term in the series obtained by integration by parts is more nearly valid for the most tightly bound electrons, and the use of hydrogenic wave functions is less in error for these electrons. Though the relativistic correction is likely to be large here, it seems reasonable to expect that the overall error would not be much larger than a factor of two. The experimental findings are discussed in reference 2. It can be concluded that the probable experimental result is of the order of 10^{-6} K-ionizations per alpha. This is consistent with the theoretical result in reference 1. The reservation relative to the dependence of the experimental result on the estimate of the internal conversion coefficient for the gamma ray of Po^{210}, voiced in reference 2, is apparently removed by the result of a x-ray-electron coincidence experiment reported by Lagasse and Doyen.[9]

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Complex Alpha and Gamma Spectra of $Cf^{250,252}$†

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The alpha and gamma spectra of Cf^{250} and Cf^{252} have been investigated with an alpha-particle spectrograph and an alpha-particle gamma-ray coincidence counter. Alpha groups of 6.112 (84.5%) and 6.069 Mev (15.5%) belonging to Cf^{252} were found, as were groups of 6.024 (83%) and 5.980 Mev (17%), belonging to Cf^{250}. L x-rays and gamma rays of 42 (0.014%) and 100 kev (0.01_3%) were assigned to Cf^{252}. Other gamma rays were assigned to odd-mass californium isotopes. The results are evaluated with respect to the current theory and systematics of complex alpha spectra and excited states of even-even nuclei.

I. INTRODUCTION

In the heavy element region, the alpha-decay characteristics of even-even nuclei show marked regularities with respect to energy level separations and the selective alpha particle population to the various states. The level spacings correlate well with the Bohr-Mottelson[1–3] formulation for collective rotational motion in highly deformed nuclei, and the alpha population to the ground and first even state follow simple alpha decay predictions closely. There are small but significant departures, however, from the simple theory.[4,5]

On the other hand, the alpha population to the second even states varies considerably from the expectations of simple alpha-decay theory.[4,6] The ratio of the predicted to the observed population follows a regular pattern which has been treated in terms of the spheroidal model by various authors.[7]

The present work was undertaken to determine to what extent the trends just mentioned would continue in the californium isotopes Cf^{250} and Cf^{252}. These are beta-stable isotopes with half-lives of ~10 years and ~2 years, respectively.[8,9]

II. METHODS AND APPARATUS

A high-resolution spectrograph[10] was used to measure the separation between the alpha groups to the ground and first even states and their relative intensities. The transmission of the instrument, however, was 4×10^{-5} so that in the weak sources available only the strongest alpha lines were observed.

The L x-ray intensity of the $Cf^{250,252}$ mixture was determined from alpha—L x-ray coincidences. The measurements were made by coincidence counting because the gamma-ray background was comparable to the intensity of L x-rays in the sample whereas the coincidence background was negligible. The alpha detector was zinc sulfide which detected not only alpha particles but also spontaneous fission particles. Compared with the alpha—L x-ray coincidences, however, the spontaneous fission coincidence contributions were very small.

The gamma-ray spectrum of the californium isotopes was also measured in coincidence with alpha particles. These coincidence measurements were necessary because of the relatively large numbers of gamma rays

† This work was performed under the auspices of the U. S. Atomic Energy Commission.
[1] F. Asaro and I. Perlman, Phys. Rev. **87**, 393 (1952); **91**, 763 (1953).
[2] A. Bohr and B. R. Mottelson, Phys. Rev. **89**, 316 (1953); **90**, 717 (1953); Kgl. Danske Videnskab Selskab, Mat.-fys. Medd. **27**, No. 16 (1953).
[3] A. Bohr, *Rotational States of Atomic Nuclei* (Ejnar Munksgaard, Copenhagen, 1954).
[4] I. Perlman and F. Asaro, Ann. Revs. Nuclear Sci. **4**, 157 (1954).
[5] P. Falk-Vairant and J. Teillac, Compt. rend. **236**, 914 (1953).
[6] Asaro, Stephens, Thompson, and Perlman, Phys. Rev. **98**, 19 (1955).
[7] J. O. Rasmussen, Jr., University of California Radiation Laboratory Unclassified Report UCRL-2431, December, 1953 (unpublished); R. F. Christy, Phys. Rev. **98**, 1205 (1955); P. O. Fröman, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. (to be published); B. Segall and J. O. Rasmussen, Jr. (to be published).
[8] Ghiorso, Thompson, Choppin, and Harvey, Phys. Rev. **94**, 1081 (1954).
[9] Diamond, Magnusson, Mech, Stevens, Friedman, Studier, Fields, and Huizenga, Phys. Rev. **94**, 1083 (1954).
[10] F. L. Reynolds, Rev. Sci. Instr. **22**, 749 (1951); Asaro, Reynolds, and Perlman, Phys. Rev. **87**, 277 (1952).

from the spontaneous fission branching of the californium isotopes compared to those accompanying the alpha decay.

