Energy Levels in $_{69}Tm^{172}$ from the Decay of $_{68}Er^{172}$†

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The radioactive nuclide $_{68}Er^{172}$ was produced in the Materials Testing Reactor, Arco, Idaho by the successive capture of two neutrons in erbium oxide enriched in Er^{170}. In addition to three erbium activities and the radioactive Tm^{172} daughter, these samples contained six active contaminants from which the erbium was separated by use of an ion-exchange column. Scintillation studies, conducted with a 256-channel coincidence scintillation spectrometer, indicate the presence of at least eight gamma-ray transitions. Two of these transitions are either highly K converted or their transition energies are approximately 50 kev. The energies of the other six transitions are about 610, 450, 408, 200, 160, and 125 kev. Beta-gamma coincidence experiments indicate the presence of two beta-ray components at approximately 310 kev (in coincidence with the 610-kev gamma ray) and 370 kev (in coincidence with the 408-kev gamma ray). The level scheme deduced for Tm^{172} has excited states at 408, 450 (or 160), 470±15, 530, and 610 kev. From the beta-ray intensities, the states at 530 and 610 kev are assigned spins of either 0 or 1 with positive parity. The spin and parity (2^-) of the thulium ground state have previously been assigned from the properties of the decay of Tm^{172}.

INTRODUCTION

IN the region of the periodic table in which $155<A<185$, many properties of nuclear decay schemes can be interpreted on the basis of the unified model of nonspherical nuclei. Experimentally, a vast amount of information has been accumulated on the level structure of even-even and odd-mass nuclides. However, only a small amount of data has been obtained on the energy levels of odd-odd nuclei. This investigation, which is the second in a series by the authors, was carried out in order to add to the data for odd-odd nuclei. The first study[1] was on the decay of Dy^{166} to the levels in $_{67}Ho^{166}$.

The radioactive nuclide Er^{172}, which decays by beta emission to Tm^{172}, has been reported by Nethaway *et al.*[2] They report a half-life of 49.8±1.0 hr for the erbium activity. No measurements of the radiations associated with this activity have been reported.[2a]

The nuclide Er^{172} was produced by the successive capture of two neutrons in the stable isotope Er^{170}.

$$\begin{array}{ccccc} Er^{170} & \xrightarrow{(n,\gamma)} & Er^{171} & \xrightarrow{(n,\gamma)} & Er^{172} \\ & & 7\tfrac{1}{2}\text{ hr} \downarrow (\beta^-) & & 50\text{ hr} \downarrow (\beta^-) \\ & & Tm^{171} & \xrightarrow{(n,\gamma)} & Tm^{172} \\ & & 2\text{ yr} \downarrow (\beta^-) & & 64\text{ hr} \downarrow (\beta^-) \\ & & Yb^{171} & & Yb^{172} \end{array} \tag{1}$$

The source material was erbium oxide enriched to 87% in Er^{170}. Most of the activations were carried out in the Materials Testing Reactor, Arco, Idaho in a flux of approximately 2×10^{14} neutrons cm^{-2} sec^{-1}. Preliminary investigations were made with samples irradiated in the Argonne CP-5 reactor in a flux of about 3×10^{13}. In addition to the activities shown in Eq. (1), these samples contained observable amounts of the radionuclides Sc^{46} (85 days), Ho^{166} (1 day), Er^{169} (9 days), Tm^{170} (125 days), Yb^{169} (32 days), and Yb^{175} (4 days).

After activation, these samples were chemically separated with an ion-exchange column. This process provided positive identification of the elements involved as well as a means of producing chemically pure erbium samples. The separation procedure has been described in detail in a previous report.[3] The separated samples contained the radionuclides Er^{169} (9 days), Er^{172}, and some Tm^{172} which had grown back in during and after the separation. The only gamma ray associated with Er^{169} is an 8-kev transition that did not interfere with these studies. The effect of the beta-ray spectrum from the Er^{169} is discussed in the next section. The radiations associated with Tm^{172} have been discussed in detail in a previous report by the authors.[3]

