Energy levels and transition probabilities in the neutron-rich lanthanide nucleus ^{156}Sm

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The decay of ^{156}Pm has been studied resulting in the first detailed information on the excited states of ^{156}Sm. About 25 levels were found, of which two were γ-decaying isomers. The expected low-lying quadrupole vibrational levels could not be identified. The observed decay rates for β and γ transitions have enabled the classification of some levels, including the β-decaying ground state of ^{156}Pm, in terms of specific two-quasiparticle states. The total beta-decay energy of ^{156}Pm was obtained as 5.155(35) MeV.

I. INTRODUCTION

The nuclei in regions transitional to the areas of strongly deformed nuclear shapes have long been used for tests of the validity of nuclear models. One such region of particular interest comprises the light neutron-rich lanthanides, which apart from being transitional to quadrupole deformation, also have recently been suggested[1,2] to possess reflection asymmetric shapes at low excitation energies. The neutron-rich lanthanides are also of interest for their ground state properties, such as binding energies and β-decay half-lives, which are necessary parameters for detailed studies of the nucleosynthesis.

Mainly due to experimental difficulties, these nuclei are very poorly known a few steps out from the line of beta stability. They can at present only be realistically produced using fission processes, and the subsequent separation of the short-lived products has proved to be particularly difficult. The chemical properties of the lanthanides make fast on-line chemistry complicated. The other commonly used method of isotope separation on line (ISOL) is hampered by the diffusion and desorption properties of these elements.

We have previously overcome the slow desorption of the lanthanides by extraction of molecular ions from a fission target[3] at moderate temperature ($\approx$1500 °C) coupled to the OSIRIS ISOL facility.[4,5] The feasibility of detailed spectroscopy of short-lived activities was demonstrated.[6] Since then a different approach for the separation of elemental ions has been implemented, using a high temperature to reduce the release time.[7] The production of many lanthanide nuclei is satisfactory using this method.

As a first step in the establishment of systematic knowledge on the level properties of neutron-rich even-even nuclei in this region, we present here the first detailed spectroscopic information on the structure of ^{156}Sm, as obtained in the decay of ^{156}Pm. We also give an accurate value for the total decay energy of the latter nucleus and identify the most likely microscopic composition of its ground state.

The identification of the neutron-rich isotope ^{156}Pm produced in fission of ^{235}U and ^{252}Cf has been reported by several independent investigators.[8–11] The half-life was given[10] as 26.7(1) s. The energies and relative intensities of some strong γ rays associated with the decay to ^{156}Sm were also reported by these authors.

II. EXPERIMENTS

A. Source production

The ^{156}Pm activity was obtained as a mass separated fission product from thermal neutron induced fission using the OSIRIS ISOL facility at Studsvik. About 1 g of ^{235}U, dispersed in a graphite matrix, served as a fission target which comprised a part of the combined target and ion-source system of the facility.

Studies of ^{235}U fission products with $A > 150$ using ISOL techniques are complicated since trace amounts of molecular ions involving fission products from the heavy mass peak contaminate the beams. The large difference in fission yields between the nuclides near the center of this peak and the activities on the high-A shoulder can lead to that the contaminating activities dominate the spectra for some isobars.

There are two simple ways to minimize this problem. One involves identification of the impurities followed by separate measurements of the contaminant nuclides. Comparison between these spectra and those from measurements at the pertinent lanthanide isobaric masses makes it possible to subtract the contribution from the impurities. Both gamma-ray energies and/or intensities and differences in half-lives between the different nuclides involved provide the necessary information.

The other consists in finding the most favorable operating conditions for the target and ion source. Temperature and ionization mode are important factors controlling the relative amounts of molecular and elemental ions that are produced inside the ion source. At the OSIRIS facility[4,5] the ion source[7] can be run at high temperatures ($>$2500 °C) and in two different ionization modes. High temperatures are necessary for fast release of some elements including the lanthanides.

A high temperature also favors the production of undesirable molecular species involving carbon atoms from

the graphite in the target. The ratio of molecular versus elemental ions at a certain isobaric mass is dependent on the temperature and on the molecular species present. A series of preparatory experiments showed that some contaminant molecular ion species, including the monovalent dicarbides of some high yield fission products, could be very strongly suppressed by selecting the thermoionization mode of the ion source. This mode, which favors elements having a low ionization potential (see, e.g., Ref. 12) resulted in beams of relatively pure isotopes of most lanthanide fission products at target temperatures in excess of 2400 °C.

