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THE LEVEL SCHEME OF ^{171}Tm

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Abstract: The gamma-ray spectrum associated with the decay of ^{171}Er has been studied with curved-crystal and Ge(Li) spectrometers. The data provide energy and intensity measurements of 40 gamma rays. A previously unreported weak 694 keV transition which appears to belong to the decay of ^{171}Er has been measured. Previously reported transitions at 166, 404, 573 and 842 keV have not been observed. Coincidence spectra show that the 372 keV transition feeds the 913 keV level. The absence of transitions at 166 keV and 404 keV together with the new placement of the 372 keV transition place the existence of a previously proposed 591 keV level in doubt. A recently proposed level at 489 keV is not supported by the energy measurements and coincidence data of the present study. The new placement of the 372 keV transition suggests a new level at 1285 keV.

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RADIOACTIVITY: ^{171}Er [from ^{170}Er(n, γ)]; measured E_γ, I_γ, $\gamma\gamma$-coin. ^{171}Tm deduced levels. Enriched target.

1. Introduction

Several investigators [1,4–12,15]) have studied the beta decay of ^{171}Er and the associated gamma radiations of ^{171}Tm. The present study was undertaken to provide additional curved-crystal spectrometer measurements and to provide improved intensity measurements through the use of high-resolution Ge(Li) spectrometers. Preliminary findings of the present study have been reported [13]).

2. Experimental arrangements

The curved-crystal spectrometer energy measurements reported in this paper were taken on The University of Michigan 2 m curved-crystal spectrometer utilizing the Ge(0$\bar{2}$2) planes as diffraction planes. This spectrometer and the experimental techniques associated with it have been described previously [16–18]). Each curved-crystal spectrometer source was an Er_2O_3-epoxy mixture irradiated for approximately 24 h in The University of Michigan Ford Nuclear Reactor (thermal neutron flux $\approx 3\times10^{13}$ neutrons/sec · cm^2). Enriched Er_2O_3 (96 %) obtained from Oak Ridge National Laboratory was used in the fabrication of these ribbon sources. The activity was about 1.5 Ci for the sample with a 130 μm width and about 0.9 Ci for the sample with 76 μm.

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The energy resolution of the spectrometer using the 130 μm and 76 μm sources was $\Delta E(\text{FWHM}) = (2.2\times10^{-5})(E^2/n)$ keV and $\Delta E(\text{FWHM}) = (1.6\times10^{-5})(E^2/n)$ keV, respectively, where n is the order of reflection and E the gamma-ray energy in keV. Most measurements were made in second order.

An Ortec 17 cm^3 coaxial Ge(Li) detector and a Nuclear Diodes 40 cm^3 trapezoidal Ge(Li) detector were used for the energy measurements of higher-energy gamma rays. The associated electronics consisted of an Ortec 118A pre-amplifier, a Tennelec TC200 amplifier and a Scipp 1600-channel analyser. The resolution of the system was 3.5 keV at 733 keV for the coaxial detector and 3.0 keV at 733 keV for the trapezoidal detector. The non-linearities in the system were accounted for using the method of Donnelly *et al.* [19]). This method gives a measure of the non-linearity associated with the entire electronic system. Sources for the Ge(Li) spectrometer were prepared by dissolving in HNO_3 some of the same enriched Er_2O_3 as used in the fabrication of the curved-crystal spectrometer sources. Irradiations were performed in The University of Michigan Ford Nuclear Reactor.

All intensity measurements reported in this paper were made with the Ge(Li) spectrometers described in the previous paragraph. A relative efficiency calibration (refs. [19,20])) of the system was performed utilizing sources for which the relative emission rates of pairs of gamma rays are precisely known. The relative efficiency curve obtained for the coaxial detector extended from 90 keV to 1400 keV and was constructed using the following four sources: ^{180m}Hf, ^{22}Na, ^{60}Co and ^{46}Sc. It is difficult to give a reliable estimate of the accuracy of this curve, because all parts are not equally well fixed. We estimate that an error of about 15 % should be assigned to intensities below 500 keV and about 10 % to those above 500 keV. The relative efficiency curve for the recently acquired trapezoidal detector was preliminary in nature and the errors associated with it are larger.

The coincidence system was of the fast-slow type. The total spectrum channel consisted of either an Ortec 8 $cm^2 \times 5$ mm planar Ge(Li) detector or the 17 cm^3 Ortec coaxial Ge(Li) detector coupled to an Ortec 118A pre-amplifier and a Tennelec TC200 amplifier. The gate channel consisted of the one of the above two detectors not being used for display purposes coupled to a similar system. The output of the gate TC200 was sent to a Tennelec TC250 biased amplifier and stretcher. Two Sturrup 1435 timing single-channel analysers were used to select the slow gates from the TC250 output spectrum. The fast timing portion of the circuit consisted of a Sturrup 1410 amplifier on the display side and a Sturrup 1415 amplifier on the gate side, two Sturrup 1435 timing single-channel analysers and a Sturrup 1441 fast coincidence unit. The fast coincidence circuit was operated in the cross-over timing mode on the display side and leading-edge timing mode on the gate side. A resolving time of 50 nsec was used for this work. The coincidence efficiency was determined to be greater than 95 % over the energy range of interest. The pulse-height analyser was operated as two 800 channel sub-groups with routing achieved by using the output pulses from the two slow gate timing single-channel analysers.

