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Beta Decay of Bk^{250} and Bk^{249}†

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The beta decay of Bk^{250} has been studied with a beta spectrometer. Bk^{250} has two beta groups: 725±15 kev (89±1% abundant) and 1760±50 kev (11±1% abundant). Conversion electron lines corresponding to 42.2, 98.2, 890, 930, 990, and 1032-kev transitions were observed and their intensities measured. The information obtained from crystal spectrometer singles and coincidence measurements was combined with beta spectrometer data to construct a decay scheme for Bk^{250} involving gamma vibrational levels in Cf^{250} analogous to those found in Pu^{238}. The beta half-life of Bk^{250} is 193.3±0.3 minutes. The electron capture partial half-life of Bk^{250} is estimated to be greater than 50 hours. The beta spectrum of Bk^{249} shows an allowed or first-forbidden transition with an end-point energy of 125±2 kev.

I. INTRODUCTION

BERKELIUM-250 has previously been observed as a neutron capture product of Bk^{249},[1] and as an alpha decay product of E^{254}.[2,3] The accumulation of larger quantities of Bk^{249} from long intense neutron irradiations of plutonium has made possible further studies of Bk^{249} and Bk^{250} using a beta-ray spectrometer and sodium iodide and anthracene crystal spectrometers in various coincidence combinations. A sample of Bk^{250} was measured in a thermal-neutron fission counter and a limit to its fission cross section was obtained. Mass spectrometric analysis of curium produced by irradiation of plutonium is used to estimate a limit to the electron capture half-life of Bk^{250}.

II. EXPERIMENTAL

(A) Preparation of Bk^{250}

Bk^{250} was formed in the irradiation of 0.04 microgram of Bk^{249} oxide for 6–10 hours in one of the high-flux vertical thimbles of the Argonne reactor CP-5′. The thermal neutron flux in this position is estimated to be $(2.5\pm0.5)\times10^{13}$ n/cm^2 sec.[4] The berkelium was purified from californium and other contaminants by extracting berkelium in the +4 oxidation state into di-(2-ethyl-hexyl)-orthophosphoric acid[5] and by elution from a cation exchange resin column using 6*M* HCl as eluting agent.[6]

(B) Beta Spectrometer Results

The Argonne double-lens spectrometer[7,8] was used to measure the beta and conversion electron spectra. The spectrometer was operated at a resolution of 3% and a transmission of 2%. The detector was a flow-type, end window, propane-gas proportional counter. The window of the gas counter was ≈900 μg/cm² Mylar with 25 μg/cm² Au volatilized on the inside and had an energy cutoff of 18 kev.

The berkelium samples were deposited from solution onto 1.7 mg/cm² aluminum foil. The ⅛-inch diameter deposits were visible. More sophisticated source preparation was rejected because of the short lifetime and the small amount of activity (about 1×10^8 disintegrations/min) available. The over-all chemical yields were of the order of 75% with about 90% of this actually transferred to the spectrometer sources.

Two groups of beta particles were observed, the low-energy group being much more abundant than the high-energy group. In Fig. 1, a Fermi-Kurie[9] plot of the low-energy beta group (obtained by conventional subtraction of the high-energy group) shows an allowed shape within the uncertainties afforded by the source preparation and backing and an end-point energy of 725±15 kev. The data show no evidence for the presence of a lower energy group. The Fermi-Kurie plot of the high-energy group (Fig. 2) appears to have an allowed shape, but the data are inadequate to rule out a first-forbidden unique shape, or to resolve the two components 42 kev apart in maximum energy that are indicated by coincidence work. The end-point energy of this group is 1760±50 kev. The abundance of the low-energy group is 89±1% and that of the high-energy group 11±1%.

The beta spectrum in the region of the conversion electron lines of the 42-kev and 98-kev transitions is shown in Fig. 3. The continuum is the $Bk^{249-250}$ beta

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† Based on work performed under the auspices of the U. S. Atomic Energy Commission.

[1] Ghiorso, Thompson, Choppin, and Harvey, Phys. Rev. **94**, 1081 (1954).

[2] Harvey, Thompson, Choppin, and Ghiorso, Phys. Rev. **99**, 337 (1955).

[3] Jones, Schuman, Butler, Cowper, Eastwood, and Jackson, Phys. Rev. **102**, 203 (1956).

[4] This information was furnished by J. G. Condelos of Reactor Operations Division, Argonne National Laboratory; periodic measurements of the activity produced in Au foils were made.

[5] Peppard, Moline, and Mason, J. Inorg. Nuclear Chem. **4**, 344 (1957).

