Investigation of γ Rays following S- and P-Wave Neutron Capture in Tin Isotopes*

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(Received 29 September 1967)

The energies and intensities of γ rays following slow-neutron capture in resonances in isotopes of tin have been studied. The angular distribution of γ rays from capture in P-wave resonances in Sn^{118}, Sn^{120}, and Sn^{124} has been measured for several γ rays in order to determine the spins and parities of initial and final states in the reaction. The following assignments for the resonances can be made: Sn^{117}(38.8 eV, 1^+), Sn^{118}(45.8 eV, $\frac{3}{2}^-$), Sn^{120}(426.9 eV, $\frac{1}{2}^-$), and Sn^{124}(61.95 eV, $\frac{1}{2}^-$). The spins of eight final states in Sn^{119} are assigned by virtue of the nonisotropic angular distribution for γ rays following P-wave capture. New data on the energy levels in Sn^{118}, Sn^{121}, and Sn^{125} are also presented. Results of the present work are compared with the results of (d,p) and other charged-particle reaction studies and theoretical calculations on the tin isotopes.

INTRODUCTION

By virtue of its position in the periodic table, tin, with a closed proton shell at $Z=50$, has been subjected to much theoretical and experimental study. With its many stable isotopes, tin appears to be an ideal case for studying the properties of the closed proton shell nucleus as the number of neutrons is varied.

Among the previous experimental studies is the (d,p) work of Cohen and Price,[1] Schneid, Prakash, and Cohen,[2] Nealy and Sheline,[3] and Allan *et al.*[4] This experimental work has been useful in determining the energies, spins, and parities of the excited states of the residual nucleus and in determining the single-particle occupation amplitudes for comparison with the calculations based on the pairing model.[5,6] The energy resolution of these experiments was about 40 keV, which is insufficient to separate some of the more closely spaced levels. Neutron-capture γ rays in the tin isotopes have been studied by Harvey *et al.*[7] with high-resolution Ge(Li) detectors using thermal neutrons and reactor spectrum neutrons filtered through cadmium. Capture from a beam heterogeneous in energy can, however, lead to difficulties in interpretation. It is especially desirable to study the capture process from a well-defined initial state in order to make spin and parity assignments to the levels of the residual nucleus.

Transmission measurements by Fuketa *et al.*[8] have indicated the presence of strong resonances due to $l=1$ neutron capture at relatively low incident neutron energy. Since thermal neutron capture is always dominated by $l=0$ neutrons, capture in P-wave resonances will generally give additional information not available in thermal capture experiments. Furthermore, it is known that if the P-wave resonance has a spin larger than $\frac{1}{2}$, the angular distribution of γ rays is not isotropic. For dipole radiation, the angular distribution has the form $a+b\sin^2\theta$, where θ is the angle between the photon propagation vector and the incident neutron direction. Observation of such anisotropy can be used to fix the initial-state parity and spin, and the relative sizes of the coefficients a and b depend on the final-state spin. Such experiments have been carried out by McNeill, McConnell, and Firk[9] and by Harvey, Slaughter, and Martin.[7]

The present experiments are unique in that they involve all three of the following features:

(a) The measurement of the neutron time of flight to identify the neutron resonance responsible for the capture γ ray.

(b) The measurement of the energy and intensity of the emitted γ rays with high-resolution solid-state radiation detectors.

(c) The measurement of γ-ray intensity at two different angles with respect to the incident neutron beams.

With the recently available intense neutron beams from the Brookhaven high-flux reactor and the availability of large (∼50–100 g) quantities of separated tin isotopes, it has become feasible to perform these three kinds of measurements.

EXPERIMENTAL PROCEDURE

A pulsed neutron beam is obtained from the H-2 fast chopper beam hole at the Brookhaven high flux beam reactor and is incident on the tin sample situated 21.7 m from the chopper. Details of the construction and performance of the chopper are given in a paper by Chrien

* This work was supported by the U. S. Atomic Energy Commission.

[1] B. L. Cohen and R. E. Price, Phys. Rev. **121**, 1441 (1961).
[2] E. J. Schneid, A. Prakash, and B. L. Cohen, Phys. Rev. **156**, 1316 (1967).
[3] C. L. Nealy and R. K. Sheline, Phys. Rev. **135**, B325 (1964).
[4] D. L. Allan, G. A. Jones, G. C. Morrison, R. B. Taylor, and R. B. Weinberg, in *Isobaric Spin in Nuclear Physics*, edited by John D. Fox and Donald Robson (Academic Press Inc., New York, 1966).
[5] L. Kisslinger and R. Sorensen, Kgl. Danske Videnskab. Selskab, Mat. Fys. Medd. **32**, No. 9 (1960); L. Kisslinger and R. Sorensen, Rev. Mod. Phys. **35**, 853 (1963).
[6] S. Yoshida, Nucl. Phys. **38**, 380 (1962).
[7] J. A. Harvey, G. G. Slaughter, and M. J. Martin, Oak Ridge National Laboratory Report No. ORNL 3924, 1965, p. 37 (unpublished).
[8] T. Fuketa, F. A. Khan, and J. A. Harvey, Oak Ridge Laboratory Report No. ORNL 3425, 1963 (unpublished).
[9] K. G. McNeill, D. B. McConnell, and F. W. K. Firk, Can. J. Phys. **43**, 2156 (1965).

and Reich.[10] In the present experiment, neutron energies ranging from 0.02 to 500 eV were covered with three rotational speeds of 1000, 6000, and 10 000 rpm. Capture γ rays were detected with germanium detectors 10 and 30 cc in size, with resolutions of 9 and 12 keV at a γ-ray energy of 7 MeV. Although the large volume detector has inferior resolution, it is useful for the measurement of γ rays at several angles to the incident neutron beam, where the separation of detectors and sample must be relatively large.

The detector events are analyzed according to time of arrival and amplitude and written on a computer-controlled magnetic tape as described by Bhat *et al.*[11] Pulses from a stable pulser are also recorded on tape for later examination for gain drift. The sorting program can utilize these "pulser tags" for correcting for drifts. Ten bits are allotted to time of flight (1024 channels) and 11 bits to pulse height (2048 channels).

Capture γ-ray spectra in the various Sn resonances are obtained by selecting the appropriate time-of-flight limits and totalizing events within those limits. This sorting process is accomplished with the aid of the BNL CDC 6600 computer, as described by Bhat *et al.*[11]

The angular distribution of the neutron-capture γ rays was measured using a detector and cryostat pivoted about the sample position. Since these dipole transitions are characterized by only two parameters, and because of the long running time involved, measurements were performed only at 90° and 135° with respect to the incident beam, as shown in Fig. 1. The samples used were 1400 and 6470 g of natural tin, 82.46 g of a sample enriched to 98.4% in Sn^{120}, and 117.7 g of a sample enriched to 97.15% of Sn^{118}.

