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Energy levels of ^{127,129,131}Sn populated in the β^- decay of ^{127,129,131}In

L.-E. De Geer and G. B. Holm*
National Defence Research Institute, S-104 50 Stockholm 80, Sweden
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The decay of 0.27 s ^{131}In to levels in the single hole nucleus ^{131}Sn have been studied using an on-line isotope separator. The $s_{1/2}$ and $g_{7/2}$ levels are found at 332.8 and 2433 keV excitation, respectively. The Q_{β^-} of ^{131}In has been determined to be 8.82 ± 0.20 MeV. To complete the series of heavy odd-mass isotopes of Sn, levels in the ^{127,129}Sn nuclei, which are populated in the decay of ^{127,129}In also have been studied. Decay schemes are proposed for the decay of two ^{127}In isomers of half-lives 1.15 ± 0.05 s and 3.7 ± 0.1 s and for the decay of two ^{129}In isomers of half-lives 0.59 ± 0.03 s and 1.20 ± 0.05 s. Low lying negative parity states of three quasiparticle character have been observed in ^{127,129}Sn where μs isomers due to the low energy $h_{11/2}$ orbit are also suggested.

[RADIOACTIVITY ^{127,129,131}In from ^{235}U(n,f), isotopically separated sources: measured $T_{1/2}, E_\gamma, I_\gamma, E_\beta, E_{ce}, I_{ce}, \gamma\gamma$-coinc., $\beta\gamma$-coinc. ^{127,129,131}Sn deduced levels, $I, \pi, \log ft$. Ge(Li), Si(Li), plastic and anthracene detectors, Ge(Li)-Ge(Li) and Ge(Li) - anthracene coinc., plastic detector - Ge(Li) delay.]

I. INTRODUCTION

One of the main goals of the cooperative fission project OSIRIS at Studsvik[1] has been the study of nuclides in the region around doubly magic $^{132}_{50}$Sn$_{82}$. This region does—together with the $^{208}_{82}$Pb$_{126}$ region—exhibit the best closed shell situation amenable to investigation. ^{132}Sn is situated relatively far from the line of β stability but just on the limit for effective production in the fission process.

Around $^{132}_{50}$Sn$_{82}$, levels of three two-particle nuclides have been studied at OSIRIS and reported ($^{134}_{52}$Te$_{82}$ Ref. 2, $^{132}_{51}$Sb$_{81}$ Ref. 3, and $^{130}_{50}$Sn$_{80}$ Ref. 4). Out of four one-particle nuclides, levels in two have been studied. One, the proton case $^{133}_{51}$Sb$_{82}$, has been published[5] and the other, the neutron hole case $^{131}_{50}$Sn$_{81}$, is the main result of the present work. Additional information has been submitted from other laboratories on ^{133}Sb.[6] The magic nucleus itself has been studied at OSIRIS,[7] at the recoil separator JOSEF at Jülich,[8] and at the ISOLDE separator at CERN.[9] The remaining seven nuclides within the two particle limit have not yet been studied due to the very low fission yields of their precursors.

The source strengths which are obtainable in the ^{132}Sn region plus the complications caused by ingrowing daughter activities with its high β background do not allow very many unambiguous spin and parity assignments. For the very short-lived nuclides, which are weakly produced, it is also relatively difficult to disentangle the decay characteristics and to make assignments as to the ground state and isomeric decays. It is therefore suitable to partly base the interpretation of the ^{131}Sn experimental results on known assignments from nuclei which are more easily produced and lie closer to the line of stability. Odd-mass tin isotopes are rather well known up to mass 125, and to form a link to these it is also desirable to study the hitherto unknown isotopes of ^{129}Sn and ^{127}Sn. (The other possible cut in the chart of nuclides, i.e., keeping $N=81$ constant has the disadvantage for direct comparison of involving another decaying state: $g_{7/2}$ instead of $p_{1/2}$ and $g_{9/2}$.)

Preliminary reports on the ^{127,129,131}In $\rightarrow$ ^{127,129,131}Sn decays have been given in several annual reports[10,11] and at the Leysin Conference on the Properties of Nuclei far from Beta Stability.[12] An important correction in the present work of one of the preliminary reports[11] concerns the $h_{11/2}$ neutron single-hole energy.

Previous results on the nuclides currently of interest are the Q values for the ^{127}In $\rightarrow$ ^{127}Sn and ^{129}In $\rightarrow$ ^{129}Sn decays[13,14] and two half-lives of ^{127}In Refs. 15, 16, two half-lives of ^{129}In Ref. 17, and one half-life of ^{131}In Ref. 16. These five In isomers have been observed to be delayed neutron precursors and the neutron emission probabilities have been measured by Lund *et al.*[17] Two half-lives are known in each of ^{127}Sn, ^{129}Sn, and ^{131}Sn, Refs. 15, 18, 19, and 20.

II. EXPERIMENTAL PROCEDURES

The experiments were performed at the on-line fission product separator OSIRIS.[1] The ion source containing 150 mg of ^{235}U is placed close to the core of the 1 MW R2-0 swimming-pool reactor at Studsvik, Sweden. The central beam of the separator is collected on an aluminized Mylar tape which can be moved continuously or stepwise for enhancement and identification of the short-lived activities. The γ detectors used for the singles and coincidence measurements were coaxial Ge(Li) detectors of 30–40 cm^3 volume and with resolutions of 2.3 keV full width at half maximum (FWHM) at 1332 keV. Cooled SIMTEC Si(Li) detectors were employed for x-ray counting and in electron conversion determinations. The β-particle energies were measured by anthracene detectors of 25 and 40 mm thickness. The detectors were connected to a NS-625 dual 4 K analog-to-digital converter (ADC) and the on-line measurements were controlled by a 8 K memory PDP-9 computer. Coincidence measurements were performed with the aid of a PDP-9 program permitting selection of a maximum of 12 double gates (peak and background) in the spectrum. Programs were also available for multiscaling of individual peaks and for multispectra measurements, in which cases a beam shutter was controlled by the PDP-9.

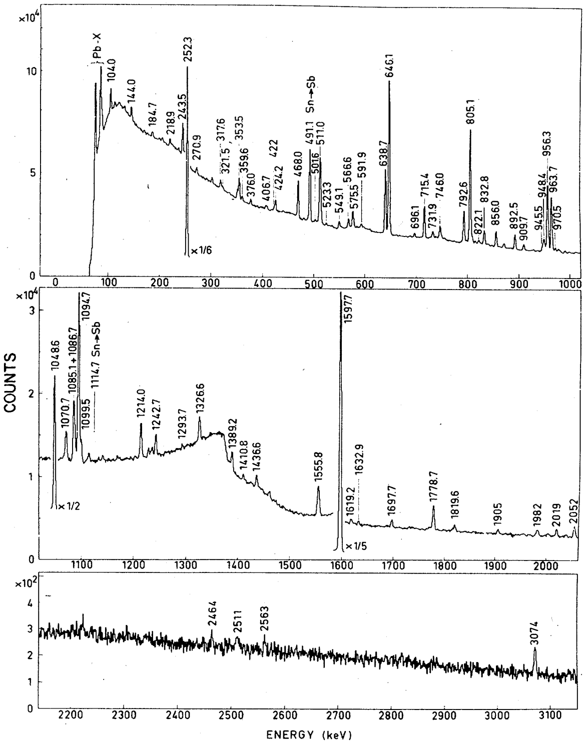

FIG. 1. A Ge(Li) detector spectrum showing γ rays from the mass 127 isobaric chain. The spectrum was recorded under conditions which enhance activities with half-lives of a few seconds. The majority of the γ peaks are due to the $T_{1/2}=1.15$ s and 3.7 s β^- decay of $^{127}In^g$, $^{127}In^m$ into $^{127}Sn^g$, $^{127}Sn^m$. None of the peaks labeled solely by its energy in keV have been shown to decay with a half-life longer than about 10 s.

