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Decays of ^{118}In, ^{120}In, and ^{122}In isomers to levels in ^{118}Sn, ^{120}Sn, and ^{122}Sn

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The nuclear excited states of ^{118}Sn, ^{120}Sn, and ^{122}Sn were studied by means of the decays of 4.45-min ^{118}In isomer, 46.2-sec and 47.3-sec ^{120}In isomers, and 10.3-sec and 10.8-sec ^{122}In isomers, respectively. The In activities were produced by the (n,p) reaction with 14-MeV neutrons on enriched samples of ^{118}Sn, ^{120}Sn, and ^{122}Sn. The γ rays, measured with a Ge(Li) detector, were incorporated into separate level schemes, each resulting from the decay of an individual In isomer. The experimental level schemes of ^{118}Sn, ^{120}Sn, and ^{122}Sn were compared with level schemes calculated on the basis of a broken-pair model that includes up to two broken pairs in the $50<N<82$ shell. This model is reasonably successful in explaining the experimental data for these nuclides.

I. INTRODUCTION

The study of the decays of even-mass In isotopes with $112 \leq A \leq 128$ is complicated because there are two, and sometimes three, isomers associated with each isotope[1–10] (see Table I). These isomers arise from the coupling of the $g_{9/2}$ proton hole with the $g_{7/2}$, $d_{3/2}$, $d_{5/2}$, $s_{1/2}$, and $h_{11/2}$ neutrons. To complicate matters further, the intermediate-spin and high-spin isomers of both ^{120}In and ^{122}In have very similar half-lives, as do the two known isomers of ^{126}In and ^{128}In. One possible approach to unraveling these isomers is to produce and study them via different nuclear reactions. Presumably the relative isomeric populations for a given nuclide would then be different enough to allow proper identification and assignment of γ rays and the construction of separate decay schemes. If the isomers are produced as fission products, another possible method of differentially enhancing the low-spin isomers is to carry out chemical separations of the Cd parents at appropriate junctures, as was done by Fogelberg and Carlé.[6]

We have produced the In isomers via the (n,p) reaction with 14-MeV neutrons. In the cases of the intermediate-spin isomer in ^{118}In, ^{120}In, and ^{122}In, our decay studies are significantly more detailed than those in the literature. Because the (n,p) cross section for the production of the high-spin isomer is much smaller than that of the corresponding intermediate-spin isomer, the amount of significant, new information generated by studying the high-spin isomer is less extensive. We have also studied the decays of ^{124}In isomers but have no results beyond what is already known.[8]

The experimental level schemes of ^{118}Sn, ^{120}Sn, and ^{122}Sn have been compared with those calculated on the basis of a broken-pair model that included up to two broken pairs (equivalent to generalized seniority $v_g \leq 4$) in the $50<N<82$ shell. The experimental level schemes have been quantitatively reproduced by these calculations. For most of the low-lying levels, it appears possible to establish a one-to-one correspondence between calculated and observed levels.

II. EXPERIMENTAL PROCEDURE

The In activities were produced by the Sn(n,p) reaction using samples of 97.1% enriched ^{118}Sn, 98.4% enriched ^{120}Sn, and 90.8% enriched ^{122}Sn. The samples were bombarded with 14-MeV neutrons from the Livermore high-flux facility, which produces $>10^{12}$ neutrons/sec from the ^{3}H(d,n)^{4}He reaction. After irradiation for approximately two half-lives of the isomer under study, each sample was transferred by pneumatic rabbit to the detection system, where successive spectra were accumulated for identification of γ rays by half-life. This cycle was repeated many times with γ-ray detection made by an 80-cm^3 closed-end coaxial Ge(Li) detector with 2.2-keV resolution at 1.33 MeV. The 4096-channel analyzer contained provisions for zero and gain stabilization, which were utilized in our measurements.

The Ge(Li) detector efficiency calibrations were done

TABLE I. Half-life ($T_{1/2}$) and spin-parity (J^π) values of pertinent In isomers.

Mass number A	Low-spin isomer $T_{1/2}$; J^π	Intermediate-spin isomer $T_{1/2}$; J^π	High-spin isomer $T_{1/2}$; J^π	Ref.
112	14.4 min; 1^+	20.9 min; 4^+		1
114	71.9 sec; 1^+	49.51 days; 5^+	43.1 msec; 8^-	2
116	14.10 sec; 1^+	54.15 min; 5^+	2.18 sec; 8^-	3
118	5.0 sec; 1^+	4.4 min; $(5)^+$	8.5 sec; $(8)^-$	4
120	3.0 sec; 1^+	44 sec; $(5)^+$		4
		46.2 sec; $(3^+,4^+,5^+)$	47.3 sec; (8^-)	5
			44 sec; $(8)^-$	6
122	1.5 sec; (1^+)	9.2 sec		4
	1.5 sec; 1^+	10.5 sec; $4^+,5^+$	10.5 sec; $(8)^-$	6
		10.3 sec; $(3^+,4^+,5^+)$	10.8 sec; (8^-)	7
124		3.17 sec; 3^+	2.4 sec; (5 to 8)	8
126		1.5 sec; 3^+	1.45 sec; (6,7,8)	9
128		0.9 sec; $(2,3)^+$	0.9 sec; $(7,8)^-$	10

with International Atomic Energy Agency (IAEA) sources, supplemented by the γ radiations from ^{56}Co, ^{82}Br, and ^{180}Hf. The uncertainties in the efficiency curves were 5% below 200 keV, 3% from 200 to 3500 keV, and 5% above 3500 keV. The photopeak positions and areas were obtained by the least-squares fitting of a modified Gaussian on a linear or quadratic background. The energy calibrations and nonlinearity corrections were determined with a large number of standard γ-ray lines, enabling us to make precise γ-energy determinations. The quoted uncertainties for γ-ray intensities include several factors, namely statistical uncertainties in peak areas and uncertainties in estimating the background of photopeaks, in decomposing complex peaks, in constructing the efficiency curve, and in the corrections for summing effects.

A great deal of information already exists in the literature concerning the energy levels in the relevant tin isotopes. Approximately 75% of the observed γ rays, especially nearly all of the relatively strong and certain ones, could be readily incorporated into these level schemes through a straightforward, albeit laborious, procedure. Therefore, we did not attempt any $\gamma\gamma$-coincidence measurements. Although not shown in the figures that follow, we also made generous use of existing relevant coincidence relationships in the construction of the level schemes.

III. EXPERIMENTAL RESULTS

Typical spectra are shown in Fig. 1. The actual energy range covered extended to 4 MeV. Only selected peaks are labeled by energy and proper account was made of all contaminant peaks through their measured energies, intensities, and half-lives. In comparing our results (see the following tables) with those obtained by previous workers, not all of the γ rays observed in the latter studies are included. Those omitted are, however, mainly weak and possibly unplaced or uncertain γ rays. Exceptions to the above are noted and discussed in the text. The Q values were taken from the Nuclear Data Sheets.[11–13]

A. ^{118}In decay

The energies and intensities of 67 γ rays assigned to the 4.45-min ^{118}In decay ($T_{1/2}$ value from Ref. 14) are given in Table II. Our overall results agree well with those reported by do Amaral *et al.*[14] and by Hattula, Liukkonen, and Kantele,[15] who produced the ^{118}In activities by the (γ,p) and (n,p) reactions, respectively. These authors reported 16 of the most intense γ rays observed in the current study (see Table II).

Fifty-one of the 67 γ rays listed in Table II were incorporated as 52 transitions (one γ ray placed twice) among 21 excited states of ^{118}Sn, as shown in Fig. 2. The unplaced γ rays are mainly very weak and some are of doubtful origin. The 971-keV γ ray was placed twice, with an intensity out of the 3374-keV level determined by the intensity balance for the 2403-keV level (where no β feeding is expected to occur), and the remaining intensity placed out of the 3460-keV level.

No evidence was found for the tentative 2779-keV level proposed by do Amaral *et al.*[14] because we were able to place the 1549-keV γ ray (which led to this level) out of the 3592-keV level. We also found no evidence for an $\simeq$1734-keV γ ray that was tentatively placed out of the 2963-keV level by both do Amaral *et al.*[14] and Hattula *et al.*[15] The weak 718-keV transition placed out of the 2999-keV, 6^+ level in Fig. 2 was assumed to be the same as the 719-keV transition observed in the ^{116}Cd(^{4}He,2nγ)^{118}Sn reaction by Bron *et al.*[16] Levels below 3.0 MeV shown in Fig. 2 are also listed in the Nuclear Data Sheets.[11]

Previous reaction studies have established the existence of a 3^-–2^+ level doublet at $\simeq$2.32 MeV. By resolving the 635.4-, 638.6-keV γ-ray doublet (see the 2963-keV level in Fig. 2) and the 1098.2-, 1095.0-keV γ-ray doublet (see the decay of the level doublet at $\simeq$2.32 MeV to the 1229.6-keV level in Fig. 2), we were able to establish precise energies for this level doublet as 2324.7 and 2327.9 keV. We further suggest a 3^- assignment for the 2324.7-keV level and 2^+ assignment for the 2327.9-keV level, the latter assignment arising from the presence of the ground-state transition. The same J^π values were also proposed by Demidov *et al.*[17] in their (n,n'γ) study, and a 3^- level was established at about 2310 keV in the

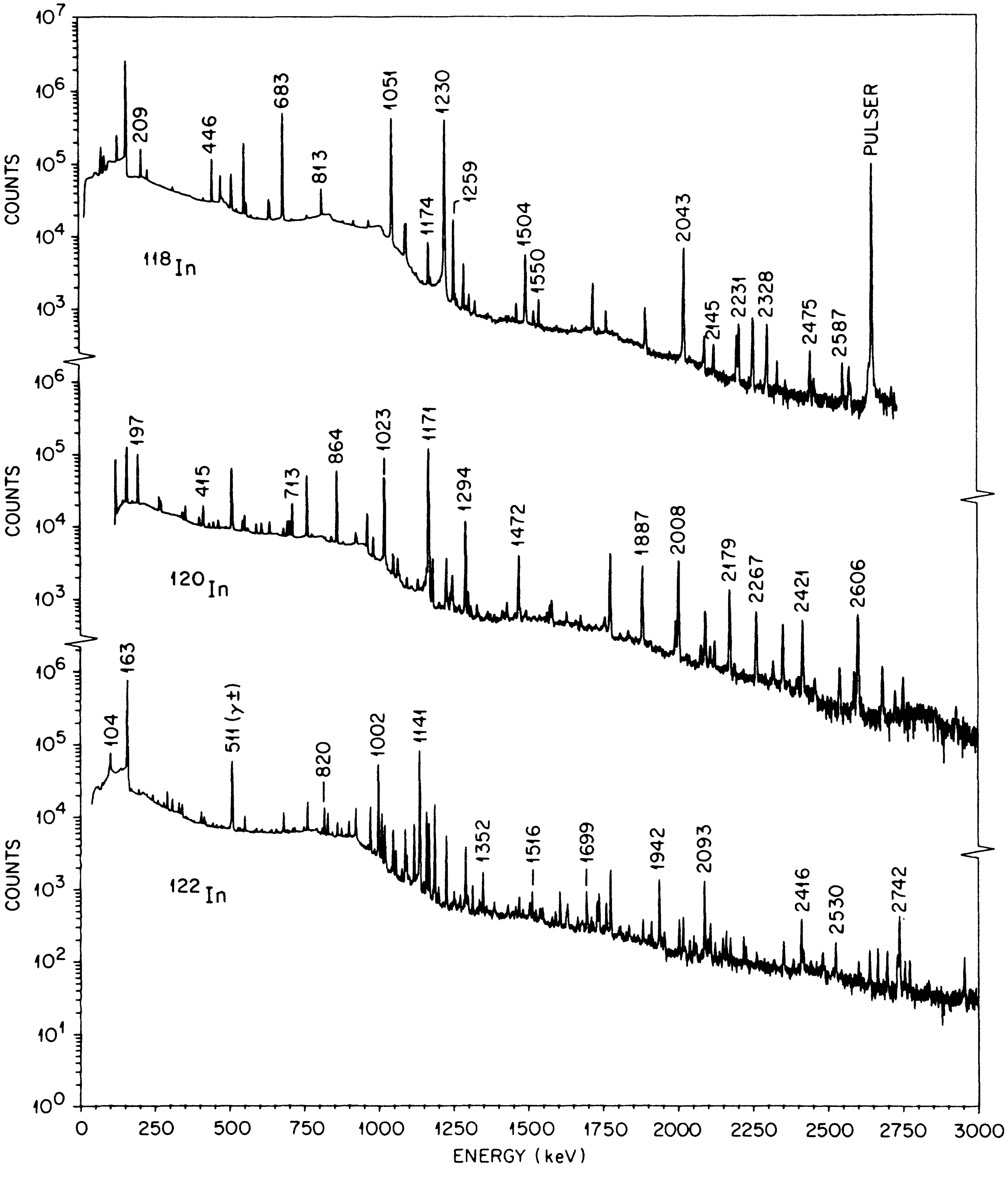

FIG. 1. γ-ray spectra obtained with a 80-cm^3 Ge(Li) detector from three sets of samples containing the 4.45-min ^{118}In, the 46.2-sec and 47.3-sec ^{120}In, and the 10.3-sec and 10.8-sec ^{122}In activities, respectively. All energies are in keV. Only selected peaks are labeled in the figure.

TABLE II. Energies (E_γ) and relative intensities (I_γ) of γ rays in ^{118}Sn from 4.4-min ^{118}In decay.