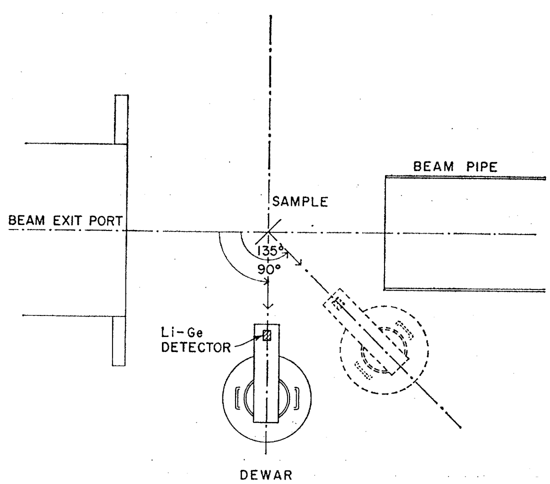

FIG. 1. A schematic diagram of the apparatus for measuring γ-ray angular distribution following capture in P-wave resonances. The target is situated 21.7 m from the chopper.

[10] R. E. Chrien and M. Reich, Nucl. Instr. Methods **53**, 93 (1967).

[11] M. R. Bhat, B. R. Borrill, R. E. Chrien, S. Rankowitz, B. Soucek, and O. A. Wasson, Nucl. Instr. Methods **53**, 108 (1967).

Although the anisotropy can be observed with natural tin, the effects of multiple neutron scattering before capture must be taken into account. In order to avoid a complex calculation of these effects, the enriched isotopes were used.

For the capture of P-wave neutrons by spin 0^+ target nuclei compound states of spin $\frac{1}{2}^-$ and $\frac{3}{2}^-$ are formed. Decay of the $\frac{1}{2}^-$ compound state leads to isotropic γ-ray emission, while decay of the $\frac{3}{2}^-$ states leads in general to an anisotropic angular distribution. The forms of these distributions may be found in any of the standard treatises on particle γ-ray correlations, such as that of Ferguson.[12] For dipole radiation to $\frac{1}{2}$, $\frac{3}{2}$, or $\frac{5}{2}$ final states, the angular distributions are given in Table I. Measurements at 90° and 135° with respect to the incident beam serve to fix the parameters of the distribution and allow the identification of the final-state spins. Secondary effects such as multiple neutron scattering and the finite size of the source tend to reduce the size of the anisotropy. The use of enriched samples in the present experiments makes the multiple

TABLE I. Angular distribution of dipole γ rays originating in a $\frac{3}{2}$ resonance.

$\frac{3}{2}\rightarrow\frac{1}{2}$	
	$I(\theta)=(1/16\pi)(2+3\sin^2\theta)$
	$I(90°)/I(135°)=10/7$
$\frac{3}{2}\rightarrow\frac{3}{2}$	
	$I(\theta)=(1/20\pi)(7-3\sin^2\theta)$
	$I(90°)/I(135°)=8/11$
$\frac{3}{2}\rightarrow\frac{5}{2}$	
	$I(\theta)=(3/80\pi)(6+\sin^2\theta)$
	$I(90°)/I(135°)=14/13$

scattering correction negligible, while the finite source size effect has been evaluated by a numerical integration of the angular distribution over the area of the sample.

The intensities of the γ rays observed were measured using a program called PEAKFIT, written for the CDC 6600. The program fits a smoothly varying background over a selected energy region, using a second-degree polynomial, subtracts the calculated background under the peaks, and performs a least-squares fit to the region of the peak. The resolution function used depends on the detector response. For the 10-cm^3 detector, the detector response can be well represented by a Gaussian curve. The response of the 30-cm^3 detector, however, is not Gaussian, but shows a decided "tail" on the low-energy side of the peak. This tail is shown explicitly in Fig. 2 and is presumably due to the poor electron collection which is an inherent property of the coaxially drifted detectors. As shown in Fig. 2, an adequate representation of the resolution function is obtained with

[12] A. J. Ferguson, *Angular Correlation Methods in Gamma-ray Spectroscopy* (North-Holland Publishing Co., Amsterdam, 1965).

a skew-Gaussian function of the form

$$R(x)=H\exp-\{(x-a)^2(1-\theta b)/2\sigma^2\},$$
$$\theta=1 \quad \text{for} \quad x<a, \qquad (1)$$
$$\theta=0 \quad \text{for} \quad x>a,$$

where the Gaussian fit is inadequate. The skew Gaussian is a four-parameter fit, i.e., the peak height H; peak position a; the width σ; and the skewness parameter b. It is especially important to take account of the skewness in closely spaced γ rays to get accurate intensities for these closely spaced peaks. The skewness and parameter width may be evaluated for the strongest γ rays and held constant in the fitting of the weaker peaks.

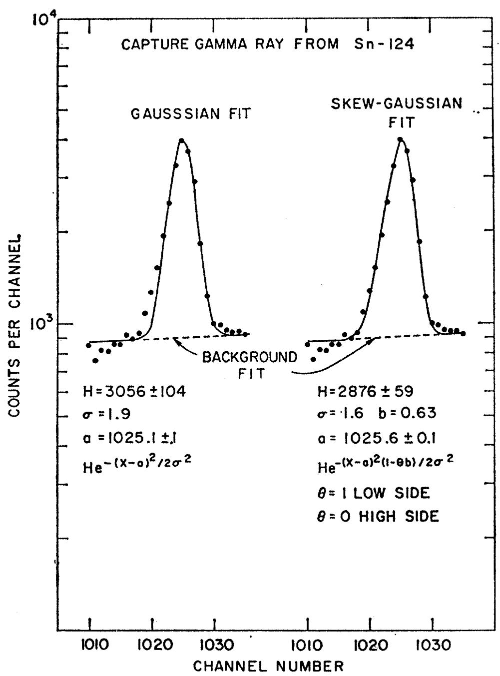

FIG. 2. The Gaussian and skew-Gaussian fits to the two-escape peak from a 30-cm³ Ge (Li) detector. The best-fit parameters are shown.

γ-ray energies were obtained with the aid of reference pulses from the pulser and the use of the $Fe^{56}(n,\gamma)Fe^{57}$ ground-state γ ray, assumed to be at 7645 keV. The one-escape and full-energy peaks of the detector were useful in comparing γ-ray energies within an MeV of the standard line, and for greater differences the pulser, with a linearity of 15 ppm, was used. The principal error in the calibration of relative energies is due to the nonlinearities of the pulse-height encoder, which is estimated to cause an error of $\simeq$2 channels in an estrapolation of 1000 channels. For the lowest energies observed in this experiment ($\sim$4.3 MeV), the calibration error is estimated to be $\sim$7 keV.

The large volume of the 30-cc detector enhances the relative size of the full energy and single-escape peaks to the two-escape peak. In some cases these subsidiary peaks coincide, or nearly so, with the two-escape peaks normally used for the energy and intensity measurements. Correction for the contributions of these peaks can be made knowing the relative size of the subsidiary peaks as a function of energy. The thermal-neutron-capture γ rays from chlorine were used to determine the ratios of full energy and single-escape peaks to the double-escape peak experimentally. The results are shown in Fig. 3. The line intensities quoted by Groshev *et al.*[13] served to establish the efficiency variation with energy for the 30-cm³ detector, while the recently available efficiency calibrations of Kane and Mariscotti[14] were used to establish the efficiency curve for the 10-cm³ detector.