3. Results

3.1. ENERGY AND INTENSITY MEASUREMENTS

The results of the gamma-ray energy and intensity measurements are presented in table 1. The intensities are given relative to the gamma-ray intensity of the 308 keV transition. Of the 40 energy measurements listed the following were determined using the curved-crystal spectrometer: 112, 117, 124, 176, 211, 237, 277, 296, 308, 363, 372, 420, 425, 784 and 797 keV. The calibration of this instrument is based upon a value of

TABLE 1

Energies and intensities of gamma-ray transitions in the decay $^{171}Er \rightarrow {}^{171}Tm$

Energy keV) [a]	Relative intensity [b]	Energy (keV) [a]	Relative intensity [b]
111.621 ± 0.004	3.16×10^{-1}	676.10 ± 0.27	5.0×10^{-3}
116.656 ± 0.006	3.02×10^{-2}	693.89 ± 0.50	2.6×10^{-4}
124.017 ± 0.004	1.45×10^{-1}	732.53 ± 0.24	1.7×10^{-3}
175.628 ± 0.032	1.3×10^{-4}	744.98 ± 0.47	1.6×10^{-4}
210.598 ± 0.030	1.1×10^{-2}	784.09 ± 0.17	3.9×10^{-3}
237.145 ± 0.040	5.2×10^{-3}	796.55 ± 0.13	1.05×10^{-2}
277.434 ± 0.048	9.3×10^{-3}	869.74 ± 0.27	1.3×10^{-3}
295.901 ± 0.014	4.54×10^{-1}	881.98 ± 0.32	6.7×10^{-4}
308.291 ± 0.018	1.00	907.70 ± 0.35	1.11×10^{-2}
362.91 ± 0.14	5.4×10^{-4}	912.63 ± 0.45	1.4×10^{-3}
371.962 ± 0.090	3.9×10^{-3}	966.10 ± 0.34	5.0×10^{-4}
419.91 ± 0.29	1.2×10^{-3}	1096.9 ± 0.8	2.5×10^{-5}
424.94 ± 0.43	4.1×10^{-4}	1109.0 ± 0.5	1.1×10^{-4}
506.88 ± 0.54	3.7×10^{-4}	1169.2 ± 0.8	3.0×10^{-5}
519.20 ± 0.54	3.8×10^{-4}	1220.8 ± 0.8	5.3×10^{-5}
547.76 ± 0.45	3.7×10^{-4}	1272.8 ± 0.8	9×10^{-6}
559.51 ± 0.31	7.6×10^{-4}	1280.6 ± 0.8	5.7×10^{-5}
609.16 ± 0.29	8.8×10^{-4}	1284.9 ± 0.8	4.3×10^{-5}
621.03 ± 0.23	1.5×10^{-3}	1395.4 ± 0.7	6.6×10^{-5}
671.08 ± 0.27	4.4×10^{-3}	1400.3 ± 0.7	5.2×10^{-5}

[a]) The 112, 117, 124, 176, 211, 237, 277, 296, 308, 363, 372, 420, 425, 784 and 797 keV energy values were determined using the curved-crystal spectrometer. The 507, 519, 548, 560, 609, 621, 671, 676, 694, 733, 745, 870, 882, 908, 913 and 966 keV energy values were determined using the coaxial Ge(Li) detector; the curved-crystal spectrometer measurements of this work gave an internal calibration. The 1097, 1109, 1169, 1221, 1273, 1281, 1285, 1395 and 1400 keV energy values were determined using the trapezoidal Ge(Li) detector; the ^{24}Na (1368.53 keV) contaminant peak and the ^{171}Er (966.10 keV) peak provided calibration points.

[b]) All intensities reported in this table were obtained from Ge(Li) spectra.

411.800 keV for the strong ^{198}Au line [16]). All energy measurements between 500 and 1000 keV were obtained with the Ge(Li) spectrometer using the 296, 308, 372, 784 and 797 keV curved-crystal spectrometer measurements for calibration purposes. A least-squares program was used to fit a straight line to the energy values and channel positions of the five calibration points. Energy measurements above 1000 keV were made using the 1368.53 keV peak of the ^{24}Na contaminant and the 966.10 keV peak of ^{171}Er for calibration of the Ge(Li) spectra.