This work		Ref. 14	Ref. 15
E_γ[a] (keV)	I_γ	I_γ	I_γ
186.24[b] *23*	0.045 *11*		
208.52 *1*	2.71 *8*	3.7 *3*	2.4 *8*
229.65 *1*	0.783 *24*	1.1 *2*	0.9 *2*
237.6 *5*	0.04 *2*		
285.22 *11*	0.081 *10*		
411.44 *18*	0.037 *7*		
445.98 *2*	5.76 *17*	5.9 *5*	6.1 *3*
472.21[b] *12*	0.207 *23*		
474.57 *2*	3.00 *10*	3.4 *4*	3.1 *3*
510.5[c] *1*	0.13[c] *2*		
528.2[d] *4*	<0.21		
560.21 *2*	0.99 *4*	1.7 *4*	1.4 *5*
568.94[b] *13*	0.072 *10*		
576.18[b] *5*	0.205 *11*		
598.34 *19*	0.069 *11*		
635.40 *2*	1.77 *6*	2.7 *5*	3.6 *5*
638.61 *2*	1.37 *4*		
642.56[b] *20*	0.060 *12*		
675.0[b] *3*	0.12 *4*		
683.06 *2*	56.6 *17*	50.3 *47*	57 *6*
718.90 *19*	0.076 *13*		
756.4 *4*	0.037 *15*		
813.20 *2*	3.88 *12*	4.3 *10*	3.4 *4*
858.84 *19*	0.117 *20*		
885.66 *8*	0.264 *20*		
908.65[b] 18	0.088 *14*		
920.57 *4*	0.506 *21*		
971.44[e] *4*	0.35 *6*		
971.44[e] *4*	0.32 *7*		
1050.65 *3*	84.4 *26*	81.0 *42*	85 *5*
1094.3 *5*	0.805 *20*		
1095.0 *10*	1.5 *5*	4.5 *9*	3.5 *10*
1098.2 *5*	1.6 *3*		
1102.54[b] *22*	0.068 *12*		
1116.42 *16*	0.071 *9*		
1132.49 *11*	0.099 *9*		
1173.52 *3*	1.43 *5*	2.1 *5*	1.3 *2*
1180.18 *7*	0.163 *10*		
1229.64 *3*	100 *3*	100 *5*	100
1259.18 *3*	3.99 *12*	4.5 *10*	4.0 *4*
1264.96 *8*	0.138 *9*		
1271.26[b] *14*	0.073 *8*		
1301.62 *16*	0.056 *6*		
1312.22 *6*	0.187 *9*		
1368.28[b] *31*	0.024 *5*		
1377.09 *20*	0.038 *5*		
1418.03 *29*	0.027 *5*		
1424.7 *4*	0.021 *5*		
1430.4[b] *4*	0.019 *5*		
1447.55 *18*	0.047 *5*		
1473.50 *7*	0.177 *8*		
1504.10 *4*	1.65 *5*	2.0 *5*	0.9 *4*
1531.96[b] *9*	0.133 *8*		
1549.63 *6*	0.281 *12*	≤1.0	<0.3
1661.93 *21*	0.041 *6*		
2042.77 *5*	3.63 *8*	2.6 *5*	3.5 *3*
2107.6[b] *5*	0.016 *5*		
2144.64 *9*	0.121 *5*		
2230.76 *7*	0.333 *11*		
2327.82 *8*	0.374 *12*		0.2 *1*
2362.78 *12*	0.068 *4*		
2475.06 *10*	0.150 *7*		
2586.90 *12*	0.096 *6*		
2609.18 *14*	0.086 *6*		
2677.4 *3*	0.039 *5*		
2903.9[b] *3*	0.028 *9*		
3104.5[b] *6*	0.016 *8*		
3669.7[b] *20*	0.004 *2*		

[a] In our notation, 186.24 *23* is 186.24 ± 0.23 keV, etc.

[b] γ ray not placed on the level scheme.

[c] γ ray and its relative intensity included as observed in Ref. 20.

[d] Transition between the 1758-keV, 0^+ state and the 1230-keV, 2^+ state (see Fig. 2 and Ref. 15).

[e] γ ray placed more than once on the level scheme. Intensity of composite peak is 0.673 *25*.

^{122}Te(d,^{6}Li)^{118}Sn study of Jänecke, Becchetti, and Thorn.[18] The remaining J^π assignments shown in Fig. 2 are adopted values from the Nuclear Data Sheets.[11]

The eight levels shown in Fig. 2 between 3.1 and 3.9 MeV are new in the sense that their energies are now known precisely. Except for the 3159-, 3817-, and 3839-keV levels, the remaining levels can be identified with levels observed in various reaction studies;[11] however, the energies reported in the latter studies are understandably less precise (typically ±7 keV).

B. ^{120}In decay

The energies and intensities of 78 γ rays assigned to ^{120}In decay ($T_{1/2} \simeq 47$ sec) are given in Table III. The measured intensities are in good agreement with those reported by Liukkonen and Hattula.[19] These authors also employed the (n,p) reaction with 14-MeV neutrons to produce the In activities.

The existence of two distinct activities with similar half-lives became apparent when the In activities were produced by entirely different methods—via the ^{238}U(p,f) reaction by Cheung *et al.*[5] and via the ^{235}U(n,f) reaction by Fogelberg and Carlé[6]—and when the γ-ray intensities were noted to be very different compared with those measured from sources produced via the (n,p) reaction. The two half-lives are now known to be 46.2±0.8 and 47.3±0.5 sec from the work of Cheung *et al.*[5]

The simplest way for us to construct separate decay schemes was first to construct a consolidated decay scheme and then to pull the two schemes apart. Just as in the case of ^{118}In decay, the construction of the decay scheme was straightforward. Except for the 2727.9- and 3857.5-keV levels, all remaining levels shown in Fig. 3

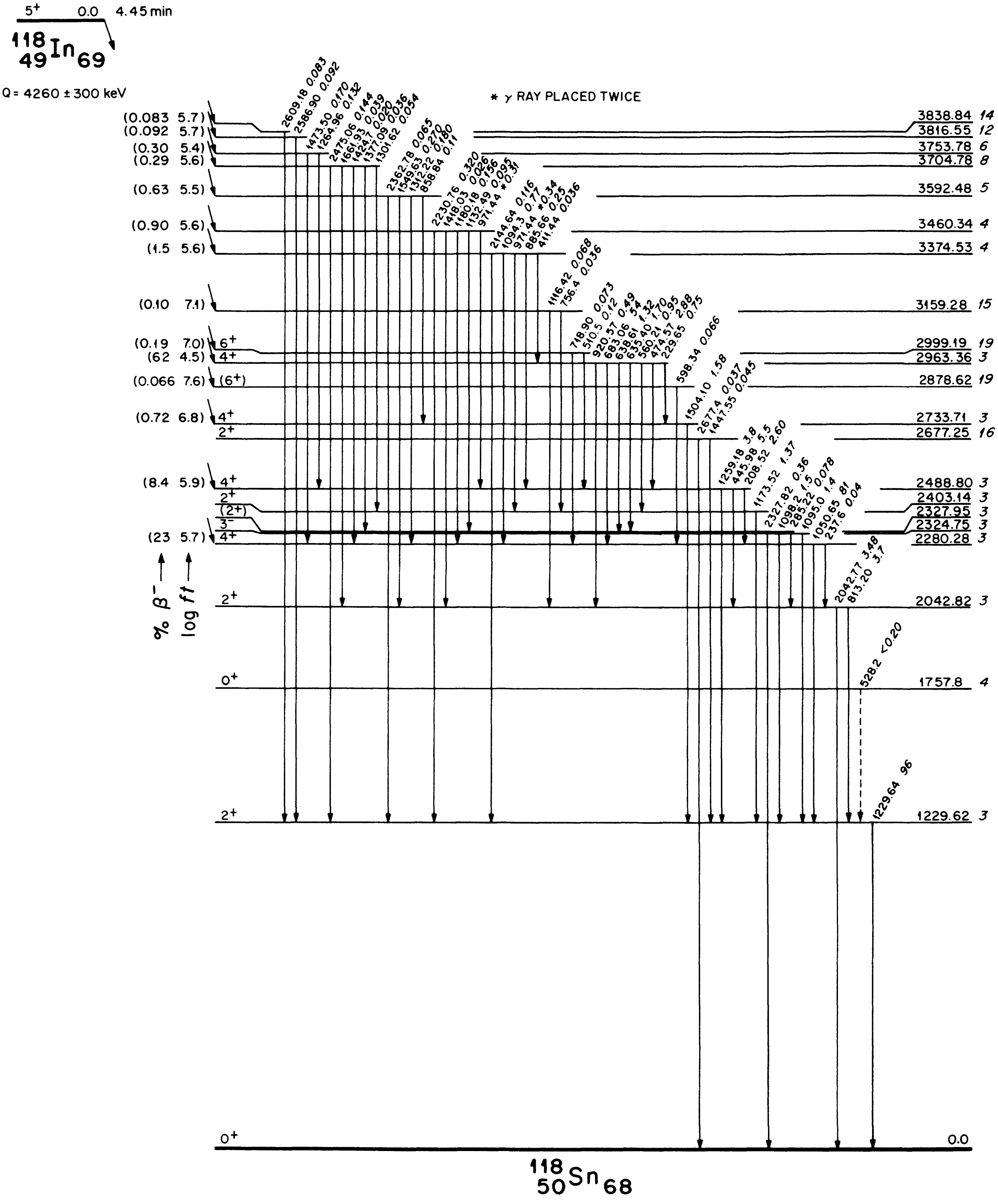

FIG. 2. Proposed decay scheme for the 4.45-min ^{118}In isomer. All energies are in keV. The numbers next to the γ-ray energies denote the absolute transition intensities per 100 disintegrations of the parent. In our notation for level energies, 1229.62 *3* ≡ 1229.62±0.03 keV, etc. In deducing these level energies, nuclear recoil has been into account.

TABLE III. Energies (E_γ) and relative intensities (I_γ) of γ rays in ^{120}Sn from ~ 47-sec ^{120}In decay.

				Both	Intermediate-spin isomer		High-spin isomer		
Both isomers				isomers	This		This		
This work				Ref. 19	work	Ref. 5	work	Ref. 5	Ref. 6
E_γ[a] (keV)		I_γ[b]		I_γ	I_γ	I_γ	I_γ	I_γ	I_γ
89.8	*3*	9.8[c]	*11*	6.5[d]	0.27		79	77.6	81.8
177.79	*9*	0.24	*3*	0.3[e]	0.27				
197.36	*3*	9.7	*10*	8.1[d]			81	80.6	87.3
268.08	*4*	1.50	*6*	1.5[d]			12.5	11.4	11.6
295.2	*4*	0.08	*4*		0.09				
323.48	*30*	0.09	*4*		0.10				
354.88	*4*	1.49	*9*	1.4[e]			1.25	13.1	13.7
400.91[e]	*5*	0.85[e]	*8*	0.8[e]		0.9[e]			
411.54	*20*	0.20	*8*		0.23				
414.57	*3*	2.33	*12*	2.8	2.65	2.5			
449.01	*7*	0.66	*8*	0.6	0.75				
465.38	*6*	0.84	*9*	0.8[e]			7.0	5.8	5.5
490.80	*24*	0.19	*7*		0.22				
546.16	*4*	1.53	*9*	1.6	1.74	1.6			
577.0[e]	*6*	0.10[e]	*5*						
592.34	*5*	1.36	*9*	1.5	1.55	2.0			
609.96	*5*	1.58	*9*	1.5[e]			13.2	9.9	13.7
637.02	*4*	1.71	*13*	1.6	1.94	3.0			
696.75	*4*	2.36	*12*	1.8[e]			19.7	15.5	18.1
702.62	*4*	2.36	*10*	2.5	2.68	1.9			
704.0[f]	*5*	<0.20			<0.23				
706.43	*8*	0.88	*8*		1.00				
713.37	*3*	7.44	*24*	7.1	8.45	7.8			
778.80[e]	*17*	0.43[e]	*11*						
808.4[g]	*4*	<0.12					<1[h]	0.8	
823.60	*17*	0.44	*10*		0.50				
863.64	*3*	31.8	*10*	31	36.1	33.8			
915.68[e]	*33*	0.23[e]	*9*						
925.96	*6*	1.78	*17*	1.5	2.02	1.3			
929.08	*11*	0.88	*16*		1.00				
964.86	*4*	7.33	*26*	8.1			61.3	58.7	72.5
975.7[e]	*5*	0.13[e]	*6*						
984.91	*4*	2.73	*14*	2.4	3.10	2.5			
988.7	*7*	0.05	*2*		0.06				
1023.02	*3*	62.8	*20*	62	58.0	56.5	99	97.4	100.0
1071.55[e]	*22*	0.36[e]	*7*						
1081.2	*6*	0.08	*4*		0.09				
1113.0	*10*	0.12	*6*		<0.01		1.0	1.1	
1133.88	*10*	0.54	*7*		0.61				
1146.23[e]	*30*	0.20[e]	*8*						
1156.09	*30*	0.50	*10*		0.57				
1162.78	*16*	1.00	*12*	2.0[d]			8.4	4.5	
1171.22	*3*	100	*3*	100	100	100	100	100	100
1184.05	*4*	2.38	*10*	2.7	2.70	2.5			
1205.60[e]	*25*	0.17[e]	*6*						
1229.9	*2*	0.75[i]	*25*		0.85	1.5?[e]		0.4?[e]	
1249.56	*5*	1.46	*7*	1.3	1.66	1.8			
1253.03	*25*	0.23	*5*		0.26			1.4[e]	
1294.32	*3*	11.2	*4*	11.1	12.7	12.7			
1311.57	*14*	0.30	*5*		0.34				
1341.1	*7*	0.07	*3*		0.08				
1376.41[e]	*28*	0.15[e]	*4*						
1389.8[e]	*3*	0.14[e]	*5*						
1417.04	*32*	0.15	*4*		0.17				
1421.6	*4*	0.11	*4*		0.12				
1472.09	*4*	4.15	*15*	4.5	4.72	4.3			

TABLE III. *(continued)*

Both isomers This work E_γ[a] (keV)		I_γ[b]		Both isomers Ref. 19 I_γ	Intermediate-spin isomer This work I_γ	Intermediate-spin isomer Ref. 5 I_γ	High-spin isomer This work I_γ	High-spin isomer Ref. 5 I_γ	High-spin isomer Ref. 6 I_γ
1477.28[e]	*16*	0.31[e]	*9*						
1494.2	*7*	0.10	*5*		0.11				
1556.8	*6*	0.09	*4*		0.10				
1567.24[e]	*22*	0.24[e]	*6*						
1582.76	*17*	0.61	*8*	~0.3	0.69				
1632.96[e]	*22*	0.24[e]	*7*						
1663.3	*6*	0.10	*5*		0.11				
1679.89	*20*	0.26	*6*		0.30				
1760.54	*20*	0.28	*8*		0.32				
1838.3[e]	*5*	0.11[e]	*5*						
1886.67	*5*	4.31	*16*	4.0	4.90	4.8			
2007.82	*4*	5.7	*3*	6.5	6.5	6.4			
2096.98	*10*	1.04	*9*	1.2	1.18	1.6			
2178.65	*5*	2.54	*14*	2.5	2.89	2.7			
2266.96	*7*	1.37	*9*	1.4	1.56	1.4			
2355.43	*9*	0.87	*7*	0.9	0.99	1.3			
2420.96	*8*	0.98	*7*	0.9	1.11	1.2			
2460.0[e]	*4*	0.08[e]	*4*						
2543.82[e]	*16*	0.24[e]	*3*						
2605.94	*8*	1.43	*9*	2.0	1.62	2.3			
2686.11	*17*	0.22	*3*		0.25	0.41?[e]		0.12?[e]	
2727.8	*5*	0.07	*3*		0.08				

[a] In our notation, 89.8 *3* is 89.8 ± 0.3 keV, etc.

