ-ray energies was taken into account. The adopted final-state energy values and their estimated uncertainties are given in Table IV. The reduced χ^2 value of the least-squares fit was ~1.3, indicating a fairly consistent set of input energy values.

The difference between the energy of 1103-keV transition and the corresponding level-energy difference is ~6 times the quoted uncertainties. The origin of this discrepancy is not clear; it may reflect a nonstatistical error in the energy value itself (possibly indicating the presence of additional components in the peak corresponding to this γ ray) or it may indicate an incorrect placement. In the following, however, we assume that our proposed placement is correct. This placement is of some interest in that it permits us to make a unique I^π assignment, namely 2^+, to the 1244-keV level.

The intensities of the β^- transitions were deduced by requiring at each level a balance between the intensities (γ-ray + conversion-electron) of the feeding and the de-exciting radiations. These data are summarized in Table IV and shown in Fig. 5. This procedure gave well-defined values in all cases except for the division of the β^- intensity between the 871- and 905-keV levels and between the ground and first excited states. The problem with these former two states arises primarily from the fact that the intensity of the 34.3-keV transition connecting them is not known. However, the total β feeding of both levels is about

TABLE IV. Summary of energy and intensity data on the β^- transitions from the decay of ^{250}Bk. The I_β values were obtained from γ-ray + conversion-electron intensity-balance considerations, assuming the validity of the decay scheme shown in Fig. 5. Approximately 0.015% of the γ-ray intensity is not placed in this scheme, and this may significantly affect the quoted intensities and their uncertainties for some of the weaker branches. Quantities in parentheses represent uncertainties in the least significant figure (or figures) of the associated value. Square brackets around a level energy indicate a tentative assignment.

Final-state energy (keV)	E_{β^-} [a] (keV)	I_{β^-} (% per decay)	$\log f_0 t$	$\log f_1 t$
0	1775	4.8 [b]	···	9.7
42.730(13)	1732	4.8 [b]	8.7	9.6
141.894(15)	1633	0.33(19)	···	$10.7^{+0.4}_{-0.2}$ [c]
871.562(27)	903	0.04 [d]	9.8	···
905.848(37)	869	0.02 [d]	10.0	···
1031.854(16)	743	83.4(14)	6.2	···
1071.382(23)	704	6.21(17)	7.2	···
1175.52(3)	600	0.0610(26)	9.0	···
1189.407(32)	586	0.0149(7)	9.6	···
1209.986(37)	565	0.0282(14)	9.3	9.3
[1218.2]	557	0.0068(14)	9.9	9.9
1244.505(35)	530	0.0069(3)	9.8	9.8
[1253.4(1)]	522	0.0011(1)	10.6	10.6
1296.639(33)	478	0.0095(4)	9.5	9.5
1385.49(5)	390	0.0039(2)	9.6	···
1411.35(6)	364	0.0037(3)	9.5	···
1657.991(25)	117	0.116(4)	6.5(1) [e]	···
1695.17(10)	80	0.0015(2)	7.9(1) [e]	···

[a] E_β values calculated assuming a value of 1775 ± 8 keV for the β-decay energy of ^{250}Bk. (See Ref. 1).

[b] Intensity of this β branch was not determined in the present work. The listed value was obtained from our measured value of (9.7 ± 1.4)% for the sum of the intensities of the β transitions to the ground and first excited states, assuming that the two branches have equal intensity (see Ref. 2).

[c] Uncertainty derived from the listed uncertainty in the intensity of the β branch to this state.

[d] See the text for a discussion of the basis for the choice of this value.

[e] The listed uncertainty is that resulting from the uncertainty in Q_β.