Samples are collected by allowing the beam from the separator to hit a moveable Al-covered plastic tape. The whole tape transport system is contained in a vacuum tank attached to the end of the beam pipe, and provides fast transport of the samples to any of several positions where detectors can be placed. Old samples are removed and can be efficiently screened. The geometry of the detector positions can be configured to allow the simultaneous use of two or more different detectors, e.g., for coincidence measurements.

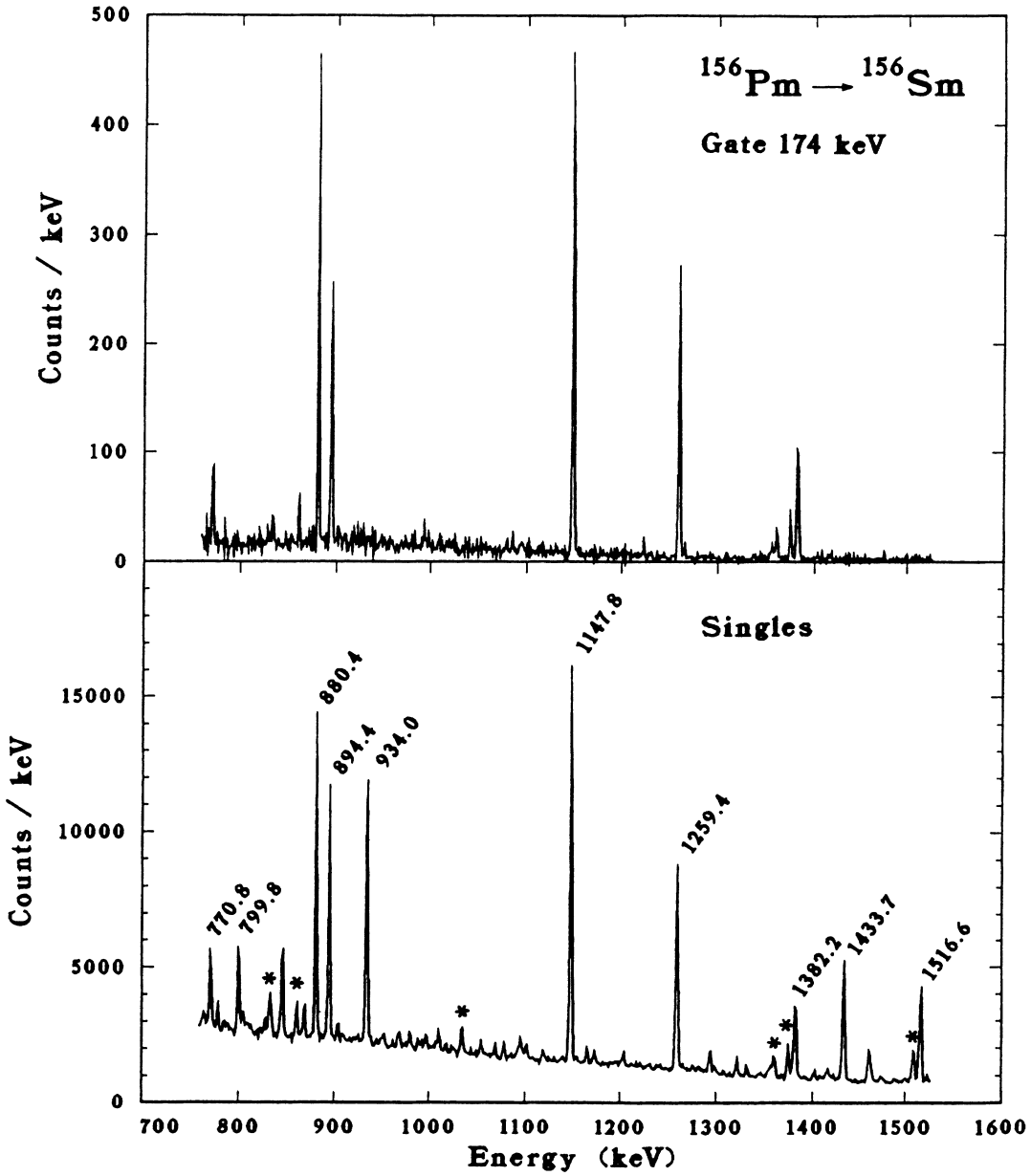

FIG. 1. The bottom panel shows a γ-ray spectrum of the $A=156$ isobars representing the first group of a multispectrum scaling experiment using a group time of 30 s following a source collection of 60 s. All strong γ-rays labeled by energies or by * follow the decay of ^{156}Pm. See also Table I. The top panel gives a projected spectrum from one of the coaxial detectors used in the $\gamma\gamma$-coincidence experiment, obtained by gating on the photo peak of the $4^+ \rightarrow 2^+$ transition in the LEP detector spectrum.

