Neutron transmission and capture gamma-ray measurements of ^{120}Sn + n†

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Neutron transmission and neutron capture γ-ray measurements have been performed upon 98.4% enriched samples of ^{120}Sn. The transmission measurements were made at 18- and 80-m neutron flight paths. Neutrons were detected by a ^{6}Li glass scintillator. Parameters have been obtained for 251 resonances up to 98 keV. From the shapes of the resonances, l-value assignments have been made for 70% of the resonances. Level spacings and strength functions for s- and p-wave neutrons have been obtained. Neutron capture γ rays from 16 resonances, obtained with a Ge(Li) detector, have been utilized to determine the levels in ^{121}Sn. New spin and parity assignments have been made for many of the levels. Four new levels have been found. The neutron separation energy was determined to be 6170.3 ± 2.0 keV. The ^{121}Sn level scheme has been compared with those for ^{117}Sn and ^{119}Sn to investigate systematic behavior.

NUCLEAR REACTIONS ^{120}Sn(n), E=0.1–100 keV; measured total $\sigma(E)$. ^{121}Sn deduced resonances, l, resonance parameters, level spacing, s-, p-wave neutron strength functions. ^{120}Sn(n,γ), E=0.1–7 keV; measured E_γ, I_γ. ^{121}Sn deduced levels, J, π, neutron separation energy. ^{117,119,121}Sn systematics. Enriched targets.

I. INTRODUCTION

The tin isotopes are well suited to a study of nuclear structure within the framework of the nuclear shell model because the magic number of protons ($Z = 50$) minimizes the need for considering n-p pairing interactions in theoretical calculations and because the large number of stable isotopes makes it possible to study systematic trends in both experimental and shell model features. Such systematic trends based on measurements and calculations prior to 1971 have been summarized by Baranger.[1] The experimental data available then and now concerning the energy levels in the odd-A tin isotopes are not as extensive as one might expect on the basis of their theoretical importance. Thermal neutron capture studies have not been widely used due to the extremely small capture cross sections for the heavier even-A tin isotopes. Most experimental studies (especially nucleon transfer studies) are beset with the problem of interference from isotopic impurities. This usually necessitates an extensive study of all tin isotopes before conclusive results may be obtained. Resonance neutron capture offers a powerful technique for studying tin isotopes because interference from unwanted isotopes can be greatly suppressed through the combination of enriched targets and selection of resonances known to be in the nucleus under study. We have, therefore, undertaken a systematic study of the level structure of five odd tin isotopes between $A = 117$ and $A = 125$. The present paper describes transmission and capture measurements carried out with a ^{120}Sn target.

Transmission measurements on all the tin isotopes were started in 1961 at the chopper facility of the Oak Ridge Research Reactor (ORR).[2] The energy resolution of these measurements was 11 nsec/m with the result that only a small number of resonances were measured in each even-A nuclide, and few if any resonances were observed above a few keV neutron energy. Early determinations of s-wave strength functions,[2,3] based on the assumption that all resonances were s-wave, were in good agreement with theoretical values predicted[4] by a two particle-one hole model. The demonstration by thick-sample transmission measurements[5] that two of the seven resonances observed in ^{120}Sn + n below 10 keV were p-wave resonances and that only one resonance was definitely s-wave reduced the s-wave strength function. Hence the good agreement obtained previously between experimental and theoretical s-wave strength functions was illusory. More recent measurements[6] with better resolution increased the number of observed resonances below 10 keV and established two resonances as definitely s-wave. With the increased neutron energy resolution ($\Delta E/E \approx 0.001$) available with the Oak Ridge Electron Linear Accelerator, we have made transmission measurements upon a thick sample of ^{120}Sn, finding some 251 resonances in the energy range below 100 keV. For several of the resonances, s-wave assignments have been made on the basis of interference observed between resonance and potential scattering.

Stripping[7-9] and pickup[7,10] reaction studies and ^{121}In ground state and metastable state decay studies[11] have provided some information on ≈90 levels in ^{121}Sn up to 5 MeV excitation energy. Spin and parity (J^π) values have been assigned to some of these levels on the basis of orbital angular momentum transfer values extracted from angular distribution data. We have obtained additional information on 20 levels in ^{121}Sn via the ^{120}Sn (n,γ) reaction with resonance energy neutrons. We have tabulated all well established energy levels in ^{121}Sn below 2.3 MeV and have proposed J^π assignments for 21 states. We have compared the ^{121}Sn level scheme with those for ^{117}Sn and ^{119}Sn, which have been studied in connection with the core-coupling model.

II. EXPERIMENTAL PROCEDURE

The Oak Ridge Electron Linear Accelerator (ORELA) was used to produce a pulsed beam of 140 MeV electrons which are stopped in a water cooled Ta target. The resulting burst of neutrons is moderated by a 3.2 cm thick water moderator of 15 cm diameter which surrounds the target.[12]

A. Transmission Measurements

Transmission measurements were initially performed at a neutron flight path of 17.86 m. The neutron beam was characterized by 6-nsec bursts at a pulse repetition rate of 700 Hz. Overlap neutrons were eliminated by ^{10}B filters at the 5- and 10-m stations. An 0.635-cm Pb filter was used to reduce the gamma flash. The sample was ≈66 g of Sn ($1/N=$ 3.85 b/atom). Even though we employed a highly enriched sample (98.4% ^{120}Sn), corrections had to be made for large resonances of other isotopes of Sn in calculating the level densities. The sample thickness was selected to achieve the maximum sensitivity for detecting small resonances and for observing asymmetries in the shapes of the resonances due to interference between resonance and potential scattering for s-wave resonances. This would then permit the assignment of the l-value of the resonances in favorable cases. Backgrounds were determined by the "blacking-out" technique using thick samples of W, Co, and Mn. The background amounted to ≈6% of the open beam counts. The neutron energy resolution (full width at half maximum) was ≈0.3%, limited by the slowing-down time in the moderator. The measurements at the 17.8-m flight path were analyzed to approximately 65 keV.

Subsequent measurements at 78.86 m using 6.5-nsec bursts extended the region of analyzed resonances to 98 keV. For these measurements, the sample was ≈131 g of Sn ($1/N$ = 7.68 b/atom) enriched to 98.4% in ^{120}Sn. The neutrons were detected by a 1.2-cm thick by 11.4-cm diameter ^{6}Li glass scintillator optically coupled to an RCA 4522 photomultiplier tube. A gating circuit was employed to "gate off" the phototube for ≈2 μsec after the decay of the gamma flash. Two constant fraction timing discriminators provided the stop pulses to the data acquisition system. One-nsec timing channels were used in the EG&G time digitizer. Data were stored in one of the ORELA data acquisition computers using timing channels from 1–128 nsec. The measurements covered the energy range from 4 to 100 keV. The neutron energy resolution (fwhm) was ≈0.1% over the entire energy region, limited mainly by the moderation time in the moderator and by the burst width.

B. Capture Gamma-Ray Measurements

The neutron capture γ-ray measurements were carried out at a flight path of 10.45 m. A 37-cm^3 Ge (Li) detector was placed 10 cm below the beam and the entire detector assembly was enclosed in a copper screen housing to shield out electromagnetic interference from the accelerator. The detector preamplifier provided both timing and analog signal outputs. The timing of the events was carried out with a filter amplifier and a constant fraction discriminator, and the resulting outputs were transmitted to a data acquisition center. The event times were digitized by a 10-nsec clock. The analog signals were digitized by a 4096-channel, 100-MHz analog to digital converter. The digitizers were interfaced together so as to maintain correct correlation between times and pulse heights for each event.

Fig. 1 shows a spectrum of neutron capture γ rays *versus* neutron flight time. From such data, appropriate time gates were selected corresponding to different neutron energies, some on resonance and some off resonance. For this experiment we utilized a computer which routed 24 spectra, 4096 channels each, to an 800,000 channel disk. Data were analyzed by a peak finding program to give γ-ray energies and intensities. The energy calibrations were provided by the 511.0 keV annihilation radiation, by the 2223.3-keV γ ray from the ^{1}H$(n,\gamma)^2$H reaction and by the 7631.6-7645.6 keV doublet from the ^{56}Fe(n,γ) reaction. The detector efficiency calibrations were carried out by utilizing the ^{53}Cr(n,γ) reaction[13] for the high energy region and calibrated radioactive sources including ^{66}Ga and ^{226}Ra for the lower energy region.