0.06%, and this value is relatively insensitive to any placement of the unplaced 555-keV γ ray. The split of this β intensity, given in Table IV, was made arbitrarily and merely reflects the predictions of the Alaga rules.[17] The problem regarding the β^- intensity to the ground and first-excited states involves the intensity of the highly converted 42.7-keV transition. The total intensity of this transition, calculated using the γ intensity given in Table I and either the measured[7] (1100 ± 140) or the theoretical[18] (1300) value for the total internal-conversion coefficient, is not large enough to yield a realistic (i.e., positive) value for the β^- intensity to the 42-keV level. To obtain the quoted values of the β^- intensities feeding the ground and first-excited states, we subtracted the total β intensity feeding the higher excited states from 100%. The difference, 9.7 ± 1.4%, was split equally between these two states, as suggested by the measurements of Vandenbosch *et al.*[2]

The $\log f_0 t$ values given in Table IV for the β transitions were calculated from the data in that table, using the computer program described in Ref. 19. A Q_β value of 1775 ± 8 keV (Ref. 1) was used. Since the I, K^π values for the ^{250}Bk ground state are 2, 2$^-$ (see Ref. 1), β transitions to $K^\pi = 0^+$ states in ^{250}Cf are expected to have first-forbidden unique character. For those cases, $\log f_1 t$ values were also computed.

B. Spin and parity assignments

The I^π assignments shown in Fig. 5 for the states at 1031 and 1071 keV, as well as those for the members of the ground-state rotational band, appear well established from the available data, as summarized in Ref. 1. The 2^-, 3^-, and 4^- assignments for the 871-, 905-, and 952-keV states, respectively, are based on the results of single-nucleon transfer-reaction studies[6] and decay-scheme studies[7] of 8.6-h ^{250}Es and appear to be similarly well established.

From its observed decay modes, the 1175-keV level can have $I^\pi = 1^-$, 1^+, or 2^+. We prefer the 1^- assignment since we believe that the 303-keV transition from this state to the 2^- state at 871 keV is $M1$. Evidence for this multipolarity is derived from the photon spectrum in coincidence with the 828-keV γ ray (see Fig. 3). The contributions to the K x rays in this spectrum come from K conversion of the 160-, 303-, 555-, and 199-keV γ rays. From its placement in the level scheme, the 199-keV transition should be $E1$; the multipolarities of the 303- and 555-keV γ's, however, are not known. The smallest inferred value of $\alpha_K(160)$ is 0.17 ± 0.02 and is obtained if both the 555- and 303-keV transitions are assumed to be $M1$ (the allowed choices being $E1$, $M1$, or $E2$). This value is in reasonable agreement with the theoretical[18] one of 0.14 for an $E1$ multipolarity. Any other assumptions concerning the multipolarities of the 303- and 555-keV transitions lead to unreasonably large $\alpha_K(160)$ values. [For example, if the 555- and 303-keV transitions are assumed to be $M1$ and $E1$, respectively, an $\alpha_K(160)$ value of 0.29 ± 0.02 is deduced. This is much larger than the theoretical values[18] of 0.14, 0.16, and 0.17, respectively, for $E1$, $E2$, and $E3$ multipolarities, and implies an $M2$ admixture of ~0.5%. We believe that such an admixture would be unreasonably large since, for reasonable estimates[20] of the lifetime of the 1031-keV (γ-vibrational) state, the transition probability of this $M2$ component would be ~6 times the single-particle estimate as given by Moszkowski.[23] Not only is this extremely large in itself but also examination of the expected[24] two-quasiparticle makeup of the initial and final states reveals that none of the larger components can give rise to $M2$ radiation at all.] Consequently, we believe that both the 555- and 303-keV transitions are, at least largely, $M1$. The I^π assignment of the 1175-keV level is thus 1^-. This assignment has appeared elsewhere in the literature (see, e.g., Refs. 24 and 25), but the experimental basis for it has not yet been reported.

Since de-exciting γ rays to the 0^+, 2^+, and 4^+ members of the ground-state band are observed from the states at 1244, 1296, and 1657 keV, I^π assignments of 2^+ can be made to each of them.

The decay of the 1189-keV state suggests $I^\pi = 3^\pm$, 4^+, or possibly 2^+. It is tempting to interpret this state as the 3^- member of the $K^\pi = 1^-$ octupole band, whose band head is the 1175-keV state. However, such an identification presents difficulties in quantitatively describing the γ-ray branching of these two states, as discussed below.

