

Decay of ^{111,112,113,114,115}Sb

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The decay of the isotopes ¹¹¹Sb ($T_{1/2} = 75.5$ sec), ¹¹²Sb ($T_{1/2} = 51.4$ sec), ¹¹³Sb ($T_{1/2} = 6.67$ min), ¹¹⁴Sb ($T_{1/2} = 3.51$ min), and ¹¹⁵Sb ($T_{1/2} = 32.1$ min) is investigated. Decay schemes are proposed and compared to previously available data and theoretical calculations. Some systematic trends are discussed.

[RADIOACTIVITY ^{111, 112, 113, 114, 115}Sb [from (^{112,114}Sn (p, xn or d, n)); measured $T_{1/2}$, E_γ , $\gamma\gamma$ coin; deduced $\log ft$, ^{111, 112, 113, 114, 115}Sn deduced levels, J , π . Enriched targets, mass separated sources.]

I. INTRODUCTION

The nuclear structure of the neutron-deficient tin isotopes has been studied by reaction spectroscopy with many different reactions.¹⁻⁸ The decay of the light Sb isotopes was investigated by Singh *et al.* and Miyano *et al.*⁹⁻¹¹ Their sources were produced with ^{112,114}Sn(p, xn) reactions. Although their results were published during the course of our investigation, we continued as our setup gave much cleaner sources, especially when mass separation could be applied, and a much better resolution could be achieved. Moreover, only very few coincidence data were given by these authors, and our use of a Compton-suppressed system gave the possibility to detect many weak γ rays which were not observed by them.

The decay of ¹¹⁵Sb was studied by several authors¹²⁻¹⁴ with some contradictory results. Kiselev and Burmistrov¹³ assigned only one γ ray to the decay of ¹¹⁵Sb and gave upper limits for the intensity of possible other γ rays. On the other hand, Rahmouni¹⁴ assigned several other γ rays to this decay, some of which with intensities exceeding the limits given by Kiselev and Burmistrov.

The much more complete decay schemes of ¹¹¹⁻¹¹⁵Sb resulting from our experiments make a comparison with detailed theoretical calculations more meaningful.

II. EXPERIMENTAL PROCEDURES

A. Source production

Sources were obtained with enriched ¹¹²Sn or ¹¹⁴Sn targets. Also natural tin targets were used in combination with isotope separation. The latter procedure could only be applied to ^{113,114,115}Sb as the half-lives of ^{111,112}Sb are too short. For the production of the activities the AVF cyclotron of the Vrije Universiteit is used. A pneumatic system for the transport of the irradiated foils from

the cyclotron to the isotope separator or the low background measuring facilities offers the possibility to start the measurements 5 sec after the end of the irradiation for unseparated sources and after about 3 min for separated Sb sources.¹⁵ The reactions used to produce the sources are tabulated in Table I.

B. Single counter γ ray spectroscopy

For the detection of the γ rays Ge(Li) detectors with relative efficiencies of about 13% and resolutions between 2.1 and 2.4 keV at 1.33 MeV were used. The area below 100 keV was measured with a röntgendetector giving a resolution of 220 eV at 5.9 keV. The sources produced on enriched targets were measured with an anti-Compton system.¹⁵ The sizes of the surrounding cylindrical NaI(Tl) crystal are 20 cm \times 27 cm, and the peak-to-Compton ratio is improved by a factor of about 7 for the Compton edge of a ⁵⁶Co spectrum. The mass separated sources are too weak to be measured with this system. An example of the resulting γ ray spectra is given in Fig. 1. For the determination of the intensity of the annihilation radiation, separate measurements were performed with the sources put between two Al absorbers with thickness of 15 mm at a distance of 15 cm from the detector.

TABLE I. Reactions used for the production of the sources.

Enriched targets	Mass separation
¹¹² Sn($p, 2n$) ¹¹¹ Sb at 28 MeV	
¹¹² Sn(p, n) ¹¹² Sb at 15 MeV	
¹¹² Sn(d, n) ¹¹³ Sb at 7 MeV	(¹¹⁴ Sn($p, 2n$) ¹¹³ Sb at 28 MeV
¹¹⁴ Sn(p, n) ¹¹⁴ Sb at 14 MeV	(¹¹⁴ Sn(p, n) ¹¹⁴ Sb at 20 MeV
	(¹¹⁶ Sn($p, 3n$) ¹¹⁴ Sb at 30 MeV
¹¹⁴ Sn(d, n) ¹¹⁵ Sb at 7 MeV	(¹¹⁶ Sn($p, 2n$) ¹¹⁵ Sb at 28 MeV

