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Neutron-capture gamma rays from ^{116}Sn and ^{122}Sn and the valence model*

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Capture γ-ray intensities from resonances of ^{116}Sn and ^{122}Sn have been measured. The results lead to binding energies of 6944 ± 2.0 keV for the product nucleus ^{117}Sn and 5948 ± 3.0 keV for the product nucleus ^{123}Sn. Resonance spins were determined: in ^{116}Sn, $E_0 = 147.9$ and $E_0 = 632$ eV resonances are $J = 3/2,\ l = 1$; in ^{122}Sn, $E_0 = 106.9$ eV resonance is $J = 3/2,\ l = 1$; $E_0 = 259.9$ eV resonance is $J = 1/2,\ l = 1$. The measured partial widths are compared to single-particle transition model predictions. The model fails to predict the observed widths.

[NUCLEAR REACTIONS Resonance capture in ^{116}Sn, ^{122}Sn, partial widths, spins, parities, angular distributions, valence model predictions.]

I. INTRODUCTION

This work describes investigation of the neutron capture γ rays from the low-lying resonances of ^{116}Sn and ^{122}Sn. These experiments were done in continuation of the work reported earlier on neutron capture γ spectra in the tin isotopes.[1] It is well known that several of the tin isotopes have prominent p-wave resonances in the few eV to a few hundred eV region. In order to make quantitative comparisons to theory, it has been necessary to measure resonance spins and to establish absolute photon intensities. In those p-wave resonances for which $J_\lambda \geq \frac{3}{2}$, the γ rays from neutron capture are expected to show a nonisotropic angular distribution. Capture γ-ray measurements at several angles to the beam can be used to determine the resonance spins. Finally, photon intensities were determined by calibration against a known line in $^{195}\text{Pt}(n,\gamma)^{196}\text{Pt}$. It is of interest to compare the measured partial capture widths of some of the prominent γ transitions in these resonances with predictions of the valency or single particle transition model[2] which has been successful for accounting for p-wave capture around $A = 90$. The results of such a comparison are given.

II. EXPERIMENTAL DETAILS

The data were obtained at the 48.8 m station of the fast chopper at the Brookhaven high-flux beam reactor. The details of this experimental setup and the two parameter data acquisition system for collecting information on the neutron time of flight and the γ-ray pulse height distribution have been described earlier.[1] The chopper speed for these runs was 15 000 rpm and the time-of-flight channels were 1 μsec wide. The data were collected with a 50 cm^3 Ge(Li) detector and the pulse height resolution was 8 keV (full width at half maximum) at 7.724 MeV. Both the samples of ^{116}Sn and ^{122}Sn were in the form of tin oxide and the oxide was packed in a thin-walled aluminum container. The ^{116}Sn sample had a net weight of 101.94 g with 95.74% enrichment in ^{116}Sn. Other isotopic impurities in this sample were ^{117}Sn (1.02%), ^{118}Sn (1.49%), ^{119}Sn (0.32%), ^{120}Sn (1.06%). Similarly the ^{122}Sn sample had a net weight of 73.52 g and was enriched to 91.24% in ^{122}Sn; impurities consisted of ^{116}Sn (0.86%), ^{118}Sn (1.64%), ^{120}Sn (3.91%), and ^{124}Sn (1.18%). In addition, data were taken with a sample of natural tin $75 \times 85 \times 12$ mm and weighing 585.4 g along with a thin foil of platinum 0.127 mm thick and weighing 17.247 g. This was done for intercalibration of the γ transitions of the tin isotopes by comparing them with the 7921 keV γ transition in the 11.9 eV resonance of platinum. This sample was mounted in a rectangular hole in a plate of iron and the whole assembly positioned in the neutron beam. By comparing the intensity of the intense iron capture γ ray lines as a function of the neutron time of flight it was possible to obtain relative neutron fluxes at the energies of the different resonances in the tin isotopes and the 11.9 eV resonance in platinum. Details of this analysis will be described in a later section.

