Decay of ^{147}Eu to Levels in ^{147}Sm

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A recent investigation of the conversion-electron spectrum of ^{147}Eu has revealed numerous new transitions in ^{147} Sm. The present study was undertaken to supplement these conversion-electron data with γ-ray information obtained with high-resolution Ge(Li) counters. Singles γ-ray spectra were obtained, and β^+-γ(NaI), e-γ(NaI), and e-γ(Ge(Li)) coincidence measurements were made. A value of 1767±10 keV was determined for the ^{147}Eu decay energy. K-shell internal-conversion coefficients were calculated for most of the observed transitions by intercomparison of the photon intensity data with published conversion-electron intensity data. The existence of previously reported ^{147}Sm excited states at 121.3, 197.4, 798.9, 1054, 1077, 1319, 1454, and 1550 keV was confirmed. The experimental information accumulated in this study also indicates new levels at (1007), 1065, 1180, (1228), 1450, 1472, 1656, and (1664) keV. (Levels enclosed in parentheses are only tentatively proposed.) A small percentage of direct ^{147}Eu decay to the first three states in ^{147}Sm was found to proceed by positron emission. The following (K-capture/β^+) ratios were measured: 258±100 (ground state), 257±100 (121.3-keV state), and 302±150 (197.4-keV state).

INTRODUCTION

THE nucleus ^{147}Sm has three neutrons beyond the 82-neutron closed shell; it is situated in the transition region, i.e., between the spherical closed-shell region and the deformed region that sets in at 90 neutrons. As such, its properties are determined by the relative strengths of two types of forces: (1) pairing forces, which tend to make the nucleus take on a spherical shape, and (2) polarizing forces, due to particles in unfilled shells, which act to deform the nucleus. For nuclei in the transition region these competing forces may be expected to be of comparable magnitudes. Theoretical calculations are therefore difficult. On the one hand, an exact account must be made of the pairing effect, while on the other the adiabatic approximation, valid for nuclei with permanent deformations, cannot be used. In addition, the energy values for single-particle states under conditions of small deformation have not been well explored experimentally. The first step in the understanding of nuclei such as ^{147}Sm is the accumulation of as much experimental information as possible concerning their level structures.

The electron-capture decay of ^{147}Eu (24-d) to levels in ^{147}Sm has been investigated several times.[1–6] However, a recent investigation[7] of the conversion-electron spectrum of ^{147}Eu with a low-background spectrometer[8] with twofold focusing at an angle of $\pi\sqrt{2}$ has revealed numerous new transitions in ^{147}Sm. The present study was undertaken to supplement these conversion-electron data with γ-ray information obtained with high-resolution Ge(Li) counters. In addition to obtaining singles γ-ray spectra, β^+-γ(NaI), e-γ(NaI), and e-γ[Ge(Li)] coincidence measurements were made. A new value for the ^{147}Eu decay energy was determined, and several new levels in ^{147}Sm were established.

EXPERIMENTAL PROCEDURE

Sources containing ^{147}Eu radioactivity were produced by means of spallation reactions from the bombardment of tantalum with 660-MeV protons accelerated in the synchrocyclotron at the Joint Institute for Nuclear Research, Dubna. After irradiation the rare-earth elements were isolated by ion-exchange techniques. The europium and gadolinium fractions were then sent to Copenhagen for measurement. Two ^{147}Eu sources were used. The first was prepared by placing the europium fraction in an isotope separator[9] and by collecting the ^{147}Eu activity on a 150-μg/cm^2 Al foil. A second and stronger source was prepared in the following manner. The gadolinium fraction was allowed to decay for about one week, after the initial chemical separation. At this time most of the ^{147}Gd (35-h) had decayed into ^{147}Eu.

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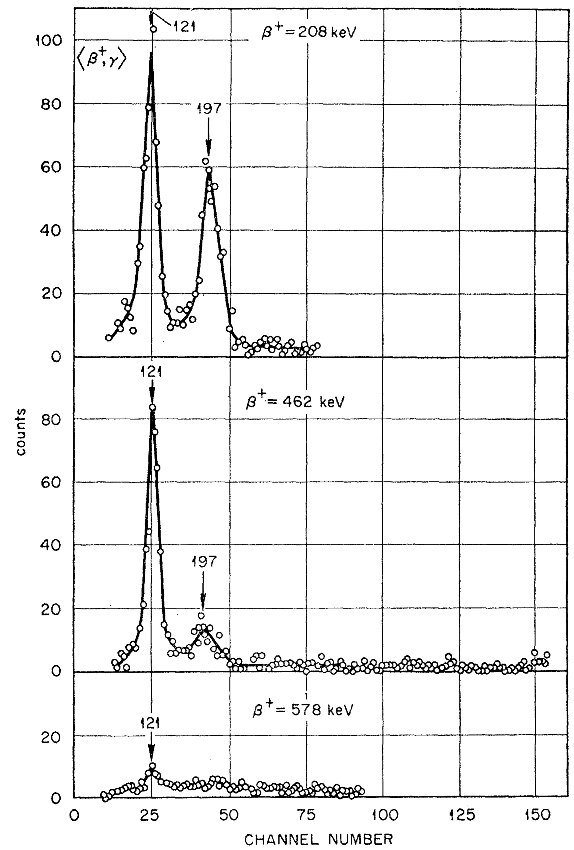

FIG. 1. Gamma-ray (NaI) spectra obtained in coincidence with β^+ particles.

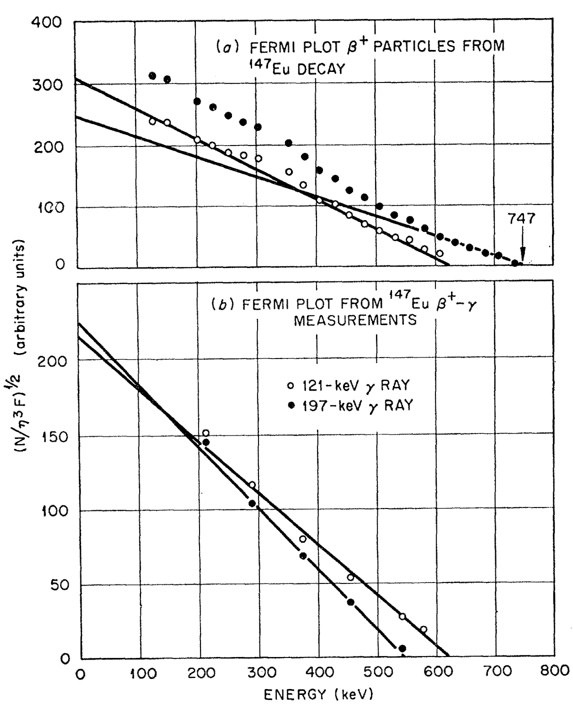

FIG. 2. Fermi plots determined from: (a) total positron spectrum measurement, and (b) β^+-γ coincidence measurements.