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

A. $^{127}In \rightarrow {}^{127}Sn$ decay

Measurements

A singles γ-ray spectrum of activity from mass chain 127 is shown in Fig. 1. The spectrum was taken in a 4 h run with activity removed by the tape transport every 2.7 s to enhance the short-lived products. The majority of the γ lines is interpreted as belonging to two modes of $^{127}In \rightarrow {}^{127}Sn$ decay, the only apparent background activity being a few lines from the $T_{1/2}=2.1$ h and 4.13 min β decay of $^{127}Sn^g$, $^{127}Sn^m$. The energies and intensities of the γ rays assigned to the decays of ^{127}In are listed in Table I together with half-life data and results from both the γ-γ coincidence experiment and a β-γ coincidence run showing association with high energy β particles.

In a γ-multiscaling experiment the strongest γ rays were judged to belong to either a $T_{1/2}=1.15\pm0.05$ s or a $T_{1/2}=3.7\pm0.1$ s decay, the half-lives being in good agreement with the results of Grapengiesser *et al.*[15] and Lund *et al.*[16] who measured β particles and delayed neutrons, respectively. Multiscaling measurements could be done only for γ rays chosen in advance. To assign the bulk of γ peaks to different half-lives a more convenient method was used. Singles spectra were recorded at two different tape speeds and ratios of corresponding peak areas in the two spectra were calculated. As a change of the tape speed influences the count rate of a long-lived activity more than the count rate of a short-lived one, one can easily sort, at least the stronger transitions, into different activities by applying suitable tape speeds. A plot of such ratios for mass 127 transitions is shown in Fig. 2, and the interpretation of the results is given in Table I. One can clearly see in Fig. 2 how most of the γ rays group together at low ratios, close to the line drawn through the ratio of the strong 1597.7 keV transition. This indicates that these γ rays belong to the $T_{1/2}=1.15$ s decay. A few γ rays are shown to probably belong to the $T_{1/2}=3.7$ s decay.

No other half-lives have been detected that could be interpreted as belonging to a $^{127}Cd \rightarrow {}^{127}In$ decay, neither in the above mentioned experiment nor in any β-multiscaling experiment in which the β-energy threshold was raised stepwise in order to emphasize short-lived components associated with high energy β particles. A search for In x rays with a Si(Li) detector and a high tape speed yielded negative results. These facts and the one that at mass 127 the independent fission yield of

TABLE I. γ rays from the mass 127 isobaric chain which have not been shown to decay with a half-life longer than about 10 s. The intensities are given in percent of the strongest γ line (1597.7 keV).

E[a] (keV)	I[b] (%)	Shown to be associated with a			Coincident γ rays (keV) or identification	Transition	
		high energy β	$T_{1/2} \simeq 1$ s decay	$T_{1/2} \simeq 4$ s decay		from (keV)	to (keV)
104.0	0.2		x				
144.0	0.2		x				
184.7	0.1		x				
218.9	0.1		x				
243.5	0.7		x			1053.3	809.8
252.3	30.7	x		x	137, 258, 696.1, 832.8, 2052	257.0	4.7
270.9	0.2		x				
317.6	0.2		x			963.7	646.1
321.5	0.1		x				
353.5	0.8		x			1909.3	1555.8
359.6	0.2		x				
376.0	0.2		x				
406.7[c]	0.3		x				
422	0.2		x			2023.8	1602.4
424.2	0.5		x				
468.0	2.0		x		646.1, 746.0, 805.1, 1555.8	2023.8	1555.8
501.6	0.1		x				
511.0	5.2		x		annihilation		
523.3	0.1		x				
549.1	0.5		x			1602.4	1053.3
566.6	0.7		x				
575.5	1.3		x		DE(1597.7)		
591.9	0.2		x				
638.7	5.1		x		646.1, 963.7	1602.4	963.7
646.1	12.7		x		317.6, 353.5, 468.0, 638.7, 909.7, 956.3	646.1	0
696.1	0.3			x		953.1	257.0
715.4	3.0		x				
731.9	0.6		x				
746.0	1.2		x			1555.8	809.8
792.6	3.2		x		805.1	1602.4	809.8
805.1	11.5	x	x		243.5, 353.5, 422, 468.0, 746.0, ~785, 792.6, 892.5, 1099.5, 1214.0	809.8	4.7
808	0.6						
822.1	0.4		x				
832.8	1.6			x		1089.8	257.0
856.0	1.7		x			1909.3	1053.3
892.5	1.8		x			1702.3	809.8
909.7	0.8		x			1555.8	646.1
945.5	0.7		x			1909.3	963.7
948.4	2.2	x	x		1070.7	953.1	4.7
956.3	9.4	x	x		646.1	1602.4	646.1
963.7	7.4	x	x		638.7, 945.5, ~2880	963.7	0
970.5	0.3		x			2023.8	1053.3
977	0.3		x	or x			
980	0.2		x	or x			
989.1	0.3						
1048.6	10.9	x	x		549.1, 856.0, 970.5, 1389.2	1053.3	4.7
1070.7	1.4		x			2023.8	953.1
1085.1	1.3			x		1089.8	4.7
1086.7	1.4	x	x		SE(1597.7)		
1094.7	7.5		x		~824, ~860, 715.4		
1099.5	0.9					1909.3	809.8

TABLE I. *(Continued)*.

E [a] (keV)	I [b] (%)	Shown to be associated with a high energy β	$T_{1/2} \simeq 1$ s decay	$T_{1/2} \simeq 4$ s decay	Coincident γ rays (keV) or identification	Transition from (keV)	to (keV)
1214.0	1.7		x			2023.8	809.8
1242.7	1.0		x				
1293.7	0.3						
1326.6	1.3		x	or x			
1389.2	0.9		x			2442.6	1053.3
1410.8	0.3						
1436.6	0.6						
1555.8	2.6		x			1555.8	0
1597.7	100.0	x	x		422	1602.4	4.7
1619.2	0.3						
1632.9	0.2					2442.6	809.8
1697.7	0.5						
1771	0.2						
1778.7	1.9		x				
1819.6	0.6		x				
1905	0.4						
1982	0.8						
2019	0.7		x			2023.8	4.7
2052	1.3				DE(3074)		
2464	0.8						
2511	1.0						
2563	0.7				SE(3074)		
3074	2.3			x		3331	257.0

[a] Uncertainty in energy is 0.3 keV up to about 1800 keV and 0.5–1 keV above this. Below 1800 keV greater uncertainties are indicated by deleted decimals.

[b] Uncertainty in relative intensities is 10% or 0.1, whichever is greater.

[c] Unresolved doublet.

Cd should be considerably lower than for In and Sn[21] allow an assignment of the 3.7 s and 1.15 s half-lives to the In → Sn decay.

The γ-γ coincidence experiment was performed for gates set on twelve photopeaks and corresponding background regions. The results are given in Table I, and in Fig. 3 some examples of the coincidence spectra are plotted with the background coincidences subtracted.

A conversion electron measurement was performed with one 2 mm thick cooled Si(Li) detector and one Ge(Li) detector, both placed about 10 mm from the collection tape and 110 mm down the moving tape. The experiment was calibrated with known conversion coefficients from transitions in the decay of ^{85}Kr^{m} and ^{135}Xe^{m} which were obtained on-line. Only the 252.3 keV transition produced good electron lines well above the high β background. The α_K was determined to be 0.039 ±0.002 and the K/L ratio to be 7.3 ±0.4, which clearly indicate the 252.3 keV to be an $M1$ transition.[22] A K-shell conversion coefficient of 0.043 ±0.017 could be deduced for the 243.5 keV transition which implies this one to be of $M1$ and/or $E2$ character with some preference

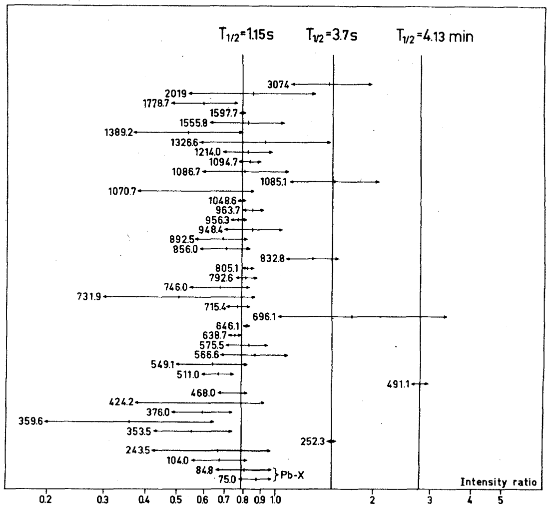

FIG. 2. Ratios of gamma intensities in the mass 127 isobaric chain as observed at two different tape speeds (2.5 and 25 mm/s). The ratio units are arbitrary, since reactor effect and measuring times were not necessarily the same at the two measurements. The statistical errors are shown with arrows and the γ-ray energies are given in keV. Vertical lines are drawn through ratios of strong γ rays with measured half-lives.

