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Rotational States in Tm^{171}

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The decay of Er^{171} has been investigated by means of a coincidence scintillation spectrometer. Eight gamma rays have been arranged in a level scheme with levels at 5, 118, 130, 337, and 425 kev. Spin and parity values have been assigned to most of levels. It is found that the first four levels form a rotational band in good agreement with the theoretical formula for the case $K=\frac{1}{2}$. The beta-ray spectrum has been resolved in components which fit very well into the level scheme. The beta- and gamma-ray transition probabilities are discussed. They are found to be in good agreement with the theory.

INTRODUCTION

THE nuclide Er^{171} decays by β^- emission to Tm^{171} with a half-life of 7.5 hours. The decay was first investigated by Ketelle and Peacock.[1] They analyzed the beta spectrum and found three gamma rays. A metastable state of 2.5-μsec half-life was found by McGowan and DeBenedetti.[2] Keller and Cork[3] investigated the internal conversion spectrum and reported seven gamma rays. The available information, however, is not sufficient for setting up a consistent decay scheme.

The level structure of Tm^{171} should be very similar to that of Tm^{169}, which has a rotational structure characteristic for nuclei with the ground state spin $\frac{1}{2}$.[4] It was therefore deemed worthwhile to make a more complete investigation of the decay of Er^{171}, in order to obtain more information about this special type of level structure.

In the present work the decay of Er^{171} was investigated by means of a coincidence scintillation spectrometer. The experimental results make it possible to set up a consistent decay scheme which in all details agrees with the unified model.

MEASUREMENTS

The radioactive sources were obtained by pile irradiation of erbium oxide. The irradiated material (supplied by Johnson, Matthey, and Company, Ltd., London) was of very high purity. Foreign elements other than the rare earths were estimated to amount to less than 0.015% of the product. The only detectable impurity was 0.05% thulium. It can be shown that this impurity does not disturb the present measurements.

Figure 1(a) shows a Kurie plot of the beta spectrum. The upper end of the spectrum has been corrected for the limited resolution of the spectrometer. Apparently there are two groups with the end points at 1.52 and 1.11 Mev. The intensities are 6% and 94%, respectively. The 0.67-Mev group reported by Ketelle and Peacock has not been found in the present work. The Kurie plot indeed starts to deviate from a straight line at about 0.5 Mev, but this is a well-known effect of the scintillation spectrometer. By comparison with simple spectra one can conclude that if there is any 0.67-Mev group at all, its intensity is less than 5%. Furthermore, as will be shown below, there are no gamma rays which can be associated with a low-energy beta group. Particularly, the 0.8-Mev gamma ray reported by Ketelle and Peacock was not found. Therefore, the

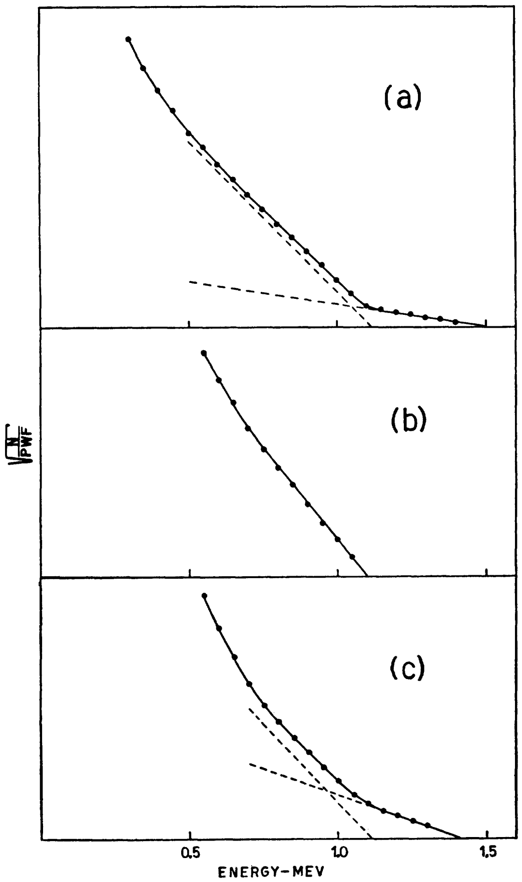

FIG. 1. Kurie plots of (a) the beta-ray spectrum of Er^{171}, (b) the beta rays in coincidence with the 300-kev gamma-ray group, and (c) the beta rays in coincidence with the 120-kev gamma-ray group.