The apparatus used in this study consists of a set of 180° magnetic internal-conversion-electron spectrographs, a 180° magnetic beta-ray spectrometer, and a 256-channel scintillation coincidence spectrometer. The scintillation spectrometer was used for both gamma-gamma and beta-gamma coincidence measurements. The gamma-ray detectors are $2\frac{1}{4}$-in. cubic NaI(Tl) crystals; an anthracene crystal $\frac{3}{16}$ in. thick by $1\frac{1}{2}$ in. in diameter is used as a beta-ray detector. For coincidence experiments, a single-channel pulse-height analyzer and "fast-slow" coincidence circuit ($2\tau\approx40$ nsec) are used to gate the multichannel analyzer. Some triple coincidence measurements were also made. In this case two single-channel analyzers and a slow coincidence circuit ($2\tau\approx9$ μsec) are used to gate the multichannel analyzer. The linear gate circuit in the analyzer serves as a second coincidence circuit ($2\tau\approx5$ μsec).

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[1] R. G. Helmer and S. B. Burson, Phys. Rev. **119**, 788 (1960).
[2] D. R. Nethaway, M. C. Michel, and W. E. Nervik, Phys. Rev. **103**, 147 (1956).
[2a] *Note added in proof*. The work of C. J. Orth and B. J. Dropesky, Phys. Rev. **122**, 1295 (1961), appeared after this report was accepted for publication.
[3] R. G. Helmer and S. B. Burson, Phys. Rev. **127**, 978 (1961).

EXPERIMENTAL STUDIES

Studies of the Internal-Conversion Electrons and the Beta-Ray Spectrum

Several attempts were made to observe the internal-conversion electrons associated with the erbium activity. Chemically separated erbium samples were used as well as sources from which the Tm^{172} daughter had not been removed. The only conversion line which was consistently observed, and which was not associated with some other activity, was interpreted as the *K* line of a transition of approximately 408 kev. As will be shown, such a transition exists in the erbium activity.

Observation of lower energy conversion lines was prevented by the presence of an intense beta-ray spectrum (end point about 330 kev) resulting from the decay of Er^{169}. This nuclide is produced by neutron capture in Er^{168} which constituted about 9% of the original source material. At the end of a 50-hr irradiation the calculated specific activity of the Er^{169} is about 6×10^{-6} active atoms per atom, compared to a value of 2×10^{-8} for the Er^{172}. After correcting for decay which took place prior to preparation of the sources, these computations indicate that the disintegration rate of the Er^{169} was about 1000 times as great as that of the Er^{172}.

The beta-ray spectrum of a chemically separated source was measured in the magnetic spectrometer. Because of the low specific activity, this source had to be made thick in order to have a usable counting rate. Because of the growth of the Tm^{172}, the counting rate at each experimental point on the spectrum was followed for a period of one month as the source decayed. Above about 880 kev, the data at each value of the magnetic field follow (within experimental error) the theoretical curve for the growth and decay of Tm^{172}. Below 330 kev only the intense beta-ray spectrum of Er^{169} is observable. In the region between about 330 and 880 kev, the experimental data indicate the presence of both Er^{172} and Tm^{172}. In order to separate the erbium spectrum it was necessary to determine what fraction of the original counting rate was due to the daughter Tm^{172}. This was done by graphically fitting the decay curve at each magnetic field setting with an empirical curve. This curve was derived by adjusting the contributions of two theoretical decay curves that represent the decay of the two activities considered separately.

The Fermi plot resulting from this analysis is shown in Fig. 1. This plot suggests the presence of beta branches of about 900 and 400 kev with relative intensities of $(10\pm8)\%$ and $(90\pm8)\%$, respectively. Because of the complexity of the analysis, the indicated uncertainties are only estimated.

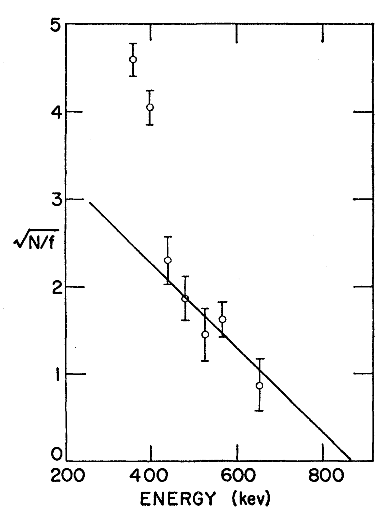


FIG. 1. Fermi plot of beta-ray spectrum of Er^{172}.