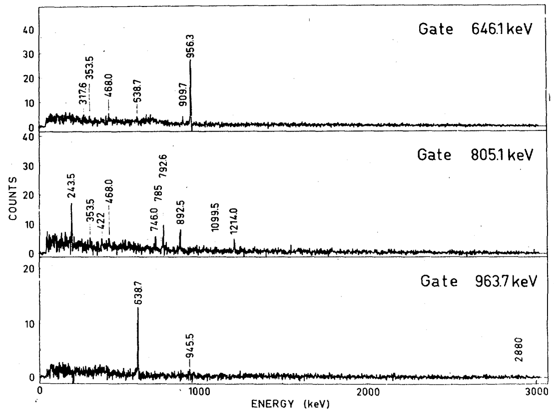

FIG. 3. Examples of γ-γ coincidence spectra with gates set on the 646.1 keV, the 805.1 keV, and the 963.7 keV transitions in ^{127}Sn. Background coincidences have been subtracted.

for $M1$. The theoretical coefficient is 0.043 for $M1$ and 0.059 for $E2$, Ref. 22. For the 646.1 keV transition an upper limit for α_K of 0.004 allows this transition to be $E1$, $E2$, or $M1$. A pertinent part of the electron spectrum is shown in Fig. 4.

Level schemes

The experimental results have been used to construct the two schemes of $^{127}\text{In}^g \rightarrow {}^{127}\text{Sn}^g$, $^{127}\text{Sn}^m$ and $^{127}\text{In}^m \rightarrow {}^{127}\text{Sn}^m$ decay proposed in Fig. 5. As for one single γ ray (1070.7 keV) and the isomeric level at 4.7 keV excitation, the "intensity flow" through the ^{127}Sn levels can be separated into one high spin part and one low spin part, corresponding to the two modes of decay. Although not firmly established, the Q values reported by Aleklett *et al.*[13] indicate, as well as the systematics, that the high spin part is connected to the ground state decay of In and that the low spin part is connected to the isomeric decay. Based on shell model considerations and systematics from lighter odd-mass In isotopes the ground state and isomeric state of ^{127}In are assumed to be $\frac{9}{2}^+$ and $\frac{1}{2}^-$ states, respectively.

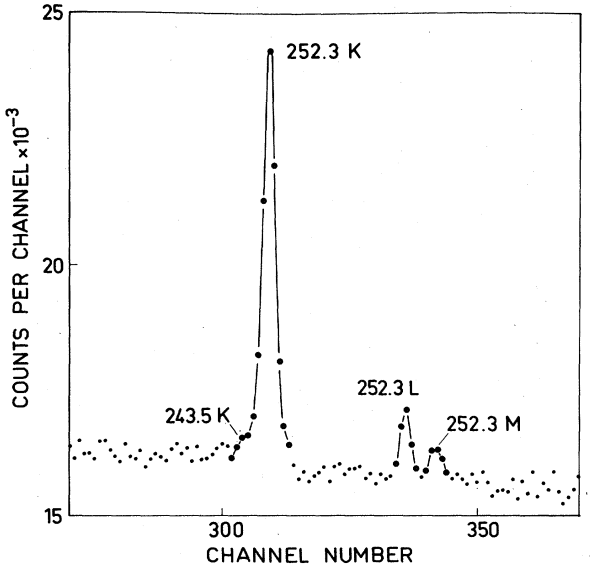

FIG. 4. Part of an electron spectrum showing the conversion lines of the 243.5 and 252.3 keV transitions in ^{127}Sn.

The currently proposed levels of ^{127}Sn are listed in Table II together with the arguments used for their proposal. Apart from the 715.4–1094.7 keV cascade all γ rays in Table I with relative intensities >2% have been placed.

The 715.4 and 1094.7 keV γ rays were shown to be delayed, with equal delayed intensities, succeeding a level of half-life 3.1 ± 0.9 μs. In determining this half-life a Naton 136 scintillator and a Ge(Li) detector were used for the detection of β particles and γ rays, respectively. The 3.1 μs level most probably is an isomeric level of ^{127}Sn, as the 715.4 and 1094.7 keV γ rays in a multispectra experiment revealed half-lives of 1.14 ± 0.10 s and 1.24 ± 0.10 s, respectively, in agreement with the 1.15 ± 0.05 s half-life of the $\frac{9}{2}^+$ ^{127}In β decay. This is consistent with the fact that isomers are expected in neutron hole nuclei close to ^{132}Sn, due to the very low lying $h_{11/2}$ orbit.

Log*ft values*

The log*ft* values have been computed assuming for the high spin decay that the first forbidden $\frac{9}{2}^+ \rightarrow \frac{11}{2}^-$ transition can be neglected as compared to the allowed $\frac{9}{2}^+ \rightarrow \frac{7}{2}^+$ ones. For the low spin decay an estimate of the relative feeding of the lowest $\frac{3}{2}^+$ and $\frac{1}{2}^+$ levels, by first forbidden transitions, was made by analyzing simultaneously collected γ and β spectra. The β spectrum, recorded with a 40 mm thick and 45 mm diameter anthracene detector, was analyzed for one high energy component terminating at the $\frac{3}{2}^+$ 4.7 keV and $\frac{1}{2}^+$ 257.0 keV levels and one component terminating at the $\frac{7}{2}^+$ 1602.4 keV level. With the feeding of other levels thus neglected this gives a rather crude estimate of the relative population of the lowest $\frac{3}{2}^+$ and $\frac{1}{2}^+$ states of 0.20 ± 0.15.

Spin and parity assignments

As was pointed out above much of the spin and parity assignments has to be based on systematics. Systematics from lighter tin isotopes and heavier $N = 77$ isotones strongly suggest that one of the two lowest states has spin and parity $\frac{11}{2}^-$ and the other $\frac{3}{2}^+$. The low log*ft* value (4.4) for decay to the 1602.4 keV level identifies this level with the

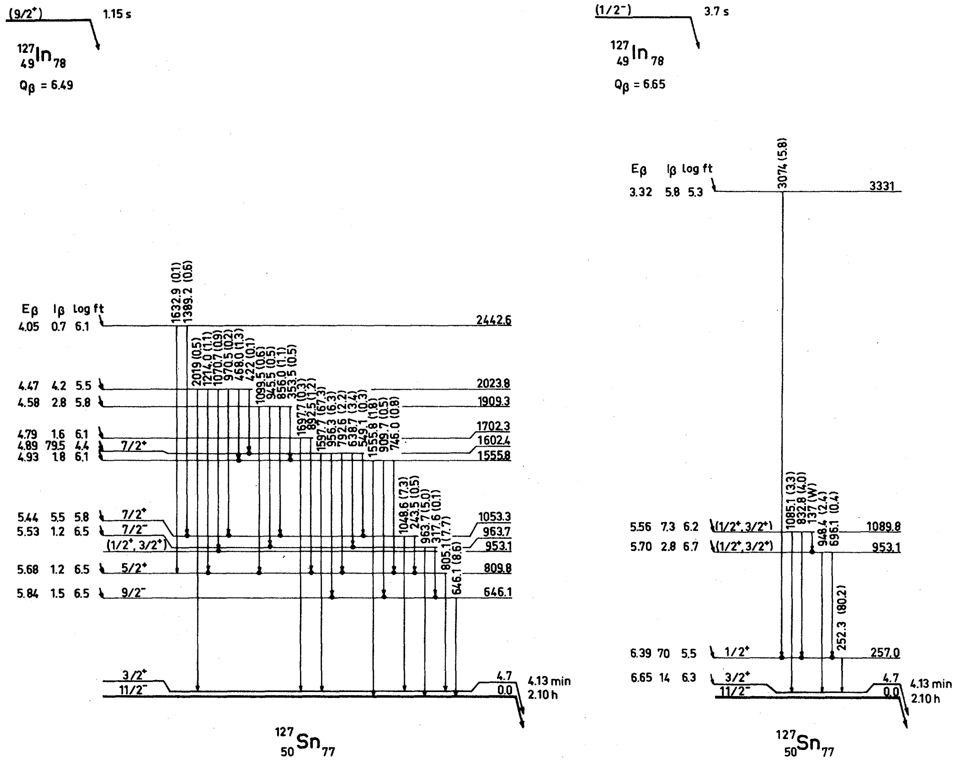

FIG. 5. Decay schemes proposed for the 1.15 s and 3.7 s states of ^{127}In. The transition intensities given within brackets are transitions per 100 decays. Observed coincidence relations are indicated by dots. The Q values are taken from Ref. 14.