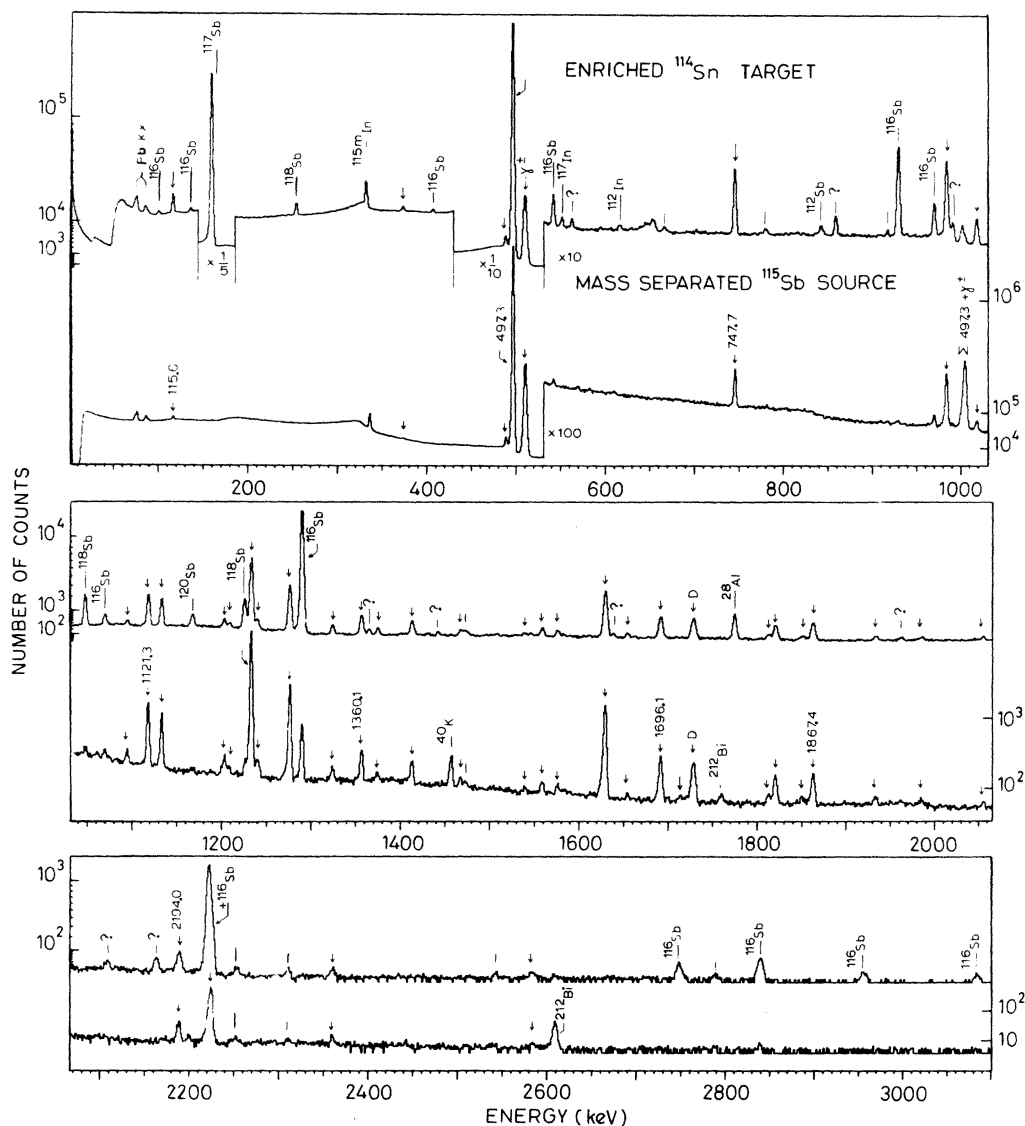


FIG. 1. Typical γ ray spectra of ^{115}Sb . The upper spectrum was measured with the anti-Compton system on sources produced on enriched targets. The lower spectrum was measured on mass-separated sources. The intensity of contaminating isotopes with $A \approx 115$ is reduced to $< 0.1\%$ of the intensity of the strongest ^{115}Sb γ ray. The ^{115}Sb γ rays are marked by arrows. Weak γ rays which also possibly belong to this decay, but could not definitely be assigned are marked by dashes.

C. γ - γ coincidence measurements

Two-dimensional Ge(Li)-Ge(Li) coincidence experiments were performed 4096×4096 in the geometry shown in Fig. 2, so large solid angles are used. Coincidences which result from Compton scattering from one detector into the other, or from detection of both β^+ annihilation quanta, are strongly reduced.

The anti-Compton system was used as level spectrometer.¹⁶ The results of these experiments were used for the assignment of ground state transitions.

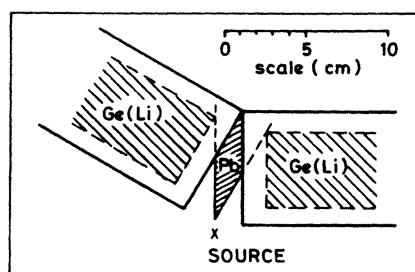


FIG. 2. The detector geometry for the γ - γ coincidence measurements.

TABLE II. Survey of some experimental results.

Isotope	Number of observed γ rays	Half-life	Part of the total observed γ ray intensity placed in decay scheme (%)	Strongest γ rays	
				$E_{\gamma} \pm \Delta E_{\gamma}$	$I_{\gamma} \pm \Delta I_{\gamma}$
^{111}Sb	49	75.5 ± 1.2 sec	98	100.24 ± 0.03	83 ± 7
				154.48 ± 0.03	1700 ± 80
				489.1 ± 0.1	1000
				$511 \gamma^{\pm}$	4800 ± 400
				755.4 ± 0.1	123 ± 7
				1032.6 ± 0.1	240 ± 20
^{112}Sb	121	51.4 ± 1.0 sec	97.5	$511 \gamma^{\pm}$	1831 ± 90
				670.0 ± 0.4	39 ± 6
				894.6 ± 0.2	28 ± 3
				990.9 ± 0.1	149 ± 4
				1098.0 ± 0.2	20 ± 2
				1257.05 ± 0.08	1000
^{113}Sb	69	6.67 ± 0.07 min	99.6	88.25 ± 0.02	34 ± 4
				332.41 ± 0.05	185 ± 8
				497.96 ± 0.09	1000
				$511 \gamma^{\pm}$	1683 ± 40
				935.77 ± 0.06	21 ± 2
				940.63 ± 0.06	33 ± 2
^{114}Sb	121	3.51 ± 0.04 min	98.4	327.18 ± 0.05	73 ± 5
				$511 \gamma^{\pm}$	1720 ± 80
				717.32 ± 0.07	47 ± 3
				887.57 ± 0.05	179 ± 5
				974.82 ± 0.07	29 ± 3
				1299.92 ± 0.07	1000
^{115}Sb	41	32.1 ± 0.3 min	>99.9	115.6 ± 0.1	2.4 ± 0.2
				489.3 ± 0.7	13 ± 3
				497.31 ± 0.08	1000
				$511 \gamma^{\pm}$	650 ± 14
				1236.6 ± 0.2	5.9 ± 0.3
				1633.8 ± 0.2	3.6 ± 0.2

III. EXPERIMENTAL RESULTS

A. Single measurements

Many previously not observed γ rays could be assigned to the decay of the investigated isotopes. Detailed lists of the γ -rays, their energies and relative intensities, and the γ ray spectra are given elsewhere.^{15,17} They have been submitted to the Nuclear Data Group. Table II gives a survey of the numbers of assigned γ rays obtained from our work, the half-lives, and the percentage of the total observed γ ray intensity that could be placed in the decay scheme. For each isotope, the energy and relative intensity of the most intense γ rays and γ^{\pm} are given in the last two columns.

The half-lives of the isotopes were determined from the decay of the most intense γ rays, which was followed during at least five half-lives. Only for ^{112}Sb a discrepancy was found with previously

given values [53.5 ± 0.5 sec (Ref. 9) and 56 ± 1 sec (Ref. 11)]. The reason for this is not clear.

B. Coincidence data

Between the γ rays, many coincidence relations were observed. Some of the coincidence spectra and the complete listing of the observed coincidence relations have been given elsewhere.^{15,17} In some cases multiplets which were not resolved in the singles measurements could be unraveled by the coincidence experiments. In Fig. 3 parts of the single ^{113}Sb γ ray spectrum and the spectra observed in coincidence with the γ rays at 332.4 and 498.0 keV are shown. The multiplet at about 1240 keV appears to be a quintet of which two components, at 1236.8 and 1242.8 keV, are coincident with the 332.4 keV γ ray and two other ones, at 1234.2 and 1246.2 keV, are coincident with the