Scintillation Studies

Singles

The scintillation spectrum of a chemically separated sample is shown in Fig. 2, along with its decomposition into individual components. The amount of Tm^{172} present is indicated by the intensities of the 181- and 79-kev photopeaks which are associated with the thulium. The spectral shapes for single gamma rays are interpolated from those of Cs^{137} (662 kev), Au^{198} (412 kev), Ce^{141} (142 kev), and Eu^{152} (122 kev). The shape of the thulium *K* x-ray peak was derived from the ytterbium *K* x-ray peak from a $Tm^{170,171}$ source. The gamma-ray energies and relative intensities calculated from this spectrum are listed in Table I.

Sum Spectra

The singles spectrum in Fig. 2 was measured in the geometric arrangement shown, in which the collimator defines a solid angle of approximately 0.3% of 4π. This small solid angle, together with the absorbers used, reduces the summing of any coincident radiations to a negligible amount. In order to investigate any strong coincidence relationships, singles spectra were taken with solid angles nominally equal to 2π (with one crystal) and 4π (with two crystals) as depicted in the insert of Fig. 3. (When two crystals were used, the gains of the photomultipliers are matched and the output pulses are added electronically before being amplified.)

TABLE I. Gamma-ray energies and relative intensities calculated from the scintillation spectrum.

Gamma-ray energy (kev)	Relative intensity
610±8	42
450±10	2.7±1.5
408±4	44 ±5
200±6	0.8±0.4
160±4	1.0±0.5
125±3	3.1±1.0
K x ray	69 ±15

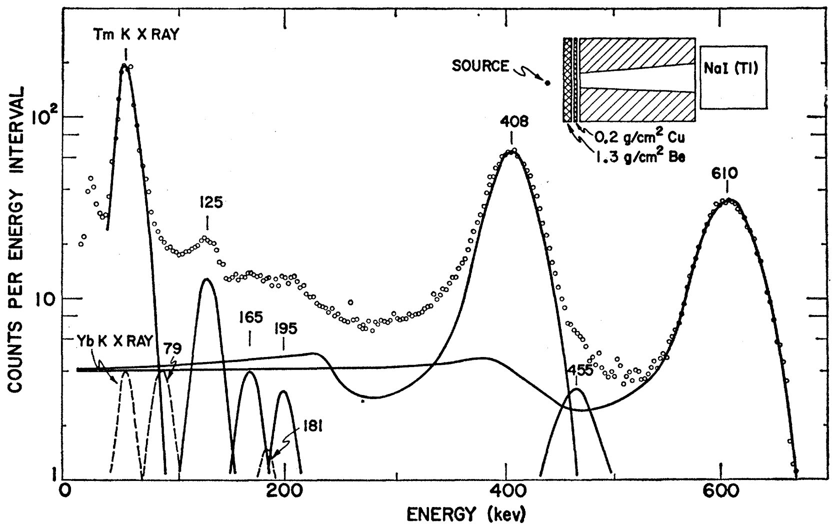


FIG. 2. Gamma-ray spectrum of Er^{172}. The dashed lines represent the contribution of the thulium daughter. The statistical uncertainties are less than or about equal to the diameter of the circles indicating the experimental points.

The observed spectra are shown in Fig. 3. There is no detectable summing with the 610-kev gamma ray; therefore, the two sets of data have been normalized at this photopeak. In curve (a) (for 2π solid angle), a sum peak appears at about 460 kev and is interpreted as being due to a 50-kev radiation in coincidence with the 408-kev gamma ray. This conclusion is supported by a simultaneous decrease in the intensity of the 408-kev photpeak. In curve (b) (the case of 4π solid angle), the effect is even more pronounced. However, in addition to the peak at 460 kev there is also a sum peak at 510 kev. The 510-kev peak is interpreted as a "double-sum" peak produced by the summing of a 408-kev gamma ray with two 50-kev radiations. The possibility that either of these sum peaks results from accidental summing of noncoincident radiations is ruled out by two independent facts. First, any radiation intense enough to cause accidental sums with the 408-kev gamma ray would produce a similar result with the 610-kev gamma ray. Since no sums of any type were observed with the 610-kev transition, both of the observed sums must be real. Second, to further verify this conclusion these spectra were also measured with a source that was one-fourth as strong. The spectral shapes so obtained were identical, within experimental errors, with those in Fig. 3. (The intensity of an accidental sum peak varies as the square of the source strength, while that of a real sum peak varies as the source strength.) Therefore, it is concluded that there must be two radiations of approximately 50 kev. These radiations are in coincidence with each other and with the 408-kev transition. Each of the 50-kev radiations could result either from a transition of approximately 50 kev, or from K conversion of a transition whose energy is higher than the K-electron binding energy of 59.4 kev. A 100-kev sum peak, corresponding to the summing of two 50-kev radiations, was also observed in many spectra taken with a large solid angle.

