PHYSICAL REVIEW VOLUME 131, NUMBER 6 15 SEPTEMBER 1963

Decay of Cs^{134} and the Level Scheme of Ba^{134}

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(Received 30 April 1963)

The energy (in keV) and the relative intensity of the gamma rays following the decay of Cs^{134} have been measured as 475(1.1), 563(9), 569(11), 605(98), 800(93), 1038(1.1), 1168(2.7), and 1367(3.5) with the help of the various scintillation spectrometry techniques. No gamma rays of energy 960, 1570, 1640, 1770, and 1970 keV reported earlier by certain workers could be detected. In addition to the already established 86 keV (26%) and 655 keV (71%) end-point beta rays, three beta rays of end points and intensities 1453 keV (0.13%), 892 keV (0.7%), 410 keV (2.1%) were confirmed by careful measurement with the help of a beta-ray spectrometer. The K-conversion coefficient of the gamma rays and the log ft value of the beta rays were obtained. The measurements established more firmly the decay scheme including the spin and parity assignments to the various levels.

I. INTRODUCTION

THE disintegration of 2.19-yr Cs^{134} which leads to the excited levels of Ba^{134} by beta emission has been extensively studied by several groups using various aspects of beta- and gamma-ray spectroscopy. Although the prominent features of the decay are well established, other features are still in doubt because of disagreement among the various reported results. From magnetic spectrometer measurements made by different workers[1] eleven gamma rays have been reported with energies of 202, 475, 563, 569, 605, 797, 802, 1038, 1168, 1367, and 1401 keV. Additional gamma rays obtained by scintillation methods have been reported at 960 and 1570 keV by Girgis and Van Lieshout,[2] and at 1640, 1770, and 1970 keV by French and Goodrich.[3] Nine beta groups have been reported, of which only the two prominent ones (those with end points of energy 86 and 655 keV) seem certain.

Energy levels in Ba^{134} have been proposed in the literature at 605, 1038, 1168, 1367, 1401, 1570, 1640, 1840, and 1970 keV in order to satisfy the data. Doubt concerning the existence of some of these levels, and of the location of some of the transitions is indicated by the Nuclear Data Group's chosen decay scheme[1] which does not include the 1367-, 1570-, and 1840-keV levels. The present study was undertaken with the hope of clarifying the situation and of establishing more certainly the spins and parities of the levels.

II. SOURCE PREPARATION

The Cs^{134} used for our measurements was obtained as $CsCl_2$ in HCl from Oak Ridge National Laboratory where it had been made by (n,γ) reaction in Cs^{133}. The sources used for the beta ray and the internal conversion electron studies were mounted on thin films of collodion (about 5–10 $\mu g/cm^2$ thickness). A drop of acid-free solution of active material was evaporated on a collodion film already treated with insulin. The sources used for gamma ray work were prepared by evaporation of a drop of active material either on aluminum foil backing or on lucite backing.

III. SINGLES GAMMA-RAY SPECTRA

The gamma rays from the decay of Cs^{134} were measured by using a cylindrical 3-in.×3-in. NaI(Tl) crystal mounted on a Du Mont 6363 photomultiplier tube in the manner described by Bell.[4] A polystyrene beta-ray absorber of 0.8 g/cm^2 thickness was used between the crystal and the axially centered sample. Pulse-height spectra were registered on a 20-channel Baird-Atomic analyzer.

A spectrum taken at 40 cm from the face of the 3-in.×3-in. NaI crystal is shown in Fig. 1. This spectrum was analyzed in the manner described by Heath.[5] The response function of the crystal for monoenergetic gamma rays was obtained from the observed pulse-height distribution of the gamma rays from Bi^{207}, Na^{22}, Zn^{65}, and Cs^{137} under the same geometrical conditions. When a response function was required with an energy different from those available, this function was obtained by interpolation. The energies of the most prominent gamma rays were determined by counting the Cs^{134} simultaneously with the standards. The average energy values and the relative intensities obtained are given in Table I. These values of the relative intensities have been estimated from a knowledge of the counts in each photopeak, the detection efficiency, and the peak-to-total ratio. The intensities are estimated to be accurate to about 10% in all cases except for the 475- and the 1038-keV gamma rays for which the error may be as large as 15%. It may be remarked here that no clear evidence of 960-, 1401-, 1570-, 1640-, 1840-, or 1970-keV

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[1] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing & Publishing Office, National Academy of Sciences–National Research Council, Washington 25, D. C., 1961), NCR-61-2-97.

[2] R. K. Girgis and R. Van Lieshout, Nucl. Phys. **12**, 672 (1959).