For alpha-gamma coincidence counting the alpha particle and fission fragment detector was a $\frac{1}{32}$-inch thick thallium-activated potassium iodide crystal optically coupled to a DuMont-6292 photomultiplier tube. The crystal counting area was masked to a rectangle $\frac{5}{16}\times\frac{1}{4}$ inch with 0.002-inch platinum foil. The output of the photomultiplier tube, after shaping and amplification, was fed into a single-channel pulse-height analyzer. The analyzer selected only the pulses caused by alpha particles and these were fed into a coincidence unit with 2-microsecond resolving time. In some cases the analyzer was adjusted to select only the pulses caused by spontaneous fission fragments. The gamma rays were detected with a $1\times1\frac{1}{2}$ inch thallium-activated sodium iodide crystal optically coupled to a DuMont-6292 tube. The output of the photomultiplier tube after shaping and amplification was fed into the coincidence unit of 2-microseconds resolving time and simultaneously into a 50-channel pulse-height analyzer. The 50-channel analyzer (8-microsecond resolving time) was gated by coincidence pulses from the 2-microsecond unit. This latter unit served to reduce the chance coincidence rate. In all runs the chance coincidences were determined experimentally and subtracted from the total coincidences.

To secure better resolution between the alpha particles and spontaneous fission fragments, the region between the sample and the alpha particle detector was evacuated.

The alpha-particle and gamma-ray detectors each subtended about 20% of 4π in the alpha-gamma coincidence measurements. In the alpha—L x-ray coincidence measurements, the zinc sulfide detector subtended about 40% and the gamma detector subtended about 30% of 4π.

III. SOURCE PREPARATIONS

The californium had been produced by intensive neutron irradiation of lower elements, initially Pu^{239}.[11,12] The pertinent reactions which resulted in the californium preparation are as follows:

$$\begin{array}{l}
Cm^{244}(n,\gamma)Cm^{245}(n,\gamma)\cdots Cm^{249}\\
\qquad\qquad\qquad\qquad\quad \downarrow\beta^-\\
\qquad\qquad\qquad\qquad\quad Bk^{249}(n,\gamma)Bk^{250}\\
\qquad\qquad\qquad\qquad\quad \downarrow\beta^- \qquad\quad \downarrow\beta^-\\
\qquad\qquad\qquad\qquad\quad Cf^{249}(n,\gamma)Cf^{250}(n,\gamma)Cf^{251}(n,\gamma)Cf^{252}(n,\gamma)Cf^{253}.\\
\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\quad \downarrow\beta^-
\end{array}$$

The isotopes listed are beta stable except those designated as β^- emitters. Of the alpha activity in the sample, about 85% was due to Cf^{252} and 15%, Cf^{250}. The Cf^{249} could be estimated from the irradiation history to contribute only about 0.04% to the alpha activity. (The mass of Cf^{249} is only about tenfold lower than that of Cf^{250} but its half-life is 400 to 500 years whereas the half-life of Cf^{250} is 10 years.) Despite the low activity of Cf^{249}, it has prominent gamma rays which showed up in the gamma-ray spectrum which will be mentioned. Similarly, the Cf^{251} and the alpha branching of Cf^{253} can be estimated to be in even lower intensity.

After chemical purification of the californium fraction, part of the activity was electroplated on to a 0.0005-inch platinum plate.[13] The plate had been masked so that the activity could deposit only on a rectangular area $\frac{1}{32}\times\frac{1}{4}$ inch. The electrolytic deposit was dried and heated to a dull red color to drive off volatile matter. This sample, containing 1.2×10^5 alpha disintegrations per minute, was used as the alpha-particle spectrograph source.