One of the Ge(Li) spectra used for the intensity measurements in the energy region below 296 keV is shown in fig. 1. There is no evidence in this spectrum for the previously reported 166 keV transition [11]). The steep rise in the back-ground in this energy region makes it difficult to estimate the upper limit on the intensity of a possible 166 keV transition. Such background problems in Ge(Li) spectra often mask weak peaks and, as has been demonstrated [21]), these situations lend themselves particularly well to curved-crystal spectrometer searches. A careful search using the curved-crystal spectrometer produced no evidence for a gamma-ray transition at 166 keV. We place an upper limit on this gamma-ray intensity of about one-fourth the gamma-ray intensity of the 176 keV transition. Artna and Johns [11]) have reported a 166 keV transition without having observed a 176 keV transition. Fig. 1 also shows no evidence for a peak at 86 keV. Gamma rays at about this energy have been reported previously [8,10-12]). Again the background problem, in this case the backscatter peaks of the 112 and 124 keV transitions, makes an intensity upper limit estimation difficult. A curved-crystal spectrometer search of the 86–87 keV region showed no evidence for a gamma ray in this region, and we place an upper limit on the gamma-ray intensity of such a transition at about $\frac{1}{40}$ the gamma-ray intensity of the 117 keV transition. Cranston *et al.* [10]) reported an 86 keV transition having a gamma-ray intensity of about $\frac{1}{36}$ the gamma-ray intensity of the 117 keV transition.

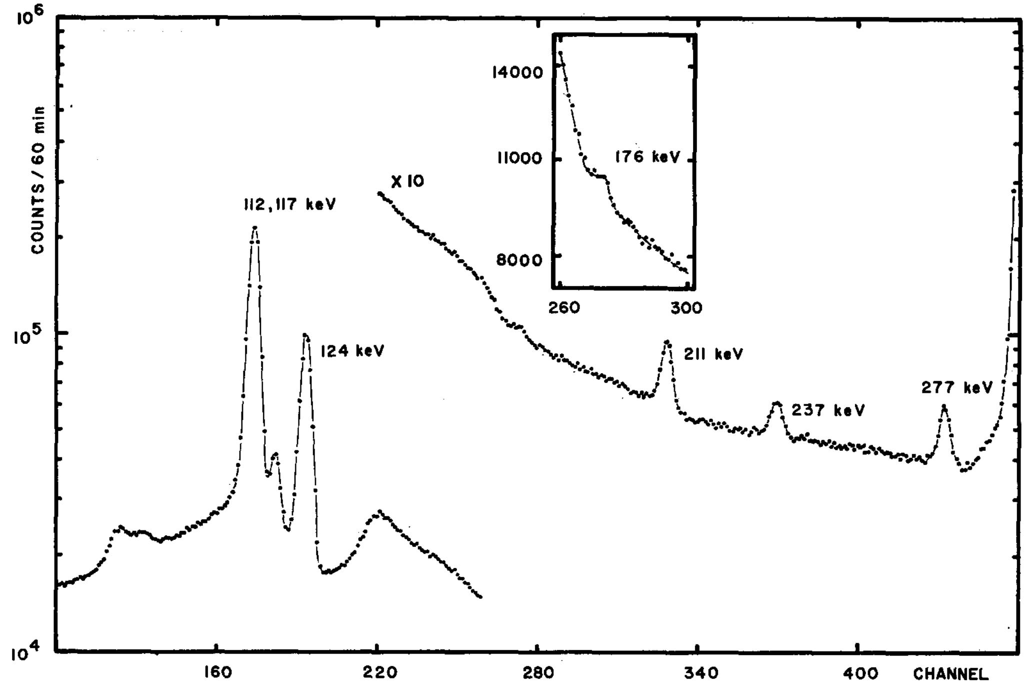


Fig. 1. The low-energy portion of the gamma-ray spectrum of ^{171}Er obtained with a 17 cm^3 coaxial Ge(Li) detector. The inset is a linear plot of the region around 176 keV. The solid lines merely indicate the trend of the data points.

Fig. 2 shows a Ge(Li) spectrum of the region between 250 and 1000 keV. Absorbers were used to reduce the count rate due to the strong lower-energy transitions. We see no evidence for peaks corresponding to the previously reported [11]) transitions at 404, 573 and 842 keV. A 573 keV transition is also reported in the recent work of Megli *et al.* [15]). Upper limits on the intensities of such transitions are given in table 2 along with the intensities which Artna and Johns [11]) report for these transitions. Three new transitions first observed in the present investigation [13]) are evident in fig. 2; i.e. 425, 507 and 519 keV. Since the 420–425 keV doublet has also been measured on the curved-crystal spectrometer with the same intensity ratio for the members of the doublet as obtained in the Ge(Li) spectra, we feel confident that neither of these peaks is due to summing. It has been suggested by Cranston *et al.* [10]) that the 420 keV peak was due to summing. We also feel confident that the 507 and 519 keV peaks are associated with gamma rays of the same energies because this doublet was observed with the curved-crystal spectrometer. The statistics, however, were too poor to allow accurate energy measurements. The weak gamma-ray peak at 694 keV decays with about the same half-life as ^{171}Er, and on this basis we have tentatively assigned it to the decay of ^{171}Er. We have noted [13]) that the energy spacing of the 733 keV doublet is 12 keV rather than the previously [11]) reported 5 keV.