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[2] F. K. McGowan and S. DeBenedetti, Phys. Rev. **74**, 728 (1948).

[3] H. B. Keller and J. M. Cork, Phys. Rev. **84**, 1079 (1951).

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0.67-Mev beta group might be ascribed to some impurity in the source.

The gamma spectrum of Er^{171} is shown in Fig. 2(a). At 50 kev there is a peak due to the *K* x-rays of thulium, showing that one or several of the gamma rays are considerably converted. The two main gamma-ray peaks fall at 120 kev and 300 kev. This is in good agreement with the gamma-ray energies reported by Keller and Cork: 113, 118, 125, 176, 295, 307, and 420 kev. The first three rays cannot be resolved but merge into the 120-kev peak. The 295- and 307-kev rays form the 300-kev peak. At higher energies there is a peak at 420 kev in agreement with the previous work. The 176-kev gamma ray is not found in the present work. In addition to the gamma rays previously reported, there are two rays at 88 kev and 207 kev. They are both very weak but they appeared consistently both in single crystal spectra and in coincidence spectra. Their relative intensities were constant over a period of several half-lives. They therefore seem to be associated with the decay of Er^{171}.

In order to establish a level scheme, a series of coincidence measurements was performed. First the relations between the beta rays and the gamma rays were investigated. The channel of the gamma-ray spectrometer was set to select the 300-kev peak. The corresponding beta-ray spectrum is shown in Fig. 1(b) as a Kurie plot. It shows a single group with the end point at 1.10 Mev. With the channel of the gamma-ray spectrometer set to select the 120-kev peak, the coincidence spectrum of Fig. 1(c) was obtained. The main component is the 1.10-Mev beta group. In addition there is a group with the end point at about 1.40 Mev.

The position of the 2.5-μsec metastable state was found in the following way. The single-channel analyzer was set to select beta rays around 300 kev. A delay of about 0.5 μsec was introduced after the beta-ray spectrometer. Hence the coincidence gamma-ray spectrum shows the gamma rays following the metastable state. The coincidence spectrum is shown in Fig. 2(b). It has nearly the same shape as the spectrum in Fig. 2(a). Even the weak gamma rays at 88 and 207 kev are present. The 420-kev gamma ray is so weak that the statistics are very poor in this region. There is, however, some indication that the 420 gamma ray is also present. Hence all the gamma rays seem to follow the metastable state.

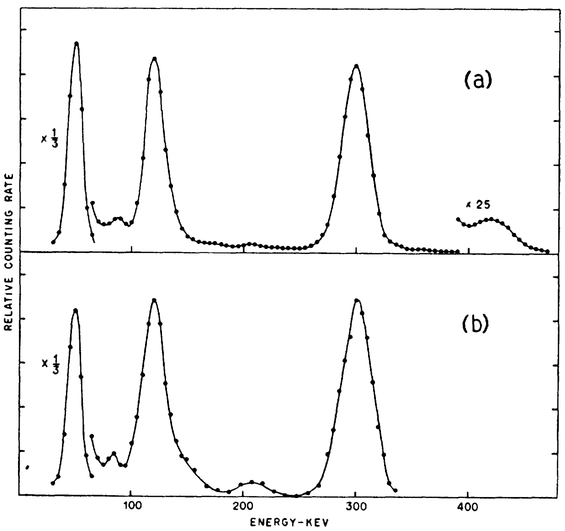

FIG. 2. (a) Gamma-ray spectrum of Er^{171}. (b) Spectrum of the gamma rays following the metastable state.

Some gamma-gamma coincidence measurements were then performed. The channel was set at 110 kev so that the 113-kev gamma ray was selected from the mixture of gamma rays in the 120-kev peak. The coincidence spectrum is shown in Fig. 3(a). Its main component is a peak at 307 kev. Hence the 113- and 307-kev gamma rays are in coincidence. With the channel set at 130 kev the 125-kev gamma ray is selected from the other rays. The coincidence spectrum is shown in Fig. 3(b). It shows a peak at about 295 kev. Hence the 125- and 295-kev gamma rays are in coincidence.