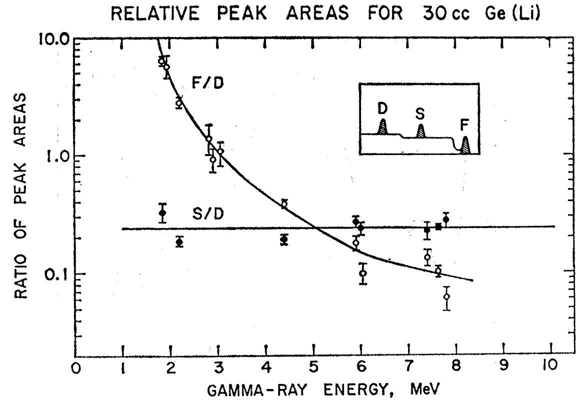

FIG. 3. The ratio of the single-escape and full-energy peaks to the two-escape peak for the 30-cm³ detector.

It is of interest to measure the partial widths $\Gamma_{\gamma i}$ for the various radiative transitions. The procedure used in the present experiment is expected to be valid when the radiation width varies little from resonance to resonance. The events recorded above a lower limit of 1.5 MeV are expected to be a measure of the total capture rate in the resonance, thus,

$$\Gamma_{\gamma i}=k\Gamma_\gamma A_{\gamma i}/A_\gamma, \qquad (2)$$

where k depends on detector efficiency, γ-ray multiplicity, and the discriminator level above which γ pulses are accepted, $A_{\gamma i}$ is the area under a two-escape peak, and A_γ is the total counts recorded above 1.5-MeV γ-ray energy. The constant k can usually be determined by measuring a line intensity in the thermal neutron region, and evaluating Eq. (2) in terms of a known capture rate in photons per neutron capture. Unfortunately, in tin very few such absolute intensity measurements have been made. To estimate values for

[13] L. V. Groshev, A. M. Demidov, V. N. Lutsenko, and V. I. Pelekhov, *Atlas of Gamma-ray Spectra from Radiative Capture of Thermal Neutrons*, translated by J. B. Sykes (Pergamon Press, Ltd., London, 1959).

[14] W. R. Kane and M. Mariscotti, Brookhaven National Laboratory Report No. BNL 11517 (unpublished).

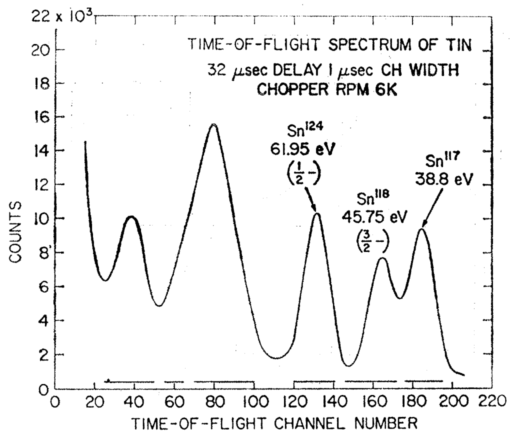

FIG. 4. The time-of-flight spectrum for γ-ray events recorded with a natural Sn sample.

the partial widths in this experiment, we use the fact that the high-energy transitions for 62.0-eV resonance in $Sn^{124}(n,\gamma)$ dominate the capture γ-ray spectrum. An examination of this spectrum suggests that a very large fraction of the radiation width is accounted for by the four γ rays observed above 4.6 MeV. This suggestion is supported by the observation of Harvey[15] that the transitions to the ground state and to the first excited state account for 65% of the primary transitions. We assume that the four γ rays in Sn^{124} account for the total primary spectrum. The widths for the other isotopes are then obtained by application of Eq. (2) and the assumption that Γ_γ does not vary appreciably in the tin isotopes. In view of the unknown errors involved in these assumptions, the absolute widths listed in this paper must be regarded as estimates, and we have not quoted errors for them. The agreement, however, with those widths reported in Ref. 15, is quite satisfactory.

RESULTS

A. $Sn^{117}(\eta,\gamma)Sn^{118}$

The time-of-flight spectrum of natural tin is shown in Fig. 4. A sample of 1400 g of natural tin was used. Resonances due to Sn^{124}, Sn^{118}, and Sn^{117} at 62, 46, and 39 eV are clearly resolved. From the total cross section work of Ref. 8, the resonance at 46 eV in Sn^{118}, as well as resonances at 62 eV in Sn^{124} and 427 eV in Sn^{120}, are known to be P-wave resonances. The appropriate resonance parameters are listed in Table II. The region over which pulse-height data were sorted is indicated below the curve. Figure 5 shows a portion of the pulse-height spectrum of the 39-eV resonance as obtained with the 10-cc detector. The ground-state transition is weakly seen; the spectrum is dominated, however, by a strong transition to the first excited 2^+ state in Sn^{118}. From the difference between the measured ground-state transition of 9328±4 keV and the 8095±5-keV γ ray to the first excited state, the energy of the 2^+ state is found to be 1233±4 keV, compared with the values of 1224 and 1229 reported by Harvey[7] and Allan *et al.*,[16] respectively. The binding energy of 9329±4 keV may be compared to the value 9315±12 keV from the $Sn^{117}(d,p)Sn^{118}$ reaction studies of Norris and Moore.[17] From the work of Fuketa *et al.*[8] it is known that the 39-eV resonance is induced by $l=0$ neutrons. The resonance spin must be 0^+ or 1^+ since the spin of Sn^{117} is known to be $\frac{1}{2}^+$. We observe the ground-state transition; hence, the spin of the resonance is 1^+, and the transitions to the 0^+ and 2^+ states are $M1$. These results are displayed in Fig. 6. The ratio of the measured photon strength function $\Gamma_{\gamma i}/D$ to the Weisskopf estimate is very large, namely 11 and 300 for the 9328- and 8095-keV γ rays, respectively. The strengths of these transitions are in good agreement with those reported by Harvey,[15] who used a NaI detector. The pulse-height spectrum of Fig. 5 shows the domination by the strong

TABLE II. Neutron resonance parameters in the tin isotopes.

Isotope (target)	E_0(eV)[a]	Γ_n^0(meV)[a]	Spin, parity[a,b]
117	38.8	0.93 ±0.05	1^+
118	45.8	0.106±0.005	$\frac{3}{2}^-$
124	61.95	1.5 ±0.3	$\frac{1}{2}^-$
118	359	18.5 ±1.1	$\frac{1}{2}^+$
120	427	1.1 ±0.2	$\frac{1}{2}^-$

[a] Taken from BNL 325 [Brookhaven National Laboratory Report No. 325 (U. S. Government Printing Office, Washington, D. C., 1958), 2nd ed.] recommended values.
[b] Determined in part from the present experiments.