Then, by several ion-exchange separations, the europium daughters were separated from the parent gadolinium fraction. By waiting for the 5-day ^{145}Eu and ^{146}Eu activities to decay, it was possible to have a source that consisted mainly of ^{147}Eu and ^{149}Eu (106 day). Long-lived ^{148}Gd (85 yr) and ^{150}Gd (2×10^6 yr) contribute no ^{148}Eu and ^{150}Eu radioactivity; the europium daughters of ^{151}Gd and ^{153}Gd are stable. The chemical separations were not perfect, however, and ^{146}Gd (48 d) and ^{149}Gd (9 d) were present in small amounts. The europium fraction prepared in this manner was then evaporated onto a 150-μg/cm^2 Al foil.

Singles γ-ray spectra were taken with a 9.5-cm^3 coaxial Ge(Li) detector connected to a field-effect transistorized preamplifier and were collected on a 1024-channel analyzer. A relative efficiency curve for the detector was constructed by using ^{207}Bi and ^{226}Ra standard γ-ray sources. Coincidence measurements were made with two six-gap β-ray spectrometers.[10,11] These instruments are characterized by high transmission efficiencies and a field-free region where γ-ray detectors may be placed and are therefore well-suited for electron-gamma coincidence experiments. One of the spectrometers,[10] located at the Niels Bohr Institute, was used in conjunction with a 3 in.$\times$3 in. NaI scintil-

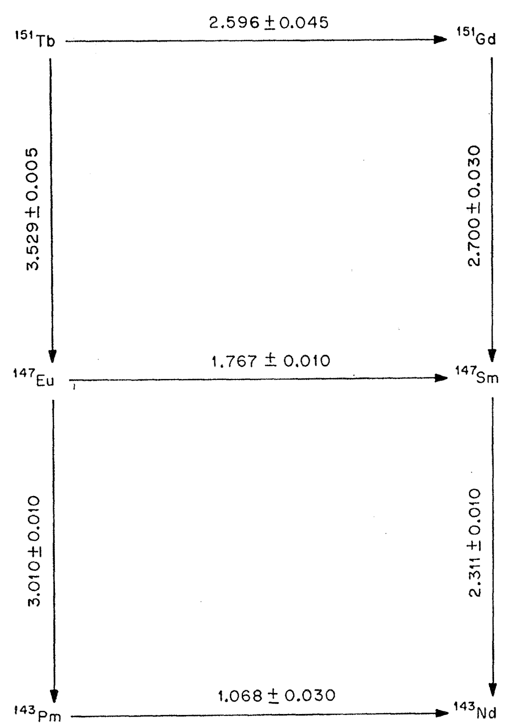

FIG. 3. Closed-energy decay cycles used to predict the electron-capture decay energies of ^{143}Pm and ^{151}Tb. Energies shown are in MeV.

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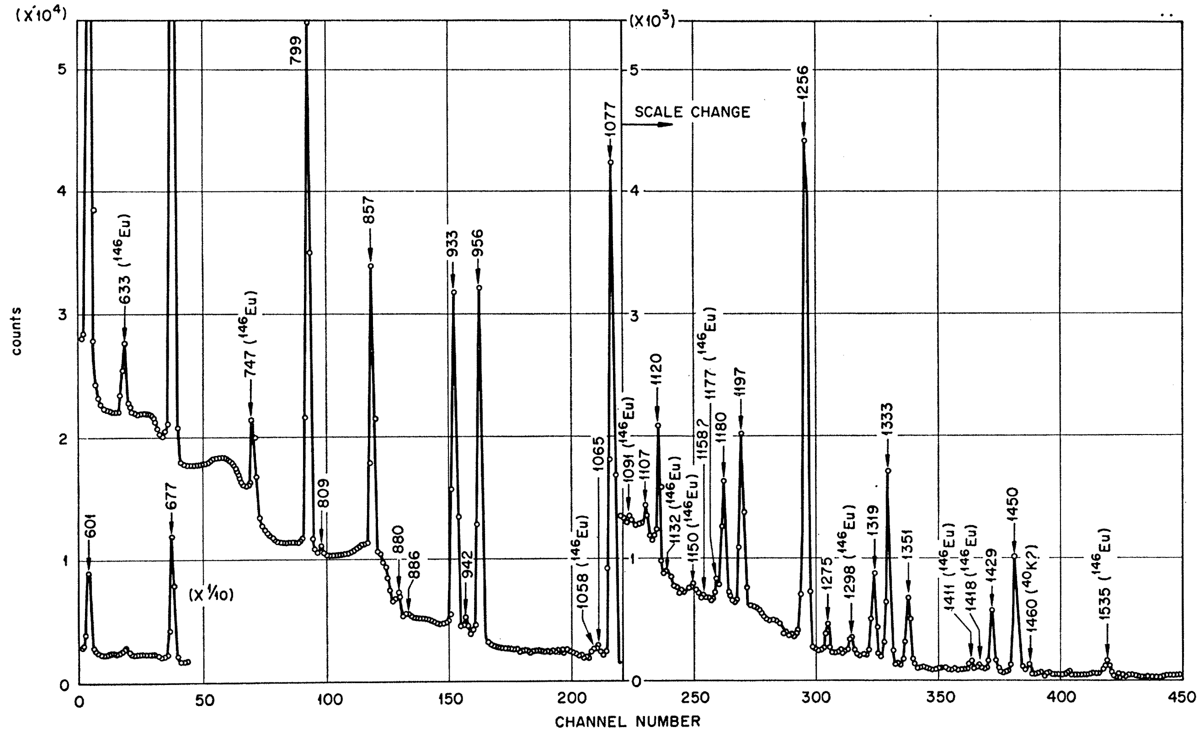

FIG. 4. Singles γ-ray spectrum taken with a 9.5-cm³ coaxial Ge(Li) detector. Only the energy region >600 keV is shown; all unlabeled peaks are assigned to ^{147}Eu decay. Source-to-counter distance was 2.5 cm.

lation crystal detector in β^+-γ and e-γ coincidence measurements. The other instrument,[11] located at the Research Establishment Risø, was used in e-γ coincidence measurements with a 2.1-cm³ Ge(Li) counter as the γ-ray detector. In all coincidence experiments the source was located approximately 5 cm from the γ-ray detector.