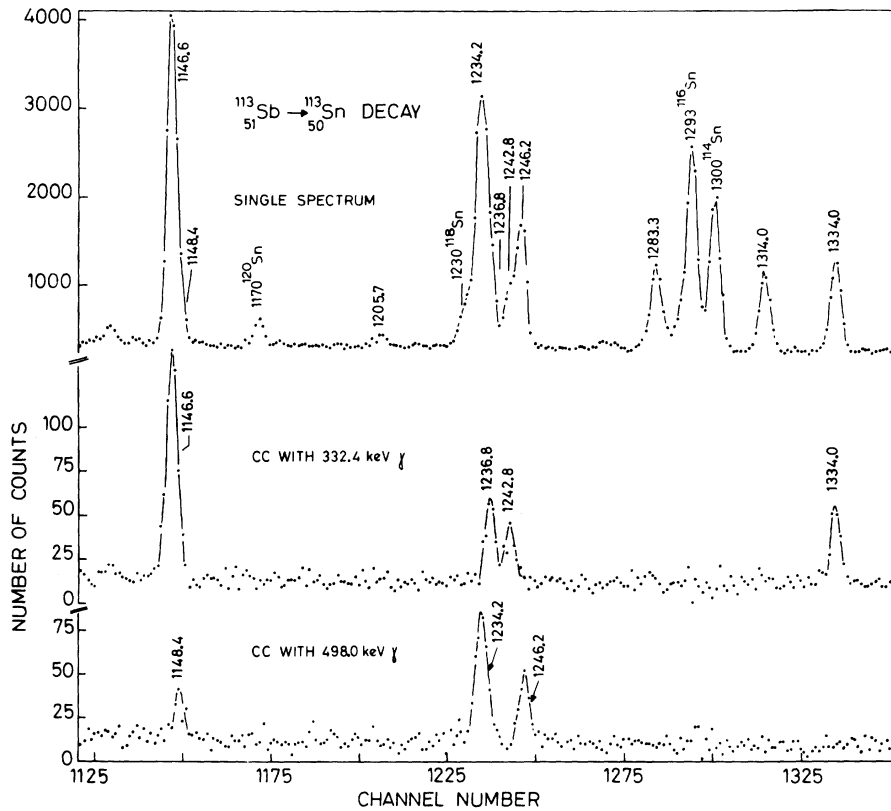


FIG. 3. The unraveling of multiplets by means of the coincidence criterion (see text).

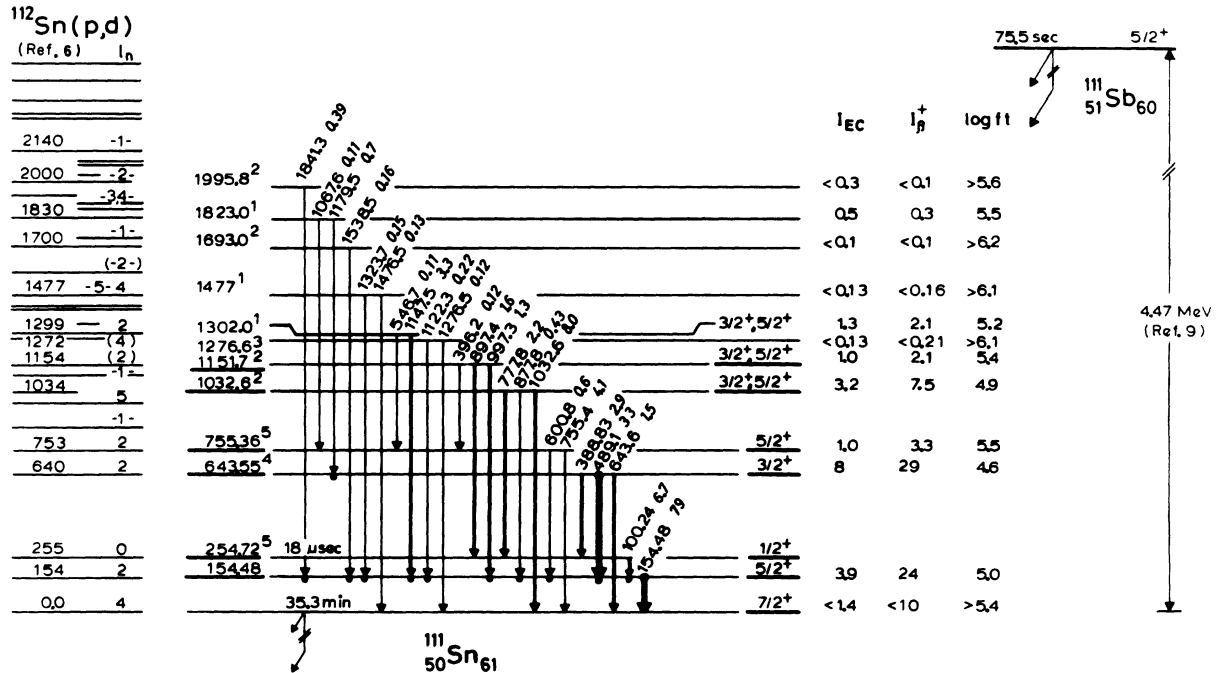


FIG. 4. The decay scheme of ^{111}Sb .

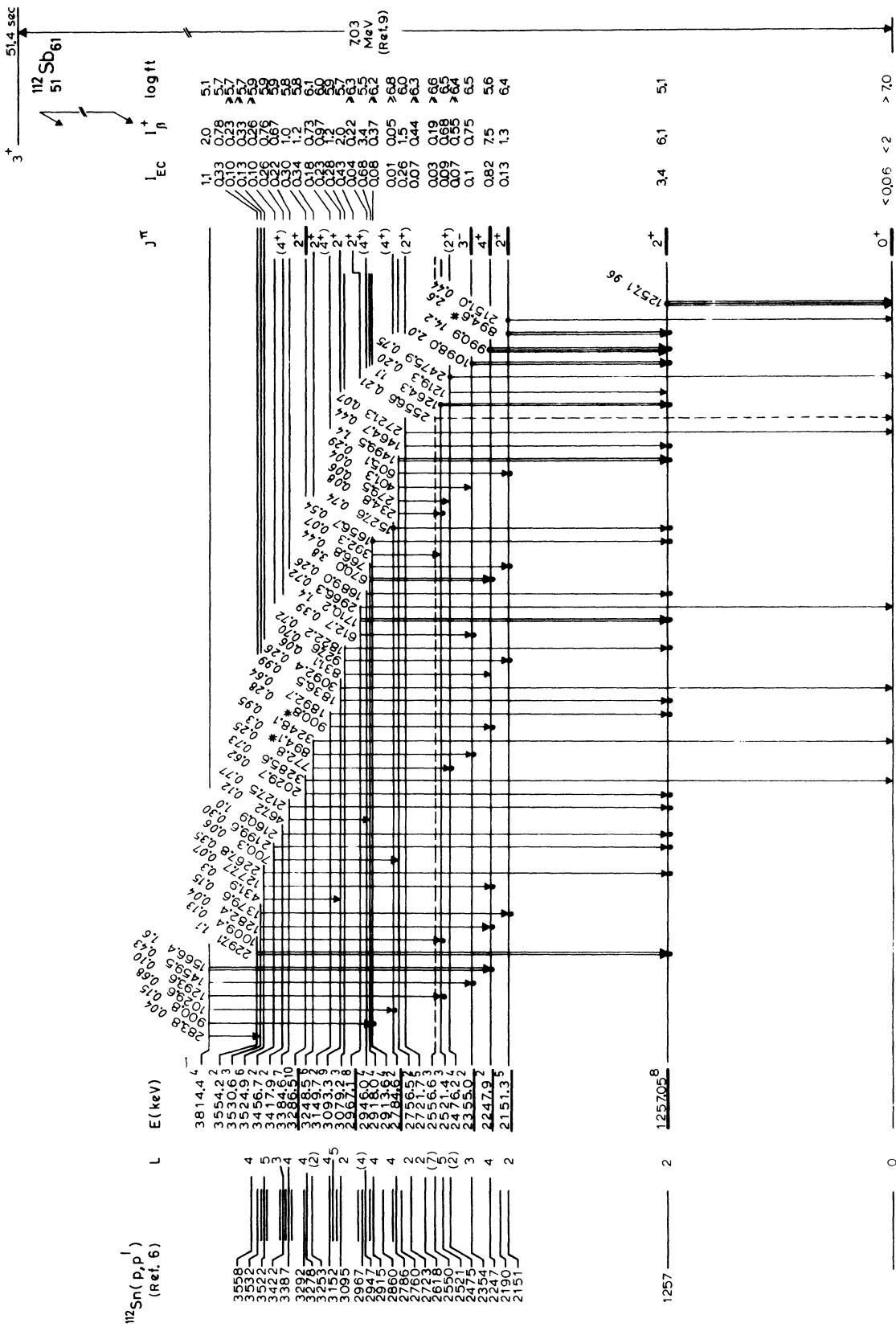


FIG. 5. The decay scheme of ¹¹²Sb.

