Angular Correlation of Gamma Rays in the Decay of Rb^{84}†

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Angular-correlation measurements have been made of the cascade gamma rays following the beta decay of Rb^{84}. The results show that the spin and parity of the second excited state of Kr^{84} is 2+. The energies of the gamma rays in this decay have also been remeasured using a lithium-drifted germanium detector and are 883, 1018, and 1901 keV with errors of ±2 keV and relative intensities of 100:0.53:1.06, respectively.

INTRODUCTION

THE decay of Rb^{84} has been investigated by a number of groups[1–11] using beta- and gamma-ray spectroscopic techniques. The beta-ray endpoint energies, the gamma-ray energies, the relative intensities of these transitions, the shape of the beta-ray spectrum, and beta-gamma and gamma-gamma coincidences have been measured. This work is summarized in the decay scheme shown in Fig. 1. Further information about the excited states of Kr^{84} has also been obtained by studies on the gamma rays following the beta decay of Br^{84}.

However, none of this previous work has been able to characterize definitely the spin and parity of the 1901-keV level. The current research was undertaken to determine these properties by a measurement of the angular correlation of the 1018–883-keV gamma-ray cascade. The 90-180° anisotropy of this cascade was measured by Johnson and O'Kelley[4] using Br^{84} as the parent nucleus. However, the Legendre polynomial expansion for the angular correlation of these gamma rays is

$$W(\theta)=1+A_2P_2(\cos\theta)+A_4P_4(\cos\theta).$$

In order to eliminate any dependence of the correlation on counter efficiency, it is necessary to normalize counting rates at different angles, that is, to use the ratio $N(\theta)/N(90°)$. Therefore, the correlation must be measured at more than two angles in order to determine both A_2 and A_4, and the 90-180° anisotropy can give no information about the spin of the 1901-keV level, as Johnson and O'Kelley pointed out. In the present experiment, both Legendre polynomial coefficients were determined and, as a result, a unique assignment could be made for the spin.

The 1018-keV transition is much less intense than the 883-keV gamma ray and is therefore nearly invisible in a scintillation-counter spectrum. Moreover, the source was contaminated with Rb^{86} which emits a 1077-keV gamma ray and has a half-life comparable to that of Rb^{84}. In order to analyze the Rb^{84} gamma rays in the 1-MeV region, spectra have been measured using a lithium-drifted germanium detector whose resolution is an order of magnitude better than that of scintillation counters.

EXPERIMENTAL APPARATUS AND PROCEDURE

Krypton gas was irradiated with protons for 2h in the Oak Ridge National Laboratory 86-in. cyclotron. The Rb^{84} source thereby produced was dissolved in dilute hydrochloric acid and, since no activities other than Rb^{83} and Rb^{86} were observed, no further chemistry was performed. For the angular correlation measurements, approximately 10 μCi of the source was encapsulated in a Teflon cylinder 3 cm long with an inside diameter of 3 mm and an outside diameter of 6 mm. For spectral measurements with the germanium detector, about 1 mCi of source was used.

The gamma-ray spectrum, as measured with a 1-in.-diam by 2-in.-long NaI(Tl) scintillation counter, is shown in Fig. 2. The intensity of the 1018-keV photo-

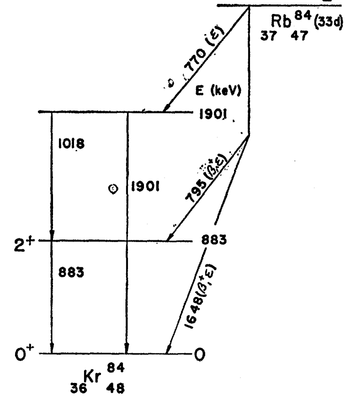

FIG. 1. Decay scheme of Rb^{84}. The energies assigned to the gamma rays are those determined in this work.

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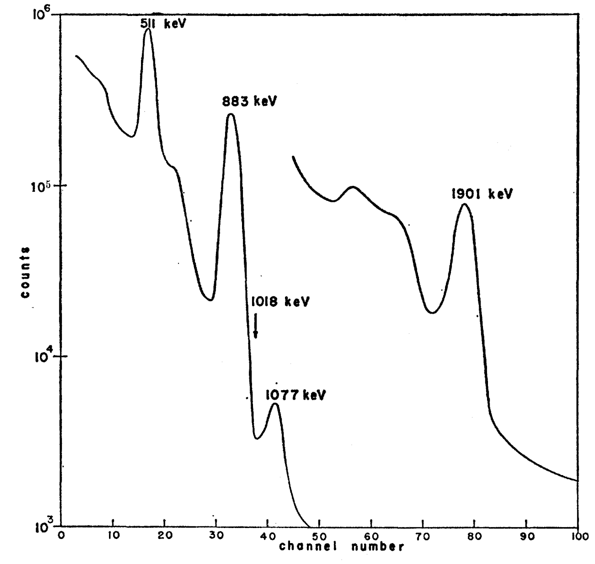

