Neutron capture gamma-ray studies of levels in ^{123}Sn and ^{125}Sn†

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Neutron capture γ-ray measurements have been performed upon enriched samples of ^{122}Sn and ^{124}Sn following resonance capture. The γ rays, measured with a Ge(Li) detector, have been incorporated in level schemes for ^{123}Sn and ^{125}Sn. New spin and parity assignments have been made for many of the levels. Three new levels have been found in ^{125}Sn. Neutron separation energies for ^{123}Sn and ^{125}Sn were determined to be 5945.8 ± 1.5 and 5732.2 ± 1.5 keV, respectively. The level schemes have been compared with those of ^{119}Sn and ^{121}Sn to investigate systematic behavior.

[NUCLEAR REACTIONS ^{122}Sn(n,γ), $E=0.1$–20 keV, ^{124}Sn(n,γ), $E=0.05$–11 keV; measured E_γ, I_γ. ^{123,125}Sn deduced levels, J, π, neutron separation energies. ^{119,121,123,125}Sn systematics. Enriched targets.]

I. INTRODUCTION

The approaches taken for experimental investigations of the level structures of ^{123}Sn and ^{125}Sn have been numerous and varied. For instance, (d,p) stripping and (p,d) and (d,t) pickup reaction (not valid for ^{125}Sn) studies[1-7] have been employed to locate many levels and to provide spin and parity (J^π) assignments for some of these levels on the basis of the ℓ values of angular momentum transfer, with additional recourse to the

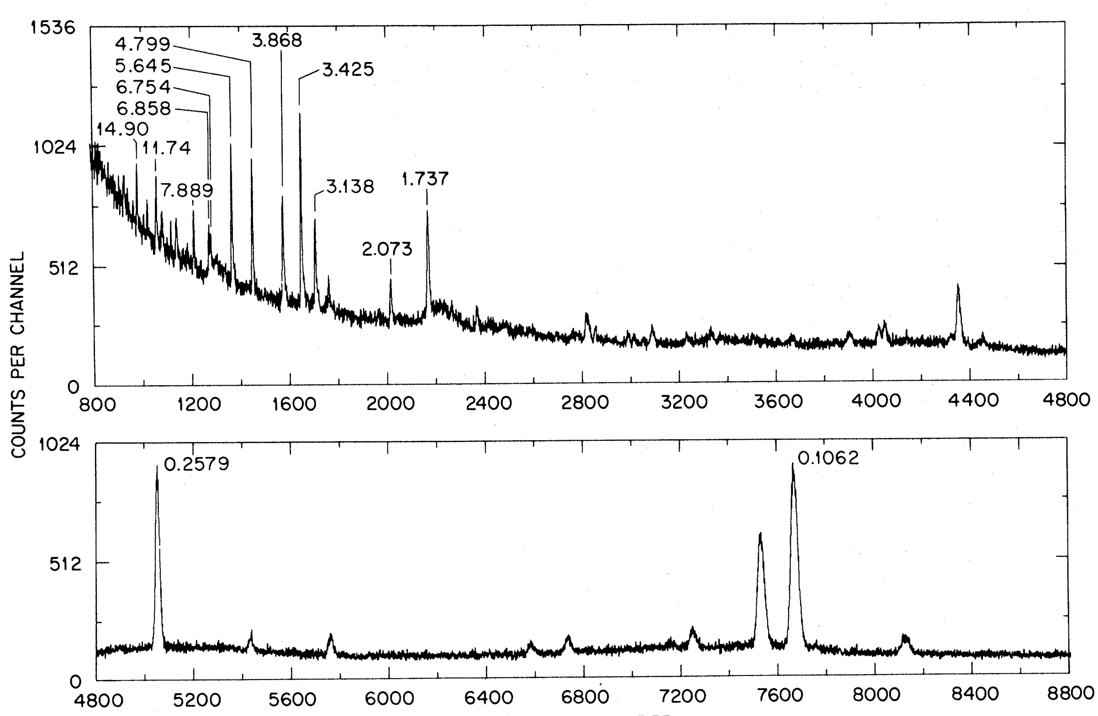

FIG. 1. Time-of-flight plot of events in the Ge(Li) detector. The peaks are labelled with neutron energies in keV (uncertainty ± 0.5%) and correspond to resonances in ^{122}Sn.