TABLE I. Gamma rays observed to follow the decay of ^{156}Pm to ^{156}Sm. $T_{1/2}=27$ s.

	Gamma-ray energy[a] (keV)		Intensity[a,b] (%/d)		Coincidence relations[c]
$E2$	75.88	5	12.5	7	174,728,800,934,1034,1434,2407,2443,2450
$M1$	117.42	5	13.8	7	223,518,685,750,827,880,1148
$E2$	173.75	5	52.0	20	76,267,626,771,860,894,1148,1259,1360, 1417,1474,2270,2276,2360,2367
	223.31	10	1.0	1	117
$E2$	267.32	5	13.3	7	174,503,880,992
	370.94	10	0.6	1	894
	376.75	10	0.9	1	117,503,771
	380.4	4	0.6	1	626,800
	494.4	4	0.3	1	503,771
	503.37	20	0.3	1	267,377,494
	518.4	4	0.9	1	117
	524.9	4	1.0	1	1259,1434
	625.27	20[d]	0.6	1	934
	626.37	20	0.6	1	174,380
	684.65	10	2.1	1	117
	690.90	10	5.6	3	992,1259,1434
	727.6	3	0.9	2	76
	750.26	10	2.1	2	117
	756.51	10	2.1	2	1259,1434
	770.77	10	2.6	3	174,377,494
	799.70	10	3.6	4	76,380
	803.9	3	1.1	2	
	827.03	10	0.6	1	117
	832.08	20	1.2	2	1259,1434
	860.26	20	1.1	1	174
	880.39	10	10.4	5	117,267
	894.35	10	8.4	4	174,371,1375,1382,1556
	934.00	10	12.3	6	76,625,1509,1517
	992.0	10	0.3	1	267,691
	1034.25	10	1.4	1	76
	1147.84	10	20.5	1	117,174
	1259.44	10	12.6	6	174,525,691,757,832
	1360.56	10	1.8	2	174
	1374.91	10	2.3	2	894
	1382.24	10	5.7	3	894
	1416.6	5[d]	0.6	1	174
	1433.70	10	8.4	4	76,524,691,757,832
	1473.6	4[d]	0.5	1	174
	1509.12	20	2.8	3	934
	1516.56	10	7.4	4	934
	1555.6	5	0.4	1	894
	2269.9	4	0.7	1	174
	2276.18	20	0.7	1	174
	2360.0	3	1.0	1	174
	2366.78	20	0.8	1	174
	2406.7	3	1.0	1	76
	2443.34	20	2.4	2	76
	2450.17	10	2.7	3	76

[a]Uncertainties are given in units of the last digit, e.g., 75.88 5 means 75.88±0.05. Transition multipolarities are from the conversion electron measurements.

[b]Intensities are given in percent per decay, as deduced from the decay scheme.

[c]All obviously indirect coincidences are omitted.

[d]Not placed in the level scheme.

B. Measurements

Singles γ-ray spectra were recorded using both a large coaxial HPGe detector and a planar low-energy-photon (LEP) detector. All singles measurements were made using a multispectrum scaling (MSS) technique implying several consecutive recordings for each collected source. More than 40 γ rays due to ^{156}Pm, with energies up to about 2.5 MeV, were identified in this way; see Fig. 1 and Table I. The MSS data provided easy identification of most of the impurity and background γ rays.

An additional dual MSS experiment was made using the LEP spectrometer and a high resolution ion implanted Si detector to simultaneously measure low energy γ rays and conversion electrons. The Si detector, operated slightly below room temperature, was introduced into the vacuum of the tape transport system facing the collected source. The geometry of this detector system was calibrated using transitions of known multipolarities in the decay of ^{124}In. The main reason for this measurement was to determine the multipolarity of the 117.42 keV γ ray, which was found to be $M1$. The conversion electron data are not tabulated separately. Instead, the multipolarities deduced for transitions in ^{156}Sm are given in Table I. A portion of an electron spectrum is shown in Fig. 2.

Two coaxial Ge detectors and the LEP detector, all equipped with β absorbers of Al, were used for a measurement of $\gamma\gamma$ coincidences. The tape was in this case moved continuously in order to remove the strong long-lived activities of the $A=156$ mass chain. The singles counting rate was almost entirely due to ^{156}Pm and was kept at about 2.5×10^3 counts/s in each of the coaxial detectors. The low rate resulted in a very small fraction of accidental coincidences. The data were collected as two-parameter events between the two coaxial detectors or between either of these and the LEP spectrometer. Some 10^7 events were stored on a DC600 cassette using a PC based multiparameter-analysis (MPA) system. An example of projected data between the LEP and one of the coaxial detectors is shown in Fig. 1.