The alpha-gamma coincidence source was prepared by evaporating to dryness a few drops of lactic acid solution containing 1.4×10^5 alpha disintegrations per minute on a 0.0005-inch platinum plate. The alpha—L x-ray source was prepared by evaporating to dryness a few drops of concentrated nitric acid containing about 2000 alpha disintegrations per minute on a 0.0005-inch aluminum plate.

IV. EXPERIMENTAL RESULTS

Alpha Spectra

The electroplated sample of mixed californium isotopes described above was exposed in the alpha-particle spectrograph for 141 hours. The alpha particles were detected by direct track counting of the photographic plate which was the receiver in the spectrograph. A graph of the alpha spectrum is shown in Fig. 1. The alpha-particle energies were determined by comparison with Em^{220} α_0 which has been measured by Briggs[14] as 6.282 Mev. The groups at 6.112 ± 0.005 and 6.024 ± 0.005 Mev were assigned to Cf^{252} and Cf^{250}, respectively, in accordance with earlier measurements with ionization chambers. Thompson *et al.* reported early values of 6.15 and 6.05 Mev[8,11,15] and

[11] Thompson, Ghiorso, Harvey, and Choppin, Phys. Rev. **93**, 908 (1954).
[12] Harvey, Thompson, Ghiorso, and Choppin, Phys. Rev. **93**, 1129 (1954).
[13] Harvey, Choppin, and Thompson (unpublished).
[14] G. H. Briggs, Proc. Roy. Soc. (London) **A157**, 183 (1936).
[15] Ghiorso, Thompson, Higgins, Harvey, and Seaborg, Phys. Rev. **95**, 293 (1954).

later revised them to 6.13 and 6.04 Mev.[16] Diamond *et al.*[9] reported alpha-particle energies of 6.12±0.01 and 6.03±0.01 Mev, and Magnusson *et al.*[17] reported values of 6.117±0.010 and 6.033±0.010 Mev for these isotopes.

Among even-even alpha emitters in this region there are prominent alpha groups some 40 kev lower in energy than the most abundant groups[4] and in an abundance of 15 to 30%.[4,6] By analogy, the groups at 6.069 and 5.980 Mev are assigned to Cf^{252} and Cf^{250}, respectively. The existence of complex structure in both Cf^{252} and Cf^{250} was determined previously from L x-ray-alpha particle coincidence measurements by Diamond *et al.*[9] Magnusson *et al.*[17] reported the energy separations to be between 40 and 45 kev.

In order to determine the energy of the first excited state of the product nucleus one must add to the 43-kev separation between the alpha groups of Cf^{252}, a nuclear recoil energy difference of 0.7 kev. Thus the energy becomes 44 kev. Similarly, in the case of Cf^{250} decay, a 43.6-kev separation in alpha-particle energy corresponds to a 44-kev first excited state energy in the daughter nucleus. To simplify their description, the alpha groups to the ground state are designated α_0, and those for the 44-kev states are designated α_{44} (an alpha group to an excited state of x kev would thus be called α_x).

The intensities of the alpha groups were determined by integrating the area under the peaks. Although the alpha particles from the electroplated sample were resolved quite well considering the objective of obtaining high transmission, there appears to be an appreciable tailing on the low-energy side of the peaks. This tailing was estimated from α_{44} of Cf^{250}, by assuming that all of the alpha peaks on the photographic plate had very nearly the same shape. After resolving the peaks in this manner intensities for Cf^{252} α_{44} and Cf^{250} α_{44} were 15.8% and 17.5%, respectively. From the spectrograph measurements, the abundance of Cf^{250} alpha activity at the time of the run was 14.2% of the total alpha activity. The remaining 85.8% was due to Cf^{252}. The weighted average of the $Cf^{250,252}$ α_{44} groups was then 16.0%. This number will be useful for comparison with the alpha-L x-ray coincidence work discussed next.

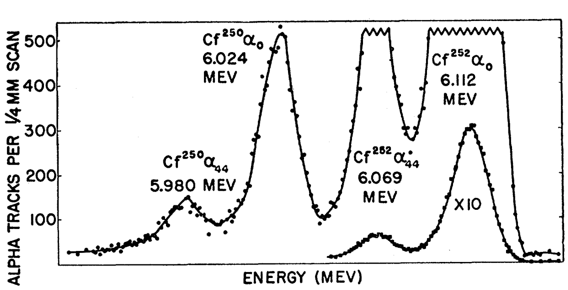

FIG. 1. Alpha spectra of Cf^{250} and Cf^{252}.