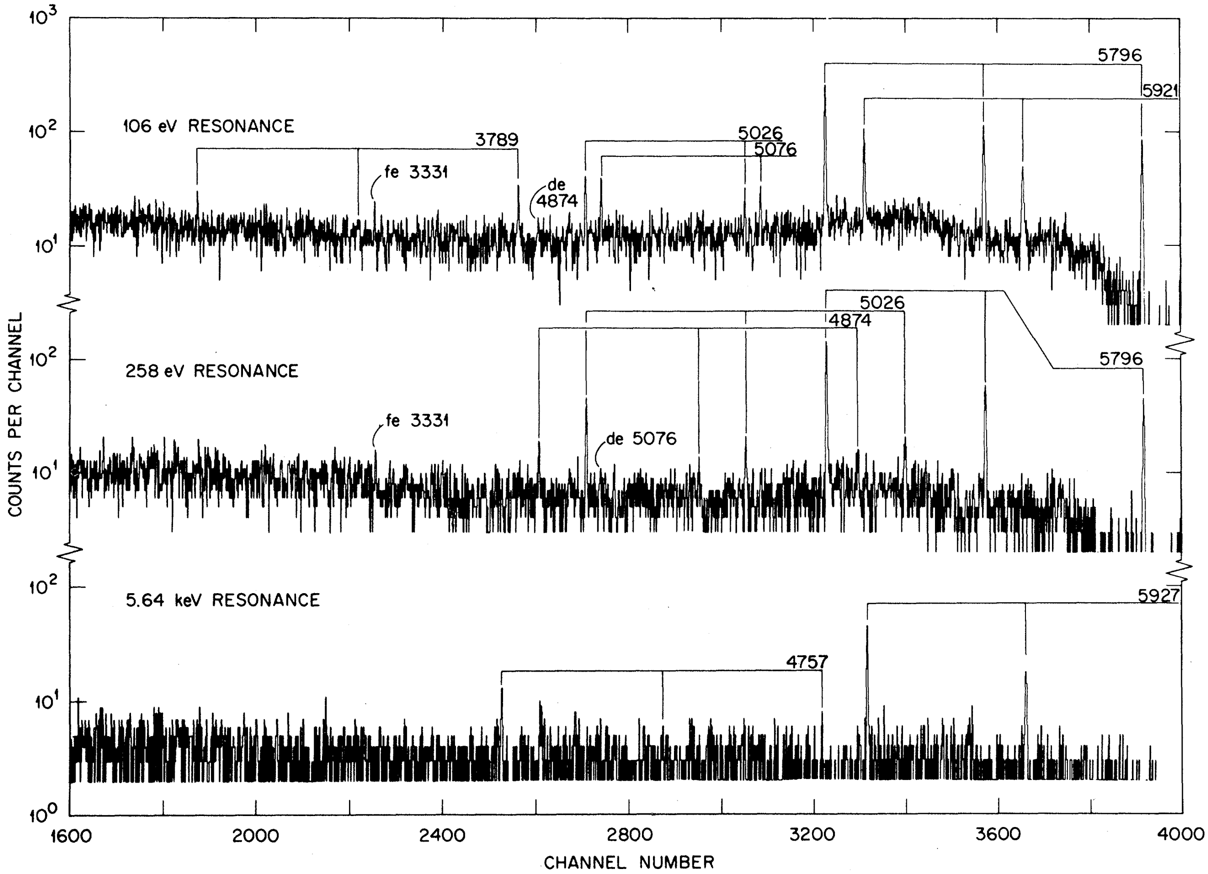

FIG. 2. High-energy portions of γ ray spectra from 3 neutron resonances in ^{122}Sn. All energies are in keV.

shell model. Transitions involving a low ℓ transfer are observed to be strongest in stripping and pickup reactions with low mass projectiles at low (≈12 MeV) bombarding energies. An enhancement of transitions with higher ℓ transfers has been found[6,7] with higher beam energies (≈30 MeV) and with heavier projectiles [e.g., the (α, ^{3}He) reaction]. Several studies[5,8,9] have focussed attention on particle-phonon states [also called three quasiparticle ($3qp$) states] built upon low-lying $d_{3/2}$ and $h_{11/2}$ quasiparticle states. Such states, predicted to occur by the weak coupling model,[10] have been observed in several odd tin isotopes. These studies on ^{123}Sn and ^{125}Sn include γ ray and conversion electron spectroscopy following β decay and (d,$p\gamma$) reactions from which γ-ray multipolarities have been established. A recent decay study[9] has identified low-lying $9/2^-$ states in the heavier ($A \geq 121$) tin isotopes, which, together with previously known $7/2^-$ states, might constitute $3qp$ states built upon the $h_{11/2}$ state. The present paper is second in a series[11] on the level structure of odd tin isotopes and contains the results of resonance neutron capture γ-ray measurements upon highly enriched isotopes of ^{122}Sn and ^{124}Sn. Results obtained with ^{114}Sn, ^{116}Sn and ^{118}Sn targets will be presented in future publications. Thermal (n,γ) studies[12] with ^{122}Sn and ^{124}Sn targets were attempted at this Laboratory in 1966 with only meager results due to their small thermal (n,γ) cross sections. The s-wave strength functions for the heavier Sn isotopes are among the lowest in the periodic table. The (n,γ) technique with resonance neutrons provides a powerful means for studying low spin states in the tin isotopes by greatly reducing isotopic interference problems. The variety of experimental results now available for ^{123}Sn and ^{125}Sn has yielded a reasonably complete picture of the low-lying level structure for