[3] John D. French and Max Goodrich, Bull. Am. Phys. Soc. **4**, 391 (1959).

[4] P. R. Bell, in *Beta and Gamma-Ray Spectroscopy*, edited by K. Sieghahn (Interscience Publishers, Inc., New York, 1955), Chap. 5.

[5] R. L. Heath, Atomic Energy Commission Report IDO-16408, 1957 (unpublished).

Table I. Gamma rays observed with their energies and intensities, and with coincident gamma rays.

Gamma-ray energy (keV)	Intensities relative to 605-keV gamma ray: From singles data	Intensities relative to 605-keV gamma ray: Best value from coincidence data	Gamma rays appearing in coincidence with it: 605 keV	800 keV	1038 keV	1168 keV	1367 keV
475±5	1.5±0.3	1.2 ± 0.2	yes	no	no	yes	no
569±3	22 ±3	20 ±2	yes	yes	no	no	no
605±3	100	100 ±10	no	yes	yes	yes	yes
800±4	98 ±8	94 ±9	yes	no	no	yes	no
1038±6	1.2±0.3	1.14± 0.15	yes	no	no	no	no
1168±4	2.7±0.3	3.0 ± 0.3	yes	yes	no	no	no
1367±4	3.6±0.4	3.6 ± 0.4	yes	no	no	no	no

gamma rays was found in ten different runs taken over these energy regions. This conflicts with the results obtained by Joshi and Thosar[6] for a 1401-keV gamma ray, by Girgis and Van Lieshout[2] for 960-, and 1570-keV gamma rays, and by two of the present authors[3] for 1640-, 1840-, and 1970-keV gamma rays (caused by an error in accounting for sum pulses).

Similar measurements were made with the sources at different distances from the crystal. Figure 2 shows the pulse spectrum for the energy region of 300 to 2000 keV. The solid line represents the spectrum with the source at 3.6 cm from the crystal while the dotted line represents the spectrum with the source at 30 cm from the crystal. The summing peaks at 1168, 1401, 1640, and 1970 keV confirm the results obtained by Lu *et al.*[7] and by Girgis *et al.*[2] An analysis of the high-energy part of the spectrum was made by using Na^{22} and Co^{60} sum peaks as reference standards. This analysis yielded the sum peaks at 1640, 1770, and 1970 keV (shown in Fig. 3). These sum peaks can be satisfactorily explained by using the cascade combination shown in Table II. Contrary to the results of Girgis *et al.*[2] no definite gamma-ray peak could be resolved at 1570 keV.

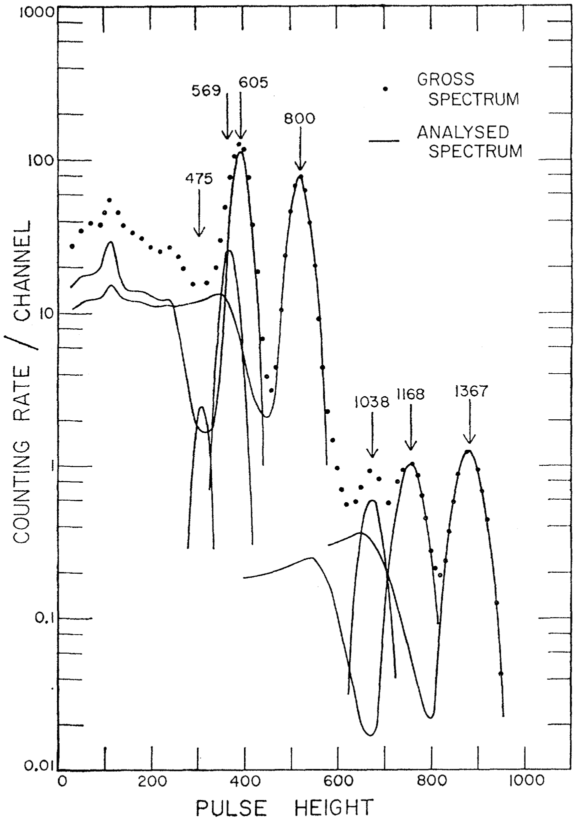

Fig. 1. Gamma-ray spectrum of Ba^{134} with source 40 cm from the face of a 3-in×3-in. NaI crystal, and with 0.8 g/cm^2 of the polystyrene absorber to stop beta rays from entering the crystal.

