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^{134}Ba level scheme as observed in the decay of ^{134}La†

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The level scheme of even-even ^{134}Ba has been studied from the decay of the ^{134}Ce (75.9 h)$\rightarrow$^{134}La (6.67 min) chain. Samples of ^{134}Ce were produced by ~800-MeV proton bombardment of Pr foils, followed by chemical and mass separation. γ-ray energy and intensity measurements were made using Ge(Li) and Si(Li) detectors. Identification of γ rays as belonging to the ^{134}La decay was made in separate experiments using sources of ^{134}La milked from the parent ^{134}Ce activity. In this manner, ~99 γ-ray transitions have been associated with the ^{134}La decay scheme. From these data and γ-γ coincidence measurements, a comprehensive level scheme is proposed for ^{134}Ba, consisting of ~41 excited states. Further information on the energies of levels in ^{134}Ba was derived from a subsidiary series of γ-ray energy measurements using a source of ^{134}Cs. For the ^{134}La decay, log*ft* values were obtained from relative x-ray, annihilation-quanta, and γ-ray intensities and using intensity-balance considerations for the individual levels in ^{134}Ba. A comparison is made of the ^{134}Ba data with the predictions of several recent theoretical calculations dealing with even-even nuclei in this mass region.

RADIOACTIVITY ^{134}La from Pr[(p, spallation)]; measured E_γ, I_γ, γ-γ; ^{134}Ba deduced levels, J, π, log*ft*. Ge(Li) and Si(Li) detectors, chemical separation, isotope separations. ^{134}Cs; measured E_γ.

I. INTRODUCTION

In this paper, we present the results of an investigation of the ^{134}Ba level scheme as observed in the decay of ^{134}La. The properties of nuclides in this mass region ($50 < Z, N < 82$) are of considerable current interest because of the information which they provide concerning the collective potential-energy surfaces and how these surfaces vary with both proton and neutron number. A number of fairly detailed calculations of the features of these potential-energy surfaces for the neutron-deficient even-even Xe, Ba, Ce, and Nd nuclei have been carried out (see, e.g., Refs. 1–3); and, quite recently, calculations of the collective energy-level spectra[4] and of the $E2$ and $E0$ transition probabilities[4,5] for many of these nuclei have appeared. These latter calculations contain a number of results which are presently not verified experimentally because of a lack of data. Additional information on the level schemes of these nuclei can serve as a check of the ideas underlying these calculations and thus help lead to an improved understanding of the features of their potential-energy surfaces.

Essentially all of our knowledge of the level structure of the even-even nucleus ^{134}Ba has come from radioactive-decay studies of both 2.06-yr ^{134}Cs and 6.67-min ^{134}La. Because of its long half-life, ease of production (by neutron capture) and relatively simple decay scheme, the most complete information is available for those states populated in the ^{134}Cs decay. Studies of this decay include measurements of the γ-ray energies and intensities,[6-9] the internal-conversion electrons,[6-10] the γ-γ coincidence relationships,[7,8] and the γ-γ angular correlations.[11] These studies have established levels in ^{134}Ba with the following energies (and I^π values): 604 (2^+), 1167 (2^+), 1400 (4^+), 1643 (3^+), and 1969 keV (4^+).

There is much less complete information available on those levels in ^{134}Ba which are populated only in the decay of ^{134}La. This is because of the complexity of the decay scheme, resulting from the larger Q value. Studies of the ^{134}La decay include measurements of the half-life,[12,13] the γ-ray energies and intensities,[12-17] the internal-conversion electrons,[17,18] the β^+ energies,[14,17-19] and the β^+-γ[14] and γ-γ[12,14,16,17] coincidence relationships. As a result of these studies, additional levels in ^{134}Ba have been reported with energies of 1760, 2029, 2088, 2159, 2336, 2379, 2489, 2565, 2601, 2698, 2748, 2826, 2946, 3413, and 3423 keV. The levels at 1760, 2336, 2379, and 2489 keV have been assigned as having $I^\pi = 0^+$ based on the observation[15,17] of ground-state $E0$ transitions.

A deficiency of previous studies of the ^{134}La decay has been in the γ-ray spectroscopy. These measurements are complicated by the fact that ~98% of the decay directly populates either the ground state (~94.6%) or the first excited state (~3.4%). Since a large fraction of these decays proceed via β^+ emission, the 511-keV annihilation line dominates the γ-ray spectrum. Thus, in order to observe lines corresponding to the weaker γ-ray transitions in the spectrum, large Ge(Li) detectors are necessary and high counting rates with long counting times must be tolerated. At the same time, summing (both real and random) must be minimized. Despite the short half-life (6.67 min) of ^{134}La, these conditions can be achieved using sources of ^{134}Ce [$T_{1/2}=75.9$ h] (Ref. 20), which decays to ^{134}La. The present work was undertaken to obtain more complete information on the ^{134}La decay by means of γ-ray singles and coincidence spectroscopy using Ge(Li) detectors with good energy resolution. Special effort was made in this work to obtain precise γ-ray energies and intensities, in addition to achieving the adequate detection sensitivity. As a complement to this work, energies of several lines from the ^{134}Cs decay were remeasured to higher precision.

While this paper was in preparation, a mass-chain evaluation for $A=134$ was published.[21] The evaluation given there for the ^{134}La decay scheme is based largely on unpublished data[22] and, consequently, detailed comparisons with the present work are difficult. The ^{134}La decay scheme presented in Ref. 21 is in substantial agreement with that proposed in the present work, although a number of differences in level placements and I^{π} assignments exist. One important difference is that, in Ref. 21, it is assumed that all the γ rays observed in the $^{134}\mathrm{Ce}\rightarrow{}^{134}\mathrm{La}\rightarrow{}^{134}\mathrm{Ba}$ decay chain are associated with the ^{134}La decay. However, in a companion work,[23] we have shown that this is in fact not the case and that the ^{134}Ce decay exhibits a rather complex γ-ray spectrum.

II. EXPERIMENTAL METHOD

A. Source preparation

The sources of ^{134}Ce-^{134}La used in these experiments were produced by spallation in praseodymium-metal targets using ~800-MeV protons from the Clinton P. Anderson Meson Physics Facility (LAMPF). Typically, samples of praseodymium foils having a total thickness of 0.030 cm were irradiated in an integrated beam flux of ~15 μAh. After bombardment, the irradiated foils were transported to the Idaho National Engineering Laboratory for study.

The Ce fraction was separated from the other spallation products and the Pr using the following procedure. The Pr foils were dissolved in 5 M HCl. Following dissolution, 1-mg Ce^{+3} carrier was added and $\mathrm{Ce(OH)_3}$ precipitated. This precipitate was washed with H_2O and converted to the nitrate by thrice heating to near dryness with concentrated $\mathrm{HNO_3}$. The Pr and Ce salts were dissolved in a 10 M $\mathrm{HNO_3}$-0.1 M $\mathrm{NaBrO_3}$ solution and the oxidized Ce^{+4} was extracted into 0.3 M di-2-ethylhexylphosphoric acid (HDEHP) in heptane. Cerium was further purified by twice washing the HDEHP with 10 M $\mathrm{HNO_3}$-0.1 M $\mathrm{NaBrO_3}$, back extracting with 6 M $\mathrm{HNO_3}$ containing several drops of 30% $\mathrm{H_2O_2}$, and finally scrubbing the strip solution with heptane. $\mathrm{Ce(OH)_3}$ was precipitated from the back extractant and washed twice with H_2O and twice with ethyl alcohol. Following the chemical separation, the residual fraction of Ce (mass ~0.5–1.0 mg) was mass separated. A surface-ionization-type ion source was employed in these separations and a complete separation typically took ~4–6 h. Immediately following separation, γ-ray spectra were measured from each mass slice, and from positions intermediate between the mass slices, to determine the magnitude of cross contamination. Such cross contamination was acceptably small and could be simply corrected for.

As a first step in determining the elemental assignment of the γ rays in the ^{134}Ce-^{134}La decay chain, the ^{134}La daughter was milked from the ^{134}Ce parent using the following procedure. The Al collector foil from the mass separation, containing the mass-134 fraction, was dissolved in HCl and converted to the nitrate. The oxidized ^{134}Ce was extracted into HDEHP and washed using the procedure described above. The ^{134}La could then rather quickly be milked repeatedly from the ^{134}Ce-HDEHP solution by extracting with 10 M $\mathrm{HNO_3}$-0.1 M $\mathrm{NaBrO_3}$ after allowing sufficient time between extractions for the ^{134}La to grow back in to near equilibrium. Because of the short half-life of ^{134}La, repetitive separations had to be made in order to accumulate a satisfactory γ-ray spectrum of ^{134}La alone. These measurements, together with a complementary set (described in detail in Ref. 23) in which the La was continuously milked from the Ce parent, established that a number of γ-ray lines in the ^{134}Ce-^{134}La equilibrium spectrum are in fact associated with the ^{134}Ce decay.

B. γ-ray spectroscopy

1. γ-ray singles measurements

Two separate Ge(Li) detector systems (each with a 4096-channel analog-to-digital converter and memory unit) were used for the γ-ray singles measurements with the ^{134}Ce-^{134}La and ^{134}Cs sources. One of these systems used a 65-cm^3 closed-ended coaxial Ge(Li) detector, while the other system used a 50-cm^3 true coaxial Ge(Li) detector. Both detector systems had an energy resolution $\lesssim 2$ keV at 1 MeV.

Methods of γ-ray singles spectroscopy with

Ge(Li) and Si(Li) detectors which we are currently using have been discussed in detail in Refs. 24–27. In brief we note that peak detection efficiencies for the principal Ge(Li) detectors used in this work have been obtained at source-to-detector distances of 3, 5, 10, 17.5, 25, and 35 cm by absolute calibration with various sources which had previously been calibrated to obtain their γ-emission rates by IAEA, NBS, or at this laboratory using a standard[28] NaI(Tl) detector system. We estimate that the resultant peak-efficiency versus energy curves that have been constructed from these data are accurate to ±3% (1σ level) below ~150 keV, to ±1.5% between 150 keV and ~2.8 MeV, and to 1.5–10% above 2.8 MeV. In all of the present measurements, corrections have been made where necessary for coincidence summing effects. The determination of the peak-efficiency curve for the $30\text{-mm}^2 \times 3$-mm planar Si(Li) detector has been described in Ref. 29.

Energies of the prominent lines in the ^{134}La spectrum were measured by recording the spectra simultaneously with the spectra from suitable radioactive sources whose γ-ray energies are precisely known.[24,25,30] Calibration sources which were used in this work included ^{7}Be, ^{46}Sc, ^{51}Cr, ^{54}Mn, ^{56}Co, ^{60}Co, ^{88}Y, ^{94}Nb, ^{137}Cs, ^{139}Ce, ^{144}Ce, ^{207}Bi, and ^{228}Th. With the energies of the prominent lines in the ^{134}La spectrum determined in this manner, these lines were themselves then used as calibration lines to determine the energies of the weaker lines in spectra of ^{134}La alone.