TABLE 2

Upper limits on the intensities of several gamma rays previously reported as occurring in the decay $^{171}\text{Er} \rightarrow {}^{171}\text{Tm}$ but not observed in the present study

Transition	Upper limit [a])	Reported intensity [b])
166	5×10^{-5}	9×10^{-3}
404	1×10^{-4}	5×10^{-4}
573	2×10^{-4}	1×10^{-3}
842	1×10^{-4}	6×10^{-4}

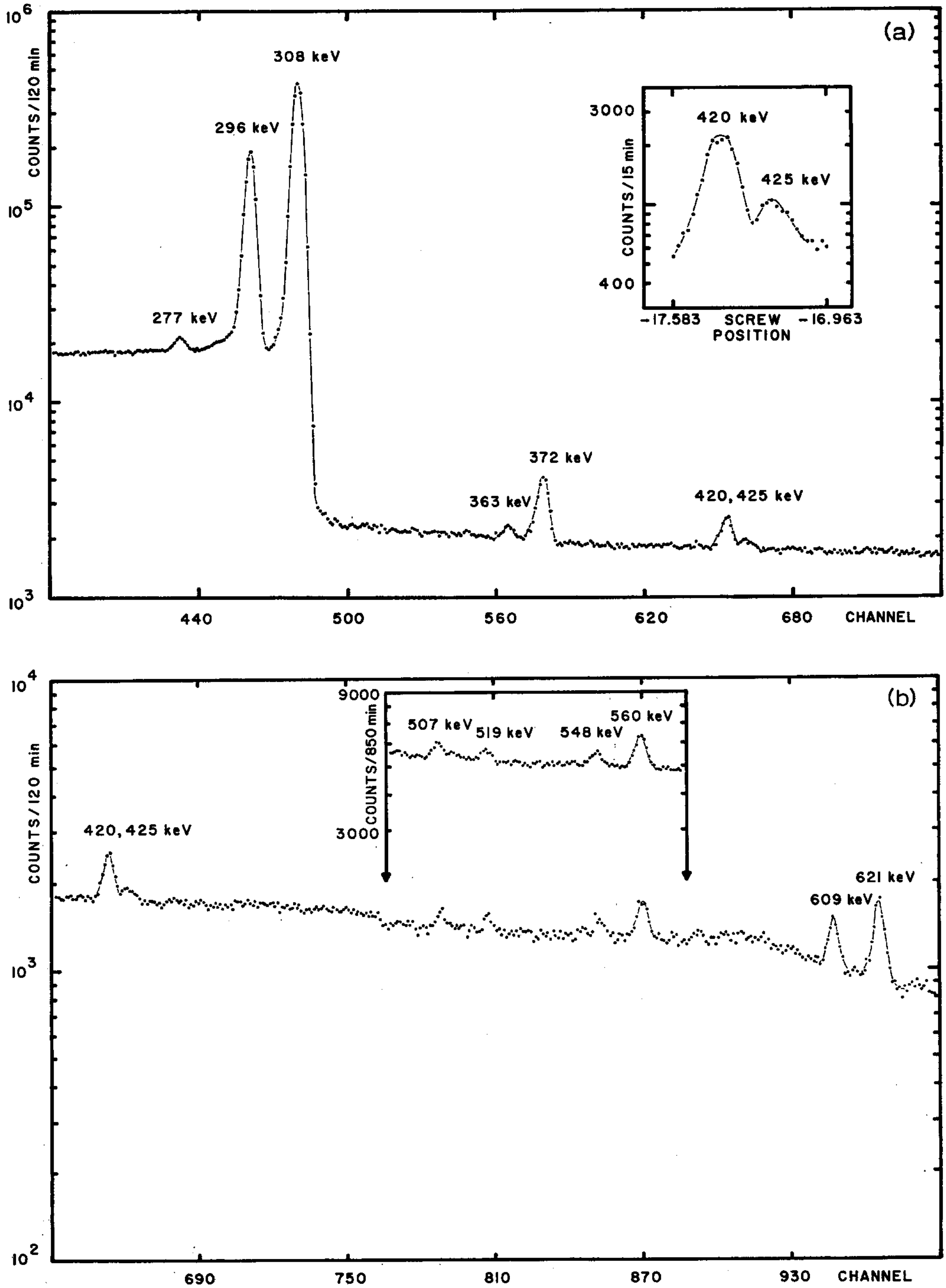
[a]) Relative to the intensity of the 308 keV gamma ray.