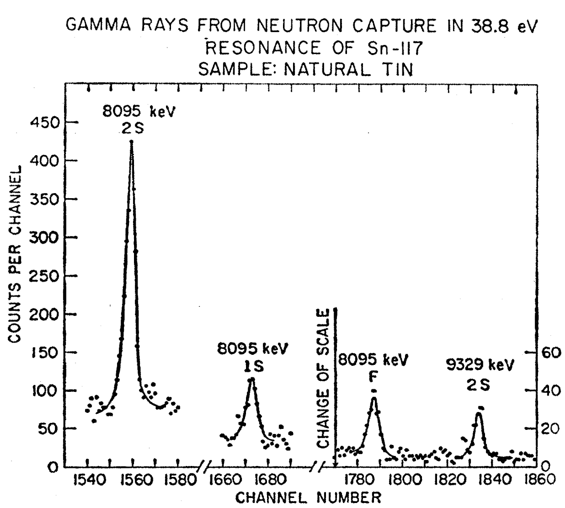

FIG. 5. Portions of the pulse-height spectrum for γ rays following neutron capture in the 38.8-eV resonance of Sn^{117}.

[15] J. A. Harvey, G. G. Slaughter, J. R. Bird, and G. T. Chapman, in *Proceedings of the International Conference on Nuclear Physics with Reactor Neutrons*, edited by F. E. Throw (Argonne National Laboratory, Argonne, Ill., 1963), Report No. ANL 6797, p. 230.

[16] D. L. Allan, B. H. Armitage, and Beryl A. Doran, Nucl. Phys. **66**, 481 (1965).

[17] L. R. Norris and C. F. Moore, Phys. Rev. **136**, B40 (1964).

8095-keV γ ray. As pointed out by Bergqvist[18] and by Harvey,[15] enhanced $M1$ transitions are expected in the tin isotopes because of a spin-flip mechanism suggested by Mottleson.[19]

B. $Sn^{118}(n,\gamma)Sn^{119}$

This target nucleus has spin and parity 0^+; therefore, P-wave capture results in excited states with $\frac{1}{2}^-$ and $\frac{3}{2}^-$ character. Transitions from these states are examined for angular isotropy with respect to the neutron beam direction to establish spins of the initial and final states.

Capture events from a sample of 97.15% Sn^{118} in the region of the 46-eV resonance were examined. The sample size of $3\times3\times\frac{1}{8}$ in. was achieved by mounting plates individually $1\times1\times\frac{1}{16}$ in., in a sheet, to take advantage of the entire neutron beam which is ~3 in. full width at half-maximum (FWHM). The sample was mounted at 45° to the incident beam, and the source center-point to detector distance was 23.5 cm, so that about 10° half-angle was subtended by the sample at the detector. The effect of the extended source has been calculated by numerically integrating the angular distributions over the source and is expressed as correction factors for the ratio of intensity at 90° to 135° as measured from the centers of the detectors and source, in Table III.

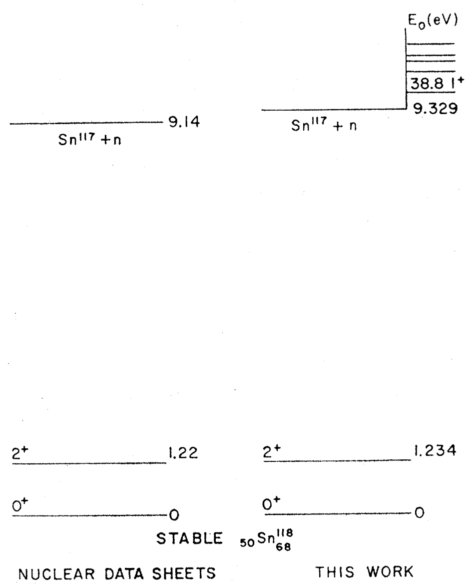

FIG. 6. The energy-level diagram of Sn^{118}, summarizing results of the present experiment. For comparison, results compiled in *Nuclear Data Sheets* [compiled by K. Way *et al.* (Academic Press Inc., New York, 1965), Part 4, 1959–1965] are shown.

TABLE III. Extended source correction factors.

Theoretical ratio $I(90°)/I(135°)$ correction factor	Final-state spin
0.9889	$\frac{1}{2}$
0.9764	$\frac{3}{2}$
0.9836	$\frac{5}{2}$

Multiple scattering effects are negligible for the enriched sample. The effect of multiple scattering in a natural tin sample is seen by comparing Figs. 7 and 8, showing the γ rays populating the $\frac{1}{2}^+$ ground state and $\frac{3}{2}^+$ first excited states of Sn^{119} at 24 keV. The thick-sample intensity ratios are 1.15 ± 0.08 (ground state)

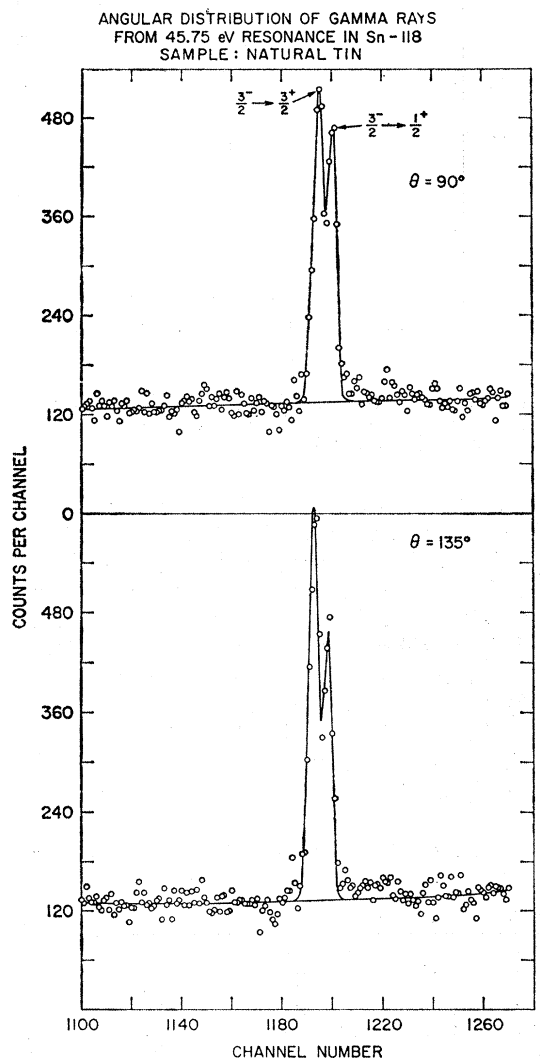

FIG. 7. The transitions to the $\frac{1}{2}^+$ ground state and $\frac{3}{2}^+$ first excited state in Sn^{119} from neutron capture in the 45.75-eV resonance of Sn^{118}. The radiation is observed at 90° and 135° from a very thick (6470-g) sample of natural tin.

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[18] I. Bergqvist, B. Lundberg, and N. Starfelt, in *Proceedings of the International Conference on Nuclear Physics with Reactor Neutrons*, edited by F. E. Throw (Argonne National Laboratory, Argonne, Ill., 1963), Report No. ANL 6797, p. 220.