III. RESULTS

A. Transmission Measurements

The transmission data have been analyzed by an area analysis program. Resonance parameters have been obtained for 251 resonances in ^{120}Sn up to a neutron energy of 98 keV. Only the ≈80 resonances above 56.6 keV are listed in Table I since the remaining ones below this energy together with their resonance parameters and l values have been already listed in the Brookhaven National Laboratory Report[14] BNL-325. For all resonances, the radiation width was taken to be 0.110 eV from capture measurements by Moxon.[15] Below 10 keV, previous investigations[6] have revealed only 19 resonances, whereas our studies show 11 additional ones. From the resonance shapes, we have concluded that 5 are definitely s-wave and 17 are definitely not s-wave (most likely p-wave). The remaining 8 resonances in this region were too weak to permit a definite l-value assignment. However, it is very unlikely that any of the resonances that we found below 98 keV are d-wave since the penetrability of d-wave neutrons at ≈50 keV is only ≈1% that of p-wave neutrons and since the d-wave strength function is expected to be only ≈10% of the p-wave strength function. Consequently, d-wave resonances would be much smaller than our limit of detectability.

The bases for l-value assignments are shown in Fig. 2. The presence of an interference minimum on the low-energy side of a resonance (e.g., 4.363 keV resonance) establishes that the resonance is formed by s-wave neutrons. Other s-wave resonances were identified in a similar manner. Neighboring resonances which are as strong and stronger than the s-wave resonances are obviously p-wave since they showed no evidence whatsoever of interference effects. For marginal cases, l-values were established by obtaining both s-wave and p-wave fits to the data using the area analysis program and by choosing the better fits via χ^2 tests. Of the 251 resonances observed up to 98 keV, 157 have been assigned as p-waves and 23 as s-waves. The remaining 71 resonances, too weak to permit l-value assignments as described above, were apportioned as p-waves and s-waves in the ratio 7:1 (p:s) in order to determine the level density.

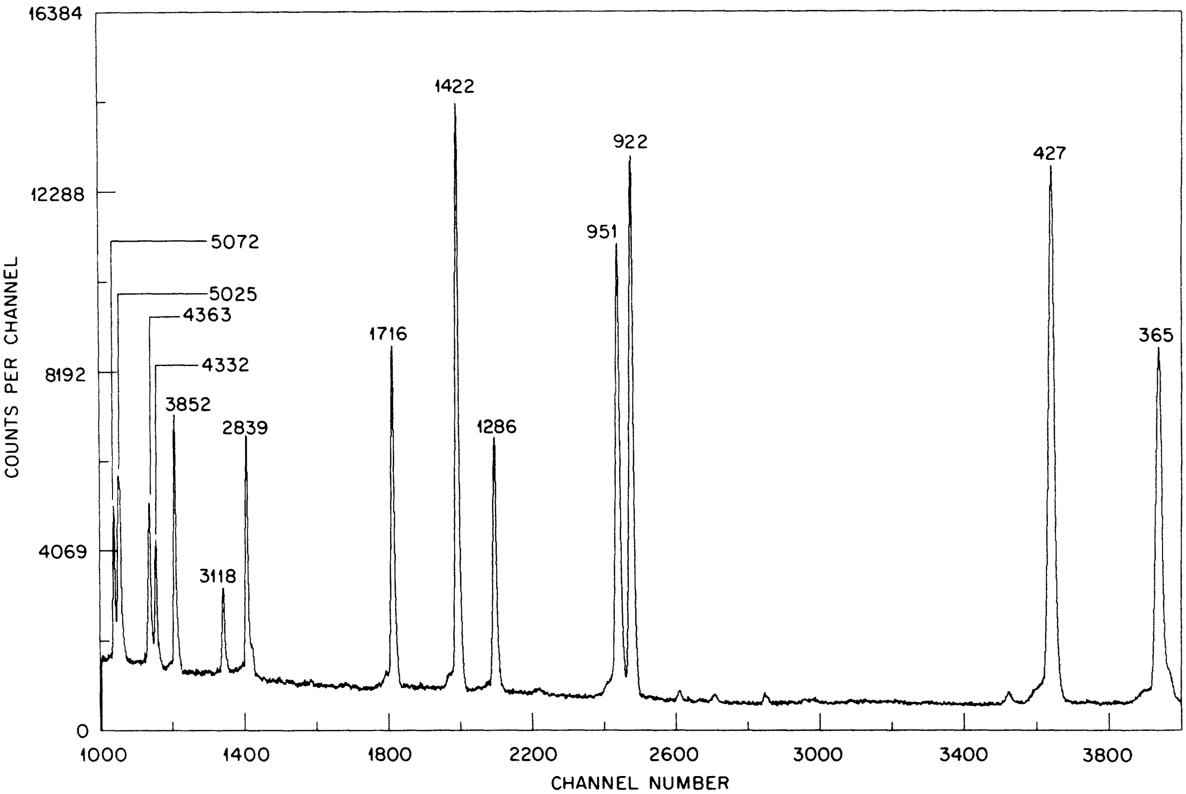

FIG. 1. Time-of-flight plot of events in the Ge(Li) detector. The peaks are labelled with neutron energies in eV.

TABLE I. Reduced neutron widths and l-value assignments for neutron resonances in ^{120}Sn

E_0^a (keV)	$g\Gamma_n^{0b}$ (meV)	l^c	E^a (keV)	$g\Gamma_n^{0b}$ (meV)	l^c	E_0^a	$g\Gamma_n^{0b}$ (keV)	l^c	E_0^a (keV)	$g\Gamma_n^{0b}$ (meV)	l^c
56.69[d]	6.5 *10*		64.86	9.9 *16*	1	74.33	13.1 *26*	1	85.11	86 *8*	1
56.76	24.3 *27*	1	65.33	34.8 *35*	1	74.50	30.1 *36*	1	85.62	31.4 *63*	1
57.17	15.4 *28*	1	65.44	33.6 *34*	1	75.44	32.8 *43*	1	86.03	14.7 *53*	1
57.81	5.3 *13*	1	66.59	69.8 *42*	1	76.05	25.6 *38*	1	86.69	41.8 *67*	1
58.21	7.7 *15*	1	66.76	25.7 *26*	1	76.24	4.0 *14*		87.19	9.5 *40*	
58.46	26.5 *26*	1	67.05	4.0 *12*	1	76.83	27.0 *32*	1	87.46	9.0 *40*	
59.67	13.2 *16*	1	67.53	10.0 *25*	1	76.89	11.1 *18*		88.25	26.6 *59*	1
59.73	28.6 *29*	1	67.99	10.9 *21*	1	76.96	22.1 *33*		89.57	103 *9*	1
59.85	36.5 *37*	1	68.60	61.1 *31*	0	78.69	35.4 *39*	1	89.89	61.7 *86*	1
60.08	15.6 *23*		69.82	33.6 *33*	1	78.97	136 *7*	1	90.47	7.8 *37*	
60.15	116.2 *58*	1	69.92	33.6 *33*	1	79.19	10.9 *27*		90.75	7.4 *34*	
60.85	300 *30*	1	70.31	43.5 *43*	1	79.69	6.2 *20*		91.42	31 *7*	1
61.00	11.7 *18*	(1)	70.97	29.6 *36*	1	80.22	9.4 *28*		93.07	93 *9*	1
61.76	30 *6*	1	71.87	305 *15*	1	81.16	109 *7*	1	93.45	28.6 *69*	1
61.85	4.7 *10*		72.21	26.1 *39*	1	81.43	12.2 *27*		94.07	10.3 *40*	
62.97	12.9 *21*	1	72.85	82.1 *57*	1	81.77	70.8 *57*	1	94.85	52.7 *79*	1
63.25	9.7 *19*	1	73.13	5.5 *13*	1	82.80	12.4 *27*	1	95.24	33.5 *67*	1
63.83	148 *7*	0	73.21	5.1 *13*	1	82.98	65.4 *52*	1	95.78	17.9 *43*	
64.51	130 *7*	1	73.54	50.0 *25*	1	83.95	90 *14*	0	96.51	24.8 *60*	1
64.69	39.5 *32*	1	73.77	33.0 *33*	0	84.26	193 *15*	1	97.05	9.4 *49*	
64.79	7.4 *12*		73.86	12.0 *26*		84.50	439 *44*	1	97.45	50.6 *61*	1

[a]Resonance energies have uncertainties of $\leqslant 0.1\%$.
[b]Reduced neutron width at 1 eV for s-wave neutrons, defined, for example, in Ref. 14. See also the expression for $g\Gamma_n^1$ given in Section IV.A. In our notation, 6.5 *10* $\equiv 6.5 \pm 1.0$, etc.
[c]$l = 1$ denotes p-wave and $l = 0$ denotes s-wave resonances. A parenthesis denotes a less certain l-value assignment.
[d]Our results for ≈ 170 resonances below 56.69 keV and above 0.36 keV have been already included in Ref. 14.