III. DESCRIPTION OF THE DATA AND ANALYSIS

The time-of-flight spectrum obtained with the ^{116}Sn sample is shown in Fig. 1. The first three resonances in ^{116}Sn at 111.2, 147.9, and 632.0 eV are shown clearly resolved. It is known from the work of Fuketa, Khan, and Harvey[3] that the first is an s-wave resonance, as their transmission data clearly show the interference between resonance and potential scattering. The remaining two resonances have been identified to be p-wave resonances with a spin of $\frac{3}{2}$ from the present work. In addition, one also observes the 38.8 eV s-wave resonance of a ^{117}Sn. Since this impurity resonance

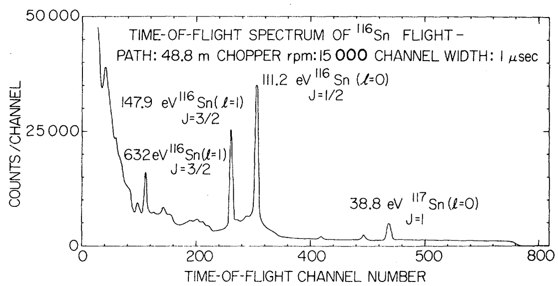

FIG. 1. Time-of-flight spectrum from the ^{116}Sn sample.

is clearly isolated and is superposed on a flat background, it was used to normalize the angular distributions.

It is possible to obtain γ rays originating from a a particular resonance by imposing corresponding limits on the time-of-flight parameter and selecting the data from the event-mode-recorded magnetic tape. Such scans indicate that the 111.2, 147.9, and 632 eV resonances each show one prominent γ ray. This occurs at 6784 ± 2.0 keV for the first and third resonances and at 6944 ± 2.0 keV for the second resonance. These energies are based on the Al capture line at 7723.8 keV and the iron doublet at 7645.6 and 7631.5 keV. The binding energy of the captured neutron in ^{116}Sn is known to be 6942.5 ± 2.9 keV from the mass tables of Wapstra and Gove.[4] Hence the 6944 keV γ ray corresponds to a transition to the $s_{1/2^+}$ ground state of ^{117}Sn and the 6784 keV γ ray to the first excited $d_{3/2^+}$ state at 160 keV.[5] The measured γ-ray energy of the ground state transition is in good agreement with the value given in the mass tables. If we assume that both the γ rays are electric dipole transitions and if the initial state corresponds to a p-wave resonance with a spin of $\frac{3}{2}$, the angular distribution of these γ rays will be anisotropic.[1] Because of the simple $a+b\sin^2\theta$ type of angular distribution expected in this case (where θ is the angle between the direction of the neutron beam and the direction of observation of the γ ray), two measurements of the angular distribution at 90° and 135° to the direction of the neutron beam suffice to fix the spin. The intensity of the observed γ ray in each resonance in the two positions were normalized with respect to the total area under the 38.8 eV s-wave resonance in the ^{117}Sn impurity. Since it is an s-wave resonance[3] the angular distribution of the γ rays from it is isotropic. The results of such a normalization are shown in Fig. 2. In this figure the γ spectra in the 147.9 and 632 eV resonances are shown at $\theta = 90°$ and 135° after normalization and slightly displaced from one another. The intensity ratio of