From the present data, definite I^π assignments cannot be made to the remaining states. The observed γ-decay modes, however, permit some restrictions to be placed on them. The state at 1218 keV appears to decay only to the 2^+ member of the ground-state band. Although several I^π assignments are possible, this apparent decay pattern is what would be observed from states with $I^\pi = 0^+$ or 2^-, and we have indicated only these two possibilities in Fig. 5 for the 1218-keV state. Very weak evidence (see Sec. III A) exists for a state at 1253 keV, decaying to the 4^+ member of the ground-state band. If this level exists, its apparent decay mode is consistent with an $I^\pi = 4^-$ assignment (although, of course, other possibilities are not excluded). The tentative 3^+ assignment to the 1695-keV level, consistent with the observed de-exciting γ rays, is based largely on our assumption that this level is a rotational state whose band head is the 2^+ state at 1657 keV. The $3^\pm$ assignment for the 1209-keV state is consistent with the proposed γ branching. However, the elimination of 0^+ and 2^- as possible I^π values for this state is dependent entirely on the placement of the 1068-keV transition from this state to the 4^+ member of the ground-state band. This placement is based only on an energy combination and is tentative. The small intensity of this γ ray relative to that of the 1167-keV γ ray (a factor of roughly 50) raises questions about this placement. At present, these two assignments (0^+ and 2^-) cannot be regarded as being definitely eliminated; in view of this former possibility we have included in Table IV the calculated $\log f_1 t$ value of the β transition to this state.

IV. DISCUSSION

Although many features of the ^{250}Bk decay scheme require additional information for their clarification, a number of conclusions can be drawn from the data obtained from this study.

A. $I^\pi = 2^+$ and 3^+ states

Table V presents a summary of the relative $B(E2)$ values for those γ rays which depopulate excited states whose I^π values are believed to be 2^+ and 3^+ to the ground-state band. (All the transitions listed are assumed to be pure $E2$). We have carried out a simple one-parameter two-band mixing analysis (see, e.g., Refs. 26 and 27) of these $B(E2)$ ratios to extract values for the band-mixing parameter z_K for assumed initial-state K values of 0 and 2. The z_K values obtained from this analysis are also summarized in Table V.

TABLE V. Summary of band-mixing parameters z_K deduced from the measured relative γ-ray intensities. Where more than one initial-state K value is believed possible, z_K values for both possibilities ($K=0$ and 2) are given. γ-ray transitions for which $\Delta K = \pm 1$ are assumed to be $E2$. Quantities in parentheses represent uncertainties in the least significant digit (or digits) of the associated value.

Initial state I^π; E (keV)	Transition ratio	$B(E2)$ ratio	Deduced z value z_2	z_0
2_γ^+; 1031	$\frac{2_\gamma^+ \to 0_g^+}{2_\gamma^+ \to 2_g^+}$	0.64(1)	+0.015(3)	...
	$\frac{2_\gamma^+ \to 2_g^+}{2_\gamma^+ \to 4_g^+}$	17.3(3)	+0.011(2)	...
	$\frac{2_\gamma^+ \to 0_g^+}{2_\gamma^+ \to 4_g^+}$	11.1(2)	+0.012(1)	...
3_γ^+; 1071	$\frac{3_\gamma^+ \to 2_g^+}{3_\gamma^+ \to 4_g^+}$	2.40(8)	+0.003(3)	...
2^+; 1244	$\frac{2^+ \to 0_g^+}{2^+ \to 2_g^+}$	0.23(2)	+0.20(2)	+0.071(4)[a] +0.262(4)
	$\frac{2^+ \to 2_g^+}{2^+ \to 4_g^+}$	3.4(6)	+0.34(8)	−0.043(7)[a] −0.10(1)
	$\frac{2^+ \to 0_g^+}{2^+ \to 4_g^+}$	0.79(13)	+0.24(2)	−0.016(4)[a] −0.17(2)
2^+; 1296	$\frac{2^+ \to 0_g^+}{2^+ \to 2_g^+}$	0.336(48)	+0.13(2)[a] −4.4(12)	+0.051(8)
	$\frac{2^+ \to 2_g^+}{2^+ \to 4_g^+}$	0.153(14)	−0.75(2)[a] −0.39(1)	+0.065(6)
	$\frac{2^+ \to 0_g^+}{2^+ \to 4_g^+}$	0.052(7)	+0.61(3)[a] +2.3(2)	+0.058(4)
2^+; 1658	$\frac{2^+ \to 0_g^+}{2^+ \to 2_g^+}$	0.521(37)	+0.051(12)	+0.023(5)[a] +0.311(5)
	$\frac{2^+ \to 2_g^+}{2^+ \to 4_g^+}$	27.5(25)	−0.020(5)	−0.061(3)[a] −0.082(3)
	$\frac{2^+ \to 0_g^+}{2^+ \to 4_g^+}$	14.4(13)	−0.0014(44)	−0.056(1)[a] −0.090(1)
3^+; 1695	$\frac{3^+ \to 2_g^+}{3^+ \to 4_g^+}$	1.32(36)	+0.051(24)	...