[b]) Data of Artna and Johns [11]) relative to the intensity of the 308 keV gamma ray.

Fig. 3 shows a Ge(Li) spectrum of the region above 950 keV. These data confirm the results of Megli *et al.* [15]) for the existence of several transitions in the ^{171}Er decay above 1000 keV. We note that the peak at 1285 keV is actually a doublet. This was unresolved in the work of Megli *et al.* [15]).

3.2. COINCIDENCE MEASUREMENTS

We have taken coincidence spectra gating the 277 keV peak, the 784–797 keV doublet and the 908–913 keV doublet. These spectra clearly show that the 372 keV gamma ray is in coincidence with the gamma rays associated with each of the three gates. Fig. 4 shows the chance corrected coincidence spectrum obtained when gating the 908–913 keV doublet. The remaining peaks in this spectrum are attributed to bremsstrahlung from the beta feedings to the 425 keV and lower levels. As a check


(a)
COUNTS/120 min
308 keV
296 keV
277 keV
372 keV
363 keV
420, 425 keV
440
500
560
620
680
CHANNEL
3000
420 keV
425 keV
COUNTS/15 min
400
-17.583
SCREW POSITION
-16.963
(b)
9000
COUNTS/850 min
507 keV
519 keV
548 keV
560 keV
3000
420, 425 keV
621 keV
609 keV
690
750
810
870
930
CHANNEL