[b] For each γ ray, multiply the intensity in the intermediate-spin column by 0.88 and the intensity in the high-spin column by 0.12 and add in order to reproduce this measured intensity.

[c] Because this γ ray was severely attenuated, the intensity value is based on intensity balance at the 2284.1-keV level.

[d] Different placement from ours.

[e] γ ray not placed on the level scheme.

[f] Transition between the 1875-keV, 0^+ state and the 1171-keV, 2^+ state (see Fig. 3 and Ref. 19).

[g] Too weak to be observed by us but observed in Ref. 5.

[h] Based on intensity balance at the 2836.3-keV level.

[i] After corrections due to a contaminant γ ray of similar energy from ^{118}In decay.

can be identified with levels listed in the Nuclear Data Sheets.[12] The J^π assignments shown are from the Nuclear Data Sheets.[12] The decay schemes shown in Fig. 3 consist of 25 excited states and account for 62 out of 78 γ rays ascribed to ^{120}In decay (see Table III).

By analogy with ^{118}In (see Table I), the two isomers, both with $T_{1/2} \simeq 47$ sec, can be referred to as an intermediate-spin isomer and a high-spin isomer. The key to separating the decay schemes of these two isomers was the 2481.4-keV, 7^- level. We assumed that this level was not at all fed by direct β decay from the intermediate-spin isomer. Therefore, all transitions associated with this level dropped out into a second picture shown in Fig. 3(b). If, for a moment, we retained the measured transition intensities (corrected, of course, for internal conversion), the intensities of the transitions deexciting the levels below 2.3 MeV (in the high-spin isomer decay) immediately followed from intensity balance requirements. The intensities in the decay scheme for the high-spin isomer could then be renormalized to 100 for the intensity of the 1171.2-keV γ ray as shown in Fig. 3(b). Having separated the transitions and, more importantly, the (unnormalized) transition intensities associated with the high-spin isomer decay, it was relatively straightforward to complete the separation of the decay scheme for the intermediate-spin isomer by requiring that the sum of the intensities of the transitions feeding the ground state also be 100 in this decay. There were only four transitions (at 89.8, 1023.0, 1171.2, and 1113.0 keV) common to both decays. For these transitions, we recommend a percentage uncertainty in the split intensity values (see Table III) that is 1.2 times the measured percentage uncertainty. For all other transitions, the uncertainties in our renormalized intensities given in Table III will be just the measured percentage uncertainties. (The same procedure applies to the γ-ray intensities in Table IV.)

C. ^{122}In decay

The existence of an intermediate-spin isomer and a high-spin isomer in ^{122}In with nearly the same half-life of

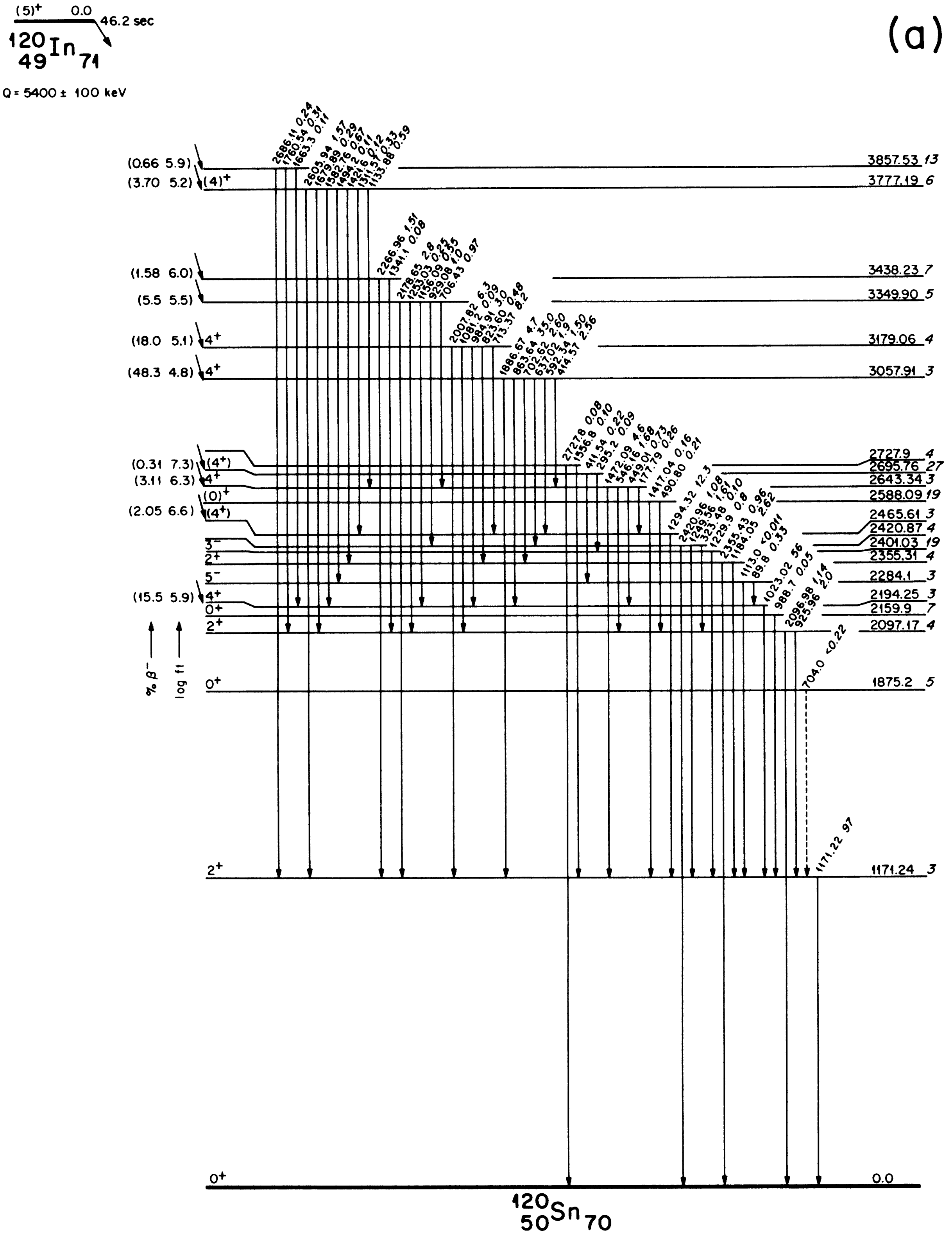

FIG. 3. (a) Proposed decay scheme for the 46.2-sec ^{120}In isomer. All energies are in keV. The numbers next to the γ-ray energies denote the absolute transition intensities per 100 disintegrations of the parent. In our notation for level energies, 1171.24 *3* ≡ 1171.24±0.03 keV, etc. In deducing these level energies, nuclear recoil has been into account. (b) Proposed decay scheme for the 47.3-sec ^{120}In isomer. All energies are in keV. The numbers next to the γ-ray energies denote the absolute transition intensities per 100 disintegrations of the parent.

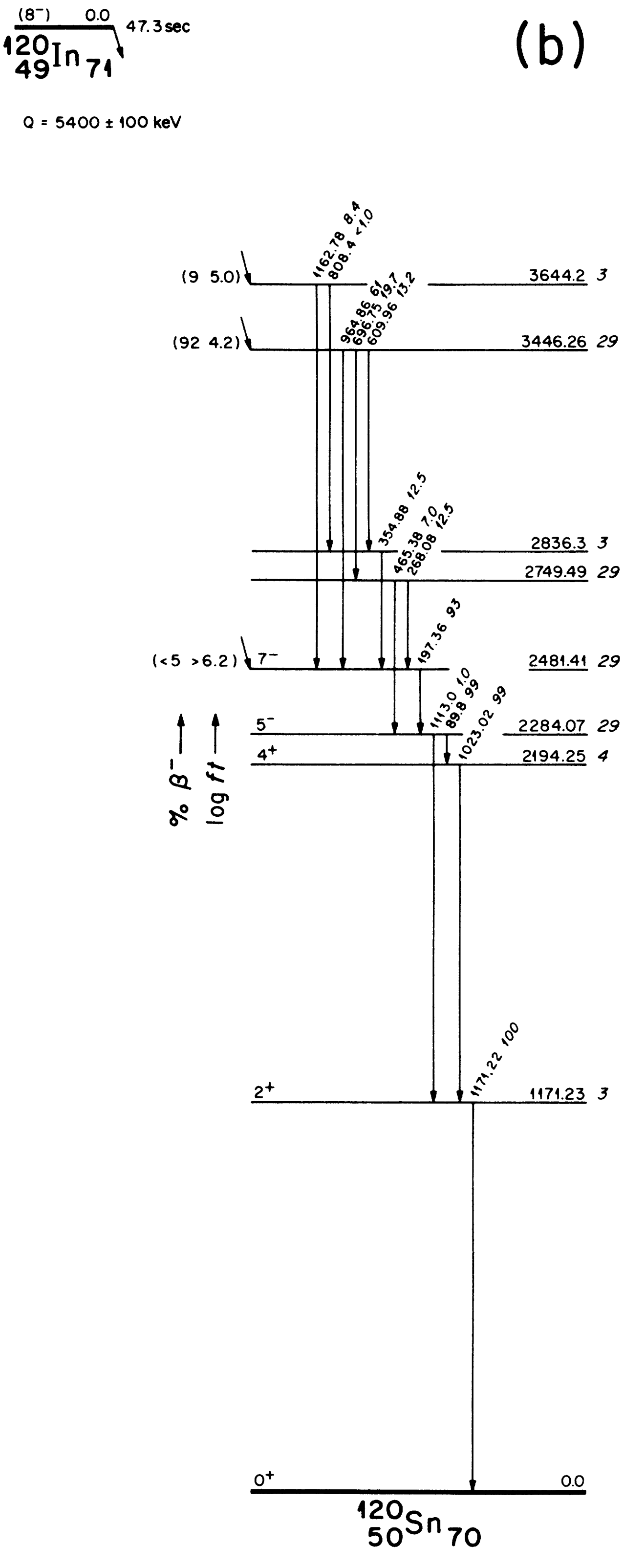

FIG. 3. (*Continued*).

$\simeq$10.5 sec was deduced independently by Cheung *et al.*[7] and by Fogelberg and Carlé.[6] The former authors employed two different methods of production [^{238}U(p,f) and ^{124}Sn(d,α)], and the latter chemical separation experiments to alter the relative production. The two half-lives were measured as 10.8±0.4 and 10.3±0.6 sec by Cheung *et al.*[7]

The energies and intensities of 102 γ rays assigned to ^{122}In decay ($T_{1/2} \simeq 10.5$ sec) are given in Table IV. Compared with the earlier results, the number of detected γ rays has now nearly tripled.

The construction of decay schemes, shown in Fig. 4, followed a procedure similar to the one used for ^{120}In. The intensities of γ rays from the decays of the intermediate-spin isomer and the high-spin isomer, normalized to 100 for the 1140.55-keV γ ray in each case, are given in Table IV, where they are also compared with results obtained earlier. The overall agreement is good. As in the previous cases, our study of the decay of the intermediate-spin isomer is considerably more detailed than others. The 33 excited states shown in Fig. 4 account for 81 out of 102 γ rays assigned to ^{122}In decay. The current work confirms several of the new levels introduced in Refs. 6 and 7. In addition, new levels are proposed, particularly above 2.6 MeV, most of which can be identified with adopted levels listed in the Nuclear Data Sheets[13] from various reaction studies. The J^π assignments shown are from the Nuclear Data Sheets.[13]

IV. THEORETICAL MODEL

A. Broken-pair model

Because of the strong pairing part of the interaction between like nucleons, the low-lying states of semimagic nuclei are expected to be mainly built of coherent pairs with $J^\pi = 0^+$ (called S pairs) created by the operator

$$S^\dagger = \sum_{n,l,j} \tfrac{1}{2}(2j+1)^{1/2} \phi_{nlj} (a^\dagger_{nlj} a^\dagger_{nlj})(0) \ . \tag{1}$$

Indeed, spectroscopic properties of the lighter Sn nuclei have been successfully analyzed with a model including states with only one broken pair[20]

$$(a^\dagger_{j_1} a^\dagger_{j_2})J^\pi (S^\dagger)^{p-1} |0\rangle \ , \tag{2}$$

or, in a more extensive theoretical study, up to two broken pairs[21]

$$[(a^\dagger_{j_1} a^\dagger_{j_2})^{J_1} (a^\dagger_{j_3} a^\dagger_{j_4})^{J_2}]^{J^\pi} (S^\dagger)^{p-2} |0\rangle \ . \tag{3}$$

In accordance with a more precise definition given earlier,[21] a state is called a one-broken-pair state, or a generalized-seniority[22] $v_g = 2$ state, if it belongs to the space of states given by Eq. (2) and is orthogonal to the state with only S pairs (the zero-broken-pair or $v_g = 0$ state). Two-broken-pair states, or $v_g = 4$ states, are those belonging to the space of states given by Eq. (3) and are orthogonal to those with fewer broken pairs. The formalism was presented in more detail previously.[21,23] In the current investigation we include up to two-broken-pair

TABLE IV. Energies (E_γ) and relative intensities (I_γ) of γ rays in ^{122}Sn from ~ 10.5-sec ^{122}In decay.