A search for γ rays depopulating long-lived levels was made in a $\beta\gamma(t)$ experiment using a small plastic scintillator to furnish start pulses (beta events) and either a coaxial detector or the LEP detector to provide stop pulses to a time-to-analog converter (TAC). A set of γ rays showing a common half-life of 185(7) ns were identified in this way. This half-life (see Fig. 3) could be ascribed to the level at 1397.4 keV. It should be remarked that Clark *et al.*[13] reported the existence of a 160(40) ns isomeric level in ^{156}Sm as a result of their studies of products from fission of ^{252}Cf. These authors were, however, not able to identify the isomeric level.

We found this long-lived state to be populated by a strong transition of 117.42 keV, which showed a delay of a few ns in the time spectra recorded with the LEP detector. To better determine this latter life time we used a triple coincidence system consisting of a plastic scintillator for β particles to furnish start pulses to two different

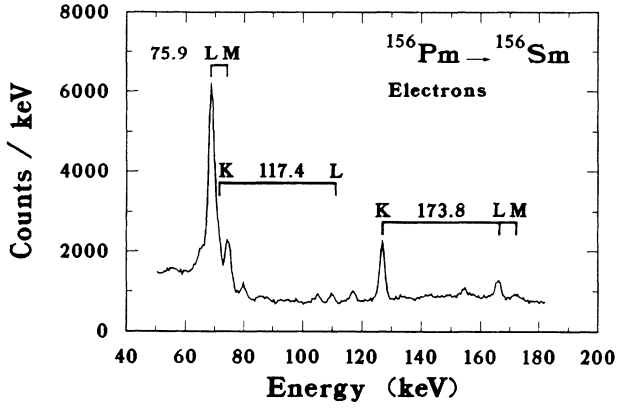

FIG. 2. A part of an electron spectrum recorded as the first group of a multispectrum scaling experiment on the $A=156$ isobars. The K-shell electron line of the 117.42 keV transition is seen as a marked shoulder on the strong L-shell line of the $2^+\rightarrow0^+$ transition in ^{156}Sm. Some of the weaker lines are due to the decay of ^{156}Sm or of impurities, as was found by observing the decay curves of the individual lines. The total time used for this measurement was somewhat less than two hours.

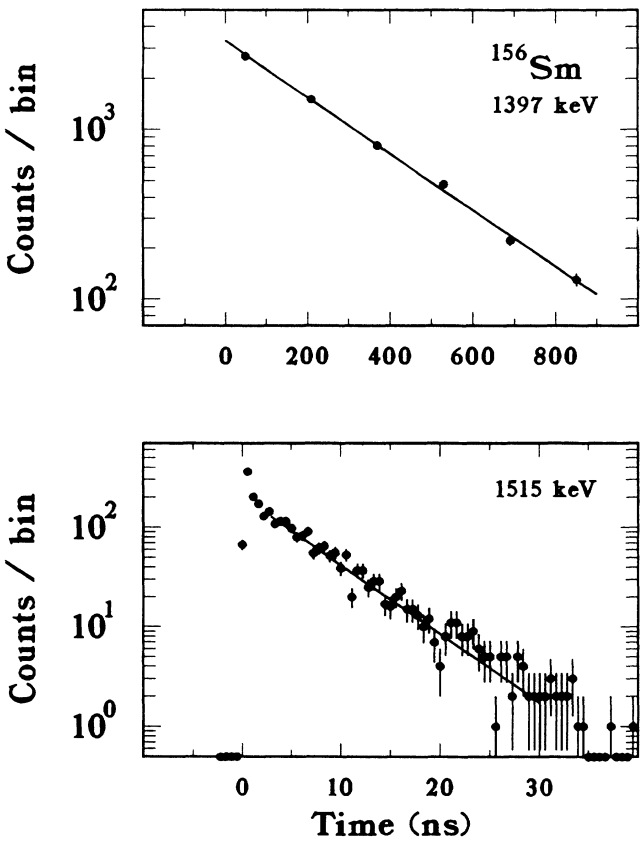

FIG. 3. The half-lives of the two 5^--isomeric levels in ^{156}Sm at 1397.4 and 1514.9 keV were determined as 185(7) and 4.5(2) ns, respectively, using two different delayed coincidence techniques. The decay curves obtained for γ rays depopulating the levels are given in the figure, using bin widths of 160 and 0.56 ns for the longer and the shorter half-lives, respectives. The time scale origin is set to the location of the prompt peak. See the text and Table II for details.