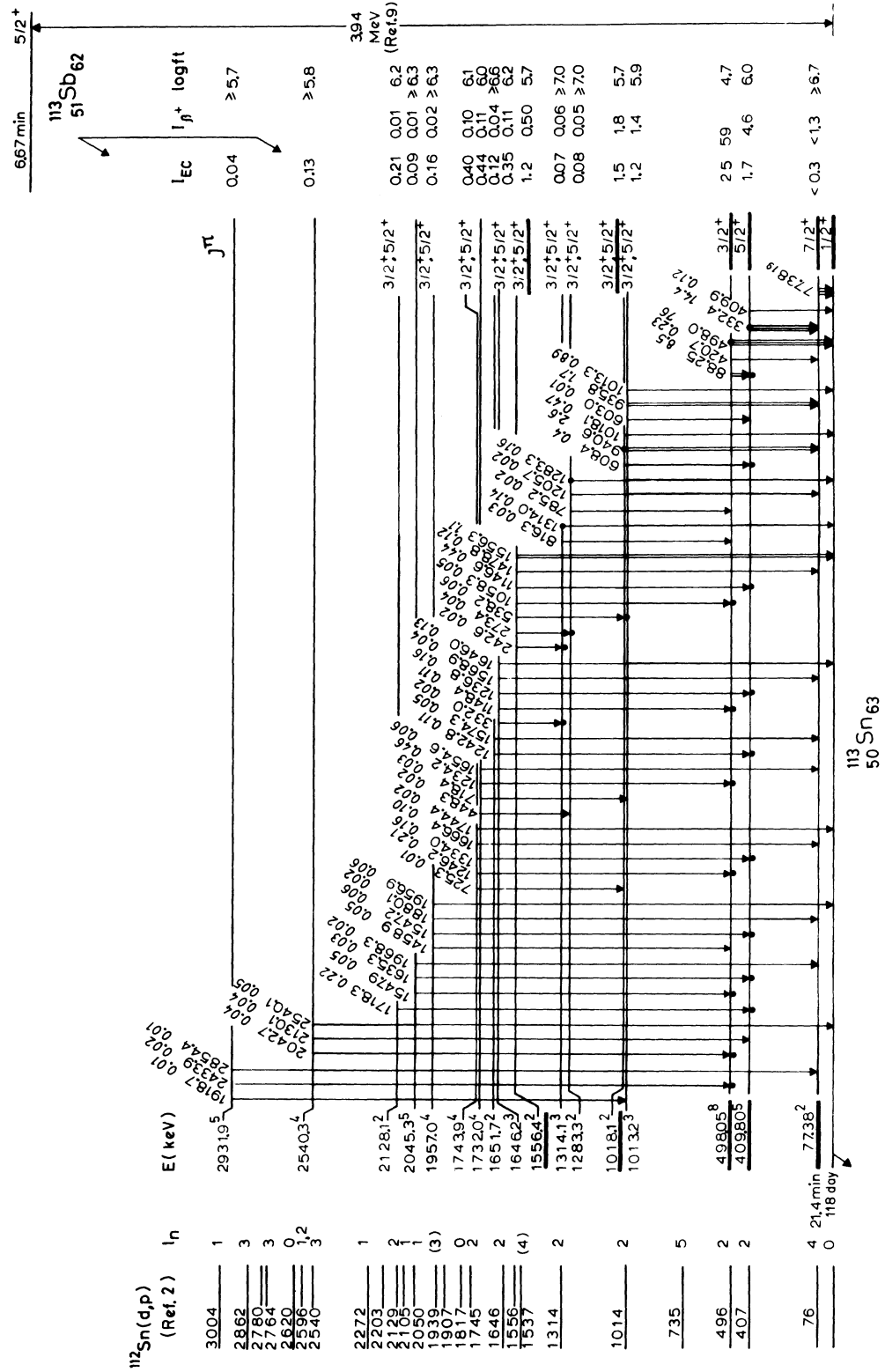


FIG. 6. The decay scheme of ^{113}Sb .