IV. COINCIDENCE SPECTRA

A. Gamma-Gamma Coincidences

Gamma-gamma coincidence measurements were made by using a "fast-slow" coincidence circuit having a re-

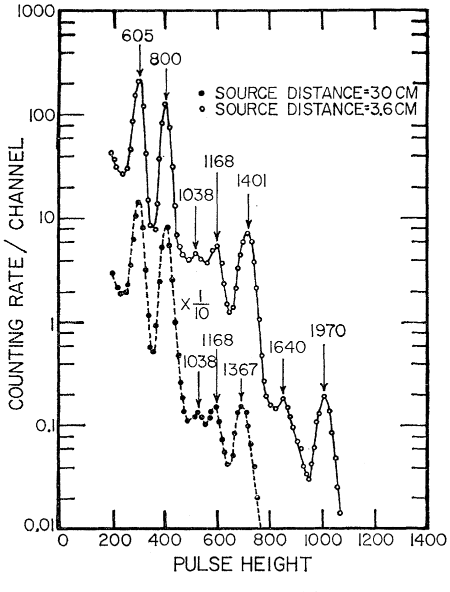

Fig. 2. Gamma-ray spectrum of Ba^{134} (a) Dotted curve: source at 30 cm from 3-in.×3-in. NaI crystal, (b) solid curve: source at 3.6 cm from the 3-in.×3-in. NaI crystal.

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[6] M. C. Joshi and B. V. Thosar, Phys. Rev. **96**, 1022 (1954).

[7] D. C. Lu and M. D. Wiedenbech, Phys. Rev. **94**, 501 (1954).

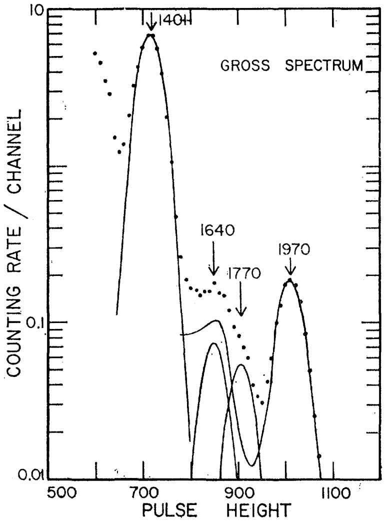

FIG. 3. High-energy part of the gamma-ray spectrum of Ba^{134} with source at 3.6 cm from 3-in.×3-in. NaI crystal. The analyzed spectrum is shown along with the gross spectrum.

solving time of 100 nsec. The source was viewed by two 3-in.×3-in. NaI(Tl) crystals with axes at 90° to each other. A shield similar to that described by Bell[4] was used to shield each crystal from Compton photons scattered in the other. For an individual run the single-channel analyzer window was set on a principal gamma-ray peak with the gamma-ray coincidence pulse spectra recorded on the twenty-channel analyzer.

Figure 4 shows the gamma-ray pulse spectrum in coincidence with the 605-keV gamma ray. The full-energy peaks were analyzed in the same manner as described for single-crystal spectra. Peaks at 800, 1038, and 1367 keV were clearly resolved. Peaks at 475 and 1168 keV were obtained only after proper subtractions were carried out. A broad peak around 580 keV can be resolved into two peaks of energy 569 and 605 keV. The 605-keV peak is attributed to the coincidences between pulses from the 569-keV gamma ray falling in the single-channel analyzer window (set to receive pulses corresponding to a range of 575 to 635 keV) and those from the 605-keV gamma ray stopped in the crystal of the multichannel analyzer. This is, therefore, a spurious coincidence peak. The coincidence peaks at 1038, 1168, and 1367 keV were corrected for summing of cascading gamma rays in order to calculate their relative intensities.

TABLE II. Cascades contributing to the high-energy sum peaks.

Energies of sum peaks (keV)	Possible cascades of gamma rays (keV)
1640	(1038,605) (1168,475) (563,605,475)
1770	(1168,605)
1970	(1168,802), (1367,605), (695,563,802), (605,797,569)

