Radioactive Decay of Lu^{172}

R. G. WILSON AND M. L. POOL
Department of Physics and Astronomy, Ohio State University, Columbus, Ohio
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Ytterbium oxide enriched to 95.9% in mass number 172 was irradiated with 6-Mev protons. An activity decaying by electron capture with a half-life of (6.70±0.04) days was produced and its assignment to Lu^{172} confirmed by the identification of the ytterbium K x ray and by comparison with the activities produced by similar proton irradiations of the other enriched isotopes of ytterbium. The 4.0-hour positron activity previously assigned to Lu^{172} was not observed and is best attributed to an impurity. The observed activity of Lu^{172} consists of the L and K x rays of ytterbium and gamma rays with energies of 79, 91, 113, 182, 203, 270, 324, 373, 490, 527, 697, 809, 900, 912, 1093, 1402, and 1583 kev. Because no positron radiation exists in the activity of Lu^{172}, the mode of decay is solely by electron capture to Yb^{172}. Gamma-gamma coincidence measurements, energy considerations, and consideration of the relative numbers of the radiations observed in the activity of Lu^{172} have led to the assignment of energy levels at 530 (6+), 1172 (3+), 1263 (4+), 1375 (5+), 1662 (3−), (1699), and 2072 (4+) kev in Yb^{172} in addition to the previously known 78.7 (2+)- and 260.2 (4+)-kev levels. The positions of all of the observed radiations and some observed only in conversion electron measurements are shown in a proposed energy level scheme for the decay of Lu^{172}. Approximate branching ratios for the electron capture disintegrations of Lu^{172} are also shown in the level scheme. Few, if any, electron capture transitions of Lu^{172} occur to the ground and first excited states of Yb^{172}. Of the two predicted spins for the ground state of Lu^{172}, 4− is more consistent with the proposed energy level scheme.

INTRODUCTION

TWO activities have been assigned to Lu^{172}; one decaying by electron capture with a half-life of 6.7 days and one decaying by positron emission with a half-life of 4.0 hours.[1] Absorption measurements led to the conclusion that the 6.7-day activity includes gamma radiation of about 1.2 Mev and that the energy of the positron in the 4.0-hour activity is about 1.2 Mev. Eight transition energies have been assigned to the 6.7-day activity following the proton irradiation of natural ytterbium oxide.[2] These data were reported to suggest energy levels of 78.7 and 260.2 kev in Yb^{172}. Twenty-nine conversion electron energies have been measured in an activity with a half-life of 7 to 8 days found in the lutetium fraction produced by the irradiation of tantalum with 660-Mev protons.[3] The corresponding transitions were associated with the activities of Lu^{171} and Lu^{172} which have similar half-lives, but no specific assignments were made. In a lutetium activity produced in the same way as that of the preceding reference and having the same half-life range, 47 transitions were observed by conversion electron measurements.[4] The transitions were again all associated with the activities of Lu^{171} and Lu^{172} but some assignments to the individual activities were made. A recent investigation of conversion electron energies following the proton irradiation of enriched isotopes of ytterbium has resulted in the assignment or confirmation of 30 transitions specifically to the activity of Lu^{171}.[5] Elimination of these latter transitions from the composite groups of the two preceding references and combination with those of reference 2 yields a group of transitions with a maximum energy of about 1100 kev which should comprise the 6.7-day activity of Lu^{172}.

Coulomb excitation of natural ytterbium oxide has led to the assignment of a 79-kev level to Yb^{172}.[6,7] Gamma rays of energies 79, 113, 181, 203, 325, 370, 525, 820, 900, and 1090 kev were associated with the electron capture decay of the 6.7-day activity of Lu^{172} produced by the irradiation of natural lutetium oxide with 250-Mev betatron bremsstrahlung.[8] Energy levels of 373.1, 576.9, 901.5, 1082, and 1990 kev were assigned to Yb^{172} in addition to the previously reported 78.7- and 260.2-kev levels. These assignments were made on the bases of some gamma-gamma coincidence measurements and energy considerations. Gamma rays of energies 0.076, 0.18, 0.40, 1.09, 1.49, and 1.79 Mev have been observed following the β^- decay of the 64-hour Tm^{172} activity.[9] Recently the enriched isotopes of ytterbium have become available and it is the purpose of this paper to discuss the results of an investigation of the activity of Lu^{172} produced by proton irradiations of the enriched isotopes of ytterbium.