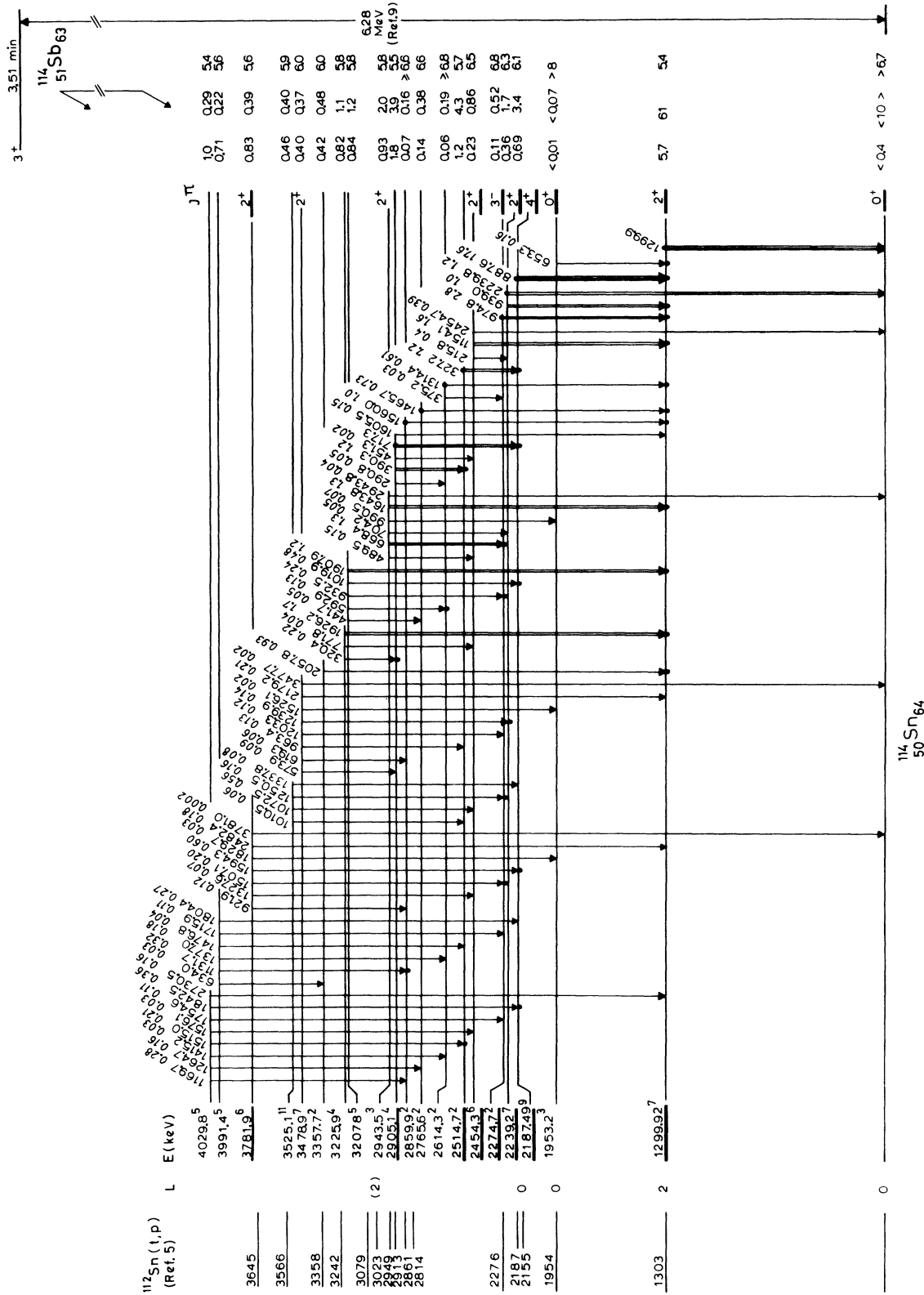


FIG. 7. The decay scheme of ¹¹⁴Sb.

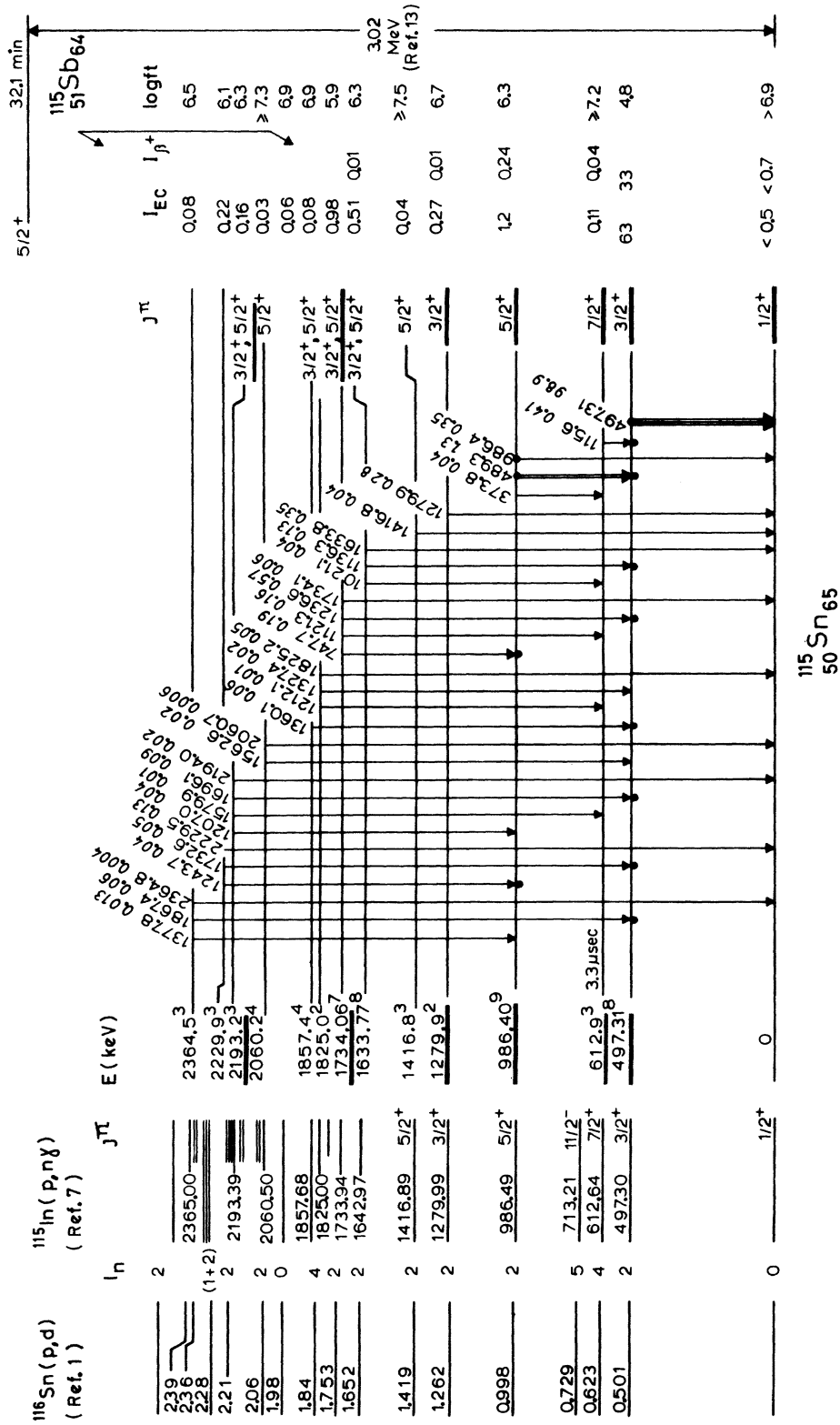


FIG. 8. The decay scheme of ^{115}Sb .

498.0 keV. The doublet at about 1147 keV is also unraveled by the coincidence spectra. In such cases the energy of the components of the multiplet could be determined more accurately from the coincidence spectra than from the single spectra.

From the Ge(Li)-NaI(Tl) anticoincidence experiments with the level spectrometer suppression factors for many γ rays could be determined. These were used afterwards for an additional check on the proposed decay schemes.

IV. DECAY SCHEMES

The decay schemes are given in Figs. 4–8. In these figures also the most relevant information from reaction studies is presented. Spins and parities for the levels were only included if the number of possible values for J^π could be restricted to one or two. A level was assumed to be directly fed if the intensity of the determined direct level feeding exceeds the total intensity of the three most intense unplaced γ rays.

New levels in the daughter nuclei were only proposed if they could be based on coincidence relations. Sum relations on the energies of γ rays were only used as additional arguments. It appeared that several levels proposed by other authors and mainly based on energy relations had to be refuted because of the results of the coincidence experiments. The energy and J^π values of levels which were already known from previous decay work, and underlined in Figs. 4–8. Levels which are based on just one γ ray are dashed if no further evidence for their existence was obtained from reaction experiments. The proposed decay schemes are consistent with the results of the level spectrometer experiments and with the measured intensity of the β^+ annihilation radiation. The following special remarks about the decay schemes of the separate isotopes should be made.