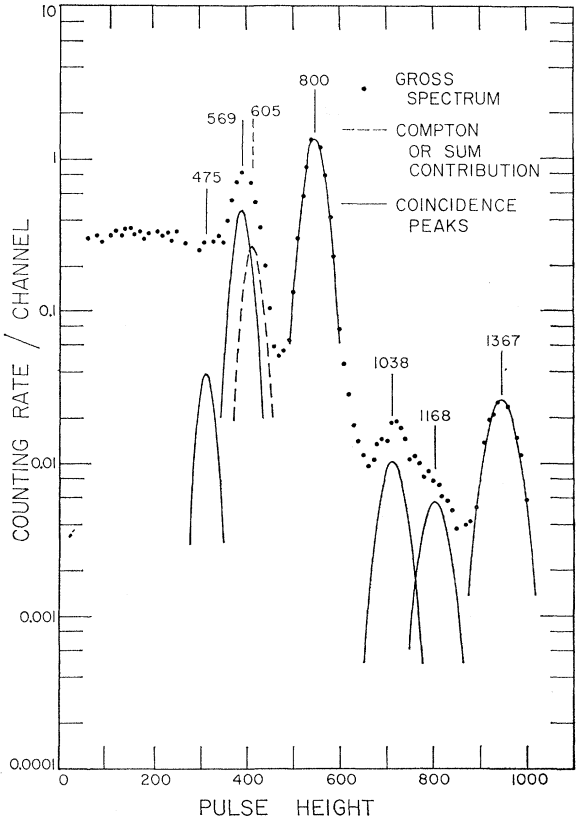

FIG. 4. Ba^{134} gamma-ray spectrum in coincidence with 605-keV gamma ray. The two 3-in.×3-in. NaI crystals were set at 90° to each other and at 5.1 cm from the source. The 605-keV peak in the coincidence spectrum is due to parts of 569-keV peak falling in the window of the single-channel analyzer.

The gamma-ray spectrum in coincidence with the 800-keV peak is shown in Fig. 5. A careful subtraction indicates a broad peak in the neighborhood of 605-keV energy which can be resolved into two gamma rays of energies 569 and 605 keV. The peak observed at 1168 keV has a small contribution due to coincidences between the 1168-keV (569+605) summing peak in the crystal on the twenty-channel analyzer and the 800-keV gamma ray in the crystal on the single-channel analyzer. The peak at 800 keV was accounted for by random coincidences, and by coincidences between the Compton-distribution pulses of the 1168-keV gamma ray falling in the single-channel analyzer window with those of the 800-keV gamma ray.

The coincidence spectrum was also taken with the single-channel analyzer set at the 1168-keV position and is shown in Fig. 6. The peak marked 569 keV arises from the coincidence of the 563- and 569-keV gamma rays with sum pulses from the (802-, 605-keV) and (797-, 605-keV) gamma-ray pairs, respectively, where the pulse from one of each pair results from a Compton process.

In addition, measurements were made on pulses coincident with those at the 1038-keV peak, and with

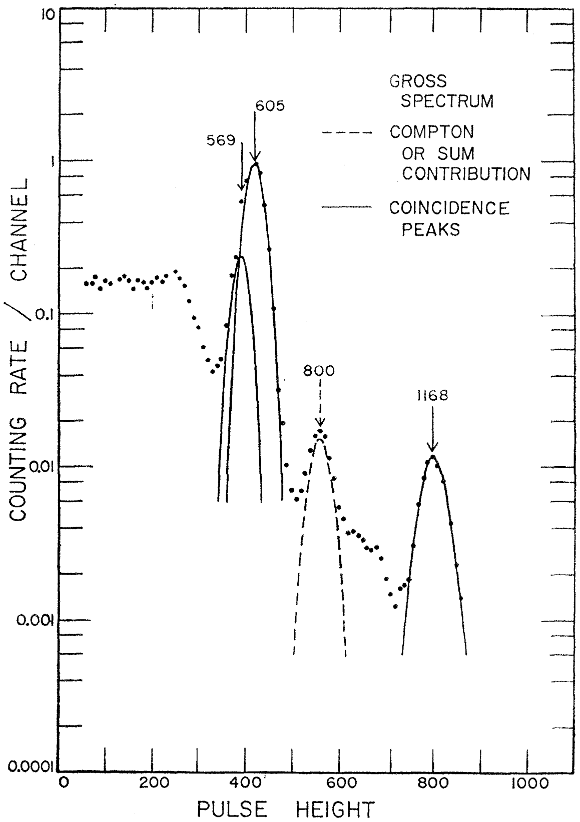

FIG. 5. Ba^{134} gamma-ray spectrum in coincidence with 800-keV gamma ray. The two 3-in.×3-in. NaI crystals were set at 90° to each other and at 5.1 cm from the source.

those at the 1367-keV peak. Table I shows the average relative intensities obtained from various coincidence measurements. The intensities listed have been corrected for summing whereas no correction has been applied for angular correlations between various pairs of gamma rays.

B. Beta-Gamma Coincidence

In order to get direct information about the placing of various beta groups in the decay scheme, a beta-gamma coincidence study was undertaken. In this study the same "fast-slow" coincidence circuit, as mentioned previously, was used. A $\frac{1}{2}$-in.×1-in. anthracene crystal mounted on a Du Mont photomultiplier was used in the multichannel-analyzer side.