EXPERIMENTAL RESULTS

Ytterbium oxide enriched to 95.9% in the 172 mass number was irradiated with 6-Mev protons. The com-

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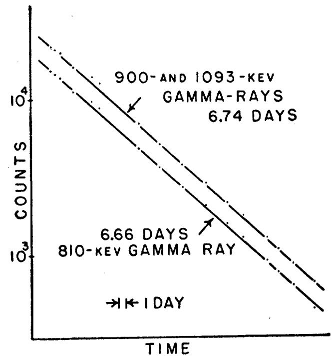

FIG. 1. Decay of three intense high-energy gamma rays in the activity of Lu^{172}.

TABLE I. Relative numbers of gamma rays, N_γ, and corresponding transitions, N_{trans}, in the activity of Lu^{172} for gamma-ray energies, E_γ, expressed in kev.

E_γ(kev)	References	N_γ	N_{trans}
78.7 $E2$	2,4	8.1	82
90.6 $E2$	2,4	~3	20
112.8 $E2(+M1)$	2,4	<1 and <3	3
181.5 $E2$	2,4	21	29
203.4 $E2$	2,4	>5	8
270	2,4	4	5
324	2,4	<1	<1
373	2,4	3	3
399[a]	4		
410[a]	4		
490	4	1	1
527	4	3	3
697	4	4	4
809	4	17	17
900	4}	37	28
912	4}		9
1002[a]	4		
1093	4	50	50
1402		2	2
1583		3	3
K x ray		100	107

[a] Not observed in the gamma-ray spectrum.

position of the remaining portion is in percent: 0.02 Yb^{168}, 0.08 Yb^{170}, 1.18 Yb^{171}, 1.47 Yb^{173}, 1.14 Yb^{174}, and 0.19 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, thullium, 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 enriched stable isotopes of ytterbium and the resulting activities intercompared. None of the activities produced by these similar irradiations of the other enriched isotopes of ytterbium was found in identifiable quantity in the activity produced by the irradiation of enriched Yb^{172}. The activity obtained by the proton irradiation of enriched Yb^{172} was found in barely identifiable amounts in the activities produced by the irradiations of enriched Yb^{171} and Yb^{173}. This may be explained by the 3.4 and 2.3% of Yb^{172} existing with the enriched Yb^{171} and Yb^{173}, respectively.

The half-life of the activity resulting from the proton irradiation of Yb^{172} is (6.70±0.04) days as determined by following the decay of the three most intense high-energy gamma rays for $5\frac{1}{2}$ half-lives as shown in Fig. 1.

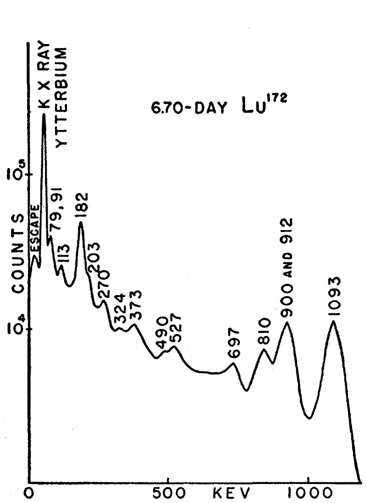

FIG. 2. Gamma-ray spectrum of 6.70-day Lu^{172} (to 1200 kev). This spectrum is a composite of spectra taken at different gains. Peak designations are in kev. A 3×3-in. crystal was used.

The original assignment of the 6.70-day activity to Lu^{172} is therefore confirmed. A careful search was made following two irradiations of enriched Yb^{172} for the 4.0 hour positron activity also previously assigned to Lu^{172}. No 4-hour annihilation radiation was observed in the gamma-ray spectrum of the activity resulting from these irradiations. It seems most probable that the 4-hour positron activity is attributable to an impurity.