TAC's, and both a BaF_2 and a coaxial Ge detector (in a 180° geometry) to provide the respective stop pulses. "Fast" delayed coincidences between the plastic scintillator and the BaF_2 crystal were gated by slower events obtained between the plastic scintillator and the Ge detector. The latter was set to accept γ rays following the decay of the 1397.4 keV isomeric level. The resulting energy spectrum in the BaF_2 channel was completely dominated by the 117.42 keV γ ray. A gate subsequently placed on this photopeak resulted in the time spectrum shown in Fig. 3.

The total beta-decay energy of ^{156}Pm was determined from the end point energies of β spectra obtained in a $\beta\gamma$-coincidence measurement. The methods used for measurements and data analysis are similar to those described previously.[14] The beta particles were detected in a planar LEP detector equipped with a 0.25 mm Be window and separated from the vacuum system by a 0.08 mm window. In the case of ^{156}Pm the β spectra were obtained by gates on γ rays deexciting levels near 2.5 MeV of excitation energy. The Q_β value was found to be 5.155(35) MeV. A discussion of this result will be postponed until more experimental information has been obtained on the mass surface in the light neutron-rich lanthanide region. Here, it suffices to say that the value is in rough agreement with the extrapolation of 5.0(3) MeV by Wapstra *et al.*[15]

III. RESULTS

Very few excited states of ^{156}Sm were known before the current work. The ground state band had been seen up to the 6^+ level in studies of radiation from fragments following ^{252}Cf fission.[16,17] The position of some higher-lying levels had also been deduced from a (t,p) experiment several years ago,[18] although this experiment gave little additional information on these states.

Our work, based on the current study of the β decay of ^{156}Pm, has revealed about 25 excited states of ^{156}Sm at energies below about 2.7 MeV. (The strong selectivity of the β decay has of course limited the observed levels to a very restricted subset of states, of which those with a substantial direct β-particle population generally have a negative parity.) The γ-ray singles and coincidence data had a good sensitivity. The construction of the decay scheme, Figs. 4(a) and 4(b), using the prompt and delayed coincidence relations, was therefore trivial. It should be pointed out that the β strength in the decay of ^{156}Pm is concentrated to excitation energies below about 2.7 MeV. We did not find any indications of significant population of still higher-lying levels.

The decay scheme incorporates well over 95% of the observed γ-ray intensity. As is discussed later in this section, the angular momentum of the ground state of ^{156}Pm is at least four units. Any direct β transition to the ground state of ^{156}Sm is thus insignificant, and the normalization of γ-ray intensities to units of %/decay could be accurately accomplished using the decay scheme. The decay scheme incorporates one weak γ ray, at 803.9 keV, which has tentatively been placed on energy considerations as a ground state transition from an otherwise established level. The placements of all other transitions are supported by the coincidence data.

The levels of ^{156}Sm are briefly discussed below, followed by arguments on the nature of the ground state of ^{156}Pm. Our decay scheme gives no information about the expected low-lying levels of quadrupole vibrational character. The only information on such levels is from the early (t,p) study of Bjerregaard *et al.*,[18] which suggests a β-vibrational bandhead near 1068 keV.

Our investigation has provided slightly more precise energies for the levels in the ground state band than were obtained in the fission work of Cheifetz *et al.*[16] No band members with I^π higher than 6^+ are known. Using our energies for the 2^+ and 4^+ levels we obtain the rotational energy parameters $A=12.717$ keV and $B=-0.0118$ keV. The $8^+\rightarrow 6^+$ transition from the unknown 8^+ level is thus expected to have an energy of about 330–380 keV. Our $\gamma\gamma$-coincidence data give an upper limit of $I_\gamma < 0.15$ %/d for any γ ray which possibly can represent this transition.

The two isomeric levels revealed by the time measurements have both been assigned $K^\pi=5^-$ on grounds of the systematics of Nilsson orbitals in this mass region, and the hindrance factors of the transitions to the ground state band; see Table II. A K value of 5 units is the maximum obtainable for two-quasiparticle states at moderate energies in ^{156}Sm (see Ref. 19 for a recent calculation of quasiparticle energies in ^{156}Sm). The negative parity is not experimentally ascertained, but appears highly probable when comparing with, e.g., the decay[20] of the 190 ps $K^\pi=4^+$ level of ^{156}Gd.

In terms of the Nilsson model, the two isomers can be interpreted as the $nn\{\frac{5}{2}^+[642],\frac{5}{2}^-[523]\}_{5^-}$ and the $pp\{\frac{5}{2}^-[532],\frac{5}{2}^+[413]\}_{5^-}$ two-quasiparticle states, for the lower and upper level, respectively. These configurations can readily explain the rather high hindrance factor, see Table II, of the 117.42 keV $M1$ transition connecting the two isomers. The two possible $M1$ transitions between these configurations are both l forbidden and "nonoverlap" forbidden as classified by Gallagher.[21] The suggested configurations are also compatible with the β-particle population of the isomers as is briefly discussed near the end of this section.

