Radioactive Decay of Lu^{171} and Level Schemes for Yb^{171} and Yb^{169}

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Ytterbium oxide enriched to 93.8% in the mass number 171 was irradiated with 6-Mev protons. An activity decaying by electron capture with a half-life of (8.28±0.04) days was produced and its assignment to Lu^{171} confirmed by the identification of the ytterbium K x ray and by comparison with the activities produced by similar proton irradiations of each of the other enriched isotopes of ytterbium. The radiations observed in this activity were the L and K x rays of ytterbium and gamma rays with energies of 72–76, 668±7, 740±3, and 841±8 kev. Because neither particle nor annihilation radiation exists in this activity, the mode of decay is solely by electron capture to Yb^{171}. Gamma-gamma coincidence measurements were performed for the observed radiations. An energy level scheme has been constructed for the decay of Lu^{171} using the results of the gamma-gamma coincidence measurements, an energy analysis of the conversion electron data, and calculations of transitions intensities for various trial multipole orders. Levels in Yb^{171} at 0 (1/2− [521]), 66.7 (3/2− 1/2), 75.9 (5/2− 1/2), 95.1 (7/2+ [633] $\tau>10^{-5}$ sec), 122.4 (5/2− [512]), 167.3 (9/2+ 7/2), 208.1 (7/2− 5/2), 230.5 (7/2− 1/2), 246.5 (9/2− 1/2), 317.3 (9/2− 5/2), (350), 835 (7/2− [514]), 862 (possibly 5/2+ [642]), 935 (9/2+ [624]), and 949 (7/2) kev account for thirty of thirty-one transitions reported for this activity. Transition probabilities and branching ratios for the electron capture decay have been calculated. Eighty-four percent of the disintegrations of the 7/2+ [404] ground state of Lu^{171} occur to the 7/2− [514] state at 835 kev in Yb^{171}. The previously reported 600-day activity of Lu^{171} was not found. An energy level scheme for the decay of Lu^{169} (1.5 days) as reported by other workers is proposed with levels in Yb^{169} at 0 (7/2+ [633]), 24.2 (1/2− [521]), 70.9 (9/2+ 7/2), 87.0 (3/2− 1/2), 99.3 (5/2− 1/2), 161.7 (11/2+ 7/2), 191.4 (5/2− [512]), 244.0 (7/2− 1/2), 264.5 (9/2− 1/2), 278.7 (7/2− 5/2), 389.7 (9/2− 5/2), 523.1 (11/2− 5/2), 570.5 (5/2+ [642]), 648.2 (7/2− [514]), 962.2, 1451.6 (9/2+ [624]), 1456 (9/2), and 1465 (9/2) kev and with less certainty, at 488.9 (11/2− 1/2), 798, 870, 953, and 973 kev. This scheme accounts for 53 observed transitions following the decay of Lu^{169}. The ground state of Lu^{169} is probably the 9/2 [514] orbital also assigned to the ground state of Lu^{173}. This scheme is based upon an energy analysis of the reported transitions, intensity calculations for various trial multipole orders, and analogy with the scheme proposed for Yb^{171}.

INTRODUCTION

TWO activities decaying by electron capture with half-lives of (8.5±0.2) days and ~600 days have been assigned to Lu^{171} by Wilkinson and Hicks.[1] Coulomb excitation experiments by Elbek, Nielsen, and Olesen[2] have led to the assignment of levels at 67 and 76 kev in Yb^{171}, which has a ground-state spin of 1/2, measured by Cooke and Park.[3] The 67-kev level has also been observed by Smith *et al.*[4] following the β^- decay of Tm^{171}.

Several references exist concerning the conversion electron spectrum[5–7] and one concerning the gamma-ray spectrum[8] of the 8-day Lu^{171}. The half-life has been reported as 8.1 days[7] and two conflicting partial energy levels schemes for Yb^{171} have been proposed by Harmatz, Handley, and Mihelich[7] and by Gromov, Dzhelepov, Dmitriev, and Preobrazhenskii.[9] Conflicts are evident between the reported conversion electron and gamma-ray spectra. In some cases difficulty was encountered because of the coexistence of the 7-day Lu^{172} with the 8-day Lu^{171}. In this investigation, in which enriched isotopes of Yb^{171} and Yb^{172} were irradiated with protons, it was possible to examine separately the gamma-ray spectra of Lu^{171} and Lu^{172}. Agreement is good with the conversion electron spectrum of Lu^{171} which was also obtained with enriched isotopes and reported by Harmatz, Handley, and Mihelich.[7]

EXPERIMENTAL RESULTS

Ytterbium oxide enriched to 93.8% in the 171 mass number was irradiated with 6-Mev protons. The composition of the remaining portion in percents is: 0.05 Yb^{168}, 0.04 Yb^{170}, 3.4 Yb^{172}, 0.93 Yb^{173}, 1.17 Yb^{174}, and 0.23 Yb^{176}. The atomic number of the resulting activity was determined by the identification of the ytterbium K x ray which was compared with the known K x rays of europium, terbium, thulium, ytterbium, lutetium, and tantalum emitted from radioactive Gd^{153}, Dy^{159}, Yb^{169}, Tm^{170}, Hf^{175}, and W^{181}, respectively. Ion-exchange separation was deemed unnecessary.