Both of the preceding spectra have a long tail below 250 kev. This could be due partly to the 207-kev gamma ray, but the statistics are too poor to allow any conclusions. In order to investigate this point further a wide channel was used to select the whole 120-kev peak. This gives a higher counting rate and better statistics. The coincidence spectrum is shown in Fig. 3(c). The main peak is now composed of the two gamma rays at 295 and 307 kev. At about 210 kev there is obviously a small peak. It is not completely resolved. To the right it merges into the tail of the 300-kev peak and to the left into the Compton distribution of the 300-kev peak. It seems probable, however, that the 207-kev gamma ray really exists and that it is in coincidence with one or several of the gamma rays in the 120-kev group.

Finally, an attempt was made to detect gamma rays preceding the metastable state. For this purpose, the channel of the first spectrometer was set on the 300-kev peak and a delay of 0.5 μsec introduced after the second spectrometer. The number of coincidence pulses was very low and no conclusion can be drawn except that any gamma ray preceding the metastable state must be of very low intensity.

LEVEL SCHEME

The present work leads to the level scheme shown in Fig. 4. It exhibits a very great similarity with the level scheme of Tm^{169}. This similarity has been used to place the 118-kev gamma ray in the scheme as shown in the figure. This implies a level at 5 kev. The main support for this arrangement is the good agreement with the theoretical level formula as discussed below.

The positions of the 88-kev and 207-kev gamma rays are not given exactly by the coincidence measurements.

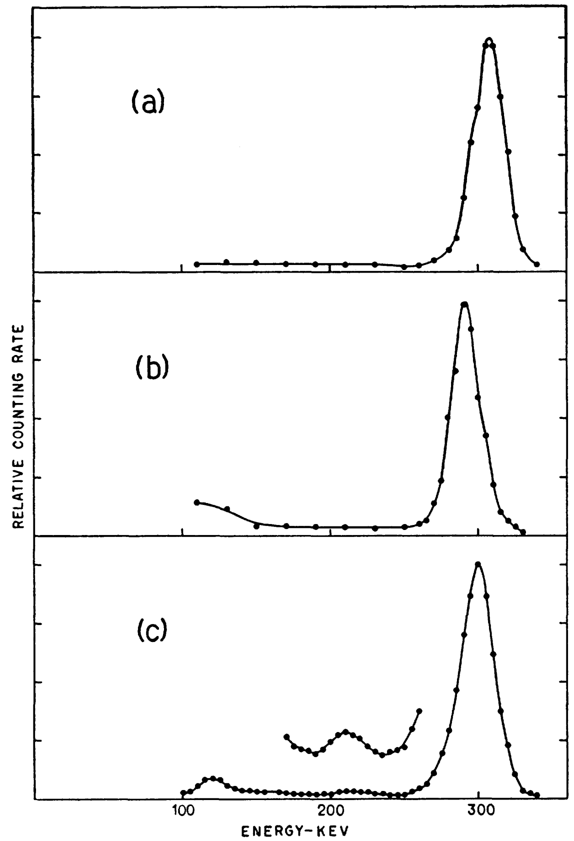

FIG. 3. Spectra of the gamma rays in coincidence with (a) the 113-kev gamma ray, (b) the 125-kev gamma ray, and (c) the 120-kev gamma-ray group.

It is known that both of them follow the metastable state and that the 207-kev transition goes to the 130-kev or the 118-kev state. The reason for placing them as indicated by the figure is the following. The theoretical formula predicts a level at 334 kev. From the spin and parity assignments it follows that this level should be populated from the 425-kev level and that it decays primarily to the 130-kev level. This would give two gamma rays with the energy values 91 and 204 kev. The good agreement with the experimental values supports the proposed position of the two gamma rays.