The beta spectra, in coincidence with each of the two prominent gamma-ray peaks at 605 and 800 keV, were measured. In both cases a beta group with end-point energy of 655 keV was detected. It was not possible to analyze this data for any beta groups of low intensity because of poor resolution of this system as compared to the magnetic spectrometer. The energy of the well-known 86-keV beta group was too low to be determined satisfactorily with the coincidence spectrometer.

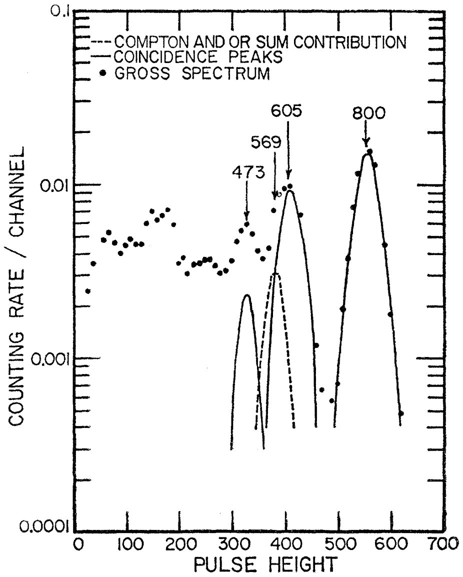

FIG. 6. Ba^{134} gamma-ray spectrum in coincidence with 1168-keV gamma ray. The two 3-in.×3-in. NaI crystals were set at 90° to each other and at 5.1 cm from the source. The 569-keV peak arises from coincidence between the pulse distributions of the sums (797+605) and (802+605) keV in the window of single-channel analyzer with the 563- and 569-keV gamma rays, respectively.

V. BETA-RAY SPECTRUM

A double-focusing magnetic spectrometer of the type discussed by Siegbahn and Swartholm[8] was used to analyze the beta-ray spectrum of Cs^{134}. A plastic phosphor 2 mm thick was employed as the detecting device.

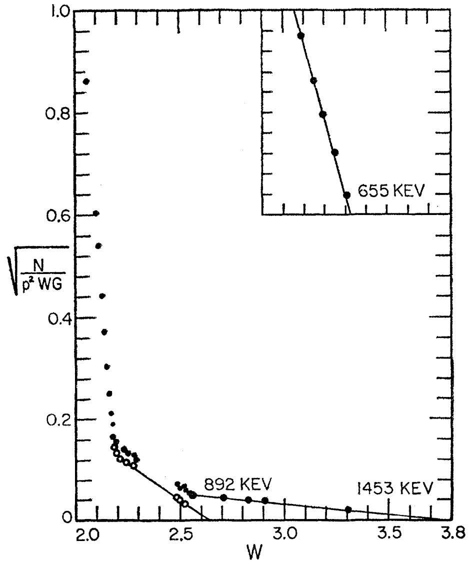

FIG. 7. Fermi-Kurie plot of the beta-ray spectra of Cs^{134} in the high-energy region.

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[8] K. Siegbahn and N. Swartholm, Nature **157**, 872 (1946); N. Swartholm and K. Siegbahn, Akad. Mat. Ast. Fys. **A33**, No. 21 (1946).

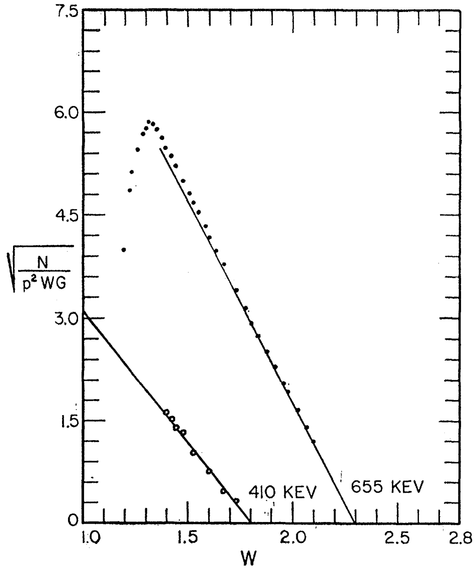

FIG. 8. Fermi-Kurie plot of the beta-ray spectra of Cs^{134} in low-energy region.

The transistorized current-control circuit described by Garwin[9] was used on the magnet current. This control circuit allowed current drifts of less than 0.001% for hour periods; thus, very careful beta measurements were made possible.