We have tentatively assigned a negative parity to a set of levels at 803.5, 875.8, 1009.9, 1020.4, and 1144.0 keV. The γ-ray decays of these levels are compatible with $I^\pi=1^-$, 3^-, 2^-, 5^-, and 4^-, respectively, and they may form a $K^\pi=1^-$ rotational band, although this is not quite in agreement with the γ-ray branching from the odd-spin levels. Another level at 1110.0 keV can be the 3^- member of a $K^\pi=0^-$ band. The assignments of negative parities are not based on experimental evidence, but rely on the fact that low-lying octupole vibrational levels are expected[22] in the heavy Sm isotopes, and that the observed levels do not show any of the expected characteristics of members of positive parity bands.

If our interpretation is correct, one would expect a rather strong interaction between the odd-spin levels of the bands, resulting in energy shifts of these levels. Such an interaction would also cause the relative intensities of γ rays to the ground state band to deviate from the Alaga

predictions.[23] The levels having even angular momentum can be expected to be little affected by band mixing perturbations. From the positions of the proposed $KI^{\pi}=12^{-}$ and 14^{-} levels we obtain a rotational parameter $A=9.58$ keV, which is about 20% less than that of the ground state band. This is reasonable for a band based on an octupole vibration.

The low-lying $K^{\pi}=1^{-}$ octupole state of ^{156}Sm will have a large component of the $nn\{\frac{3}{2}^{-}[521],\frac{5}{2}^{+}[642]\}_{1^-}$ two-quasiparticle configuration, which cannot be effectively populated in the β decay of ^{156}Pm, having the configuration $pn\{\frac{5}{2}^{+}[413],\frac{3}{2}^{-}[521]\}$; see below. Experimentally, we find a very weak β-particle feeding of the proposed band members having $I=3,4,5$, which are accessible through allowed transitions from ^{156}Pm.

Apart from the levels of the ground state band, we have only been able to assign a positive parity to one level of ^{156}Sm, at 1509.1 keV. This level γ decays to the 2^{+}, 4^{+}, and 6^{+} members of the ground state band and can thus reasonably only be assigned 4^{+}. The 4^{-} alternative, deexcited by $M2$ transitions, would imply a level half-life in the ns region, which is contrary to our observations. The γ-ray branching is close to the Alaga prediction for $K=2$ but higher values are not excluded. [A $K^{\pi}=4^{+}$ state at this energy would, as in ^{156}Gd (Ref. 20), still be expected to have a subnanosecond half-life.] The level is strongly populated in the β decay of ^{156}Pm, with a log ft value as low as 6.3. This is an indication that the 4^{+} level has a strong component of the $pp\{\frac{5}{2}^{+}[413],\frac{5}{2}^{+}[413]\}$ configuration, with the consequence that the β transition essentially has the character $h_{9/2}\rightarrow g_{7/2}$. Our data give no evidence for other levels possibly belonging to the same band as the 4^{+} state at 1509.1 keV. The value of K is probably 3 or 4, since lower values most likely would have resulted in a weak β transition to this level.

At higher excitation energies, near 2.5 MeV, we observe a pair of strongly populated levels separated by about 7 keV. Another pair with nearly the same separa-