V. COINCIDENCE STUDIES

Alpha-L X-Ray Coincidences

The abundance of an alpha group in an even-even nucleus which populates the first excited state can be determined indirectly from the intensity of L x-rays since the corresponding gamma ray transition is by far the most prominent and is heavily converted in the L shell. The intensity is best measured by determining the alpha-L x-ray coincidence rate per alpha disintegration. The corrections which must be applied to the raw data to obtain the total population of the first excited state are the following: (1) allowance for fluorescence yield of the L x-rays; (2) conversion in M, N . . . shells; (3) geometry factor; (4) L x-ray attenuation between source and detector. The geometry factor was determined by measuring the coincidence rate of the alpha particles of Am^{241} with its 60-kev gamma ray whose abundance is known.[18] In order to minimize some of the uncertainties in the other correction factors, Cm^{242} was used as a standard for comparison. The alpha population to the first excited state for this isotope is known fairly accurately[19] and its alpha-L x-ray coincidence rate was measured under the same experimental conditions. The population of the first excited state defines the total electron vacancies and from the conversion electron spectrum[20] the number of L-shell vacancies can be calculated. The measured L x-ray intensity must then be brought into agreement with this value by correcting for fluorescence yield and L x-ray absorption. These two factors were dissociated by accepting the calculated[21] fluorescence yield, thereby ending up with an effective absorber thickness to produce the required attenuation of the particular L x-rays from Cm^{242} decay. Now the desired values for the californium isotopes could be obtained by applying these corrections in reverse fashion. Since the Cm^{242} was used as a standard, the errors are only those of second-order nature in extrapolating fluorescence yields and x-ray attenuation factors over two units of atomic number.

The results of these measurements and calculations gave 15.5% as the weighted average for the abundances of the α_{44} groups of Cf^{250} and Cf^{252}. This is to be compared with the 16.0% value from direct alpha track counting already cited. The complete independence of the two methods lends some confidence to the alpha-L x-ray coincidence counting method which can be applied to sources of this type which are too weak to obtain the alpha spectrum.

[16] Thompson, Ghiorso, Harvey, and Choppin (unpublished data, 1954).
[17] Magnusson, Studier, Fields, Stevens, Mech, Friedman, Diamond, and Huizenga, Phys. Rev. **96**, 1576 (1954).
[18] Beling, Newton, and Rose, Phys. Rev. **86**, 797 (1952).
[19] Asaro, Thompson, and Perlman, Phys. Rev. **92**, 694 (1953).
[20] T. O. Passell, Ph.D. thesis, University of California Radiation Laboratory Unclassified Document UCRL-2528, March, 1953 (unpublished).
[21] B. B. Kinsey, Can. J. Research **A26**, 404 (1948).

TABLE I. Alpha-particle gamma-ray coincidence results.

Exp. No.	42-kev gamma-ray[a] Energy (kev)	Abundance ($\times 10^{-4}$)	67-kev radiation Energy (kev)	Abundance	100-kev gamma ray Energy (kev)	Abundance ($\times 10^{-4}$)	K-ray maximum abundance ($\times 10^{-5}$)	~180-kev gamma ray Energy (kev)	Abundance	Other radiations Energy (kev)	Abundance
1	43	1.5	66–73	2.6	99	1.3	5	~190	>8[b]	[c]	...
2	41	1.3	67	4.3	96	1.0	7	[c]		[c]	...
3	~40	1.5	70	1.2	99	1.4	9	~180	22	[c]	...
4	~40	1.4	63–67	2.5	100	1.4	7	~180	8	350–400	3
Best value[d]	42[a]	1.4	...	...	100	1.3	7	...	...	350–400	3

[a] This energy value is not as accurate as that derived from the separation of the peaks in the alpha spectrum.
[b] The gamma-ray peak would have been just partially observed in this experiment.
[c] These gamma rays would not have been observed in this experiment.
[d] The contribution of gamma rays of 99^{253} produced by Cf^{253} decay would be less than 10% of any of californium gamma rays.

Magnusson *et al.*[17] reported abundances of about 10% for both of these groups from L x-ray alpha-particle coincidence measurements using the abundance of Pu^{238} α_{44}, 24%, as a standard. A later value of 28%[22] for the abundance of Pu^{238} α_{44} would then raise the californium abundances of Magnusson[17] to about 12%.