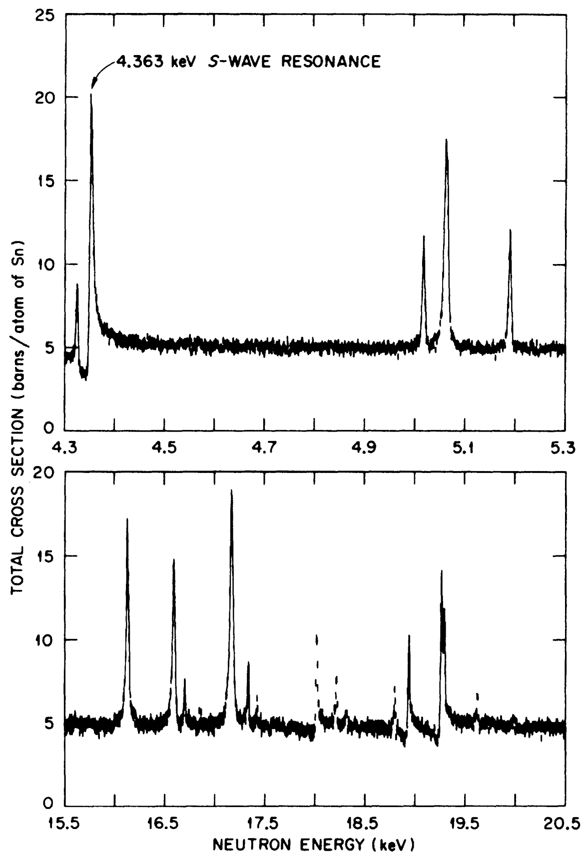

FIG. 2. Neutron total cross section *vs.* energy for ^{120}Sn.

B. Capture Measurements

The high-energy portions of the γ-ray spectra from five resonances are shown in Fig. 3. Eighteen γ rays were assigned as primary γ rays based on evidence of kinematic shifting of their energies in various neutron resonances. These primary γ rays were, in turn, used to establish the low-lying levels in ^{121}Sn. The primary γ rays leading to the ground state and second excited state, respectively, were seen in virtually every resonance. Their presence in the 951 eV resonance (known to be $1/2^+$ due to s-wave interference in transmission) is evidence for the unusually strong $M1$ transitions previously reported in the tin isotopes.[16] Of the γ-ray spectra from the resonances shown in Fig 1, only those pertaining to resonances below 1.8 keV were used in developing the ^{121}Sn level scheme, since the spectra from the higher resonances (except the 6.67-keV resonance) provided no additional information.

The low-energy (secondary) capture γ-ray spectrum from the 951 eV resonance is shown in Fig. 4. Most of the low-energy γ rays correspond to de-excitation of various excited states in ^{121}Sn. A listing of primary γ rays and their relative intensities in each neutron resonance is presented in Table II while the secondary γ rays are listed in Table III. The decay scheme based on the observed γ rays is shown in Fig. 5. All levels except those at 8, 926 and 951 keV are populated by primary γ transitions. In particular, the levels at 0, 60, 869, 1101, 1912, 2067, 2163 and 2285 keV are populated by primary γ rays from the 951 eV, $1/2^+$ resonance. The levels at 0, 60, 1101, 1653, and 1960 keV are populated by primary γ rays from the 427 eV resonance. In earlier transmission studies upon a 10-cm thick ^{120}Sn sample carried out at the ORR chopper facility, the 427 eV resonance was found not to exhibit the asymmetry computed for an s-wave resonance, thereby suggesting a p-wave assignment.[5] It has been further shown that the spin of the 427 eV resonance is $1/2$ on the basis of isotropic angular distribution deduced for the 6170 and 6110 keV γ rays in the ^{120}Sn (n,γ) reaction measured at 90° and 135° with respect to the incident neutron beam.[17]

The energies of 15 states populated in the (n,γ) reaction agree well (See Table IV) with those for states excited in previous reaction and decay studies.[7-11] Four new levels have been identified in this work at 1653, 1876, 2163 and 2525 keV. The neutron separation energy, S_n, was determined to be 6170.3 ± 2.0 keV. The present S_n value for ^{121}Sn is in good agreement with $S_n = 6176 \pm 5$ keV obtained earlier in (n,γ) measurements,[17] and with $S_n = 6170.8 \pm 1.7$ keV deduced from recent ^{120}Sn (d,p) experiments[9] but not with $S_n = 6191 \pm 6$ keV deduced from the $^{121}\mathrm{Sn} \rightarrow {}^{121}\mathrm{Sb}$ β-decay energy[18] and the known masses for ^{120}Sn and ^{121}Sb from mass doublets.[19]

IV. DISCUSSION

A. Strength Functions for the ^{120}Sn + n Reaction

Fig. 6 shows a cumulative histogram of reduced neutron widths for the s-wave resonances. The solid histogram represents the contribution of those resonances which were found to be definitely s-wave. The s-wave strength function ($S_0 = \langle\Gamma_n^0\rangle/\langle D\rangle$) obtained from the solid histogram was $(0.10 \pm 0.03) \times 10^{-4}$. The value obtained from the dashed histogram, which included 10 other possible s-wave resonances, was $(0.11 \pm 0.03) \times 10^{-4}$. This result is in excellent agreement with the value of 0.095×10^{-4} predicted by theory.[4] Fig. 7 shows a histogram plot of $\Sigma g\Gamma_n^1$ *versus* neutron energy for the p-wave resonances where

$$g\Gamma_n^1 = g\Gamma_n\sqrt{1\ \mathrm{eV}/E}\,[1 + (1/k^2R^2)]\ .$$

In this expression E is the resonance energy in eV, k is the neutron wave number and R is the nuclear radius. In terms of the s-wave reduced neutron width and for a nuclear radius[6] of 6.24×10^{-15}m, this expression reduces to

$$g\Gamma_n^1 = g\Gamma_n^0\,[1 + (5.3 \times 10^5/E_0)]\ .$$

As in the case of s-waves, the lower histogram is due to definite p-waves and the upper histogram is due to definite + probable p-waves. The p-wave strength function was calculated from the expression