FIG. 2. Pulse-height spectrum of Rb^{84} as measured with a 1-$\times$2-in. NaI(Tl) scintillation counter. The photopeak of 1018 keV is not resolved in this spectrum. The 1077-keV line belongs to the Rb^{86} contaminant.

peak is too small relative to that of the 883-keV transition to be clearly resolved with the scintillation counter. However, Fig. 3 shows the gamma-ray spectrum of the same source, using a lithium-drifted germanium detector operated at liquid-nitrogen temperature. The detector was fabricated by conventional techniques[12] and had an area of 3 cm^2 and a depletion layer of 5 mm. The resolution of this detector was 10 keV at 1077 keV, 7 keV at 662 keV, and 5 keV at 122 keV. The linearity of the energy response of the detector was checked using 37 well-known gamma rays from 14 isotopes. The only deviations from linearity were those which could be attributed to the uncertainties in the gamma-ray energies. The energies of the Rb^{84} gamma rays were found to be 883, 1018, and 1901 keV with uncertainties of ± 2 keV. The gamma ray which can be observed in Fig. 3 at 1077 keV indicates the presence of Rb^{86} contamination. The spectrum from 500 to 600 keV is more clearly shown in Fig. 4. The 511-keV gamma ray is annihilation radiation, and the 521, 530, 553 keV triplet has recently been identified[13] with the decay of Rb^{83}. No other gamma-ray transitions which could be assigned to the Rb^{84} decay were observed either with the germanium detector or with scintillation counters.

The relative intensities of the three gamma-ray transitions of 883, 1018, and 1901 keV were determined by using the photopeaks of these gamma rays. Since the energies of these transitions are quite different, corrections must be made for the different photoelectric efficiencies at the different energies. These efficiencies were first calculated for germanium using the Hall formula for the cross section.[14] In order to determine the accuracy of this calculation over the range from 800 to 1900 keV, the relative intensities of the 1837- and 898-keV transitions of Y^{88} were measured. The Y^{88} spectrum as measured with the germanium detector is shown in Fig. 5. The ratio of the intensity of the 1837-keV transition to that of the 898-keV transition is 100:92.[15] Using this ratio and the area under the photopeaks of Fig. 5, the ratio of the cross-section of 898 keV to that at 1837 keV was found to be 4.15, which is in good agreement with the value of 4.08 obtained for this ratio using the calculated cross sections.

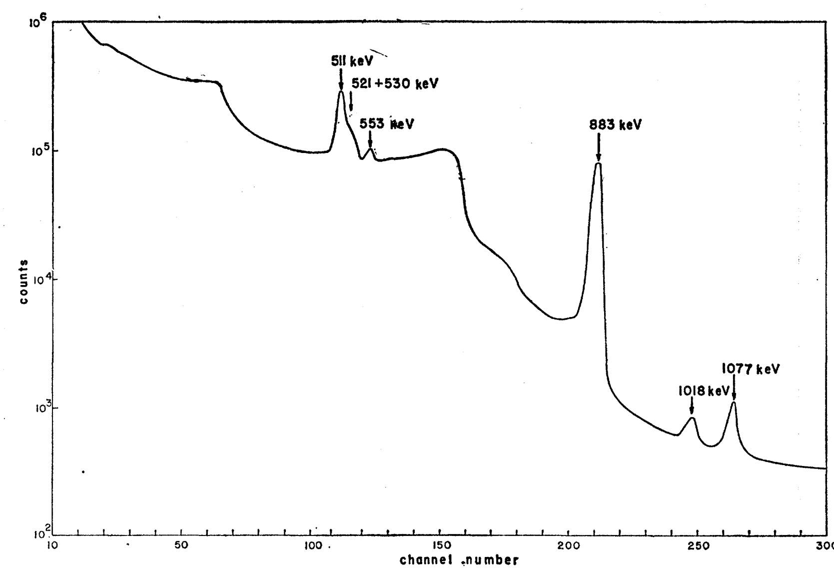

FIG. 3. Pulse-height spectrum of Rb^{84} as measured with a lithium-drifted germanium detector. The structure near 500 keV is shown in Fig. 4.