Fermi-Kurie plots of the various beta-ray spectra observed are shown in Figs. 7 and 8. In order to be consistent and accurate in analyzing the end-point energies and the relative intensities of the various beta groups, a program for the IBM 650 was written to get Fermi plots from the data points. The usefulness of this procedure was exhibited when weak low-energy beta groups could be consistently analyzed without subjecting them to personal evaluation.

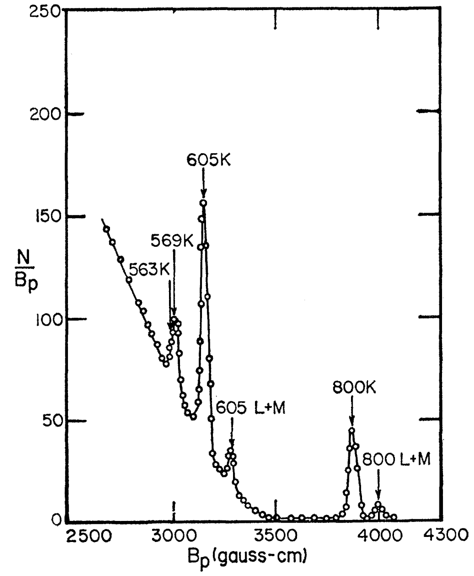

FIG. 9. Internal-conversion spectra of Cs^{134} in the low-energy region.

Figure 7 shows a typical Fermi-Kurie plot for the high-energy region. Three beta groups with end-point energies of 655, 892, and 1453 keV were found. A very careful study was made of the region around 600 to 700 keV but no indication was obtained for a beta group of 683-keV end point reported by earlier workers.[10,11]

Figure 8 shows a typical Fermi-Kurie plot of beta distribution up to about 600 keV. This curve is found to have two distinct slopes with end-point energies of 655 and 410 keV. No indication was found for a 280-keV beta group as reported earlier.[12,13] Detection of the beta-ray group with end-point energy of 86 keV was not possible because of low detector efficiency in this region. The energies and the intensities of the various beta-ray groups with an estimate of the error have been given in Table III. The intensity of the 86-keV beta group was chosen to make the experimental data self-consistent.

The internal-conversion spectrum for the source is shown in Figs. 9 and 10. The internal-conversion coefficient for the 605-keV gamma ray was determined by a "comparison method" wherein the internal-conversion lines from two similar sources of Cs^{134} and Cs^{137} were measured in the beta-ray spectrometer under the same conditions. Subsequently, the same sources were em-

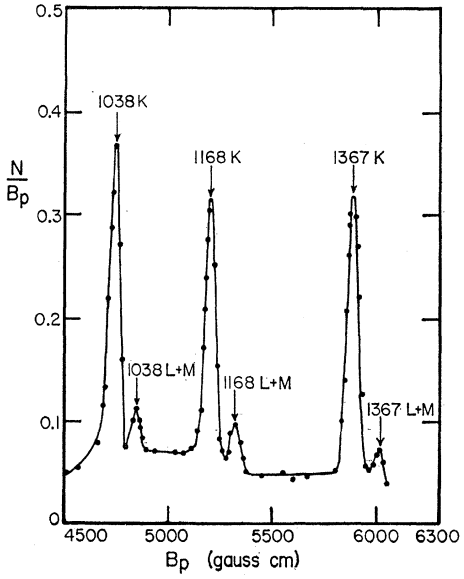

FIG. 10. Internal-conversion spectra of Cs^{134} in the high-energy region.

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[9] Richard L. Garwin, Rev. Sci. Instr. **29**, 223 (1958).

[10] H. H. Forster and J. S. Wiggins, Nuovo Cimento **2**, 854 (1955).

[11] G. L. Keister, E. B. Lee, and F. H. Schmidt, Phys. Rev. **97**, 451 (1955).

[12] K. Gromov and B. Dzhelepov, Dokl. Akad. Nauk SSSR **85**, 299 (1952).

[13] C. L. Peacock, U. S. Atomic Energy Commission file number NP-6325 (unpublished).

TABLE III. Energy and intensity of the beta rays.

Energy (keV)	Intensity (%)
86	26 (adopted)
210	None observed
280	0.2
410±6	2.1±0.2
655±2	71 ±3
686	None observed
892±5	0.7 ±0.08
1453±10	0.13±0.02

ployed to measure their respective unconverted gamma-ray spectra using the scintillation spectrometer discussed earlier. Using the value of the *K*-conversion coefficient of the 662-keV gamma ray of Cs^{137} equal to 0.096 as measured by Azuma,[14] the *K*-conversion coefficients of the various gamma rays were computed. Also the ratios $K/(L+M)$ for the various gamma rays were obtained. Table IV shows these values along with theoretically expected values as computed by Rose.[15] The multipolarities assigned to the various gamma rays are also listed.