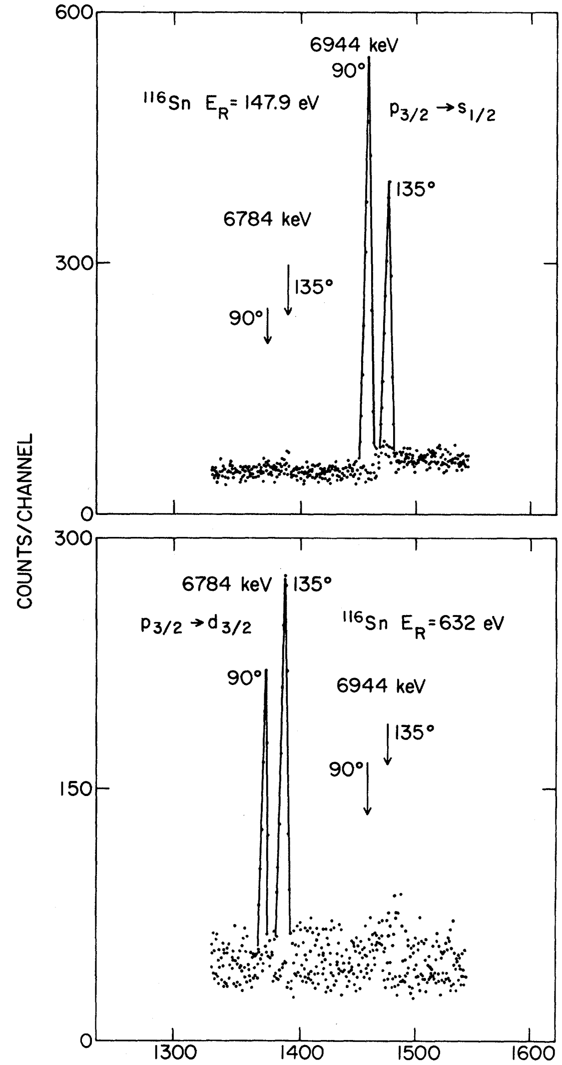

FIG. 2. Angular dependence of the 6944 and 6784 keV γ rays depopulating the 147.9 eV (top) and 632 eV resonances. The spectra at 90° and 135° are shown displaced to clarify the differences in intensities at these angles.

the $\frac{3}{2} \rightarrow \frac{1}{2}$ transition in the 90° and 135° positions is given by theory to be 10/7, whereas for the $\frac{3}{2} \rightarrow \frac{3}{2}$ transition it is 8/11. The measured intensity ratios are found to 1.28 ± 0.06 for the 6944 keV γ ray from the 147.9 eV resonance and 0.71 ± 0.04 for the 6784 keV γ transition from the 632.0 eV resonance in reasonable agreement with theory. Hence, both these resonances in ^{116}Sn have been assigned to be p-wave resonances with a spin of $\frac{3}{2}$.

The time-of-flight spectrum obtained with the ^{122}Sn sample is shown in Fig. 3. Beginning at the low-energy end, the first resonance at 38.8 eV is an s-wave resonance due to the ^{117}Sn impurity.

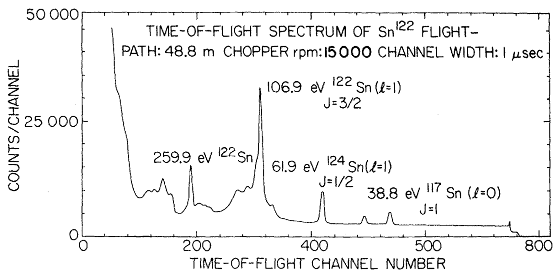

FIG. 3. Time-of-flight spectrum for the ^{122}Sn sample.

The next one (unlabeled) at 45.75 eV is due to ^{118}Sn. One observes the 61.9 eV p-wave resonance with a spin of $\frac{1}{2}$ due to the ^{124}Sn in the sample. In addition, the 106.9 and 259.9 eV resonances due to ^{122}Sn are clearly seen. A scan of the capture γ-ray spectra due to the 106.9 eV resonance at the two positions making an angle of 90° and 135° to the incident beam direction are shown in Fig. 4. Two prominent γ rays are observed at 5924 ± 2.0 and 5798 ± 2.0 keV. These have been assigned to be

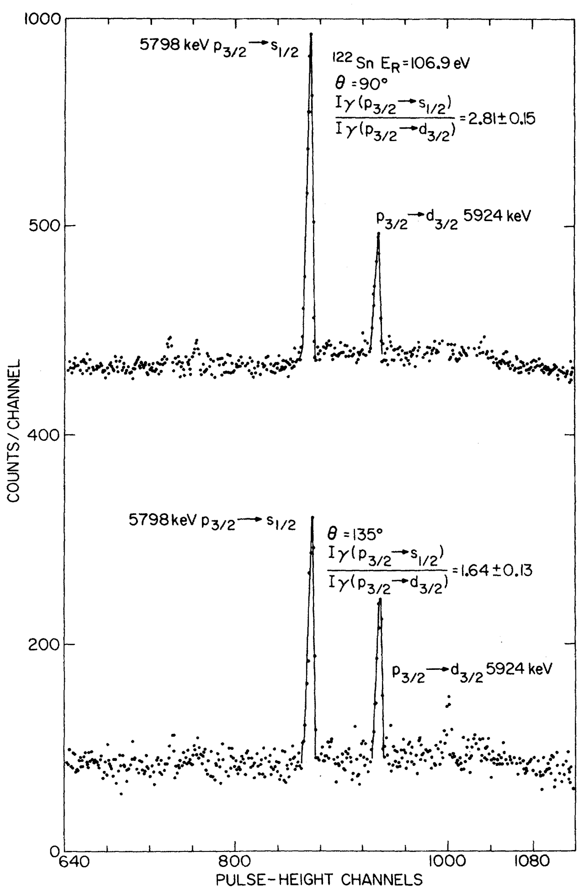

FIG. 4. Spectra from the 106.9 eV resonance in ^{122}Sn at 90° (top) and 135° (bottom). The angle dependent ratios indicate that this resonance has $J=\frac{3}{2}$ and $l=1$.