[6] A. Chetham-Strode, Jr., University of California Radiation Laboratory Report UCRL-3322, 1956 (unpublished), p. 14.

[7] Porter, Freedman, Novey, and Wagner, Phys. Rev. **103**, 921 (1956).

[8] Porter, Wagner, and Freedman, Phys. Rev. **107**, 135 (1957).

[9] *Tables for the Analysis of Beta Spectra*, National Bureau of Standards Applied Mathematics Series No. 13 (U. S. Government Printing Office, Washington, D. C., 1952).

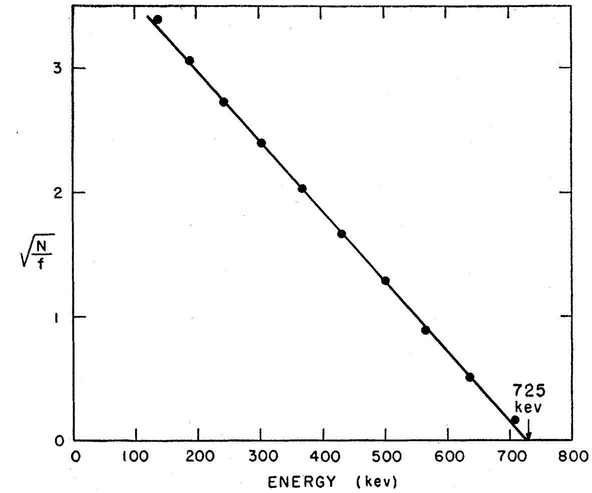

FIG. 1. Fermi-Kurie plot of the low-energy beta spectrum of Bk^{250}. Contributions from the high-energy Bk^{250} beta spectrum have been subtracted.

spectrum. Figure 4 shows the beta spectra taken in the region of the conversion electron lines of the ~1-Mev gamma transitions. These lines consist mostly of conversion electrons from 1032- and 990-kev gamma transitions and possibly also of lines from 890- and 930-kev transitions. Here the conversion electrons are superimposed on the beta spectrum of the high-energy Bk^{250} group. The energy and intensity of the conversion electron lines observed in Bk^{250} beta decay are listed in Table I. All of these lines decayed with a three-hour

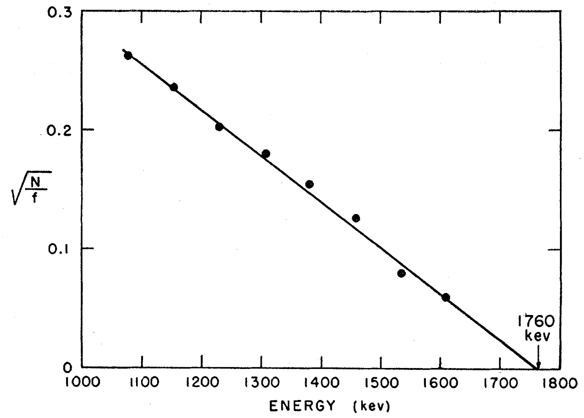

FIG. 2. Fermi-Kurie plot of the high-energy beta spectrum of Bk^{250}.

half-life. Conversion coefficient ratios calculated from these data are listed in Table II. The spectrum in the region of K conversion lines of 890- and 930-kev transitions (Fig. 4, Run II) indicates that such transitions may be present although in very low abundance. Levels of Cf^{250} at 0, 42.2, 140.4 (98.2+42.2), 1032, and possibly a weakly populated level at 1074 kev can be deduced from these conversion electron measurements. The energy difference between the 1032-kev and 990-kev conversion electron lines suggests that the 1032-kev level de-excites by means of 1032-kev and 990-kev transitions to the ground state and 42-kev level, respectively. Scintillation counter measurements [Secs.