A slight bump in the continuous beta-ray spectrum was repeatedly observed at 165-keV energy. Presuming it to be a *K*-conversion line the corresponding gamma transition would be about 200 keV, and would have an intensity of (0.8±0.4)% of that of the 605-keV gamma ray.

VI. DISCUSSION OF DECAY SCHEME

The data obtained in this study are best satisfied by the decay scheme shown in Fig. 11. The energy levels are just those published by the Nuclear Data Group[1] two of which (1641 and 1773 keV) were indicated at that time as uncertain. The evidence for such a 1641-keV level is quite conclusive. This evidence comes from the strong sum peak observed at about 1640 keV (from the transition energies we have chosen 1643 keV for the level) in the spectrum taken at small distance from NaI crystal, and from coincidences found between the 1168- and 475-keV gamma rays. Also the 410-keV end-point beta group fits very well with this level.

TABLE IV. *K*-conversion coefficients and $K/(L+M)$ ratio for Cs^{134} decay

Transition (keV)	K(exp) $\times10^3$	Theoretical value of K(after Rose) $\times10^3$			$K/(L+M)$ (exp)	Multipole order adopted
		$E1$	$E2$	$M1$		
563 ±1 569 ±0.5	8.28±1	2.1	5.9	8.5		$E2+M1$ $M1$
605 ±0.4	5.5 ±0.4	1.9	5.15	7.5	5.2	$E2$
800 ±0.6	2.6 ±0.3	1.03	2.6	3.8	5.43	$E2$
1038 ±0.5	1.53±0.2	0.6	1.45	2.1	5.1	$E2$
1168 ±0.5	0.9 ±0.2	0.48	1.1	1.67	6.08	$E2$
1367 ±1	0.7 ±0.15	0.36	0.79	1.19	6.95	$E2$

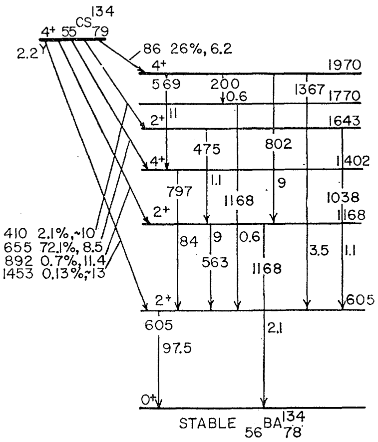

FIG. 11. Decay scheme of Cs^{134}.

The existence of a level at about 1773-keV is confirmed by the sum peak at 1770 keV in the spectrum taken at small source distance, and from the coincidence observed between the 605- and 1168-keV gamma rays. No beta ray could be found to feed this level. It is presumed to be fed by a 200-keV transition from the 1970-keV level. A weak electron line corresponding to *K*-conversion of such a transition was observed (see previous section) and has also been reported by others.[1] Very careful search gave no evidence for the 1570-keV level and the transition from it to the 605-keV level reported by Girgis *et al.*[2] No sign of a beta group of 686-keV end-point energy was found. Since the 1367-keV gamma ray is satisfactorily accounted for by the 1970- to 605-keV transition, there is no evidence for a 1367-keV level adopted by various authors.[1,3]

The assignment of the spin and the parity is made by use of the internal-conversion coefficient for the various gamma rays, the log *ft* values of the various beta groups, and the accepted 4^+ assignment[1] for the ground state of Cs^{134}.

The internal-conversion coefficient for the 605-keV gamma ray is found to lie close to the $E2$ value calculated theoretically by Rose.[15] Since the ground state is 0^+, the transition must then be $2^+ \rightarrow 0^+$. The log *ft* value of 1453-keV beta group feeding the 605-keV level is found to be 13; this suggests that the transition is a second-forbidden one with $\Delta J = \pm 2$ and no change in parity.[16] Thus, the 605-keV level is the first 2^+ level. The angular correlation measurements done by Everett and Glaubman[17] support this 2^+ assignment.

From the systematics of even-even nuclei[18] the next level at 1168 keV is expected to be a second 2^+, and the corresponding cascade gamma ray of energy 563 keV is expected to be an $E2$ transition with a small admix-

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[14] T. Azuma, J. Phys. Soc. Japan **9**, 1 (1954).

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

[16] C. S. Wu, in *Nuclear Spectroscopy*, edited by Fay Ajzenberg-Selove (Academic Press Inc., New York, 1960), Part A, Chap. I. E.