Gamma Rays

Four measurements of the alpha-particle gamma-ray coincidence spectrum were made. The energies and abundances of the observed radiations are shown in Table I. A graph of the results of Exp. 2 are shown in Fig. 2.

Spontaneous fission fragment gamma-ray coincidence measurements were also taken. With our detection system, a gamma-ray "continuum" was observed which rose to a plateau at $125 \rightarrow 200$ kev and then decreased continuously out to several Mev. Superimposed on the continuum was a peak at ~63 kev which might well have been due to platinum K x-rays produced in the platinum sample mounting by the fission gamma rays. Figure 3 shows the fission fragment-photon coincidences in the region of interest. From this spectrum it seems unlikely that any of the gamma rays shown in Table I are a result of the spontaneous fission process.

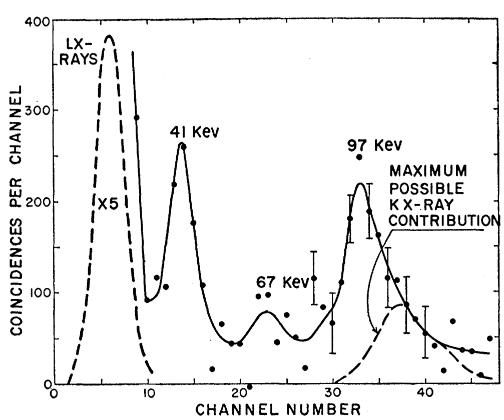

FIG. 2. Alpha-particle gamma-ray coincidence spectrum of $Cf^{250,252}$ from experiment 2 (see Table I).

[22] F. Asaro and I. Perlman, Phys. Rev. **94**, 381 (1954).

44-kev Transition

The "42-kev" gamma ray is interpreted as belonging to the highly converted transitions of 44 kev leading from the first excited states to the ground states in both Cf^{250} and Cf^{252} decay. The energy measurement from the alpha data is somewhat better than the gamma-ray value, so the 44-kev value is preferred. The abundance of this gamma ray is 1.4×10^{-4} per alpha particle (Table I). With the weighted abundance of the alpha groups to the 44-kev levels of 16%, the conversion coefficient is 1.1×10^{3}. Since this value is nearly the same as found for the analogous transition in Cf^{246},[23] it is reasonable to assume that the corresponding conversion coefficients of Cf^{250} and Cf^{252} will not differ markedly. Therefore, as the sample activity is predominantly Cf^{252}, the measured conversion coefficient applies principally to Cf^{252}. By comparing this conversion coefficient with theoretical values[24,25] it is found that the transition can only be $E2$. The observed value is about a factor of 3 lower than the calculated value[25] for an $M2$ transition but conversation of parity requires that gamma transitions to the ground state of an even-even nucleus from states populated by alpha emission be electric transitions.

Inasmuch as the 44-kev state of Cm^{248} (populated by Cf^{252} alpha decay) de-excites to the ground state by an $E2$ transition, the spin of the 44-kev state is 2, even parity. This is, of course, expected since nearly all even-even nuclei are found to have a 2+ first excited state.[26–28]

100-kev Transition

Whenever a photon of ~100 kev is seen in the heavy element region it is necessary to consider the possibility

[23] Hummel, Stephens, Asaro, Chetham-Strode, and Perlman, Phys. Rev. **98**, 22 (1955).
[24] Gellman, Griffith, and Stanley, Phys. Rev. **85**, 944 (1952).
[25] Rose, Goertzel, and Swift (privately circulated tables).
[26] M. Goldhaber and A. W. Sunyar, Phys. Rev. **83**, 906 (1951).
[27] Horie, Umezawa, Yamaguchi, and Yoshida, Progr. Theoret. Phys. (Japan) **6**, 254 (1951).
[28] G. Scharff-Goldhaber, Phys. Rev. **90**, 587 (1953).

that it may be a K x-ray or a gamma ray or both. For curium, the K x-ray group should produce a peak of approximately 108 kev and it is seen from Fig. 2 that most of the peak at ~100 kev lies at too low an energy. However, the peak does tail on the high-energy side, and it seems likely that it is not produced by a single photon. In order to get a reasonable minimum value for the intensity of the gamma ray, a peak centering on the K x-ray energy of 108 kev was resolved. The shape of the subtracted peak was obtained by weighting the different components of the K x-ray group according to the relative intensities observed for uranium.[29]

The intensity of the 100-kev gamma ray after subtracting the maximum possible K x-ray contribution was $1.3\times10^{-2}\%$ of the total californium alpha particles. The group attributed to K x-rays has a corresponding maximum intensity of $7\times10^{-3}\%$. The best energy of the gamma ray is 99 kev; it would be 101 kev if the K x-ray subtraction is not made.