$$S_1 = (\Sigma g\Gamma_n^1)/3(\Delta E)\ ,$$

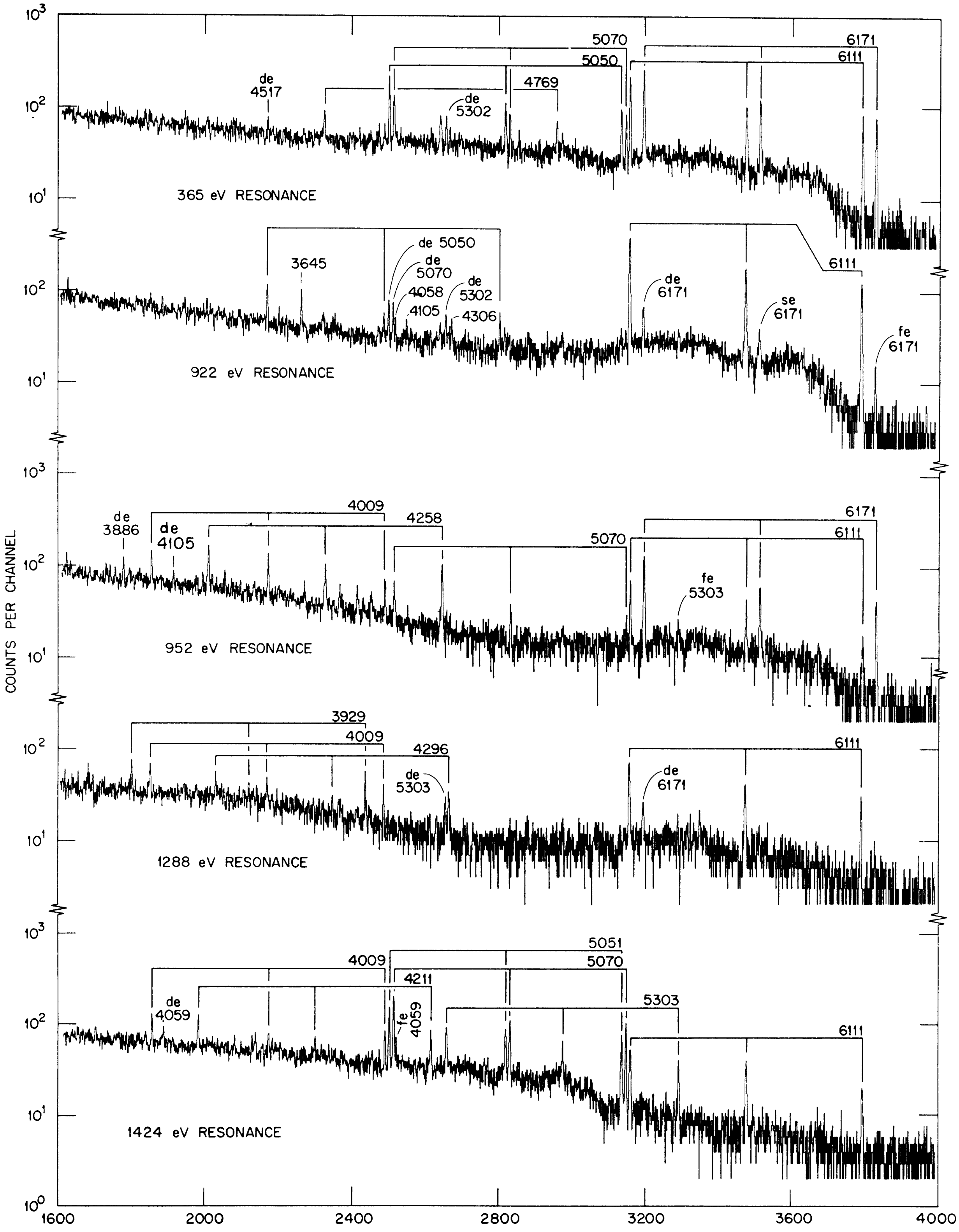

FIG. 3. High-energy portions of γ-ray spectra from 5 neutron resonances. All energies are in keV.

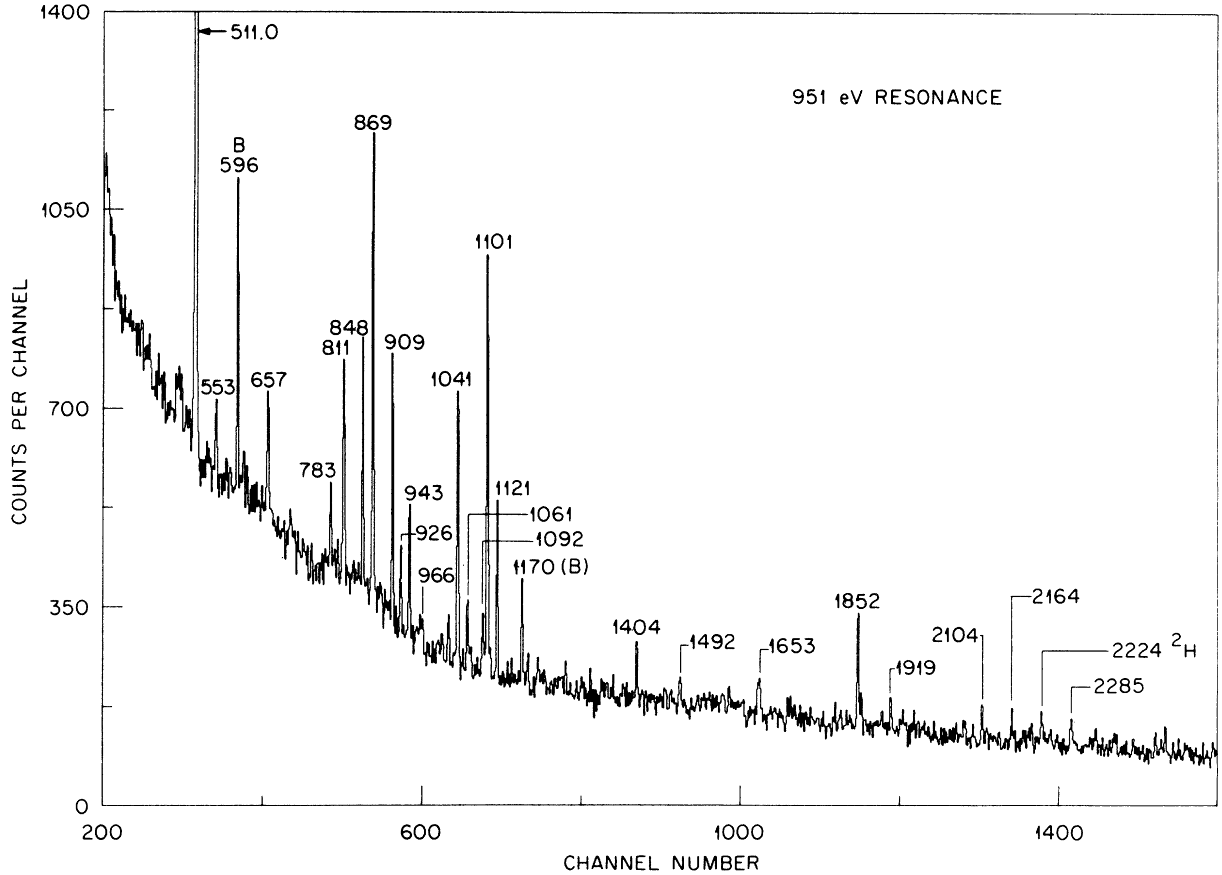

FIG. 4. Low-energy portion of γ-ray spectrum from the 951 eV neutron resonance. All energies are in keV.

TABLE II
Relative photon intensities of the primary γ-rays from the ^{120}Sn$(n,\gamma)^{121}$Sn reaction

	Neutron resonance energy (eV)						
E_γ^a(keV)	365 I_γ^b	427 I_γ^b	922 I_γ^b	951 I_γ^b	1286 I_γ^b	1422 I_γ^b	1716 I_γ^b
6170.2 *20*	9.0 *5*	27.0 *15*	1.6 *2*	4.3 *2*	2.2 *3*		2.4 *6*
6110.1 *20*	7.0 *4*	53.0 *30*	14.0 *7*	3.6 *2*	6.3 *4*	2.5 *3*	45.0 *25*
5302 *3*	1.0 *2*		1.0 *3*	0.6 *6*	1.2 *6*	3.0 *3*	
5263[c] *3*							
5069.1 *20*	3.6 *3*	3.3 *3*		1.2 *2*		7.0 *4*	2.2 *6*
5049.3 *20*	5.2 *3*		1.2 *2*			5.0 *3*	
4768.4 *20*	2.6 *2*						
4517.1 *25*	0.7 *2*	1.0 *3*	1.7 *4*				
4306 *3*			0.8 *4*				
4294.8 *25*	0.6 *3*				3.1 *5*		1.3 *5*
4257.4 *25*			1.2 *5*	5.2 *3*			
4209.7 *25*		0.7 *3*	0.5 *5*			2.8 *4*	
4104.7 *25*			1.0 *4*	0.7 *3*			2.4 *5*
4057.3 *25*			1.0 *9*			1.3 *4*	
4007.3 *25*			1.2 *6*	1.8 *4*	3.0 *5*	2.2 *4*	
3927.6 *25*					3.4 *6*		
3884.7 *25*				1.2 *3*			1.3 *6*
3644.2 *25*			2.2 *4*				

[a]In our notation 6170.2 *20* ≡ 6170.2 ± 2.0, etc. The γ-ray energies correspond to zero neutron energy.
[b]Relative photon intensity based on a value of 100 for the sum of Ge(Li) detector counts between 2.3 and 3.5 MeV. In our notation 9.0 *5* ≡ 9.0 ± 0.5, etc. The intensity values are based on data obtained at only 90°.
[c]Observed in 6674 eV resonance only.