γ-ray spectra were analysed to obtain peak positions and peak areas using the GAUSS V program.[31] In order that precise γ-ray energy measurements might be made, correction curves for the total system nonlinearity were determined for each detector-amplifer-analyzer system using the techniques described in Refs. 24 and 25.

2. *γ-γ coincidence spectroscopy*

The 50-cm^3 coaxial Ge(Li) detector used in the singles γ-ray spectral measurements was used together with a ~55-cm^3 coaxial Ge(Li) detector in the γ-γ coincidence system. Generally, a 180° geometry was used for these measurements, with the ^{134}La source sandwiched between 1.25-g/cm^2 Be absorbers to prevent positrons from reaching the detectors. For coincidences with the 511-keV annihilation radiation, though, a 90° geometry was used, with a Cd + Pb anti-Compton shield placed between the detectors. In these latter measurements, the Be-absorber sandwich served to localize the production of annihilation radiation to the vicinity of the source position. The fast coincidence gate was operated at resolving times (2τ) of either 20 or 40 ns. A 4096-channel coincidence spectrum was collected in coincidence with pulses corresponding to a γ ray of interest. The latter were selected by means of a single-channel analyzer.

III. EXPERIMENTAL RESULTS

A. γ-ray singles data

1. *γ-ray singles measurements*

A typical γ-ray spectrum of a mass-separated ^{134}Ce-^{134}La sample, measured at a source-to-detector distance of 10 cm using the 65-cm^3 Ge(Li) detector system, is shown in Fig. 1. Immediately obvious from this figure is the extent to which the 511-keV annihilation radiation peak dominates the spectrum. Two deleterious effects of this are (i) the high counting rates and long running times (~2 days) which must be tolerated in order to achieve reasonable counting statistics in the higher energy portion of the spectrum and (ii) the consequent higher level of random coincidence summing effects (the prominence of the 511-511 random coincidence summing is readily apparent in Fig. 1). In order to achieve the maximum sensitivity for detection of peaks in spectra such as that shown in Fig. 1, it proved to be desirable not to have complete positron annihilation immediately adjacent to the ^{134}Ce-^{134}La source. Instead, only a single 1.25-g/cm^2 Be absorber was located adjacent to the source, between the source and the detector. As a consequence of this experimental arrangement, the 511-keV intensity ratio obtained from the spectra was incorrect, and this intensity had to be obtained in separate experiments (Sec. III A 2).

Real coincidence summing with the 604-keV γ ray, deexciting the first excited state, was also troublesome in that it tended to enhance the peak intensity of other ground-state transitions. In order to correct for this effect, it was necessary to measure spectra of ^{134}Ce-^{134}La at a variety of source-to-detector distances. Thus, such spectra were measured at source-to-detector distances of 3, 5, 10, and 25 cm. Even so, it has not yet been established unambiguously whether or not ground-state γ-ray transitions with energies of 2159 and 2747 keV exist.

To confirm that lines observed in the spectrum from the ^{134}Ce-^{134}La sources indeed originated from this decay chain, each source used was periodically remeasured over an ~3-week period. In this way it could be confirmed that the peaks all decayed with approximately the same half-life. Apart from the background lines seen in the spectrum, e.g., ^{228}Th, ^{40}K, and ^{60}Co, no other lines were seen which could not be associated with the

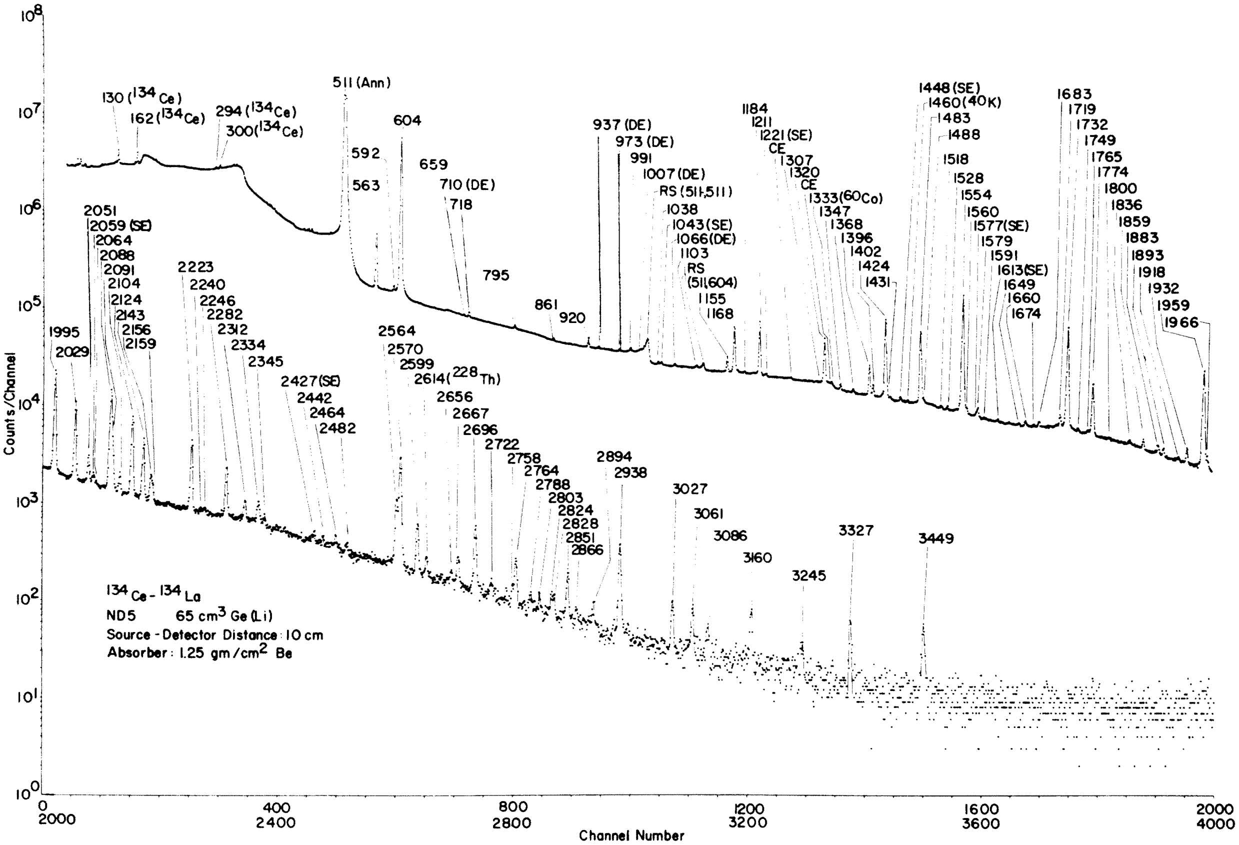

FIG. 1. γ-ray spectrum of ^{134}Ce-^{134}La equilibrium source obtained using a 65-cm^3 Ge(Li) detector. In this spectrum it should be noted that channels at the peak of the 511-keV annihilation radiation have overflowed (maximum channel capacity 2^{24}). The lowest energy peaks (< 511) identified in this spectrum are all associated with the ^{134}Ce decay, while at higher energies the peaks result from the ^{134}La decay. Peaks labeled SE and DE result from one and two annihilation quanta escape processes, while RE indicates a random coincidence summing process.

^{134}Ce-^{134}La decay chain.

In Fig. 1, and all other ^{134}Ce-^{134}La spectra, there are a number of lines with energies below that of the 511-keV peak (e.g., the 130-, 162-, 294-, and 300-keV peaks identified in Fig. 1) which also appear to decay with a half-life consistent with that of the ^{134}Ce-^{134}La decay chain. In the γ-ray spectrum obtained from pure ^{134}La sources, however (prepared as described in Sec. II A) these peaks were not present. Further studies with sources depleted in ^{134}La confirmed that these transitions originated in the ^{134}Ce decay.[23]

A listing of the averaged energies and intensities (relative) of the γ-ray transitions which could be associated with the ^{134}La decay in the present work is given in Table I.

2. *Annihilation radiation intensity*

In order to estimate the intensity of the positron decay component of ^{134}La, as well as to eventually estimate absolute γ-ray transition intensities, it is necessary to have a measure of the 511-keV annihilation radiation peak relative to the ^{134}La decay γ rays. To accomplish this, ^{134}Ce-^{134}La samples were sandwiched between two Be absorbers, each 1.25 g/cm^2 thick, to achieve complete positron annihilation in the Be. γ-ray spectra of these sources were measured at source distances of 3, 5, and 10 cm. After correcting for γ-ray self-absorption in the Be we obtained the following relative γ-ray intensity ratio:

$$\frac{I(511)}{I(604)} = 23.9 \ (\pm 3\%) .$$

In this analysis it is assumed that all the 511-keV γ rays result from the annihilation of positrons. While pair production of γ rays with energies $\geq 2m_0c^2$ in the materials surrounding the Ge(Li) detector will contribute to the area of the 511-keV peak, the relative intensity of the annihilation radiation is such that this contribution will be negligibly small compared to the quoted uncertainty.

TABLE I. γ-ray energies and intensities from ^{134}La decay.