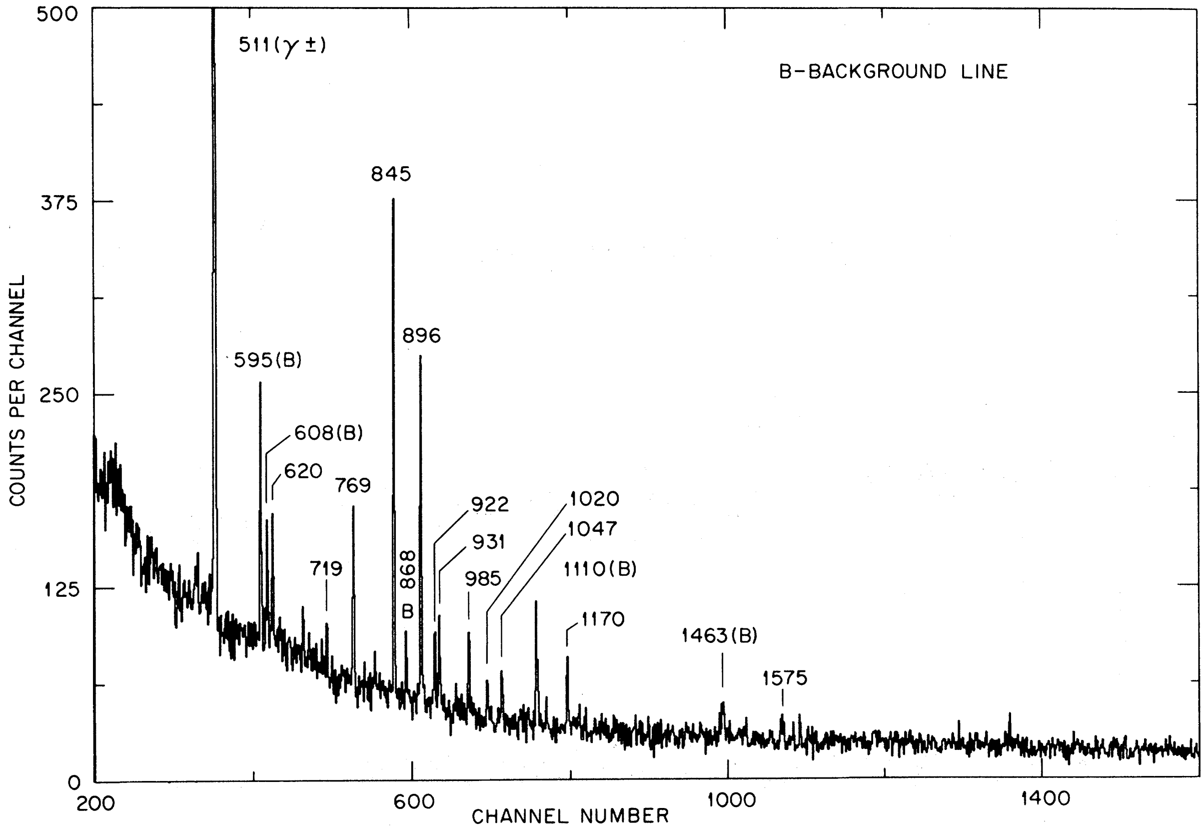

FIG. 3. Low-energy portion of γ ray spectrum from the 106 eV resonance in ^{122}Sn. All energies in keV.

TABLE I

Relative photon intensities of the primary γ rays from the ^{122}Sn(n,γ) ^{123}Sn reaction

	Neutron resonance energy (eV)						
	106	258	1737	2073	3138	3425	4799[c]
E_γ[a] (keV)	I_γ[b]	I_γ[b]	I_γ[b]	I_γ[b]	I_γ[b]	I_γ[b]	I_γ[b]
5921.0 *15*	0.49 *2*		*	0.87 *1*	0.84 *6*	*	0.61 *9*
5795.5 *15*	1.42 *4*	1.10 *4*				0.41 *2*	
5076.2 *15*	0.20 *2*	*	*			0.37 *4*	
5025.7 *25*	0.20 *2*	0.34 *3*					
4874.2 *25*	*	0.14 *2*					
4750.8 *25*							0.22 *6*
3789.1 *25*	0.14 *2*						
3331 *3*	0.05 *1*	*					

[a]In our notation 5921.0 *15* ≡ 5921.0 ± 1.5, etc. The γ-ray energies correspond to thermal neutron energy.

[b]Relative photon intensity based on a value of 100 for the sum of Ge(Li) detector counts between 2.5 and 3.5 MeV. In our notation 0.49 *2* ≡ 0.49 ± 0.02, etc. The intensity values are based on data obtained at only 90°. An asterisk denotes that the γ ray was observed very weakly at the corresponding resonance.

[c]Useful data were obtained up to 15 keV neutron energy (see, for example, the spectrum from the 5.64 keV resonance in Fig. 2) but no new γ transitions were found.

TABLE II

Secondary γ rays from the $^{122}Sn(n,\gamma)\ ^{123}Sn$ reaction

$E_\gamma{}^a$ (keV)	$E_\gamma{}^a$ (keV)
619.5 *5*	930.9 *10*
719.0 *10*	985.3 *10*
769.3 *5*	1019.5 *10*
845.0 *5*	1046.8 *10*
895.8 *10*	1169.8 *5*
921.9 *5*	1575.1[b] *10*

[a]In our notation 619.5 *5* ≡ 619.5 ± 0.5, etc.
[b]Not placed on the level scheme.

these isotopes.

We have obtained information on 11 levels in ^{123}Sn and 15 levels in ^{125}Sn. We have tabulated all well-established low-lying levels in both nuclei and have proposed J^π assignments. Finally, the resulting level schemes have been compared with those for ^{119}Sn and ^{121}Sn.

II. EXPERIMENTAL PROCEDURE

The Oak Ridge Electron Linear Accelerator (ORELA) facility was used to provide a pulsed beam of neutrons for capture studies on ≈40 g samples of ^{122}Sn and ^{124}Sn which were enriched to 90.80% and 93.28%, respectively. The neutron beam was characterized either by 30 nsec bursts at a pulse repetition rate of 500 Hz or 12 nsec bursts at 800 Hz. The data obtained constitute a total running time of approximately 4 weeks. Experimental details follow closely those outlined in Ref. 11.

III. RESULTS

A. Levels in ^{123}Sn

Fig. 1 shows the counting rate for the total γ-ray spectrum *versus* neutron flight time. From such data, appropriate time gates were selected corresponding to different neutron energies, some on resonance and some off resonance. Fig. 2 shows the high-energy portions of the γ-ray spectra from three resonances and Fig. 3 shows the low-energy portion from the 106 eV resonance. A listing of the γ-ray energies and relative intensities is given in Tables I and II. The seven γ rays with energies above 3.7 MeV are most probably primary capture γ rays. In the case of the 5076, 5796 and 5921 keV γ rays, kinematic