TABLE II. Arguments for the proposal of levels in ^{127}Sn. Symbol key: S = systematics. $E(i-(j+k) = \cdots = e)$ = energy difference fitting. The energy difference between a γ ray i and an established γ-ray cascade $j+k$ agrees with similar energy differences to suggest a level of e keV excitation or a level e keV apart from some other level. B = β feeding considerations, log*ft*. T = depopulating γ ray associated with a half-life of about 4 s. I = intensity balance. $C(i,j\,[k])$ = γ ray i coincident with γ ray j, where j built on level depopulated by i adds up to k which is currently proposed or has been proposed before. $NC(i;j,k\ldots)$ = γ ray i not coincident with any one of γ rays $j, k, \ldots$. $\gamma(i)$ = γ ray i is present.

Energy of level (keV)	Arguments for proposal
0	S
4.7	S, E(646.1 + 956.3 − 1597.7 = 1555.8 − 746.0 − 805.1 = 963.7 + 638.7 − 1597.7 = 4.7)
257.0	S, B, T
1602.4	S, B, NC(1597.7, anything but 422)
646.1	S, I, C(646.1, 956.3 [1602.4])
809.8	I, C(805.1, 792.6 [1602.4])
963.7	S, I, C(963.7, 638.7 [1602.4])
1053.3	S, I, C(1048.6, 549.1 [1602.4])
1089.8	T, C(252.3, 832.8 [1089.8]), γ(1085.1)
1555.8	C(646.1, 909.7 [1555.8]), γ(1555.8)
1702.3	C(805.1, 892.5 [1702.3]), γ(1697.7)
1909.3	C(805.1, 1099.5 [1909.3]), C(963.7, 945.5 [1909.2]), C(1048.6, 856.0 [1909.3])
2023.8	C(805.1, 1214.0 [2023.8]), C(1555.8, 468.0 [2023.8]), γ(2019)
953.1	T, C(252.3, 696.1 [953.1]), γ(948.4), C(948.4, 1070.7 [2023.8])
2442.6	C(1048.6, 1389.2 [2442.5]), γ(1632.9)
3331	T, C(252.3, 2052(DE3074) [3331])

SQP (single quasiparticle) $g_{7/2}$ state, which is expected from the shell model. A similarly low log*ft* value has been observed for the spin flip β^- transition ($\pi^{-1}\, g_{9/2} \rightarrow \nu^{-1}\, g_{7/2}$) in several other odd-mass In isotopes.[23] The strong γ ray from the $\frac{7}{2}^+$ 1602.4 keV level to the first excited state now gives spin and parity $\frac{3}{2}^+$ for that state and leaves $\frac{11}{2}^-$ for the ground state. The deduced *M*1 character of the 252.3 keV γ ray and the shell model prediction of an $s_{1/2}$ neutron hole orbit establish spin and parity $\frac{1}{2}^+$ for the 257.0 keV level.

A collective $\frac{7}{2}^+$ state should arise from the coupling of a $d_{3/2}$ quasiparticle with a phonon of the core. This state can be identified with the 1053.3 keV level in ^{127}Sn on grounds of the log*ft* value, the corresponding energies in ^{123,125}Sn, Ref. 23, and the energy of the one-phonon 2$^+$ state in ^{128}Sn (1168.80 keV), Ref. 24. Candidates for the other members of the one-phonon $d_{3/2}$ multiplet are the 953.1 and 1089.8 keV levels for the $\frac{1}{2}^+$ and $\frac{3}{2}^+$ and the 809.8 keV level for the $\frac{5}{2}^+$ member. The interpretation of the 809.8 keV level having spin and parity $\frac{5}{2}^+$ is supported by the implication that the 243.5 keV γ ray from the $\frac{7}{2}^+$ 1053.3 keV level most probably includes *M*1 character.

Low-lying negative parity states of three quasiparticle character are expected to occur in odd-mass heavy isotopes of Sn due to the coupling of the $h_{11/2}$ quasiparticle to a phonon of the even core.[23,25] From systematics of the $\frac{9}{2}^-$ and $\frac{7}{2}^-$ levels in ^{121,123,125}Sn, Ref. 23, and the modes of population and decay, it is obvious that the 646.1 and 963.7 keV levels, respectively, are candidates for the two states in ^{127}Sn. Due to the high β background no conversion data could be extracted to support these interpretations more than that the 646.1 keV transition has to be *E*1, *E*2, or *M*1.

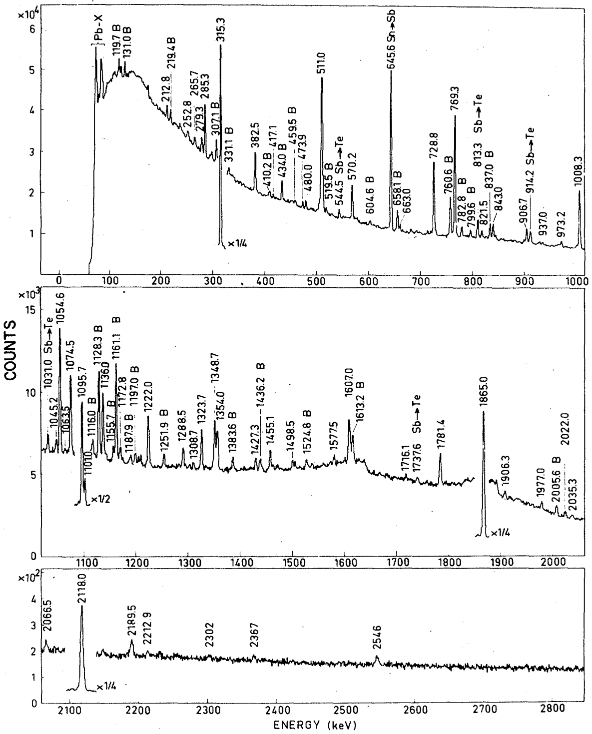

FIG. 6. A Ge(Li) detector spectrum showing γ rays from the mass 129 isobaric chain. The spectrum was recorded under conditions which enhance activities with half-lives of a few seconds. About half of the γ peaks are due to the $T_{1/2}=0.59$ s and 1.20 s β^- decay of ^{129}In^g, ^{129}In^m into ^{129}Sn^g, ^{129}Sn^m. None of the peaks labeled solely by its energy in keV have been shown to decay with a half-life longer than about 10 s. A longer half-life is indicated by a B or by the known origin. Most of the background rays are due to the $T_{1/2}=2.16$ min and 6.7 min β^- decay of ^{129}Sn^g, ^{129}Sn^m into ^{129}Sb.

B. ^{129}In → ^{129}Sn decay

Measurements

A singles γ-ray spectrum of activity from mass chain 129 is shown in Fig. 6. The spectrum was taken in a 5 h run with activity removed by the tape transport every 2.7 s to enhance the short-lived products. About half of the γ peaks are interpreted as belonging to two modes of ^{129}In → ^{129}Sn decay. Most of the background γ rays are due to the $T_{1/2}=2.16$ min and $T_{1/2}=6.7$ min β^- decay of ^{129}Sn^g, ^{129}Sn^m (the half-lives 2.16 ± 0.04 min and 6.7 ± 0.4 min were determined in multiscaling experiments of the 645.6 and 1161.1 keV γ rays respectively). The energies and intensities of the γ rays assigned to the decays of ^{129}In are listed in Table III together with half-life data and results from both the γ-γ coincidence experiment and a β-γ coincidence run showing association with high energy β gates.