[19] B. R. Mottleson, in *Proceedings of the International Conference on Nuclear Structure*, edited by D. A. Bromley and E. W. Vogt (University of Toronto Press, Toronto, 1960), p. 525.

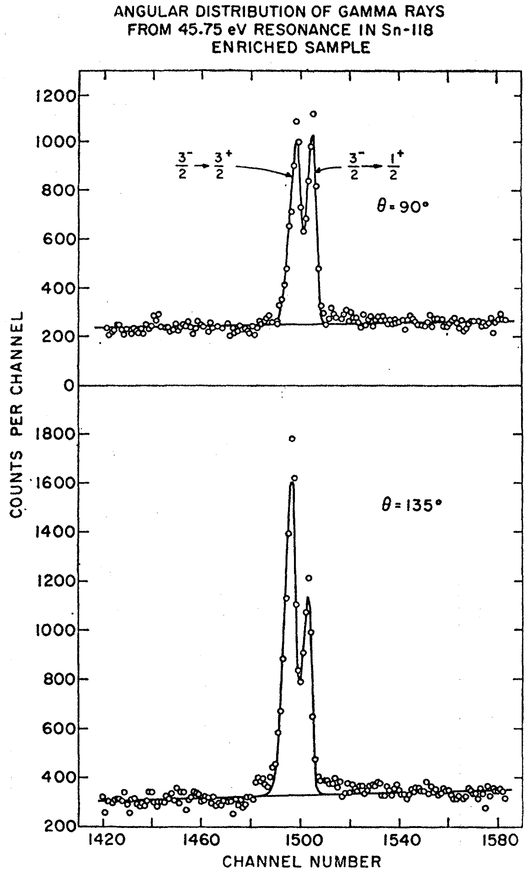

FIG. 8. The transitions of Fig. 7, except for a much smaller (117.7-g) sample of Sn enriched to 97% Sn^{118}. Note the enhanced asymmetry relative to Fig. 7.

and 0.84±0.06 (first excited state), while for the enriched sample, they are 1.26±0.17 and 0.75±0.10, respectively. The observed anisotropy confirms the conclusions of Harvey,[7] which were based on experiments with filtered beams of reactor neutrons, and definitely establishes the capturing level as $\frac{3}{2}^-$. After correction for the extended source size, the ratios $I(90°)/I(135°)$ are 1.29 and 0.70 and are in good agreement with the theoretical values of 10/7 and 8/11. It is important to observe that the anisotropy is not completely masked by multiple scattering even in the very large (6470-g) sample of Fig. 7. This observation permits us to draw conclusions about resonances in Sn^{124} which will be developed below.

TABLE IV. Angular distribution of γ rays from $Sn^{118}(n,\gamma)$.

E (keV)	Ex (keV)	$I(90°)/I(135°)_{expt}$	$I(90°)/I(135°)_{theor}$	Spin of final state
6484	0	1.26±0.17	10/7	$\frac{1}{2}$
6461	23	0.75±0.10	8/11	$\frac{3}{2}$
5563	921	0.58±0.10	8/11	$\frac{3}{2}$
5394	1090	0.95±0.15	14/13	$\frac{5}{2}$
5297	1187	0.57±0.15	8/11	$\frac{3}{2}$
5232	1252	1.37±0.20	10/7	$\frac{1}{2}$
4910	1574	0.71±0.09	8/11	$\frac{3}{2}$
4706	1778	1.30±0.28	10/7, (14/13)	$\frac{1}{2}$, ($\frac{5}{2}$)[a]

[a] $\frac{1}{2}$ is preferred, but $\frac{5}{2}$ cannot be excluded.

In addition to the strong γ rays at 6484 and 6461 keV mentioned above, additional states indicating anisotropic distributions were observed. Figure 9 shows these states corresponding to excitation energies from 921 to 1778 keV. These data have been normalized with respect to beam monitor counts and corrected for a 4% difference in solid angle between the 90° and 135° positions. The intensity ratios of Table IV have also been corrected for the finite extent of the target where the assignment is definite enough to select the proper angular distribution for evaluating the correction.

Table V summarizes the relative and absolute intensities of the γ rays observed from $Sn^{118}(n,\gamma)Sn^{119}$. The absolute intensities were derived by applying Eq. (2) and using the measured Sn^{124} resonance data.

These results are compared, in Table VI, to the (d,p) work on Sn^{118} of Allan *et al.*[4] and Schneid *et al.*[2] The improved resolution of the present experiment shows additional levels not seen in the earlier (d,p) work.[2] The agreement with the work of Allan *et al.*[4] is excellent except for a 20- to 40-keV discrepancy in excitation energy. The spin assignments in the (d,p) experiments are based on the angular distributions of the outgoing proton and must be regarded as less reliable than the method employed in the present work. The assignment of $\frac{3}{2}$ for the spin of the 921-keV level agrees with recent Coulomb-excitation measurements of Stelson *et al.*[20] The energy levels of Sn^{119} obtained from the present work are shown in Fig. 10.

The resonance at 359 eV has been identified as an S-wave resonance by Fuketa from total-cross-section measurements. Transitions are observed from the $\frac{1}{2}^+$ resonance to the $\frac{1}{2}^+$ ground state and $\frac{3}{2}^+$ first excited state in Sn^{119}. These are an additional confirmation of strong $M1$ transitions, and the photon strength function ratios are given in Table V. The agreement with earlier estimates by Harvey is good.

As is well known, the low-lying excitations of an even-mass nucleus like Sn^{118} are described as one- and two-phonon states corresponding to the vibrational states of the nucleus. In the case of the odd-mass nuclei like Sn^{119}, Sn^{121}, and Sn^{125}, the last odd particle can be considered as being coupled to these phonon states, thus splitting these states, their position being determined by the strength of the interaction between the odd particle and the vibrational states. In the case of these tin isotopes there have been extensive calculations of Kisslinger and Sorensen,[5] Sorensen,[21] and by Yoshida[6] using a pairing plus quadrupole force for the residual interaction between nuclei. Since we have been able to determine spins of the levels of Sn^{119} in addition

[20] P. H. Stelson, W. T. Milner, F. K. McGowan, and R. L. Robinson, Bull. Am. Phys. Soc. **12**, 19 (1967).
[21] R. A. Sorensen, Nucl. Phys. **25**, 674 (1961).