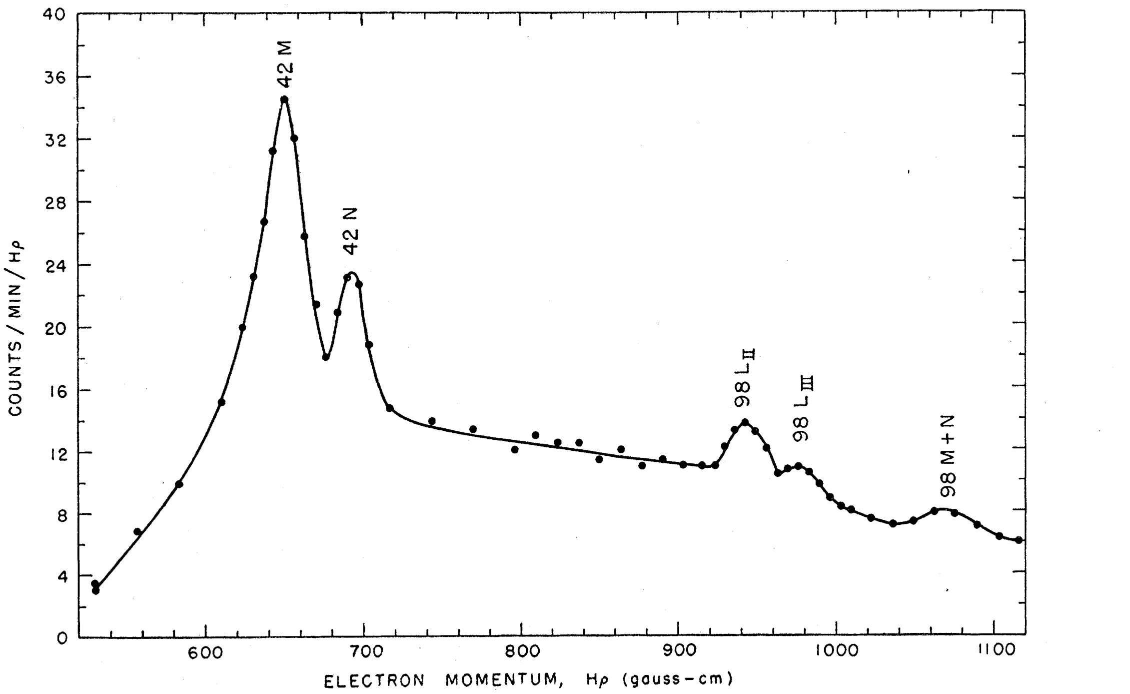

FIG. 3. Electron spectrum of Bk^{250} in the region of the conversion lines from the 42.2- and 98.2-kev transitions.

TABLE I. Conversion electron lines observed in Bk^{250} beta decay.

Electron line energy[a]	Shell converting	Electron binding energy[b]	Gamma energy		Intensity per Bk^{250} decay		Gamma-ray intensity per Bk^{250} decay[e]	Total conversion coefficient
36.30	ΣM	5.81[c]	42.11	42.2±0.5	d		f	g
40.80	ΣN	1.49[c]	42.29					
73.28	L_{II}	25.07	98.35	98.2±0.5	0.0145	0.0286	f	
77.99	L_{III}	19.95	97.94		0.0072			
93	$\Sigma M+N$				0.0069			
854.8	K	134.77	989.6	990 ±5	0.0056	0.0077	0.47	0.017
970	$L+M+N$				0.0021			
896.6	K	134.77	1031.5	1032 ±5	0.0044	0.0059	0.39	0.015
1010	$L+M+N$				0.0015			
755	K	134.77		~890	<0.0002			
795	K	134.77		~930	<0.0002			

[a] The K_{134} line of Ce^{144} was used for energy calibration of the conversion electrons. The value of $H\rho$ for this line, 1064.8 gauss-cm, was measured by F. T. Porter and P. P. Day (to be published).

[b] Binding energies were taken from Hill, Church, and Mihelich, Rev. Sci. Instr. **23**, 523 (1952).

[c] These binding energies represent weighted averages of the M_{II} and M_{III} and the N_{II} and N_{III} subshell binding energies. The values $M_{II}/M_{III}=1.22$ and $N_{II}/N_{III}\sim 1$ for the intensity ratios of these conversion electrons from the 44.11-kev level of Pu^{238} measured by W. G. Smith and J. M. Hollander, Phys. Rev. **101**, 746 (1956) were used in calculating these binding energies.

[d] No intensities are reported for the 42-kev level because the transmission of these low-energy conversion electrons is uncertain for the window thickness used in this experiment.

[e] Obtained from gamma scintillation measurements, this work.

[f] Gammas not observed.

[g] Asaro, Stephens, Thompson, and Perlman, Phys. Rev. **98**, 19 (1955), observed the 42-kev level of Cf^{250} in the alpha decay of Fm^{254} and report the conversion coefficient to be 750.

II(C) and II(D)] established the magnitude of this branching. The 42- and 140-kev levels which emit highly converted $E2$ gammas have been observed in Fm^{254} [10] alpha decay.