In order to determine the mass number of the activity, similar proton irradiations were performed on each of the other stable enriched isotopes of ytterbium and the resulting activities intercompared. The well-known activities of Lu^{176}, Lu^{174}, Lu^{173}, and Lu^{172} were produced

[1] G. Wilkinson and H. G. Hicks, Phys. Rev. **81**, 540 (1951).
[2] B. Elbek, K. O. Nielsen, and M. C. Olesen, Phys. Rev. **108**, 406 (1957).
[3] A. H. Cooke and J. G. Park, Proc. Phys. Soc. (London) **A69**, 282 (1956).
[4] W. G. Smith, R. L. Robinson, J. H. Hamilton, and L. M. Langer, Phys. Rev. **107**, 1314 (1957).
[5] Iu. G. Bobrov, K. Ia. Gromov, B. S. Dzhelepov, and B. K. Preobrazhenskii, Izvest. Akad. Nauk S. S. S. R. Ser. Fiz. **21**, 940 (1957) [translation: Bull. Acad. Sciences U. S. S. R. **21**, 942 (1957)].
[6] V. M. Kel'man, R. Ya. Metskhvarishvili, B. K. Preobrazhenskii, V. A. Romanov, and V. V. Tuchkevich, Zhur. Eksp. i Teoret. Fiz. **35**, 1309 (1958) [translation: Soviet Phys.—JETP **35(8)**, 914 (1959)].
[7] B. Harmatz, T. H. Handley, and J. W. Mihelich, Phys. Rev. **114**, 1082 (1959).
[8] A. I. Lebedev, A. N. Silant'ev, and I. A. Iutlandov, Izvest. Akad. Nauk S. S. S. R. Ser. Fiz. **22**, 839 (1958) [translation: Bull. Acad. Sciences U. S. S. R. **22**, 833 (1958)].
[9] K. Ia. Gromov, B. S. Dzhelepov, A. G. Dmitriev, and B. K. Preobrazhenskii, Izvest. Akad. Nauk S. S. S. R. Ser. Fiz. **21**, 1573 (1957) [translation: Bull. Acad. Sciences U. S. S. R. **21**, 1562 (1957)].

by the irradiation of Yb^{176}, Yb^{174}, Yb^{173}, and Yb^{172}, respectively, with no evidence of reactions other than (p,n). The activity produced by the irradiation of enriched Yb^{171} was different from all of these activities. A small amount of the activity of Lu^{172} was observed with the activity of Lu^{171} and is attributed to the 3.4% of Yb^{172} existing with the enriched Yb^{171}.

The half-life of Lu^{171} is (8.28±0.04) days as measured by following the straight-line decay of the strongest gamma ray, 740 kev, for over seven half-lives with a 100-channel scintillation spectrometer. The assignment of the 8.3-day activity to Lu^{171} is therefore confirmed. One sample of enriched Yb^{171} was irradiated with 6-Mev protons for a long period of time in an attempt to build up any long half-life Lu^{171} activity which might exist. The gamma-ray spectrum of this sample after 320 days of decay can be entirely accounted for by the spectrum of the long-lived Lu^{173}, which was produced by a (p,n) reaction with the 0.93% Yb^{173} existing with the enriched Yb^{171}. No long half-life gamma activity of Lu^{171} exists with an intensity greater than 10^{-7} that of the 8-day activity. The long half-life activity previously assigned to Lu^{171} is best attributed to an impurity.

The L and K x rays of ytterbium were detected in the activity of Lu^{171} with a Geiger tube used with aluminum and beryllium absorbers. By use of the scintillation spectrometer, gamma rays of 72–76, 668 ±7, 740±3, and 841±8 kev in addition to the ytterbium K x ray were found as shown in Fig. 1. A peak at 112 kev was shown by absorption measurements to be the sum peak of two coincident K x rays. No gamma ray with an energy greater than 860 kev exists in the activity of Lu^{171} in an amount greater than 0.1% of that of the 740-kev gamma ray. This upper limit is in agreement with the conversion electron data of reference 7 and in conflict with the previously reported gamma-ray spectrum.[8] The gamma-ray spectrum of Lu^{172} has already been reported.[10] It is now clear in nearly all cases which of the transitions reported in references 5 and 6 belong to the individual activities of Lu^{171} and Lu^{172}.

No evidence of positron radiation was found in the activity of Lu^{171} by the method of plastic scintillation spectrometry, by the use of a Geiger tube with aluminum and beryllium absorbers, nor by a search for

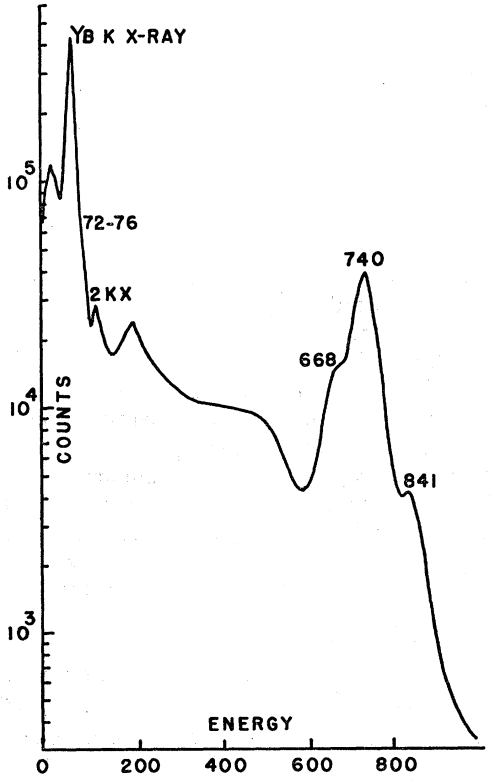

FIG. 1. Gamma-ray spectrum of 8.28-day Lu^{171}.