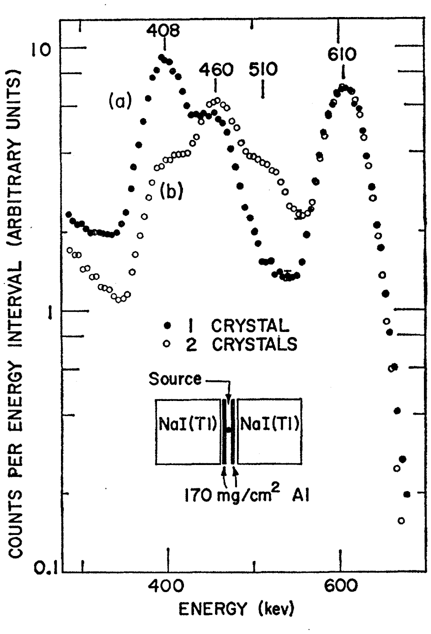


FIG. 3. Sum spectra of Er^{172} measured with solid angles nominally equal to 2π and 4π.

Beta-Gamma Coincidence Measurements

The end-point energies of the beta-ray components in coincidence with the dominant gamma-ray transitions were measured by the standard aluminum absorption method. These data indicate that the 610- and 408-kev gamma rays are in coincidence with beta branches (310 ± 30) and (370 ± 30) kev, respectively. The difference in the energies of these two beta-ray components is estimated to be 60 ± 20 kev.

It was not possible to determine the energies of the beta rays in coincidence with the other radiations. However, there was no indication of the existence of any beta branches other than these two.

Gamma-Gamma Coincidence Measurements

No gamma rays were found to be in coincidence with the 610-kev transition.

A series of coincidence spectra were measured in order to determine the radiations in cascade with the 408- and 450-kev transitions. This set of runs was taken with the window width of the single-channel analyzer set at about 20 kev. Five successive spectra were measured with the analyzer set to accept adjacent portions of the spectrum between about 380 and 480 kev. The geometric arrangement, shown in the insert of Fig. 4, was chosen to prevent scattering from one crystal to the other. The Cu absorbers are used to reduce the 100- and 460-kev sum peaks in the multichannel and single-channel spectra, respectively. Two of the resulting spectra are shown in Fig. 4. These two spectra are normalized to the same counting interval and source strength for the erbium activity. Analysis of these spectra indicates that the 408-kev transition is in coincidence with radiations of 200±6, 160±15, and 125±4 kev, in addition to the K x ray. The 450-kev gamma ray is in coincidence only with a (160±4)-kev transition and the K x ray. This analysis also indicates that the numbers of 160-kev gamma rays in coincidence with the 408- and 450-kev gamma rays are about equal. The photopeaks at 79 and 181 kev, as well as a portion of the K x-ray peaks, result from coincidences following the decay of the daughter Tm^{172}. These transitions are in coincidence with several radiations between 400 and 1600 kev.[3]