EXPERIMENTAL RESULTS

β^+-γ Coincidence Measurements

The most recent value[4] reported for the electron-capture decay energy of ^{147}Eu is 1652±15 keV; but the possibility of the existence of a 1656-keV transition[7] in ^{147}Sm casts doubt on this value. A part of the present investigation was therefore devoted to the measurement of the decay energy by the β^+-γ coincidence technique. A small portion, (0.2–0.3)%, of all ^{147}Eu decays proceed by positron emission. This weak-positron branch populates not only the ground state but also the first two excited states (121.3 and 197.4 keV) in ^{147}Sm. The experimental procedure was to observe γ rays in coincidence with the continuous β^+ spectrum; end-point energies were then determined by measuring the intensities of the de-excitation γ rays as a function of the β^+ energy spectrum. Figure 1 shows γ-ray spectra (taken with a 3 in.×3 in. NaI crystal) observed in coincidence with β^+ particles whose energies were 208, 462, and 578 keV. The β spectrometer was also used to measure the total number of positrons as a function of the energy. Figure 2 shows the Fermi plots constructed on the basis of this and the β^+-γ measurements. From the coincidence data [Fig. 2(b)] the end-points to the excited states were determined to be 548 and 622 keV. The ratio of intensities are:

$$N_{\beta^+_2}/N_{\beta^+_1}=0.86\pm10,$$

where $N_{\beta^+_1}$ and $N_{\beta^+_2}$ are the intensities of the positron branches feeding the 121.3- and 197.4-keV states, respectively. The six high-energy points of the Fermi plot constructed from the gross positron spectrum [Fig. 2(a)] lie on a straight line, with a 747-keV end-point. The line apparently represents the positron branch proceeding to the ^{147}Sm ground state. It was not possible to resolve the two excited-state branches after the ground-state contribution, $N_{\beta^+_0}$, had been subtracted from the total spectrum. It was found, however, that

$$(N_{\beta^+_1}+N_{\beta^+_2})/N_{\beta^+_0}=1.14\pm0.10.$$

By combining the two ratios the relative intensities of all three β^+ components were determined:

$$N_{\beta^+_0}:N_{\beta^+_1}:N_{\beta^+_2} = (0.47\pm0.09):(0.29\pm0.06):(0.24\pm0.07).$$

After the positron spectrum measurements were completed the same source to detector geometry was used to measure the intensity of the K-conversion-electron line of the 197.4-keV transition. It was found that

$$(N_{\beta^+_0}+N_{\beta^+_1}+N_{\beta^+_2})/N_{K197.4}=0.07\pm0.01.$$

TABLE I. Intensities and K-shell internal-conversion coefficients (ICC).

Energy (keV)	I_K	I_γ	Total intensity	Exper. K-shell ICC×100	Theoretical (Sliv and Band) values for K-shell ICC×100 $E1$	$E2$	$M1$	$M2$	Multipole assignments
76.1	4000	1590	8290	252.6	48	240	330	3250	$M1+E2$; from Ref. 6
121.3	45 000	64 200	120 200	70.1	14	69	86	640	$M1+E2$; from Ref. 6
197.4[a]	10 000[a]	69 900	83 900	14.3[a]	3.7	14.3	20	105	$E2$; from Ref. 6
601.1	160	18 550	18 710	0.857	0.25	0.66	1.20	3.3	$M1+E2$
677.4	230	28 000	28 230	0.821	0.19	0.50	0.90	2.3	$M1+E2$
798.9	52.2	13 750	13 800	0.379	0.135	0.33	0.58	1.45	$E2+M1$
809.3	0.60	200	200	0.301	0.133	0.32	0.57	1.43	$E2$
828.9	0.21								
856.9	12.2	7980	7992	0.153	0.120	0.30	0.50	1.25	$E1+M2$
867.9	0.17								
879.8	3.4	518	521	0.666	0.115	0.29	0.47	1.10	$M1$; see text
885.7	0.39	118	118	0.331	0.113	0.28	0.46	1.08	$E2+M1$
933.2	12.8	9510	9523	0.135	0.103	0.25	0.41	0.99	$E1+M2$
942.3	0.83	705	706	0.117	0.099	0.24	0.40	0.95	$E1+M2$
955.8	55.0	10 360	10 410	0.531	0.095	0.23	0.38	0.90	$M1$; see text
963.9	0.14								
1053	0.31								
1065	0.26	318	318	0.082	0.080	0.187	0.295	0.69	$E1$
1077	38.3	18 080	18 120	0.211	0.078	0.185	0.290	0.67	$E2+M1$
1107		87	87						
1120	<1	515	515	<0.194	0.074	0.172	0.268	0.61	$E1$; see text
1158	0.18								
1180	0.57	549	550	0.104	0.067	0.152	0.235	0.53	$E1+M2$; or $E2$
1197	2.9	787	790	0.368	0.066	0.150	0.230	0.52	$M2+E1$
1256	11.7	2720	2732	0.430	0.060	0.130	0.200	0.46	$M2$
1275	0.31	139	139	0.223	0.057	0.128	0.193	0.44	
1319	1.47	378	379	0.389	0.054	0.122	0.182	0.40	$M2$
1333	3.61	928	931	0.389	0.053	0.120	0.180	0.39	$M2$
1351	0.99	402	403	0.246	0.051	0.115	0.170	0.38	
1429	0.66	352	353	0.188	0.047	0.105	0.147	0.34	
1450	2.48	717	719	0.346	0.045	0.102	0.142	0.33	$M2$
1467	0.13								
1542	0.05								
1656	0.10								

[a] Intensities and conversion coefficients are based on an arbitrary intensity of 10^4 for the K-conversion-electron line and on a theoretical $E2$ value of 0.143 for the K-shell conversion coefficient for that particular transition. The $M1$ admixture, based on L-shell ratios, is <1% (Ref. 6).

With this intercomparison the relative intensities of the β^+ components could be converted to percentages of the total number of ^{147}Eu disintegrations, after the decay scheme had been put together (see discussion in final section of the paper).

The average of the three end-point determinations gave 1767±10 keV for the electron-capture decay energy of ^{147}Eu. This value was then used to predict the electron-capture decay energies of ^{151}Tb and ^{143}Pm by means of closed energy cycles. The method consists of constructing an energy-balance cycle from two α- and two β-decay energies. If three of the four pieces of information that constitute a cycle are known, then the fourth can be calculated. Figure 3 shows the two cycles used. The ^{147}Eu and ^{147}Sm α-decay energies were taken from Ref. 12; the ^{151}Tb and ^{151}Gd values were obtained from Refs. 13 and 14, respectively. α-decay energies used in Fig. 3 are total disintegration energies of the bare nuclei. They are equal to the energy in the laboratory system plus the recoil energy plus the orbital electron-screening correction, which is about 20 keV for the rare-earth nuclides. In this manner then the ^{151}Tb and ^{143}Pm electron-capture decay energies were calculated to be 2.596±0.045 and 1.068±0.030 MeV, respectively.