This gamma ray probably represents a transition from the second even spin state[30] to the first even spin state of each of the isotopes, Cf^{252} and Cf^{250}. This assignment is made by analogy with other even-even alpha emitters in this region.[4,31] For example, the gamma spectra of Cm^{242} [19] and Pu^{238},[22] have gamma rays of about 100 kev which are known to decay from the second to the first even states. Because of the preponderance of Cf^{252} in the sample, the measured energy and abundance of the gamma ray apply principally to Cf^{252} decay. As these values are much the same as found in Cf^{246} decay,[24] however, Cf^{250} would be expected to show in its decay a gamma ray of similar energy and abundance.

Other Radiations

Radiations of approximately 67, approximately 180, and approximately 350 → 400 kev were also observed.

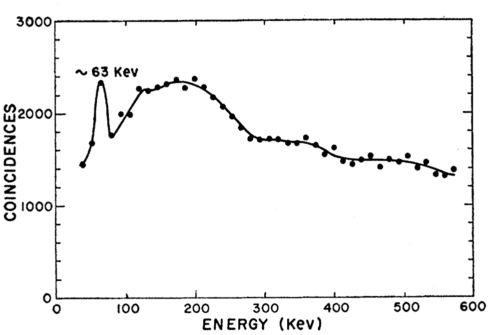

FIG. 3. Partial spontaneous fission fragment gamma-ray coincidence spectrum of $Cf^{250,252}$.

[29] Extrapolation of curves given by A. H. Compton and S. K. Allison, *X-Rays in Theory and Experiment* (D. Van Nostrand Company, Inc., New York, 1935), p. 641.

[30] The term *even spin states* refers to the sequence of 2+, 4+, 6+ excited states which is characterized as a rotational band based on the 0+ ground state of an even-even nucleus in this region.

[31] F. Asaro and I. Perlman, Phys. Rev. **91**, 763 (1953).

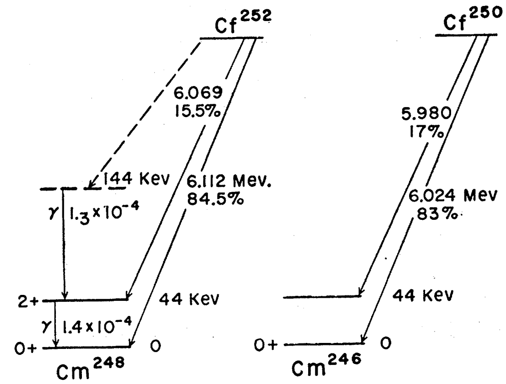

FIG. 4. Alpha-decay schemes of Cf^{250} and Cf^{252}.

The 67-kev radiation is probably due in large part to platinum K x-rays arising from the fluorescence excitation of the sample backing plate by the higher energy gamma rays.

A sample of highly enriched Cf^{249} which had grown into previously purified Bk^{249} containing small amounts of Cf^{250} and Cf^{252} was separated and subjected to alpha-gamma coincidence counting. Two gamma rays of 340 and 395 kev with abundances of 16 and 60%, respectively, relative to the Cf^{249} alpha activity, were observed. These gamma rays correspond well with the 350 → 400 kev radiations seen in the mixed californium isotopes (see Table I). Since the alpha activity due to Cf^{249} in this sample is estimated to be ~0.04%, the observed intensities of these gamma rays, 0.03%, is not out of line. The gamma ray at 180 kev is not accounted for by the Cf^{249} but could possibly come from the Cf^{251} or Cf^{253}. From estimations of the amounts of Cf^{251} and Cf^{253}, their alpha-emission half-lives, and alpha-particle energies, it seems barely possible for Cf^{253} to have an alpha group in as large an abundance as the 180-kev gamma ray but quite reasonable for Cf^{251}.