TABLE I. Data concerning the transitions in Yb^{171} following the decay of Lu^{171}.

Transition energy	Conversion electron references	Multipole order	Reason for M.O. choice	Gamma-ray intensity (this work)	Transition probability (per 100 disintegrations)
(9.2)[a]		$(M1+E2)$	a		27
(16.0)[a]		$(M1+E2)$	a		0.8
19.2	7	$E1$	b		93
27.3	7	$E1(+M2)$	a		0.6
46.5	7	$M1+E2(25\%)$	c		0.84
55.7	5, 6, 7	$M1+E2(2\%)$	c		4.0
66.7	5, 6, 7	$M1+E2(39\%)$	b		32
72.2	5, 6, 7	$M1+E2(8\%)$	c, d	(1.2)	17.5
		$(E1)$		5.5	43
75.9	5, 6, 7	$E2$	b	(4.3)	68
85.7	5, 6, 7	$M1+E2$	a		3.5
91.4	5, 6, 7	$M2$	a		0.9
109.2	7	$M1+E2$	c		1.8
142	7				~0.3
154.6	7	$M1+E2$	b		0.15
163.8	7	$E2$	b		0.64
170.6	7	$E2$	b		0.05
183	7				~0.05
194.9	7	$E2$	c		0.3
499	7				≤1
518	6, 7	$M1+E2(10\%)$	c, a		0.7
627	6, 7	$M1+E2(10\%)$	c, a		1.5
668	6, 7	$E1+M2(50\%)$	d, c	10	12.5
689	6, 7	$E1+M2$	a		0.8
713	6, 7	$M1+E2(10\%)$	c, a		2.1
740	6, 7	$E1+M2(38\%)$	d, c	50	68
768	6, 7	$M1+E2$	a	~3[e]	2.0
782	6, 7	$M1+E2$	c, a		2.6
786	7				≤0.1
795	7				≤0.1
827	7	$(E1+M2)$	a		≤0.1
841	6, 7	$M1+E2(15\%)$	d, c	5	6.8
854	6, 7	$M1+E2(20\%)$	c		1.1
K x ray				100(107)[f]	140

[a] Implied by level scheme.
[b] See reference 7.
[c] Required by intensity calculations and by fit with conversion electron data.
[d] Required by gamma-ray data.
[e] Observed only in coincidence measurements.
[f] Corrected for fluorescence [A. H. Wapstra, G. J. Nijgh, and R. Van Lieshout, *Nuclear Spectroscopy Tables* (North-Holland Publishing Company, Amsterdam, 1959)].

[10] R. G. Wilson and M. L. Pool, Phys. Rev. **118**, 1067 (1960).

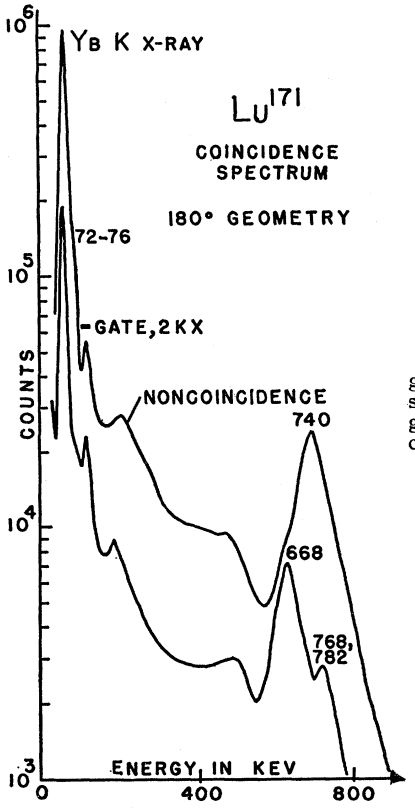

FIG. 2. Gamma-gamma coincidence spectrum of Lu^{171} gated by two coincident K x rays.

annihilation radiation in the gamma-ray spectrum. Therefore, the mode of decay is solely by electron capture to Yb^{171}.

The transitions in Yb^{171} following the decay of Lu^{171} are listed in Table I with the appropriate conversion electron references from which the transition energies are obtained. In the fifth column are presented the relative numbers of counts under the spectral distributions corrected for crystal efficiency of the observed gamma rays. These intensities were obtained with a 3×3-inch shielded NaI(Tl) crystal. The multipole orders in the third column are those used together with the conversion electron data of reference 7, the gamma-ray intensities of column five, and the internal conversion coefficients calculated by Rose,[11] to calculate the relative transition intensities which appear in the last column of Table I. These latter intensities have been normalized to read in percentages of disintegrations according to the decay scheme to be proposed. The multipole orders have been chosen for the reasons presented in the fourth column of Table I and will be discussed in some detail together with the level scheme in the Discussion.