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Gamma-Ray Intensities and K-Conversion Coefficients

The ^{147}Eu γ-ray spectrum (source-to-counter distance was 2.5 cm) that was obtained with the 9.5-cm^3 coaxial Ge(Li) detector is shown in Fig. 4. The source used in this measurement was produced by milking the europium daughters from the parent gadolinium fraction after ^{147}Gd had decayed. Only the portion above 600 keV is displayed. Aside from the 76.1-, 121.3-, and 197.4-keV transitions[6] no γ rays were found below 600 keV that could be assigned to ^{147}Eu decay. As mentioned in the section on experimental procedure, the source contained a small amount of the gadolinium fraction. Assignment of the observed γ rays to various nuclides present was made on the basis of half-lives, γ-ray spectra obtained with mass-separated sources, and available conversion-electron spectra. When the measurement shown in Fig. 4 was made,

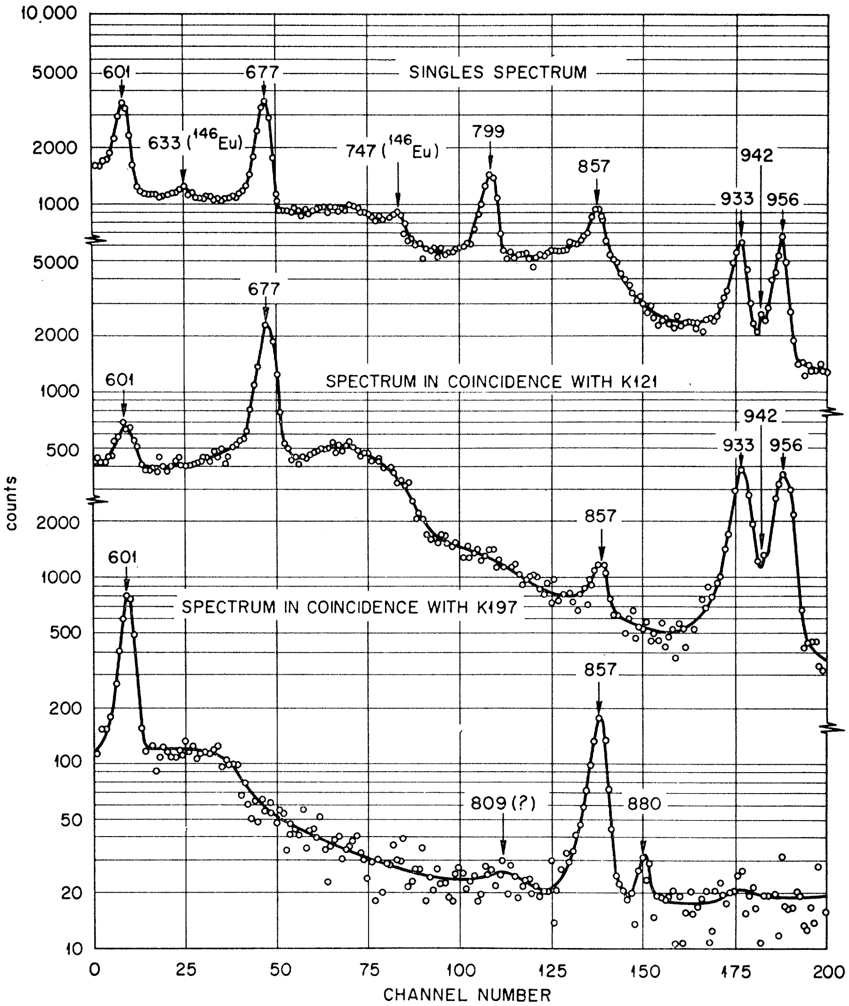

FIG. 5. Gamma-ray spectra measured in coincidence with K-shell conversion electrons of the 121.3- and 197.4-keV transitions. A singles spectrum is included for comparison. A flat 2.1-cm^3 Ge(Li) detector was used to obtain the γ-ray spectra.

^{149}Gd had decayed. With the exception of the ^{40}K 1.46-MeV γ ray, only γ rays of ^{146}Eu (present in equilibrium with ^{146}Gd) were observed in addition to those of ^{147}Eu; ^{146}Gd and ^{149}Eu do not emit γ rays above 600 keV in energy.

Table I summarizes ^{147}Eu γ ray and conversion-electron data. Energies and electron intensities were taken mainly from the work of Adam *et al.*[7] Because the twofold focusing spectrometer that they used is unsuitable for the detection of low-energy transitions, energies and intensities listed for the 76.1-, 121.3-, and 197.4-keV transitions are from the work of Avotina *et al.*[6] The upper limit for the K-conversion-electron intensity of the 1120-keV γ-ray observed by McNulty *et al.*[5] is also taken from Ref. 6. Adam *et al.*[7] did not observe this particular electron line and did not list an upper limit for its intensity. Gamma-ray intensities given in Table I were measured in this investigation. Of the 29 transitions above 600 keV reported in Ref. 7, 21 could be identified in the γ-ray spectrum. In addition, the 1120-keV γ ray was observed as well as a 1107-keV γ ray that has not been reported previously.

The intensities and internal conversion coefficients listed in Table I are based on an arbitrary number of 10^4 for the 197.4 K-conversion-electron intensity and on a theoretical $E2$ value of 0.143 for the K-conversion coefficient for that particular transition. Accurate multipole-order assignments based on L-subshell ratios have been made[6] for the three low-energy transitions; the $M1$ admixture in the 197.4-keV transition is $<1\%$. Experimental K-shell conversion coefficients are compared in Table I with theoretical values for $E1$, $E2$, $M1$, and $M2$ transitions. Probable multipole order assignments made on the basis of this comparison are listed in the extreme right-hand column. The assignments take into account the results obtained from coincidence measurements, i.e., transitions proceeding from the same state to the first three ^{147}Sm levels (all of negative parity[1–6]) must have compatible multipole orders. Thus the 879.8- and 955.8-keV transitions that deexcite a level at 1077 keV are assigned $M1$ multipole orders; the 1077-keV transition to the ground state is known to be predominantly $E2$ in character not only from the present investigation but also from previous studies.[5,6] Based on

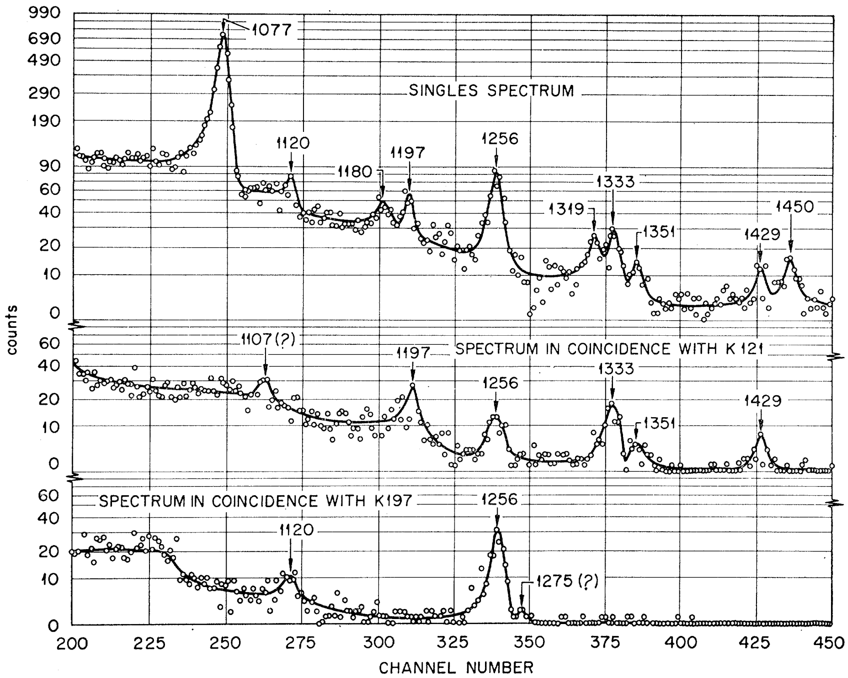

FIG. 6. Gamma-ray spectra measured in coincidence with K-shell conversion electrons of the 121.3- and 197.4-keV transitions. A singles spectrum is included for comparison. A flat 2.1-cm^3 Ge(Li) detector was used to obtain the γ-ray spectra.