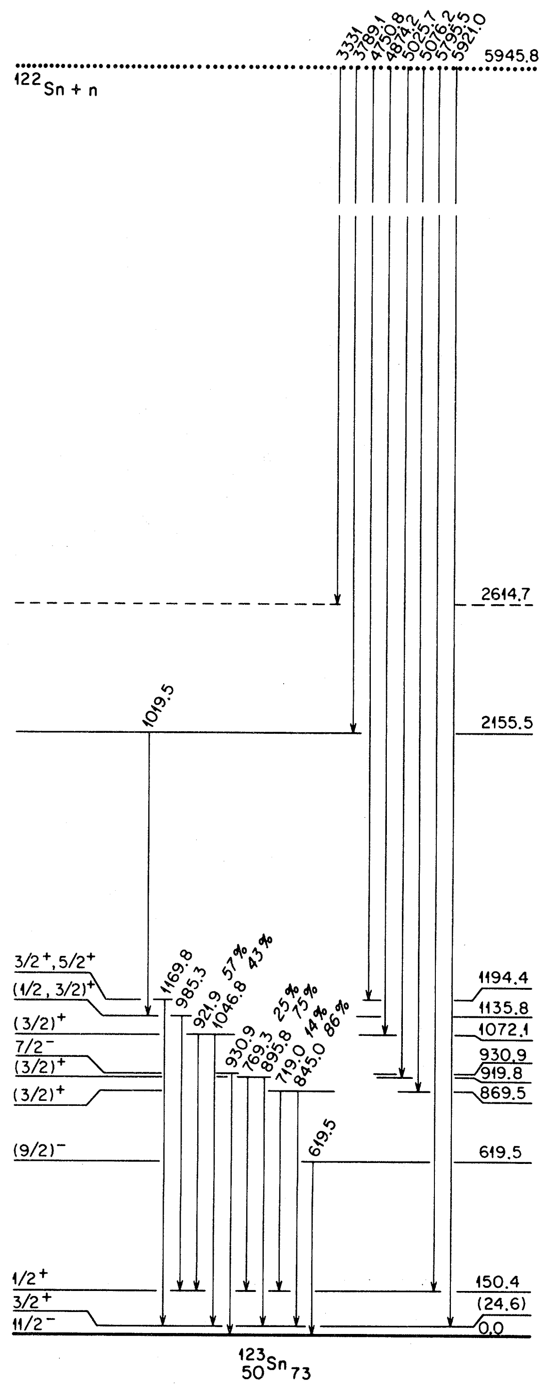

FIG. 4. Level scheme for ^{123}Sn from present experiment. All energies are in keV. The γ branching ratios are based on data obtained at only 90°.

TABLE III

Energy Levels in ^{123}Sn

Other Works[a] Energy (keV)		Present Work Energy (keV)		$J^{\pi b}$	Reasons for J^{π} assignments[c]
0.0		0.0		11/2$^-$	First forbidden unique shape of the β group to the ^{123}Sb, 7/2$^+$ ground state; ℓ_n = 5 in (*d*,*p*)
24.6	*4*	(24.6	*4*)[d]	3/2$^+$	Atomic beam; ℓ_n = 2 in (*d*,*p*)
150.4	*4*	150.4	*8*	1/2$^+$	ℓ_n = 0 in (*d*,*p*) and (*p*,*d*)
618.8	*3*	619.5	*5*	(9/2)$^+$	Fed by γ rays from 7/2$^+$ levels following (9/2)$^+$, ^{123}In^g decay; γ ray to 11/2$^-$ ground state is *M1* or *E2* or (*M1* + *E2*); level systematics.
870.3	*4*	869.5	*6*	(3/2)$^+$	De-excites to 1/2$^+$ and 3/2$^+$ levels; fed by primary γ ray from 258 eV, 1/2$^-$ resonance; excitation function in (*d*,*p*γ); γ ray to 25 keV level is *M1* or *E2* or (*M1* + *E2*).
920.5	*8*	919.8	*8*	(3/2)$^+$	ℓ_n = 2 in (*p*,*d*); fed by primary γ ray from 258 eV, 1/2$^-$ resonance.
931.4	*5*	930.9	*10*	7/2$^-$	ℓ_n = 3 in (*d*,*p*); de-excites to 11/2$^-$ ground state, not to 3/2$^+$, 25 keV level.
1044.3	*4*			(7/2)$^+$	Log *ft* = 5.0 from (9/2)$^+$, ^{123}In^g decay; strong γ ray to 25 keV level.
1071.4	*10*	1072.1	*8*	(3/2)$^+$	Fed by primary γ ray from 258 eV, 1/2$^-$ resonance; γ ray to 150 keV level is *M1* or *E2* or (*M1* + *E2*); excitation function in (*d*,*p*γ).
1109 ?	*10*				
1136.4	*8*	1135.8	*12*	(1/2, 3/2)$^+$	Excitation function in (*d*,*p*γ); γ ray to 25 keV level is *M1* or *E2* or (*M1* + *E2*).
1155.0	*3*			7/2$^+$	ℓ_n = 4 in (*d*,*p*); Log *ft* = 4.6 from (9/2)$^+$, ^{123}In^g decay; strong γ ray to 25 keV level.
1195.4	*10*	1194.4	*7*	3/2$^+$, 5/2$^+$	ℓ_n = 2 in (*d*,*p*)
1488.8	*11*			3/2$^+$, 5/2$^+$	ℓ_n = 2 in (*d*,*p*)
...					
...					
2001.2	*3*				
2157	*10*	2155.5	*14*		
2260	*10*				
2362	*10*				
2612	*10*	2614.7?	*14*		
2621	*3*				
2667	*10*				
...		...			
...		...			
		5945.8[e]	*15*		

[a]Mainly from (*d*,*p*γ)-Ref. 5; [(9/2)$^+$, ^{123}In^g decay]-Ref. 9; and (1/2$^-$, ^{123}In^m decay)-Ref. 8. In our notation for level energy 24.6 *4* ≡ 24.6 ± 0.4, etc. Above 1.2 MeV excitation, this column is not complete. See, for example, the compilation by R. L. Auble, *A*=123, Nuclear Data Sheets 7, 363 (1972).