Table II is a presentation of the coincidence information obtained for the activity of Lu^{171} with a coincidence circuit of resolving time $2\tau = 1.5\ \mu$sec. Figure 2

[11] M. E. Rose, *Internal Conversion Coefficients* (North-Holland Publishing Company, Amsterdam, 1958).

TABLE II. Gamma-gamma coincidence information for the activity of Lu^{171}.

	K x ray	72–76	2 K x	668	740	768, 782	841
K x ray	yes	yes	yes	yes	yes		yes
2 K x rays	yes	yes	*w*	yes	no	yes	no
668	yes	yes	yes	no	no		no
740	yes	no	no	no	no		no
841	yes	no	no	no	no		no

shows the gamma-ray spectrum in coincidence with two coincident K x rays. The upper curve is the noncoincidence spectrum. This coincidence spectrum is interpreted to mean that the 668-kev gamma ray and possibly either or both of the 768- and 782-kev gamma rays are in coincidence with at least one highly K-converted low-energy transition in addition to the K x ray resulting from preceding K capture; and that the 740- and 841-kev gamma rays are in coincidence with no more than one K x ray. The 668-kev gamma ray, as shown in Fig. 3, is in coincidence with the 72–76-kev peak but the 740-kev is not. Nothing but the single K x ray is in coincidence with the 740-kev gamma ray.

DISCUSSION

A ground state ($K=1/2$) rotational band which is consistent with the results of the Coulomb excitation experiments[2] has been formulated for Yb^{171} by Harmatz *et al.*[7] The scheme presented in reference 9 is not considered here because it differs from the results of the Coulomb excitation experiments and contains a

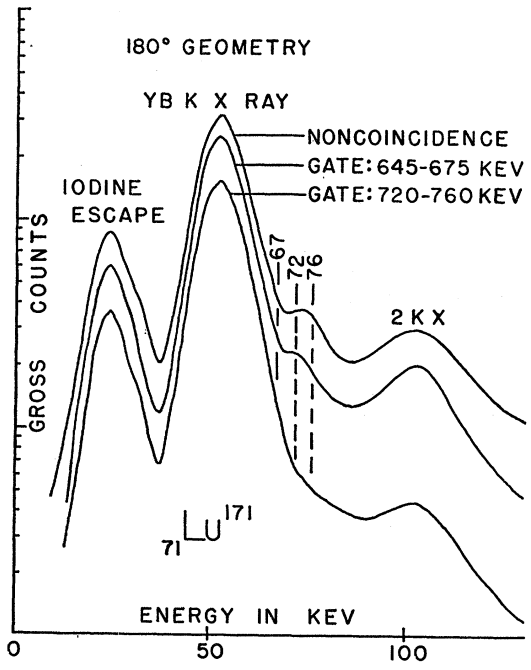

FIG. 3. Low-energy gamma-gamma coincidence spectra for the activity of Lu^{171}.

crucial transition, 90.6 kev, which has been shown in these investigations[10] to belong to the 7-day activity of Lu^{172}. The former ground-state band has been used as the basis for the proposed energy level scheme of Yb^{171} shown in Fig. 4. This scheme has been constructed with the aid of the coincidence information for the gamma rays of Lu^{171} described in the Experimental Results, from an energy analysis of the reported transitions,[7] and from the results of calculations of transition intensities for various trial multipole orders assumed for all of the observed transitions. The transition probabilities listed in the last column of Table I are also shown in Fig. 4. These figures have been used to calculate the branching ratios of electron capture from Lu^{171} to the levels of Yb^{171} and are shown in Fig. 4. The relative number of K x rays corrected for fluo-