γ-ray energy[a] (keV)	Error (keV)	Relative γ-ray intensity[b]	Error (%)
Ba *K*-x		7020	8
475.33	0.21	1.27	30
511 (Ann)		29130	4
563.226	0.013	86.7	2.5
592.577	0.038	3.98	7
604.699	0.012	1218.7	2.5
659.85	0.09	0.62	10
718.709	0.028	2.90	7
795.907	0.032	1.83	7
861.286	0.047	0.99	10
920.347	0.024	4.32	5
991.725	0.042	1.38	7
1038.68	0.05	0.91	7
(1103.5)	0.5	0.2	50
1155.826	0.028	4.68	5
1168.1	0.1	18.5	7
1168.63	0.08	5.2	20
1184.92	0.12	0.42	15
1211.145	0.026	28.59	2.5
(1243.84)	0.21	0.54	20
(1255.06)	0.26	0.35	40
(1260.1)	0.6	0.35	40
1307.0	0.7	0.18	50
1320.701	0.028	19.80	2.5
1347.34	0.05	1.18	5
1368.96	0.07	0.74	10
1396.730	0.029	8.55	2.5
1402.889	0.034	2.47	5
1424.506	0.030	45.4	2.5
1431.35	0.13	0.54	20
1483.516	0.031	35.9	2.5
1488.29	0.27	1.05	20
1528.54	0.07	0.64	10
1554.934	0.032	100.0	2.5
1560.42	0.48	1.18	30
1579.92	0.15	1.14	20
1591.1	1.1	0.22	30
1649.68	0.16	0.29	15
1660.57	0.07	0.73	10
(1674.6)	0.5	0.14	40
1683.33	0.07	0.77	10
1719.04	0.05	1.50	5
1732.129	0.035	56.6	2.5
1749.41	0.13	0.34	15
1765.71	0.22	0.53	20
1774.353	0.036	11.55	2.5
(1800.8)	0.5	0.084	40
1836.43	0.15	0.40	15
1859.43	0.06	0.86	7
1883.74	0.12	0.80	10
1893.20	0.08	0.56	10
(1918.0)	0.5	0.18	40
1932.16	0.06	1.07	7
1959.956	0.043	23.55	2.5
1966.07	0.12	1.03	15
1995.138	0.044	21.57	2.5
2029.191	0.044	9.49	2.5
2051.55	0.10	1.42	10
(2064.4)	0.5	0.15	30
2088.24	0.05	14.0	5
2091.99	0.10	2.38	10
2104.11	0.06	0.75	7
2124.482	0.050	7.50	2.5
2143.222	0.050	3.87	5
2156.03	0.08	1.01	10
(2159.5)	0.5	0.06	100
2223.781	0.048	4.38	2.5
2240.4	0.6	0.12	30
2246.67	0.35	0.13	30
2282.290	0.054	2.12	5
2312.91	0.07	0.54	7
2334.7	0.4	0.45	20
2345.56	0.21	0.155	15
2442.68	0.26	0.104	20
2464.15	0.13	0.174	15
2482.24	0.17	0.145	15
2564.84	0.07	1.36	5
2570.87	0.054	4.56	2.5
2599.84	0.06	0.68	7
2656.11	0.18	0.115	15
2667.37	0.09	0.270	7
2696.54	0.07	0.73	7
2722.51	0.25	0.109	15
(2748.1)	0.5	0.02	100
2758.90	0.32	0.110	15
2764.16	0.08	0.334	10
2788.72	0.21	0.075	15
2803.51	0.32	0.069	15
2824.08	0.25	0.081	20
2828.05	0.28	0.082	20
2851.05	0.12	0.268	7
2866.44	0.24	0.057	15
2894.92	0.14	0.100	10
2938.92	0.15	0.68	7
3027.11	0.18	0.147	10
3061.33	0.15	0.147	10
3086.59	0.15	0.082	15
3160.04	0.15	0.135	10
3245.84	0.19	0.055	20
3327.18	0.15	0.139	10
3449.46	0.18	0.143	10

[a] Parentheses around a γ-ray energy indicate a tentative assignment.

[b] These values must be multiplied by a factor 4.14 × 10^{-3} to convert to absolute intensities (in γ/100 disintegrations). Since the uncertainty in this conversion factor is ±4.1%, this should be added in quadrature to the error assigned to the relative intensities to obtain the total error assigned to the absolute intensity values.

In using the above ratio to estimate the positron-decay component of ^{134}La, it is necessary to correct for positron-annihilation processes which do not result in 511-keV photons. One such process is positron annihilation in flight, which we estimate to occur in ~3.5% of positron annihilations from ^{134}La decay based on the data provided in Ref. 32. Including this correction, we obtain the following ratio for the total positron decay to 604-keV γ-ray intensity:

$$\frac{I(\beta^+)}{I(604)}=12.36\ \ (\pm 3\%).$$

3. *Ba K x-ray intensity*

As a result of the predominant decay of ^{134}La to the ground state of ^{134}Ba and the relative weakness of internal-conversion processes in this decay, a measure of the Ba K x-ray intensity can be directly related to the intensity of the electron-capture decay component. In γ-ray spectra of the ^{134}Ce-^{134}La equilibrium source measured with the large Ge(Li) detectors, the Ba and La K x-ray peaks are unresolved. From spectra measured with the 50-cm^3 coaxial detector we obtain, then, the following ratio for the total K x-ray intensity:

$$\frac{I[K\ \mathrm{x(Ba+La)}]}{I(604)}=20.1\ \ (\pm 5\%).$$

The relative Ba-to-La K x-ray intensities were obtained from a measurement of an equilibrium ^{134}Ce-^{134}La source with the 30-mm$^2\times$3-mm Si(Li) detector. This spectrum is illustrated in Fig. 2. Based on an analysis of this spectrum we obtain the following ratio for the relative K x-ray intensities:

$$\frac{I[K\ \mathrm{x(La)}]}{I[K\ \mathrm{x(Ba)}]}=2.49\ \ (\pm 5\%).$$

(We note that this value is in close agreement with the value 2.43 ± 0.10 reported for this ratio in Ref. 33.) Based on the ratios given above, we obtain

$$\frac{I[K\ \mathrm{x(Ba)}]}{I(604)}=5.76\ \ (\pm 7\%).$$

Since the contribution to the Ba K x-ray peak from internal-conversion processes is negligible (the 604-keV transition would be the major contributor and it will account for only ~0.08% of the Ba K x-ray intensity) compared with our uncertainty estimate, this ratio can be used to estimate the ratio of the total K-electron capture intensity to that of the 604-keV γ ray. Using a value of 0.901 for the K x-ray fluorescence yield[34] in Ba, we obtain the following result:

$$\frac{I(\epsilon_K)}{I(604)}=6.39\ \ (\pm 7\%).$$

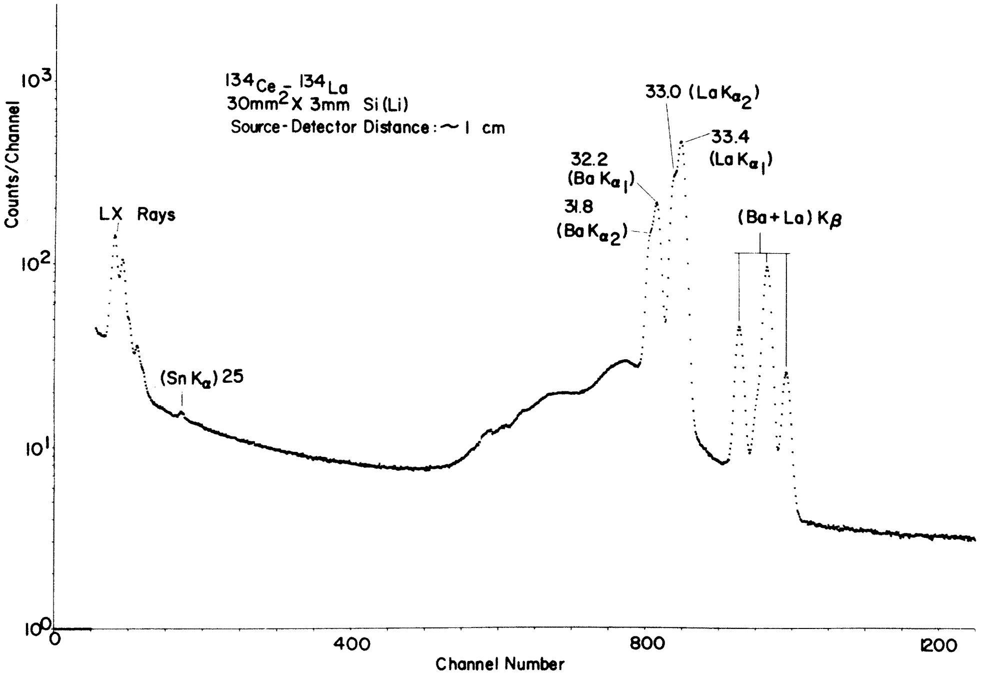

FIG. 2. Spectrum of x rays emitted by ^{134}Ce-^{134}La equilibrium source obtained using a 30-mm$^2\times$3-mm Si(Li) detector.

4. *γ-ray energy measurements of ^{134}Cs*

The energy shown in Table I for the apparent crossover transition from the second 2^+ excited state of ^{134}Ba to the ground state is in poor agreement with the cascade sum (they differ by 0.18 keV). Furthermore, the γ-ray intensity ratio for the 1168-to-563-keV transitions in Table I is 0.274, which is significantly higher than the value of 0.217 which can be computed using the intensities given in Ref. 9 for the ^{134}Cs decay. This evidence suggests that the 1168-keV peak in the ^{134}Ce-^{134}La spectrum is a doublet, which is confirmed by our later coincidence measurements (Sec. III B). In order to confirm that the 1167-keV peak seen in the ^{134}Cs decay is in fact the crossover transition we remeasured its energy, together with those of the 604- and 563-keV cascade transitions, as precisely as possible. These energies, together with those of several other γ rays emitted in the ^{134}Cs decay, are shown in Table II. In these data, transition energies for the cascade sum and crossover are quite consistent, the difference being only 15 eV. This suggests that the 1167-keV peak seen in the ^{134}Cs decay is truly a singlet and contains only the crossover transition.

TABLE II. γ-ray energies measured from ^{134}Cs decay.

γ-ray energy (keV)	Error (keV)
563.227	0.015
569.315	0.015
604.699	0.015
795.845	0.022
801.932	0.022
1038.571	0.026
1167.938	0.026
1365.152	0.032