similar arguments the upper limit for the conversion coefficient of the 1120-keV transition is taken to mean that the transition's multipole order is $E1$ and not $E2$. It must be remembered, however, that large errors could exist in some of the experimental K-shell conversion coefficients. Most of the relative γ-ray intensities are estimated to be reliable to within ~15%. Additional errors, difficult to assess, are also present in those instances where judgment played a large role in the analysis of peak shapes of some weak γ rays. The electron intensities published in Ref. 7 were not accompanied by experimental uncertainties. To illustrate the size of errors that might be involved, however, electron data for transitions reported in both Refs. 6 and 7 are compared in Table II. While transition energies agree well, intensities in some cases disagree as much as a factor of 3. The results of Ref. 7 were used in this study because: (1) Many transitions unobserved previously are reported in that work; (2) the low-background β-ray spectrometer used in the investigation is expected to give better intensities for weak electron lines; and (3) their results agree within 30% with those of Ref. 6 for the stronger transitions.

TABLE II. Comparison of electron data from Refs. 6 and 7.

Ref. 7		Ref. 6	
Transition energy (keV)	K-conversion-electron intensity[a]	Transition energy (keV)	K-conversion-electron intensity[a]
601.1±0.5	159	601.5±0.3	200±20
677.4±0.5	230	677.5±0.3	230±20
798.9±0.5	52.2	798.7±0.4	47± 5
856.9±0.7	12.2	857.3±0.5	10± 2
879.8±0.7	3.4	880.3±0.5	3± 1
933.2±0.7	12.8	933.2±0.5	7± 2
955.8±0.8	55.0	955.8±0.4	42± 4
1077.2±0.9	38.3	1077.1±0.4	50± 5
1196.6±1.0	2.9	1196.9±0.7	~1
1255.5±1.0	11.7	1256.1±0.7	4± 1
1333.3±1.1	3.6	1331.7±0.7	2± 1

[a] Normalized to an intensity of 10^4 for the K-shell conversion-electron line of the 197.4-keV transition.

e-γ Coincidence Measurements

Only the K-conversion electron lines of the 121.3- and 197.4-keV transitions were intense enough for e-γ coincidence measurements with a Ge(Li) crystal as the γ-ray detector. The coincidence spectra are shown in Figs. 5 and 6; a singles spectrum is included for comparison. The following γ rays can be noted in coincidence with:

(1) K 197.4-keV,—601.1, 856.9, 879.8, 1120, 1256, and possibly 809.3 and 1275 keV;

(2) K 121.3-keV,—601.1, 677.4, 856.9, 933.2, 955.8, 1197, 1256, 1333, 1351, 1429, and possibly 942.3 and 1107 keV.

About 10% of the de-excitation of the 197.4-keV state proceeds via the 76.1-keV transition to the 121.3-keV level. Therefore, the stronger γ rays coincident with the 197.4-keV transition, i.e., 601.1, 856.9, 1256 keV, also appear as coincidences in the 121.3-keV spectrum. Transitions that apparently proceed directly to ground are: 798.9, 1077, 1180, 1319, and 1450 keV.

While the bulk of coincidence data used in the unraveling of the decay scheme came from the above-described measurements, confirmatory results were obtained from e-γ experiments with a 3 in.×3 in. NaI crystal as the γ-ray detector. Five of the transitions above 600 keV had K-conversion electron lines sufficiently intense to permit coincidence measurements. Low-energy γ-ray spectra revealed the following information:

(1) the 121.3-keV γ ray was observed in coincidence with K 677.4 and K 955.8;

(2) the 197.4-keV γ ray was seen when gating with K 601.1; and

(3) only x rays were observed in coincidence with K 798.9 and K 1077.

As in the case of the Ge(Li) spectra, no new γ rays below 600 keV were seen. If there are cascading transitions connecting the excited states above 197.4 keV, they must be weak.

Figure 7 shows high-energy portions of NaI γ-ray spectra coincident with K 121.3, K 197.4, and K 677.4. The two upper spectra confirm the over-all picture seen in Figs. 5 and 6. The bottom spectrum indicates a 750-keV γ ray together with a possible peak at ~500 keV in coincidence with K 677.4. The 750-keV γ ray could be a transition from the state at 1550 keV [1429+121 keV, see the Ge(Li) results above] to the 789.9-keV level. However, neither the singles nor the coincident Ge(Li) spectra nor the conversion-electron data reveal a transition of this energy. The probable explanation is that the spectrum represents coincidences with the L-conversion lines of the 633-keV doublet transition (seen in Fig. 4) in ^{146}Eu decay.[15,16] The two transitions populate the 747-keV 2^+ ^{146}Sm first excited state. They are in coincidence not only with the 747-keV transition (also observed in Fig. 4) but also with a 3% positron branch which feeds the close-lying doublet at 1380 keV. The coincident positrons would account for the small peak at 500 keV. The L lines of the 633-keV doublet are separated by ~5 keV from the K line of the 677.4-keV transition while the spectrometer resolution, with all 6 gaps open, is not better than ~1%. Since the ^{147}Eu decay energy is 1.767 MeV, it is possible that some of the weaker transitions in Table I below a MeV in energy could populate the 789.9-keV state. The experimental evidence, however, speaks against this possibility since the bottom spectrum in Fig. 7 represents a 24-h count.

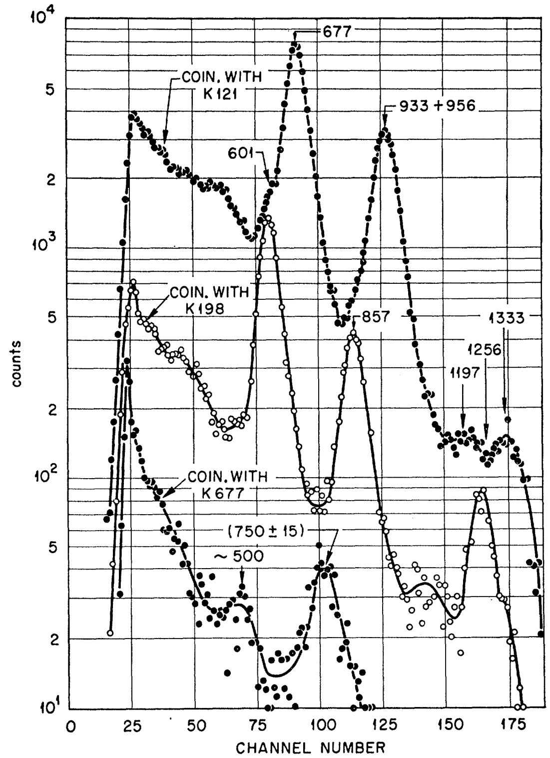

FIG. 7. Gamma-ray (NaI) spectra obtained in coincidence with K-shell conversion electrons of the 121.3-, 197.4-, and 677.4-keV transitions.