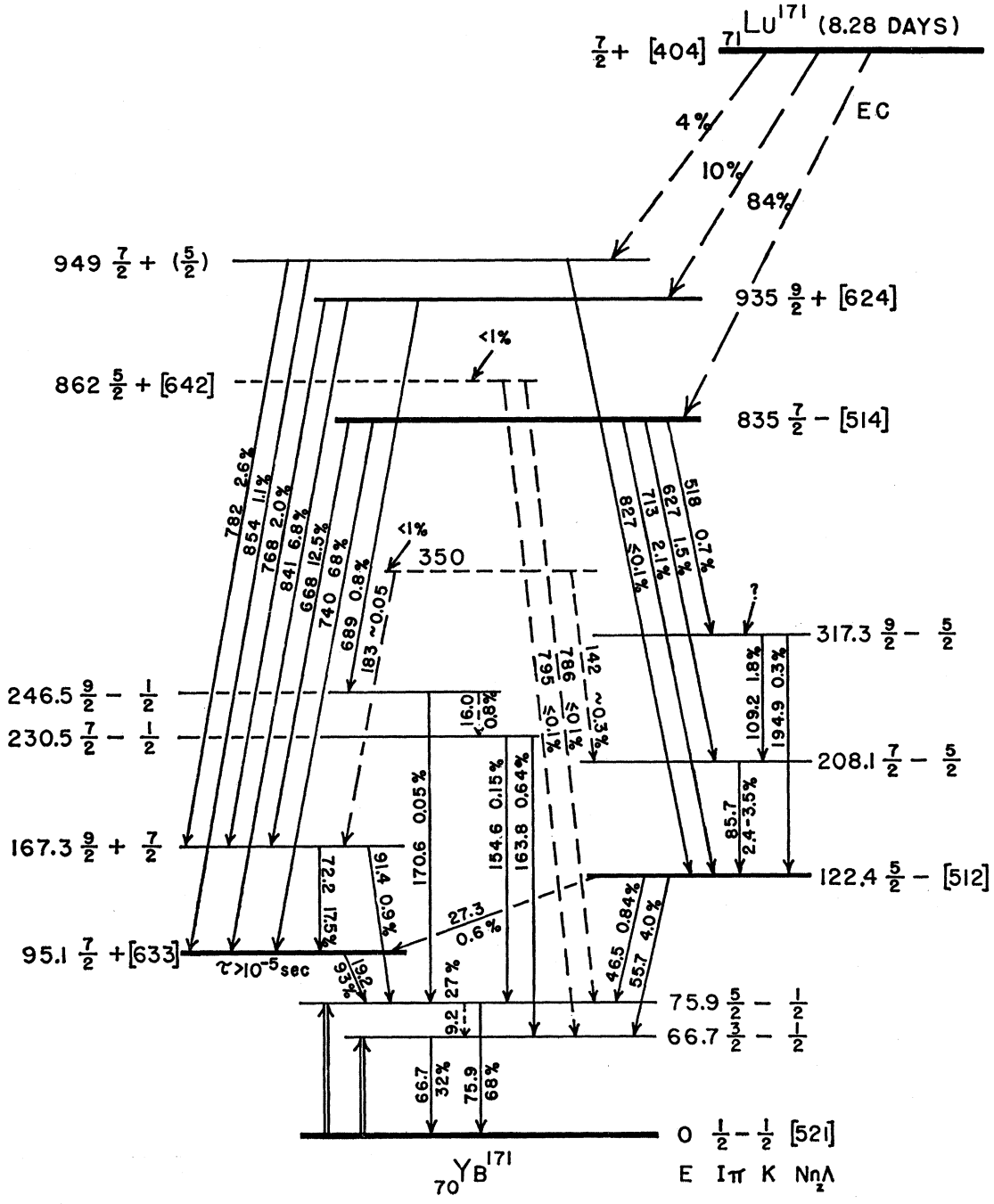

FIG. 4. Proposed energy level scheme for the decay of Lu^{171}.

rescence accounts for about 95% of the electron capture transitions after subtraction of K x rays from K conversion of the transitions in Yb^{171}. L capture probably accounts for the remaining disintegrations. Intrinsic orbital assignments have been made for the levels of Yb^{171} where appropriate, following the system of Mottelson and Nilsson[12] and are shown in Fig. 4. A discussion of some of the details of the level scheme for Yb^{171} is given below.

As seen in Fig. 1, the gamma-ray spectrum of Lu^{171} is dominated by the transitions of 740, 668, 841, and 72–76 kev in addition to the K x ray. The energy difference between the 740- and 668-kev transitions is 72 kev and a 72-kev transition is observed in both the conversion electron[7] and gamma-ray spectra. The interpretations given above for the results of the gamma-gamma coincidence measurements require that the 72-kev transition is highly K converted and that the 740- and 841-kev transitions are not in coincidence with the 72-kev, while the 668- and either or both of the 768- and 782-kev transitions are in coincidence with the 72-kev transition. An energy analysis of the transitions shows that the 841- and 768-kev transitions differ by about 72 kev and that if the 854-kev transition is combined with the 782-kev, three pairs of transitions can be matched with the 72-kev transition in a manner which explains the results of the coincidence measurements. The coincidence measurements also imply that these six transitions are not in coincidence with the 76-kev transition to the ground state of Yb^{171} within the instrumental resolving time. A low-lying isomeric state (7/2+ [633]) is expected[12] to exist in Yb^{171}. If this state is placed at 95 kev, the strong 19-kev $E1$[7] and the weaker 91-kev transitions serve as the link between the ground-state band and these three pairs of transitions. Some of the isomerism of the 95-kev level is removed by the occurrence at lower energy of the second and third members of the ground-state band but enough hinderance is apparently provided by the difference in K of three units to make the lifetime of the 95-kev level longer than 10^{-5} second.

The establishment of the 7/2+ [633] orbital at 95 kev implies levels at 167 kev depopulated by the 72- and 91-kev transitions and at 835, 935, and 949 kev which lead to the three pairs of high-energy transitions differing by 72 kev. It is instructive to note at this point that these three high-energy levels are also depopulated by transitions to other levels according to the scheme of Fig. 4.