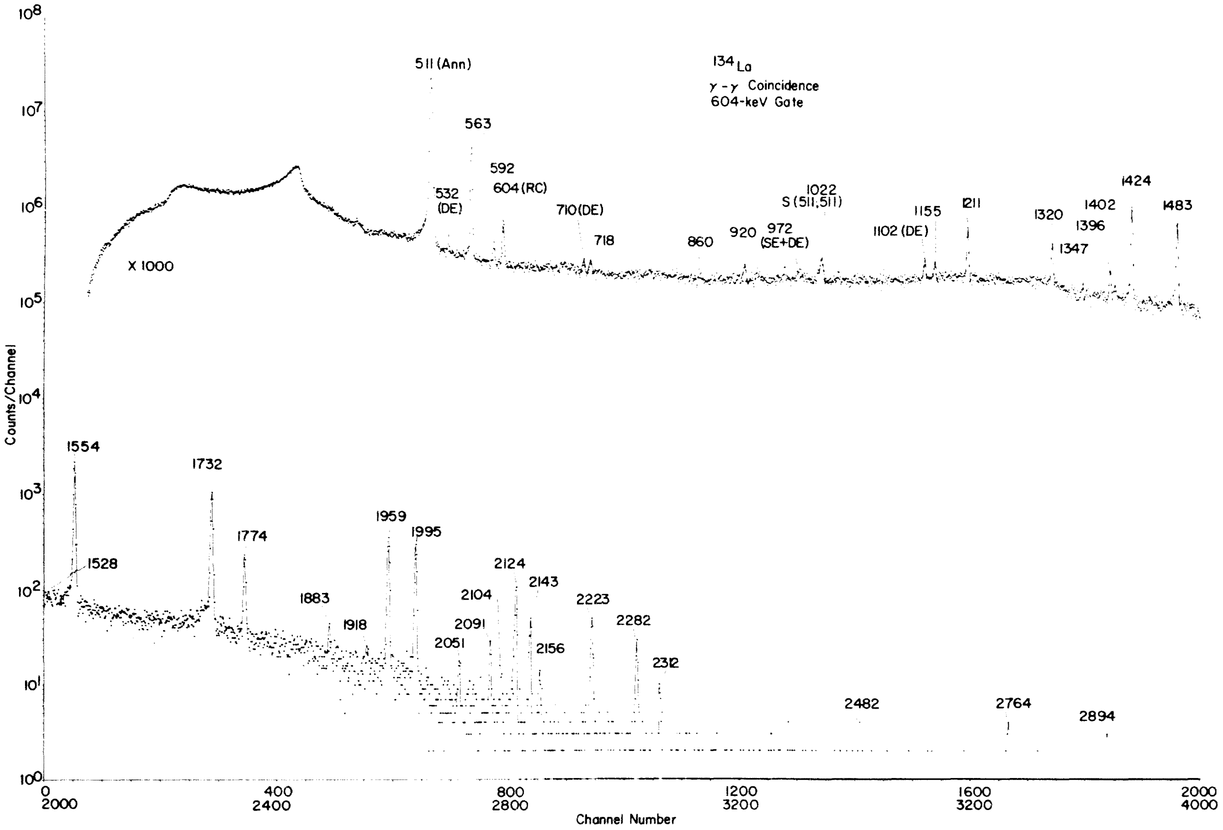

FIG. 3. Spectrum of γ rays in coincidence with the 604-keV γ ray. The symbol (RC) associated with some of the peaks in this spectrum and in Fig. 4 indicates that they result from random coincidence summing.

B. γ-γ coincidence data

Coincident γ-ray spectra were measured for several of the strongest γ-ray lines in the ^{134}La spectrum. These lines were those at 563, 604, 1211, 1424, 1483, 1554, and 1732 keV, as well as the 511-keV annihilation radiation peak (employing 90° geometry as described in Sec. II B 2). The coincident γ-ray spectrum obtained for the 604-keV gate is illustrated in Fig. 3. The γ-ray coincidence relationships which have been established from these data are summarized in Table III.

Additional information which can usefully be extracted from these data include the delineation of noncoincident γ rays. In order to do this, it was necessary to establish sensitivity limits for observation of a true coincidence. This was simply accomplished by normalizing the singles γ-ray spectrum to the γ-γ coincidence spectrum using the intensities of the stronger transitions which are clearly in coincidence. In this manner, we determined that the 563- and 604-keV coincidence spectra have comparable sensitivities (with that of the 563-keV γ ray being slightly superior). Hence we can infer that those γ-ray transitions which are shown in Table III to be in coincidence with the 604-keV γ ray but not with the 563-keV γ ray must either populate the 604-keV level in ^{134}Ba directly or populate higher-lying levels which in turn deexcite principally to the 604-keV level. Those γ rays which are established to be noncoincident with both the 604- and 563-keV γ rays, and therefore must either be direct ground-state transitions or populate higher-lying levels which in turn deexcite principally to the ground state, are listed in Table IV.

The γ-ray spectrum in coincidence with the 511-keV annihilation radiation, shown in Fig. 4, was measured specifically to obtain information on the relative β^+ branching ratios to excited states in ^{134}Ba. Based on these data, only the γ rays with energies 563, 604, and 1167 keV can be unambiguously assigned as being in coincidence with the annihilation radiation. Coincident relative intensities obtained from the data in Fig. 4 for these three γ rays are 12.6, 1000, and 4.2, respectively. Hence we obtain the following value for the relative β^+ branching to the 1167- and 604-keV levels in ^{134}Ba:

$$\frac{I[\beta^+(1167)]}{I[\beta^+(604)]}=0.0168\,.$$

IV. ^{134}La DECAY SCHEME

A. Levels populated in ^{134}Ba

A decay scheme for ^{134}La is quite readily constructed from the data obtained in the present study. The extensive γ-γ coincidence relationships, summarized in Table III, generally give quite unambiguous evidence as to the placement of γ-ray transitions in the ^{134}Ba level scheme. These coincidence data are further supplemented by the noncoincident γ-ray transitions, summar-

TABLE III. γ-γ coincidence relationships.

Gate energy (keV)	Coincident γ-ray energies [a] (keV)
563	475,511, 592, 604, 861, 920, 991, 1168, 1211, 1320, 1368, 1396, 1402, 1528, 1579, 1660, 1683, 1719, 1749, 1836, 1859, 1893, 1918, 2104
604	511, 563, 592, 718, 861, 920, 1155, 1168, 1211, 1320, 1347, 1396, 1402, 1424, 1483, 1528, 1554, 1732, 1774, 1883, 1918, 1959, 1995, 2051, 2091, 2104, 2124, 2143, 2156, 2223, 2282, 2312, (2482), 2764, (2894)
1211	563, 604, 1168
1424	604, 718
1483	604, 659
1554	604
1732	604

[a] Parentheses around a γ-ray energy indicates a tentative assignment.

TABLE IV. Ground-state γ-ray transitions established from the 604- and 563-keV coincidence data.

Ground-state γ-ray transitions (keV)
2029
2088
2564
2570
2599
2696
2938

ized in Table IV, which are therefore inferred to be ground-state transitions. Since the decay energy of ^{134}La is quite well known ($Q = 3720 \pm 25$ keV, from averaging the values in Refs. 17,19) we can also infer that those γ-ray transitions with energies $\gtrsim 3140$ keV must populate the ^{134}Ba ground state, while those transitions with energies $\gtrsim 2580$ keV must populate either the ground state or the 604-keV first excited state (assuming that the second excited state in ^{134}Ba is at 1167 keV).

The placement of other γ-ray transitions, which were not sufficiently intense to be observed in the coincidence spectra or by the energy limits noted above, was facilitated by the high precision attained for the γ-ray energy measurements. Such γ-ray transitions could then generally be placed in the level scheme from the Ritz combination principle, using the NUCLEV computer program.[35] In a few cases levels were assigned on the basis of energy combinations alone.

We can summarize the placement of levels in ^{134}Ba (excluding those also populated in the ^{134}Cs

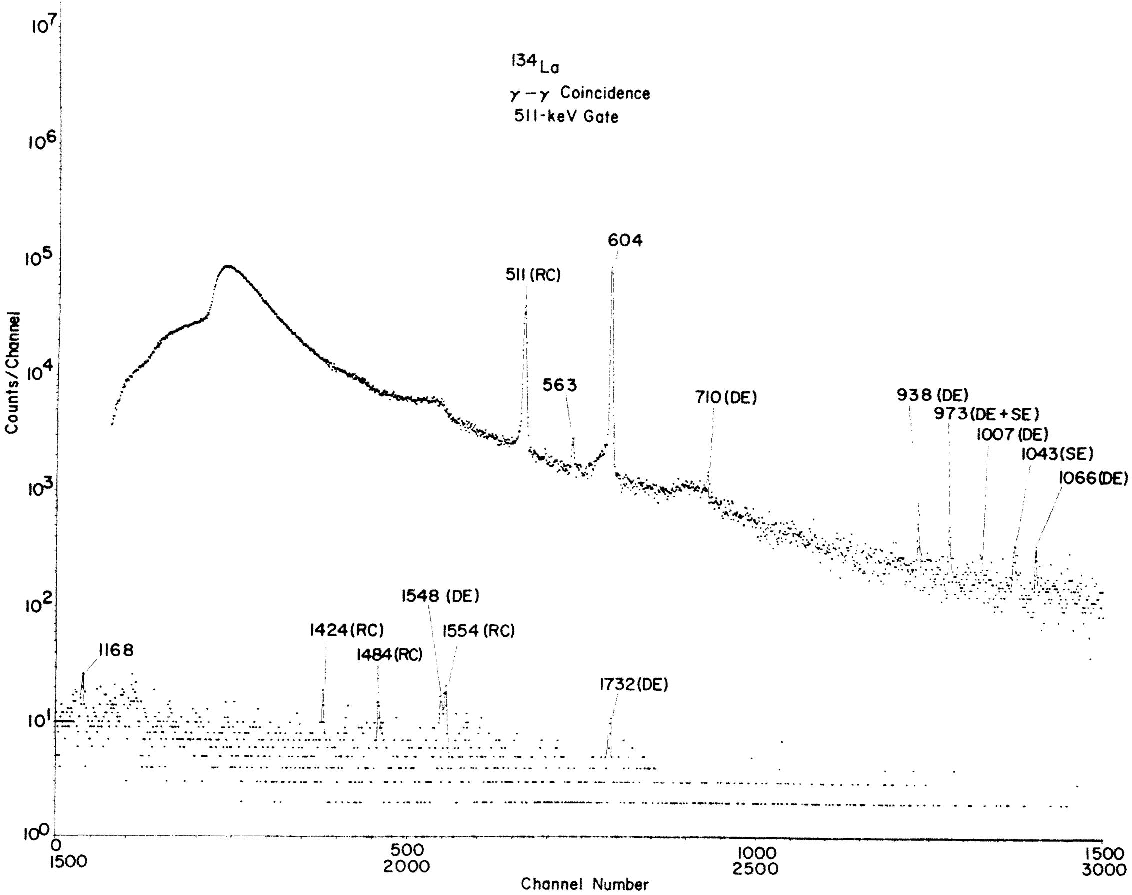

FIG. 4. Spectrum of γ rays in coincidence with the 511-keV annihilation radiation measured using a 90° detector geometry. The majority of peaks in this spectrum can be identified as resulting from γ-ray pair production occurring in one detector with one of the escaping annihilation quanta being detected by the gate detector. See also the caption to Fig. 3.

decay) from the ^{134}La decay data as follows.

The assignment of levels at 1760, 2029, 2088, 2159, 2336, 2379, 2488, 2564, 2696, 2747, 2828, 2886, 2917, and 3086 keV was based on observation of γ-ray coincidences with both the 604- and the 563-keV γ rays.

The assignment of levels at 2536, 2570, 2599, 2656, 2851, 3004, 3027, 3061, 3086, 3272, and 3327 keV was based on γ transitions identified to be in coincidence with the 604-keV line, but not with the 563-keV line, together with additional transitions identified by energy sums.

The assignment of levels at 2729, 2760, 3368, and 3499 keV was based on γ transitions identified to be in coincidence with the 604-keV line but not with the 563-keV line.

The assignment of levels at 2029, 2088, 2564, 2570, 2599, 2696, and 2938 keV was based on the ground-state γ-ray transitions, identified from the γ-γ coincidence data, listed in Table IV.