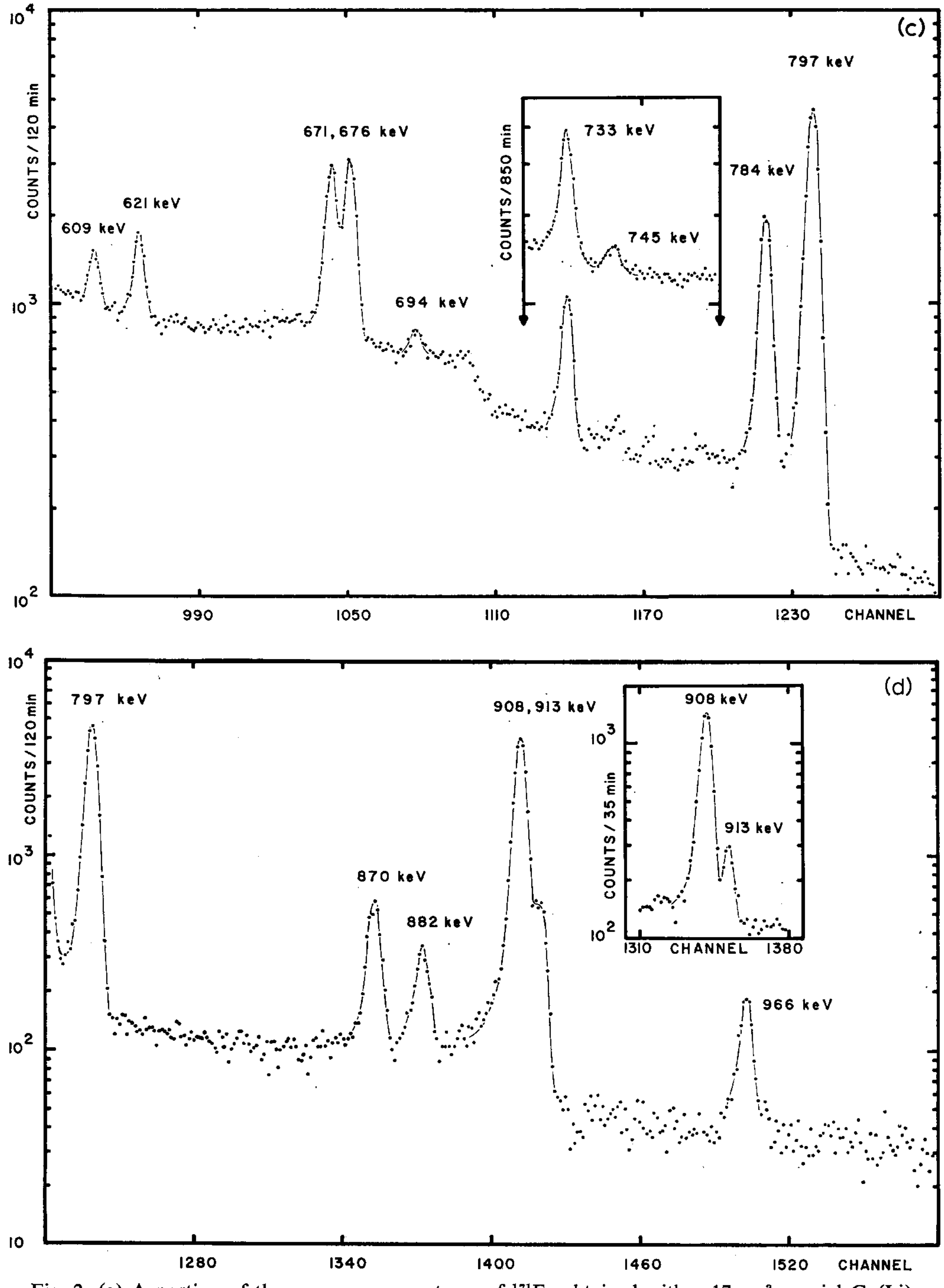


Fig. 2. (a) A portion of the gamma-ray spectrum of ^{171}Er obtained with a 17 cm^3 coaxial Ge(Li) detector. The inset shows the 420–425 keV doublet as observed with the curved-crystal spectrometer. (b) A portion of the gamma-ray spectrum of ^{171}Er obtained with a 17 cm^3 coaxial Ge(Li) detector. The inset data are taken from a run having a longer counting time than the main spectrum run. (c) A portion of the gamma-ray spectrum of ^{171}Er obtained with a 17 cm^3 coaxial Ge(Li) detector. The inset data are taken from a run having a longer counting time than the main spectrum run. (d) A portion of the gamma-ray spectrum of ^{171}Er obtained with a 17 cm^3 coaxial Ge(Li) detector. The inset shows the 908–913 keV doublet as observed with an 8 cm$^2 \times 5$ mm planar Ge(Li) detector. The solid lines merely indicate the trend of the data points. Absorbers were used to reduce the count rate due to the intense low-energy gamma rays.

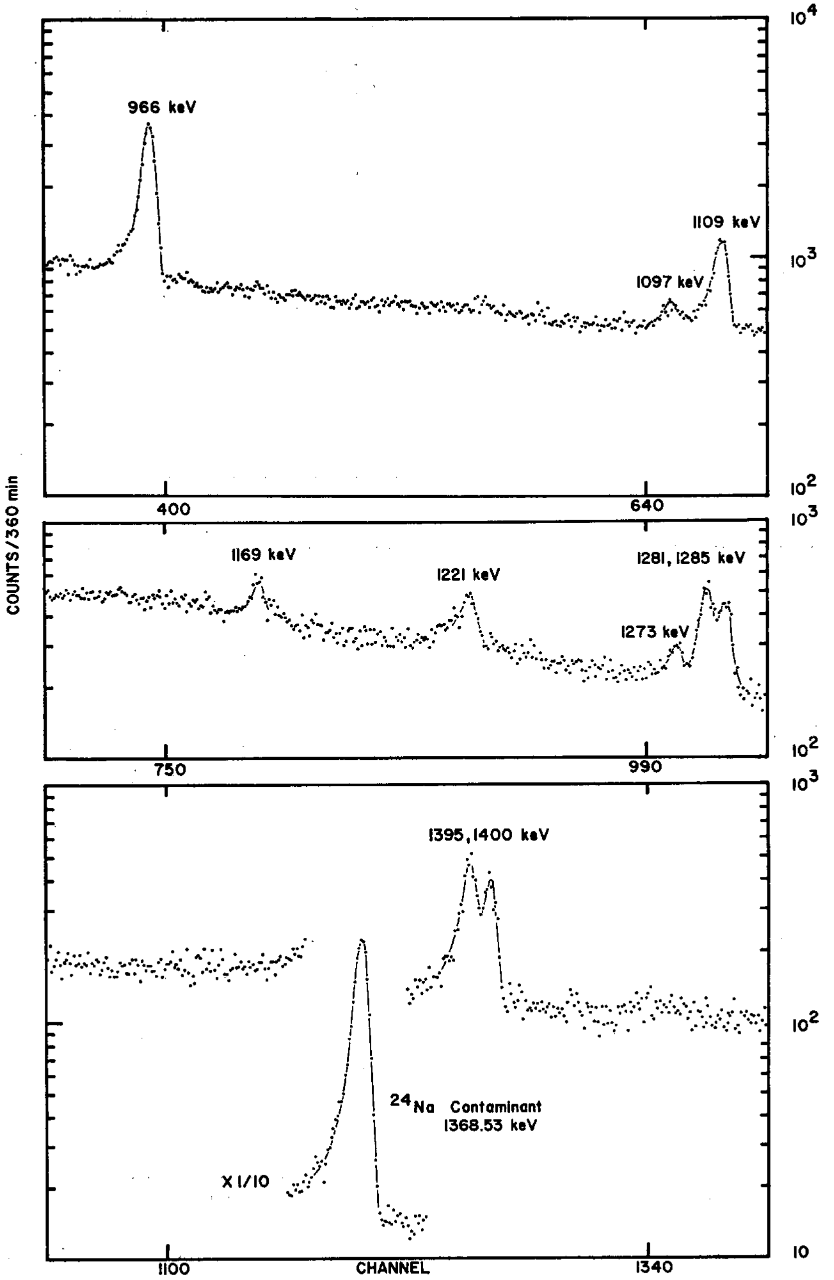


Fig. 3. The higher-energy portion of the gamma-ray spectrum of ^{171}Er obtained with a 40 cm^3 trapezoidal Ge(Li) detector. The solid lines merely indicate the trend of the data points. Absorbers were used to reduce the count rate due to the intense low-energy gamma rays.

the same run was made with a lead absorber in front of the gate detector; a pronounced increase in the size of the 296 and 308 keV peaks relative to the 372 keV peak was noted.