[b]Parentheses around a J^{π} value imply that the assignment is most probable but not certain beyond reasonable doubt.

[c]The J^{π} = 11/2$^-$ assignment for the ground state is from β-decay studies by B. H. Ketelle, C. M. Nelson, and G. E. Boyd, Phys. Rev. 79, 242A (1950). The atomic beam measurements are by A. Y. J. Chong, M. H. Prior, and H. A. Shugart, Bull. Am. Phys. Soc. 13, No. 12, 1650 (1968). The other data referred to in this column are from the following references: (*d*,*p*)-Refs. 1, 3 and 5; (*p*,*d*)-Ref. 6; Log *ft* values-Refs. 8 and 9; multipolarities from conversion electron studies following (*d*,*p*γ)-Ref. 5; excitation function in (*d*,*p*γ)-Ref. 5; and (*n*,γ)-present paper.

[d]Assumed value obtained by a least squares adjustment of data presented in Ref. 9.

[e]Neutron separation energy.

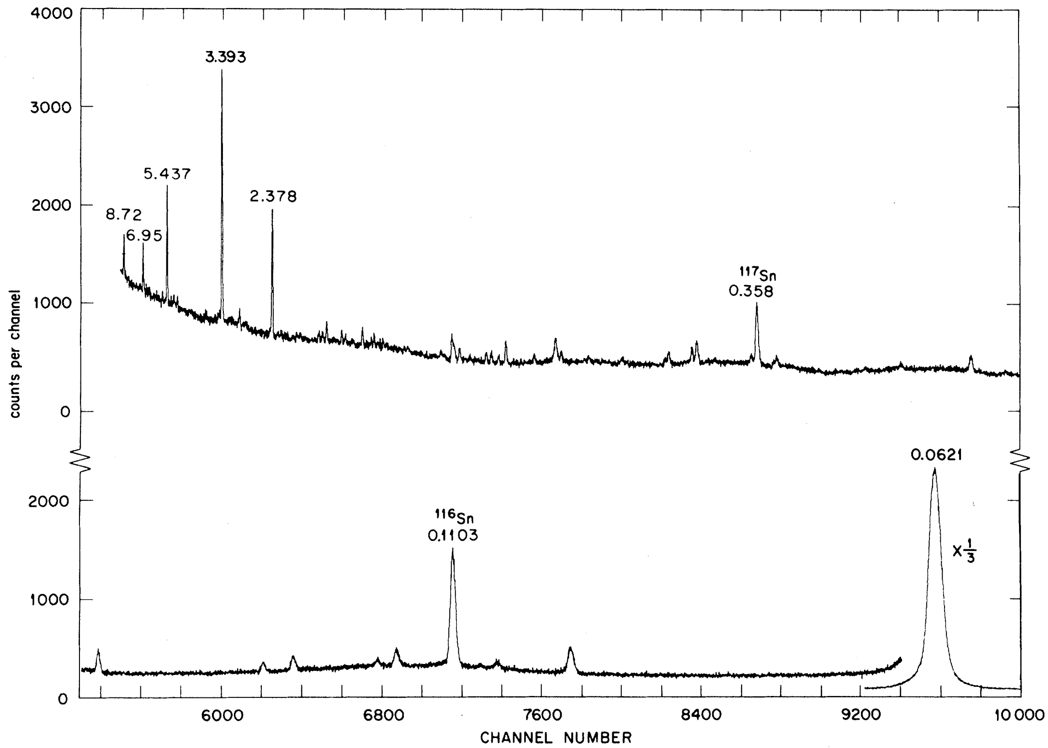

FIG. 5. Time-of-flight plot of events in the Ge(Li) detector. The peaks are labelled with neutron energies in keV (uncertainty ± 0.5%) and correspond to resonances in ^{124}Sn, except where stated otherwise.

TABLE IV

Relative photon intensities of the primary γ rays from the $^{124}Sn(n,\gamma)\ ^{125}Sn$ reaction

	Neutron resonance energy (eV)				
	62	2378	3393	5437	10180^{c}
$E_\gamma{}^{a}$ (keV)	$I_\gamma{}^{b}$	$I_\gamma{}^{b}$	$I_\gamma{}^{b}$	$I_\gamma{}^{b}$	$I_\gamma{}^{b}$
5706.3 *20*	38.0 *20*	20.0 *17*		5.5 *7*	9.9 *17*
5518.6 *20*	18.0 *10*	5.0 *12*		9.3 *11*	7.5 *21*
4803.4 *25*	5.3 *3*	6.7 *11*	*		
4659.6 *30*	2.0 *2*		5.7 *13*		
4473.5 *30*			6.0 *8*	*	
3975.7 *30*	1.5 *1*		3.4 *7*		
3856.6 *30*	*	2.5 *7*			
3482.8 *30*	0.80 *5*				
3447.0 *30*	0.40 *6*				
3400 *4*	0.18 *3*				
3384.4 *30*	0.53 *5*				
3203.9 *30*	0.18 *4*				

[a] In our notation 5706.3 *20* ≡ 5706.3 ± 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 2.5 and 3.5 MeV. In our notation 38.0 *20* ≡ 38.0 ± 2.0, etc. An asterisk denotes that the γ ray was observed very weakly at the corresponding resonance. The intensity values are based on data obtained at only 90°.
[c] Not shown in Fig. 5.