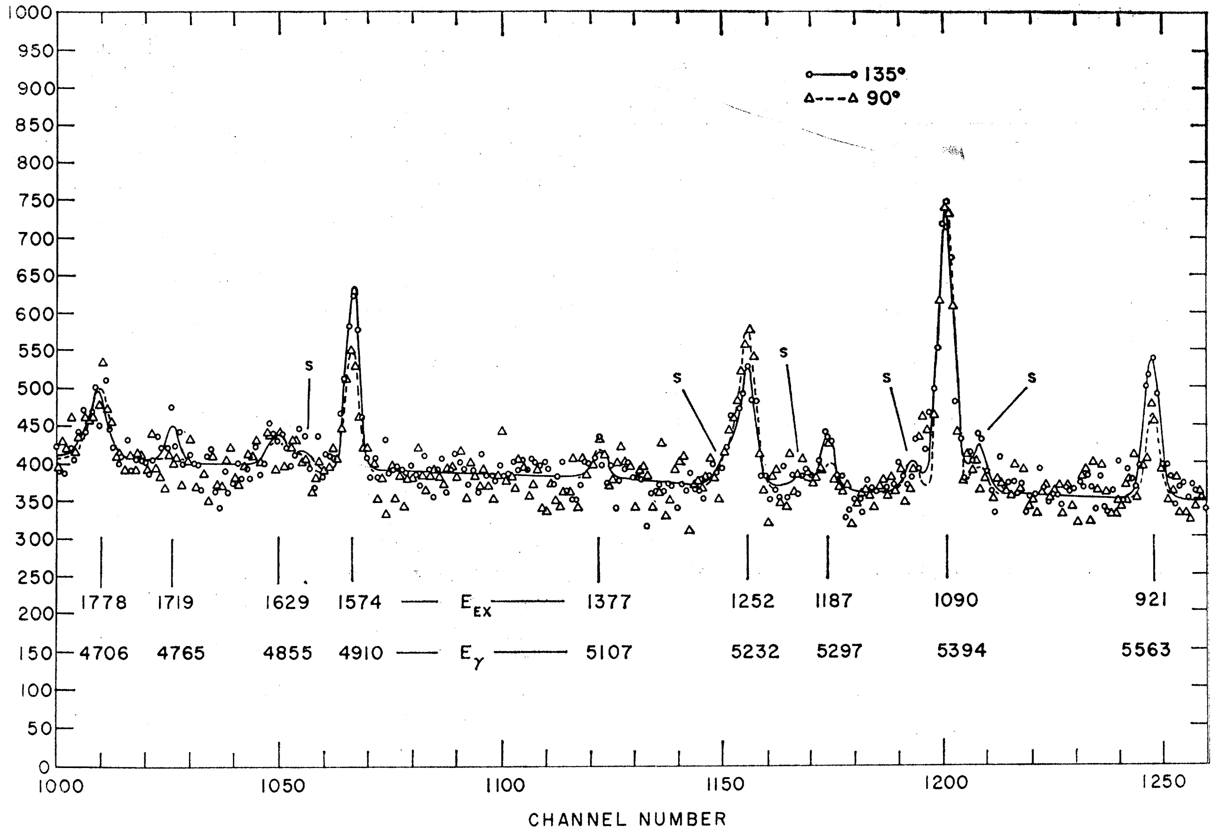

FIG. 9. A portion of the spectrum from Sn^{118} capture leading to states in Sn^{119} between 900- and 1800-keV excitation energy. The results at 90° and 135° to the incident beam are shown superposed. The runs are normalized with respect to elapsed time, except for a 4% solid-angle correction.

TABLE V. Table of γ-ray intensities.

Target nucleus Sn	E_0 (eV)	Type γ transition	E_γ (keV)	E (kev) excitation residual nucleus $A+1$	I relative	$\Gamma_{\gamma i}$ (eV)	$\Gamma_{\gamma i}/\Gamma$ (single particle)
117	39	$M1$	9328±5	0	0.064±0.02	0.00033	~11[a]
117	39	$M1$	8095±5	1233	1.00	0.0055	~300[b]
118	46	$E1$	6484±3	0	0.73 ±0.04	0.021[c]	
118	46	$E1$	6461±3	23	1.00	0.029[c]	
118	46	$E1$	5563±5	921	0.097 ±0.012	0.0028	
118	46	$E1$	5394±5	1090	0.24 ±0.02	0.0069	
118	46	$E1$	5297±5	1187	0.021 ±0.01	0.0006	
118	46	$E1$	5232±5	1252	0.131 ±0.05	0.0038	
118	46	$E1$	5107±5	1377	0.024 ±0.01	0.0007	$\langle\Gamma_{\gamma i}\rangle/\Gamma_w \cong 2$
118	46	$E1$	4910±5	1574	0.110 ±0.01	0.0032	
118	46	$E1$	(4855)[d]	(1629)[d]	0.024 ±0.007	0.0007	
118	46	$E1$	(4765)[d]	(1719)[d]	0.0275±0.01	0.0008	
118	46	$E1$	4706±7	1778	0.0655±0.009	0.0019	
118	46	$E1$	4347±7	2137	0.0275±0.009	0.0008	
118	359	$M1$	6484±3	0	≤0.004	≤0.001	<15
118	359	$M1$	6461±3	23	1.00	0.025	~370[e]
120	427	$E1$	6176±5	0	1.00		
120	427	$E1$	6118±5	58	0.47 ±0.07	...	....
124	62	$E1$	5701±5	26	1.00	0.0635[f]	
124	62	$E1$	5512±5	215	0.488 ±0.029	0.0310[g]	$\langle\Gamma_{\gamma i}\rangle/\Gamma_w \cong 3$
124	62	$E1$	4796±7	931	0.153 ±0.013	0.0097	
124	62	$E1$	4652±7	1075	0.070 ±0.006	0.0050	

[a] Harvey reports ~11.
[b] Harvey reports ~500.
[c] Harvey reports 0.04 for the sum of 6484 and 6461.
[d] Existence not certain.
[e] Harvey reports ~400.
[f] Harvey reports 0.055.
[g] Harvey reports 0.017.

TABLE VI. Comparison of $Sn^{118}(n,\gamma)$ and $Sn^{118}(d,p)$.

Present work Sn^{119} E_x (MeV)	Spin	Schneid *et al.*[a] E_x (MeV)	Spin	Allan *et al.*[b] E_x (MeV)
0	$\frac{1}{2}$	0	$\frac{1}{2}^+$	...
0.023	$\frac{3}{2}$	0.024	$\frac{3}{2}^+$	...
0.921	$\frac{3}{2}$	0.93	$\frac{5}{2}^+$	0.90
1.090	$\frac{5}{2}$	1.10	$\frac{5}{2}^+$	1.07
1.187	$\frac{3}{2}$			1.17
1.252	$\frac{1}{2}$	1.22	$\frac{5}{2}^+$	1.22
				1.29
1.377	...	1.37	$\frac{5}{2}^+$	1.34
1.574	$\frac{3}{2}$	1.59	$\frac{5}{2}^+$	1.54
(1.629)	...			1.62
(1.719)	...			1.70
1.778	$\frac{1}{2}$, $\frac{5}{2}$	1.74	$\frac{5}{2}^+$	1.78
2.137	...			...