L and K x rays of ytterbium were detected in the activity of Lu^{172} with a Geiger tube used with aluminum and beryllium absorbers. Figure 2 shows the observed gamma-ray spectrum (to 1200 kev) of Lu^{172} which includes gamma rays with energies of 79±1, 90±5,

TABLE II. Calculations for relative numbers of low-energy transitions in the activity of Lu^{172}. Columns 2, 3, and 4, respectively, are the ratios of the total number of transitions to the number of gamma rays, K-converted transitions, and transitions converted in the i shell as indicated in column 5. The α's were obtained from Rose.[a] N_t are the relative total numbers of transitions obtained from the products of the values in column 4 by the appropriate relative numbers of conversion electrons given by Mihelich et al.[b]

E_γ(kev)	$(1+\Sigma\alpha)/1$	$(1+\Sigma\alpha)/\alpha_K$	$(1+\Sigma\alpha)/\alpha_i$	i	N_t
78.7	10.1	7.2	4.2	L_3	4200
90.6	6.2	5.4	5.0	L_2, L_3	1000
112.8	3.1	4.0	7.7	L_2, L_3	175
			4.0	K	140
181.5	1.4	6.4	6.4	K	1350
			26	L_2	1690
			31	L_3	1400
203.4	1.3	8.5	8.5	K	340
			39	L_2	550
			52	L_3	415
270.1	1.1	16	16	K	300

[a] M. E. Rose, *Internal Conversion Coefficients* (North-Holland Publishing Company, Amsterdam, 1958).
[b] See reference 2.

TABLE III. Coincidence data for Lu^{172}. Gamma-ray energies in kev.

	Kx	79	91	113	182	203	270	373	527	697	810	900	912	1093	1402	1583
Kx	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
79 (91)	yes	no	yes	yes	yes	yes	yes	yes	yes	yes	yes	w	yes	yes	yes	yes
113	yes	yes	yes	w	yes	no		yes	no	yes						
182 (203)	yes	yes		yes	no	yes	yes	w	w	yes	w	w	yes	no	yes	no
270	yes	yes		yes	yes									no		
373	yes	yes	yes	no	yes	yes	yes	no	yes	no	no	no	yes	yes		
527 (490)	yes	yes		yes	yes	yes	yes	yes	no	no	no	no	yes	yes		
697	yes	yes	yes	yes	w	yes		yes		no	no		yes	yes		
810	yes	w	yes	no	yes			no	no		no		yes	yes		
900 (912)	yes	yes		yes	yes	no	no	no	no	no	no	(yes)	yes	yes		
1093	yes	yes	yes	yes	no	yes	no	yes	yes	yes	yes	yes	no	no	no	no

113±2, 182±2, 203±7, 270±3, 324±5, 373±3, 490±7, 527±4, 697±5, 809±5, 900±7, 912±7, 1093±4, 1402±15, and 1583±10 kev. No evidence of positron activity was found in Lu^{172} by the method of plastic scintillation spectrometry, by the use of a Geiger tube with aluminum and beryllium absorbers, nor by a search for annihilation radiation in the gamma-ray spectrum. Therefore the mode of decay of Lu^{172} is solely by electron capture to Yb^{172}.

The fourth column of Table I gives the relative number of counts under the spectral distribution after correction for crystal efficiency of the observed radiations listed in the third column. The value 82 in the last column of Table I was obtained by multiplying 8.1 in the third column by 10.1 in the second column of Table II. The value 29 was obtained in a similar manner. The values 20, 3, 8, and 5 in the last column of Table I were obtained by multiplying, respectively, the appropriate numbers in the last column of Table II by the ratio 82/4200. The last number in the fifth column of Table I, 107, is the number of K x-ray producing events of which only 100 are observed because the K-fluorescence yield in ytterbium is 0.937.[10]

Table III is a tabulation of the coincidence information for the activity of Lu^{172} obtained with a coincidence circuit of resolving time $2\tau = 3\times10^{-6}$ sec and with two $1\frac{3}{4}$-inch by 2-inch NaI(Tl) crystals used at either 90° or 180°. This information was obtained from the analysis of 25 coincidence measurements some of which lasted for 14 hours. Figure 3 shows four typical coincidence spectra. The upper curve in each case is the noncoincidence spectrum. Curve A shows the 91-kev gamma ray which is obscured by the 79-kev gamma ray in the noncoincidence spectrum and that the 91-, 113-, and 182-kev gamma rays are in coincidence with the 79-kev gamma ray. Curve B shows the 203- and 270-kev gamma rays which are obscured in the noncoincidence spectrum and that the 79-, 113-, 203-, and 270-kev gamma rays are in coincidence with the 182-kev gamma ray. Curve C shows clearly that the 527- and 373-kev gamma rays are in coincidence and that this cascade is parallel to the 697-, 810-, and 900-kev gamma rays but in coincidence with the 1093- and 912-kev gamma rays. Curve D shows that the 373-, 527-, 697-, 809-, and 900-kev gamma rays are in coincidence with the 1093-kev gamma ray. This coincidence spectrum was interpreted to show the relative amounts of the 809 and 900 gamma rays in coincidence with the 1093 gamma ray and hence in the absence of the 912 gamma ray. The ratio of the heights of the 809 and 900 photopeaks was corrected for energy efficiency and found to be 1.00/1.64. The ratio of the heights of the 900+912 gamma rays to the 809 gamma ray in the noncoincidence spectrum is 37/17 as shown in Table I. From these two ratios, the ratio of 900 to 912 gamma rays is 3.1. A similar calculation was made using the coincidence spectrum gated by the 900, 912 peak. The result gave a range of values which includes that obtained above.