In a γ multiscaling experiment the strongest γ rays were judged to belong to either a $T_{1/2}=0.59 \pm 0.03$ s or a $T_{1/2}=1.20 \pm 0.05$ s decay, the half-lives in good agreement with the results of Lund *et al.*,[17] who measured delayed neutrons. In Fig. 7 the ratios of the peak areas at 2.5 and 25 mm/s tape speeds are plotted in the same way as in Fig. 2 for mass 127 transitions. The interpretation of the results is given in Table III. One can see in Fig. 7 that many γ rays group together close to the line drawn through the ratios of the 2118.0 and 1865.0 keV transitions which represent the 0.59 s half-life. The 315.3 keV γ ray, which was measured to belong to the $T_{1/2}=1.20$ s decay, has a higher ratio. The γ rays with ratios above 1.6 belong to longer-lived isotopes in the isobaric chain.

The same efforts were made to look for any evidence for Cd → In decay in the mass 129 beam

TABLE III. γ rays from the mass 129 isobaric chain which have not been shown to decay with a half-life longer than about 10 s. The intensities are given in percent of the strongest γ line (2118.0 keV).

E^{a} (keV)	I^{b} (%)	Shown to be associated with a				Coincident γ rays (keV) or identification	Transition	
		High energy β	$T_{1/2} \leq 10$ s decay	$T_{1/2} \simeq 0.6$ s decay	$T_{1/2} \simeq 1.2$ s decay		From (keV)	To (keV)
212.8	0.4		x					
252.8	0.6		x					
279.3	0.8		x				1043.5	764.0
285.3	2.3		x	x			1054.6	769.3
315.3	42.4	x	x		x	501.2, 906.7, 973.2	315.3	0
382.5	2.8		x	x				
417.1	0.2	x	x					
473.9	0.6		x					
480.0	0.7		x					
501.2	0.8		x					
511.0	16.6					annihilation		
570.2	3.8		x					
663.0	0.7	x	x					
728.8	10.4	x	x	x		279.3, 1101.0, 1354.0	764.0	35.2
769.3	20.4	x	x	x		285.3, 1095.7, 1348.7, 1781.4, 2066.5, 2212.9	769.3	0
821.5	1.1		x				1865.0	1043.5
843.0	2.0	x	x			DE(1865.0)		
906.7	2.4	x	x			315.3	1222.0	315.3
937.0	0.5		x					
973.2	0.9	x	x				1288.5	315.3
1008.3	13.5	x	x	x		212.8, 821.5, 1074.5, 2546	1043.5	35.2
1045.2	0.1		x					
1054.6	8.2	x	x	x		480.0, 1781.4	1054.6	0
1063.5	0.3		x					
1074.5	5.3	x	x	x		382.5, 1008.3	2118.0	1043.5
1095.7	14.4	x	x	x		511.0, 769.3, 6.6% units due to DE(2118.0)	1865.0	769.3
1101.0	3.3	x	x	x			1865.0	764.0
1136.0	4.2		x	x				
1172.8	0.3		x					
1222.0	3.8	x	x			–	1222.0	0
1288.5	1.5		x				1288.5	0
1308.7	0.5							
1323.7	3.4		x			382.5		
1348.7	4.7	x	x	x		769.3	2118.0	769.3
1354.0	3.9	x	x	x		2.1% units due to SE(1865.0)	2118.0	764.0

TABLE III. *(Continued)*

E[a] (keV)	I[b] (%)		Shown to be associated with a			Coincident γ rays (keV) or identification	Transition	
		High energy β	$T_{1/2} \leq 10$ s decay	$T_{1/2} \simeq 0.6$ s decay	$T_{1/2} \simeq 1.2$ s decay		From (keV)	To (keV)
1427.3	1.0							
1455.1	1.5	x	x					
1498.5	0.8							
1577.5	0.6		x					
1607.0	5.8	x	x	x		SE(2118.0)		
1716.1	0.5		x	x				
1781.4	4.2	x	x				2836.0	1054.6
1865.0	72.4	x	x	x		–	1865.0	0
1906.3	0.9	x						
1977.0	1.0							
2022.0	0.9	x						
2035.3	0.8					SE(2546)		
2066.5	2.1		x				2836.0	769.3
2118.0	100.0	x	x	x			2118.0	0
2189.5	3.7		x					
2212.9	1.4		x				2982.2	769.3
2302	1.2							
2367	1.5							
2546	3.5		x				3590	1043.5

[a] Uncertainty in energy is 0.3 keV up to about 2200 keV and 0.5–1 keV above this. Below 2200 keV greater uncertainties are indicated by deleted decimals.

[b] Uncertainty in relative intensities is 10% or 0.1, whichever is greater.

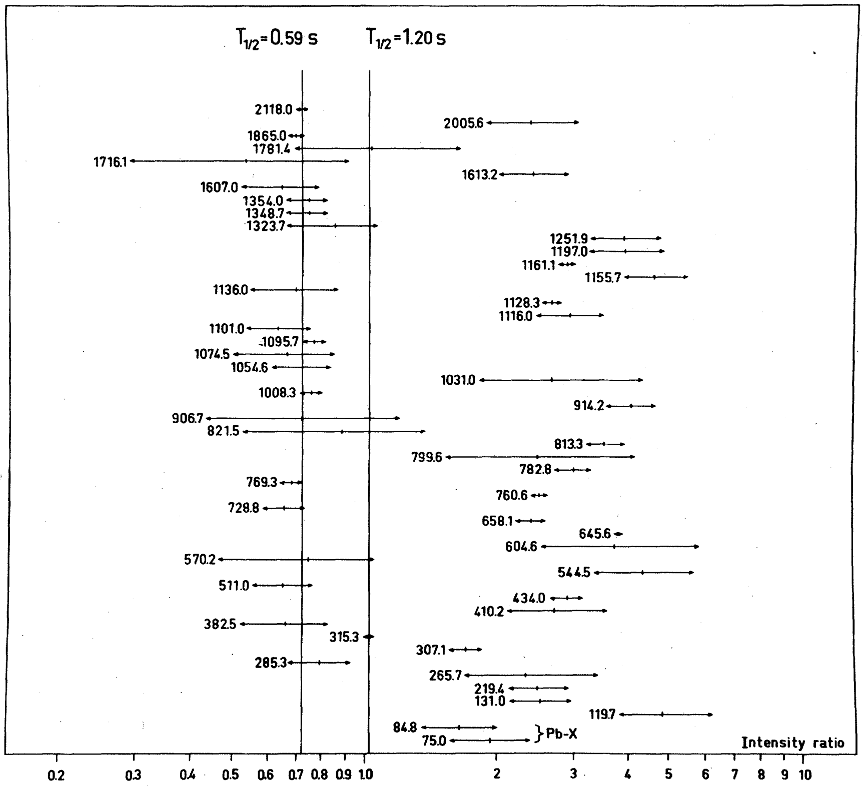

FIG. 7. Ratios of gamma intensities in the mass 129 isobaric chain as observed at two different tape speeds (2.5 and 25 mm/s). The ratio units are arbitrary, since reactor effect and measuring times were not necessarily the same at the two measurements. The statistical errors are shown with arrows and the γ-ray energies are given in keV. Vertical lines are drawn through ratios of strong γ rays with measured half-lives.

as in the mass 127 beam, but with negative results. A conversion electron measurement was performed with the same setup as for mass 127. For the 315.3 keV transition α_K was determined to be 0.025 ±0.002 and the K/L ratio to be 6.9 ±1.7, which indicate the 315.3 keV to be an $M1$ $+E2$ or $E2$ transition.[22] A K-shell conversion of 0.03 ±0.01 could be deduced for the 285.3 keV transition which implies this one to be of $M1$ and/or $E2$ character.[22]

Level schemes

The experimental results have been used to construct the two schemes of ^{129}In^{g} → ^{129}Sn^{g}, ^{129}Sn^{m} and ^{129}In^{m} → ^{129}Sn^{g} decay proposed in Fig. 8. As for the isomeric level at 35.2 keV excitation, the "intensity flow" through the ^{129}Sn levels can be separated into one high spin part and one low spin part corresponding to the two modes of decay. Systematics indicate that the high spin part is connected to the ground state decay of In and that the low spin part is connected to the isomeric decay. Based on shell model considerations and systematics from lighter odd-mass In isotopes the ground state and isomeric state of ^{129}In are assumed to be $\frac{9}{2}^{+}$ and $\frac{1}{2}^{-}$ states, respectively.