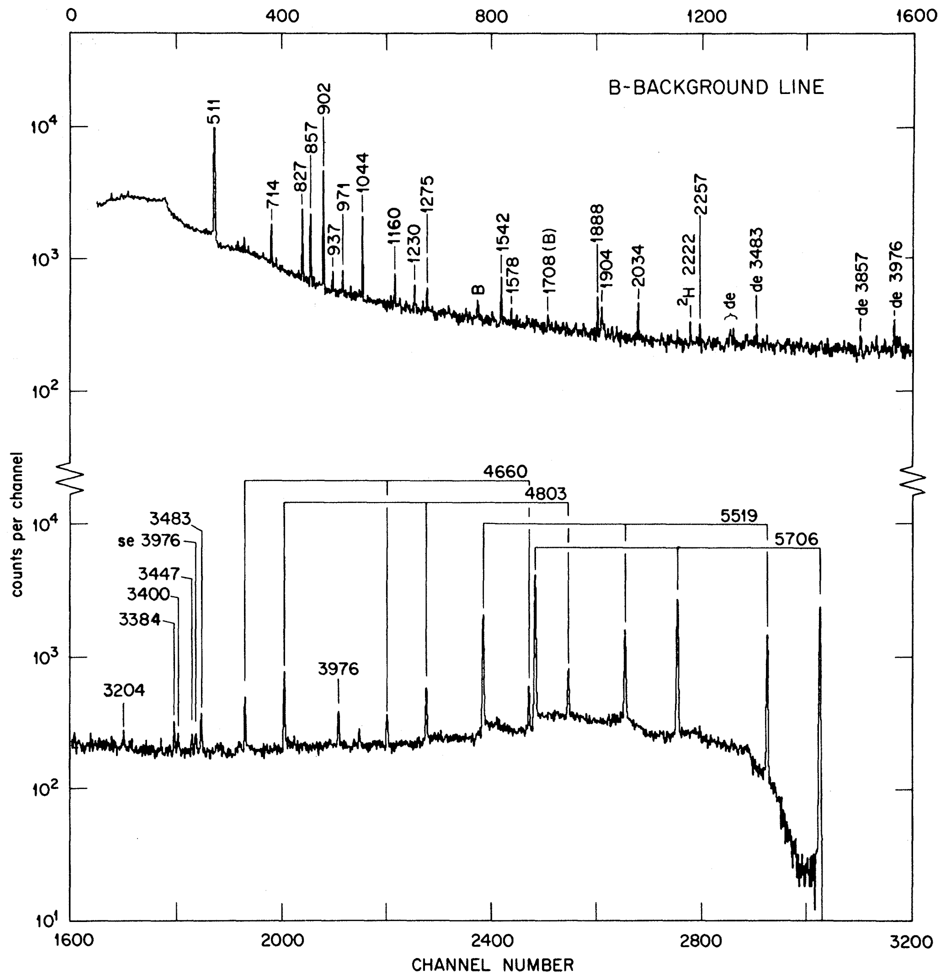

FIG. 6. Gamma-ray spectrum from the 62 eV resonance in ^{124}Sn. All energies are in keV.

shifting of their energies corresponding to the appropriate neutron energies was observed. The decay scheme based on the present data is shown in Fig. 4. All levels in this scheme except those at 0, 620, 931 and 1136 keV were populated by primary γ transitions. The energies of 10 excited states determined in the present (n,γ) reaction agree well (see Table III) with those for states excited in previous reaction and decay studies. The neutron separation energy, S_n, was determined to be 5945.8 ± 1.5 keV. This S_n value is based on the value of 24.6 ± 0.4 keV for the energy of the first excited state[9] in ^{123}Sn. While the neutron resonances decay to this level either via a direct γ transition or via two-step cascades, these resonances are not connected to the ground state through the γ rays identified in our study.

In Table III we have collected all well-established energy levels in ^{123}Sn below 1.2 MeV and several levels up to 2.7 MeV. We have also indicated in the table J^π assignments for most of the levels based on the reasonings given therein. We have made the assumption that the observed primary γ rays are of dipole character. The 106 and 258 eV resonances are known[13] to be p-wave resonances based on a lack of interference between resonance and potential scattering in the curve of neutron transmission versus neutron energy. Furthermore, the 106 eV resonance is known to be $3/2^-$ and the 258 eV resonance $1/2^-$ from angular distribution measurements[14] (90° and 135°) involving the 5921 and 5796 keV γ transitions. The levels at 150, 920 and 1072 keV are strongly populated by primary γ rays from the 258 eV, $1/2^-$ resonance. This fact has been utilized in making J^π assignments in Table III.

A recent study[5] of conversion electrons following the ^{122}Sn($d,p\gamma$) reaction shows that the 620, 769, 845, 896, 922 and 931 keV transitions are all *M1* or *E2* or (*M1* + *E2*). (The conversion data were sufficiently accurate to rule out *E1, M2, E3,* etc.). The same study also included the determination of excitation functions for specific γ rays in the ($d,p\gamma$) reaction, which could be employed to rule out certain J^π values.

The present (n,γ) study is expected to be especially sensitive to finding low spin final states since the resonances studied are believed to be *p*-wave resonances with an occasional *s*-wave resonance. Therefore, it was surprising that a primary γ ray was not observed to populate the 1136 keV level from any of the resonances studied. This level has a tentative J^π assignment of $1/2^+$ or $3/2^+$.

B. Levels in ^{125}Sn

The neutron time of flight spectrum is shown in Fig. 5. The 62 eV resonance is known[13,15] to be a *p*-wave, J = 1/2 resonance. The γ-ray spectrum from this resonance is shown in Fig. 6. This spectrum contained virtually all γ rays (see Tables IV and V) used in constructing the level scheme for ^{125}Sn shown in Fig. 7. In Table VI, we have collected all well-established levels in ^{125}Sn below 2.2 MeV. All levels except those at 0, 855, 937 and 1186 keV were populated by primary γ transitions. The levels at 2284, 2331 and 2531 keV have not been reported previously. We have placed the 827 keV γ ray, observed in the spectra from all the resonances, between a state at 855 keV and the 28 keV first-excited state. The 855 keV state is well-established through γγ coincidence measurements following $(9/2)^+$, ^{125}In^g decay. An alter-

TABLE V

Secondary γ rays from the ^{124}Sn(n,γ) ^{125}Sn reaction

$E_\gamma{}^a$ (keV)	$E_\gamma{}^a$ (keV)
616.4 *10*	1259.5 *15*
714.5 *10*	1275.2 *10*
827.0 *10*	1460.6 *15*
856.9 *5*	1541.9 *10*
902.1 *5*	1578.3^b *15*
936.9^b *10*	1888.0^b *10*
971.5 *10*	1904.4^b *10*
1043.6 *5*	2034.5 *10*
1159.6 *15*	2221.5 *15*
1230.0 *10*	2256.7 *10*

^{a}In our notation 616.4 *10* ≡ 616.4 ± 1.0, etc.
^{b}Not placed on the level scheme.