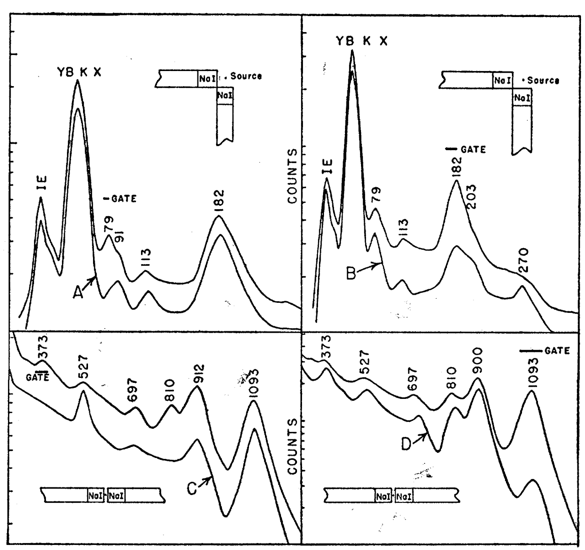

FIG. 3. Typical gamma-gamma coincidence spectra obtained for the activity of Lu^{172} with a coincidence circuit of resolving time $2\tau = 3\times10^{-6}$ sec. Peak designations are in kev. The upper curve in each case is the noncoincidence spectrum. Individual coincidence spectra are coincidences gated by 79-kev events for curve A, by 182-kev events for curve B, by 373-kev events for curve C, and by 1093-kev events for curve D.

[10] A. H. Wapstra, G. J. Nijgh, and R. Van Lieshout, *Nuclear Spectroscopy Tables* (North-Holland Publishing Company, Amsterdam, 1959).

DISCUSSION

Figure 4 shows a proposed energy level scheme for the decay of Lu^{172}. Energy levels of 530 (6+), 1172 (3+), 1263 (4+) 1375 (5+), 1662 (3−), (1699), and 2072 (4+) kev are assigned to Yb^{172} in addition to the previously known 78.7 (2+)- and 260.2 (4+)-kev levels. These new assignments are made on the bases of gamma-gamma coincidence measurements and by consideration of the energies and the relative numbers of the gamma rays and of the rules governing transitions among levels in the region of elliptically deformed nuclei, particularly the rules of K forbiddenness. The accuracy of the energies of these levels has been obtained by the use of the energies of the transitions in Yb^{172} resulting from the conversion electron measurements of references 2 and 4. Because this energy level scheme differs greatly from the one previously proposed as mentioned in the Introduction, an explanation of the scheme resulting from this investigation is given below.

The 1093- and 900-kev gamma rays are intense and in coincidence in agreement with reference 8. Four arguments for placing the 1093-kev transition immediately preceding the 79-kev transition, and the 900-kev transition therefore preceding the 1093-kev transition implying levels of 1172 and 2072 kev in Yb^{172} are (1) the 1093- and 900-kev gamma rays are both in coincidence with the 79-kev gamma ray, (2) the 900-kev gamma ray is, and the 1093-kev gamma ray is not in coincidence with the 182-kev gamma ray, (3) the number of K x rays after accounting for K conversion of the low-energy transitions in Yb^{172} is not sufficient to account for K capture to the levels of Yb^{172} if the 79-kev transition and the 900–1093-kev cascade both occur to the ground state of Yb^{172}, (4) the 79- and 1093-kev transitions have been observed following the β^- decay of Tm^{172} but the 900-kev transition has not. For these reasons levels of 1172 and 2072 are assigned to Yb^{172}.