A. ^{111}Sb

The intensities of the 100.24 and 154.48 keV transitions have been arbitrarily corrected with the theoretical conversion coefficients $\alpha = 1.43$ and 0.32,¹⁸ respectively, under the assumption of pure $E2$ transitions, as the $d_{5/2} \rightarrow g_{7/2}$ $M1$ transition is l forbidden. From this, an upper limit for the β feeding of the ^{111}Sn ground state is given. Supporting evidence for the proposed decay scheme was gained from the analysis of an in-beam γ - γ coincidence measurement on the reaction $^{112}\text{Sn}(p, pn\gamma)^{111}\text{Sn}$ by Kamermans.¹⁹ Some levels which are only weakly populated in the ^{111}Sb decay, are excited more strongly in this reaction. The spin and parity of the first five states in ^{111}Sn were

already well known.^{1,9} We assigned $J^\pi = \frac{3}{2}^+, \frac{5}{2}^+$ to levels at 1032.6 and 1151.7 keV, which are fed by allowed β decay and feed the $\frac{1}{2}^+$ state at 254.7 keV. Moreover, $J^\pi = \frac{3}{2}^+, \frac{5}{2}^+$ was assigned to the 1302.0 keV level because of the allowed β feeding and the $l = 2$ angular distribution in the (p, d) experiment of Blankert and Blok.⁶

B. ^{112}Sb

The well-established spin and parity assignments for the levels at 1257.05, 2247.9, and 2355.0 keV, being $J^\pi = 2^+, 4^+$, and 3^- , respectively, are based on the results of inelastic scattering,^{6,20,21} (p, t) ,⁴ and $(\alpha, 2n\gamma)$ ⁸ experiments. The allowed β transitions to the 2_1^+ and 4_1^+ levels indicate that ^{112}Sb has a 3^+ ground state.⁹ From this, 2^+ could be assigned to levels which are fed by allowed or first order forbidden nonunique β decay and from which the ground state transition is observed. J^π values are given between brackets if the assignment was based on the L values found from the (p, p') experiment by Blankert and Blok.⁶

C. ^{113}Sb

Concerning the normalization, a special problem arose from the fact that the intensity of the 77.38 keV transition could not be determined directly, as the 77.38 keV isomeric state in ^{113}Sn is very strongly produced in the irradiation. Its total intensity was deduced from the decay scheme and the intensity of γ^{\pm} , assuming that there is no direct ground state feeding. The observed 88.25 keV γ ray transition intensity had to be corrected for internal conversion. A value $\alpha = 1.6 \pm 0.8$ was used for this purpose.^{15,18} Spin and parity of the first four levels were known from previous studies.^{1,2,3,22} $J^\pi = \frac{3}{2}^+, \frac{5}{2}^+$ was assigned to levels which are fed by allowed β decay and feed the ground state.

D. ^{114}Sb

In their work Singh *et al.*⁹ found two γ rays, at 545 and 974 keV, which have a 8 ± 2 min component in their decay. They assigned these γ rays to the decay of an unknown 8^- isomeric state in ^{114}Sb which should have a half-life of 8 ± 2 min. This is not confirmed by our measurements. From a mass-separated source measurement, it appears that the decay of the 974.8 keV γ ray can be fitted very well with just a 3.5 min component (cf. Fig. 9). In the γ ray spectrum, no peak was observed at 545 keV while a γ ray with the intensity given by Singh *et al.*⁹ should have been visible. Probably contaminating activities, viz., ^{111}In and ^{116m}Sb are responsible for the phenomena observed by Singh *et al.*⁹ The strong β branching to the 2_1^+ and 4_1^+ in-

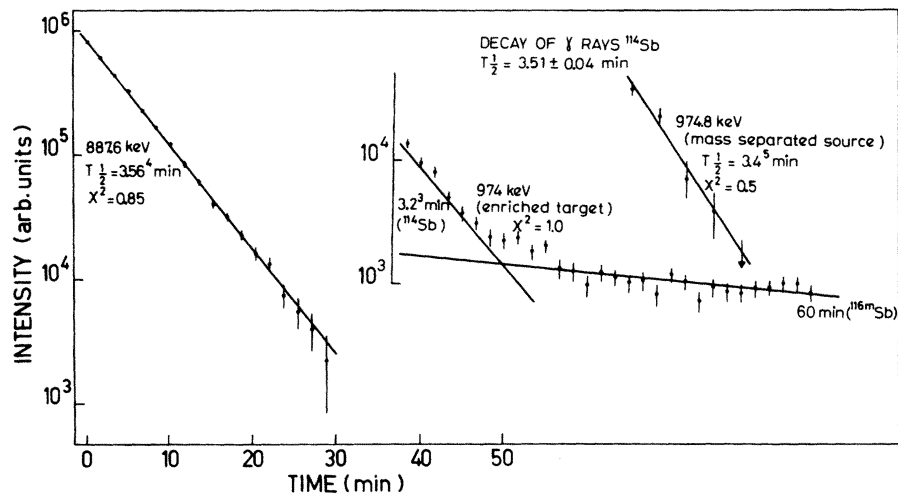


FIG. 9. The decay of some ^{114}Sb γ rays together with the results of a computer fit. The decay of the 974 keV γ ray is given for sources produced on enriched ^{114}Sn targets and for mass-separated sources.

dicates that ^{114}Sb has a 3^+ ground state.⁹ Hence, 2^+ was assigned to levels which are fed by allowed or first order forbidden nonunique β decay and have a ground state transition.

A very low-lying 0^+ state in ^{114}Sn , at 1.58 MeV,

reported by Schneid, Prakash, and Cohen,³ was not observed in the decay of ^{114}Sb . Another low-lying 0^+ state, however, was observed in our experiments. This level, at 1953.2 keV, was also reported by several other authors.^{3, 5, 23}

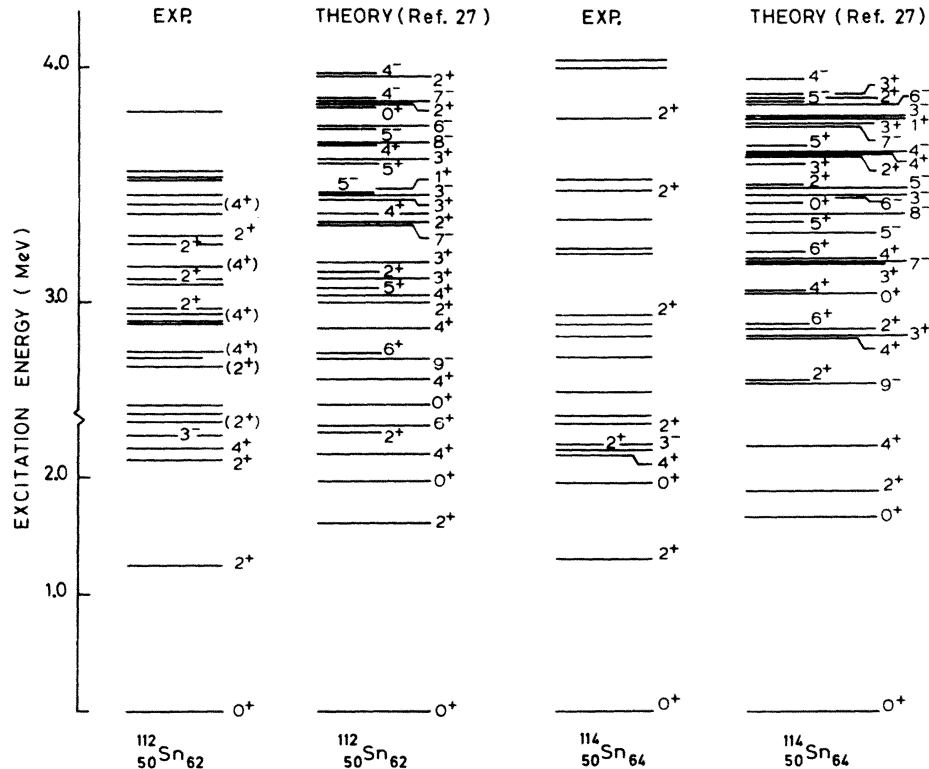


FIG. 10. Comparison of the experimental level schemes of $^{112,114}\text{Sn}$ as found from β decay with the theoretical results of van Gunsteren *et al.* (Ref. 27).