transitions to the spin $\frac{3}{2}^+$ first excited state of ^{123}Sn at 24 ± 2.0 keV and to the spin $\frac{1}{2}^*$ second excited state at 150 keV.[5] Since the ground state of ^{123}Sn has a spin-parity assignment of $\frac{11}{2}^-$, one does not expect to observe a direct high-energy transition to it. Our data would give a value of 5948 ± 3.0 keV for the binding energy of the captured neutron in ^{123}Sn. This agrees quite well with 5945 ± 6 keV given in the compilation of Gove and Wapstra and 5945.2 ± 2.9 keV reported by Slaughter and Raman.[17] Since both the transitions to the $\frac{1}{2}^+$ and $\frac{3}{2}^+$ final states in ^{123}Sn are observed, the intensity ratios of these two γ rays at $\theta = 90°$ and 135° can be compared without the need for any other intensity normalization. Such a comparison shows that $I_\gamma(5798\ \text{keV})/I_\gamma(5924\ \text{keV}) = 2.81 \pm 0.15$ in the $\theta = 90°$ position and the same ratio is 1.64 ± 0.13 in the $\theta = 135°$ position. The ratio of these ratios is 1.72 ± 0.16. If the neutron resonance is a p-wave resonance with a spin of $\frac{3}{2}$, the theoretical value of this ratio of the intensity ratios for the two γ rays is 1.96. Hence, a spin of $\frac{3}{2}$ may be assigned to this resonance. A scan of the 259.9 eV resonance shows only the γ ray at 5798 keV. Therefore, the two intense γ rays due to capture in the 61.9 eV resonance of ^{124}Sn were used to normalize the intensity of the ^{122}Sn γ ray. The ^{124}Sn γ rays correspond to transitions to the $\frac{3}{2}^+$ ground state and the $\frac{1}{2}^+$ first excited state in ^{125}Sn. It has also been shown[1,6] that the angular distribution of the γ rays is indeed isotropic. Therefore, their intensity could be used to normalize the 5798 keV γ ray in the 259.9 eV resonance. Such a comparison indicates that the 5798 keV γ ray in the $\theta = 90°$ and 135° position gives an intensity ratio of $1.03 \pm .06$ indicating an isotropic angular distribution. Therefore, the 259.9 eV resonance in ^{122}Sn has a spin of $\frac{1}{2}$ if it is indeed a p-wave resonance, as is indicated by the size of the neutron width.

In addition to the angular distribution of the observed γ rays, their absolute intensities were also measured in terms of the 7921 keV ground state transition in the 11.9 eV resonance of ^{195}Pt. The intensity of the γ ray was determined to be 0.078 ± 0.005 γ rays per neutron capture by Wasson[7] by comparison with the capture γ rays in the 4.9 eV resonance of gold. The intensities of the γ rays from the 4.9 eV resonance and thermal capture in gold are due to Kane,[8] whose thermal intensities are in good agreement with the recent data of Loper, Thomas, and Bollinger.[9] This represents a 25% increase in the intensity of the platinum γ ray as compared to the value one would have obtained by using the gold data of Groshev, Demidov, and Shadiev.[10]

For an intercomparison of tin and platinum γ rays, a separate experiment using a natural tin

TABLE I. Resonance parameters used in calibration of widths in this experiment.

Target	E_0 (eV)	J	Γ_n (meV)	Γ_γ (meV)	Source
^{195}Pt	11.9± 0.1	1	10.1 ± 0.4	107± 8	BNL-325 (Ref. 15)
^{116}Sn	147.9± 0.3	$\frac{3}{2}$	1.6 ± 0.2	110	Fuketa **et. al.** (Ref. 3)
^{116}Sn	148	$\frac{3}{2}$	1.85 ± 0.1	33± 15	Julien **et. al.** (Ref. 16)
^{116}Sn	632	$\frac{3}{2}$	15 ± 3	110	Fuketa **et. al.** (Ref. 3)
^{122}Sn	106.9	$\frac{3}{2}$	0.385± 0.04	110	Fuketa **et. al.** (Ref. 3)
^{124}Sn	61.95	$\frac{1}{2}$	11 ± 0.6	110	Fuketa **et. al.** (Ref. 3)