The beta-ray spectrum fits very well into the level scheme. The 1.52-Mev group goes to the ground state and the first excited state and the 1.10-Mev group to the 425-kev state. The 1.40-Mev group is in coincidence with the 120-kev gamma ray peak. It therefore goes to one or both of the levels at 118 and 130 kev. In calculating its intensity from the coincidence spectrum in Fig. 1(c), it is necessary to take into account the fact that the 1.10-Mev group goes to a metastable state. The half-life of the metastable state is considerably longer than the resolving time of the coincidence circuit. The states at 118 and 130 kev, on the other hand, have lifetimes shorter than the resolving time. The intensity of the 1.40-Mev group is therefore enhanced in the coincidence spectrum of Fig. 1(c). After correction for this effect, the true intensity amounts to about 1%. The high-energy group in the beta spectrum of Fig. 1(a) is therefore composed of two components, one 1.52-Mev group with 5% intensity and one 1.40-Mev group with 1% intensity.

For determining the multipolarity of the gamma rays, the following information is available. The K/L ratios of the interval conversion spectrum have been measured by Keller and Cork.[3] The K-conversion coefficients have not been accurately determined. The present work shows, however, that the 120-kev group is rather strongly converted but that the 300-kev group is only weakly converted. Furthermore, lifetime considerations show that no higher multipolarities than two can be involved. This information is enough to classify the 295-kev and 307-kev gamma-ray transitions as electric dipole, the 113-kev transition as magnetic dipole, and the 118- and 125-kev transitions as electric quadrupole.

Nothing is known experimentally about the spin and parity of the Tm^{171} ground state. In view of the great similarity between the level schemes of Tm^{169} and Tm^{171}, it seems justified to assume that they have the same ground state configuration, i.e., $\frac{1}{2}+$. The multipole assignments then uniquely determine the spin and parity values shown in Fig. 4. The spin of the 337-kev state cannot be assigned in this way. The value 9/2+ is the most likely one from the intensities of the beta and gamma rays.

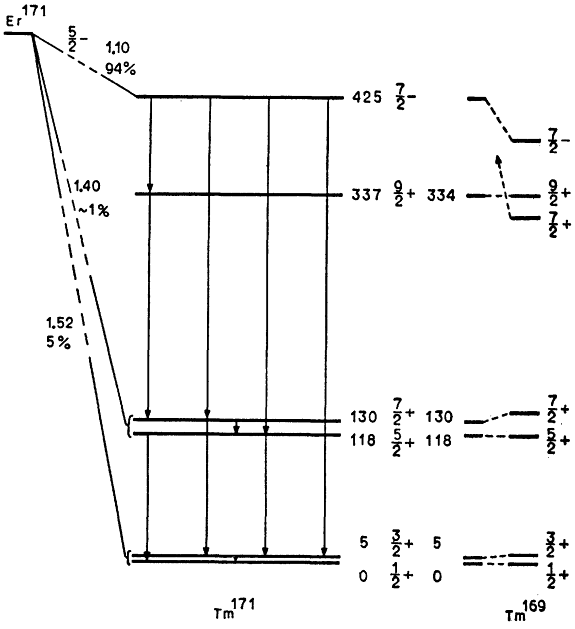

FIG. 4. Level scheme proposed for Tm^{171}. The numbers to the right of the levels are the experimental energies in kev, the spin and parity, and the calculated energies in kev. The level scheme of Tm^{169} is shown for comparison to the right in the figure.

DISCUSSION

The ground state and the first four excited states form a rotational band. The spin and parity values are the ones expected for a rotational band. The anomalous level spacings are characteristic for bands with $K=\frac{1}{2}$. The energy values fit the theoretical formula very well. The values to the right in Fig. 4 are calculated using the following values on the parameters $\hbar^2/2\mathfrak{J}=12.15$ and $a=-0.860$. The agreement with the experimental values is quite good and lends very strong support to the proposed decay scheme.

The transition probabilities in the decay of Er^{171} give information about the properties of the rotational and intrinsic levels. It therefore might be worth while to discuss them in some detail.