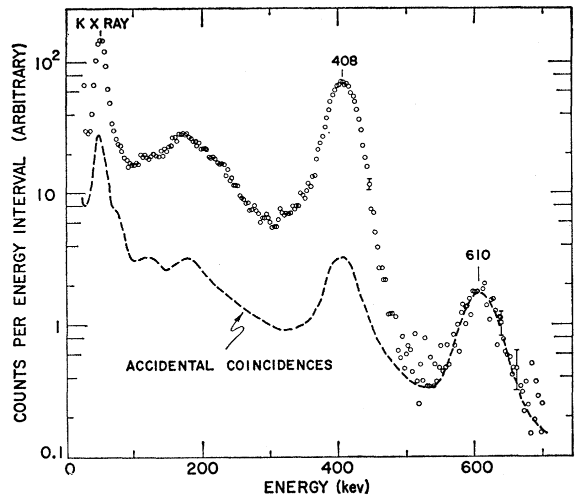
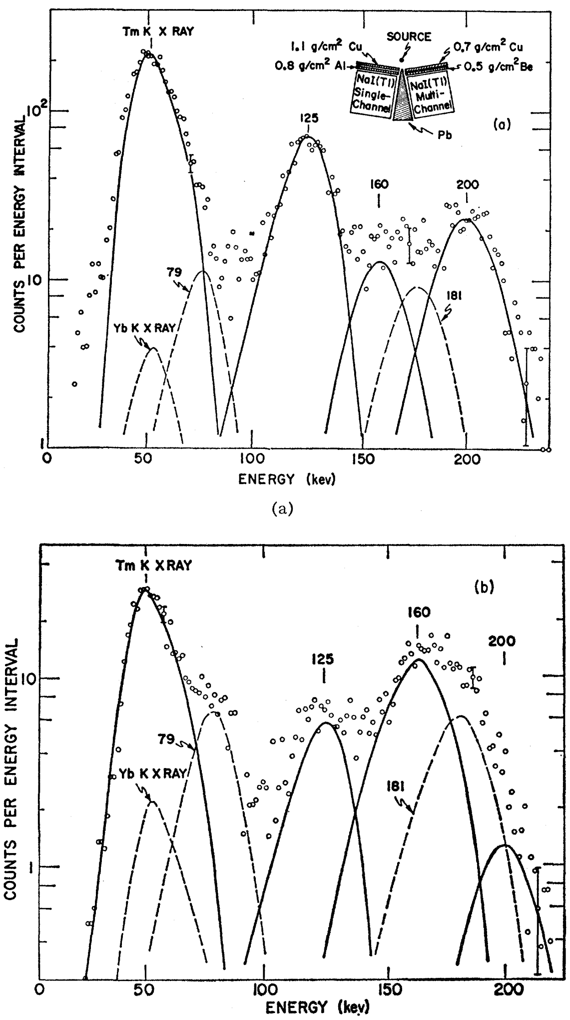


FIG. 5. Gamma-ray spectrum in coincidence with two 50-kev radiations.



(a)

(b)

FIG. 4. Gamma-gamma coincidence spectra in coincidence with pulses in the (a) 410-kev and (b) 450-kev regions.

A series of spectra was taken with the single-channel analyzer window accepting portions of the spectrum below 250 kev. The results of the analysis of these data are consistent with the above interpretation.

In addition to the experiments described above, a thorough search was made for any coincidences between the 125-, 160-, and 200-kev gamma rays. None were found.

In order to investigate further the nature of the 50-kev radiations which sum with the 408-kev peak, a triple-coincidence circuit was used. Two triple-coincidence spectra were measured. In the first, the two single-channel analyzers were set to bracket the 408- and 50-kev peaks. The resulting coincidence spectrum displayed only a peak corresponding to the K x ray. In the second experiment, both single-channel windows were set to bracket the K x-ray peak. The resulting spectrum, which is shown in Fig. 5, exhibits peaks at 408 kev and at the K x-ray energy. This result suggests two possibilities. Either there are three low-energy transitions producing 50-kev radiations, all of which are in coincidence with each other; or the x rays in Fig. 5 result from internal conversion of the 408-kev transition; or both effects may be present in combination.

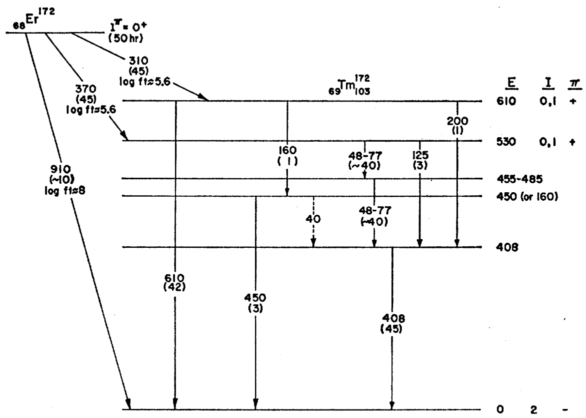


FIG. 6. Proposed decay scheme of Er^{172}. The relative photon intensities (in percent of decays) are shown in parentheses. All energies are in kev.