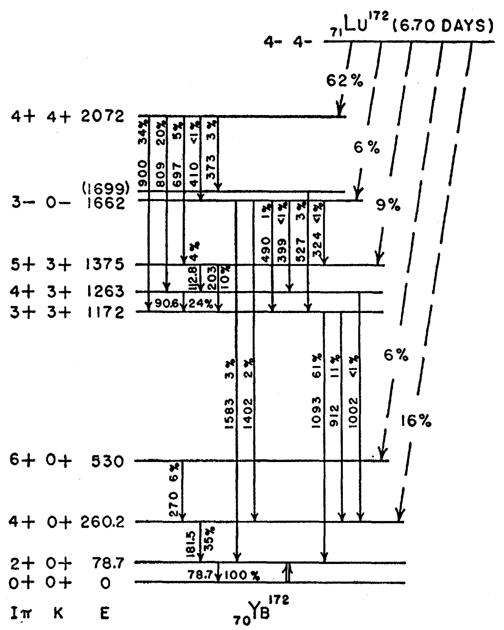

FIG. 4. Proposed energy level scheme for the decay of Lu^{172}. Energy level designations are in kev.

The 900-kev gamma ray is in coincidence with the 912-kev gamma ray and the latter transition fits between the 1172- and 260-kev levels. The 809-kev gamma ray is in coincidence with the 1093-kev gamma ray and the composite 900- and 912-kev peak although more predominantly with the former, implying that the 809-kev transition is in coincidence with only one of the two transitions in the composite peak. The 809-kev gamma-ray coincidence spectrum shows both the 79- and the 91-kev gamma rays but the 91-kev more predominantly. It is observed that the sum of the energies of the 809- and the 91-kev gamma rays is 900 kev. Thus the 809–91-kev cascade parallels the 900-kev transition with their orders as yet undetermined. The 91-kev transition has been designated as E_2 from conversion electron measurements[2] and is highly internally converted. This explains why the 91-kev gamma ray is weaker than the 809-kev gamma ray in the gamma-ray spectrum. The 697- and 203-kev gamma rays are in coincidence and their energies total 900 kev. The 113-kev gamma ray and the 91- and 697-kev gamma rays are in coincidence, and the 203-kev gamma ray is in coincidence with neither the 91- nor the 113-kev gamma rays. The 113- and 203-kev gamma rays have been designated as E_2 from conversion electron measurements.[2] The 79-, 113-, and 203-kev transitions may be assumed to be transitions among the levels of an excited rotational band with the 1172-kev level as its ground state.These levels are then all populated by transitions from the 2072-kev level. Thus levels of 1263 and 1375 kev are proposed as members of an excited rotational band in Yb^{172}.

The 373-, 527-, and 1093-kev gamma rays are all in coincidence and the energies of the first two total 900 kev. Thus there is another cascade between the 2072- and 1172-kev levels. The 373- and 527-kev gamma rays have nearly the same intensity, however their order has not been proved. The existence of a weak 324-kev transition in both the observed gamma-ray spectrum and the conversion electron spectrum of reference 4 favors the placement of the 373-kev transition higher because the energy difference between the implied 1699-kev level and the 1374-kev level is 324 kev. Thus a level of 1699 kev is tentatively assigned to Yb^{172}.

The low intensity 1402- and 1583-kev gamma rays are both observed in the coincidence spectrum of the 79-kev gamma ray but only the lower energy one is observed in coincidence with the 182-kev gamma ray. A level of 1662 kev is therefore implied from which transitions occur to the first and second excited levels of the ground state rotational band. It should be noted that these are the only observed transitions which cross over

the 1172-kev level. This 1662-kev level is also favored by the existence of 410- and 399-kev transitions in the conversion electron spectrum of reference 4. These two transitions may occur between the 2072- and the 1662-kev levels and between the 1662- and the 1263-kev levels, respectively. One other transition, 1002 kev, observed in the conversion electron spectrum of reference 4 but not in the gamma-ray spectrum has been fitted into the level scheme of Yb^{172}.

Only the 270-kev gamma ray remains to be placed in the level scheme of Yb^{172}. This gamma ray is in coincidence with the 182-kev gamma ray. The theoretical ratios for the excited ground-state rotational energies of even-even nuclei in this region of elliptically deformed nuclei are 1.00:3.33:7.00 for the first, second, and third levels, respectively. The experimentally observed values of these ratios are consistently smaller or about 1.00:3.30:6.75. These later ratios predict levels of 260 and 531 kev in Yb^{172} for the second and third ground-state rotational levels. The 260-kev level has previously been established. Because the 270-kev gamma ray is in coincidence with the 182-kev gamma ray and the placement of the 270-kev transition immediately preceding the 182-kev transition results in a level with the energy predicted for the third rotational level, a 530-kev level with a spin of 6+ is assigned to Yb^{172}.