The $\log ft$ values of the beta groups at 1.52, 1.40, and 1.10 Mev are 8.2, 8.8, and 6.4, respectively. The spin and parity of Er^{171} are not known experimentally, but the most likely assignment[5] according to the unified model is $5/2-$. The beta transitions to the ground state and the first four excited states are then classified as first forbidden, unhindered according to the selection rules given by Alaga[6] for beta transitions in strongly deformed nuclei. The relative intensities of the five groups are rather difficult to estimate. The ground state transition has $\Delta I=2$ and is therefore expected to be weaker than the transition to the first excited state. The latter one, however, is K-forbidden. The influence of these two effects is not known exactly but it seems probable that the intensities of the two beta groups are of the same order of magnitude. The experimental $\log ft$ values for the 1.52-Mev and 1.40-Mev groups are in agreement with the proposed classification.

The beta transition to the $9/2+$ state has the same character as the ground state transition. Due to the lower energy its intensity is smaller, probably below 1%. It is therefore very difficult to detect experimentally. The 1.10-Mev group leading to the $7/2-$ level is classified as allowed, hindered, in good agreement with the $\log ft$ value.

Two low-energy gamma rays with the energy values 5 kev and 12 kev are expected to go from the 5-kev level and 130-kev level, respectively. They are not observed because the energies are too small for the scintillation spectrometer. The intensity of the transition from the $9/2+$ level to the $5/2+$ level can be calculated. It turns out to be very small. The corresponding gamma ray has not been found experimentally. The $7/2-$ level decays mainly by electric-dipole emission but the lifetime is as long as $2.5\,\mu$sec. The retardation of the transition probability relative to the single-particle estimate is 10^7. The reason for this is that the electric-dipole transitions from this level to members of the rotational band are K-forbidden. The difference between the change in K and the multipolarity is two. The 420-kev gamma ray is a magnetic quadrupole transition. Even if its intensity is very low, it is rather surprising that it can compete with electric dipole transitions. This is partly due to the higher energy. The main reason, however, is that the K-forbiddenness of the 420-kev transition is only one unit. It is therefore not as much retarded as the electric-dipole transitions.

It is interesting to compare the level schemes of Tm^{169} and Tm^{171}. This comparison is made in Fig. 4 where the levels of Tm^{169} are shown to the right. As can be expected the two nuclei have almost identical rotational bands. The parameters $\hbar^2/2\mathfrak{J}$ and a have the following values: 12.60 kev and -0.76 for Tm^{169} and 12.15 kev and -0.86 for Tm^{171}, respectively. Hence Tm^{171} has greater moment of inertia than Tm^{169}. This would imply greater deformation for Tm^{171}. This is in agreement with the fact that the two extra neutrons in Tm^{171} fill up a level which tends to increase the deformation of the nucleus.[5] The value of a as a function of the deformation has been calculated by Mottelson and Nilsson.[7] It turns out that a varies very little with the deformation. The change of a found here is within the limits of error of the calculation.

Tm^{169} has two intrinsic levels with the spin $7/2+$ and $7/2-$. The latter one is also found in Tm^{171} with only a slight change of energy. This is in agreement with the fact that the position of this level changes only slightly with the deformation.[5] The $7/2+$ level does not show up in Tm^{171}. Hence it must have shifted upwards close to or above the $7/2-$ level. Otherwise one would expect an electric dipole transition between these two levels. Since this transition would not be K-forbidden it would be by far the strongest transition from the $7/2-$ level. If the distance between the two levels is small the intensity would be less and the gamma ray would also be more difficult to detect due to the low energy. If the $7/2+$ level is above the $7/2-$ level, the intensity of the connecting gamma ray is determined by the intensity of the corresponding beta-ray group. It is classified as first forbidden, hindered. Hence it is considerably weaker than the main beta group at 1.10 Mev and the associated gamma ray might easily escape detection. The upward shift of the $7/2+$ level is in agreement with the fact that this level, according to the theoretical calculations, rises strongly with increasing deformation.[5]

The $7/2-$ level should be the ground state of a rotational band. The first excited state of this band has in fact been observed in Tm^{169}.[8] This state would be very difficult to observe in Tm^{171}, since the corresponding beta-ray group is second forbidden and therefore of very low intensity.

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[6] G. Alaga, Phys. Rev. **100**, 432 (1955).

[7] B. R. Mottelson and S. G. Nilsson, Z. Physik **141**, 217 (1955).

[8] Hatch, Boehm, Marmier, and DuMond, Bull. Am. Phys. Soc. Ser. II, **1**, 170 (1956).