Both isomers		Intermediate-spin isomer			High-spin isomer		
This work		This work	Ref. 7	Ref. 6	This work	Ref. 7	Ref. 6
E_γ[a] (keV)	I_γ[b]	I_γ	I_γ	I_γ	I_γ	I_γ	I_γ
103.74 *1*	15.8 *8*	6.1	4.0		81	87.5	82.0
138.35[c] *11*	0.72[c] *12*						
163.48 *20*	8.7 *6*	0.20			66	71.2	69
212.64[c] *25*	0.26[c] *8*						
243.8 *3*	0.9 *1*				7.0	6.1	5.8
246.4 *8*	0.4 *2*	0.5					
261.79 *9*	0.74 *9*	0.85					
281.03 *9*	0.66 *9*				5.1	5.4	5.5
309.70 *4*	1.99 *12*	2.28		2.9[c]			
332.27 *5*	1.55 *10*	1.78		1.0[c]			
360.53 *33*	0.16 *7*	0.18					
381.9[c] *4*	0.20[c] *10*						
405.3[c] *4*	0.81[c] *11*						
407.17 *7*	1.22 *15*				9.5	7.8	7.8
440.50[d] *20*						0.7	0.6[c]
457.81 *19*	0.32 *9*	0.37					
530.10 *17*	0.46 *9*	0.53					
544.8 *4*	0.23 *10*	0.26					
592.27 *14*	0.50 *10*				3.9	2.8	2.6[e]
596.5 *10*	0.08 *3*	0.09					
642.59 *21*	0.43 *14*	0.49					
643.45[f] *20*							0.7[c]
678.10 *25*	0.34 *12*	0.39					
692.4 *4*	0.38 *10*				2.9	2.5	3.0[e]
750.76 *13*	0.74 *12*	0.85					
791.10[c] *25*	0.51[c] *15*						
794.46 *22*	0.60 *16*	0.69					
812.99 *10*	1.20 *14*	1.38		2.5[c]			0.9[c]
819.54 *3*	6.8 *3*	7.8		8.9			
831.35 *3*	4.9 *2*	5.6		8.1			
840.4[d] *3*						0.7	1.6
877.70 *8*	1.44 *14*				11.2	10.7	11.5
902.62 *4*	3.13 *18*	3.59	3.0	5.6			
947.7[g] *5*	<0.31	<0.36					
974.61 *3*	11.5 *4*	13.2	13.0	14.3			
987.60 *16*	0.72 *15*	0.83					
1001.58 *3*	57.7 *18*	51.7	58.5	54	98.4	98.3	97
1007.5 *4*	0.46 *15*				3.6	1.0	4.6
1013.34 *3*	9.3 *4*	10.7	h	11.6			
1013.4[d] *5*						1.3	3.4
1044.42[c] *20*	0.39[c] *8*						
1057.2 *4*	0.25 *8*			5.0[c]	1.9	1.2	1.8[c]
1059.92 *4*	2.41 *12*	2.77	3.2				1.2[e]
1065.97[c] *28*	0.24[c] *7*						
1071.35 *29*	0.24 *7*	0.28					
1080.00 *9*	0.74 *7*	0.85					
1091.67 *3*	6.9 *2*	7.9	7.8	9.7			
1105.66 *25*	0.29 *7*	0.07	<0.1		1.8	1.5	1.2
1121.68 *3*	7.9 *3*				61.2	60.9	68
1140.55 *3*	100 *3*	100	100	100	100	100	100
1163.61 *3*	13.7 *5*	15.7	14.5	26.3			
1190.58 *3*	18.2 *6*	20.9	20.0	28.2			
1197.69[c] *18*	0.28[c] *6*						
1242.2[c] *6*	0.10[c] *5*						
1250.8[c] *5*	0.11[c] *5*						
1254.80 *11*	0.50 *5*	0.57					
1268.9[c] *4*	0.16[c] *6*						

TABLE IV. *(continued)*

Both isomers This work		Intermediate-spin isomer			High-spin isomer		
E_γ[a] (keV)	I_γ[b]	This work I_γ	Ref. 7 I_γ	Ref. 6 I_γ	This work I_γ	Ref. 7 I_γ	Ref. 6 I_γ
1275.06 *14*	0.43 *6*	0.49					
1294.34[d] *10*						6.7	7.5
1296.37 *33*	0.36 *9*	0.41					
1301.11 *14*	0.46 *7*				3.6	1.6	2.6
1340.0 *5*	0.23 *9*	0.26					
1352.15 *4*	1.81 *9*	2.08					
1363.40[c] *33*	0.19[c] *9*						
1367.9 *10*	0.05 *2*	0.06					
1385.8[c] *5*	0.13[c] *6*						
1389.22 *18*	0.39 *10*	0.45					
1393.1 *6*	0.10 *5*	0.11					
1432.6[c] *5*	0.18[c] *9*						
1467.7 *7*	0.11 *5*	0.13					
1484.97 *29*	0.20 *8*	0.23					
1516.49 *8*	0.92 *7*	1.06		1.3[c]			0.45[c]
1527.84 *22*	0.26 *7*	0.30					
1539.4 *10*	0.10 *5*	0.11					
1546.2 *8*	0.09 *4*	0.10					
1550.82 *17*	0.41 *7*	0.47					
1594.01 *18*	0.36 *8*	0.41		2.5[c]			0.9[c]
1630.44 *22*	0.33 *9*	0.38					
1634.73 *11*	0.71 *9*	0.82					
1698.54 *9*	1.38 *11*	1.58		2.5			
1740.17 *7*	1.23 *7*	1.41					
1806.3 *7*	0.08 *4*	0.09					
1905.2[c] *5*	0.13[c] *6*						
1941.66 *5*	2.76 *12*	3.17	4.0				1.6[e]
1957.61[c] *33*	0.25[c] *7*						
1960.4[c] *6*	0.15[c] *6*						
2065.6[i] *2*	<0.09	<0.10					
2093.23 *3*	2.85 *12*	3.27	3.1	4.3			
2153.65 *19*	0.26 *6*	0.30		0.8			
2165.05 *15*	0.38 *6*	0.44					
2230.85 *25*	0.19 *4*	0.22					
2415.62 *7*	0.97 *7*	1.11					
2486.20 *27*	0.22 *7*	0.25					
2529.63 *15*	0.39 *6*	0.45					
2642.28 *18*	0.32 *6*	0.37					
2669.25[c] *14*	0.34[c] *6*						
2700.42 *16*	0.35 *6*	0.40					
2734.50 *18*	0.31 *5*	0.36					
2741.50 *6*	1.32 *7*	1.52		1.5[c]			0.55[c]
2759.1[i] *2*	<0.17	<0.20					
2775.55 *21*	0.22 *5*	0.25					
2957.76[c] *16*	0.30[c] *5*						

[a] In our notation, 103.74 *1* is 103.74 ± 0.01 keV, etc.

[b] For each γ ray, multiply the intensity in the intermediate-spin column by 0.87 and the intensity in the high-spin column by 0.13 and add in order to reproduce this measured intensity.

[c] γ ray not placed on the level scheme.

[d] γ ray included as observed in Refs. 6 and 7.

[e] Different placement from ours.

[f] γ ray assigned to the intermediate-spin isomer in Ref. 6 but unobserved in our work. If genuine, this γ ray probably comes from the high-spin isomer.

[g] Transition between the 2088-keV, 0^+ state and the 1141-keV, 2^+ state (see Fig. 4 and Ref. 6).

[h] Interference from unidentified contaminant peak.

[i] Strong transition in the low-spin isomer decay (see dashed transitions in Fig. 4, Part 1 and Ref. 6).

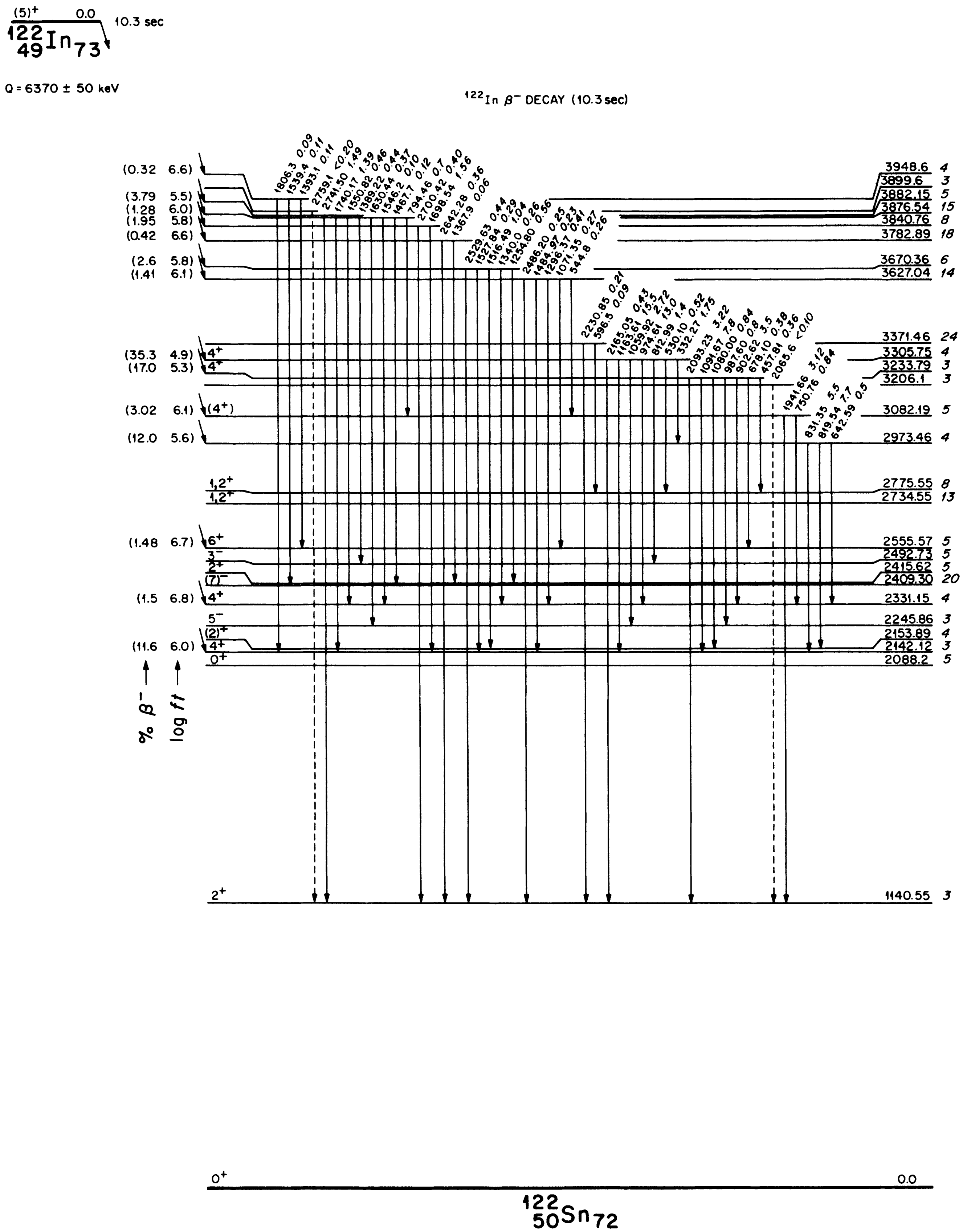

FIG. 4. Proposed decay schemes for the ≃10.5-sec ^{122}In isomers. All energies are in keV. The numbers next to the γ-ray energies denote the absolute transition intensities per 100 disintegrations of the parent. In our notation for level energies, 1140.55 *3* ≡ 1140.55±0.03 keV, etc. In deducing these level energies, nuclear recoil has been taken into account.