The assignment of levels at 3160, 3245, 3272, 3327, and 3449 keV was based on the existence of γ-ray transitions of these energies and on the considerations of the Q value of the decay and the energy of the first excited state.

The assignment of the level at 3408 keV and the tentative levels at 2758, 3068, 3074, and 3561 keV was based on energy sums.

TABLE V. K internal-conversion coefficients computed using conversion-electron intensities measured by Aleksandrov *et al.* (Ref. 17) for ^{134}Ce-^{134}La and our γ-ray intensities from Table I.

Transition energy (keV)	K-electron intensity[a]	γ-ray intensity[a]	Experimental $\alpha_K(\times 10^4)$[a, b]	Theoretical $\alpha_K(\times 10^4)$[c]			Inferred multipolarity
				$E1$	$E2$	$M1$	
563	10.6(20)	86.7(22)	75(15)	21.5	60.4	85.4	$M1/E2$
604	≡100	1219(24)	≡50.3	18.3	50.3	71.8	≡$E2$
1155	0.13(6)	4.68(23)	17(8)	5.04	11.5	15.6	$M1/E2$
1168.1 1168.6	0.50(12)	23.75(59)	12.9(32)	4.94	11.2	15.3	$E2/M1$
1211	0.66(20)	28.59(72)	14.2(44)	4.63	10.4	14.1	$M1/E2$
1320	0.35(6)	19.80(50)	10.8(19)	3.98	8.75	11.6	$M1/(E2)$
1396	0.19(4)	8.55(21)	13.6(30)	3.61	7.83	10.2	$M1$
1424	0.78(18)	45.4(11)	10.5(25)	3.49	7.54	9.80	$M1/E2$
1483 1488	0.55(8)	35.9(9) 1.05(21)	9.1(15)	3.26	6.96	8.96	$M1$
1554 1560	1.21(22)	100.0(25) 1.18(35)	7.3(14)	3.03	6.38	8.01	$M1/E2$
1732	0.50(8)	56.6(14)	5.4(9)	2.54	5.20	6.33	$E2/M1$
1749 1759.9[d] 1765	1.73(20)	0.34(5) ≤0.2 0.53(11)	≳990	2.47	5.05	6.12	$E0$
1774	0.14(3)	11.55(29)	7.4(16)	2.44	4.97	6.01	$M1$
1959 1966	0.18(3)	23.55(59) 1.03(15)	4.5(8)	2.08	4.14	4.85	$M1/E2$
1995	0.21(7)	21.57(54)	6.0(20)	2.02	4.00	4.67	$M1/E2$
2029	0.08(2)	9.81(25)	5.0(13)	1.97	3.88	4.51	$M1/E2$
2143	0.034(8)	3.87(19)	5.4(14)	1.81	3.51	4.02	$M1/(E2)$
2223	0.03(1)	4.38(11)	4.2(14)	1.71	3.29	3.72	$M1/E2$
2334.7 (2335.0[d])	~0.02	0.45(9)	≥27	1.59	3.01	3.36	$E0$
2379.6[d]	0.19(4)	≤0.1	≥1160	1.55	2.91	3.24	$E0$
2482 2487.0[d]	0.09(2)	0.145(22) ≤0.1	≥22.5	1.45	2.69	2.96	$E0$
2564 2570	0.022(9)	1.38(10) 4.51(11)	2.3(10)	1.38	2.56	2.84	$E2/M1/(E1)$

[a] Uncertainties in the least significant figures are indicated in parentheses.

[b] Conversion coefficients are computed on the assumption that the 604-keV transition is pure $E2$.

[c] The theoretical conversion coefficients were interpolated from the tables of Hager and Seltzer (Ref. 36), Sliv and Band (Ref. 37), and Trusov (Ref. 38) for transition energies < 1550 keV, 1550–2500 keV, and > 2500 keV, respectively.

[d] Energies reported in Ref. 17 based upon conversion electron energies.

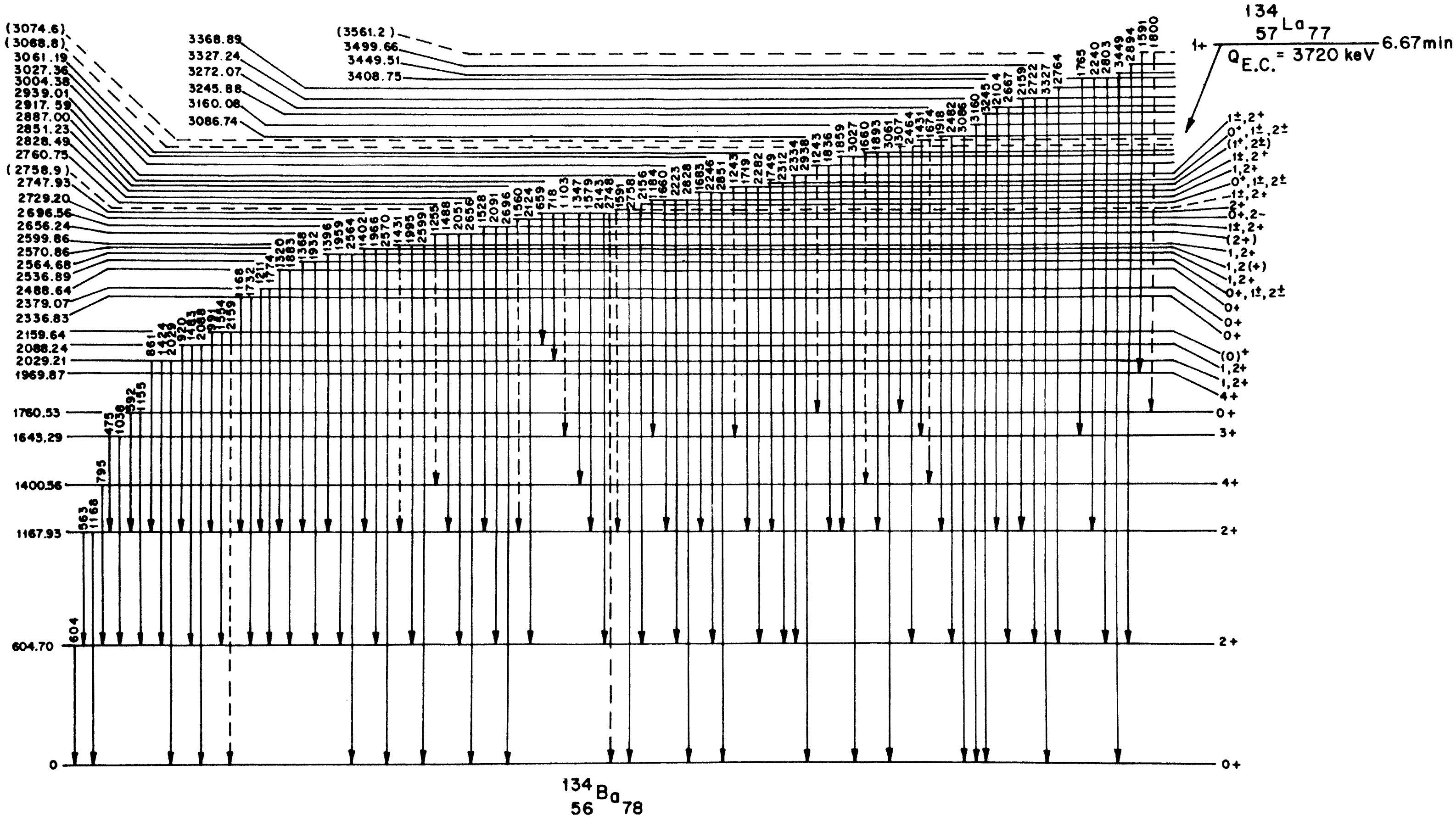

FIG. 5. Proposed decay scheme for ^{134}La. Spin and parity assignments are listed only for those states below 3.0 MeV. For more detailed information, see Table VI.

Where a combination of these methods was used to locate a level, it is listed above in each category.

Parity assignments of several of the levels in ^{134}Ba were made with the aid of the K-electron conversion data reported by Aleksandrov *et al.*[17] Conversion coefficients computed using these electron intensities and the γ-ray intensities shown in Table I are given in Table V. For essentially all of the transitions shown, the accuracy of the data is sufficient to discriminate between $E1$ and $M1/E2$ multipole assignments, but not to distinguish between an $M1$ or an $E2$ assignment. Thus, these data are of limited utility for spin assignments; the $E0$ transitions identified in Ref. 17, and noted in Table V are, of course, an exception. Levels in ^{134}Ba (excluding those also populated in ^{134}Cs decay) which can be assigned to have positive parity based on these conversion coefficients occur at 1760, 2029, 2088, 2159, 2336, 2379, 2488, 2564, 2599, 2747, 2828, and probably 2570 keV.

In the following section (Sec. IV B) absolute electron capture and positron branching ratios together with the corresponding $\log ft$ values are derived for ^{134}La decay. Generally, these $\log ft$ values range between ~6.0 and ~8.0 for decay to excited states in ^{134}Ba and thus these β transitions can be simply assigned as being either allowed or first forbidden (although those near ~6 are most likely allowed). Hence the $\log ft$ values provide no unique information on the parity of the states which they populate in ^{134}Ba. Since, however, the ground state of ^{134}La can be assigned as having $I^{\pi}=1^{+}$ (see Sec. IV B), states in ^{134}Ba which are directly populated in the ^{134}La decay can be limited to having spin values of 0, 1, or 2.

The decay scheme of ^{134}La which was proposed from the present data, using the considerations cited above, is shown in Fig. 5. While many of the features of this decay scheme are in substantial agreement with those proposed by earlier investigators,[15,16,17] the number of states in ^{134}Ba observed to be populated is ~3 times greater than in these previous investigations. In addition, spin and parity assignments have been made to a number of additional levels. The energies of levels in ^{134}Ba are listed in Table VI together with a summary of their deexciting γ-ray transitions observed from the ^{134}La decay. These level energies represent a "best" set obtained by means of a linear least-squares fitting program[39] using the γ-ray energies and uncertainties shown in Tables I and II (but with a 19 ppm reference contribution removed from the uncertainty). This least-squares fit included the transitions associated with the 38 excited states in ^{134}Ba that we consider to be firmly established. The reduced χ^2 value for the fit was 1.9. The fact that this value is greater than unity (the value expected for a consistent set) suggests that some of the measurement uncertainties are underestimated slightly. In some cases this probably results from a peak being an unresolved doublet. In computing these level energies, the γ-ray energies were all corrected for nuclear recoil, using a recoil correction term ΔE_R (eV) $=4.01E^2$ (where E is the γ-ray energy in MeV).