Because the energy of the 72-kev transition is typical of rotational transitions in this region, the possibility that the 167-kev level is the 9/2 rotational state associated with the 7/2 [633] orbital at 95 kev is considered. The 72-kev transition would then be $M1+E2$. Internal conversion data for the transition of 72 kev in Yb^{171} is displayed in Table III. A mixture of 92% $M1$ and 8% $E2$ provides an excellent fit for the data of Table III while no mixture of $E1+M2$ can account for the relative numbers of observed L_{II} and L_{III} conversion electrons. Pure $E1$ involves a 50% error in these numbers. Two other arguments against an assignment of $E1$ for the 72-kev transition exist. As shown in Table II, the calculated relative number of 72-kev transitions when added to the corresponding number of 740-kev transitions yields a number of populations of the 95-kev level which is 20% greater than can be carried away by both of the 67- and 76-kev transitions to the ground state. Trial multipole order calculations for the intensities of the transitions of 740, 668, and 841 kev when combined with the corresponding gamma-ray intensities, lead to the conclusion that the 740- and 668-kev transitions are $E1+M2$ and the 841-kev transition is $M1+E2$. The conclusion that the 668- and 740-kev transitions are both of the same multipole order indicates that the 72-kev transition is $M1+E2$. As discussed by others,[7] another weaker rotational band with $K=5/2$ and composed of the transitions of 86, 109, and 195 kev, probably exists in Yb^{171}. The three remaining low-energy transitions of Lu^{171}, 27, 46.5, and 55.7 kev,[7] serve to link this band with the two other bands as shown in Fig. 4. The multipole order admixtures given in Table I for the transitions of 45.6 and 55.7 kev provide excellent fits with the relative numbers of L conversion electrons,[7] while no mixtures of $E1+M2$ are satisfactory. The parity of this band, the ground state of which is at 122 kev, is therefore odd. The 5/2− [512] orbital, which is the ground state of Yb^{173}, is expected to occur in Yb^{171} and has been assigned to the level at 122 kev. Three transitions, all originating from the previously established level at 835 kev with negative parity, serve to populate the three states of this $K=5/2$ band. The implied multipole orders of these three transitions are $M1+E2$. When trial multipole order intensity calculations are made for these three transitions, it is found that mixtures of about 10% $E2$ with 90% $M1$ provide the number of populations of this band which are carried away by the three transitions which depopulate the 122-kev ground state. Any appropriate mixtures of $E1+M2$ result in more populations of this band than are carried away.

TABLE III. Internal conversion data for the transition of 72.2 kev in Yb^{171} following the decay of 8.28-day Lu^{171}.

Shell	Internal conversion coefficients[a] $E1$	$E2$	$M1$	$M2$	Number of conversion electrons[b]
K	0.554	1.52	6.32	59.9	$\gg 50$
L_I	0.0540	0.167	0.799	15.7	90
L_{II}	0.0176	2.77	0.0653	1.63	30
L_{III}	0.0219	2.87	0.0102	4.34	22

[a] See reference 11.
[b] See reference 7.

[12] B. R. Mottelson and S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. 1, No. 8 (1959).

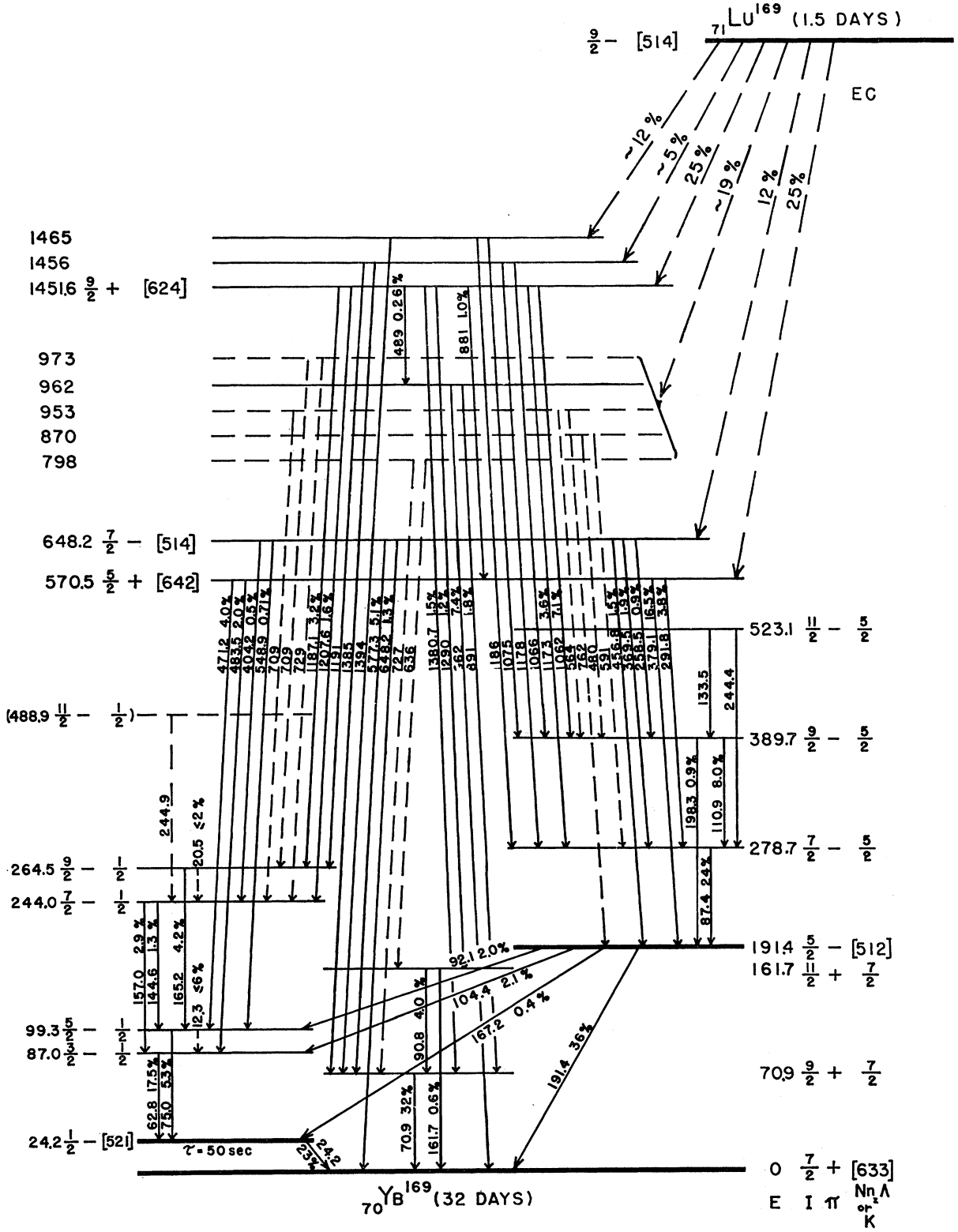

FIG. 5. Proposed energy level scheme for the decay of Lu^{169}.