TABLE III.
Secondary γ-rays from the ^{120}Sn(n,γ) ^{121}Sn Reaction

E_γ^a(keV)		E_γ^a(keV)	
553.2	*10*	1121.2	*5*
657.4^b	*5*	1141.7	*10*
782.9	*10*	1254.5	*10*
809.0	*5*	1403.5	*5*
810.5	*5*	1491.9^b	*10*
848.2	*5*	1653.0	*5*
868.8	*5*	1816.6	*10*
908.5	*5*	1852.3	*5*
925.7	*10*	1899.9	*5*
942.9	*5*	1918.8^b	*10*
966.0	*10*	2103.7	*10*
1041.1	*5*	2113.6	*10*
1051.4	*10*	2163.7	*20*
1060.7	*10*	2242.8	*5*
1091.7	*10*	2285.2	*5*
1100.7	*5*	2524.0	*20*

^{a}In our notation 553.2 *10* $\equiv 553.2 \pm 1.0$, etc.
^{b}Not placed on the level scheme.

where ΔE is the energy range over which the summation was taken and the factor 3 is the angular momentum weighting factor for p-waves. The p-wave strength function was $(2.36 \pm 0.28) \times 10^{-4}$ from the solid histogram and $(2.56 \pm 0.26) \times 10^{-4}$ from the dashed histogram (see Fig. 7). Our values are considerably more accurate than the value $S_1 = (3.7^{+1.8}_{-0.9}) \times 10^{-4}$ obtained by Muradian *et al.*[6] on the basis of 9 resonances below 5 keV. Moreover, these authors assumed that the 4.4 keV resonance was p-wave whereas our work establishes (see Fig. 2) this resonance as definitely s-wave. Fig. 8 shows a cumulative plot of the number of resonances observed as a function of neutron energy for all assigned s-waves and all assigned p-waves. From these we obtain an s-wave level spacing of 1800 ± 200 eV and a p-wave level spacing of 425 ± 25 eV. It can be seen that s-wave resonances were being missed above 50 keV. Therefore, the s-wave (and p-wave) level spacings given above must be corrected for this effect. From the strength functions and level spacings, it can be shown that the average p-wave neutron width at 30 keV is approximately the same as that of an s-wave at this energy. However, at 60 keV, the average p-wave neutron width is approximately twice that of an s-wave. Therefore, fewer p-wave resonances are missed at higher neutron energies. Based on the limit of detectability of small resonances and a Porter-Thomas distribution, we can estimate the number of small resonances which are being missed. We find that, in the case of s-wave resonances, about 10% of the resonances are missed up to 30 keV and about 25% up to 60 keV. Hence the corrected s-wave level spacing should be 1640 ± 200 eV. In the p-wave case, the correction is approximately 15% resulting in a p-wave level spacing of 370 ± 25 eV.

B. The ^{121}Sn Level Scheme

In Table IV we have collected all well-established energy levels in ^{121}Sn below 2.3 MeV. We have also indicated in the table spin and parity (J^π) assignments for 21 out of 29 bound states based on the reasonings given therein. In 10 out of 21 cases, the final J^π assignments were arrived at through the use of data obtained in the present study with the further assumption that the observed primary capture γ rays are of dipole nature. The quadrupole transitions, if any, should be weak enough to be unobservable, given the sensitivity of the present study. In a few cases, we have employed the shell model or the ratio of spectroscopic factors for stripping and pickup reactions in order to select one out of the two J^π values suggested for a particular level by the value of angular momentum transfer in nucleon transfer reactions.

The 16 neutron resonances investigated have $J^\pi = {}^1/_2{}^+$, ${}^1/_2{}^-$ or ${}^3/_2{}^-$. If the primary transitions are restricted to be dipole, a $J = {}^1/_2$ or a $J = {}^3/_2$ final state can be reached from any of these resonances whereas a $J = {}^5/_2$ final state can be reached only from the ${}^3/_2{}^-$ resonances. An expected dipole transition from a particular resonance need not be present, of course, due to the well-known Porter-Thomas fluctuations. Nevertheless, the present (n,γ) experiment should be especially sensitive to low-lying $J = {}^1/_2$ and $J = {}^3/_2$ final states. Therefore, it was surprising that a primary γ ray to the (948 ± 5) keV, ${}^1/_2{}^+$ state was not observed from any of the 16 resonances. For this reason, we have also not placed the 943 keV γ ray, observed in the spectra from nearly all the resonances, between this ${}^1/_2{}^+$ state and the ${}^3/_2{}^+$ ground state.

The ${}^1/_2{}^+$ ($l_n = 0$) assignment for the 948 keV level was made by Casten *et al.*[8] on the basis of comparison between the measured angular distribution in the ^{120}Sn(t,d) reaction at $E_t = 13$ MeV and that obtained from distorted-wave calculations. Flynn,[8] who has rechecked the data and the analysis, has pointed out that the assignment appears sound, supported further by the similarity of the angular distribution for the 948 keV level with that for the known ${}^1/_2{}^+$ level at 60 keV. On the other hand, a $({}^7/_2)^-$ level at $\approx$941 keV has been reported by Bechara and Dietzsch[9] from a ^{120}Sn(d,p) study at $E_d = 17$ MeV with a convincing $l_n = 3$ angular distribution. We have assumed that the 943 keV γ ray de-excites a ${}^7/_2{}^-$ level at 951 keV to the 8 keV, ${}^{11}/_2{}^-$ level.

The 908-keV level has $J^\pi = {}^3/_2{}^+$ or ${}^5/_2{}^+$ from $l_n = 2$ in the ^{120}Sn(t,d) reaction.[8] We favor a ${}^5/_2{}^+$ assignment since a primary γ ray to this level was observed in the (n,γ) spectrum only from the 6674 eV resonance. Casten *et al.*[8] favor instead a ${}^3/_2{}^+$ assignment based on the $S(t,d)/S(p,d)$ ratio. The 869 and 1101 keV levels were known to be ${}^3/_2{}^+$ or ${}^5/_2{}^+$ levels (See Table IV). Our study strongly suggests that both of these are ${}^3/_2{}^+$ levels. This is the first time that ${}^3/_2{}^+$ states have been clearly identified in the 0.8–1.5 MeV region in ^{121}Sn.

The shell-model states pertinent to the ^{121}Sn ground state are shown in Fig. 9. The known levels below 1.5 MeV in ^{117}Sn and ^{119}Sn are shown in Fig. 10 along with levels in ^{121}Sn. The ^{117}Sn data were from a forthcoming compilation[20] while the ^{119}Sn data were based on Coulomb excitation measurements,[21] on ^{119}In decay studies,[22] and on ^{118}Sn(n,γ) measurements which will be reported in a future paper. The (n,γ) measurements suggest that the 1090 keV level in ^{119}Sn, which was known to be a ${}^3/_2{}^+$ or ${}^5/_2{}^+$ level, is a ${}^3/_2{}^+$ level since a strong primary γ transition to this state is observed from a ${}^1/_2{}^+$ neutron resonance. Except for this change, the J^π assignments for the levels in ^{117}Sn and ^{119}Sn were also obtained from the references cited just above.