(C) Scintillation Counting

The gamma spectrum of Bk^{250} from sodium iodide crystals was displayed in an Argonne 256-channel pulse-height analyzer.[11] Three peaks were seen in the electromagnetic singles spectrum: a 1.005-Mev peak which beta-spectrometer conversion electron data show to be composed of 1.032- and 0.990- and possibly 0.890- and 0.930-Mev components, the K x-ray peak which obscures any 98-kev gamma rays which might be present, and L x-rays. A $2\frac{1}{2}$-in. diameter×$2\frac{1}{8}$-in. thick thallium-activated sodium iodide crystal with a 180-mg/cm² aluminum window was used to measure the energy and intensity of the composite peak at 1.005 Mev. The efficiency of this crystal for various energies and geometries has been calibrated by Engelkemeir.[12] The ratio of energy width at half-height to the energy of the 1.005-Mev photopeak (resolution) was 11.7%. This shows that the 1.005-Mev photopeak must be composite since the resolution of the 1.064-Mev Bi^{207} photopeak was only 8.1%. This 1-Mev Bk^{250} gamma peak decayed with a half-life of 3.3 hours.

The L x-rays were measured using a $\frac{1}{8}$-in. thick×$1\frac{1}{4}$-in. diameter sodium iodide crystal with 70-mg/cm²

TABLE II. Electron conversion coefficient ratios in Bk^{250} beta decay.

Energy of transition (kev)	$K/(L+M+N)$	L_{II}/L_{III}	$\Sigma L/(\Sigma M+\Sigma N)$	$\Sigma M/\Sigma N$
42.2				~3.5[a]
98.2		2.0	3.2	
990	2.7			
1032	2.9			

[a] This value is approximate because of the uncertain transmission of these low-energy electrons.

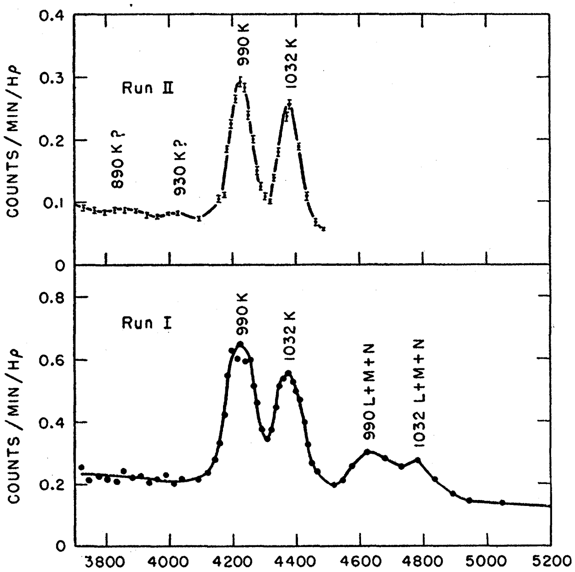

FIG. 4. Electron spectrum of Bk^{250} in the region of the conversion lines from the ~1-Mev gamma transitions.

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[10] Asaro, Stephens, Thompson, and Perlman, Phys. Rev. **98**, 19 (1955).

[11] R. W. Schumann and J. P. McMahon, Rev. Sci. Instr. **27**, 675 (1956).

[12] Unpublished graphs obtained from Dr. D. W. Engelkemeir, Argonne National Laboratory.

beryllium window. The geometry of the counting arrangement used was determined by counting the 60-kev gamma of a known Am^{241} source. The intensity value of 0.359 60-kev photons per alpha disintegration and escape peak correction of 11% determined by Magnusson[13] was used.

To calculate the relative intensity of the 990-kev gamma (in coincidence with L x-rays from the highly converted 42-kev level) it is necessary to evaluate the number of L x-rays arising from various sources. L vacancies arise both from the filling of primary K vacancies and from direct conversion in the L shell. The conversion of the 990- and 1032-kev gammas is obtainable (Table I) from beta-spectrometer data. The number of vacancies in the L shell resulting from a vacancy in the K shell was estimated from the data of Beckman to be 0.7[14] The total conversion of the 42-kev gamma in Cf^{250} has been reported[10] to be 750. The ratio of L: $(M+N)$ conversions of this gamma has been taken to be the same as that found for a similar 44-kev $E2$ gamma transition in Pu^{238} 2:1.[15] The fluorescence yield (photons per vacancy) of these L shell vacancies in californium was estimated to be 0.57 from an extrapolation of the treatment by Kinsey,[16] assuming the relative conversion of 42-kev gamma in $L_{I}:L_{II}:L_{III}$ to be 0.02:0.52:0.46 as extrapolated from Rose's tables.[17] These estimates (none of which are precise) imply that for each 42-kev transition in Cf^{250} there will be 0.38 L x-ray photons of about 20-kev energy. L x-rays from conversions of other gammas and of 42-kev gammas in coincidence with high-energy betas and with the 98-kev transition account for ~20% of the observed L x-rays. The abundance of the 990-kev gammas which are in coincidence with 42-kev transitions can be estimated by comparing the remaining number of L x-rays with the total number of composite 1-Mev gammas shown by coincidence measurements (Sec. IID) to consist largely of 990-kev gammas populating the 42-kev level and 1032-kev gammas populating the ground state. The resultant 990-kev gamma intensity averaged from two runs is 0.5±0.1 of all high-energy gammas.