The currently proposed levels of ^{129}Sn are listed in Table IV together with the arguments used for their proposal. Apart from the 2189.5 keV γ ray and the four γ rays of energies 382.5, 570.2, 1136.0, and 1323.7 keV, all γ rays in Table III with relative intensities >1.5% have been placed.

The four γ rays mentioned most probably are the same as those, which from experiments at the fission-fragment separator Lohengrin at Grenoble were proposed to deexite a 3 μs level of ^{129}Sb, Ref. 26. However, while the 3 μs delay was confirmed in our experiment, a multispectra measurement showed half-lives of the four γ rays which reasonably well agree with the 0.59 ±0.03 s of the $\frac{9}{2}^{+}$ ^{129}In β decay. The resulting half-lives were 0.73 ±0.10 s for the 382.5 keV, 0.72 ±0.10 s for the 570.2 keV, 0.62 ±0.15 s for the 1136.0 keV, and 0.68 ±0.15 s for the 1323.7 keV γ rays. This suggests that the isomer is in fact an isomer of ^{129}Sn, probably an analog to the $T_{1/2}$ = 3.1 μs isomer suggested in ^{127}Sn.

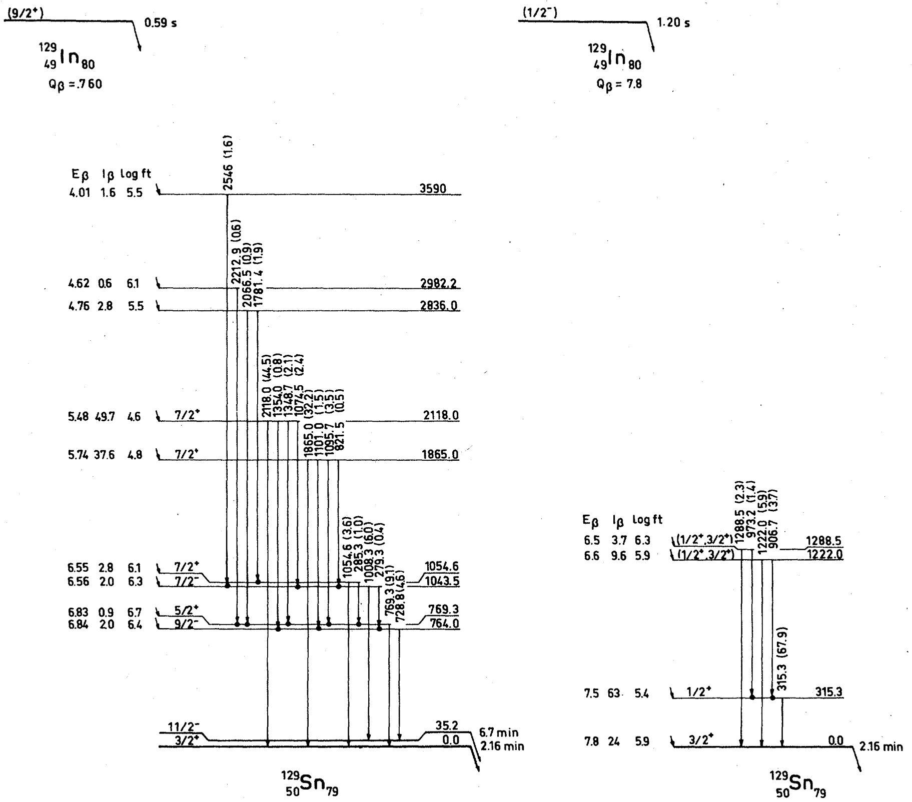

FIG. 8. Decay schemes proposed for the 0.59 s and 1.20 s states of ^{129}In. The transition intensities given within brackets are transitions per 100 decays. Observed coincidence relations are indicated by dots. The Q values are taken from Ref. 14.

Log *ft* values

As in the $A = 127$ case the log*ft* values for the high spin decay have been computed under the assumption that the first forbidden $\frac{9}{2}^+ \to \frac{11}{2}^-$ transition can be neglected as compared to the allowed $\frac{9}{2}^+ \to \frac{7}{2}^+$ ones. For the low spin decay a crude estimate, made in the same way as for ^{127}Sn,

TABLE IV. Arguments for the proposal of levels in ^{129}Sn. The symbol key is the same as in Table II, only that T means that depopulating γ ray is associated with a half-life of about 1.2 s.

Energy of level (keV)	Arguments for proposal
0	S
35.2	S, E(2118.0 − 1074.5 − 1008.3 = 1865.0 − 1101.0 − 728.8 = 35.2)
315.3	S, B, *T*
1865.0	S, B, NC(1865.0, anything)
2118.0	B
764.0	S, I, C(728.8, 1101.0[1865.0]), C(728.8, 1354.0[2118.0])
769.3	I, C(769.3, 1095.7[1865.0]), C(769.3, 1348.7[2118.0])
1043.5	S, I, C(1008.3, 821.5[1865.0]), C(1008.3, 1074.5[2118.0])
1054.6	S, NC(1054.6, anything but 1781.4)
1222.0	C(315.3, 906.7[1222.0]), γ(1222.0)
1288.5	C(315.3, 973.2[1288.5]), γ(1288.5)
2836.0	C(1054.6, 1781.4[2836.0]), C(769.3, 2066.5[2835.8])
2982.2	C(769.3, 2212.9[2982.2])
3590	C(1008.3, 2546[3590])

yields a relative feeding of the lowest $\frac{3}{2}^{+}$ and $\frac{1}{2}^{+}$ states of 0.38 ±0.20.

Spin and parity assignments

The discussion of spin and parity assignments very much resembles that for ^{127}Sn. There are even fewer conversion data present in the case of ^{129}Sn, but on the other hand arguments based on systematics are strengthened by the link formed by ^{127}Sn.

In ^{123,125,127}Sn the ground states have spin and parity $\frac{11}{2}^{-}$ with a close lying excited state of spin and parity $\frac{3}{2}^{+}$. In ^{129}Sn the two states have obviously reversed, making $\frac{3}{2}^{+}$ the ground state spin and parity, and $\frac{11}{2}^{-}$ spin and parity of the 35.2 keV excited state.

Although not ruled out, $M1$ character could not be established for the 315.3 keV transition from conversion data. However, the shell model prediction of an $s_{1/2}$ neutron hole orbit and the systematic trends give strong enough arguments for the assignment of spin and parity $\frac{1}{2}^{+}$ to the 315.3 keV level.

The low logft values for decay to the 1865.0 and 2118.0 keV levels identify these as being partial SQP $g_{7/2}$ states. In ^{123}Sn, Ref. 23, the $g_{7/2}$ SQP state appears so close to a $\frac{7}{2}^{+}$ core-particle state that a division of the single particle strength occurs, but in ^{125}Sn, Ref. 23, and ^{127}Sn the $g_{7/2}$ state has moved up and away from that collective state so as to become relatively pure. In ^{129}Sn, with the $g_{7/2}$ even higher up, it apparently comes closer to a new $\frac{7}{2}^{+}$ state, which again leads to a strong division of the single particle strength. As in ^{123}Sn the sum of the β feedings to the two $\frac{7}{2}^{+}$ states yields a logft of 4.4 which is the same as has been found in all odd mass In → Sn decays between A =117 and A =127.

All four levels in ^{127}Sn believed to belong to a multiplet (2^{+} phonon $d_{3/2}$ quasiparticle) have their counterparts in ^{129}Sn. Candidates for the $\frac{7}{2}^{+}$ and $\frac{5}{2}^{+}$ members of such a multiplet in ^{129}Sn are the 1054.6 and 769.3 keV levels, respectively, and candidates for the lowest spin members are the 1222.0 and 1288.5 keV levels. The analogy in decay schemes for ^{127}Sn and ^{129}Sn forms the basis for these assignments. However, the logft for the transition to the 1054.6 keV level is the lowest in the high spin decay terminating at less than 1.2 MeV excitation, and this supports the $\frac{7}{2}^{+}$ interpretation. The $M1$ and/or $E2$ character of the 285.3 keV does not contradict the assignments of $\frac{7}{2}^{+}$ and $\frac{5}{2}^{+}$ to the 1054.6 and 769.3 keV levels, respectively.