The spins of the excited levels of Yb^{172} other than the ground-state rotational band will now be considered. The rotational band with a ground-state energy of 1172 kev is assigned the K quantum number 3+ and hence spins of 3+, 4+, and 5+ to the 1172-, 1263-, and 1375-kev levels for the following reasons: (1) transitions from the 1172-kev level occur to the 2+ and 4+ ground-state rotational levels only, (2) no transitions are observed from the 1263- and 1375-kev levels to the members of the ground-state rotational band but rather to the 1172-kev ground-state level of this band, (3) the observed ratio of the energies of these levels above the 1172-kev ground state is exactly the same as the theoretical ratio of the energies of the levels of a rotational band with $K=3+$. The theoretical ratio is 2.25:1.00 from the formula $E_1 \propto [I(I+1)-I_0(I_0+1)]$ where I_0 is the spin of the ground state of the band and I is the spin of the excited level. Reason (2) implies that K is greater than 2 for this band. For rotational bands with $K=2$, transitions to the $K=0+$ ground state do occur. For $K=3$, the rule of K forbiddenness, $\Delta K \leq L$, makes transitions within the band where $\Delta K=0$ much more probable than to the ground-state band for which $\Delta K=3$. These transitions are either nonexistent or very weak.

The fact that the 91- and 113-kev transitions are both predominantly E_2 is consistent with this choice because M_1 radiation between members of a $K=3$ rotational band is highly hindered. The 203-kev crossover transition is also E_2 in agreement with this choice.

The choices of $I=4+$ and $K=4+$ for the 2072-kev level are made because transitions occur from this level to the three levels of the $K=3+$ rotational band in the relative amounts shown in Fig. 4 and because no transitions occur from this level to those of the ground-state rotational band. These latter transitions are highly K forbidden.

The choices of $I=3-$ and $K=0-$ are made for the 1662-kev level because (1) transitions occur from this level to the 2+ and 4+ levels of the ground-state rotational band, (2) these transitions cross over the $K=3+$ rotational band implying a low value for K, (3) this level is not strongly populated by electron capture as would be expected consistent with the spin assignment for the ground state of Lu^{172}. If this choice is correct, then the level with $I=1-$ and $K=0-$ is not expected to be populated.

${}_{71}Lu_{101}{}^{172}$ is an odd-odd nucleus in the region of elliptically deformed odd-odd nuclei. The collective model predicts a doublet of states for such a nucleus, one of which is the ground state. ${}_{71}Lu^{175}$ and ${}_{70}Yb_{101}{}^{171}$ have measured ground-state spins of 7/2+ and 1/2−, respectively. Therefore ${}_{71}Lu_{101}{}^{172}$ would be expected to have spins of 3− and 4−. The choice of $I=4-$ and therefore $K=4-$ for the ground-state spin of Lu^{172} is made because of the population by electron capture from Lu^{172} to the 4+ (0+), 6+ (0+), 5+ (3+), and 4+ (4+) levels of Yb^{172}. The level scheme of Fig. 4 accounts for all of the radiations observed in this investigation and includes transitions corresponding to all 8 of those reported from conversion electron measurements in reference 2 and for 18 of those of reference 4. The coincidence data of this investigation agree in some part with those of reference 8 but the few cases of disagreement have resulted in very different energy level schemes for the decay of Lu^{172}. However, all of the gamma rays reported in reference 8 were observed in this investigation.

The bases for the spin and parity assignment made for the levels of Yb^{172} populated by the electron capture of Lu^{172} have been given. The multipole orders for the transitions between levels of Fig. 4 are shown in the third column of Table I. All of those multipole orders which have been determined from conversion electron measurements agree with these assignments.

The approximate percentages of electron capture from Lu^{172} to the levels of Yb^{172} shown in Fig. 3 were obtained as described below. L capture is considered negligible with respect to K capture to all of the levels of Yb^{172}. From the 107 K x rays of Table I, one K x ray was subtracted for every K capture required to balance the difference between the number of transitions from an excited level and the number of transitions to the same level. K x rays were also subtracted to account for K conversion of all of the transitions in Yb^{172} for which this process is significant. The number of K x rays remaining indicate that few if any electron capture transitions from Lu^{172} occur to the ground and first excited level of Yb^{172}.