A coincidence spectrum was taken gating the 966 keV peak; but no gamma rays were observed to be in coincidence with the 966 keV gamma ray. A coincidence spectrum was also taken gating the 870–882 keV doublet, but no coincidence peaks above 125 keV were observed.

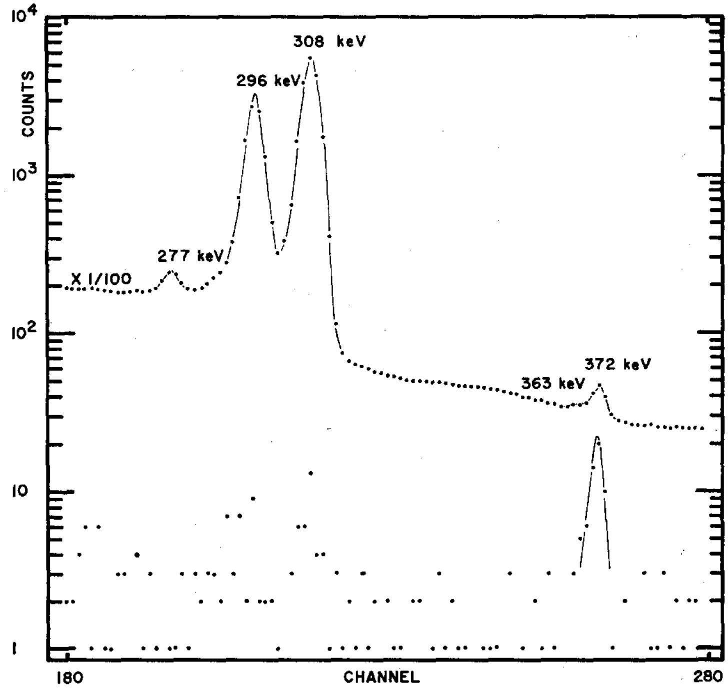


Fig. 4. The chance corrected coincidence spectrum obtained when gating the 908–913 keV doublet. No absorbers were used in front of the gate detector. A singles spectrum is shown above the coincidence spectrum for comparison. The solid lines merely indicate the trend of the data points.

4. Decay

The data of the present work are consistent with the decay scheme shown in fig. 5. This level scheme does not contain the level at 489 keV which was recently proposed by Megli *et al.* [15]). Their 489 keV level is given no feeding and is supposedly depopulated by a 12 keV doublet whose members have energies of 360 keV and 372 keV. Such a situation is neither consistent with our coincidence results concerning the 372 keV gamma ray nor with the fact that our curved-crystal spectrometer measurements yield energies of 363 keV and 372 keV for the two gamma rays of the doublet. Because of the lack of evidence for transitions at 166 and 404 keV and the new placement of the 372 keV transition, the 591 keV level proposed by Artna and Johns [11]) has been deleted. In the placement of the 372 keV transition, we confirm the recent observation of Geiger and Graham [14]) that the 372 keV gamma ray feeds the 913 keV level. Cranston *et al.* [10]) have reported coincidences between the 372 and 211 keV gamma rays. In addition to the new 1285 keV level, fig. 5 shows a level at 862 keV. This level is placed on the basis of our observation of a 12 keV spacing in the 733 keV doublet [13]). Our energy sums, however, are also consistent with the 733 keV transition depopulating the level at 738 keV. We have not placed the 966 keV transition. Since this transition does not appear to be in coincidence with any ob-