TABLE III. Comparison of experimental and theoretical results for the even-even Sn nucleus.

Isotope	Number of 2^+ states		Number of 4^+ states		Number of states with $J^\pi = 2^+, 3^+, 4^+, 2^-, 3^-, \text{ and } 4^-$	
	Exp.	Theory (Ref. 27)	Exp.	Theory (Ref. 27)	Exp.	Theory (Ref. 27)
^{112}Sn	8	7	6	6	≥ 17	19
^{114}Sn	5	6	?	5	≥ 17	20

E. ^{115}Sb

Corrections for internal conversion were applied for the 115.6 and 497.31 keV transitions, employing the conversion coefficients measured by Ivanov *et al.*²⁴ and Selinov *et al.*²⁵ The J^π values given by Cavanagh *et al.*¹ and Swengler and Stelzer⁷ were taken over by us, as our data are not in contradiction with them. Furthermore, $J^\pi = \frac{3}{2}^+, \frac{5}{2}^+$ was assigned to levels at 1633.77, 1734.08, 1825.0 and 2193.2 keV, because these levels are fed by allowed or first order forbidden nonunique β decay and decay to the $\frac{1}{2}^+$ ground state and the $\frac{7}{2}^+$ state at 612.9 keV.

V. DISCUSSION

A. Even-even tin nuclei $^{112,114}\text{Sn}$

The lowest-lying states in $^{112,114}\text{Sn}$, viz., the 2_1^* , the $0_2^*, 2_2^*, 4_1^*$ triplet, and the 3_1^- states might be considered as vibrational states. From our work, a large two-phonon component in the wave function of the 2_2^+ state is suggested from the branching ratio of its γ decay. If the transition $2_2^+ - 2_1^+$ is assumed to be pure $E2$, we find for the experimental branching ratios $B(E2)_{2_2^+ - 0_1^+}/B(E2)_{2_2^+ - 2_1^+}$ values of 2×10^{-3} for ^{112}Sn and 1.5×10^{-2} for ^{114}Sn . However, the E_2/M_1 mixing ratios for the $2_2^+ - 2_1^+$ transition which were measured for some of the heavier tin isotopes²⁶ (e.g., 23.6% $M1$ in ^{116}Sn) are in contradiction with this assumption of pure vibrational states. Also the two-quasiparticle description, which we discuss in the following, contradicts the vibrational character of the $0_2^*, 2_2^*, 4_1^*$ triplet.

In Fig. 10 the level schemes of $^{112,114}\text{Sn}$ as constructed from the $^{112,114}\text{Sb}$ decay data are compared with the ones as calculated by van Gunsteren, Boeker, and Allaart²⁷ in their number-projected BCS model. They performed number-projected 2QP (QP denotes quasiparticle) calculations for a whole sequence of even Sn isotopes. The quasiparticles were distributed among the five subshells $2d_{5/2}, 1g_{7/2}, 2d_{3/2}, 3s_{1/2}, \text{ and } 1h_{11/2}$. The single-particle energies and the strength of the single-particle interactions were deduced from

spectroscopic data on the odd Sn isotopes and the odd-even mass difference. Unfortunately no transition probabilities were calculated, which makes a unique assignment difficult. In Table III the number of 2^+ and 4^+ states and the number of states with $J^\pi = 2^+, 3^+, 4^+, 2^-, 3^-, \text{ and } 4^-$, which can be fed by allowed or first order forbidden nonunique β decay, as found from our experiments and the calculations by van Gunsteren, are given for the region 0–4 MeV; these data agree very well. An interesting feature of the calculated spectra given in Fig. 10 is the occurrence of a low-lying 9^- state due to the coupling of $1h_{11/2}$ to $1g_{7/2}$ quasiparticles. If this state happens to occur as low as predicted, it would be an isomeric state, which might even be β unstable in ^{114}Sn .

B. Odd tin nuclei $^{111,113,115}\text{Sn}$

The lowest-lying states, viz., the first $\frac{5}{2}^+, \frac{7}{2}^+, \frac{1}{2}^+, \frac{3}{2}^+$, and $\frac{11}{2}^-$ states can be easily understood in terms of the simplest shell model as being single-neutron states. Also in quasiparticle calculations it turns out²⁸⁻³⁰ that the single quasiparticle strength is strongly concentrated in these states. Evidence for the admixture of more complex components in the wave functions may, among other things, be obtained from $\log ft$ values. For the $\frac{5}{2}^+ - \frac{3}{2}^+$ transition, we found values of 4.6, 4.7, and 4.8 in the decay of ^{111}Sb , ^{113}Sb , and ^{115}Sb , respectively, the single-quasiparticle value being 3.6.^{28,31}

It is interesting to compare the $\log ft$ values for the three low-lying states which are fed by allowed decay, viz., the $\frac{3}{2}^+, \frac{5}{2}^+, \text{ and } \frac{7}{2}^+$ states. They

TABLE IV. $\log ft$ values from the decay of neutron-deficient odd Sb ground states ($J^\pi = \frac{3}{2}^+$).

Isotope	Transition $J^i \rightarrow J^f$		
	$\frac{5}{2}^+ \rightarrow \frac{3}{2}^+$	$\frac{5}{2}^+ \rightarrow \frac{5}{2}^+$	$\frac{5}{2}^+ \rightarrow \frac{7}{2}^+$
^{111}Sn	4.6	5.0	≥ 5.4
^{113}Sn	4.7	6.0	≥ 6.7
^{115}Sn	4.8	6.3	≥ 7.2
^{117}Sn	4.8	6.5	7.6