[a]For these cases, no basis exists for rejecting one of the two possible z values obtained from analysis of the $B(E2)$ ratios. Consequently, both are shown here.

Inspection of Table V reveals that the three transitions from the 2^+ member of the γ-vibrational band can be quite well described by a band-mixing parameter, z_2, whose value is $+0.013$. For the transitions from the 3^+ state, however, a much smaller z_2 value is required. The reason for this apparent discrepancy is not known at the present time. The assumption that the transitions from the 3^+ state have a significant $M1$ admixture is not entirely satisfying, since this would imply the existence of an $M1$ component in the $2_\gamma^+ \to 2_g$ transition as well. In the conventional two-band mixing analysis summarized in Table V, it is implicitly assumed that the intraband $E2$ matrix elements of the two bands are equal. If these two quantities are significantly different, the form of the expressions for the band-mixed $E2$ transition probabilities is modified. The expressions for the $B(E2)$ values in this case have been presented elsewhere[28] in the context of an analysis of the $E2$-transition data involving the well-studied γ-vibrational band in ^{166}Er. In the spirit of the analysis presented in Ref. 28, we have investigated the extent to which the different deduced z_2 values for the 2^+ and the 3^+ states could be accounted for in terms of different $E2$ matrix elements within the two bands. The results of this analysis, however, do not provide definite information either for or against this assumption.

If the 1296-keV state is assumed to have $K=0$, its $B(E2)$-ratio data can be well described by a single value of the band-mixing parameter, namely $z_0 \sim 0.058$, whereas, if it is assumed to have $K=2$, no single z value can be found to describe these data (see Table V). Consequently, the 1296-keV state is most likely the 2^+ member of a $K=0$ band. This finding implies the existence of a 0^+ band head approximately 30–40 keV below this 2^+ state. A 1223.9-keV γ ray, currently unplaced in the level scheme, is observed in the γ-ray spectrum; this might represent the transition from this 0^+ state to the 2^+ member of the ground-state band. However, in the absence of additional information, this placement is only a conjecture.

Similarly, the 1244-keV state is most likely the band head of a $K^\pi = 2^+$ band; the $B(E2)$ data can be rather well described with $z_2 \sim 0.24$. Although not excessive, the spread in the values of this parameter deduced from the various $B(E2)$ ratios can be explained if it is recognized that, relative to those of the $2^+ \to 0_g^+$ and $2^+ \to 2_g^+$ transitions, the strength of the $2^+ \to 4_g^+$ transition is somewhat large. Since the 2^+ states at 1244 and 1296 keV are most likely mixed to some extent (which mixing is not included in the simple analysis summarized in Table V) and this mixing will have a greater influence on the $2^+ \to 4_g^+$ transition than on the other two, this possibility of a somewhat enhanced strength for the $2^+ \to 4_g^+$ transition is not unreasonable. [Note, however, the discussion in Sec. III A above regarding the placement of this 1103-keV transition, upon which this analysis is partially based.] Our deduced z_2 value for these transitions is considerably larger than those commonly observed for collective transitions between γ-vibrational and ground-state bands and may simply indicate a relatively small intrinsic $E2$ matrix element between the 1244-keV band and the ground-state band in ^{250}Cf.