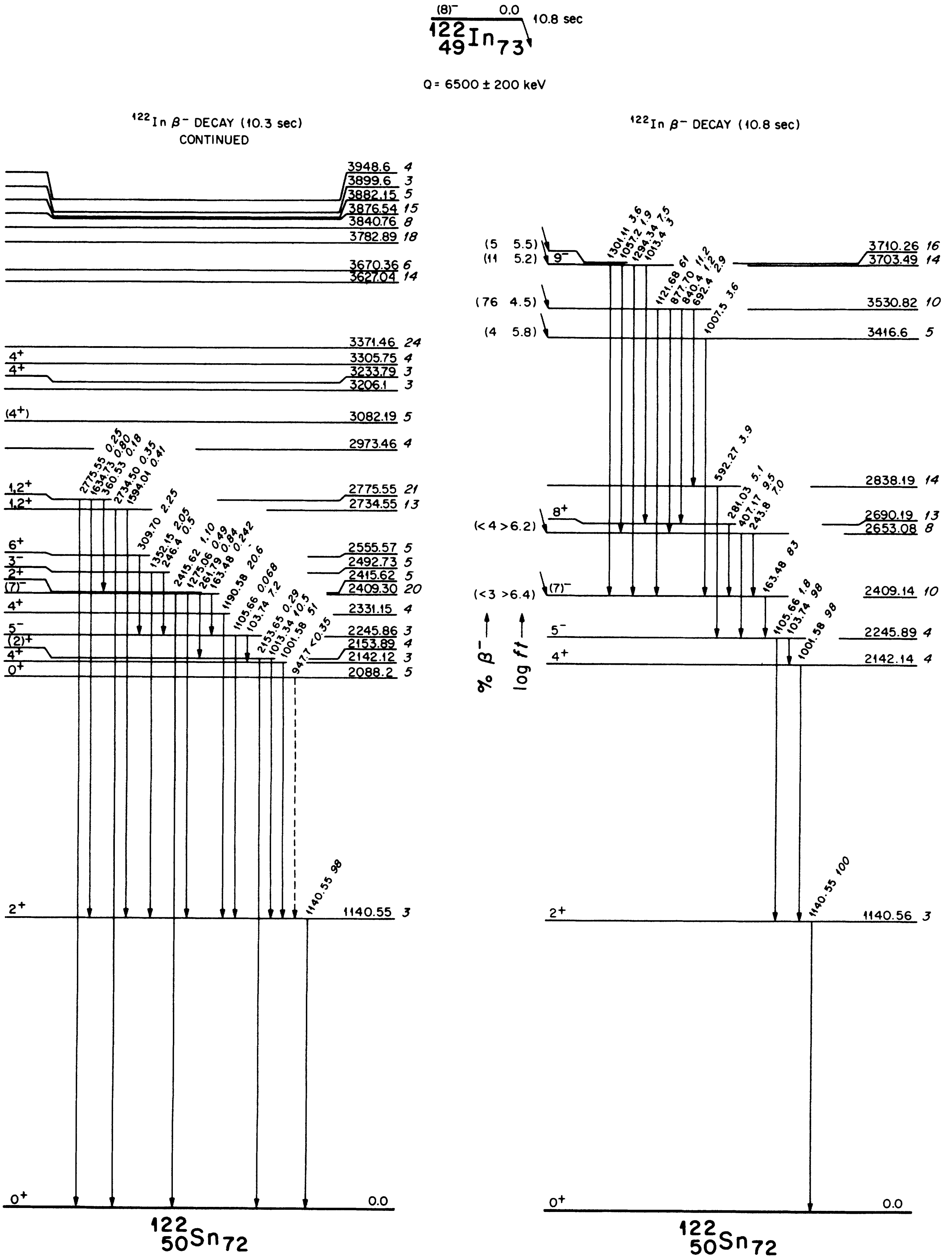

FIG. 4. (*Continued*).

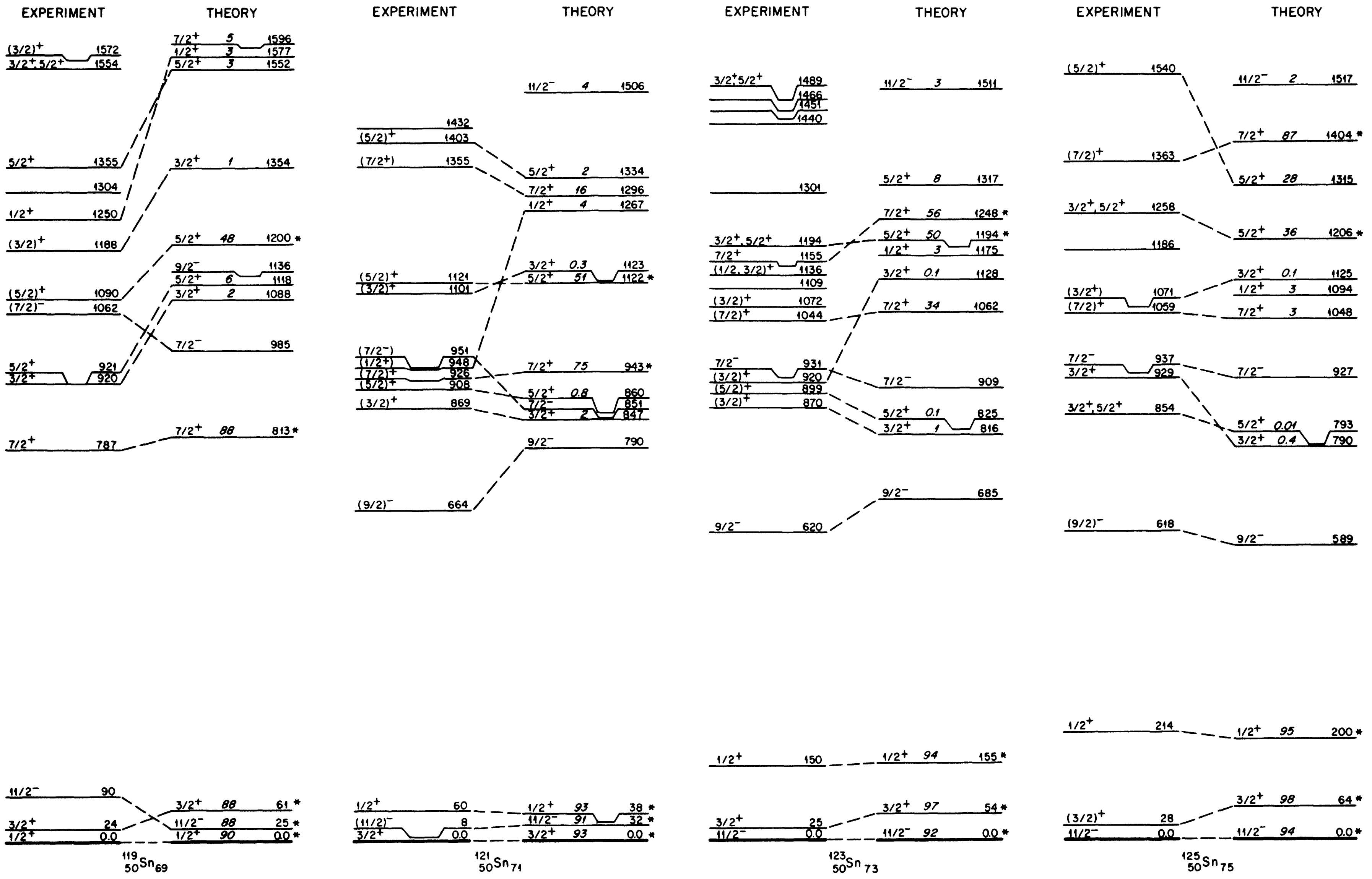

FIG. 5. Comparison of experimental and calculated levels below the 1600-keV excitation energy in ^{119}Sn, ^{121}Sn, ^{123}Sn, and ^{125}Sn. The asterisk symbol denotes that the corresponding experimental level energy was used in the fit to determine the single-particle energies. The percentage of generalized seniority $v_g = 1$ amplitude in the wave function is given by italics next to the spin-parity value for each calculated level. The spin-parity combinations $\frac{7}{2}^-$ and $\frac{9}{2}^-$ require at least three unpaired particles in our model space. Therefore, these levels are pure $v_g = 3$ states.

excitations in the $50<N<82$ shells $1g_{7/2}$, $2d_{3/2}$, $2d_{5/2}$, $3s_{1/2}$, and $1h_{11/2}$.

B. Effective Hamiltonian

In a previous study of the lighter Sn isotopes[21] it was found that a simple Gaussian effective yields much better results than a surface-delta interaction. In the current work we started, a bit more ambitiously, with a G matrix that was obtained from the realistic meson-exchange Bonn-potential.[24] It is known that such a force, when applied within a space of only one major shell, has pairing and other multipole components that are too weak.[25] We therefore supplemented the G matrix with a monopole pairing, a quadrupole pairing, and an octupole particle-hole component, the strengths of which were fixed such that, on the average, the odd-even mass differences and the energies of the lowest 2^+ and 3^- states were reproduced. These extra multipole forces should simulate the renormalization of the G matrix by core polarization. The octupole component especially must be rather strong in order to simulate the coherent effect of the many 3^- configurations involving orbits from other major shells.

The force being now given, we determined the single-particle energies in a fit to the spectra of the odd nuclei, particularly those states that have large amplitudes in one-neutron transfer reactions. The spectra that are obtained in a generalized seniority $v_g \leq 3$ model are displayed in Fig. 5 and are compared with known levels. The experimental data for ^{119}Sn, ^{121}Sn, and ^{123,125}Sn are from Refs. 26, 27, and 28, respectively, where detailed reasons are given for J^{π} assignments. In ^{121}Sn the 664-keV level is from Ref. 29 and the 1355-keV level is from Ref. 30. In ^{123}Sn the 1301-, 1440-, 1451-, and 1466-keV levels are from Ref. 31 and the 899-keV level is from Ref. 32. In ^{125}Sn the spin-parity assignment for the 854-keV level is based on systematics. One many notice in Fig. 5 that not only the fitted levels, but also the others, which are predominantly built of configurations with three unpaired particles, are well reproduced. With the current choice of effective interaction, the results are much better than those obtained before within the same model space.[33] Also, the smooth variation of the obtained single-particle energies, as displayed in Fig. 6, is an indication that the effective interaction is reasonable.[34] This smooth and almost constant behavior with mass number makes it easy to carry out an interpolation to obtain the single-particle energies for the even nuclei. The even nuclei are then described without any further adjustment of the Hamiltonian parameters.

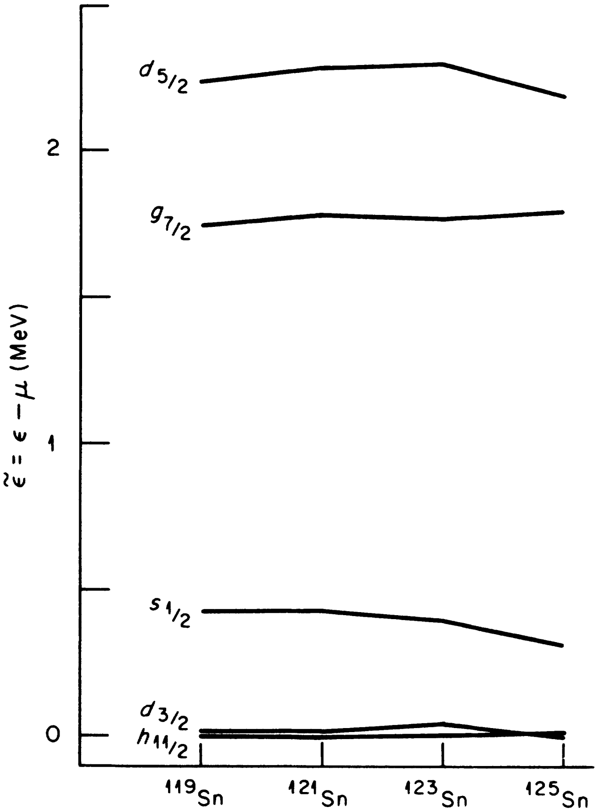

FIG. 6. Relative single-particle energies (ϵ) minus self-energies (μ) for the neutron valence orbits as obtained from the fits shown in Fig. 5. Single-particle energies for the even isotopes are obtained by interpolation.

V. CALCULATED RESULTS AND COMPARISONS WITH EXPERIMENTS

Calculated excitation energies of two-broken-pair levels are presented in Tables V, VI, and VII for ^{118}Sn, ^{120}Sn, and ^{122}Sn, respectively, for all the spin-parity combinations allowed in our model space. In general, we have listed levels only to about 4.5 MeV; above this energy, we have listed only two or three levels of a particular J^{π} combination. Beside each level the percentage of two-broken-pair admixture is also given. In these tables, the calculated energy of the first-excited 2^+ state was matched with the corresponding energy known from experiment. This became necessary because of difficulties in deriving a reliable, effective Hamiltonian in the small model space of one major shell, the maximum size that one can handle in a two-broken-pair model. The octupole force especially, which must supplement the bare interaction, introduces such a strong (and probably unphysical) two-broken-pair correlation in the ground state that we were forced to give up the idea of a simultaneous description of the properties of the ground state and the excited states.

A. Levels in ^{122}Sn

We first discuss the case of ^{122}Sn because it can provide a guideline to the understanding of the other isotopes. In Fig. 7, calculated levels below 3470 keV are compared with levels known from the present investigation and from the Nuclear Data Sheets.[13] For all levels up to 2840 keV, except those marked with a cross, it appears possible to establish a reasonable one-to-one correspondence between experiment and calculations based on the known J^{π} assignments. The average deviation between experiment and theory is only 48 keV. The largest discrepancies occur for the calculated 0_2^+ state at 2273 keV and the

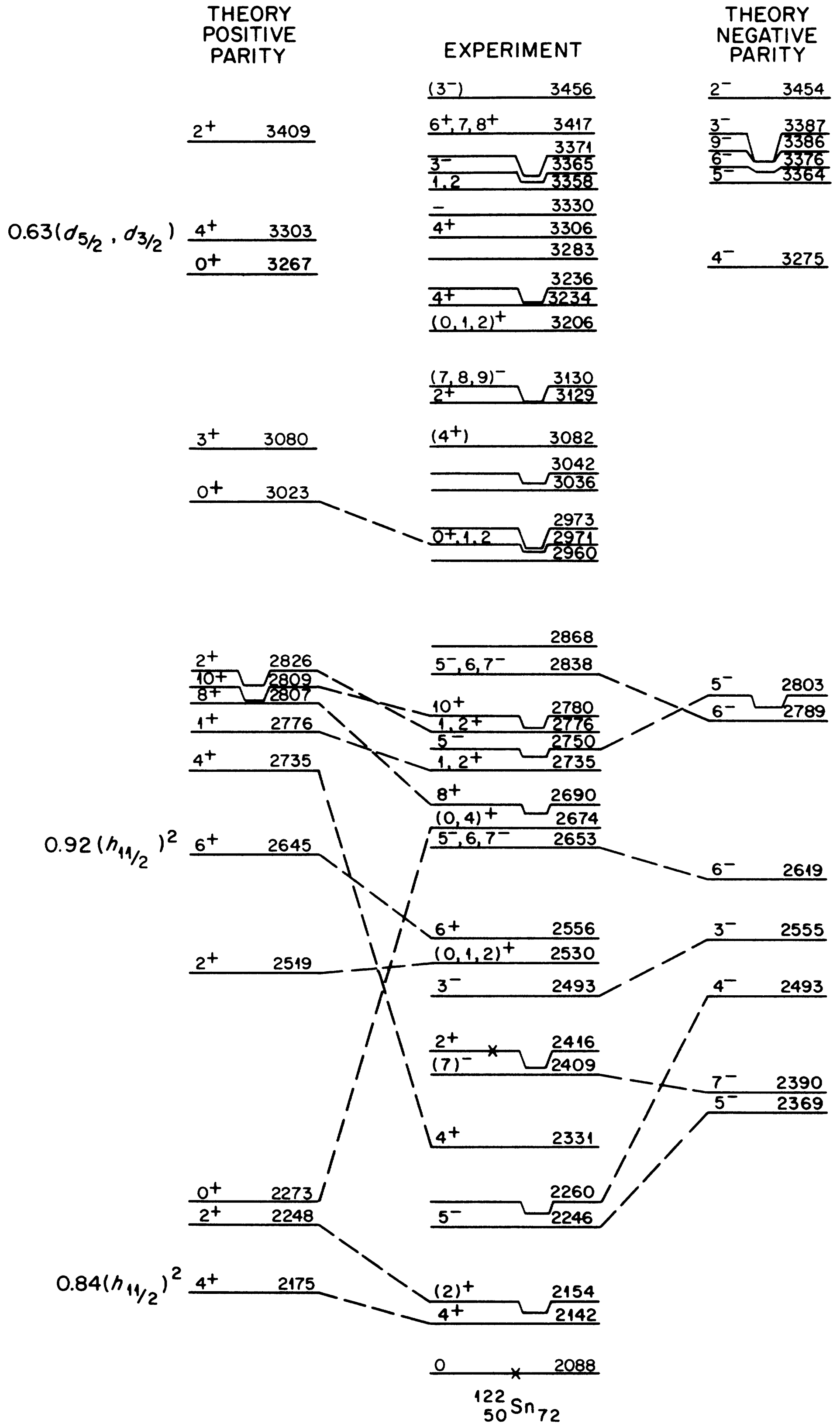

FIG. 7. Comparison of experimental and calculated levels below the 3470-keV excitation energy and above the first excited state for ^{122}Sn. Dashed lines denote our one-to-one correspondences. The fractional admixtures of one-broken-pair configurations are shown to the left of selected calculated positive-parity levels. Experimental levels marked with a cross originate mainly from proton 2p-2h excitations not included in our model.