Further comments regarding the assignment of spins to levels in ^{134}Ba are appropriate. The identification of four $E0$ transitions by Aleksandrov *et al.*[17] and their placement as ground-state transitions from levels at 1760, 2336, 2379, and 2488 keV, whose existence is confirmed by their other modes of deexcitation, provide conclusive evidence that these four levels each have $I^{\pi}=0^{+}$. The level at 2159 keV can also be considered as a probable candidate for an $I^{\pi}=0^{+}$ assignment in view of the assigned positive parity and probable nonexistent ground-state transition $[I(2159)/I(1554)\leq 6\times10^{-4}]$. However, we note that in the spectrum of internal-conversion electrons shown in Fig. 1 of Ref. 17, there is no evidence of a K-conversion line corresponding to that of a 2159-keV $E0$ transition, although that portion of the spectrum in which it should appear is illustrated. While an $E0$ transition could be suppressed sufficiently to be below the sensitivity limit of the experimental measurements in this region, we prefer to make the assignment of $I^{\pi}=0^{+}$ to the 2159-keV level only tentative in view of this nonobservation of the $E0$ transition. The absence of a ground-state transition in the deexcitation of the level at 2729 keV $[I(2729)/I(1554)<7\times10^{-3}]$ might also be indicative of an $I^{\pi}=0^{+}$ assignment. Since, however, the parity of this state is also unknown, an $I^{\pi}=2^{-}$ assignment could equally well account for the absence of the ground-state transition. Since the $\log ft$ value for electron-capture decay to this level does not permit us to choose between these two I^{π} assignments, they must be considered equally probable at this time.

Apart from the lowest-lying excited 2^{+} states, the only other state which we feel confident of assigning as $I^{\pi}=2^{+}$ is that at 2747 keV. This assignment is based on its positive parity and the fact that deexcitation occurs to final states having $I^{\pi}=0^{+}$, 2^{+}, and 4^{+}. States with energies 2656 and 3061 keV have potential decay modes to the 4^{+} state at 1400 keV, as well as to the ground state. However, in the former case, the 1255-keV γ ray is only tentative (see Table I) and in the latter case, the 1660-keV transition is seen in spectra coincident with the 563-keV γ ray and thus it must principally, if not wholly, be assigned as deexciting the state at 2828 keV. Hence, we can make only a tentative $I^{\pi}=2^{+}$ assignment to the state at 2656

TABLE VI. The "best" set of energies for levels in ^{134}Ba, together with a summary of their $\beta^+ + \epsilon$ feeding transitions and their deexciting γ-ray transitions observed in the ^{134}La decay.

		$\beta^+ + \epsilon$ feeding		γ-ray deexcitation		
Level energy[a,b] (keV)	I^{π} [c]	Branching intensity (%)	Log*ft*	γ-ray energy[a,b] (keV)	Relative γ-ray intensity	Final state *E*(keV); I^{π}
0	0^+	94.7(2)	4.89			
604.703(12)	2^+	3.35(11)	6.00	604.699(12)	1218.7	0; 0^+
1167.934(23)	2^+	0.11[d]	7.17	1168.1(1)	18.5	0; 0^+
				563.226(13)	86.7	604; 2^+
1400.560(29)	4^+	<0.004	>8.5	795.907(32)	1.83	604; 2^+
1643.295(35)	3^+	<0.004	>8.3	1038.68(5)	0.91	604; 2^+
				475.33(21)	1.27	1167; 2^+
1760.530(37)	0^+	0.032(2)	7.37	1759.9(7)[e]	···	0; 0^+
				1155.826(28)	4.68	604; 2^+
				592.577(38)	3.98	1167; 2^+
1969.872(39)	4^+	<0.01	>7.7			
2029.216(40)	1^+, 2^+	0.220(11)	6.38	2029.191(44)	9.49	0; 0^+
				1424.506(30)	45.4	604; 2^+
				861.286(47)	0.99	1167; 2^+
2088.249(41)	1^+, 2^+	0.223(11)	6.34	2088.24(5)	14.0	0; 0^+
				1483.516(31)	35.9	604; 2^+
				920.347(24)	4.32	1167; 2^+
2159.648(42)	$(0)^+$	0.422(21)	6.02	(2159.5(5))	0.06	0; 0^+
				1554.934(32)	100.0	604; 2^+
				991.725(42)	1.38	1167; 2^+
2336.838(46)	0^+	0.256(13)	6.13	2335(3)[e]	···	0; 0^+
				1732.129(35)	56.6	604; 2^+
				1168.63(8)	5.2	1167; 2^+
2379.078(45)	0^+	0.166(8)	6.29	2379.6(15)[e]	···	0; 0^+
				1774.353(36)	11.55	604; 2^+
				1211.145(26)	28.59	1167; 2^+
2488.640(49)	0^+	0.085(4)	6.50	2487.0(15)[e]	···	0; 0^+
				1883.74(12)	0.80	604; 2^+
				1320.701(28)	19.80	1167; 2^+
2536.89(6)	0^+, $1^{\pm}$, $2^{\pm}$	0.0075	7.5	1932.16(6)	1.07	604; 2^+
				1368.96(7)	0.74	1167; 2^+
2564.680(49)	1^+, 2^+	0.139(7)	6.23	2564.84(7)	1.36	0; 0^+
				1959.956(43)	23.55	604; 2^+
				1396.730(29)	8.55	1167; 2^+
2570.86(5)	$1^{(+)}$, $2^{(+)}$	0.033	6.8	2570.875(54)	4.56	0; 0^+
				1966.07(12)	1.03	604; 2^+
				1402.889(34)	2.47	1167; 2^+
2599.86(5)	1^+, 2^+	0.093(5)	6.38	2599.84(6)	0.68	0; 0^+
				1995.138(44)	21.57	604; 2^+
				(1431.35(13))	0.54	1167; 2^+
2656.24(9)	(2^+)	0.011	7.3	2656.11(18)	0.115	0; 0^+
				2051.55(10)	1.42	604; 2^+
				1488.29(27)	1.05	1167; 2^+
				(1255.06(26))	0.35	1400; 4^+
2696.56(6)	$1^{\pm}$, 2^-	0.016	7.1	2696.54(7)	0.73	0; 0^+
				2091.99(10)	2.38	604; 2^+
				1528.54(7)	0.64	1167; 2^+
2729.20(7)	0^+, 2^-	0.034	6.7	2124.482(50)	7.50	604; 2^+
				(1560.42(48))	1.18	1167; 2^+
2747.93(6)	2^+	0.041	6.6	(2748.1(5))	0.02	0; 0^+
				2143.222(50)	3.87	604; 2^+
				1579.92(15)	1.14	1167; 2^+
				1347.34(5)	1.18	1400; 4^+
				(1103.5(5))	0.2	1643; 3^+
				718.709(28)	2.90	2029; 1^+, 2^+
				659.85(9)	0.62	2088; 1^+, 2^+

TABLE VI *(Continued)*

		$\beta^{+}+\epsilon$ feeding		γ-ray deexcitation		
Level energy [a,b] (keV)	I^{π} [c]	Branching intensity (%)	Log*ft*	γ-ray energy [a,b] (keV)	Relative γ-ray intensity	Final state *E*(keV); I^{π}
(2758.94(31))	$1^{\pm}$, 2^{+}	0.0014	8.1	2758.90(32)	0.110	0; 0^{+}
				(1591.1(11))	0.22	1167; 2^{+}
2760.75(9)	0^{+}, $1^{\pm}$, $2^{\pm}$	0.0042	7.6	2156.03(8)	1.01	604; 2^{+}
2828.49(6)	1^{+}, 2^{+}	0.023	6.8	2828.05(28)	0.082	0; 0^{+}
				2223.781(48)	4.38	604; 2^{+}
				1660.57(7)	0.73	1167; 2^{+}
				1184.92(12)	0.42	1643; 3^{+}
2851.23(8)	$1^{\pm}$, 2^{+}	0.0048	7.4	2851.05(12)	0.268	0; 0^{+}
				2246.67(35)	0.13	604; 2^{+}
				1683.33(7)	0.77	1167; 2^{+}
2887.00(6)	(1^{+}, $2^{\pm}$)	0.016	6.9	2282.290(54)	2.12	604; 2^{+}
				1719.04(5)	1.50	1167; 2^{+}
				(1243.84(21))	0.54	1643; 3^{+}
2917.590(8)	0^{+}, $1^{\pm}$, $2^{\pm}$	0.0036	7.5	2312.91(7)	0.54	604; 2^{+}
				1749.41(13)	0.34	1167; 2^{+}
2939.01(14)	$1^{\pm}$, 2^{+}	0.0047	7.4	2938.92(15)	0.68	0; 0^{+}
				2334.7(4)	0.45	604; 2^{+}
3004.38(15)	($1^{\pm}$, 2^{+})	0.0039	7.4	1836.43(15)	0.40	1167; 2^{+}
				(1243.84(21))	0.54	1760; 0^{+}
3027.36(8)	$1^{\pm}$, 2^{+}	0.0042	7.3	3027.11(18)	0.147	0; 0^{+}
				1859.43(6)	0.86	1167; 2^{+}
3061.19(9)	$1^{\pm}$, 2^{+}	0.0044	7.2	3061.33(15)	0.147	0; 0^{+}
				1893.20(8)	0.56	1167; 2^{+}
				(1660.57(7)) [f]	0.73	1400; 4^{+}
(3068.84(13))	$1^{\pm}$, 2^{+}	0.0015	7.7	2464.15(13)	0.174	604; 2^{+}
				1307.0(7)	0.18	1760; 0^{+}
(3074.69(13))	(2^{+})	0.0028	7.4	(1674.6(5))	0.14	1400; 4^{+}
				1431.35(13)	0.54	1643; 3^{+}
3086.74(11)	$1^{\pm}$, 2^{+}	0.0017	7.6	3086.59(15)	0.082	0; 0^{+}
				2481.24(17)	0.145	604; 2^{+}
				1918.0(5)	0.18	1167; 2^{+}
3160.08(15)	$1^{\pm}$, 2^{+}	0.000 56	8.0	3160.04(15)	0.135	0; 0^{+}
3245.88(19)	$1^{\pm}$, 2^{+}	0.000 23	8.2	3245.84(19)	0.055	0; 0^{+}
3272.07(7)	0^{+}, $1^{\pm}$, $2^{\pm}$	0.0042	6.9	2667.37(9)	0.290	604; 2^{+}
				2104.11(6)	0.75	1167; 2^{+}
3327.24(13)	$1^{\pm}$, 2^{+}	0.0039	6.8	3327.18(15)	0.139	0; 0^{+}
				2722.51(25)	0.109	604; 2^{+}
				2159.5(5)	0.7	1167; 2^{+}
3368.89(8)	0^{+}, $1^{\pm}$, $2^{\pm}$	0.0014	7.1	2764.16(8)	0.334	604; 2^{+}
3408.75(18)	1^{+}, $2^{\pm}$	0.0036	6.6	2803.51(32)	0.069	604; 2^{+}
				2240.4(6)	0.12	1167; 2^{+}
				1765.71(22)	0.53	1643; 3^{+}
3449.51(18)	$1^{\pm}$, 2^{+}	0.000 59	7.3	3449.46(18)	0.143	0; 0^{+}
3499.66(14)	0^{+}, $1^{\pm}$, $2^{\pm}$	0.000 41	7.2	2894.92(14)	0.100	604; 2^{+}
(3561.28(46))	(2^{+})	0.0013	6.4	(1800.8(5))	0.084	1760; 0^{+}
				1591.1(11)	0.22	1969; 4^{+}

[a] The uncertainties in the least significant figure are indicated in parentheses.