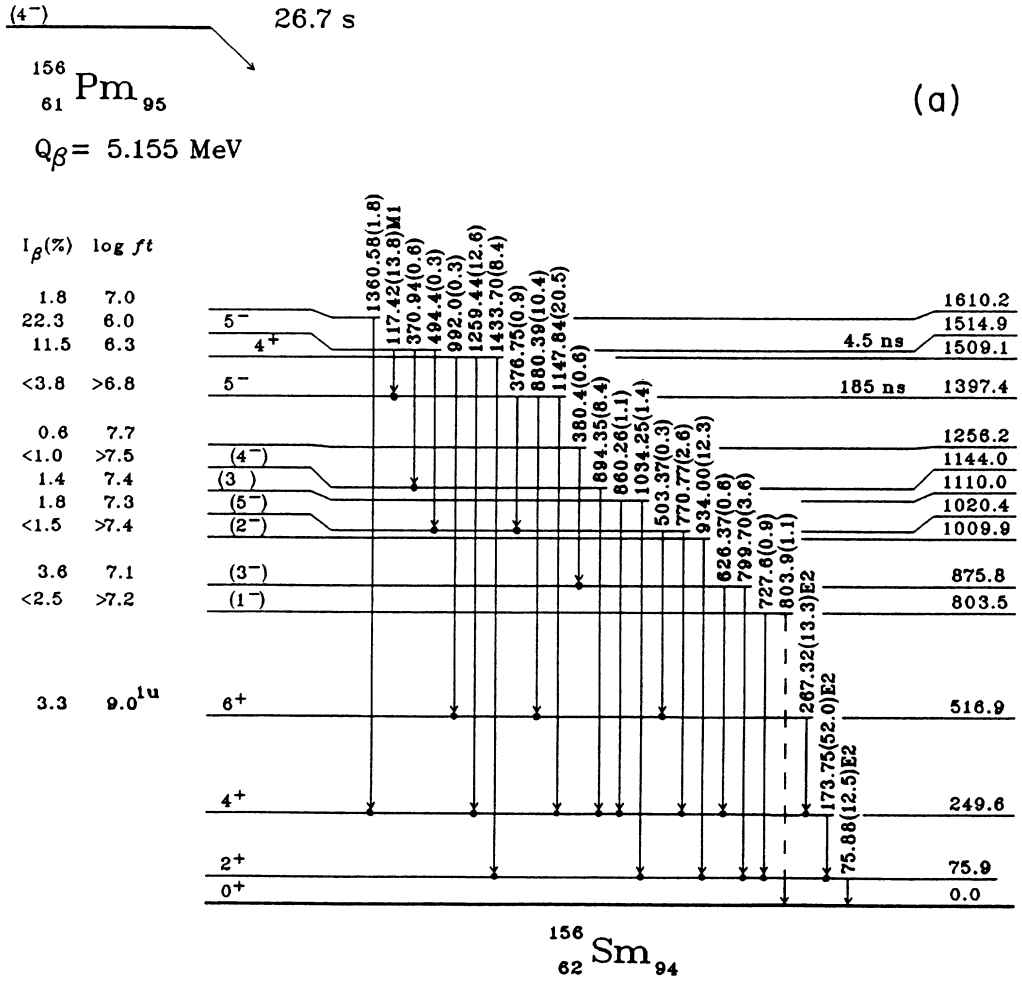

FIG. 4. (a) Lower energy part of the decay scheme of ^{156}Pm as obtained in the current work. Transition intensities are given in units of %/decay. Observed coincidences are indicated by dots. The Q_{β} value was determined using a $\beta\gamma$-coincidence technique. The figure is not drawn to scale. Energies of levels and transitions are in keV. See the text, Sec. III, for a discussion of these results. (b) Higher energy part of the decay scheme of ^{156}Pm. See caption of (a).