TABLE V. Calculated energy levels (in keV) in ^{118}Sn together with their corresponding two-broken-pair admixtures (% 2bp) grouped according to their spin-parity (J^{π}) values.

No.	E (level)	% 2bp	E (level)	% 2bp	E (level)	% 2bp	E (level)	% 2bp	E (level)	% 2bp	E (level)	% 2bp
	0^+ levels		0^- levels		1^+ levels		1^- levels		2^+ levels		2^- levels	
1			4552	100	2148	11	3534	100	1230	8	3117	100
2	1999	13	5402	100	3533	97	4245	100	2045	24	3605	41
3	2375	12			3849	100	4486	100	2181	22	3869	72
4	3167	18			4009	99			2550	68	4094	99
5	3622	92							2835	29		
6	3948	96							3397	35		
7	4426	94							3546	94		
8									3611	47		
9									3787	96		
10									3942	86		
	3^+ levels		3^- levels		4^+ levels		4^- levels		5^+ levels		5^- levels	
1	2822	14	2255	6	2389	25	2362	17	2969	11	2041	23
2	2955	14	3388	64	2749	18	3238	14	3717	100	2614	13
3	3193	96	3569	99	2934	18	3443	98	3877	99	3256	27
4	3820	93	3646	54	3053	80	3696	100	4121	98	3327	78
5	3875	49	3967	96	3581	79	3847	97			3720	99
6	3902	93	4191	98	3743	86	4022	99			3806	90
7	4024	48			3830	25					4142	58
8					3998	42						
9					4070	95						
10					4100	96						
	6^+ levels		6^- levels		7^+ levels		7^- levels		8^+ levels		8^- levels	
1	2856	16	2325	15	3959	100	2269	16	2997	15	3024	18
2	3798	90	2581	12	4211	100	3167	14	3675	96	3763	98
3	3916	36	3168	15			3495	99	4263	99	4099	94
4	4024	83	3723	97			3865	95				
5			3929	97			4016	89				
6			3983	99								
7			4231	90								
	9^+ levels		9^- levels		10^+ levels		10^- levels		11^+ levels		11^- levels	
1	4159	100	2949	7	3034	14	4298	100	4593	100	4213	100
2	4510	100	4193	100	4431	98	4562	100	4782	100	4740	100
	12^+ levels		12^- levels		13^+ levels		13^- levels		14^+ levels		14^- levels	
1	4415	100	5602	100	5085	100	5713	100	5227	100	6059	100
2	5319	100	5821	100	5479	100	5763	100	5499	100	6240	100
	15^+ levels		15^- levels		16^+ levels		16^- levels		17^- level			
1	5306	100	5967	100	5980	100	6205	100	6051	100		
2	6248	100	6295	100	7202	100	7960	100				

calculated 4_2^+ state at 2735 keV. The level at 2260 keV without a J^{π} assignment is tentatively identified with the calculated 4^- level at 2493 keV. The 2088- and 2416-keV levels marked with a cross are assumed, based on systematics,[16] to originate mainly from proton two-particle–two-hole (2p-2h) excitations and are therefore not represented in the neutron $v_g \leq 4$ model.

For the 0_2^+ state an accurate prediction is always difficult to give because the pairing matrix elements ($J=0$ matrix elements) are large and, therefore, the prediction may easily miss the energy by several hundred keV. The experimental 4_2^+ state is considerably lower than the calculated one. This state is possibly pushed down by mixing with the 4^+ state of the 2p-2h proton intruder band which, on the basis of systematics,[16] is expected to lie slightly above 2.5 MeV. Another possible reason why we calculate the 4_2^+ state too high in energy is that this state will be, to a large extent, a two-phonon (92% $v_g=4$) state, while the lowest 4^+ state is predominantly a one-broken-pair ($v_g=2$) state of $(h_{11/2})^2$ configuration. The

TABLE VI. Calculated energy levels (in keV) in ^{120}Sn together with their corresponding two-broken-pair admixtures (% 2bp) grouped according to their spin-parity (J^π) values.

No.	E (level)	% 2bp	E (level)	% 2bp	E (level)	% 2bp	E (level)	% 2bp	E (level)	% 2bp	E (level)	% 2bp
	0^+ levels		0^- levels		1^+ levels		1^- levels		2^+ levels		2^- levels	
1			4761	100	2529	9	3701	100	1171	12	3195	97
2	2066	13	5281	100	3508	97	4424	100	2146	24	3776	41
3	2761	10			3622	98	4544	100	2364	68	3991	79
4	3324	88			3914	68			2628	29	4281	99
5	3704	96			4156	93			3205	16		
6	3817	24							3496	90		
7	4445	98							3570	79		
8									3659	78		
9									3886	75		
10									4015	89		
	3^+ levels		3^- levels		4^+ levels		4^- levels		5^+ levels		5^- levels	
1	3029	96	2431	10	2214	26	2367	15	3430	12	2178	20
2	3319	18	3484	100	2817	89	3324	99	3528	100	2672	11
3	3450	17	3523	65	3174	17	3481	20	3974	98	3325	93
4	3786	94	3875	69	3416	38	3716	100	4171	100	3503	29
5	3853	81	3927	88	3469	53	3777	97			3548	98
6	3905	75	4080	92	3683	92	3909	95			3678	73
7	3975	52			3839	88	3963	82			3943	98
8	4016	93			3906	97	4104	79			4117	92
9					4220	73						
	6^+ levels		6^- levels		7^+ levels		7^- levels		8^+ levels		8^- levels	
1	2664	16	2461	13	3831	100	2281	14	2823	15	3278	24
2	3622	97	2637	10	4274	100	3421	15	3596	97	3726	99
3	3726	97	3411	44			3531	99	3947	97	4101	88
4	4185	99	3514	70			3801	94	4357	100		
5			3803	98			3916	56				
6			3981	99			4096	96				
7			4154	48								
	9^+ levels		9^- levels		10^+ levels		10^- levels		11^+ levels		11^- levels	
1	3976	100	3162	8	2831	14	4486	100	4533	100	4385	100
2	4410	100	4094	100	4177	97	4793	100	4723	100	4726	100
	12^+ levels		12^- levels		13^+ levels		13^- levels		14^+ levels		14^- levels	
1	4143	100	5502	100	5220	100	5302	100	5296	100	5815	100
2	5112	100	5564	100	5521	100	5515	100	5636	100	5896	100
	15^+ levels		15^- levels		16^+ levels		16^- levels		17^- level			
1	5290	100	5527	100	6302	100	6214	100	5920	100		
2	6641	100	5945	100	6592	100	7934	100				

collectivity of the two-phonon state is probably not sufficiently well described within the small valence space of only one major shell. The fractional admixture of one-broken-pair configurations for levels in ^{122}Sn is presented in Table VIII and shown to the left of those levels that appear in Fig. 7.

Between 2.84 and 3.47 MeV, we calculate five positive-parity and six negative-parity states. The experimental level density is expected to be higher in this energy region because admixture with three-broken-pair configurations may push higher states downwards. As shown in Fig. 7, there are at least twenty levels known in this energy region, in agreement with these expectations.

B. Levels in ^{120}Sn

For ^{120}Sn the comparison between experimental and calculated levels is slightly more ambiguous than for ^{122}Sn because of experimental uncertainties. This comparison is presented in Fig. 8 for energies below 3470 keV, using experimental data from the present work and the Nuclear Data Sheets.[12] Dashed lines again represent

TABLE VII. Calculated energy levels (in keV) in ^{122}Sn together with their corresponding two-broken-pair admixtures (% 2bp) grouped according to their spin-parity (J^π) values.

No.	E (level)	% 2bp	E (level)	% 2bp	E (level)	% 2bp	E (level)	% 2bp	E (level)	% 2bp	E (level)	% 2bp
	0^+ levels		0^- levels		1^+ levels		1^- levels		2^+ levels		2^- levels	
1			4952	100	2776	9	3866	100	1140	14	3454	91
2	2273	11	5039	100	3550	90	4430	100	2248	51	3934	80
3	3023	12			3575	95	4620	100	2519	51	4047	48
4	3267	92			3812	64			2826	12		
5	3709	92			4149	97			3409	91		
6	4308	25							3503	33		
7									3632	60		
8									3678	79		
9									3872	65		
10									4002	86		
	3^+ levels		3^- levels		4^+ levels		4^- levels		5^+ levels		5^- levels	
1	3080	97	2555	14	2175	25	2493	12	3505	100	2369	18
2	3669	21	3387	100	2735	92	3275	99	3752	18	2803	9
3	3728	74	3743	70	3303	52	3672	71	4117	95	3364	96
4	3769	54	3882	95	3536	50	3717	86	4264	96	3517	98
5	3802	67	3986	73	3682	86	3827	70			3656	70
6	3943	75	4215	80	3753	64	3869	87			3750	62
7	3950	52			3810	65	3962	54			3863	56
8	4030	80			3935	59	4163	94			4066	94
9					4298	95						
	6^+ levels		6^- levels		7^+ levels		7^- levels		8^+ levels		8^- levels	
1	2645	16	2619	11	3790	100	2390	12	2807	15	3543	31
2	3470	100	2789	10	4394	100	3617	99	3587	99	3739	100
3	3714	95	3376	99			3664	19	3897	96	4127	78
4	4148	99	3719	29			3768	54	4298	100		
5	4265	100	3787	88			3814	85				
6			3996	88			4163	98				
7			4059	56								
	9^+ levels		9^- levels		10^+ levels		10^- levels		11^+ levels		11^- levels	
1	3891	100	3386	8	2809	15	4662	100	4520	100	4576	100
2	4484	100	4004	100	4154	97	4914	100	4706	100	4789	100
	12^+ levels		12^- levels		13^+ levels		13^- levels		14^+ levels		14^- levels	
1	4116	100	5282	100	5436	100	5137	100	5463	100	5575	100
2	5026	100	5384	100	5681	100	5397	100	5846	100	5862	100
	15^+ levels		15^- levels		16^+ levels		16^- levels		17^- level			
1	5430	100	5300	100	6268	100	6293	100	5974	100		
2	7049	100	5990	100	6473	100	8045	100				

our attempts at a one-to-one correspondence. Experimental levels marked with a cross originate mainly from proton 2p-2h excitations and are therefore excluded from our model. Fractional admixtures of one-broken-pair configurations are shown to the left of calculated positive-parity levels.

If the state at 2696 keV is indeed a 4^+ state, then this state is either missing from our calculations or is predicted considerably too high. But already below this state there are several problems. The calculated negative-parity states at 2367, 2461, and 2637 keV appear to have no clear experimental analogs. On the other hand, the 2172- and 2323-keV levels were seen in the (γ,γ') reaction,[35] and therefore they have $J \leq 3$. These states appear to have no theoretical analogs.