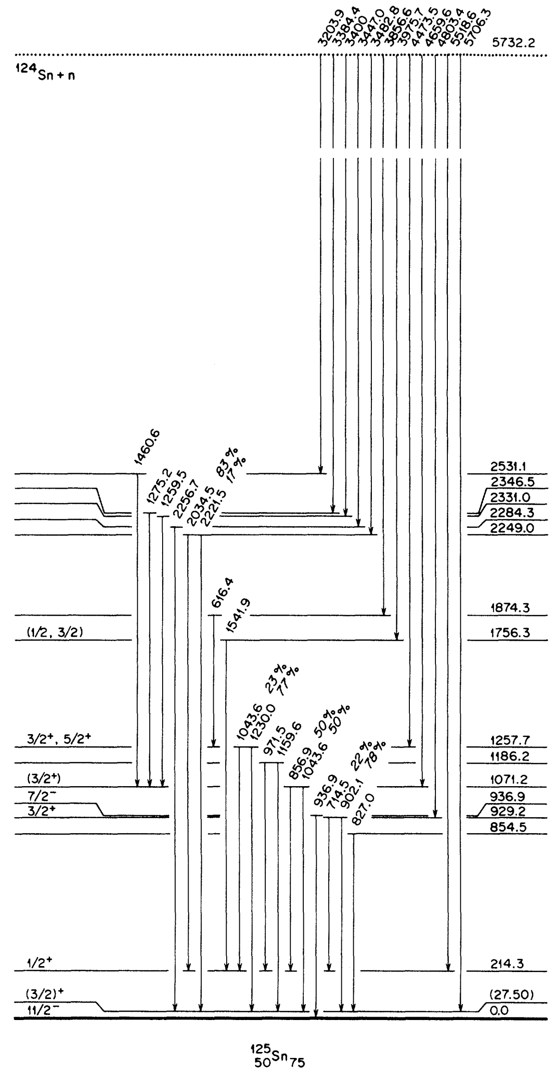

FIG. 7. Level scheme for ^{125}Sn from present experiment. All energies are in keV. The γ branching ratios are based on data obtained at only 90°.

TABLE VI

Energy Levels in ^{125}Sn

Other Works[a] Energy (keV)		Present Work Energy (keV)		$J^{\pi b}$	Reasons for J^{π} assignments[c]
0.0		0.0		$11/2^-$	First forbidden unique shape of the β group to the ^{123}Sb, $7/2^+$ ground state; $\ell_n = 5$ in $(\alpha,{}^3\mathrm{He})$
27.50	*14*	(27.50	*14*)[d]	$(3/2)^+$	$\ell_n = 2$ in (d,p); level systematics; (d,p) strength
215.13	*14*	214.3	*5*	$1/2^+$	$\ell_n = 0$ in (d,p)
617.89	*9*			$(9/2)^-$	Fed by γ rays from $7/2^+$ levels following $(9/2)^+$, $^{123}\mathrm{In}^g$ decay; γ ray to $11/2^-$ ground state is *M1* or *E2* or (*M1* + *E2*); level systematics
854.69	*15*	854.5	*10*		
930.4	*3*	929.2	*8*	$3/2^+$	$\ell_n = 2$ in (d,p); fed by primary γ ray from 62 eV, $1/2^-$ resonance
936.49	*9*	936.9	*10*	$7/2^-$	$\ell_n = 3$ in (d,p); de-excites to $11/2^-$ ground state not to $(3/2)^+$, 28 keV level.
1059.25	*17*			$(7/2)^+$	Log ft = 5.4 from $(9/2)^+$, $^{125}\mathrm{In}^g$ decay; strong γ ray to 28 keV level
1072.5	*6*	1071.2	*5*	$(3/2^+)$	Fed by primary γ ray from 62 eV, $1/2^-$ resonance; excitation function in $(d,p\gamma)$
1188.0	*8*	1186.2	*9*		
1259.6	*11*	1257.7	*5*	$3/2^+$, $5/2^+$	$\ell_n = 2$ in (d,p)
1362.51	*10*			$(7/2)^+$	$\ell_n = 4$ in (d,p); Log ft = 4.3 from $(9/2)^+$, $^{125}\mathrm{In}^g$ decay; strong γ ray to 28 keV level
1540.3	*10*			$3/2^+$, $5/2^+$	$\ell_n = 2$ in (d,p)
1756.5	*10*	1756.3	*11*	(1/2, 3/2)	Fed by primary γ ray from 62 eV, $1/2^-$ resonance
1803	*10*				
		1874.3	*11*		
1892	*10*				
2176.1	*4*				
...					
...					
		2249.0	*10*		
		2284.3	*10*		
		2331.0	*15*		
		2346.5	*11*		
		2531.1	*15*		
...		...			
...		...			
		5732.2[e]	*15*		