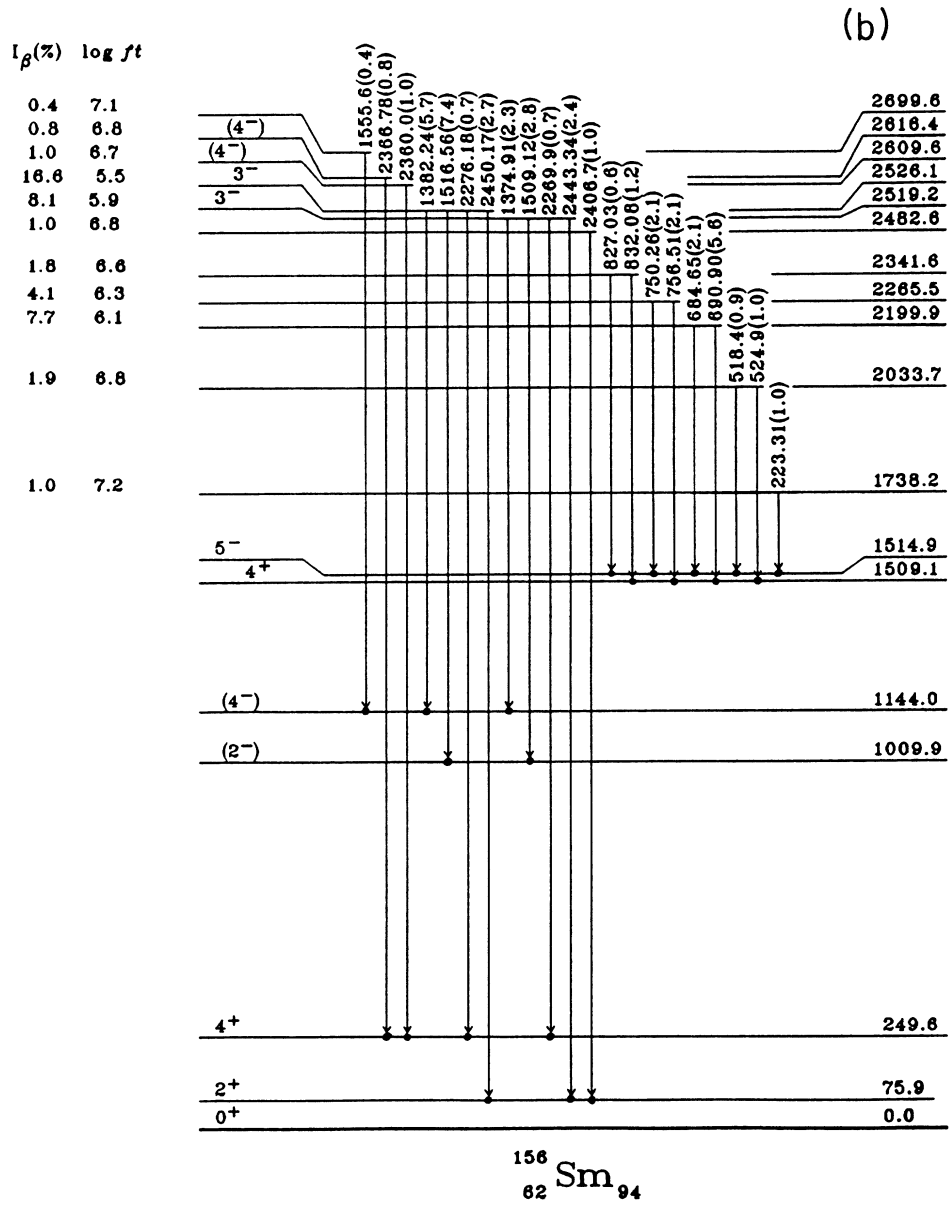

FIG. 4. (*Continued*).

TABLE II. Hindrance factors for transitions from the two 5^- isomers of ^{156}Sm. All energies are in keV.

Level energy (and $t_{1/2}$ in ns)	Gamma-ray energy	Multipolarity[a]	Hindrance F_W[b]
1397.4	376.8	$M1$	$1.61\cdot10^7$
(185±7)	880.4	$E1$	$1.66\cdot10^9$
	1147.8	$E1$	$1.87\cdot10^9$
1514.9	117.4	$M1$	$7.27\cdot10^2$
(4.5±0.2)	370.9	$M1$	$5.27\cdot10^5$
	494.4	$M1$	$2.50\cdot10^6$
	998.0	$E1$	$>1.9\cdot10^9$
	1265.3	$E1$	$>3.8\cdot10^9$

[a]Multipolarities were deduced from the level scheme, except for the 117.4 keV transition; see Table I.
[b]The hindrance is relative the Weisskopf estimates (Ref. 25).

tion is found at an additional excitation energy of 90 keV. The modes of γ-ray decay suggest strongly that the lower and higher pairs are, respectively, the 3^- and 4^- members of two very close lying rotational bands. A strong configuration mixing of the bands is evident from the very similar decay patterns of the levels and the nearly identical separations between the 3^- and 4^- levels of each band. The total β strength to the two proposed 3^- states is high enough to suggest that the essential character of this β transition is of the type $h_{9/2} \rightarrow h_{11/2}$, which is the only fast allowed transition in this mass region.

A consistent picture of the ^{156}Pm decay is only found if the ground state is assumed to have $KI^{\pi}=44^-$. The reason for this assignment is the observation of significant β feeding of two levels in the 1 MeV region, presumably having a spin of three units, and of the 6^+ level of the ground state band. These observations would limit the possible alternatives to 4^- or 5^+ for the ^{156}Pm ground state. A positive parity is ruled out with a high degree of probability, since one of the two isomeric 5^- levels is populated with a β transition having a logft as low as 6.0. The positive parity alternative is also inconsistent with the population of the proposed pair of rotational bands near 2.5 MeV. The microscopic composition of the ^{156}Pm ground state is then most likely given by the configuration $pn\{\frac{5}{2}^+[413],\frac{3}{2}^-[521]\}_{4-}$, which accounts for the strong β-particle population of the higher-lying (pp) of the 5^- isomers and the weak population of the lower-lying (nn) one.

The direct β transition to the 6^+ level of the ground state band has a logft value of 9.0^{1u}, which is quite reasonable. The absence of significant direct population of the 4^+ level of the ground state band may be understood if this expected K-forbidden transition also mainly proceeds through its unique (multipole order $=2$) component. The theoretical prediction[23,24] of the intensity, based on geometrical factors, is then only about 10% of the intensity feeding the 6^+ level and the transition to the 4^+ level is thus too weak to be observed in our experiment.

ACKNOWLEDGMENTS

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