As in the case of ^{122}Sn, the lowest 4^+ state in ^{120}Sn is predominantly a one-broken-pair state of $(h_{11/2})^2$ configuration, and the next calculated 4^+ state is mainly of a two-broken-pair nature. We presume, based on the systematics of the lighter Sn isotopes,[16] that the experi-

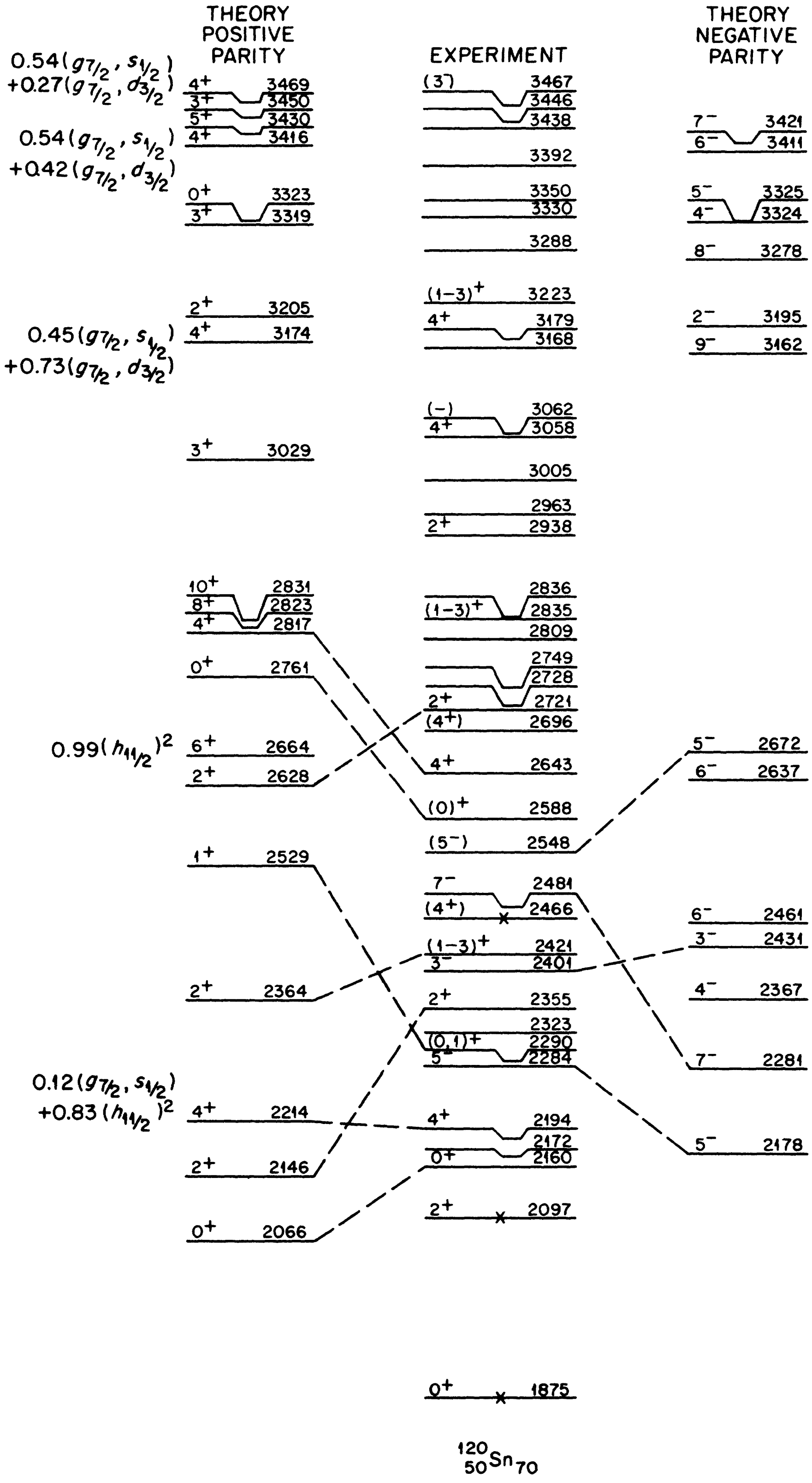

FIG. 8. Comparison of experimental and calculated levels below the 3470-keV excitation energy and above the first excited state for ^{120}Sn. Dashed lines denote our one-to-one correspondences. The fractional admixtures of one-broken-pair configurations are shown to the left of several calculated 4^+ levels and the calculated 2664-keV, 6^+ level. Experimental levels marked with a cross originate mainly from proton 2p-2h excitations not included in our model.

TABLE VIII. Fractional admixtures of one-broken-pair configurations for selected calculated energy levels in ^{122}Sn.

E (level) (keV)	J^π	Fractional admixture
2175	4^+	$0.84(h_{11/2})^2$
2645	6^+	$0.92(h_{11/2})^2$
3303	4^+	$0.63(d_{5/2},d_{3/2})$
3536	4^+	$0.64(g_{7/2},d_{3/2})$
3682	4^+	$0.31(g_{7/2},s_{1/2})$
3753	4^+	$0.53(g_{7/2},s_{1/2})$
3810	4^+	$0.23(g_{7/2},s_{1/2})$
3935	4^+	$0.054(g_{7/2},s_{1/2})$

mental 4^+ state at 2466 keV is basically a proton 2p-2h state, which may be mixed, however, with 4^+ states composed of neutron configurations.

C. Levels in ^{118}Sn

The spectrum of ^{118}Sn is the most difficult to interpret. This is partly due to the several cases of very close-lying states that make their separation and identification very difficult. The comparison of calculated levels with experimental data from the present work and the Nuclear Data Sheets[11] is shown in Fig. 9 for energies below 3470 keV. Again, dashed lines represent our tentative correspondences, experimental levels marked with a cross are proton 2p-2h excitations excluded from our model, and one-broken-pair configurations are shown to the left of calculated positive-parity levels.

All experimental levels below 2600 keV are shown with their tentative theoretical analogs. However, correspondences for 2^+ and 4^+ states are especially speculative due to the uncertainty of the spins of the 2120- and 2328-keV levels and the possible existence of a level at 2405 keV. The latter state, with a suggested 4^+ assignment from the (t,p) reaction,[36] is included as a dashed line in Fig. 9. This level is not listed as an adopted level for ^{118}Sn in the Nuclear Data Sheets.[11] Also, we did not include the 2276.4–2280.3 keV level doublet listed in the Nuclear Data Sheets[11] because we concluded that the existing data are consistent with a single level at 2280.3 keV. Similarly, we replaced a 2325.7–2327.7–2328.3 keV level triplet listed in the Nuclear Data Sheets[11] with a 2324.8–2328.0 keV level doublet.

Only three calculated negative-parity levels can be identified with known levels, whereas all calculated positive-parity levels below 2.8 MeV, except the 1^+ level at 2148 keV, appear to have an experimental analog. Between 2580 and 3470 keV there are $\simeq 48$ levels known from experiment. The 13 positive-parity and 12 negative-parity states calculated in this energy region can thus account for half of the observed levels. The remaining levels probably contain significant or even predominant three-broken-pair ($v_g = 6$) components not included in our calculations.

The lowest 4^+ state is again the $(h_{11/2})^2$ broken-pair configuration. Our calculated 4_2^+ state in ^{118}Sn is predominantly a $(g_{7/2},d_{3/2})$ broken-pair configuration, while the calculated 4_2^+ state in ^{120}Sn and ^{122}Sn is a two-broken-pair (i.e., predominantly a two-phonon) state. Because the 2^+ phonon, when calculated in larger model spaces, always contains large contributions from core polarization, one should expect that the two-phonon state mixes strongly with the proton 2p-2h band member. So we think that this mixing is stronger in ^{120}Sn and ^{122}Sn than in ^{118}Sn. In ^{118}Sn the two-phonon 4^+ state is calculated to be above 3 MeV.

D. The 4^+, 5^+, and 6^+ states

The β-decay pattern of the intermediate-spin [5^+] isomer is strikingly similar in all three cases; in the 2.1–4.0 MeV excitation energy region, 14 states in ^{118}Sn, 10 states in ^{120}Sn, and 14 states in ^{122}Sn account for nearly 100% of the decays. It is reasonable to conclude that the states fed by β decay are 4^+, 5^+, and 6^+ states even though this conclusion is strictly valid[37] only when $\log ft \leq 5.9$. There are at least six states in each nucleus that satisfy this $\log ft$ rule. All levels fed directly by β decay are reproduced in Fig. 10 for these three nuclides. Based on the above $\log ft$ arguments and knowledge of the γ transitions that deexcite the levels, we propose spin-parity values as shown in Fig. 10. (We have not formally inserted all of these J^π values into Figs. 2–4 or 7–9 because, when dealing with weak β feedings, we felt it is prudent to wait for independent confirmations.) Our 4^+ and 6^+ assignments are based mainly on detected transitions to a 2^+ level and a 7^- level, respectively. We can account for the observance of so many 4^+ states because the current experiment is particularly sensitive to 4^+ states as opposed to 5^+ or 6^+ states. The γ rays deexciting the 4^+ states to the first-excited 2^+ state are easier to detect because of the relatively low background in the higher-energy region of our γ spectra.

In Fig. 10 we also display the calculated 4^+, 5^+, and 6^+ states in the vicinity of the states fed by β decay. As seen by the dashed lines showing our suggested correspondences in this figure, the calculated results are consistent with the experimentally known data including our proposed spin-parity assignments. The general trend is such that the calculated states are a few hundred keV higher than the experimental ones. The fact that there is strong β feeding (low $\log ft$ value) to so many states indicates a strong configuration mixing not only in the Sn levels but also in the corresponding initial 5^+ state in In. For levels in Sn, this mixing is reflected by the dominant one-broken-pair configurations shown in Figs. 7–9 and listed in Table VIII.

In ^{118}Sn the lowest $\log ft$ value is to the 4^+ state at 2963 keV. In our calculation there is a 4^+ state at 2934 keV that is predominantly a one-broken-pair $(g_{7/2},s_{1/2})$ configuration. If these states are identified with each other, then the 5^+ parent state in ^{118}In would have to be predominantly a $(\pi g_{9/2}^{-1},\nu s_{1/2})$ configuration to yield such a low $\log ft$ value. Our calculated 4^+ state at 3053 keV, which is predominantly a two-broken-pair state but has a considerable $(g_{7/2},s_{1/2})$ component, may correspond to the 3159-keV state. The two-broken-pair nature

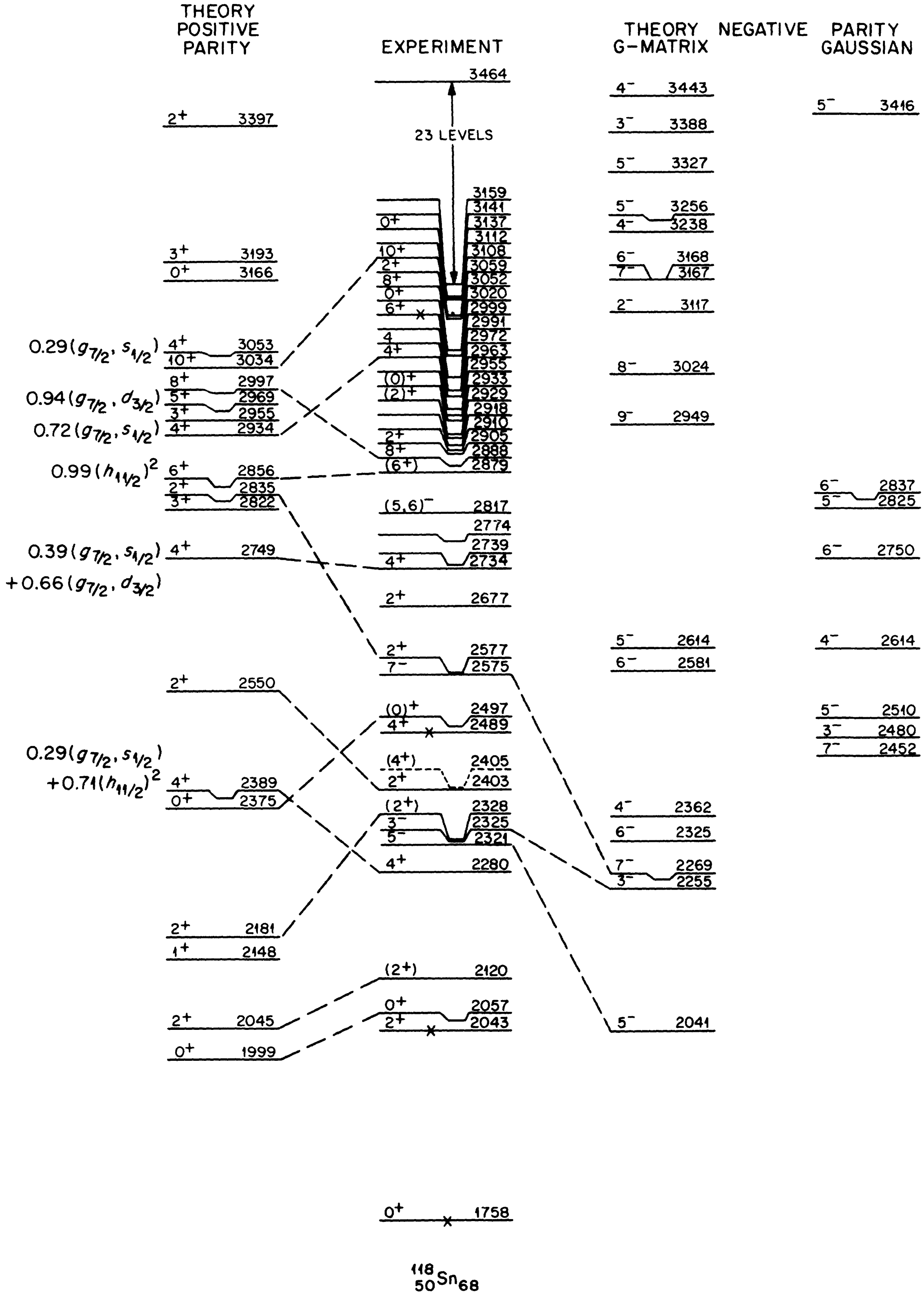

FIG. 9. Comparison of experimental and calculated levels below the 3470-keV excitation energy and above the first excited state for ^{118}Sn. Dashed lines denote our one-to-one correspondences. The fractional admixtures of one-broken-pair configurations are shown to the left of several calculated positive-parity levels. Experimental levels marked with a cross originate mainly from proton 2p-2h excitations not included in our model. The negative-parity spectrum calculated with the current G matrix effective interaction is compared with that calculated with an earlier Gaussian interaction (Ref. 21) at the far right.