PROPOSED DECAY SCHEME AND DISCUSSION

Decay Scheme

The proposed decay scheme of ^{147}Eu (Fig. 8) is based on results obtained from e-γ coincidence measurements and on accurate determination of transition energies.

A large amount of information has been accumulated[1–6] on the properties of the ground and first two excited states of ^{147}Sm. The ground-state spin of ^{147}Sm has been measured to be $\frac{7}{2}$. Since it is likely that the state, on the basis of the shell model, would be represented by the orbital of the odd 85th $f_{7/2}$ neutron, the parity is inferred to be negative. The spins and parities of the 121.3- and 197.4-keV states are then $\frac{5}{2}^-$ and $\frac{3}{2}^-$, if the multipole orders of the three low-energy transitions are taken into account.[6] In the following discussion we consider each of the remaining levels shown in Fig. 8.

798.9 keV. This state is well established not only from the present coincidence measurements but also from previous investigations. The parity of the state must be negative because of the multipole orders of the 601.1-, 677.4-, and 798.9-keV transitions. The spin assignment as deduced from angular correlation experiments[5] and transition multipolarities is either $\frac{3}{2}$ or $\frac{5}{2}$, with $\frac{3}{2}$ being favored.[6] The predominant quadrupole nature of the 798.9-keV transition (Table I) also indicates a $\frac{3}{2}$ spin.

1007 keV. A new level at 1007 keV is tentatively proposed because of an indication (Fig. 5) that the 809.3-keV γ ray may be in coincidence with K 197.4. Supporting evidence is found in the agreement between the following two energy sums: (a) 809.3+197.4=1006.7 ±0.8 keV, and (b) 885.7+121.3=1007.0±0.8 keV. From K-conversion coefficients it appears that the

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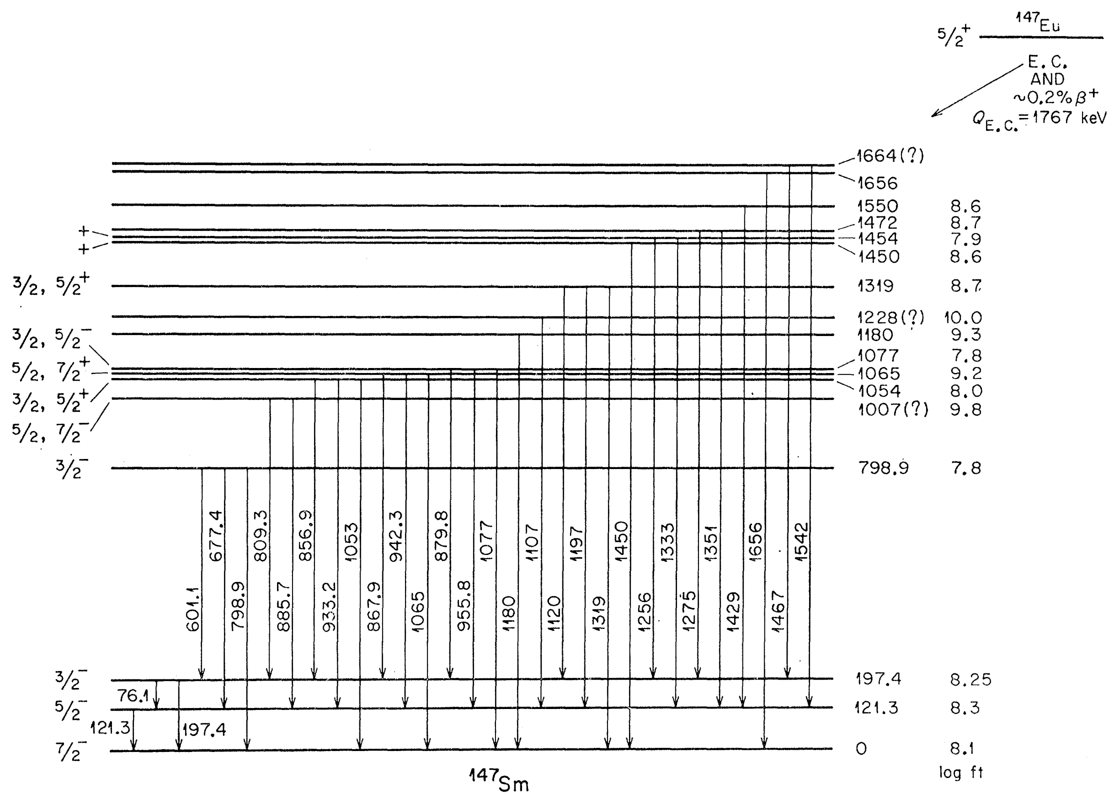

FIG. 8. Proposed ^{147}Eu decay scheme.

809.3- and 885.7-keV transitions are $E2$ and $E2+M1$ in character. If these multipole orders are correct, then the spin assignment of this state would be $\frac{5}{2}^-$ or $\frac{7}{2}^-$.

1054 keV. This level is presumably equivalent to the one reported by McNulty *et al.*[5] at 1060 keV. Their proposed spin assignments $\frac{3}{2}^+$ or $\frac{5}{2}^+$ were made on the basis of the predominant $E1$ character of the transition that proceeds to the 197.4-keV level. Avotina *et al.*[6] were, in addition, able to observe the transition to the first-excited state. The transition to the ground state has now also been observed.[7] Based on conversion coefficients measured in this investigation we propose a spin assignment of $\frac{3}{2}^+$ or $\frac{5}{2}^+$.

1065 keV. A new level at 1065 keV is established. There is an apparent coincidence between K 121.3 keV and the 942.3-keV γ ray (Fig. 5). Also, the energy of the transition to the ground-state 1064.6 keV[7] agrees with the two energy sums: (a) $942.3+121.3=1063.6\pm0.9$ keV, and (b) $867.9+197.4=1065.3\pm0.8$ keV. From the multipolarities of the 942.3- and 1065-keV transitions, the parity of the state seems to be positive, and the possible spins either $\frac{5}{2}$ or $\frac{7}{2}$.