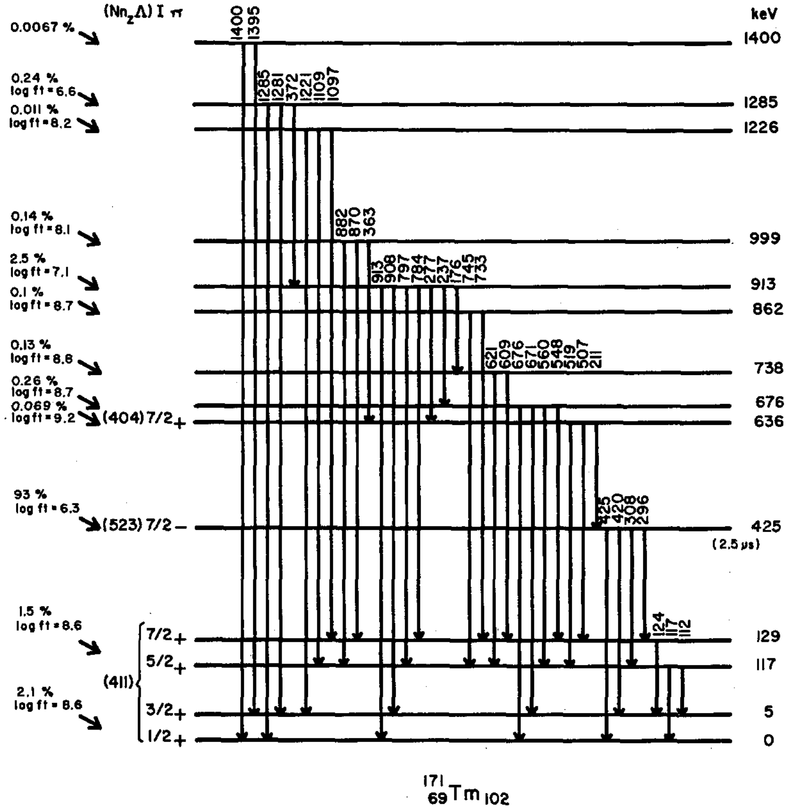


Fig. 5. The level scheme of ^{171}Tm populated in the beta decay of ^{171}Er. The beta feedings and log *ft* values for levels below the 636 keV level are taken from ref. [10]).

servable gamma ray, it probably feeds either the ground state or first excited state at 5 keV. The possibility that this transition de-excites through the metastable state at 425 keV cannot be excluded, however. The weak 694, 1169 and 1273 keV gamma rays have not been placed. We have not shown the 5 keV and 12 keV gamma rays in fig. 5 because they were not directly observed in this investigation. Hatch and Boehm [9]), however, have made measurements on the internal conversion electrons from the 5 keV and 12 keV transitions.

We have calculated the log ft values shown in fig. 5 on the basis of transition intensities of the present work and on the assumption that the beta feeding to all levels above 425 keV level is 3.4 % of the total decay [10].

5. Discussion

The ^{171}Tm nucleus is a deformed odd-proton nucleus [22]) having a ground state spin of $\frac{1}{2}$. The curves given by Mottelson and Nilsson [23,24]) for odd-proton orbitals in a deformed nuclear potential predict a $\frac{1}{2}^+$[411] orbital for the ground state of ^{171}Tm. This prediction is based on the assumption that the ^{171}Tm deformation parameter is approximately equal to the deformation parameter for ^{169}Tm. The great similarity between ^{169}Tm and ^{171}Tm has been adequately discussed [5,7-9]), and the properties of the ^{171}Tm ground state rotational band have been thoroughly investigated [25-27]). When the energy measurements of the present work are substituted into the theoretical expression for the ground state rotational levels

$$E(I) = E_0+E_1[I(I+1)+a(-1)^{I+\frac{1}{2}}(I+\tfrac{1}{2})]+E_2[I(I+1)+a(-1)^{I+\frac{1}{2}}(I+\tfrac{1}{2})]^2,$$

we find $E_1 = 11.498$ keV, $E_2 = 0.03462$ keV and $a = -0.8664$.

The first intrinsic excited state in ^{171}Tm occurs at 425 keV and appears to correspond to the $\frac{7}{2}^-$[523] orbital. It is an isomeric state with a 2.5 μs half-life [2,3]). The 636 keV level is most likely the second intrinsic excited state and, from consideration of the neighboring $Z = 69$ nucleides, appears to correspond to the $\frac{7}{2}^+$(404) orbital. These assignments are in agreement with those of Cranston *et al.* [10]) for the 425 and 636 keV levels.

Because of the lack of sufficient multipolarity information, the state assignments for the higher levels in ^{171}Tm are very uncertain. In contemplating a possible state assignment for the new 862 keV level, we note that energy and moment of inertia considerations suggest that the 636, 738 and 862 keV levels form a rotational band headed by the $\frac{7}{2}^+$, 636 keV state. The gamma-ray pattern associated with the decay of these levels does not, however, seem to support such an identification. The 425 keV transition has been placed solely on the basis of an energy fit, even though this gives rise to a rather unusual situation – an E3 transition in competition with an E1 transition. This observation is, however, consistent with the fact that, unlike the other transitions depopulating the 425 keV state, the 425 keV transition is not K-forbidden.

We wish to take this opportunity to express our sincere gratitude to I. P. Auer for the use of the least-squares program for the energy determinations and to M. A. Ludington for assistance in the reduction of the data used in the relative efficiency calibration. One of us (D.E.R.) would like to acknowledge the generosity of the National Science Foundation in providing a fellowship for the latter part of this study.

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