(D) Coincidence Scintillation Measurements

Both gamma-gamma and beta-gamma coincidence measurements were made. The crystals used in gamma counting have been described in the previous section. For beta counting a $\frac{1}{4}$-in. thick by $1\frac{1}{4}$-in. diameter anthracene crystal with a 1.37-mg/cm^2 plastic window was used. A "fast-slow" coincidence circuit similar to that of Bell, Graham, and Petch[18] was used. The resolving time of this circuit is about 80 millimicroseconds. In these experiments the sample was placed directly between the two crystals such that the geometry for each crystal was a measured value varying from 5 to 10%.

Some of these coincidence measurements explored the relative branching of the unresolved gamma singles complex peak of 1005 kev. In one experiment the gate of the single channel analyzer was set to accept L x-rays and the high-energy gammas in coincidence with these x-rays were displayed in the 256-channel analyzer. A 3.6-g/cm^2 aluminum absorber was placed between the sample and the $2\frac{1}{2}$-in. crystal used to detect the high-energy gammas. The energy of the high-energy gamma peak observed was 990 kev which is appreciably lower than the gamma singles peak (1005 kev). The intensity of this 990-kev gamma coincidence peak was calculated using the geometry, efficiency, and the number of L photons per 42-kev transition (0.38). A comparison of the intensity of the 990-kev gamma coincidence peak with the intensity of the composite 1-Mev gamma singles peak showed that 40% of the high-energy gammas go to the ground state of Cf^{250}. From beta-spectrometer conversion electron data for the 98-kev transition (which coincidence measurements show to be highly converted) the total population of the 140-kev state is 2.9% of all betas. Assuming that this level is populated entirely by 890-kev and 930-kev gammas, 3.3% of the high-energy gammas go to the 140-kev level and the remainder or 57% go to the 42-kev state. This agrees with the branching ratio obtained from analysis of L x-ray singles data discussed in the previous section. Another experiment in which high-energy gammas gated the circuit and L x-rays in coincidence were analyzed, confirmed this value. A weighted average of the gamma singles experiments and the L x-ray–high-energy gamma coincidence experiments gives a branching ratio for the high-energy gammas of 44% to the ground state, 53% to the 42-kev state, and 3.3% to the 140-kev state.

Beta-gamma coincidence measurements showed that only low-energy betas were in coincidence with high-energy gammas. Both high-energy betas and low-energy betas are in coincidence with L x-rays. No high-energy betas were observed in coincidence with gammas in the 98-kev region. This indicates either that the conversion coefficient of the 98-kev transition must be greater than 50 or that the 140-kev level is not populated by beta decay. Comparison of the intensity of the high-energy betas ($E>1.25$ Mev) in coincidence with L x-rays, with the intensity of high-energy beta singles shows that about half of all high-energy betas are in coincidence with 42-kev transitions. This assumes that the 140-kev level is populated predominantly by high-energy gammas. Combining this information with the value of 11% for the abundance of high-energy betas obtained from beta-specrometer data, 5.5% of the

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[13] L. B. Magnusson, Phys. Rev. **107**, 161 (1957).

[14] O. Beckman, Arkiv Fysik **9**, 518 (1955).

[15] W. G. Smith and J. M. Hollander, Phys. Rev. **101**, 746 (1956).

[16] B. B. Kinsey, Can. J. Research **26A**, 404 (1948).

[17] M. E. Rose, *Internal Conversion Coefficients* (Interscience Publishers Inc., New York, 1958).

[18] Bell, Graham, and Petch, Can. J. Phys. **30**, 35 (1952).

betas populate the ground state, 5.5% the 42-kev state and 89% the 1031-kev state.

Several unsuccessful attempts were made to observe 98-kev gammas in coincidence with high-energy gammas as well as the previously discussed measurements with betas. The lower limit of 50 which can be set for the conversion coefficient of the 98-kev transition is high compared with the conversion coefficient of about 27 for a 98-kev $E2$ transition extrapolated from Rose's tables.[17] An attempt was also made to find an 892-kev gamma which would populate the 140-kev state. Comparison of the 990-kev gamma peak (in coincidence with L x-rays) with a Zn^{65} standard showed that an 892-kev peak might have been present.