[a]Mainly from $(d,p\gamma)$-Ref. 5; [$(9/2)^+$, 2.3 *s* ^{125}In decay]-Ref. 9; (d,p)-Ref. 4 and 7. In our notation for level energy 27.50 *14* ≡ 27.50 ± 0.14, etc. Above 2.2 MeV excitation, this column is not complete. See, for example Ref. 4.
[b]Parentheses around a J^{π} value imply that the assignment is most probable but not certain beyond reasonable doubt.
[c]The $J^{\pi} = 11/2^-$ assignment for the ground state is from β-decay studies by R. W. Hayward, Phys. Rev. 79, 409 (1950). The other data referred to in this column are from the following references: $(\alpha,{}^3\mathrm{He})$-Ref. 7; (d,p)-Refs. 1, 2, 5, and 7; log ft values-Ref. 9; multipolarities from conversion studies following $(d,p\gamma)$-Ref. 5; excitation function in $(d,p\gamma)$-Ref. 5; (n,γ)-present paper.
[d]Assumed value obtained by a least-squares adjustment of data presented in Ref. 9.
[e]Neutron separation energy.

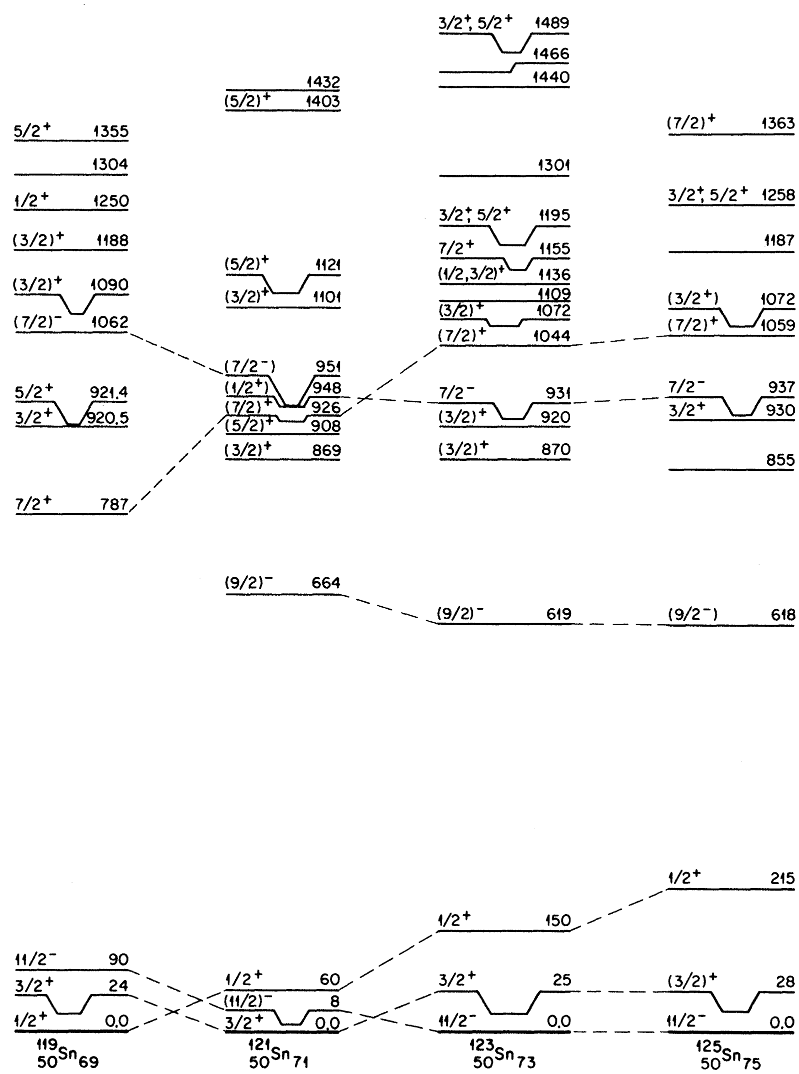

FIG. 8. A comparison of the energy levels below 1.5 MeV in ^{119}Sn, ^{121}Sn, ^{123}Sn and ^{125}Sn.

nate placement for the 827 keV γ ray between a proposed new $(7/2^-)$ level at 827 keV and the ground state has been suggested in a recent $(d,p\gamma)$ study but the evidence for such a level is very weak at present. Conversion coefficient measurements in the $(d,p\gamma)$ study[5] show that the γ transitions of energy 618 (618 keV level $\rightarrow$ ground state), 827, 902, 937, 1160 and 1230 keV (see Fig. 7) are all *M1* or *E2* or (*M1* + *E2*) transitions. The proposed J^π assignments together with their rationale have also been given in Table VI. The neutron separation energy, S_n, was determined to be 5732.2 ± 1.5 keV based on the value of 27.50 ± 0.14 keV for the energy of the first-excited state[9] in ^{125}Sn.

IV. DISCUSSION

The known levels[11] below 1.5 MeV in ^{119}Sn and ^{121}Sn are shown in Fig. 8 along with levels in ^{123}Sn and ^{125}Sn. The lowest three states in these isotopes with $11/2^-$, $3/2^+$ and $1/2^+$ assignments are believed to be predominantly one quasiparticle (1*qp*) states. In addition to further 1*qp* states, several 3*qp* states resulting from the coupling of the 1*qp* states to the 2^+ excitations of the even core are expected in the 0.6-1.5 MeV region. The identification of these states must await additional measurements to establish definite J^π assignments. Moreover, lifetime determinations are needed to establish various transition rates. Below 1.1 MeV, there exists extraordinary similarity between the level structures of ^{123}Sn and ^{125}Sn. The tentative identification of $7/2^-$ and $9/2^-$ levels in the heavier ($A \geqslant 121$) Sn isotopes was accomplished only recently.[3,5,9] The present (n,γ) measurements essentially complement these studies and the earlier nuclear reaction studies.

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