The low lying $\frac{9}{2}^{-}$ and $\frac{7}{2}^{-}$ states of three quasiparticle character observed in odd-mass $^{121\text{-}127}$Sn can only be identified in ^{129}Sn through systematics supported by modes of population and decay. Obvious candidates for these $\frac{9}{2}^{-}$ and $\frac{7}{2}^{-}$ states in ^{129}Sn are the 764.0 and 1043.5 keV levels, respectively.

C. ^{131}In → ^{131}Sn decay

Measurements

At mass 131 the In fission yield has decreased so much that spectroscopic investigations are marginal. With the aid of the moving tape, only one very short-lived γ transition of energy 2433 ±1 keV could be observed (Fig. 9 in Ref. 1). To get better information on the spectrum it is, how-

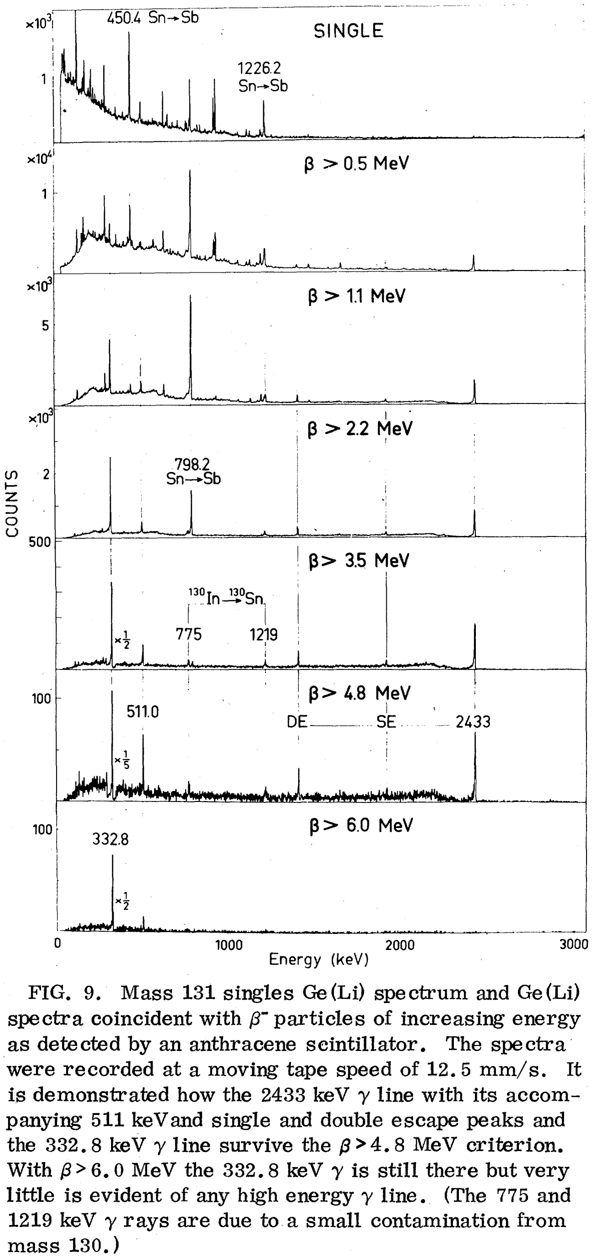

FIG. 9. Mass 131 singles Ge(Li) spectrum and Ge(Li) spectra coincident with β^{-} particles of increasing energy as detected by an anthracene scintillator. The spectra were recorded at a moving tape speed of 12.5 mm/s. It is demonstrated how the 2433 keV γ line with its accompanying 511 keV and single and double escape peaks and the 332.8 keV γ line survive the $\beta > 4.8$ MeV criterion. With $\beta > 6.0$ MeV the 332.8 keV γ is still there but very little is evident of any high energy γ line. (The 775 and 1219 keV γ rays are due to a small contamination from mass 130.)

ever, safer to make use of the high β energy of the decay in a β-γ coincidence measurement. The results of such a measurement are shown in Fig. 9 for successively increasing β energies (up to >6.0 MeV). In this way the 2433 keV γ ray gets more prominent and a new γ ray, at 332.8 ± 0.2 keV, grows up, which was previously impossible to observe, even at high tape speeds, in the singles measurements. The intensity of this new transition was estimated to be about 10% of the 2433 keV transition. The 775 and 1219 keV γ rays which apparently are coincident with high energy β particles occur in ^{130}Sn and derive from a small contamination in the beam from mass 130, Ref. 4.

A multiscaling measurement of the high energy β rays yielded the short half-life of 0.27 ± 0.02 s as is shown in Fig. 10. Approximately the same half-life was obtained by multiscaling the 2433 keV γ ray. In order to get an estimate of the half-life of the 332.8 keV γ ray β-γ coincidence experiments were performed at several different tape speeds. As the intensity ratio of the 332.8 and 2433 keV transitions did not vary, it is concluded that the half-lives are approximately the same. Although the decay of ^{131}In is supposed to involve two half-lives, as do the lighter odd-mass In decays, it has not been possible to find a second half-life, e.g., by varying the β energy in β multiscaling experiments. Two very close half-lives do, however, fit the systematics as the lifetime ratio of the $\frac{9}{2}^+$ and $\frac{1}{2}^-$ In isomers more and more approaches unity when the mass gets closer to 131. The 0.27 s half-life is therefore assigned to both types of ^{131}In decay, but with a larger estimated error, ±0.10 s, for the decay of the $\frac{1}{2}^-$ state, which had a lower intensity. A γ-γ coincidence measurement with the gate at 2433 keV yielded negative results.

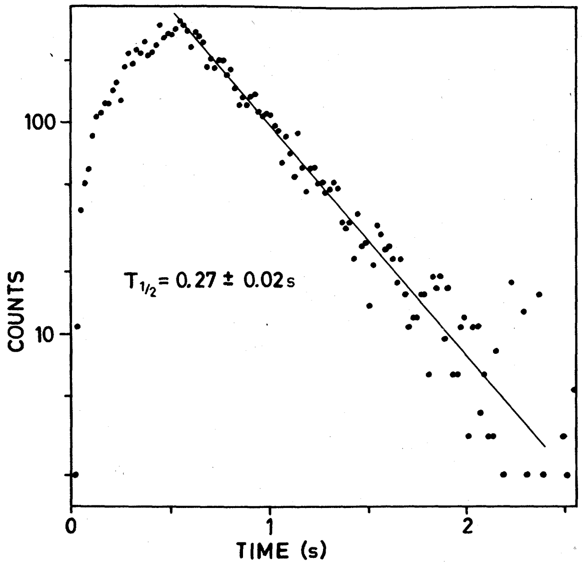

FIG. 10. Decay curve for β particles of energy greater than 4.0 MeV at mass 131. The curve displays a half-life of 0.27 ± 0.02 s.