The lowest three states in ^{121}Sn with ${}^3/_2{}^+$, ${}^{11}/_2{}^-$ and ${}^1/_2{}^+$ assignments and similar states in ^{117}Sn and ^{119}Sn (see Fig. 10) are believed to be predominantly one-quasi-particle

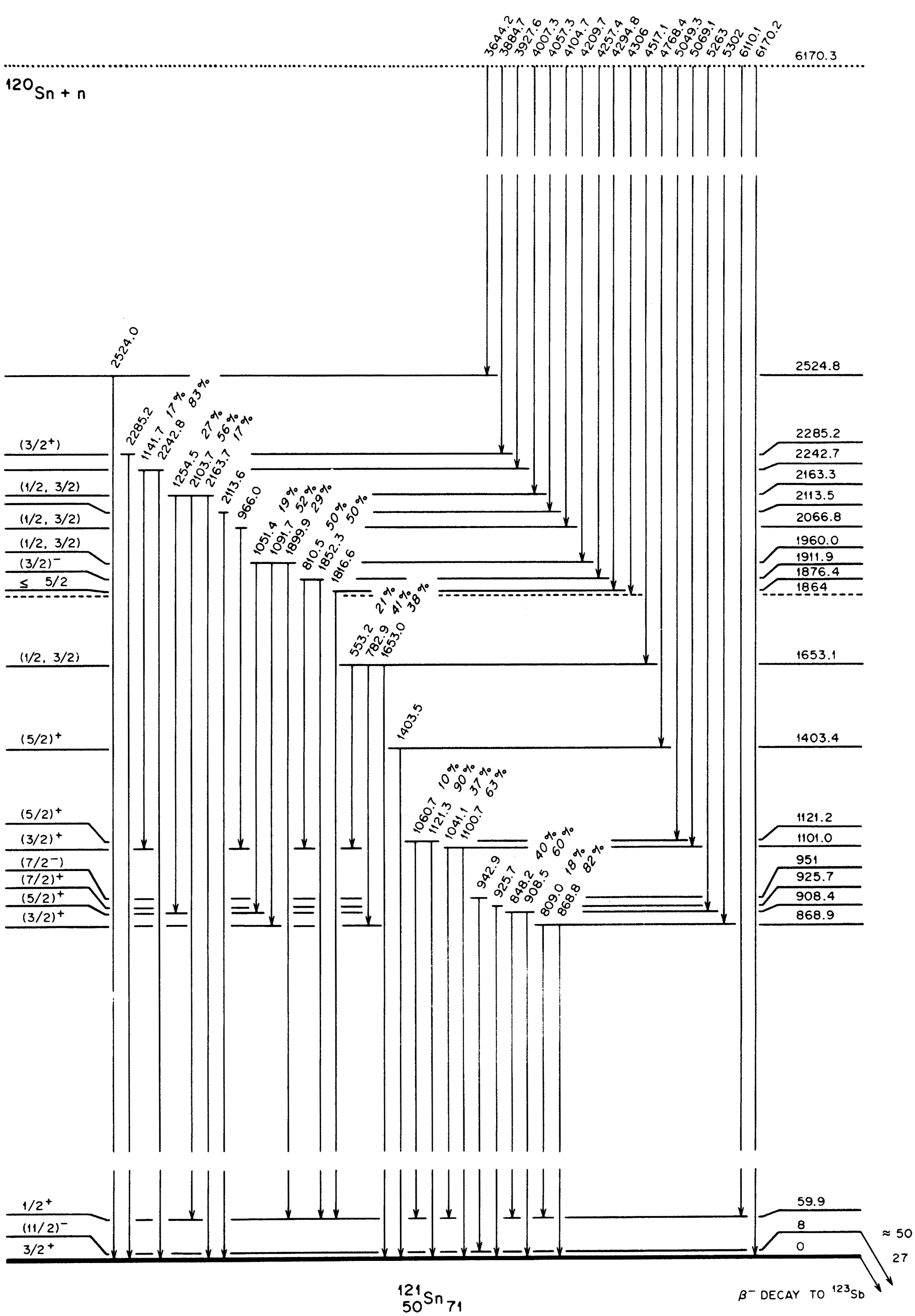

FIG. 5. Level scheme for ^{121}Sn from present experiment. All energies are in keV. The γ-branching ratios are based on data obtained at only 90°.

TABLE IV. Energy levels in ^{121}Sn

Other Works[a] Energy (keV)		Present Work Energy (keV)		$J^{\pi\,b}$	Reasons for J^π assignments[c]
0.0		0.0		$^3/_2{}^+$	Atomic beam; $l_n = 2$ in (d,p), (p,d) and (t,d)
8	*6*	8[d]	*6*	$(^{11}/_2)^-$	$l_n=5$ in (d,p) and (p,d); Shell model
60.1	*2*	59.9	*3*	$^1/_2{}^+$	$l_n=0$ in (d,p), and (t,d)
869	*5*	868.9	*4*	$(^3/_2)^+$	$L = 2$ in (t,p); Fed by primary γ ray from 951 eV, $^1/_2{}^+$ resonance
908.9	*5*	908.4	*4*	$(^5/_2)^+$	$l_n = 2$ in (t,d); Fed by primary from only the 6674 eV resonance
925.3	*10*	925.7	*10*	$(^7/_2)^+$	$l_n = 4$ in (t,d); Shell model
948	*5*			$(^1/_2{}^+)$	$l_n = 0$ in (t,d)
		951	*6*	$(^7/_2{}^-)$	$l_n = 3$ in (d,p); Shell model
1101.9	*5*	1101.0	*3*	$(^3/_2)^+$	$l_n=2$ in (t,d) and $L=2$ in (t,p); Fed by primary γ ray from 951 eV, $^1/_2{}^+$ resonance
1120.4	*2*	1121.2	*5*	$(^5/_2)^+$	$l_n=2$ in (d,p), (p,d) and (t,d); $L=2$ in (t,p); $S(t,d)/S(d,t)$ favors $^5/_2{}^+$
1403	*1*	1403.4	*5*	$(^5/_2)^+$	$l_n = 2$ in (d,p) and (p,d); $S(t,d)/S(d,t)$ favors $^5/_2{}^+$
1432	*8*				
		1653.1	*4*	$(^1/_2, {}^3/_2)$	Fed by primary γ ray from 427 eV, $^1/_2{}^{(-)}$ resonance
1708	*10*			$^3/_2{}^+, {}^5/_2{}^+$	$l_n = 2$ in (d,p)
1870	*7*	1864 ?	*3*	$(^3/_2)^-$	$l_n = 1$ in (d,p); Shell model
		1876.4	*10*	$\leqslant {}^5/_2$	Strong γ ray from this level to 60 keV, $^1/_2{}^+$ state
1919	*9*	1911.9	*5*	$(^3/_2)$	Fed by primary γ ray from 951 eV, $^1/_2{}^+$ resonance; $l_n = 1$ in (d,p); Shell model
1963	*9*	1960.0	*5*	$(^1/_2, {}^3/_2)$	Fed by primary γ ray from 427 eV, $^1/_2{}^{(-)}$ resonance
1986	*10*				
2069	*10*	2066.8	*10*	$(^1/_2, {}^3/_2)$	Fed by primary γ ray from 951 eV, $^1/_2{}^+$ resonance
2109[e]	*9*	2113.5	*10*		
		2163.3	*7*	$(^1/_2, {}^3/_2)$	Fed by primary γ ray from 951 eV, $^1/_2{}^+$ resonance
2170	*10*			$^7/_2{}^+, {}^9/_2{}^+$	$L = 4$ in (t,p)
2225	*10*				
2233	*10*				
2246	*10*	2242.7	*3*		
2290	*10*	2285.2	*5*	$(^3/_2{}^+)$	Fed by primary γ ray from 951 eV, $^1/_2{}^+$ resonance; $L = 2$ in (t,p) suggests $^3/_2{}^+$
...		...			
...		...			
		2524.8	*16*		
...		...			
...		...			
		6170.3[f]	*20*		

[a]Mainly from Refs. 8 and 11. Not included here are ≃10 levels excited weakly in (d,p) reaction and reported in Ref. 9. These levels have not been observed in any other experiments. In our notation for level energy, 60.1 *2* ≡ 60.1 ± 0.2, etc.

[b]A parenthesis around a J^π value has the usual meaning—the assignment is most probable but not certain beyond reasonable doubt.