TABLE IV. Data concerning transitions in Yb^{169} following the decay of Lu^{169}.

Transition energy	Conversion electron references	Multipole[b] order	Reason for M.O. choice	Transition[b,e] intensity
(12.3)[a]		$(M1+E2)$	a	$\leqslant 6$[a]
(20.5)[a]		$(M1+E2)$	a	$\leqslant 2$[a]
24.2	6, 7	$E3$	c	23[a] ($\gg$11 calc.)
62.8	6, 7	$M1+E2(18\%)$	c	18
70.9	6, 7	$M1+E2(32\%)$	a	32
75.0	7	$E2$	c	5.3
87.4	6, 7	$M1+E2(7\%)$	a	24
90.8	7	$M1+E2(6\%)$	a	4.0
92.1	7	$M1$	a, d	2.0
104.4	7	$M1$	a, d	2.1
110.9	6, 7	$M1+E2(10\%)$	a	8.0
133.5	7	$M1+(E2)$	a	0.6
144.6	7	$M1+(E2)$	c	1.3
157.0	6, 7	$E2$	c	2.9
161.7	7	$E2$	c	0.6
165.2	6, 7	$E2$	c	4.2
167.2	7	$E2$	a	0.4
191.4	6, 7	$E1$	d	36
198.3	7	$E2$	a	0.9
244.4(244.9)	7	$E2$	c	0.08
259	7	$M1+E2$	a	0.90
292	6, 7	$E1+M2$	a	3.8
370	6, 7	$M1+E2$	a	1.9
379	6, 7	$E1+M2$	a	16.5
404	7	$M1+E2$	a	0.50
457	6, 7	$M1+E2$	a	1.5
471	7	$E1+M2$	a	4.0
484	7	$E1+M2$	a	2.0
489	7	$M1+E2$	a	0.26
549	7	$M1+E2$	a	0.71
577	7	$E1+M2$	a	5.1
648	7	$E1+M2$	a	1.3
881	7	$E2$	a	1.0
890	7	$M1+E2$	a	1.8
962	7	$M1+E2$	a	7.4
1062	7	$E1+M2$	a	7.1
1173	7	$E1+M2$	a	3.6
1187(2)	7	$E1+M2$	a	9.2
1207	7	$E1+M2$	a	1.6
1290	7	$M1+E2$	a	1.0
1380	7	$M1+E2$	a	1.5

[a] Implied by level scheme and consistent with conversion electron data.
[b] All unstated multipole order admixtures are arbitrarily chosen as 70% dipole and 30% quadrupole for intensity calculations.
[c] See reference 7.
[d] Required by trial multipole order intensity calculations.
[e] Per 100 disintegrations if electron capture to ground state is negligible.

It is now evident that there exists a negative parity level at 835 kev in Yb^{171} which is highly populated by the electron capture decay of Lu^{171} to which has been assigned the 7/2+ [404] orbital.[12] The 7/2− [514] orbital is expected[12] to occur at a higher energy in Yb^{171}. This orbital has been assigned to the 835-kev level because it is consistent with the high population by electron capture from Lu^{171} and accounts well for the mode of depopulation of this level. Tentative assignments for the levels at 935 and 949 kev are shown in Fig. 4 and less certain levels at 862 and 350 kev have been suggested in order to account for the remaining transitions reported for Lu^{171}.[7]

According to the scheme of Fig. 4, the primary mode of decay of Lu^{171} is by electron capture to the 835-kev level of Yb^{171}, which is depopulated by a strong 740-kev gamma ray which places the system in a spin 7/2 semi-isomeric state 95 kev above the spin 1/2 ground state of Yb^{171}. This state at 95 kev is depopulated by a strong 19-kev radiation which leads to the two ground-state transitions at 67 and 76 kev. A strong 9-kev radiation is then implied but has not yet been observed unless it is the "poorly discernible" 11-kev transition mentioned in reference 9.

A proposed level scheme for Yb^{169}, which has been constructed with the aid of a previously proposed partial scheme,[7] an energy analysis of the transitions reported for the activity of Lu^{169},[7] intensity calculations for various trial multipole orders assumed for the transitions, and from analogy with the scheme proposed for Yb^{171}, is presented in Fig. 5. This scheme accounts for 53 of the transitions observed following the decay of Lu^{169}. Information concerning the transitions in Yb^{169} for which multipole order choices have been made is displayed in Table IV. As for Yb^{171}, where the admixture percentages could not be calculated from the conversion electron data, the percentage of quadrapole radiation was arbitrarily assumed to be 30% for the calculations. The multipole order choices are based upon assignments to some of the levels in Yb^{169} of intrinsic orbitals and their rotational states according to the system of Mottelson and Nilsson.[12] Some of the multipole orders are assigned in reference 7. Because intrinsic level assignments could be made with some degree of certainty for only some of the levels proposed in Yb^{169}, Table IV contains only a partial list of the

TABLE V. Energy ratios for rotational bands in the rare-earth region. All energies, E, are in kev.