(E) Beta Half-Life of Bk^{250}

A sample of purified Bk^{250} was counted with an end window proportional counter using an absorber to cut out the low-energy Bk^{249} betas. After subtraction of a single very long-lived component, the plot of the remaining activity *versus* time was a straight line for more than eight half-lives. Least-squares analysis of the data[19] gave a half-life value of 193.3±0.3 minutes. This value was crudely confirmed by decay of the high-energy gammas and the conversion electrons.

III. SPIN AND PARITY ASSIGNMENTS FOR Bk^{250} AND THE EXCITED LEVELS OF Cf^{250}

The 42.2-kev and 98.2-kev transitions, which have also been observed[10] in coincidence with the alpha decay of Fm^{254}, can clearly be identified with highly converted $E2$ transitions between the $2+\rightarrow 0+$ and $4+\rightarrow 2+$ rotational levels based upon the ground state of Cf^{250}. The measured energy of the second excited state, 140 kev, is consistent with that predicted by the rotational formula $E=(\hbar^2/2\mathscr{I})I(I+1)$. The value $\hbar^2/2\mathscr{I}=7.03$ kev, evaluated from the 42.2-kev (2+) level agrees with the values[20] calculated from the spacing of rotational levels of other heavy ($A>230$) even-even nuclides. No lower values of $\hbar^2/2\mathscr{I}$ have been reported, implying that Cf^{250} is as highly deformed as any nuclide in this region.

The K conversion coefficients of the 990- and 1032-kev gamma are 0.012 and 0.011, respectively, in agreement with the values 0.011 and 0.010 for these energy $E2$ gamma transitions extrapolated from Rose's tables.[17] A 1-Mev $E1$ transition would have a conversion coefficient of ~0.0037. This implies that the 1032-kev level is not a (1−) single-particle state. The fact that a 1032-kev gamma was observed rules out the possibility of the 1032-kev level being a $K=0$, $I=0$, $\pi=+$, (0, 0+) beta vibrational level since if this were the case a completely converted $E0$ transition between the 1032-kev state and the 0+ ground state would be expected. Two further possibilities are a (0, 2+) beta vibrational state or a (2, 2+) gamma vibrational state. Alder *et al.*[21] predict that the relative reduced transition probability from a beta vibrational state to the 0+, 2+, and 4+ ground-state rotational levels will be 1:1.43:2.57 whereas that from a gamma vibrational state to these levels will be 1:1.43:0.07. The reduced transition probability ratios calculated from the experimentally determined branching ratio of the 1032-kev level to the 0+, 2+, and 4+ levels of Cf^{250} are 1:1.5:<0.08 definitely favoring a (2, 2+) gamma vibrational state assignment to the 1032-kev level.

The small bump in the conversion electron spectrum (Fig. 4, Run II) corresponding to a 930-kev K conversion line suggests the presence of an ~1074-kev (2, 3+) first excited member of a rotational band based on the 1032-kev (2,2+) level. Similar "excited" rotational bands have been observed in other nuclides with an energy spacing equal to that of the ground-state rotational band.[22] This 1074-kev (2, 3+) state would be expected to decay to the 2+ and 4+ states of the ground-state rotational band by 1032- and 934-kev $E2$ gamma transitions. The relative reduced transition probability for these two transitions was calculated using the formula given by Alaga *et al.*[23] and Clebsch-Gordan coefficients by Sears and Radtke.[24] A fifth-power energy dependence factor was used to calculate the $(2, 3+\rightarrow 0, 2+)/(2, 3+\rightarrow 0, 4+)$ branching ratio of 4.2 from the reduced transition probability. This ratio has not been experimentally verified since a 1032-kev gamma from the 1074-kev level is indistinguishable from a very abundant 1032-kev level to ground-state gamma. However, this ratio can be used to set an upper limit to the beta population of the 1074-kev level. Analysis of the conversion electron data shows the 930-kev gamma to consist of less than 1.5% of all Bk^{250} beta transitions (assuming an $E2$ transition) and this information combined with the branching ratio of the 1074-kev level sets an upper limit of <8% to the population of the 1074-kev level. The experimental evidence for this level (a possible 930-kev K conversion line) is weak and its existence is uncertain.

Logft values of 6.3 for the 725-kev beta group and 8.7 for the two high-energy beta groups of Bk^{250} have been calculated from Moszkowski's nomogram.[25] The logft value of 6.3 for the Bk^{250} beta decay to the 1032-kev (2, 2+) state limits the spin of Bk^{250} to being greater than 0 and similarly the value logft=8.7 for

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[19] This was done by W. G. Greenhow, Applied Mathematics Division, Argonne National Laboratory.

[20] G. T. Seaborg, *The Transuranium Elements* (Yale University Press, New Haven, 1958), p. 229.