The apparent lack of a consistent z_2 value for the transitions from the 1657-keV, 2^+ state to the ground-state band can be traced to excessive strength in the $2^+ \to 2_g^+$ transition. From the $B(E2)$ ratio involving the $2^+ \to 0_g^+$ and $2^+ \to 4_g^+$ transitions (which must be pure $E2$), a z_2 value that is essentially zero is deduced. This suggests to us that the assumption of pure $E2$ multipolarity for the $\Delta I = \pm 1$ transitions from the members of this band to the ground-state band is not valid and casts doubt on the $B(E2)$ data listed in Table V for the 3^+, 1695-keV state. However, at present it is not known whether these $\Delta I = \pm 1$ transitions do in fact have significant $M1$ components and that the $E2$ components can be adequately described by a z_2 value that is essentially zero.

B. Octupole-vibrational bands

From the present study an interesting, although as yet only tentative, picture of the octupole-band structure in ^{250}Cf can be inferred. The assignment of the states at 871, 905, and 952 keV as the 2^-, 3^-, and 4^- members, respectively, of the $K^\pi = 2^-$ octupole band presents no problems and has been proposed from other studies.[6,7] The 1175-keV level is most plausibly assigned as the band head of the $K^\pi = 1^-$ octupole-vibrational band. The other members of this band cannot be definitely assigned from the present data. The 1189-keV state, if its I^π value is in fact 3^-, is a candidate for the 3^- member. The relatively small spacing (~14 keV) between the 1^- and 3^- band members implied by this assignment can be accounted for fairly easily in terms of the expected strong Coriolis coupling between the $K^\pi = 0^-$ and 1^- octupole bands if, as seems reasonable, the 0^- band lies above the 1^- band.[29] The $I^\pi = 2^-$ band member, unaffected by such a coupling, will lie higher in the spectrum. Possible candidates for this state are the levels at 1209 keV (if the weak, tentatively placed 1068-keV transition in fact occurs elsewhere in the level scheme) and 1218 keV. One of the potential problems raised by the above interpretation of the 1189-keV states lies in quantitatively describing the γ branching of the 1175- and 1189-keV states to the ground-state band. The $E1$ branching of the odd-spin members of $K^\pi = 1^-$ octupole bands is expected, and generally found,[30] to be strongly influenced by Coriolis mixing with 0^- octupole bands because the intrinsic $E1$ matrix element with $\Delta K = 0$, introduced by the mixing, is much larger than that with $|\Delta K| = 1$. While it is not difficult to describe the relative $B(E1)$ values from either of these states separately, we have not been able to reproduce both ratios with the same set of assumed intrinsic $E1$ matrix elements.

ACKNOWLEDGMENTS

The able assistance of J. D. Baker in carrying out the chemical separations is gratefully acknowledged. Comments from R. C. Greenwood during the preparation of this manuscript were most helpful and are also gratefully acknowledged. This work was performed under the auspices of the U. S. Department of Energy.