1077 keV. This level has been established previously.[5,6] The proposed spin assignments have been $\frac{5}{2}$, $\frac{7}{2}$, $\frac{9}{2}^-$ (Ref. 5) and $\frac{7}{2}^-$ (Ref. 6). From these two investigations and the present one the 1077-keV transition appears to be an $E2+M1$ admixture. The e-γ measurements show that the 879.8 and 955.8 keV transitions deexcite this level. Therefore, in Table I both transitions are assigned $M1$ multipole orders, even though the conversion coefficients are $\sim35\%$ larger than theoretical values. If the electron intensities of Avotina *et al.*[6] are used, then the experimental coefficient for the 955.8-keV transition almost coincides with the theoretical $M1$ value, while that of the 879.8-keV transition is $\sim20\%$ too large. The spin of $\frac{7}{2}$ is then eliminated if the two transitions are dipole in character. Our proposed assignment is therefore $\frac{3}{2}^-$ or $\frac{5}{2}^-$.

1180 keV. This new level is proposed because the 1180-keV γ ray while prominent in singles spectra, is not seen in the two coincidence spectra in Fig. 6. While the transition seems to be of $E1+M2$ character, an $E2$ multipolarity is not excluded. No spin assignment is proposed.

1228 keV. A new level at 1228 keV is tentatively proposed. The 1107-keV γ ray appears to be in coincidence with K 121.3 (Fig. 5). A conversion electron corresponding to this transition has not been observed.

1319 keV. This level has been previously reported.[5,6] Our e-γ measurements (Fig. 6) support its existence, since the 1197-keV γ ray is in coincidence with K 121.3 and there is a good indication of a peak at 1120 keV in coincidence with K 197.4. No spin assignment has been made previously. On the basis of the multipole orders

TABLE III. Percentages of direct electron-capture population and corresponding log ft values.

Level (keV)	Direct E. C. population[a]	Percentage	Decay energy (keV)	log ft
0	98 610	29.3	1767	8.1
121.3	60 456	17.9	1646	8.3
197.4	61 381	18.2	1570	8.25
798.9	60 740	18.0	968	7.8
1007	320	0.095	760	9.8
1054	17 505	5.2	713	8.0
1065	1024	0.30	702	9.2
1077	29 050	8.6	690	7.8
1180	550	0.16	587	9.3
1228	87	0.026	539	10.0
1319	1684	0.50	448	8.7
1450	720	0.21	317	8.6
1454	3661	1.1	313	7.9
1472	542	0.16	295	8.7
1550	353	0.10	217	8.6

[a] Based on an intensity of 10^4 for the K-shell conversion electron line of the 197.4-keV transition.

TABLE IV. Experimental and theoretical (K-capture/β^+) ratios.

Transition	Transition energy (keV)	Theoretical (K/β^+) ratio; allowed transition	Experimental (K/β^+) ratio	Ratio of experimental to theoretical value
$\frac{5}{2}^+ \to \frac{7}{2}^-$	745±10	53± 2.5	258±100	4.9±2.0
$\frac{5}{2}^+ \to \frac{5}{2}^-$	624±10	104± 6	257±100	2.5±1.2
$\frac{5}{2}^+ \to \frac{3}{2}^-$	548±10	171±12	302±150	1.8±0.9

listed in Table I for the three de-excitation transitions, we propose a spin assignment of $\frac{3}{2}^+$ or $\frac{5}{2}^+$.

1450 and 1454 keV. A single level has been proposed earlier at 1448 keV[5] and, more accurately, at 1453 keV.[6] Our data indicate a doublet at 1450 and 1454 keV. The e-γ spectra (Fig. 6) show that the 1256-keV γ ray is in coincidence with K 197.4 and the 1333-keV γ ray with K 121.3. The 1450-keV γ ray, prominent in the singles spectrum, does not appear in the coincidence spectra; therefore, it is assumed to proceed to ground. The energy of this transition from conversion-electron studies[7] is 1450.0±1.2 keV. By using energies from Ref. 6, the following two sums are obtained:

(1) (121.3±0.1)+(1331.7±0.7)=(1453.0±0.8),
(2) (197.4±0.1)+(1256.1±0.7)=(1453.5±0.8).

If the values in Ref. 7 are used for the two high-energy transitions, then these sums are obtained:

(1) (121.3±0.1)+(1333.3±1.1)=(1454.6±1.2),
(2) (197.4±0.1)+(1255.5±1.0)=(1452.9±1.1).

The 1450.0±1.2-keV value is outside the error limits of all four sums. By using peak positions of 7 high-energy, intense ^{147}Eu γ rays and by assigning their energies from conversion electron data,[6,7] our Ge(Li) spectra gave 1450.1, 1332.8, and 1257.2 keV for the three transition energies. The corresponding level energies are then 1450.1, 1454.1, and 1454.6 keV. An unlikely error of 2 channels in peak assignments would have to be assumed if the discrepancy in energy is to be removed. Our proposal is that there are two states, one at 1450 and the other at 1454 keV. From the $M2$ character of all three transitions, the states presumably have positive parity. A wide range of spins is possible for the two states.

1472 keV. This new level is proposed because the e-γ measurements indicate the 1351-keV γ ray in coincidence with K 121.3 and the 1275-keV γ ray with K 197.4. Multipole order assignments for the two transitions are uncertain, and no spins are proposed for this level.

1550 keV. A level at 1546 keV has been previously reported.[5] Figure 6 shows the 1429-keV γ ray in coincidence with K 121.3 keV; this result establishes a level at 1550 keV. The multipole order of the 1429-keV transition is uncertain and no spin assignment is proposed for the 1550-keV level.

1656 keV. If a 1656-keV transition does indeed exist[7] then a new level at the same energy is established. The conclusion follows from the fact that the ^{147}Eu decay energy is 1767 keV, and the transition, therefore, cannot represent a deexcitation to any ^{147}Sm excited state. Since the γ ray was not observed in our Ge(Li) spectra, neither a transition multipole order nor a level spin assignment can be made.

1664 keV. This new level is tentatively based on the following two energy sums derived from conversion-electron data[7]:

(1) (1542.0±1.2)+(121.3±0.1)=(1663.3±1.3),
(2) (1467.1±1.2)+(197.4±0.1)=(1664.5±1.3).

The corresponding γ rays were not observed and nothing can be said about multipole orders and spin assignment.

The decay scheme shown in Fig. 8 incorporates all but three of the transitions listed in Table I, i.e., 828.9, 963.9, and 1158 keV. There is a possibility that the 1158-keV transition proceeds to the ground state while the 963.9-keV transition proceeds from the same state to the 197.4-keV level. However, the sum, 197.4+963.9 =1161.3±0.9 keV, does not agree with 1158.2±0.9 keV.