If one assumes that the 408-kev transition is in cascade with only two 50-kev radiations, an estimate of its K conversion coefficient can be made from these data. This computation yields $\alpha_K^{408}=0.12\pm0.06$. For any other decay scheme, this calculation yields an upper limit for α_K^{408}. The corresponding theoretical values[4] of α_K^{408} are:

$E1$	0.0077	$E2$	0.023	$E3$	0.063
$M1$	0.055	$M2$	0.18	$M3$	0.50

Lifetime considerations restrict the multipole order to dipole or quadrupole. The value $\alpha_K^{408}\approx0.12$ is then consistent with a transition which is either predominantly $M1$ or $M2$.

DECAY SCHEME

Construction

The proposed decay scheme is shown in Fig. 6. The relative photon intensities are shown in parentheses. The lack of conversion-electron data precludes the possibility of calculating the total transition intensities. It should be acknowledged that there may be other decay schemes which are consistent, within experimental uncertainties, with these data.

The absence of any gamma rays in coincidence with the 610-kev transition indicates that this transition goes to the ground state and that there is an excited state at 610 kev. From the observation of coincidences between this gamma ray and a beta-ray branch of approximately 310 kev, it follows that the total decay energy is about 900 kev.

The observation of coincidences between the 408- and 200-kev gamma rays suggests that this cascade is parallel to the 610-kev transition. The intermediate level is placed at 408 kev for several reasons. First, the 408-kev gamma ray is much more intense than the 200-kev transition, even when possible conversion is considered. Second, the 408-kev transition is in coincidence with a beta branch of about 370 kev, and therefore cannot depopulate the 610-kev level. These beta-gamma coincidence data require that the 408-kev level be populated predominantly through a level at about 530 kev ($900-370=530$). The two transitions which produce the intense 50-kev radiations are concluded to be in cascade between these two levels. The 125-kev gamma ray is then interpreted as representing the direct transition between the two states. The energy of each of the two transitions producing 50-kev radiations must be above about 47 kev. If it is accepted that the sum of the two transitions is 125 kev, an upper limit of about 78 kev may be placed on the energy of each of these transitions. Thus the intermediate level is placed at 470 ± 15 kev.

The coincident gamma rays of 450 and 160 kev also sum to 610 kev. The sequence of the transitions is not unambiguous. However, placement of the intermediate level at 450 kev is preferred. With the intermediate state at 450 kev, as is shown in Fig. 6, one must postulate an additional transition to explain the 408–160-kev coincidences. This gamma ray might be either a 150 ± 20 kev transition between the 610- and 470-kev levels, or a 40-kev transition between the levels at 450 and 408 kev. The latter possibility is shown in the decay scheme. If the intermediate state were placed at 160 kev, one would have to postulate a transition of about 150 kev between the 610- and 470-kev levels in order to explain the observed 408–160-kev coincidences. Also in this case one might expect to observe transitions from the high-energy states to the 160-kev level.

There is no experimental evidence for beta-ray transitions to the 408-, 450-, and 470-kev levels. For the beta-ray branches to the 530- and 610-kev levels, the logft values can be computed by use of the relative intensities of the 408- and 610-kev transitions. These logft values indicate that both transitions have allowed character. The logft value of the branch to the ground state suggests that this transition probably has unique-first-forbidden character.

Spin Assignments

Since Er^{172} is an even-even nucleus, the spin and parity of its ground state are assumed to be 0^+.

From the study of the decay of Tm^{172}, the spin and parity of the ground state of Tm^{172} were concluded[3] to be 2^-. These two spin assignments are consistent with the unique-first-forbidden character of the beta transition to the ground state.

Since the beta transitions to the 610- and 530-kev levels are allowed, the spin of each of these levels is either 0 or 1 with positive parity. There is no experimental information on which to base a choice between these values.

[4] L. A. Sliv and I. M. Band, Leningrad Physico-Technical Institute Report, 1956 [translation: Report 57ICCK1, issued by Physics Department, University of Illinois, Urbana, Illinois (unpublished)].