[c]The $J = {}^3/_2$ assignment for the ground state is from atomic beam measurements by M. H. Prior, A. Dymanus, H. A. Shugart and P. A. Vanden Bout, Phys. Rev. **181**, 1665 (1969). The reaction data referred to in this column are from the following references: (d,p)—Refs. 7 and 9; (p,d)—Ref. 10; (t,d) and (t,p)—Ref. 8; $S(t,d)/S(d,t)$—Ref. 8; and (n,γ)—present paper.

[d]Assumed value.

[e]Possible doublet.

[f]Neutron separation energy.

states (with respect to the ground state of the even isotopes) because most of the single-nucleon stripping and pickup strengths to states with the above J^π values are found in these states. In the 0.8–1.5 MeV region, in addition to the one-quasi-particle $^7/_2{}^+$, $^5/_2{}^+$, and $^7/_2{}^-$ states, one might expect to see some three-quasi-particle states resulting from the coupling of the single quasi particles to the 2^+ excitations of the even core. In ^{121}Sn such coupling would lead to the following levels:

$$(^3/_2{}^+ \otimes 2^+) \rightarrow {}^1/_2{}^+, {}^3/_2{}^+, {}^5/_2{}^+, \text{ and } {}^7/_2{}^+$$

$$(^{11}/_2{}^- \otimes 2^+) \rightarrow {}^7/_2{}^-, {}^9/_2{}^-, {}^{11}/_2{}^-, {}^{13}/_2{}^-, \text{and } {}^{15}/_2{}^-$$

$$(^1/_2{}^+ \otimes 2^+) \rightarrow {}^3/_2{}^+ \text{ and } {}^5/_2{}^+$$

With the exception of a second $^7/_2{}^+$ level, all of the positive parity states expected in the 0.8–1.5 MeV region according to the above simple picture appear to have been found. The only negative parity level known in this energy region is the 951 keV, $^7/_2{}^-$ level.

Two strongly collective $^3/_2{}^+$ and $^5/_2{}^+$ states have been identified in ^{117}Sn at 1004 and 1020 keV, and in ^{119}Sn at 920.5 and 921.4 keV, respectively, from Coulomb excitation measurements.[21] These states have been interpreted as predominantly $(^1/_2{}^+ \otimes 2^+)$ states. The ^{120}Sn(n,γ) measurements were undertaken in part to identify the corresponding doublet in ^{121}Sn. We suggest that the 1101–1121 keV, $^3/_2{}^+ - {}^5/_2{}^+$ doublet would be an appropriate

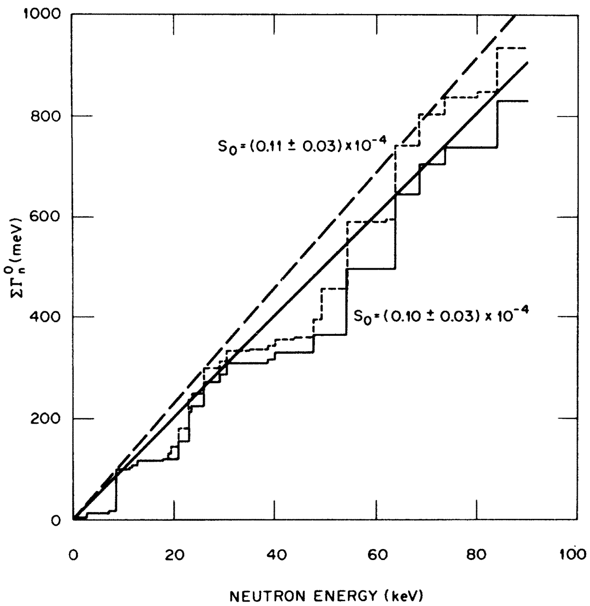

FIG. 6. Cumulative histogram of the reduced neutron width for s-wave resonances $vs.$ neutron energy for ^{120}Sn.

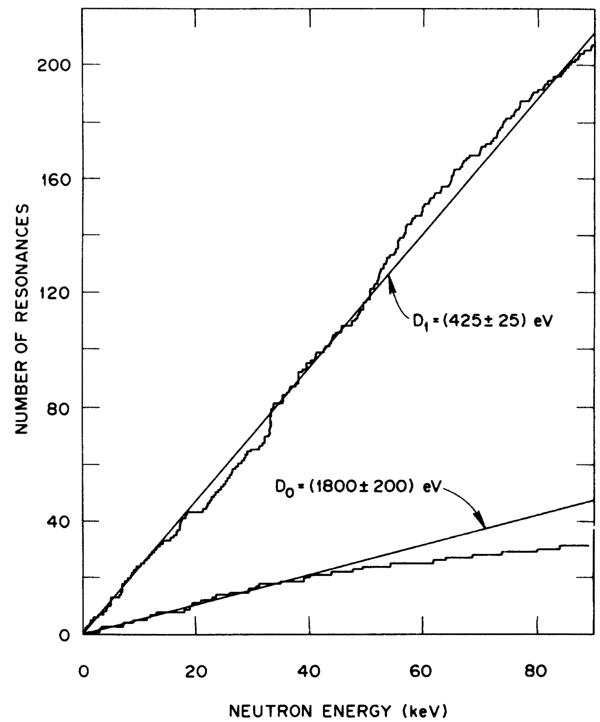

FIG. 8. Cumulative plot of the number of s- and p-wave resonances $vs.$ neutron energy for ^{120}Sn.

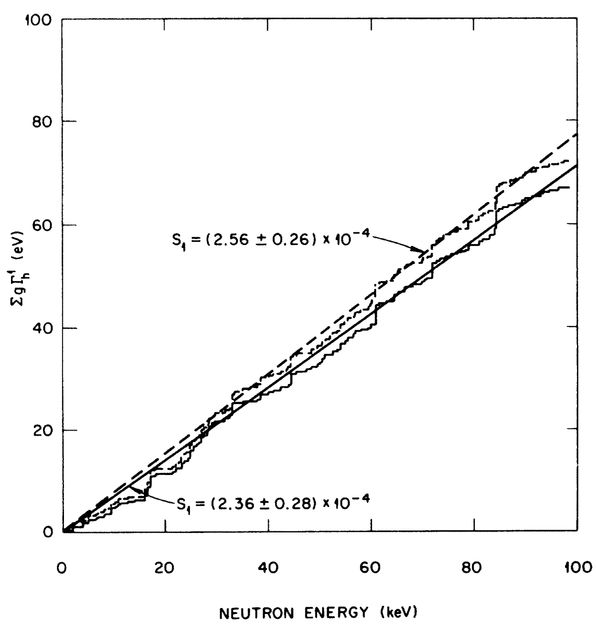

FIG. 7. Cumulative histogram of the reduced neutron width for p-wave resonances $vs.$ neutron energy for ^{120}Sn.

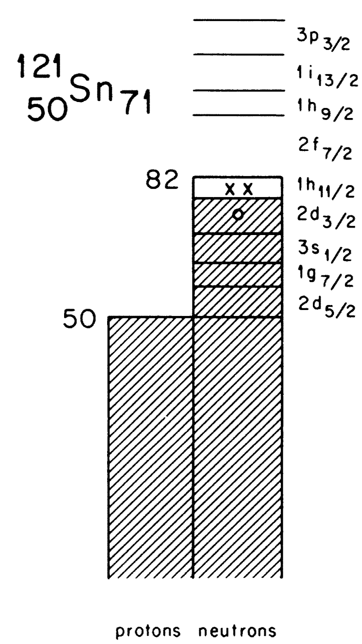

FIG. 9. Shell model states pertinent to the ^{121}Sn ground state.