Discussion

The intensities in Table I were used to determine the amount of direct electron-capture decay to each ^{147}Sm level. The number of decays proceeding directly to the ground state was computed on the basis of the K x-ray peak intensity reported by McNulty *et al.*[5] The percentages of electron-capture decay, together with the corresponding log ft values, are summarized in Table III. Log ft values were calculated by taking a decay energy of 1767 keV and by using the curves of Moskowski[17] in a slightly modified version.[18]

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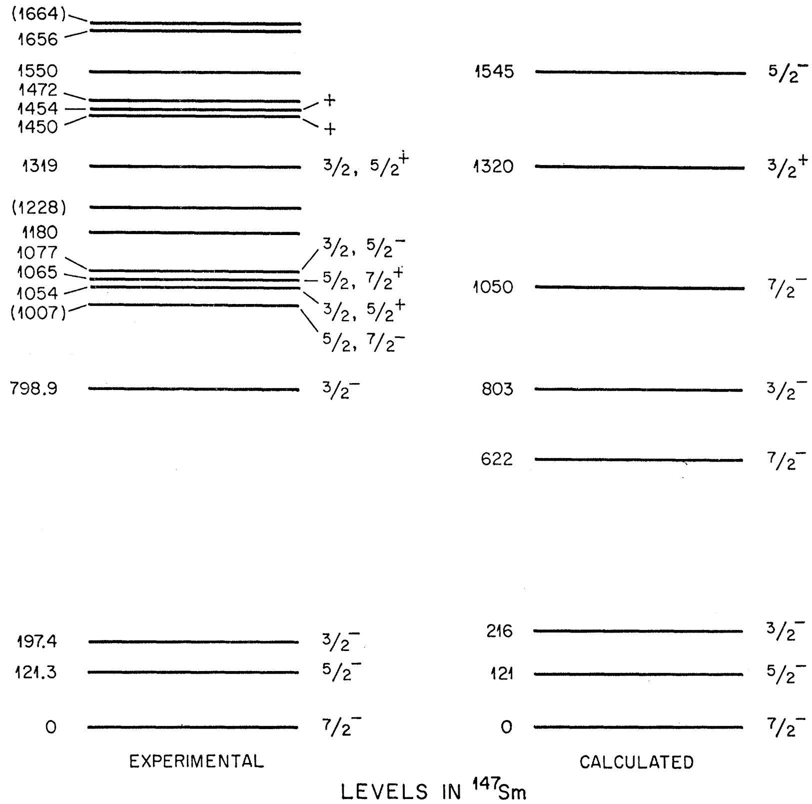

FIG. 9. Comparison of the proposed ^{147}Sm level scheme with that calculated by Schima.

From the information given in Tables I and III, it was found that $N_{K\,197.4}$ was equal to 2.97% of all ^{147}Eu decays. The relative intensities of the three β^+ components (presented in an earlier section of this paper) were then converted into percent of decay:

$$N_{\beta^+_0}=(0.097\pm0.020)\%,\quad N_{\beta^+_1}=(0.060\pm0.012)\%,$$

and

$$N_{\beta^+_2}=(0.051\pm0.015)\%.$$

By using the results in Table III the ratio $(N_{K\text{-capture}}/N_{\beta^+})$ was calculated for all three transitions. These ratios are shown in Table IV, where they are compared with theoretical predictions for allowed transitions. Theoretical ratios were obtained from the calculations of Zweifel[19] as presented in Ref. 18. The three transitions under consideration are first forbidden. According to Brysk and Rose,[20] however, K-capture/β^+ ratios should be approximately the same in allowed and first-forbidden transitions. Experimentally, the indication is that deviations from allowed values are not uncommon.[18,21] Deviations as high as 50% have been noted.[21] The ratios measured in this investigation appear to be in disagreement with allowed values. The experimental errors are large, however, and it is only for the transition proceeding to ground that disagreement is outside uncertainty limits.

On the basis of quadrupole moment measurements, ^{147}Sm has been suggested[1,22] to have a small negative deformation, i.e., $\delta=-0.02$ or -0.03. Lifetime measurements[23] of the 121.3- and 197.4-keV levels and transition intensities and multipole orders[1,6] indicate that $E2$ transition probabilities are enhanced for transitions proceeding from both levels. This enhancement has been taken[5] as an indication of the collective nature of the two excited states. Inelastic proton scattering data[24] show, however, that the 121.3- and 197.4-keV levels are no more intensely excited than some of the higher levels. This is especially curious for the 197.4-keV state which could be Coulomb excited; the evidence has been interpreted[24] as indicating the noncollective character of these two states.

Schima[25] has attempted an interpretation of the levels and lower energy transitions in ^{147}Sm based on the method of Baranger[26] and Yoshida.[27] The calculation utilized quasiparticle states to account for short-range

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forces and zero, one, and two phonon states for collective effects. In this way the first eight levels and the transition probabilities for the deexcitation of the first two-excited states were predicted. In the case of transition probabilities the agreement, though not exact, was improved[5] over the theoretical single-particle values. The eight calculated states are compared in Fig. 9 with the decay scheme proposed in this investigation. While there is a reasonable amount of agreement, three discrepancies are apparent. First, more levels are seen experimentally than are predicted by the calculation. Second, the level at 622 keV is not observed in ^{147}Eu decay. This level may correspond to the one observed at 708 keV in inelastic proton scattering.[24] Also, Nathan and Popov[28] have observed what is probably the same level at 730±15 keV by means of Coulomb excitation. The third point of disagreement involves the calculated level ($\frac{7}{2}^-$) at 1050 keV which apparently corresponds to the state observed experimentally at 1077 keV. Our multipole-order data seem to rule out $\frac{7}{2}^-$ as the assignment; previous investigators,[5,6] however, favor a $\frac{7}{2}$ spin for the state. The conclusion in the present investigation is based on the predominant $M1$ character of the 879.8-keV transition (see discussion in the subsection concerned with the level scheme). An error in either the K-conversion electron or the γ-ray intensity could account for the disagreement with the calculated spin value.

Twenty-one ^{147}Sm levels have been observed in inelastic proton scattering.[24] The 121.3-, 197.4-, and 798.9-keV levels reported in this investigation were also seen in the scattering experiment. If the two experimental level schemes are compared then in the energy range above 800 keV only the levels at 1054 keV (decay scheme) and 1053 keV (p,p') agree well in energy. The measured energies for the same $\frac{3}{2}^-$ level at ~800 keV disagree, however, by 5 keV. It is difficult therefore to say whether some of the levels observed in (p,p') scattering and in ^{147}Eu decay are actually different or only appear to be so because of disagreement in energy assignments. It should be noted that the two most intense inelastic peaks, 708 and 1097 keV,[24] are apparently not populated either in direct ^{147}Eu decay or in subsequent γ-ray cascades.

In conclusion we would like to mention an interesting proposal put forth recently by Berlovich[22,29] that may have a bearing on the decay of ^{147}Eu. His contention is that in the transition region odd-proton nuclei have small equilibrium deformations while odd-neutron nuclei are spherical. Beta and electron-capture transitions between odd-proton and neighboring odd-neutron nuclei are characterized by large log ft values.[22,29] According to Berlovich these values may be accounted for by changes in the shapes of nuclei connected by these transitions. Log ft values for such transitions are consistently higher[22,29] than the average values for similar transitions (with regard to forbiddenness) that connect nuclei known to be both either spherical or deformed.

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