[1]M. R. Schmorak, Nucl. Data Sheets 17, 436 (1976).
[2]S. E. Vandenbosch, H. Diamond, R. K. Sjoblom, and P. R. Fields, Phys. Rev. 115, 115 (1959).
[3]P. H. Stelson, R. W. Lide, and C. R. Bingham, Nucl. Phys. A144, 254 (1970).
[4]I. Ahmad, R. K. Sjoblom, R. F. Barnes, E. P. Horwitz, and P. R. Fields, Nucl. Phys. A140, 141 (1970).
[5]C. M. Lederer, thesis, Report No. UCRL-11028, 1963 (unpublished).
[6]S. W. Yates, I. Ahmad, A. M. Friedman, K. Katori, C. Castaneda, and T. E. Ward, Phys. Rev. Lett. 36, 1125 (1976).
[7]M. S. Freedman, I. Ahmad, F. T. Porter, R. K. Sjoblom, R. F. Barnes, J. Lerner, and P. R. Fields, Phys. Rev. C 15, 760 (1977).
[8]R. A. Meyer, R. W. Lougheed, J. E. Evans, and R. W. Hoff, Bull. Am. Phys. Soc. Series II, 17, 464 (1972).
[9]J. W. Uecke, thesis, Report No. ORO-3346-167, 1975 (unpublished).
[10]R. C. Greenwood, R. G. Helmer, and R. J. Gehrke, Nucl. Instrum. Methods 77, 141 (1970).
[11]R. G. Helmer, R. C. Greenwood, and R. J. Gehrke, Nucl. Instrum. Methods 96, 173 (1971).
[12]R. C. Greenwood (private communication).
[13]R. J. Gehrke and R. A. Lokken, Nucl. Instrum. Methods 97, 219 (1971).
[14]R. G. Helmer and M. H. Putnam, U. S. AEC Report No. ANCR-1043, 1972 (unpublished); R. G. Helmer, R. L. Heath, M. H. Putnam, and D. H. Gipson, Nucl. Instrum. Methods 57, 46 (1967).
[15]P. J. Campion, Int. J. Appl. Radiat. Isot. 4, 232 (1959).
[16]A. Spernol, E. DeRoost, and D. Lerch, EURATOM Report No. EUR 477.e, 1964 (unpublished).
[17]G. Alaga, K. Alder, A. Bohr, and B. R. Mottelson, Mat. Fys. Medd. Dan. Vid. Selsk. 29, No. 9 (1955).
[18]R. S. Hager and E. C. Seltzer, Nucl. Data A4, 1 (1968).
[19]N. B. Gove and M. J. Martin, Nucl. Data A10, 206 (1971).
[20]Based on an assumed value of 4. $B(E2)_{s.p.}$ for $B(E2)\uparrow$, which, although currently unmeasured, is a reasonable estimate in light of measured (see Ref. 21) $B(E2)\uparrow$ values for γ-vibrational states in near-lying nuclei. We use here $B(E2)_{s.p.} = 3\times10^{-5}A^{4/3}\,e^2b^2$ (see, e.g., Ref. 22), which is 5 of the single-particle units as defined by Moszkowski (Ref. 23).
[21]F. K. McGowan, C. E. Bemis, Jr., W. T. Milner, J. L. C. Ford, Jr., R. L. Robinson, and P. H. Stelson, Phys. Rev. C 10, 1146 (1974).
[22]K. Alder, A. Bohr, T. Huus, B. Mottelson, and A. Winther, Rev. Mod. Phys. 28, 432 (1956).
[23]S. A. Moszkowski, in *Alpha-, Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland, Amsterdam, 1965), Vol. 2, Chap. XV, p. 863.
[24]S. P. Ivanova, A. L. Komov, L. A. Malov, and V. G. Soloviev, Fiz. Elem. Chastits At. Yadra 7, 450 (1976), [Sov. J. Part. Nucl. 7, 175 (1976)].
[25]S. P. Ivanova, A. L. Komov, L. A. Malov, and V. G. Soloviev, Izv. Akad. Nauk SSSR, Ser. Fiz. 37, 911 (1973) [Bull. Acad. Sci. USSR, Phys. Ser. 37, No. 5, 5 (1973)].
[26]O. Nathan and S. G. Nilsson, in *Alpha-, Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland, Amsterdam, 1965), Vol. I, Chap. X.
[27]B. R. Mottelson, J. Phys. Soc. Japan Suppl. 24, 87 (1968).
[28]C. W. Reich and J. E. Cline, Nucl. Phys. A159, 181 (1970).
[29]K. Neergård and P. Vogel, Nucl. Phys. A149, 217 (1970).
[30]L. Kocbach and P. Vogel, Phys. Lett. 32B, 434 (1970).