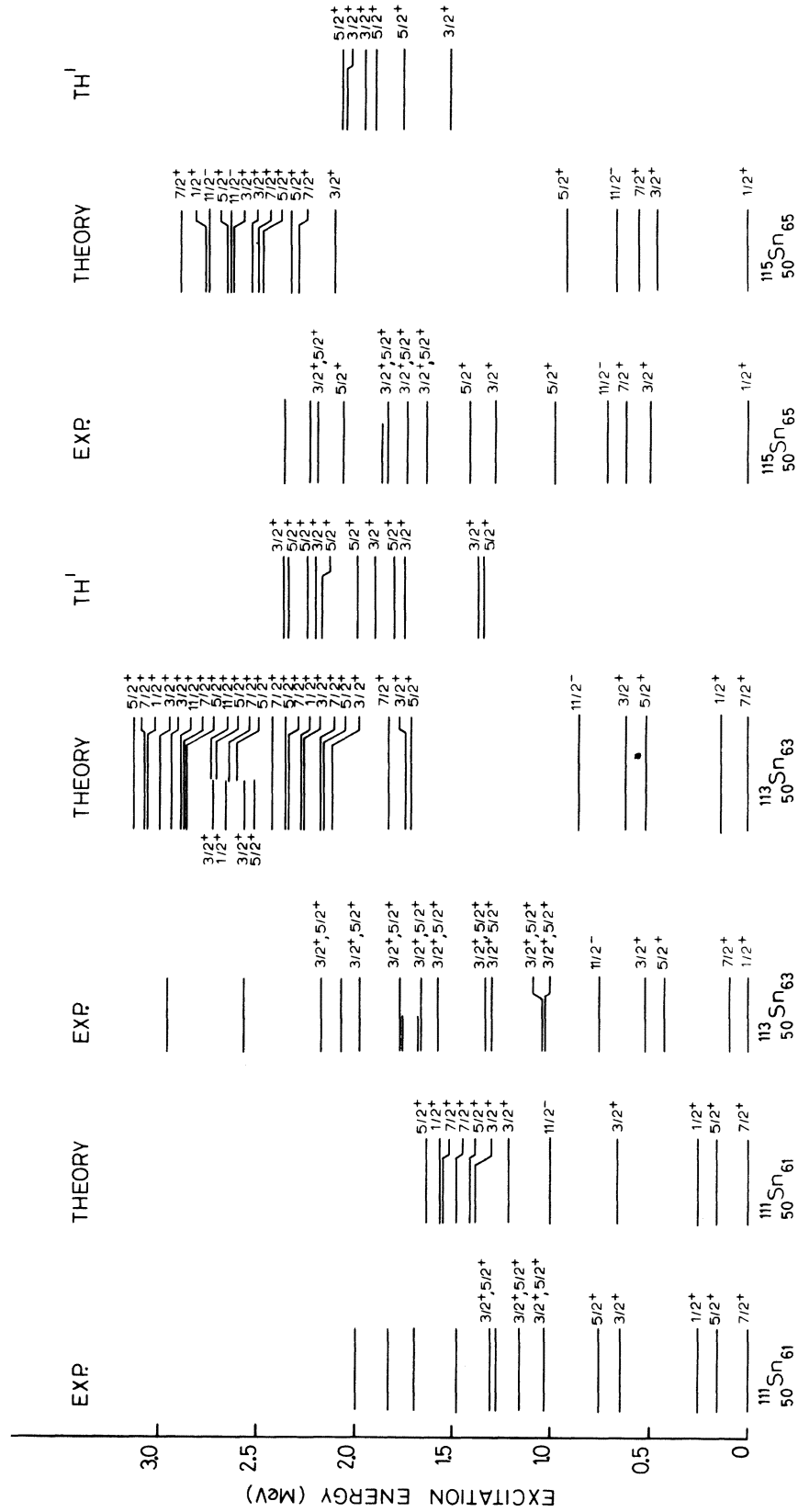


FIG. 11. Comparison of the experimental level schemes of ^{111}Sn , ^{113}Sn , ^{115}Sn as found from β decay with the theoretical results of van Gunsteren *et al.*, (Ref. 30).

are given in Table IV. The data on ^{117}Sn were taken from Ref. 32. The large values for the $\frac{7}{2}^+$ level can be explained by the fact that the $\pi d_{5/2} - \nu g_{7/2}$ transition is l forbidden. The differences between the $\log ft$ values for the feeding of the $\frac{5}{2}^+$ and $\frac{3}{2}^+$ levels might be understood from the fact that the $2d_{3/2}$ shell is almost empty and the $2d_{5/2}$ shell is almost filled for these nuclei. A decrease of the $\log ft$ values with decreasing neutron number is consistent with this consideration.

Above 1 MeV the level density increases. The weak-coupling model might be useful in discussing this particular energy region. It has been applied to ^{117}Sn by Kuo, Baranger, and Baranger²⁹ and the results show a reasonable agreement with the experiments. In such a model, we expect for $^{111,113,115}\text{Sn}$ in the region between 1 and 2.5 MeV four $\frac{3}{2}^+$ states and four $\frac{5}{2}^+$ states by coupling of a quasiparticle to a quadrupole phonon. Experimentally, we find in this region at least four, nine, and seven states with $J^\pi = \frac{3}{2}^+, \frac{5}{2}^+$ for 111,113 , and ^{115}Sn , respectively.

Recently, van Gunsteren³⁰ performed number-projected 3QP calculations for the odd Sn isotopes with $A = 111-125$. The single-particle energies were chosen such that the energies of the lowest-lying levels of each J^π were best fitted to the experiment in a 3QP calculation. In Fig. 11 the experimental level schemes are compared with the results of such a calculation. Just as in the even Sn isotopes where the 2_1^+ state is calculated too high, here the distance between levels which mainly have a 1QP character and the levels whose wave functions mainly contain 3QP components is calculated too large. In the column TH' we selected the $\frac{3}{2}^+$ and $\frac{5}{2}^+$ levels found in the calculation and shifted them with an amount equal to the difference

between the experimental and calculated excitation energy of the 2_1^+ state in the even Sn nucleus with one neutron less. As van Gunsteren *et al.*²⁷ did not perform calculations on ^{110}Sn , this procedure was only applied to $^{113,115}\text{Sn}$. The energy shift amounts to -0.36 and -0.58 MeV for ^{113}Sn and ^{115}Sn , respectively. Now there is a reasonable agreement with the experimental level schemes. From this comparison, it seems that nearly all the $\frac{3}{2}^+$ and $\frac{5}{2}^+$ states in the region 1–2 MeV are found in the decay studies. It is remarkable that probably some of the $\frac{7}{2}^+$ states as predicted by this calculation are missing, although they may be fed by allowed β decay. It appears that, e.g., in ^{113}Sn the main components (25–35%) of the three lowest-lying $\frac{7}{2}^+$ states in this energy region are

$$\begin{aligned} & \{ [1g_{7/2}(n), 1g_{7/2}(n)]^{J=0}, 1g_{7/2}(n) \}^{J^{\pi}=7/2^+} \\ & \{ [3s_{1/2}(n), 3s_{1/2}(n)]^{J=0}, 1g_{7/2}(n) \}^{J^{\pi}=7/2^+} \\ & \{ [2d_{5/2}(n), 2d_{5/2}(n)]^{J=4}, 1g_{7/2}(n) \}^{J^{\pi}=7/2^+} \end{aligned}$$

and that in $>85\%$ of the wave functions $1g_{7/2}$ quasiparticles are involved. Just as for the 1QP state, the β transitions to these $\frac{7}{2}^+$ states could be hindered by l forbiddenness.

Just as for the even Sn nuclei, transition probabilities have to be calculated for further tests.

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