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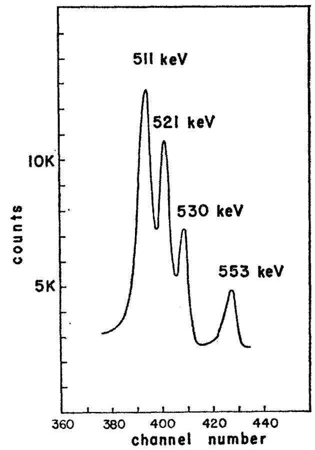

FIG. 4. Expanded view of the pulse-height spectrum of Rb^{84} near 500 kev as measured with a lithium-drifted germanium detector. The 521-, 530-, 553-keV triplet belongs to the Rb^{83} decay.

In Fig. 5, the intensity of the 815-keV double escape peak of the 1837-keV gamma ray is 44% of that of the 1837-keV photopeak after correction for the pair production and photoelectric efficiency. In Rb^{84}, the 1901-keV photopeak has a double escape peak at 889 keV which is not resolved from the 883-keV gamma ray. Extrapolation of the Y^{88} data shows that the contribution to the 883-keV photopeak from the 889-keV double escape peak is about 0.6%. Corrections for this effect and the photoelectric efficiency were applied to the Rb^{84} spectrum, and the relative intensities of the 883-, 1018-, and 1901-keV transitions were determined to be 100:0.53:1.06, respectively. This compares favorably with the ratios 90:0.6:1.0 of Johnson and O'Kelley[4], but less so with those of Welker and Perlman,[2] who obtained 64:0.3:0.9.

The angular-correlation apparatus consisting of one fixed and two movable scintillation counters has been previously described.[16] The main difference in the present experimental arrangement is that cylindrical lead shields with an annular thickness of 1 in. were placed around each crystal to minimize the scattering of gamma rays among the counters. The counters were also shielded from beta rays with 1-cm-thick Lucite absorbers. Finally, the coincidence resolving time was narrowed to 18 nsec in order to minimize the chance coincidence rate.

When the discriminator for the fixed base detector was set to span the combined 883–1018-keV peak, the coincidence spectrum of Fig. 6 was obtained in one of the movable detectors. This particular spectrum represents an accumulation time of 90 h. The chance coincidence rate of the 883-keV gamma ray was found to be greater than 50% of the real rate whereas that of the 1018-keV gamma ray was only about 3%. This explains the observed effect that the total number of 883-keV gamma rays is more than twice the total number of 1018-keV gamma rays in the coincidence spectrum. Ideally, these two numbers should be the same. Owing to the high chance-coincidence rate for the 883-keV gamma rays, only the 1018-keV gamma rays in the movable detectors, in coincidence with the 883-keV gamma rays in the fixed base detector, were used in the analysis. These gamma rays were distinguished by using a multichannel analyzer in conjunction with a subgroup programmer as described previously.[16]

The counting rate of the 883–1018-keV coincidences is very low. The counting time in each angular position was 1 h, the integrated number of coincidences under the 1018-keV peak during this time being an average of 9.4. One complete run (three angular positions) took 5 h of clock time, and a total of 35 runs was performed.

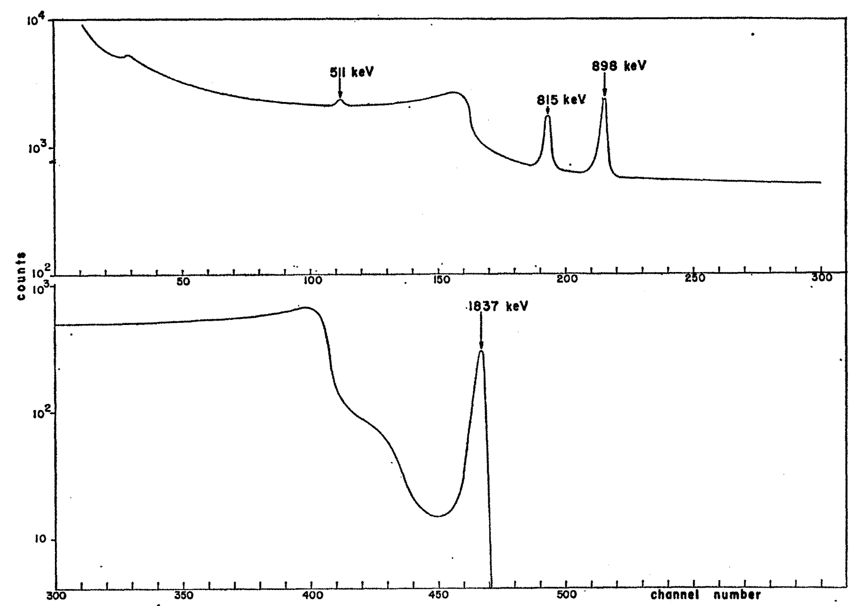

FIG. 5. Pulse-height spectrum of Y^{88} measured with a lithium-drifted germanium detector.