[21] Alder, Bohr, Huus, Mottelson, and Winther, Revs. Modern Phys. **28**, 432 (1956).

[22] A. S. Davidov and G. F. Filippov, Nuclear Phys. **8**, 237 (1958).

[23] Alaga, Alder, Bohr, and Mottelson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **29**, No. 9 (1955).

[24] B. J. Sears and M. G. Radtke, Chalk River Report TPl-75, August, 1954 (unpublished).

[25] S. A. Moszkowski, Phys. Rev. **82**, 35 (1951).

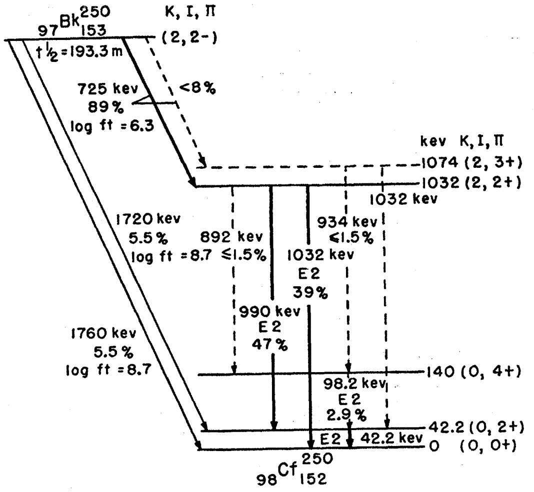

FIG. 5. Proposed decay scheme for Bk^{250}. The intensities given represent the percentage of total beta disintegrations. To convert the gamma branching to percent of high-energy gammas, divide by 0.89. Dotted lines are used to represent transitions and levels which have been deduced from scanty experimental data and hence are considered to be tentative.

the beta decay to the ground (0, 0+) state indicates that the Bk^{250} spin must be less than 3 and probably is not 2+. A 1+ assignment is also considered to be unlikely since in this case the beta decay to the ground state should be allowed and this is inconsistent with the $\log ft$ value of 8.7 for this transition. The remaining choices 1− and 2− are among the spin and parity possibilities obtained using Nilsson plots[26] to assign probable orbitals to the odd neutron and odd proton in Bk^{250} and the strong-coupling rules (for deformed odd-odd heavy nuclides) of Gallagher and Moszkowski[27] to combine these orbitals.

The 1− assignment is consistent with equal beta branching between the 42-kev level and the ground state. However, with this spin assignment it is difficult to explain why the 725-kev beta transition to the 1032-kev (2, 2+) level should be so highly favored over the high-energy beta transition to the 42-kev (0, 2+) level since in each case $\Delta I = 1$ and $\Delta K = 1$ and energy considerations favor the latter transition. This anomaly should not be used to rule out a 1− assignment because selection rules for the beta decay of highly deformed odd-odd heavy nuclides are not well understood. A ($K = I = 2$, $\pi = -$) assignment to Bk^{250} agrees well with the observed beta branching. The beta decay to the 1032-kev (2, 2+) level would be a first-forbidden $\Delta K = 0$, $\Delta I = 0$ transition consistent with the $\log ft$ value of 6.3. The transition to the 42-kev ($K = 0$, $I = 2$, $\pi = +$) state would be inhibited by violation of the K selection rule $\Delta I \geqslant \Delta K$.[23] The high $\log ft$ value, 8.7 for this first-forbidden, $\Delta I = 0$ transition, is consistent with the postulated K forbiddenness. The $\log ft = 8.7$ value is consistent with the beta decay to the ground state being first-forbidden unique. If the spin of Bk^{250} were 2−, about 3% population of the 140-kev level by beta decay would be expected. No beta decay to this state from a 1− state is likely. Since no measurements of high-energy beta particles in coincidence with conversion electrons from the 140-kev level were made, it is not known whether the 140-kev level is populated by beta decay as well as by high-energy gammas. The total population of the 140-kev level of Cf^{250}, 2.9% of all betas, is well established from the presence of 98-kev conversion lines. Should part of this population arise from beta decay, the high-energy gamma branching is different than assumed in the decay scheme.

Because a (2, 2−) spin assignment for Bk^{250} is much more consistent with the observed beta branching than a (1, 1−) spin assignment, only the (2, 2−) value is shown in the decay scheme in Fig. 5. The existence of the 1074-kev level is uncertain and therefore dotted lines are used to indicate the level and gamma branches from this level.