[b] Parentheses around a level energy, or a γ-ray energy, indicate a tentative assignment.

[c] Parentheses are used to indicate probable spin or parity values.

[d] Calculated using theoretical estimates of the electron-capture to positron branching together with our measured ratio $I[\beta^{+}(1167)]/I[\beta^{+}(604)]=0.0168$.

[e] Energy is that determined by Aleksandrov *et al.* (Ref. 17) from their conversion-electron data.

[f] Based on coincidence relationships, this transition can principally, or wholly, be assigned as deexciting the 2828-keV level.

keV with the 3061-keV state being left as $(1^{\pm}, 2^{+})$. We further note that, if the tentatively assigned levels with energies 3074 and 3561 keV exist, with the deexcitation modes proposed, they would of necessity have $I^{\pi}=2^{+}$.

The remaining group of levels concerning whose I^{π} assignments we should comment on are those with energies 2029, 2088, 2564, 2570, 2599, and 2828 keV. Each of these states has been assigned as having positive parity (the 2570 keV only probably) and each has established deexcitation modes to the ground and first excited states. Assignment of $I^{\pi}=1^{+}$ or 2^{+} can therefore be made to these states. We do not consider the nonobservation of γ-ray transitions to the 4^{+} states at 1400 or 1969 keV to be sufficient justification for eliminating the $I^{\pi}=2^{+}$ assignment.

B. Positron, electron-capture, and absolute γ-ray intensities

In Sec. III A 3 we obtained a value for the ratio of the total K-electron capture intensity to that of the 604-keV γ ray [6.39($\pm$ 7%)]. The relative contribution of the higher shells $(L, M, N, \ldots)$ to the electron capture decay can be estimated quite accurately for allowed transitions using the expressions and tabulated values given in Ref. 40. This contribution can be expressed as

$$\frac{I(\epsilon_{L,M,N,\ldots})}{I(\epsilon_K)}=0.1670\left(\frac{q_{L_1}}{q_K}\right)^2 .$$

Thus, as a result of the large Q value for the ^{134}La decay [average value, 3720 ± 25 keV (Refs. 17 and 19)] with 98% of the decay via transitions of over 3 MeV, we computed an average value of 0.1699 for this ratio. Hence, the total electron-capture probability in the ^{134}La decay is

$$\frac{I(\epsilon)}{I(604)}=7.48 \quad (\pm 7\%) .$$

Combining this value with that given in Sec. III A 2 for the ratio of the total positron decay to 604-keV γ-ray intensity [12.36 ($\pm$ 3%)], we compute the following:

^{134}La total electron capture probability, $I(\epsilon) = 37.7 \pm 1.8)\%$;
^{134}La total positron decay probability, $I(\beta^{+}) = (62.3 \pm 1.8)\%$; and
Probability for emission of the 604-keV γ ray in ^{134}La decay $=(5.04 \pm 0.17)\%$.

Evidence has been reported (see, e.g., Ref. 41) suggesting that, for some transitions, the measured electron-capture to positron ratios can deviate markedly from the theoretical values. While it is of interest to see if such deviations occur in the ^{134}La decay, the features of this decay scheme are such that only one such ratio—that for the ground-state transition—can be determined with reasonable precision. The intensity of the ground-state β^{+} branch was determined by subtracting from the total β^{+} intensity in the ^{134}La decay that due to β^{+} branches to the excited states. The β^{+} intensity feeding the 604-keV first excited state was estimated to be ~1.6%, based on the theoretical[42] ϵ/β^{+} ratio for this transition and its total intensity (determined as described below to be ~3.3%). (Even if the ϵ/β^{+} ratio for this transition is markedly different from the theoretical prediction, the total transition intensity is sufficiently small that no significant error is introduced into this estimate of the β^{+} component in the ground-state transition.) The β^{+} feeding to the second and higher excited states was neglected, a justifiable procedure in view of the weak feeding of these states and the rapid decrease of the β^{+}/ϵ ratio with increasing excitation energy. With the intensities of the β^{+} and $\beta^{+}+\epsilon$ branches (see below) to the ground state known, we deduce

$$\left(\frac{\epsilon}{\beta^{+}}\right)_{\text{ground}}=0.560 \pm 0.034 ,$$

a value which is in good agreement with the theoretical[42] value of 0.533.

A direct measure of the β^{+} branch to the ^{134}Ba ground state can be deduced from the measured[17] value of $(4.2 \pm 0.8)\times 10^{-4}$ for the ratio of the intensity of the K-conversion line of the 604-keV $E2$ transition to that of the ground-state β^{+} branch. This ratio gives a value of (60 ± 11)% for the intensity of the ground-state β^{+} branch. This value is quite consistent with the above-mentioned estimates but it is unfortunately not sufficiently precise to yield significant information on the intensity of β^{+} branches in excited states in ^{134}Ba. Where β^{+} branching ratios to excited states in ^{134}La are given, either here or by previous investigators,[13,14,17] they are or have been theoretical estimates.

The total electron-capture plus positron feeding of levels in ^{134}Ba populated in the decay of ^{134}La was determined from the total transition intensity balance into and out of each level, using the γ-ray intensities shown in Table I, a conversion factor between relative and absolute γ-ray intensities of 4.14×10^{-3} ($\pm$ 4.1%) obtained from the absolute 604-keV γ-ray intensity determined above, and either the measured internal conversion coefficients or theoretical coefficients[36-38] for the most reasonable multipolarities of the transitions. The results of this analysis to determine branching ratios are given in Table VI. Also given in Table VI are the logft values for these transitions calculated using a computer program described in

Ref. 42. For these logft calculations, a half-life of 6.67 min and a Q value of 3720 ± 25 keV were employed.

These logft values are such that, except for the ground-state transitions, either allowed or first-forbidden transition assignments are permissible (see, for example, Ref. 43 for ranges of logft values measured for allowed and forbidden β transitions). The logft value of the ground-state transition is sufficiently low to permit only an allowed assignment. This assignment then limits the permissible values of I^π for the ground state of ^{134}La to 0^+ or 1^+. The smallness of the logft value of the transition to the first excited 2^+ state, however, eliminates a 0^+ assignment and thus requires that the ground state of the ^{134}La have $I^\pi = 1^+$.

V. DISCUSSION

In Table VII are summarized the reduced transition probabilities of the electric-multipole transitions involving those ^{134}Ba states whose I^π assignments seem reasonably firmly established at present. The $E0$-related quantities for the decay of the excited 0^+ states are analogous to the parameter X, which is customarily employed in describing the decay of 0^+ states to the ground-state rotational bands in strongly deformed nuclei.[44] It has been calculated using the relation (see, e.g., Ref. 45)

$$X = 2.56\times 10^9 A^{4/3} E_\gamma^{\,5}\ [\mathrm{MeV}]\,\Omega_K^{\,-1}\cdot I_K(E0)/I_\gamma(E2)\,.$$

Here, the electronic factor Ω_K was derived from the tables of Bell *et al.*[46] The conversion-electron intensity data were taken from Aleksandrov *et al.*[17]

Also included in Table VII are the results of two recent theoretical calculations[4,5] in which certain of the properties of the lighter-mass even-even Xe, Ba, Ce, and Nd nuclides were treated. The approach employed by Habs *et al.*[4] is based on the generalized collective model of Gneuss and Greiner.[47] In their approach, Habs *et al.*[4,48] utilized the then-known energy-level spectra and $E2$ transition probabilities to determine the appropriate model parameters for each nuclide; these parameters were then used to generate the respective collective potential-energy surfaces, level spectra, and $B(E2)$ values. For ^{134}Ba, the resulting $E2$ transition data are given in Table VII, and the predicted collective energy level spectrum is shown in Fig. 6. Using a somewhat different approach, Rohozinski *et al.*[5] employed a Wilets-Jean[49] Hamiltonian to which they added a term producing a small oblate-prolate asymmetry. Although they give no level energies, they do list the calculated $E0$ and $E2$ transition probabilities. For ^{134}Ba, they present these transition probabilities calculated for two different assumptions concerning the choice of parameters of the Hamiltonian. Both sets of calculated values are summarized in Table VII. These authors treat two types of 0^+ states: a "β vibration", with quantum numbers[5] $n_\beta = 1$, $\lambda = 0$; and a state which, in a spherical-nucleus coupling scheme, corresponds to the 0^+ member of the three-phonon multiplet, with quantum numbers $n_\beta = 0$, $\lambda = 3$. Since no association of either of these two types of nuclear excitation with the excited 0^+ levels of ^{134}Ba is made in Ref. 5, we have included in Table VII the predictions for both types of state in our comparison of theory and experiment for the 0^+ states. There, the first value listed is that for the β vibration and the second, listed immediately below, is that for the 0^+ state with $n_\beta = 0$, $\lambda = 3$.

As illustrated in Fig. 6, the agreement between the theoretical[4,48] and the experimental level structure below ~1.7 MeV is quite good, reflecting the fact that this region of the spectrum was utilized in determining a number of the model parameters. Above this energy, however, the situation is less clear. The second 4^+ state predicted by the calculation lies ~0.46 MeV above the observed 4^+ state at 1969 keV. This may not represent a serious deficiency, though, since this latter state has been interpreted[52] as being largely two-neutron-quasiparticle in character and hence would not be included within the model space of these calculations. The third 2^+ state is calculated to lie within ~80 keV of the level at 2747 keV, which is known to have $I^\pi = 2^+$. However, it is not certain whether this latter state can be correctly identified as this predicted 2_3^+ state; a number of lower-lying states in ^{134}Ba (such as, e.g., those at 2029 and 2088 keV) exist which are possible candidates for 2^+ states. On the other hand, these ^{134}Ba states, if one or more of them do in fact have $I^\pi = 2^+$, may arise from modes of motion (e.g., two-quasiparticle excitations) not treated in Refs. 4 and 48; and hence the association indicated by the question mark in Fig. 6 may be correct. Comparison of the predicted and the observed $E2$ branching might be helpful in resolving this question, but the appropriate theoretical $B(E2)$ values are not given[48] and the experimental ones are not well established experimentally (cf. Table VI) at present.