$K\pi$	E_{K+2}/E_{K+1}	Nucleus	E_{K+1}	E_{K+2}
3/2	2.400	calculated		
3/2−[a]	2.43	Gd^{155}	60	146
3/2+	2.40	Tb^{155}	65	156
3/2−[a]	2.40	Gd^{157}	54.5	131.0
3/2+	2.37	Tb^{157}	60.8	143.9
3/2+[a]	2.37	Tb^{159}	58.0	137.5
3/2+	2.37	Tb^{161}	57	135
3/2−	2.44	W^{183}	83	203
5/2	2.286	calculated		
5/2−	2.27	Dy^{161}	77.5	175.6
5/2−[a]	2.29	Dy^{163}	74	170
5/2−	2.27	Yb^{169}	87.4	198.3
5/2−	2.27	Yb^{171}	85.7	194.9
5/2−[a]	2.28	Yb^{173}	78.7	179.5
5/2−	2.28	Hf^{175}	81.6	186.0
5/2+	2.27	Re^{183}	114.4	259.8
5/2+[a]	2.29	Re^{185}	125	286
5/2+	2.25	Re^{187}	134	301
7/2	2.222	calculated		
7/2−[a]	2.21	Ho^{165}	94.8	210
7/2+[a]	2.21	Er^{167}	78	172
7/2+	2.28	Yb^{169}	70.9	161.7
7/2+[a]	2.21	Lu^{175}	113.8	251.1
7/2−[a]	2.21	Hf^{177}	113.0	249.7
7/2+[a]	2.21	Ta^{181}	136	301
9/2	2.182	calculated		
9/2+[a]	2.17	Hf^{179}	121	262

[a] Measured.

transitions reported for the activity of Lu^{169}. Intensity calculations assuming both $M1+E2$ and $E1+M2$ admixtures for the other transitions shown in Fig. 5 have been made, however, and rough estimates of the relative population of the unassigned levels have been made. From all of the calculations, branching ratios for the electron capture decay of Lu^{169} have been estimated and are shown in Fig. 5. Electron capture to the ground state of Yb^{169} has been assumed negligible for this calculation. If this mode of decay is significant, then all of the other relative intensities must be adjusted for it. However, the positions and calculated intensities of the higher energy radiations imply that little if any electron capture occurs to the members of the three low-lying rotational bands. K-electron capture cannot occur to the $K=1/2$ band and the intensities calculated for the transitions populating the members of this band account well for the intensities of the transitions internal to this band.

The ground state of Lu^{169} is expected to be either the $7/2+$ [404] orbital or the $9/2-$ [514] orbital, both of which occur as ground and first excited states of other lutetium isotopes. The three rotational bands in Yb^{171} exhibit the spin 9/2 state and the $7/2-$ [404] orbital has been chosen for the ground state of Lu^{171}. The same three rotational bands in Yb^{169} exhibit the spin 11/2 member. The choice of the $9/2-$ [514] orbital for the ground state of Lu^{169} therefore seems better. Levels in Yb^{169} with probable spins of 9/2 are populated directly by electron capture which favors this choice for Lu^{169}. The 1.5-day half-life of Lu^{169} which is six mass numbers from the stability line, may be an indication of the higher spin ground state.

If the ground state of Lu^{169} is the $9/2-$ [514] orbital and if there does exist a 798-kev level in Yb^{169} which is depopulated as shown in Fig. 5, then this level at 798 kev could be the $11/2-$ [505] orbital specifically discussed by Mottelson and Nilsson.[12] These authors feel that this orbital should be populated in this region if conditions permit. The population of this orbital by the electron capture decay of Lu^{169} would be an allowed transition and would involve no asymptotic quantum number changes greater than one unit. This level is seen to be depopulated by a rather strong transition to the 161.7-kev level with spin 11/2, the highest spin and highest K level of lower energy. A second weaker transition occurs, as might be expected, to the lower rotational level.

During the work on the construction of the level schemes for Yb^{171} and Yb^{169}, a possible method for aid in the determination of the rotational structure of nuclei in this region was investigated. The results of the investigation are presented below. The method involves the use of the theoretical formula for the rotational energies, $E \propto [I(I+1)-K(K+1)]$ for $K > 1/2$. The formula for $K=1/2$ and a discussion of the fit of experimental data with the predictions of the formula are given by Harmatz *et al.*[7] and will not be discussed here. The above formula predicts ratios for the energies of rotational levels which are not very different for different values of K. However, as seen in Table V, the experimental energy ratios seem to be consistent enough to determine the value of K for a pair of rotational transitions in spite of the small differences. The experimental data of Table V is taken from references 7 and 12 and from the Nuclear Research Council Data Sheets. Only one exception is seen; the $7/2+$ band in Yb^{169}, which fits better the $K=5/2$ ratio. The $7/2+$ [633] assignment is fairly certain for this band, however, because of the spins of other nuclei with 99 neutrons and because of the well-studied decay of Yb^{169} (see reference 12).

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