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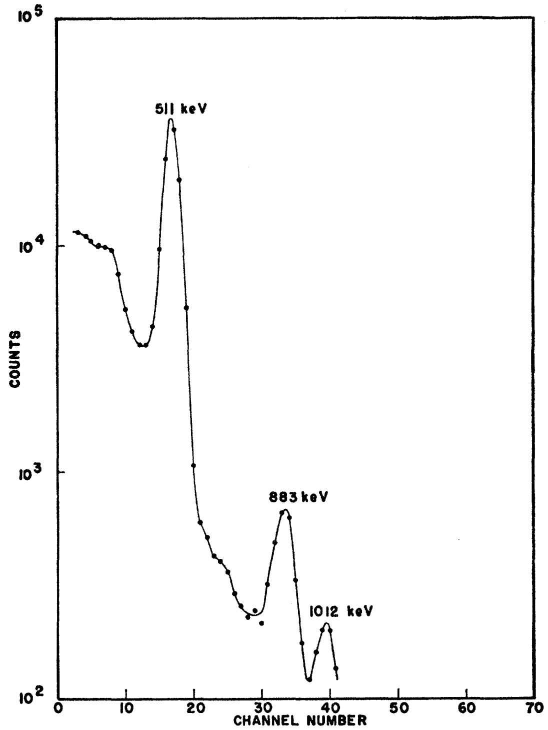

FIG. 6. Scintillation-counter spectrum of Rb^{84} in coincidence with the combined 883–1018-keV photopeak.

The A_2 and A_4 coefficients were corrected for solid-angle attenuation,[17] but since the time of one run, about 5 h, is very small compared to the 33-day half-life of Rb^{84}, no correction for source decay was necessary. Neither was it necessary in this case to correct for any interference from coincidences from other gamma rays. The corrected values of A_2 and A_4 were, finally,

$$A_2 = -0.056 \pm 0.050$$
$$A_4 = +0.426 \pm 0.089.$$

DISCUSSION

The angular correlation data is easily interpreted using the graphs shown in Fig. 7. These are plots of A_2 versus A_4 with δ^* as a parameter for the most probable spin sequences. The mixing ratio δ is related to the parameter δ^* by the equation

$$\delta = \delta^* / (1 - |\delta^*|).$$

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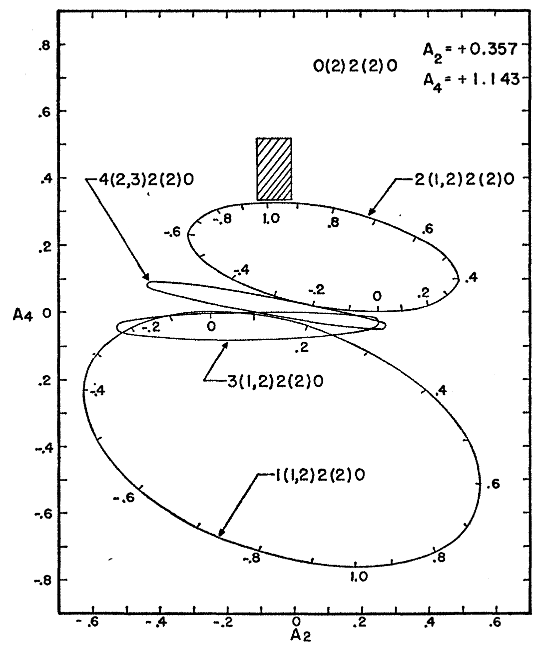

FIG. 7. Parametric curves of the angular correlation coefficients for possible spin sequences. The experimental result for Rb^{84} is indicated by the cross-hatched rectangle.

Although the experimental value of A_4 is somewhat high, the only possible spin of the 1901-keV level is 2. The mixing ratio δ is >10, therefore the 1018-keV transition must be $E2$ with less than 1% admixture of M1, and the parity of the 1901-keV level is positive.

The 1901-keV level is clearly collective in nature, although neither a 0+ nor a 4+ state appears to be excited near this level by the decay of Rb^{84}. These collective aspects are illustrated by the following points:

(1) The second excited state should have an energy roughly twice that of the first excited state. For Kr^{84} this ratio is 2.15.

(2) The $M1$ contribution to the $2+ \to 2+$ transition is very weak. For the 1018-keV transition, this contribution is less than 1%.

(3) The $E2$ rates between adjacent levels substantially exceed the single-particle estimates, and the crossover transition from the second 2+ state to the ground state is strongly inhibited. In this case the relative intensity of the 1901-keV crossover transition to the 1018-keV gamma ray is only 2.0, which is an order of magnitude smaller than the single-particle estimates.