^{134}Ba exhibits an interesting spectrum of excited 0^+ states (e.g., Fig. 6). The decay of the 0^+ state at 1760 keV is characterized by a very large $B(E0)/B(E2)$ (i.e., X) value. This is suggestive of β-vibrational states in strongly deformed nuclei, and indeed this state has been classified[53] as a "quasi-β" vibrational bandhead. However, its $E2$ decay, which shows a marked preference for decay to the second rather than to the first excited 2^+ state, suggests that another configuration assignment for this state is more appropriate. The three 0^+ states clustered near ~2.4 MeV have quite different $E0$ and $E2$ decay patterns. The collective-model calculations reported by Habs *et al.*[4,48] do not predict any 0^+ states in this energy region (the next excited 0^+ state above that at ~1.7 MeV is predicted to occur at ~6.2 MeV). The number and spacing of these three 0^+ states suggests

TABLE VII. Summary of the $E2$ and $E0$ branching-ratio data from the ^{134}Ba states whose spin and parity values appear to be unambiguously established. Also included are the relevant theoretical values from the calculations presented in Refs. 4, 48, and 5. The $B(E2)$ values are expressed in units of $e^2 b^2$. The quantities in parentheses following the experimental values represent the uncertainties in the least significant figure (or figures) of the associated value.

		Reduced transition probability data			
			Theoretical values		
Initial state I^π; E (keV)	Quantity	Experimental value	Ref. 48	Ref. 5 version(i)	Ref. 5 version(ii)
2_1^+; 604	$B(E2; 2_1^+ \rightarrow 0_1^+)$	0.134(3) [a]	0.135	0.14	0.44
2_2^+; 1167	$B(E2; 2_2^+ \rightarrow 0_1^+)/B(E2; 2_2^+ \rightarrow 2_1^+)$	0.0057(4) [b]	0.0014	0.0062	0.0085
4_1^+; 1400	$B(E2; 4_1^+ \rightarrow 2_1^+)$	0.020(4) [c]	0.23	⋯	⋯
3_1^+; 1648	$B(E2; 3_1^+ \rightarrow 2_1^+)$	0.000 19(6) [b,c]	0.003	0.000 19 [e]	0.000 19 [e]
	$B(E2; 3_1^+ \rightarrow 2_2^+)$	0.017(8) [b,c]	0.29	0.016 [e]	0.014 [e]
	$B(E2; 3_1^+ \rightarrow 4_1^+)$	0.0078(25) [c,d]	⋯	0.0064 [e]	0.0056 [e]
0_2^+; 1760	$B(E2; 0_2^+ \rightarrow 2_1^+)/B(E2; 0_2^+ \rightarrow 2_2^+)$	0.042(4)	⋯	94 0.008	16 0.007 [f]
	$B(E0; 0_2^+ \rightarrow 0_1^+)/B(E2; 0_2^+ \rightarrow 2_1^+)$	2.93(38)	⋯	0.02 0.06	0.13 0.14 [f]
4_2^+; 1969 [g]	$B(E2; 4_2^+ \rightarrow 2_1^+)/B(E2; 4_2^+ \rightarrow 2_2^+)$	0.0243(3)	0.01	0.014	0.012
	$B(E2; 4_2^+ \rightarrow 3_1^+)/B(E2; 4_2^+ \rightarrow 2_2^+)$	0.147(6) [h]	0.3	0.010	0.0037
	$B(E2; 4_2^+ \rightarrow 4_1^+)/B(E2; 4_2^+ \rightarrow 2_2^+)$	0.76(11)	0.6	0.91	0.91
(0_3^+); 2159	$B(E2; 0_3^+ \rightarrow 2_1^+)/B(E2; 0_3^+ \rightarrow 2_2^+)$	7.65(57)	⋯	94 0.008	16 0.000 [f]
0_4^+; 2336	$B(E2; 0_4^+ \rightarrow 2_1^+)/B(E2; 0_4^+ \rightarrow 2_2^+)$	1.52(30)	⋯	94 0.008	16 0.007
	$B(E0; 0_4^+ \rightarrow 0_1^+)/B(E2; 0_4^+ \rightarrow 2_1^+)$	~0.015	⋯	0.02 0.06	0.13 0.14 [f]
0_5^+; 2379	$B(E2; 0_5^+ \rightarrow 2_1^+)/B(E2; 0_5^+ \rightarrow 2_2^+)$	0.060	⋯	94 0.008	16 0.007 [f]
	$B(E0; 0_5^+ \rightarrow 0_1^+)/B(E2; 0_5^+ \rightarrow 2_1^+)$	0.0010(2)	⋯	0.02 0.06	0.13 0.14 [f]
0_6^+; 2488	$B(E2; 0_6^+ \rightarrow 2_1^+)/B(E2; 0_6^+ \rightarrow 2_2^+)$	0.0068(10)	⋯	94 0.008	16 0.007 [f]
	$B(E0; 0_6^+ \rightarrow 0_1^+)/B(E2; 0_6^+ \rightarrow 2_1^+)$	0.103(22)	⋯	0.02 0.06	0.13 0.14 [f]

[a] Value from Ref. 50.

[b] $E2$ content of the transition derived from the mixing-ratio data of Ref. 11.

[c] Based on the measured (Ref. 51) initial-state lifetime and the observed γ-ray branching.

[d] Calculated assuming a pure $E2$ multipolarity for this transition and the relative γ-ray intensity data summarized in Ref. 21.

[e] Only relative $B(E2)$ values are quoted for these transitions. These theoretical relative values have been normalized to the experimental value for the $3_1^+ \rightarrow 2_1^+$ transition.

[f] The two values listed correspond to the two different assumptions made concerning the makeup of the excited 0^+ state. For further discussion, see the text.

[g] This state not observed in the ^{134}La decay. The experiment data listed are those from the ^{134}Ce decay, as summarized in Ref. 21. The theoretical branching ratios assume a collective character for this state. However, evidence has been presented (Ref. 52) which suggests that it is, at least predominately, a two-neutron-quasiparticle state.

[h] The multipolarity of the $4_2^+ \rightarrow 3_1^+$ transition is not measured. The listed value has been calculated assuming a pure $E2$ multipolarity for this transition.

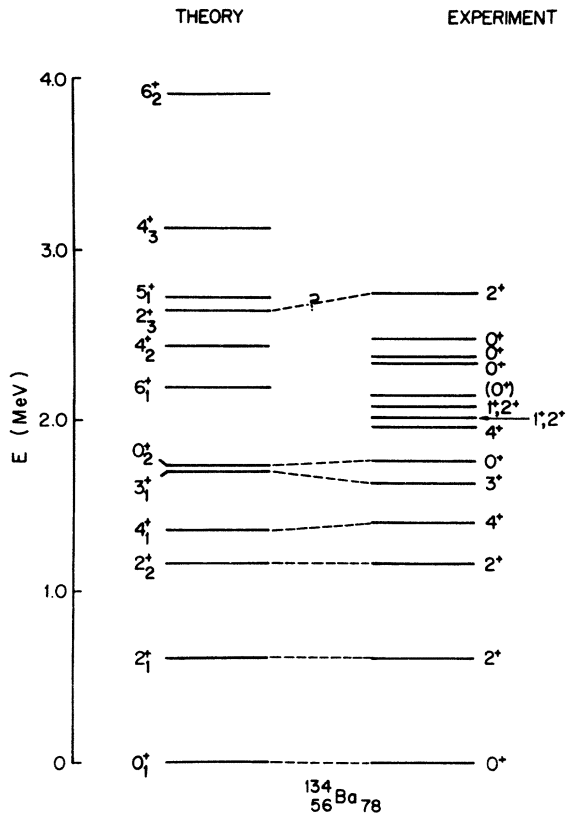

FIG. 6. Comparison of the calculated (Ref. 48) collective energy-level spectrum of ^{134}Ba and the experimentally determined level scheme. While all the experimental levels below 2.0 MeV are shown, for simplicity in comparison only a few known levels above this energy are included (for more detail, see Fig. 5 and Table VI).

that types of nuclear excitations such as, e.g., two-quasiparticle excitations, in addition to those of collective character, may play a role in their makeup. The fact that they are fed by β transitions with comparable $\log ft$ values suggests the presence of a common two-quasiparticle component, with a comparable amplitude, in each of these states. However, additional information is required before definitive statements can be made concerning the detailed wave functions of these states.

Although at one time it was thought that nuclei in this mass region were characterized by oblate deformations, recent measurements[54] of the quadrupole moments of the first 2^+ states in ^{130,134}Ba indicate that the deformation is, in fact, prolate. The general picture of the neutron-deficient nuclides in this mass region is one of moderately deformed shapes that are somewhat "soft" towards deformation; and the low-energy ($\lesssim 1.7$ MeV) level structure of ^{134}Ba seems to be consistent with this. One of the features of such a picture is the absence of a 0^+ state in the energy region of what, in a spherical-nucleus spectrum, would be designated as the two-phonon triplet. We have searched for the existence of such a 0^+ state in ^{134}Ba, exploiting the fact that it might be more strongly populated in the decay of ^{134}La ($I^\pi = 1^+$) than in the well-studied decay of ^{134}Cs ($I^\pi = 4^+$). This was done by looking for a γ ray from the deexcitation of such a state to the first excited 2^+ state at 604 keV. From our data, we have found no evidence for the existence of such a γ ray. Assuming that it is not present in one of the prominent peaks (e.g., 511, 563, 604, 718 keV) in the γ-ray spectrum coincident with the 604-keV transition (see Fig. 3), we can place, from sensitivity considerations, an upper limit of 0.005% on the absolute intensity of a γ ray with energy ~0.6 MeV and, hence, on the strength with which such a "two-phonon" 0^+ state is populated. The question of "γ softness" has recently received increased attention as a result of studies of unique-parity states in the odd-A nuclei in this mass region. It has been shown[55] that a large amount of data can be described quite well in terms of a simple model consisting of the coupling of the odd particle to a rotating triaxial core. From the success of this model, it has been suggested[55] that the nuclei in this "transitional" region have triaxial shapes that are considerably more stable than expected from the theoretical potential-energy surfaces. (In this connection it should be mentioned that the authors of Ref. 5 point out that their calculations indicate that the wave functions have to be γ-localized more strongly than those given by their model.)

A further point is worthy of mention. Quite recently, a measurement of the lifetimes of the 4^+ and 3^+ states at 1400 and 1643 keV, respectively, has been reported.[51] These data yield a value for $B(E2, 4^+ \rightarrow 2^+)$, which is much lower than that expected on the basis of either a rotational or a vibrational picture. Further investigation to uncover the origin of this discrepancy and related ones[51] in other near-lying nuclei seems warranted.

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