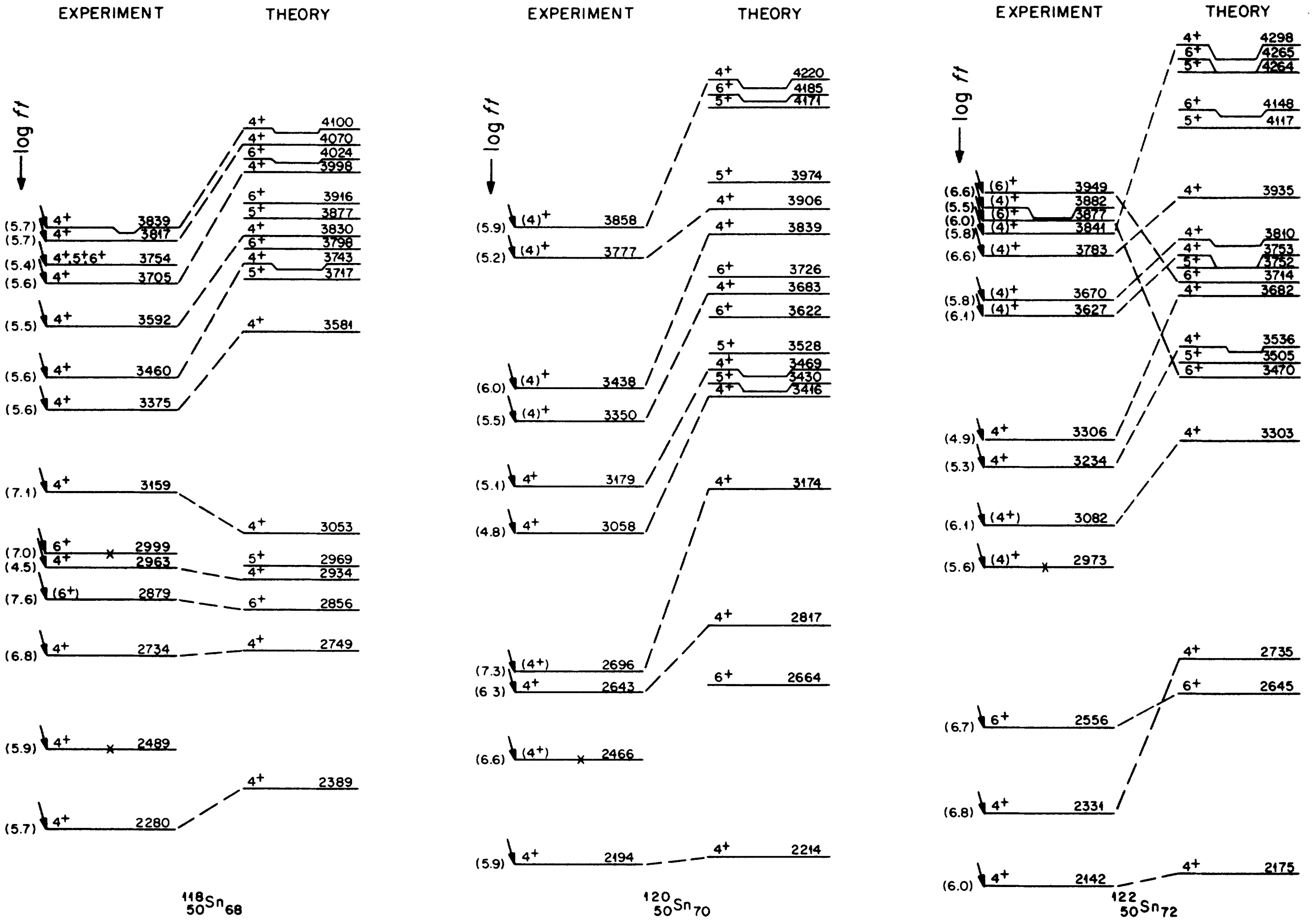

FIG. 10. Comparisons of calculated 4^+, 5^+, and 6^+ levels of ^{118}Sn, ^{120}Sn, and ^{122}Sn with all levels fed directly by β decay of the corresponding intermediate-spin (5^+) In isomer. Experimental levels marked with a cross originate mainly from proton 2p-2h excitations not included in our model. The J^π assignments for all levels above 3 MeV in ^{118}Sn, for the 3350-, 3438-, and 3858-keV levels in ^{120}Sn, and for the 2973-keV level and all levels above 3.5 MeV in ^{122}Sn are based on the current work (see Sec. V D). The remaining J^π assignments are from the Nuclear Data Sheets (Refs. 11–13).

of this state could explain the rather weak feeding ($\log ft = 7.1$) in the β decay because the one-body β-decay operator cannot at the same time break a second neutron pair and fill the proton hole. The 4_2^+ state at 2489 keV is basically the proton 2p-2h state[16] not included in our model space, possibly mixed, however, with 4^+ states composed of neutron configurations. Indications of direct β feeding to the 6^+ state at 2999 keV, which is mainly a proton 2p-2h state, also suggest admixtures of complicated components in the initial state. There is very little feeding to the known (6^+) state at 2879 keV, an observation that is easy to understand if this state corresponds to the calculated $(h_{11/2})^2$ state at 2856 keV because such a decay from the initial $(\pi g_{9/2}^{-1}, \nu s_{1/2})$ configuration would be highly l forbidden. The only low-lying 4^+, 5^+, or 6^+ state in our ^{118}Sn calculation (see Fig. 10) for which there is no clear experimental counterpart is the 5^+ state at 2969 keV. From the angular-momentum coupling rules discussed in Ref. 6, one expects that the feeding of this 5^+ state is considerably weaker than that of the $(g_{7/2}, d_{3/2})$, $J^\pi = 4^+$ configuration. We conclude that the decay of the 5^+ isomer of ^{118}In can be reasonably well understood if this state is predominantly in a $(\pi g_{9/2}^{-1}, \nu s_{1/2})$ configuration but with appreciable admixtures of other configurations.

Because the decay patterns are so similar, the above considerations pertaining to ^{118}Sn can also be extended, at least qualitatively, to ^{120}Sn and ^{122}Sn.

E. Two-phonon states

In a model space containing up to two-broken-pair excitations we obtain at least one 0^+, 2^+, and 4^+ state of mainly two-broken-pair nature around twice the excitation energy of the 2_1^+ states. These are the calculated 2_4^+ and 4_4^+ states in ^{118}Sn and the 2_2^+ and 4_2^+ states in ^{120}Sn and ^{122}Sn. Indeed, we calculate also the largest $B(E2;J \rightarrow 2_1^+)/B(E2;2_1^+ \rightarrow 0_1^+)$ ratio for these states. For 0^+ states, this $B(E2)$ ratio is large both for the 0_2^+ and the lowest-lying two-broken-pair 0^+ state, which is the calculated 0_5^+ state in ^{118}Sn and the calculated 0_4^+ state in ^{120}Sn and ^{122}Sn. The appearance of a noticeable two-phonon strength in the 0_2^+ states, which are mainly of one-broken-pair nature, should not be a surprise. There are no reasons why a two-phonon state should be a mainly two-broken-pair state. Especially for 0^+ configurations, a state obtained by breaking a second pair may sometimes have a dominant one-broken-pair nature due to angular momentum recouplings, as has been shown in Ref. 38. In a previous calculation on lighter Sn isotopes,[21] the two-phonon strength was found rather fragmented. Our calculation suggests that in heavier Sn isotopes more well defined 2^+ and 4^+ two-phonon states occur, whereas the 0^+ states remain fragmented. As experimental counterparts one may search for those states that decay preferentially to the 2_1^+ state. This happens in ^{118}Sn for the 2403-keV, 2^+ state, for which no transition to the ground state has been observed, and for the 2328-keV, $(2)^+$ state. According to the same criterion the best candidate in ^{120}Sn is the 2^+ state at 2355 keV and in ^{122}Sn it is the $(2)^+$ state at 2154 keV. Due to lack of more reliable experimental evidence, such as $B(E2)$ or half-life measurements, the existence of other two-phonon states can only be based upon rather weak arguments.

F. Negative-parity states

From Figs. 7–9, in which the calculated and experimental spectra are displayed, one observes that the broken-pair model is rather successful for the negative-parity states. Especially in ^{120}Sn and ^{122}Sn the lowest states are well reproduced. The calculated 9_1^- state is probably much too low and is expected above the 8_1^- and 7_2^- states, as is known from the lighter Sn isotopes.[20] The energy of the 9_1^- state is very sensitive to the triplet-odd force, which is therefore probably not well represented by our effective interaction. With the Gaussian force we employed earlier,[21] the 9_1^- state occurs indeed above the 8_1^- and 7_2^- states, but other features of the level scheme are slightly less well reproduced. Independent of the interaction, however, is the feature that 7_2^-, 8_1^-, and 9_1^- states occur around 3.4 MeV, where indeed the strongest β-decay feeding from the high-spin isomer is observed. That this isomer has indeed $J^\pi=8^-$ is supported by the fact that there is no decay to lower-lying states with $J<7$, which makes $J<8$ for the isomer unlikely. Also, $J>8$ is unlikely because then it is difficult to understand the four allowed decays to states between 3.4 and 3.8 MeV in ^{122}Sn (see Fig. 4). It is difficult to decide which of the states around 3.5 MeV in ^{120}Sn and ^{122}Sn are the 7_2^- and 8_1^- states. Rules of angular momentum coupling predict that the logft value for the 7^- state should be about 0.5 smaller than for the 8^- state, given that both have the $(g_{7/2},h_{11/2})$ neutron one-broken-pair configuration and that the initial state is the $8^-,(\pi g_{9/2}^{-1},\nu h_{11/2})$ state. From this argument one might assign $J^\pi=7^-$ to the 3446-keV state in ^{120}Sn and to the 3531-keV state in ^{122}Sn. According to our calculations, however, the 7_2^- state lies higher than the 8_1^- state in all three isotopes. If it transpires that the 7_2^- state does not possess the lowest logft value as expected, this fact can perhaps be explained as resulting from the strong fragmentation of the $(g_{7/2},h_{11/2})$ neutron broken-pair configuration over several 7^- states.

We should draw attention to the low-lying 4^- state, which we calculate at 2.36 MeV, 2.37 MeV, and 2.49 MeV in ^{118}Sn, ^{120}Sn, and ^{122}Sn, respectively, with a predominant $(d_{3/2},h_{11/2})$ one-broken-pair configuration. It is not clear to which observed states they correspond although there are some candidates, e.g., the states at 2.2 MeV without spin assignments in ^{120}Sn and ^{122}Sn.

Also, from the point of view of our calculations, the negative-parity spectrum was especially found to be most sensitive to the interaction used. This was the situation when we did the same broken-pair calculation for the $^{118-124}$Sn nuclei[21] with a phenomenological Gaussian interaction found suitable for the lighter Sn nuclei. Whereas, in ^{120}Sn and ^{122}Sn the differences between the calculated energy levels for the two interactions are only a few hundred keV, for ^{118}Sn they appear to be sometimes as large as 400 keV for the negative-parity states. For this reason we have also plotted the negative-parity spectrum of this Gaussian interaction in Fig. 9. One observes, however, that the same group of low-lying states is predicted by both interactions, the main feature being an overall relative shift of about 300 keV.

G. Low-lying 1^+ states

One other difference between the interactions that should be mentioned is that the energy of the 1^+ state is almost 700 keV higher with the Gaussian force for ^{118}Sn, almost 500 keV for ^{120}Sn, and 350 keV for ^{122}Sn. Therefore, the experimental identification of a low-lying 1^+ state would provide a sensitive test of the effective interaction.

Together with the above-mentioned 4^- states, the 1^+ states are the lowest unnatural-parity states in our calculation with predominantly a $(d_{3/2},s_{1/2})$ neutron broken-pair configuration. We predict these states at 2.15 MeV, 2.53 MeV, and 2.78 MeV in ^{118}Sn, ^{120}Sn, and ^{122}Sn, respectively. The prediction of about 2.5 MeV is the same as for lighter Sn isotopes.[21] In ^{120}Sn and ^{122}Sn there are several candidates for a $J^\pi=1^+$ assignment. The 1^+ state in ^{118}Sn is predicted to lie exceptionally low. If the 2120-keV state, instead of being a (2^+) state as suggested from the (d,^{6}Li) reaction,[11] is actually a 1^+ state, this state would provide an interesting case for studying l-forbidden magnetic dipole excitations.

VI. SUMMARY AND CONCLUSIONS

We have performed a detailed study of the decays of the 4.4-min ^{118}In, the $\simeq$47-sec ^{120}In, and the $\simeq$10.5-sec ^{122}In isomers using the (n,p) reaction to produce these activities. The study of the decays of even-mass In isotopes in this region is complicated because of the existence of multiple isomers for each isotope, some of which have nearly identical half-lives. Production of the isomers via different nuclear reactions is one way to try to unravel the separate decay schemes. The results of our decay studies of the intermediate-spin isomer of ^{118}In, ^{120}In, and ^{122}In are significantly more detailed than any corresponding data previously published for these cases.

Theoretical calculations were made of the complete spectroscopy for ^{118}Sn, ^{120}Sn, and ^{122}Sn in a generalized seniority $v_g \leq 4$ (up to two-broken-pair) model. The effective Hamiltonian used was derived from a realistic meson-exchange Bonn-potential, supplemented by multipole components. Shell model parameters were derived from a fit with known data of the odd Sn isotopes in a generalized seniority $v_g \leq 3$ model. The spectra of the even Sn nuclei were subsequently calculated without any readjustment of these parameters.

A comparison was made of our calculated results with all known experimental data for ^{118}Sn, ^{120}Sn, and ^{122}Sn. Reasonable one-to-one correspondences exist for a number of levels in each nucleus. Although the mere fact that one can perform model calculations for such complex nuclei with some success is remarkable in itself, the model we used has a predictive power for the energies of the low-lying states that is much better than could be anticipated. More complete experimental data for these levels would be especially useful in testing this model further.

We have also learned of shell-model calculations in a seniority $v \leq 4$ space with additional energy truncation by Momoki *et al.*[39] The calculations were carried out for the 0^+, 2^+, 4^+, and 6^+ states with a combination of a surface-delta interaction (SDI) and a quadrupole force. Also, $\frac{1}{2}^+$-$\frac{7}{2}^+$ and $\frac{11}{2}^-$ states in odd Sn nuclei were calculated. The results of these authors are rather similar to ours. The degree of seniority mixing that they find is larger than one would obtain for a pure SDI.[40] Such a seniority mixing is also found in the present calculation as it is, in general, with finite-range forces. Such a mixing was also shown to be necessary to reproduce the measured $B(E\lambda)$ values in the lighter nuclei.[21]

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