[17] A. E. Everett and M. J. Glaubman, Phys. Rev. **100**, 955 (1955).

[18] D. M. Van Patter, Nucl. Phys. **14**, 42 (1959).

ture of $M1$. From the measurement of conversion coefficients Keister *et al.*[11] has assigned $M1$ multipolarity to the 569-keV gamma ray. Adopting this assignment, the value of the combined K-conversion coefficient for the (563+569)-keV gamma ray measured in the present experiment requires that the 563-keV gamma-ray transition be 80% $E2$ and 20% $M1$. Thus, the 1168-keV level can be assigned 1^+, 2^+, or 3^+ spins. The log ft value of the beta-ray transition of energy 892 keV which feeds this level is 11.4. This requires $\Delta J = \pm 2$, no change in parity.[16] Thus, the spin assignment for this level is 2^+.

There is no ground-state transition observed from the level at 1402 keV, which implies a high spin value for this level. The measured value of the conversion coefficient of 800-keV cascade gamma ray is in agreement with the theoretical estimates of an $E2$ transition. This favors 2^+, 3^+, and 4^+ assignment to this level. The log ft value of the 655-keV beta group feeding this level is 8.5, and appears a little high for an allowed transition. But, from the shape of this beta group, it appears to be an allowed transition. Thus, the 1402-keV level appears to be 3^+ or 4^+. The angular correlation work[17] favors a 4^+ assignment to this level.

The level at 1643 keV has two gamma rays leaving it. The 1038-keV gamma ray is found to be an $E2$ transition from internal-conversion measurements (refer to Table IV), and the 475-keV transition is known[11] to be $E2$. Thus, this level can be assigned 0^+, 1^+, 2^+, 3^+, or 4^+ spin values. It is fed by the beta group of energy of 410 keV which has a log ft value of 10 and is probably a second-forbidden transition with $\Delta J = \pm 2$, and with no change in parity[16]; the beta-ray data support a 2^+ assignment to the 1643-keV level.

ACKNOWLEDGMENTS

The authors wish to thank Dr. J. S. Levinger for valuable discussions during the course of this work.

PHYSICAL REVIEW VOLUME 131, NUMBER 6 15 SEPTEMBER 1963

Scattering of He^3 by Alpha Particles*

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(Received 3 May 1963)

The elastic scattering of He^3 by alpha particles in the energy range 0–20 MeV is considered using the method of resonating-group structure in the one-channel approximation. A two-body, central potential of Gaussian form which fits the low-energy nucleon-nucleon scattering data as well as possible is used. Saturation is taken approximately into account by choosing the radii of the clusters according to the experimental data. Phase shifts are computed up to $l=6$. The presence of a $l=3$ resonance is predicted with an excitation energy of about 6 MeV. Angular distributions at 1.7 and 16.6 MeV in the c.m. system are also calculated. At 1.7 MeV, the theoretical result agrees very well with the experimental data. At 16.6 MeV, the calculation predicts correctly the position of the diffraction minima and maxima, but the differential cross sections are somewhat larger than the experimental values in the forward angular region. An optical-model analysis is also performed at these two energies. It is found that at the higher energy, an imaginary optical potential of about 2 MeV is necessary to obtain the best fit with experiment. This indicates that in the resonating-group calculation, channels other than the He^3-α channel are also important in determining the elastic scattering cross section at relatively high energies. Specifically, one can see from the existing reaction data that the other important channels are the p-Li^6 channels with Li^6 in the ground and the first excited state. Calculations are also done with a second two-body potential which was extensively used in resonating-group calculations by the London-group of Massey and Collaborators.

I. INTRODUCTION

THE method of the resonating-group structure[1] has been used extensively in recent years to analyze scattering problems where both the incident and the target nuclei are composed of only a few nucleons. The main advantage of this method is that it employs a two-body potential in the calculation and takes into account the indistinguishability of the nucleons correctly. Up to the present moment, the problems treated with this method are the scattering of n-d,[2]

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* This work was supported by the U. S. Atomic Energy Commission and the U. S. Office of Naval Research.

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[1] J. A. Wheeler, Phys. Rev. **52**, 1083 (1937); see also K. Wildermuth and T. Kanellopoulos, Nucl. Phys. **7**, 150 (1958); **9**, 449 (1958).

[2] R. A. Buckingham, S. J. Hubbard, and H. S. W. Massey, Proc. Roy. Soc. (London) **A211**, 183 (1952); P. G. Burke and H. H. Robertson, Proc. Phys. Soc. (London) **A70**, 777 (1957).