[a] Reference 2.
[b] Reference 4.

to their energies, it is of interest to compare our experimental results with these calculations, though detailed agreement is not to be expected in view of the approximate nature of the calculations. It is found that the $\frac{3}{2}$ level at 921 keV and the $\frac{5}{2}$ level at 1090 keV are not predicted by either Sorensen or Yoshida. The $\frac{3}{2}^+$ level observed at 1187 keV agrees with a $\frac{3}{2}^+$ level at 1.200 MeV predicted by Sorensen and the 1.15 level of Yoshida. There is a $\frac{1}{2}^+$ level at 1.26 MeV predicted by Yoshida and not predicted by Sorensen. This level has not been seen in the (d,p) work of Schneid *et al.* This level seems to correspond to the 1.252 level seen in the present work. Both these calculations predict a $\frac{5}{2}^+$ level at about 1.5 MeV, and we see a $\frac{3}{2}^+$ level at 1.57 MeV. The 1.778 level with a spin of either $\frac{1}{2}$ or $\frac{5}{2}$ seen in our data is also not predicted in these calculations.

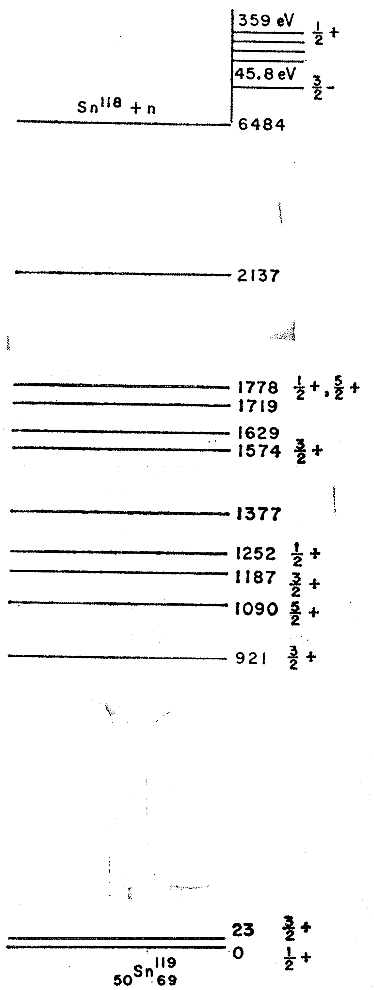

FIG. 10. The energy-level diagram of Sn^{119} summarizing results of the present experiment.

C. $Sn^{120}(\eta,\gamma)Sn^{121}$

Examination of the strong 427-eV P-wave resonance in Sn^{120}, in the form of a sample of 82.5 g enriched to 98.4% Sn^{120}, shows strong transitions to the $\frac{3}{2}^+$ ground state and to the $\frac{1}{2}^+$ first excited state with energies of 6176 and 6118 keV, respectively. The spin assignments to these states are from the work of Richard *et al.*[22] and Allan *et al.*[23] For $\frac{1}{2}^-$ capturing state, the expected ratio from 90° to 135° for the ratio of intensities of these γ rays should change by almost a factor of 2 (1.96). Our measurements for this ratio of intensity ratios is 0.95 ± 0.17, and we therefore assign a spin and parity

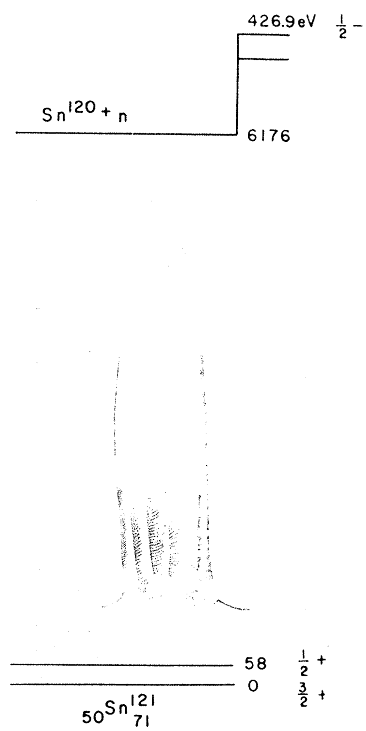

FIG. 11. The energy-level diagram of Sn^{121}.

[22] P. Richard, C. F. Moore, J. A. Becker, and J. D. Fox, Phys. Rev. 145, 971 (1966).
[23] D. L. Allan, G. A. Jones, R. B. Taylor, and R. B. Weinberg, Phys. Letters 21, 197 (1966).

of $\frac{1}{2}^-$ to the 427-eV resonance (see Fig. 12). Table V summarizes the energies and relative intensities. (It was not possible to estimate absolute widths for these transitions because the resonance could not be resolved in the natural tin runs used for calibrations.)

The present work indicates an energy difference of 58 keV between the low-lying $\frac{1}{2}^+$ and $\frac{3}{2}^+$ single-particle states in Sn^{121}. This difference is to be compared with a value of 75 keV obtained by Richard *et al.*[22] and Allan *et al.*[23] and a value of 50 keV obtained by Schneid *et al.*[2] The partial energy-level diagram of Sn^{121} is shown in Fig. 11.

D. $Sn^{124}(n,\gamma)Sn^{125}$

The 62-eV resonance has also been identified as a *P*-wave resonance by Fuketa. Angular distribution measurements have been performed with a NaI detector on this resonance by McNeill *et al.*[9] Epithermal capture in Sn^{124} has also been studied by Harvey,[7] using a beam of epithermal neutrons without neutron energy selection. The conclusion of these previous experimenters is that the spin and parity of this resonance is $\frac{1}{2}^-$. The present experiment confirms this conclusion. The strong γ rays to the $\frac{3}{2}^+$ ground state of Sn^{125} and to the $\frac{1}{2}^+$ first excited state at 213 keV show no asymmetry (see Fig. 13) as in the case of Sn^{120} above.

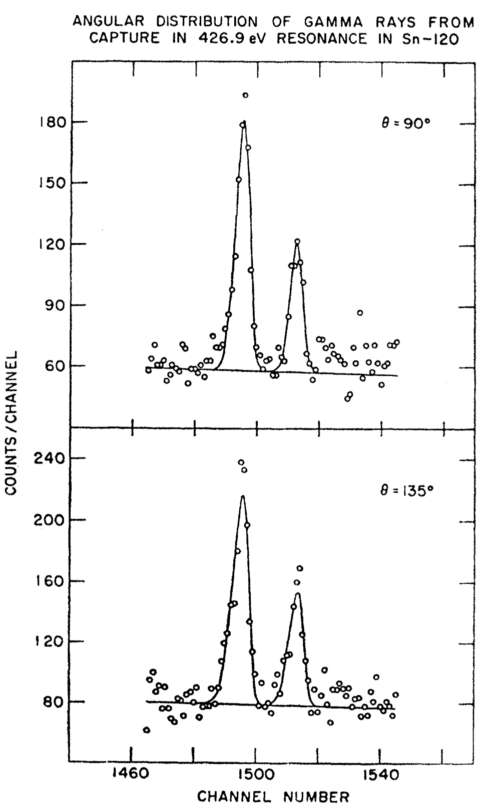

FIG. 12. The angular distribution of γ rays from capture in Sn^{120} to states in Sn^{121}. The ground-state spin is $\frac{3}{2}^+$, and the first excited state is $\frac{1}{2}^+$.