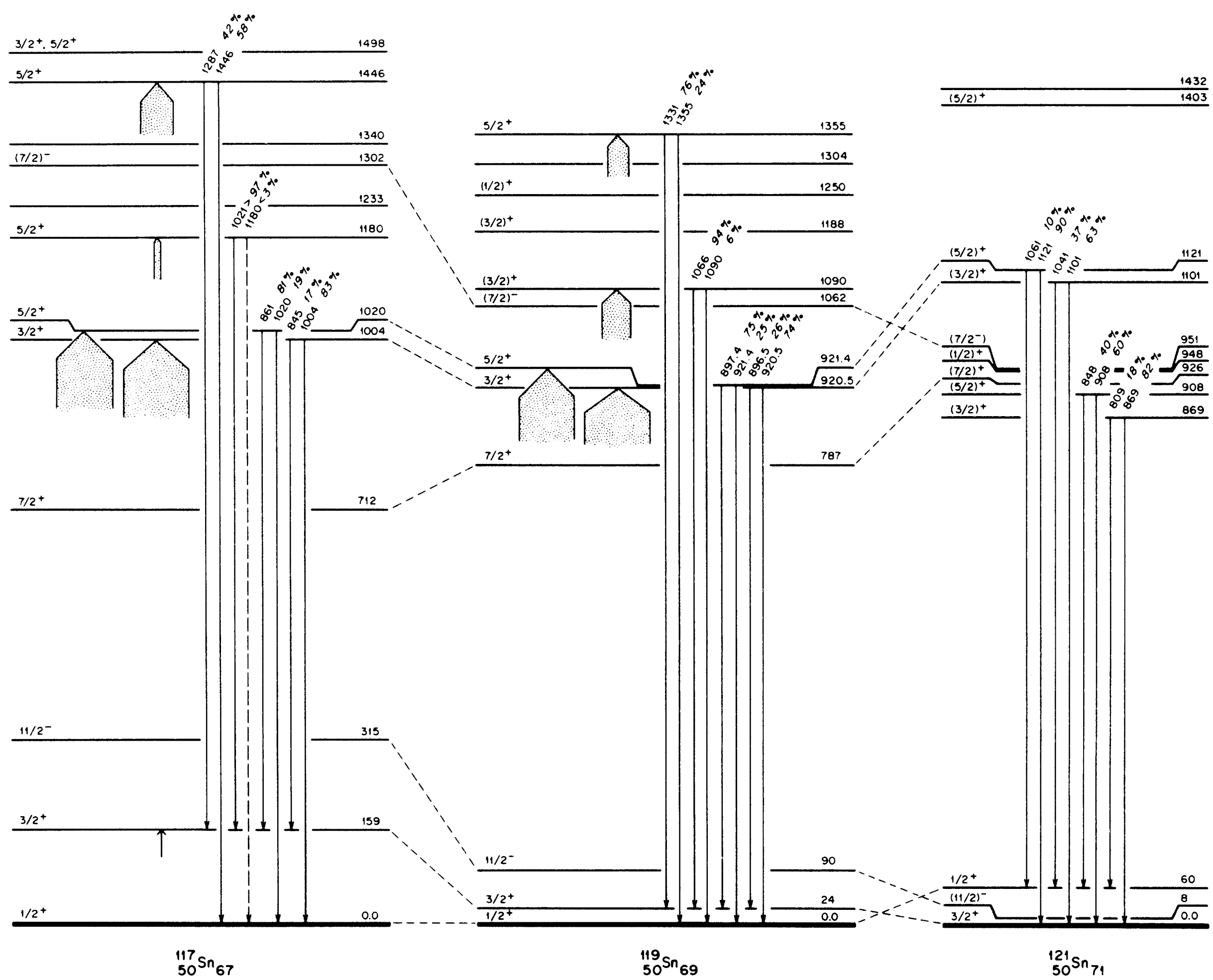

FIG. 10. A comparison of the energy levels in ^{117}Sn, ^{119}Sn and ^{121}Sn. An upward arrow indicates a Coulomb-excited level, the width of the arrow being proportional to the $B(E2)\uparrow$ value. When comparing the γ-ray branchings shown for selected levels, the reader is warned that the $^3/_2{}^+ - {}^1/_2{}^+$ level ordering is inverted going from ^{119}Sn to ^{121}Sn.

candidate with the understanding that states with equal spin and parity might be appreciably mixed. Further discussion of the energy level systematics will be taken up after we have completed our (n,γ) measurements on the remaining stable even Sn isotopes.

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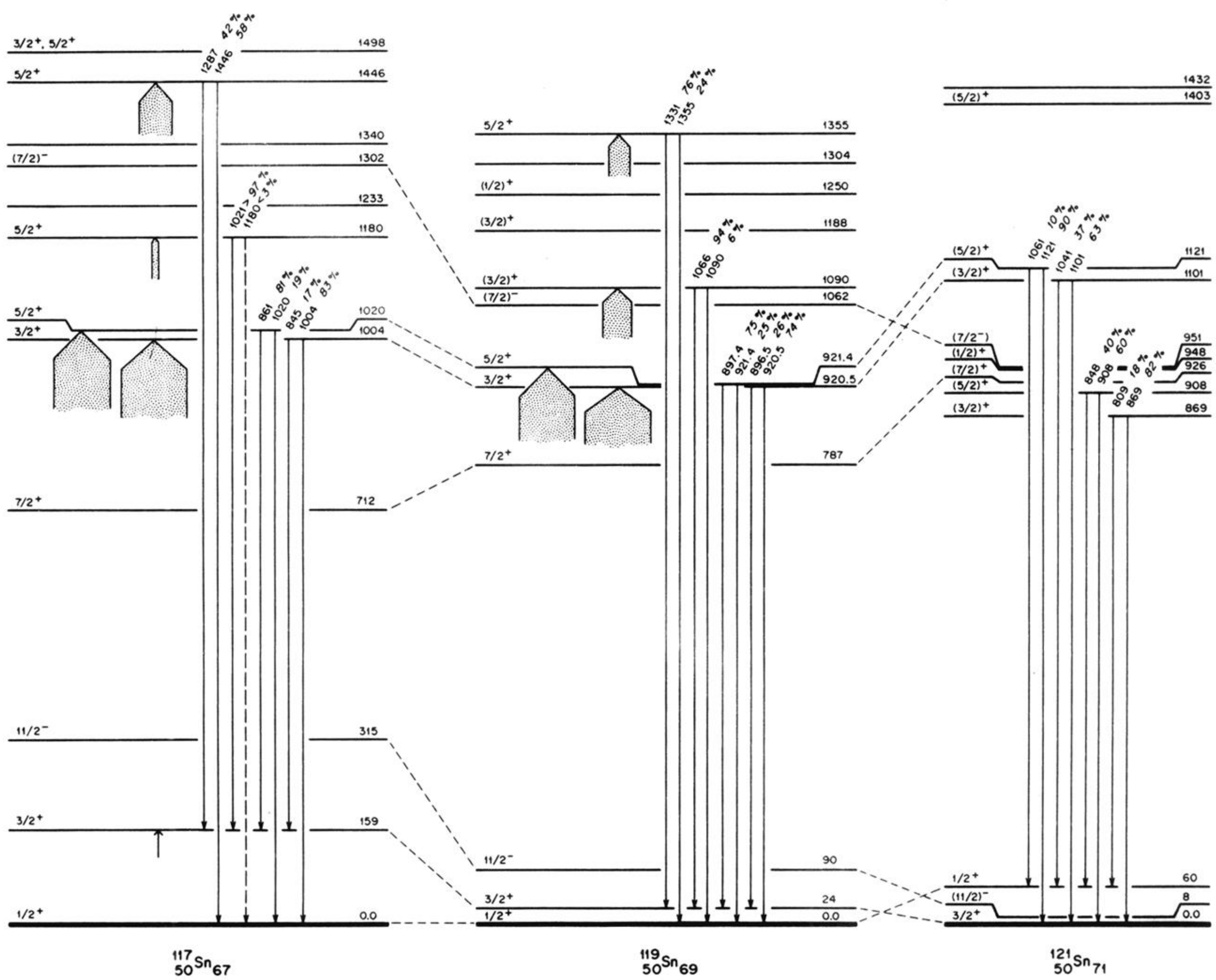

FIG. 10. A comparison of the energy levels in ^{117}Sn, ^{119}Sn and ^{121}Sn. An upward arrow indicates a Coulomb-excited level, the width of the arrow being proportional to the $B(E2)\uparrow$ value. When comparing the γ-ray branchings shown for selected levels, the reader is warned that the $^{3}/_{2}^{+} - ^{1}/_{2}^{+}$ level ordering is inverted going from ^{119}Sn to ^{121}Sn.