sample and a platinum foil was run with a 20 cm^3 Ge(Li) detector. The dimensions of these samples have been given earlier. The platinum foil was mounted on the tin sample and both of them inserted in a rectangular hole in an iron plate. The data obtained with this sample were analyzed to determine the intensities of the iron capture doublet as a function of the neutron time of flight. A plot of these intensities thus obtained could be used to determine the relative neutron flux at different neutron energies. The area A_γ under a particular γ-ray peak is equal to the product of $\epsilon_\gamma I_\gamma I_n$, where ϵ_γ is the efficiency of the Ge(Li) detector for the γ ray, I_γ its absolute intensity in γ rays per neutron capture and the I_n the total number of neutrons absorbed in the sample at a particular resonance. The last quantity could be determined from the known resonance parameters. Using standard methods,[11] wing corrections were applied to the results of the time-of-flight scans with finite limits. Corrections were also applied for the multiple scattering of neutrons in the sample using the Monte Carlo code SCAT-2 by Friedes.[12] This intercalibration of the γ intensities obviously depends very much on the resonance parameters assumed in the analysis. They are listed in Table I with their sources. The resonance spins given for the ^{116}Sn and ^{122}Sn resonances were determined in this work and Γ_n in the table have been extracted from the $g\Gamma_n$ given by the different sources. The intensity of the 6944 keV γ ray in the 147.9 eV resonance was determined in terms of the 7921 keV γ ray in ^{195}Pt; and the 6784 keV γ ray in the 632.0 eV resonance was calibrated in terms of the 6944 keV γ ray in the 147.9 eV resonance. The absolute intensities thus determined could be converted to partial widths if the total capture widths of resonances are known. These are given in Table II as determined by using the parameters of Fuketa *et al.*[3] or Julien *et al.*[16] In the last column of this table are shown the width of these transitions as calculated according to the single particle model of Lane and Lynn. In these calculations the radial integrals were taken from the tabulation by Lynn[13] and the final state spectroscopic factors are from the work of Schneid, Prakash, and Cohen.[14] These calculated widths have been corrected for the anisotropic intensity distribution of these γ rays and the fact that the observed widths were determined at 90° to the direction of the neutron beam. The agreement between the calculations and the observed widths could be considered as good even if they differ by a factor of 2–3 considering the complex nature of the phenomenon and the simple model involved. Thus the agreement is apparently good for the 147.9 eV resonance, but there is complete disagreement between the observed data and the calculations for the 632.0 eV resonance even though the reduced neutron widths of these two resonances are the same.

The widths of the two intense transitions in the 106.9 eV resonance of ^{122}Sn could be determined in terms of the 61.95 eV resonance of the ^{124}Sn impurity in it. These two γ rays seem to account for virtually all of the capture width and are much larger than the widths calculated using the valency model. The observed widths are 36 and 103 meV for the 5924 and 5798 keV γ rays, respectively.

TABLE II. Comparison of observed widths with valence model calculations.

Target	E_0 (eV)	E_γ (keV)	Observed partial width (meV) [a]	Observed partial width (meV) [b]	Calculated partial width (meV)
^{116}Sn	147.9	6944	47	14	13
		6784	0	0	0.6
^{116}Sn	632	6944	0	0	14
		6784	30	9	0.7
^{122}Sn	106.9	5924	36	···	0.1
		5798	103	···	1.5

[a] Based on Fuketa **et. al.** resonance parameters for the 147.9 eV resonance.

[b] Based on Julien **et. al.** resonance parameters for the 147.9 eV resonance.

They are subject to large errors because of the normalization and errors from the resonance parameters.

The valence model has been able to account for the correlation between radiative and neutron widths which has been quite generally observed in the mass region near the position of the $3p$ size resonance, for $A \approx 90$. The model has been quantitatively successful in predicting the absolute intensities of ground state transitions in this region. The present experiment, however, shows that the validity of the model does not extend to the region outside the giant resonance region.

It appears, in view of the discrepancy between experiment and prediction for 632 eV resonance in ^{116}Sn and in the 106.9 eV resonances in ^{122}Sn, that the valence model is unable to give a good account of the transition strengths in p-wave resonances in Sn.

This is not surprising in view of the fact that the single particle component in the capturing state must be very small in this mass region. All the tin isotopes exhibit rather small strength functions for s- and p-wave resonances. Clearly the strong transitions we observe in these isotopes are not explicable as single-particle transitions.

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