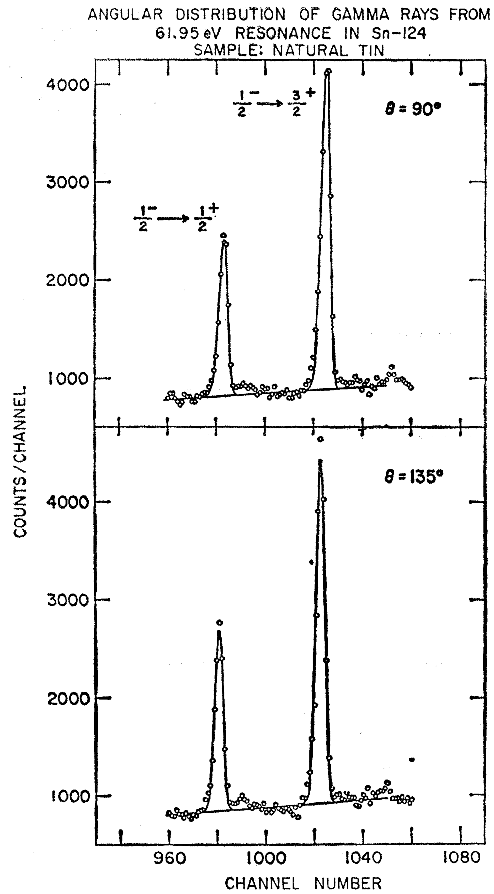

FIG. 13. The angular distribution of γ rays from capture in the 62-eV resonance in Sn^{124} to the $\frac{3}{2}^+$ ground state and $\frac{1}{2}^+$ first excited state in Sn^{125}.

The measured ratio of peak ratios is 1.07±0.03. In the present experiment, a natural tin sample was used, but as demonstrated in the section on Sn^{118} above, multiple scattering effects could not mask a presumed asymmetric distribution.

The energies and intensities of the observed γ-ray transitions are included in Table V. In Sn^{124} we observe primary transitions from capture in the $\frac{1}{2}^-$ resonance at 62 eV, and if we assume these to be electric dipole, the final-state spins would be $\frac{1}{2}^+$ or $\frac{3}{2}^+$. We observe a level at 931 keV which agrees quite well with the value of 936 keV obtained from the (d,p) data.[3] We also see a level at 1075 keV not seen in the (d,p) data. Sorensen's calculations,[21] however, give a level with a spin of $\frac{5}{2}$ at 1.07 MeV. The energy-level diagram obtained in this work is shown in Fig. 14.

SUMMARY

The neutron binding energies for Sn^{118} (9328±5 keV), Sn^{119} (6484±3 keV), Sn^{121} (6176±5 keV), and Sn^{125} (5727±5 keV) measured in the present experiment may be compared to the mass spectroscopic results of

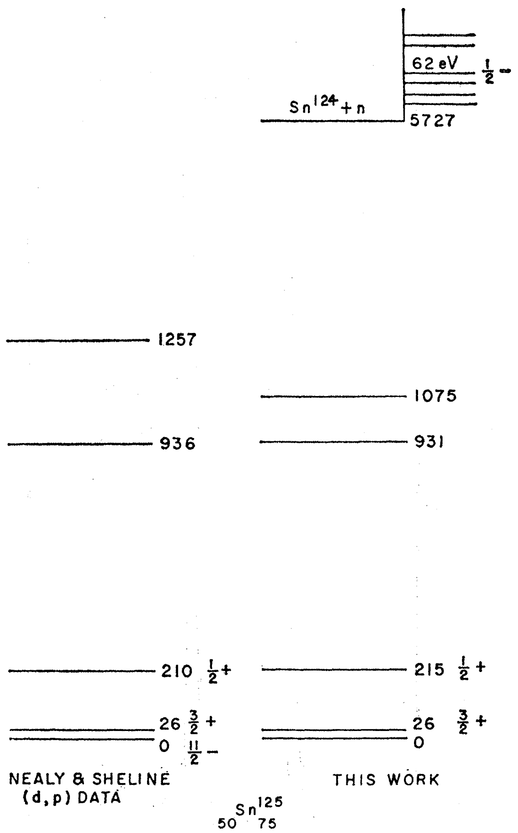

FIG. 14. The energy-level diagram of Sn^{125}. The work of Nealy and Sheline is shown for comparison.

Damerow, Ries, and Johnson.[24] They measure the following: Sn^{118} (9322±14 keV), Sn^{119} (6491±9 keV), Sn^{121} (6159±13 keV), and Sn^{125} (5744±15 keV). The agreement is within experimental errors and constitutes an independent check of our energy scale. Recoil corrections for the Q value of the (n,γ) reaction are 0.5 keV or less and have not been applied.

The capture γ-ray spectra for resonances in the tin isotopes show strong $E1$ and $M1$ transitions. The $E1$ strengths predicted by the single-particle estimates are given by the relationship obtained from the review article of Bartholomew.[25]

$$(\Gamma_{\gamma i})_{E1}=0.179E^3D\,,$$

where D is the level spacing in MeV near the capturing state, for levels of the same spin and parity, and E is the γ-ray energy in MeV. For the isotopes Sn^{124} and Sn^{118}, where enough electric-dipole γ rays are seen to permit a meaningful comparison, the measured average widths are a factor of 2 to 3 larger than the single-particle estimates, which are approximately 0.009 and 0.004 eV, respectively. This agreement is reasonable in view of the approximate nature of the calculation and the probability of missing small transitions experimentally, thus producing a sample mean biased toward larger values. On the other hand, extremely strong $M1$ transitions are observed for the 8.095- and 9.328-MeV transition of the Sn^{117} resonance at 39 eV and the 6.461-MeV transition of the Sn^{118} resonance at 359 eV. These are 500, 11, and 370 times larger than the single-particle estimates. These large values are extremely improbable if viewed as fluctuations in the Porter-Thomas distribution of partial radiation widths, and provide further evidence of the giant $M1$ resonance proposed by Bergqvist.

Radiation from P-wave neutron capture is expected to be asymmetric in cases where the capturing level has spin $\geq\frac{3}{2}$. This asymmetry can be used to establish spin values for final-state spins as we have demonstrated in Sn^{118}. In favorable cases, for $J\geq\frac{3}{2}$ resonances, the observation of an asymmetry can also indicate the parity of the initial state, thus identifying P-wave resonances. The lack of asymmetry, conversely, can be used to determine that the spin of the capturing state is less than $\frac{3}{2}$ as in the case of the $\frac{1}{2}^+$ resonances observed in Sn^{120} and Sn^{124}.

ACKNOWLEDGMENTS

The authors wish to acknowledge the help of J. A. Harvey and of C. S. Wu in obtaining the enriched samples used in the present work. They also thank Miss Judy Harte for programming assistance.

[24] R. A. Damerow, R. R. Ries, and W. H. Johnson, Jr., Phys. Rev. **132**, 1673 (1963).

[25] G. A. Bartholomew, Ann. Rev. Nucl. Sci. **11**, 259 (1961).