The Q value of ^{131}In has not been measured previously. In order to do that, β spectra were collected by an anthracene detector, first at the beam deposition point and then, to get the background, 110 mm down the tape. With a tape speed of 12.5 mm/s this corresponds to an average delay of 9 s. The spectra are shown in Fig. 11. The bump in the lower spectrum at about 6.5 MeV is due to the fact that the range in anthracene of β particles above about 6.5 MeV exceeds the thickness (25 mm) of the detector that was available for use. A Kurie plot analysis of the 4–6 MeV portion of the lower spectrum yields an end-point energy of 6.39 ± 0.20 MeV. The error includes the uncertainties due to a β branch corresponding to the high energy bump. With the 6.39 MeV component subtracted the next end-point analysis yields 3.80 ± 0.15 MeV, in agreement with the results for the ^{131}Sn^g → ^{131}Sb (798 keV level) decay by Aleklett *et al.*[13] and Keyser *et al.*[27] of 3.82 ± 0.30 MeV and 3.89 ± 0.15 MeV, respectively. With a ^{131}In → ^{131}Sn high spin decay as proposed below, the 6.39 MeV end-point energy corresponds to a Q value of 8.82 ± 0.20 MeV. The high energy β

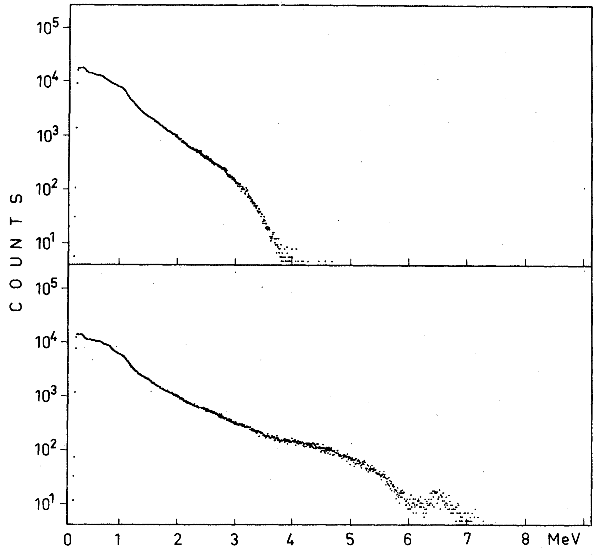

FIG. 11. Mass 131 β spectra recorded with an anthracene detector at a moving tape speed of 12.5 mm/s. The lower spectrum was obtained directly and the upper one after an average delay of 9 s. The bump in the lower spectrum at about 6.5 MeV is due to the limited thickness (25 mm) of the detector. A Kurie plot analysis of the 4–6 MeV portion of the direct spectrum yields an end-point energy of 6.39 ± 0.20 MeV.

particles detected in the bump are supposed to be due to the low spin decay, which, with the unknown separation of the ^{131}In isomers ignored, should correspond to an end-point energy of 8.5 MeV.

The low spin decay amounts to about 12% of the high spin decay, but this number and the relative intensities of the 332.8 and 2433 keV γ rays are too uncertain to make possible an estimate of the relative β feeding of the $d_{3/2}$ and $s_{1/2}$ states as was done for the ^{127}In and ^{129}In decays. For the logft calculation it is assumed that the feedings of the two levels are equal.

Level schemes

The 2433 and 332.8 keV transitions are the only ones in the two schemes of $^{131}\mathrm{In}^{g} \rightarrow {}^{131}\mathrm{Sn}^{g}$ and $^{131}\mathrm{In}^{m} \rightarrow {}^{131}\mathrm{Sn}^{g}$ decay proposed in Fig. 12. The assignment of the 2433 keV γ ray to the decay of the expected $g_{7/2}$ neutron hole state in ^{131}Sn is based on the low logft value for the assumed allowed $g_{9/2} \rightarrow g_{7/2}$ spin flip β^- transition and on systematics from the now long series of lighter odd-mass Sn nuclides. The 332.8 keV γ ray has been assigned to be a $s_{1/2} \rightarrow d_{3/2}$ transition based mainly on systematics. It cannot be due to an $h_{11/2} \rightarrow d_{3/2}$ $M4$ transition as it is observed in coincidence with β particles. A possibility is of course that the 332.8 keV transition represents a state in In populated in the decay of Cd. In such a case it would be the transition between the $f_{5/2}$ and $p_{1/2}$ excited states, whereas the latter mainly decays by β emission. However, this interpretation would imply an unexpectedly high fission yield of ^{131}Cd.

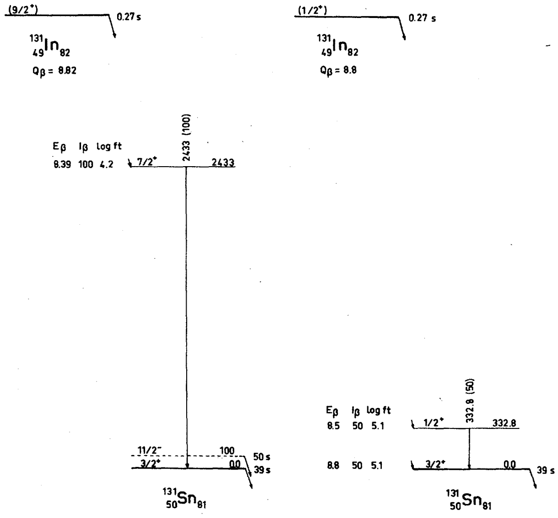

FIG. 12. Decay schemes proposed for the 0.27 s $g_{9/2}$ and 0.27 s $p_{1/2}$ states of ^{131}In. The excitation energy of the $h_{11/2}$ isomeric state is obtained only from extrapolation from neighboring odd-mass nuclides with more protons or neutron holes. In the high spin decay it is assumed that the direct feed of the $h_{11/2}$ state by a first forbidden β^- transition can be neglected as compared to the allowed transition to the $g_{7/2}$ state. In the low spin decay equal feeding of the $d_{3/2}$ and $s_{1/2}$ states is assumed.

If one follows the $N=81$ and $Z=50$ systematics one can predict a ^{131}Sn $d_{3/2}$ ground state and a $h_{11/2}$ isomer at about 0.1 MeV. Because of its low excitation and high probability for β emission, the $h_{11/2}$ state is not expected to be observed through an isomeric transition. The only way to establish such a state would be to observe two ^{131}Sn half-lives. These have also been observed (39 s for the $d_{3/2}$ decay, and 50 s for the $h_{11/2}$ decay).[20]

IV. CONCLUSIONS

The measurements on the decay of ^{131}In have, with the aid of studies of the ^{127}In and ^{129}In decays, resulted in the determination of the relative $2d_{3/2}$, $3s_{1/2}$, and $1g_{7/2}$ neutron single-hole energies. Relative to the $2d_{3/2}$ orbit these are 0, 332.8 ± 0.2, and 2433 ± 1 keV, respectively. The position of the $1h_{11/2}$ single hole has not been measured but can, from the systematic picture which is now complete both from the proton particle and neutron hole sides, be predicted at about 100 keV. The remaining single hole energy in the fifth major shell, the $2d_{5/2}$, which is expected above the $1g_{7/2}$ has not been observed, presumably due to a very low intensity of a ≤ 6 MeV first forbidden unique $p_{1/2} \rightarrow d_{5/2}$ β transition.

In ^{127}Sn and ^{129}Sn negative parity three quasiparticle states have been identified at 0.64–1.05 MeV excitation. These have been discussed together with corresponding states in lighter odd-mass

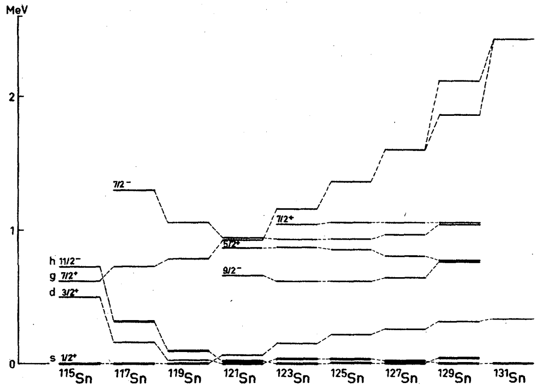

FIG. 13. Energy level systematics in odd-mass heavy isotopes of Sn. In addition to the $s_{1/2}$, $d_{3/2}$, $h_{11/2}$, and $g_{7/2}$ single quasiparticle energies the $\frac{9}{2}^-$ and $\frac{7}{2}^-$ three quasiparticle states and the $\frac{7}{2}^+$ and $\frac{5}{2}^+$ members of the one-phonon $d_{3/2}$ multiplet are shown.

Sn nuclides in a previous publication.[23] Candidates are also given for all members of a one-phonon $d_{3/2}$ multiplet in ^{127,129}Sn.

Figure 13 gives the energy systematics in heavy odd-mass Sn of the states of high single particle strength, of the identified negative parity three quasiparticle states and of the $\frac{7}{2}^+$ and $\frac{5}{2}^+$ members of the one-phonon $d_{3/2}$ multiplet.

Isomers are expected to occur in several neutron hole nuclei close to ^{132}Sn due to the low lying $h_{11/2}$ orbit. In the short-lived decay of mass 127 and 129 isotopes γ rays occur which are delayed by isomeric levels of 3 μs half-lives. From multispectra measurements it is suggested that these isomeric levels are levels in Sn.

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