It should be noted that the energy of the levels populated by Bk^{250} beta decay are nearly identical with the levels populated by beta decay of Np^{238}, another odd-odd nuclide in this mass region.[28] Also, both Bk^{250} and Np^{238} in beta decay to the (0, 2+) state show approximately the same degree of K forbiddenness. Neither Bk^{250} nor Np^{238} seem to beta decay to a (0, 1−) level which is observed in many heavy even-even nuclides.[29] This is consistent with such a transition being K forbidden.

IV. NEUTRON CROSS SECTIONS

The course of irradiation of the heaviest elements in projected high-flux reactors would be affected if a substantial portion of Bk^{250} were to fission before it decayed or was transmuted into another heavy element. An attempt was made to measure the thermal neutron fission cross section of Bk^{250} in a set of back-to-back fission chambers in the thermal column of the Argonne reactor CP-5′.

The berkelium was separated from californium and irradiated in a vertical thimble of CP-5′ for 380 minutes The product was again separated from californium. A large aliquot was mounted on a 5-mil platinum plate, and placed in the fission counter along with a similarly mounted Pu^{239} standard. The neutron fissionability of

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[26] S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **29**, No. 16 (1955). The revised plots given by Stephens, Asaro, and Perlman, University of California Radiation Laboratory Report UCRL-8376, July, 1958 [Phys. Rev. **113**, 212 (1959)] were used.

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the sample grew in a manner compatible with the growth of Cf^{249} in the sample from the beta decay of Bk^{249}. All half-lives were taken from reference 29. No decline in fissionability with the characteristic 193-minute half-life of Bk^{250} was observed.

A smaller aliquot of the irradiated berkelium was alpha-counted continuously for two weeks to determine the amount of Bk^{249} and Bk^{250} in the neutron fission counter. The alpha count increased rapidly, at first, as Cf^{250} activity grew in from Bk^{250} beta decay. A much slower linear growth of activity was due to Cf^{249} from the beta decay of Bk^{249}. From this assay an upper limit of 1000 barns for the thermal neutron fission cross section of Bk^{250} was calculated. This limit is substantially lower than an earlier estimate.[30] It implies that Bk^{250} will undergo beta decay in a high-flux reactor without substantial loss to neutron fission.

The growth of Cf^{250} alpha activity allowed the determination of the ratio Bk^{250} to Bk^{249} at the time of removal from the reactor. The thermal flux was estimated[4] from periodic measurements of gold foils at the site of the irradiation. These led to a pile capture cross section for Bk^{249} of 800 barns. The error is estimated to be ±25%.

V. LOWER LIMIT TO THE ELECTRON CAPTURE HALF-LIFE OF Bk^{250}

Mass spectrometric measurements by C. M. Stevens set an upper limit of Cm^{250} to be 5×10^{-7} of the total curium (about 6 mg) obtained by irradiating plutonium with 5×10^{22} neutrons/cm². In the same sample, about 0.05 microgram of californium was produced, over 90% of which came from beta decay of Bk^{250}. If the burnout of californium and curium are neglected, these data lead to a lower limit to the Bk^{250} beta electron capture partial half-life of 50 hours.

VI. Bk^{249} BETA DECAY

The same beta-spectrometer source used to study Bk^{250} was used to study the beta decay of 314-day Bk^{249}. The Fermi-Kurie plot of the single beta group observed (Fig. 6) shows a maximum energy of 125±2 kev. Previous absorption measurements gave values of 114±15 kev,[31] 80+20 kev,[32] and 100±20 kev.[33] The source and backing are such that no particular significance should be attached to the deviation from the allowed shape. The logft value is 7.1 which is consistent with the Nilsson orbitals 7/2+[633] for the 97th proton of Bk^{249} and 9/2−[734] for the 151st neutron of Cf^{249} suggested by Stephens, Asaro, and Perlman.[26] No conversion lines were seen in the spectrum, so if Bk^{249} decays to some state other than the ground state of Cf^{249} the half-life of such a state is longer than a week or its energy is lower than 40 kev.

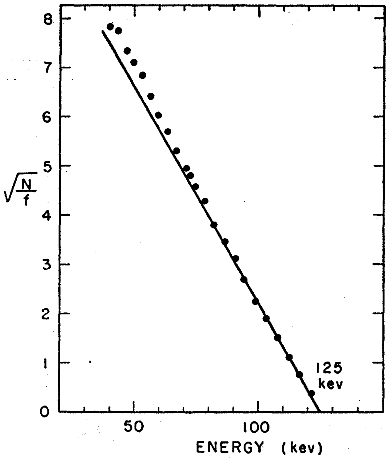

Fig. 6. Fermi-Kurie plot of the Bk^{249} beta spectrum. The deviation from the straight line at the low-electron-momentum part of the plot is not inconsistent with the type of source and detector window used in this experiment.

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