VI. DISCUSSION AND SUMMARY

Cf^{250} and Cf^{252} have alpha and gamma spectra which are typical of heavy element even-even alpha emitters. Their decay schemes are shown in Fig. 4. In both decays the most abundant alpha group goes to the ground state of the daughter nucleus. The decay of Cf^{249}, however, indicates a different type of spectra in which the most abundant alpha group populates an excited state in the daughter nucleus which then decays to the ground state by one or more gamma transitions. A corollary to this effect is that the ground-state alpha groups in the even-even decay have hindrance factors of about 1, whereas the ground-state transitions for odd mass emitters may be hindered[32] by many orders of magnitude.

[32] "Hindrance" or "hindrance factor" as used here is defined as the ratio of the expected abundance from alpha-decay theory to the experimental abundance.

Cf^{250} and Cf^{252} each populate first excited states in their respective daughters of about 44 kev in an abundance corresponding roughly to the predictions of alpha-decay theory. More precisely these alpha groups are hindered by about a factor of 3, similar to Cf^{246}, somewhat lower than in 100^{254} decay and somewhat higher than in the decay of elements of lower atomic number. The spin and parity of the first excited state populated by Cf^{252} decay was deduced from the conversion coefficient to be 2+ in common with nearly all other even-even nuclei.

The 100-kev gamma ray in Cf^{252} decay is interpreted as the transition from the second even state to the first even state. The energies of the first and second states are such that they can be interpreted as a Bohr-Mottelson rotational band with a consequent spin of 4+ for the second even state. The alpha decay to the second even state as deduced from the abundance of the 100-kev gamma ray is lower by over two orders of magnitude from the predictions of spin-independent alpha-decay theory. This hindrance factor is very similar to that of Cf^{246} and appears to follow the general trends observed for corresponding transitions in other even-even nuclides.

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Double *K* Capture and Single *K* Capture with Positron Emission

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Transition probabilities are estimated for double K capture and for single capture with single positron emission. With real neutrino emission, the mean lives for both processes should be greater than 10^{24} years. Without real neutrino emission, as with Majorana neutrinos, the mean life for K capture in conjunction with positron emission is about 10^{15} years in the allowed approximation. Double K capture, however, is then at least a third-order process because an additional step is necessary to remove the energy, with the result that the mean life exceeds 10^{18} years.

I. INTRODUCTION

FOUR possible types of double beta processes[1] are double negatron emission, double positron emission, double negatron capture, and single capture with single positron emission. Double negatron emission probabilities have been calculated with various theories, while double positron probabilities are given, except for the Coulomb distortion of the wave functions of each of the emitted electrons, by similar calculations. Most experiments have been searches for these double emission processes.

One published experiment[2] and some private speculation, however, involved attempts to detect double capture or single capture with single positron emission. Double capture will be the only energetically possible transition if the mass difference between the parent atom and the isobaric atom with atomic number less by two lies between 0 and $2mc^2$. Either double capture or one capture and one positron emission can occur if the atomic mass difference is between $2mc^2$ and $4mc^2$. Both of these processes and double positron emission can occur if the difference is greater than $4mc^2$.

It is the purpose of this note to exhibit rough estimates of the transition probabilities for double capture and for single capture with positron emission.

[1] See references in Rolf G. Winter, Phys. Rev. **99**, 88 (1955).
[2] Berthelot, Chaminade, Levi, and Papineau, Compt. rend. **236**, 1769 (1953).

II. DIRAC NEUTRINOS

If the neutrino is a Dirac particle, double capture probabilities can be calculated from a second order perturbation. Both steps consist of the capture of a K negatron and the emission of a neutrino. The calculation is like that used by Goeppert-Mayer,[3] except that K negatrons are captured rather than free negatrons being emitted. If one intermediate nuclear state s, about mc^2 above the initial state i, contributes most of the result, the probability of transition to the final state f is given by

$$w_{if}=\frac{2\pi}{\hbar}\rho\left|\sum_s \frac{H_{is}H_{sf}}{mc^2+E_\nu}\right|^2, \quad (1)$$

where the energy of the first neutrino is E_ν.

If the total energy that must be removed by the neutrinos is E, one obtains, for unit volume normalization,

$$\rho\left(\sum_s \frac{1}{mc^2+E_\nu}\right)^2 = (2\pi^2\hbar^3c^3)^{-2}\int_0^E (E-E_\nu)^2E_\nu^2\frac{dE_\nu}{(mc^2+E_\nu)^2}. \quad (2)$$

If the lepton spin sums and nuclear wave function

[3] M. Goeppert-Mayer, Phys. Rev. **48**, 512 (1935).