The β^- decay of Tm^{172} as reported in reference 9 fits into the proposed energy level scheme of Yb^{172}. Spins

of 2− and 3− are predicted for the ground state of Tm^{172} by the method described above. Tm^{172} with either of the two predicted spins and at sufficiently high energy might be expected to decay into the 2+ level of the ground-state rotational band, to the 1172-kev 3+ level, and to the 1− and 3− levels of the $K=0-$ band which would produce the observed radiations mentioned in the Introduction.

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Multiple Scattering of Polarized Electrons

M. K. Sundaresan
Department of Physics, Panjab University, Chandigarh, India
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The theory of multiple scattering derived earlier is used to evaluate the numerical magnitudes of the depolarization produced due to multiple scattering in gold foil of thickness 1 mg/cm² for polarized electrons of velocities: $\vartheta/c=0.6$, 0.7, 0.8, 0.9. The depolarization effect is found to be extremely small. The correction due to multiple scattering to the electrostatic rotation of spins is also computed.

In a recent paper, Mühlschlegel and Koppe[1] have investigated the single and multiple scattering of polarized electrons with a view to obtaining expressions for the amount of depolarization produced due to these processes. They found that, since in the nonrelativistic approximation the polarization due to Mott scattering vanishes, the magnitude of the polarization vector **P** of the initial electrons remains unchanged; however, its direction is altered. In fact they have shown that this change in the direction of the vector **P** is exactly as though the polarized electrons were subjected to a transverse cylindrical electric field of constant magnitude. They have investigated the possibility that, although the single scattering of the electrons leads only to a pure rotation of the polarization vector, the multiple scattering could lead to some depolarization due to the fact that electrons scattered at a given angle, on account of their different paths, would have their polarization vectors pointing in different directions. However, in their final analysis, they have used Molière's theory of multiple scattering which has been recently shown[2] to involve an inconsistent approximation. It is the purpose of this note to use the theory of multiple scattering of reference 2 to evaluate the numerical magnitude of the electrostatic rotation of the spins and the amount of depolarization produced, respectively.

In the theory of multiple scattering, an expression for the "screening angle," χ_α, has been derived on the basis that the experimental single scattering cross section at small angles is correctly represented if terms of the first and second Born approximations alone are retained in the theoretical formula. χ_α is given by[2,3]

$$\chi_\alpha^2=\chi_0^2\left[1+4\alpha\chi_0\left(\frac{1-\beta^2}{\beta}\ln\chi_0+\frac{0.2310}{\beta}+1.4480\beta\right)\right], \quad (1)$$

where $\alpha=zZ/137$ (Z being the atomic number of the scatterer and z the number of units of charge on the particle undergoing scattering), β the velocity of the particle in units of the velocity of light, and

$$\chi_0=\mu(\hbar Z^{\frac{1}{3}}/0.885pa_0). \quad (2)$$

Here p represents the momentum of the particle undergoing scattering, a_0 the Bohr radius, and μ a parameter to be suitably chosen to describe the multiple scattering angular distribution properly. By fitting the angular distributions of electrons multiply scattered in gold and beryllium at high energies (15 Mev), the value of μ is found to be 1.80. A direct calculation of χ_α for beryllium from the variational wave function of the atom yields the value $\mu=2.1$. There are reasons to believe that this value of μ does not change very much with the energy of the incident particle as long as it is relativistic ($\beta\sim1$).

The formula given above for χ_α, due to the very assumptions on which it is based, has greater validity for β values close to unity. We estimate that it should be quite good even for β values for the electron of the order of 0.6. For values of β much smaller than 0.6, errors will be introduced due to the more and more unreliable nature of the Born approximation itself.

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[1] B. Mühlschlegel and H. Koppe, Z. Physik **150**, 474 (1958).

[2] B. P. Nigam, M. K. Sundaresan, and Ta-You Wu, Phys. Rev. **115**, 491 (1959).

[3] For comparison we also give Molière's expression for χ_α:
$\chi_\alpha^2=\chi_{0M}^2[1.13+3.76(\alpha^2/\beta^2)]$; $\chi_{0M}=\hbar Z^{\frac{1}{3}}/0.885pa_0$.