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Inelastic proton scattering and particle-vibration coupling in ^{115}Sn, ^{117}Sn, and ^{119}Sn

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Inelastic proton scattering on the stable odd-*A* tin isotopes ^{115}Sn, ^{117}Sn, and ^{119}Sn has been carried out at 18 MeV on isotope separated targets. Angular distributions were not obtained but, nevertheless, the individual spectra reveal a large number of strongly populated states in the energy region of the known octupole strength of the even-*A* nuclei, permitting several new (tentative) $5/2^-, 7/2^-$ spin assignments. General comparisons are made of the observed relative strengths with those obtained from other reactions populating the same final states, revealing a complex nuclear structure in the odd-*A* tins which is not understood theoretically.

[NUCLEAR REACTIONS, NUCLEAR STRUCTURE ^{115}Sn, ^{117}Sn, ^{119}Sn (p,p'); isotope separated targets; 18 MeV, 15 keV resolution; relative intensities only; new $\frac{5}{2}^-$, $\frac{7}{2}^-$ spin assignments.]

I. INTRODUCTION

The nuclear structure of both the even and odd tin isotopes has been studied extensively[1]; in particular, by inelastic scattering[2-7] and one[8-13] and two[14,15] neutron transfer reactions. Much of this interest can be traced to the availability of extensive model calculations based on the BCS theory of nuclear pairing.[1,8,16-18] It is worthwhile to compare cross sections to the same final states populated in the largely noncoherent single-neutron transfer reaction with those in the coherent inelastic scattering and two-neutron transfer processes; the (p,p') reaction samples predominantly the particle-hole nature of the residual force (quadrupole or octupole transitions) involving both proton and neutron excitations while the (p,t) reaction probes the particle-particle nature of the force (pairing excitations) involving only neutron degrees of freedom. Indeed, in the even tin nuclei, the levels most strongly populated in both (p,t) (Refs. 5 and 14) and (p,p') (Refs. 2, 3, 5, and 7) are the lowest-lying collective states of spins 2^+, 3^-, and 4^+, particularly the 2^+ level in the case of the (p,t) reaction. (The predominantly particle-hole 3^- levels are strongly excited in inelastic scattering.) It is an interesting question then as to what happens to this core 2^+ and 3^- (and 4^+, etc.) strength in the neighboring odd-*A* tin nuclei. Such strength should be found in three quasiparticle (qp) states corresponding to the particle-vibration coupling of the even core phonon strength with the lowest-lying 1 qp states in the odd nuclei; in particular, the excitation of $\frac{3}{2}^+$, $\frac{5}{2}^+$ and $\frac{5}{2}^-$, $\frac{7}{2}^-$ levels due to the coupling $(\frac{1}{2}^+\times 2^+)$ and $(\frac{1}{2}^+\times 3^-)$ is expected in both (p,t) and (p,p'). Previous papers have demonstrated that the Pauli exclusion principle in the odd tin nuclei considerably "blocks" the core 2^+ strength in the (p,t) reaction[14] but has only a small effect on the (t,p) reaction.[19] This effect should be minimal, however, in the (p,p') reaction. The expected 3^- (or 4^+) strength was not seen in the (p,t) reaction (at 20 MeV), although in this case there should be relatively little blocking effect. The (t,p) results found 85% of the expected octupole strength, supporting this concept.

II. EXPERIMENTAL RESULTS

The present report describes measurements of the (p,p') reaction on ^{115}Sn, ^{117}Sn, and ^{119}Sn at 18 MeV bombarding energy. The targets used were prepared by isotope *separation* with implantation into carbon backings at the Niels Bohr Institute, Copenhagen. The experiments were performed with the FN tandem accelerator of the Niels Bohr Institute at Risø, employing photographic plates in a magnetic (Elbek) spectrometer. The availability of isotope separated targets ensures an unambiguous identification of lines belonging to the target of interest, which is not always guaranteed in the

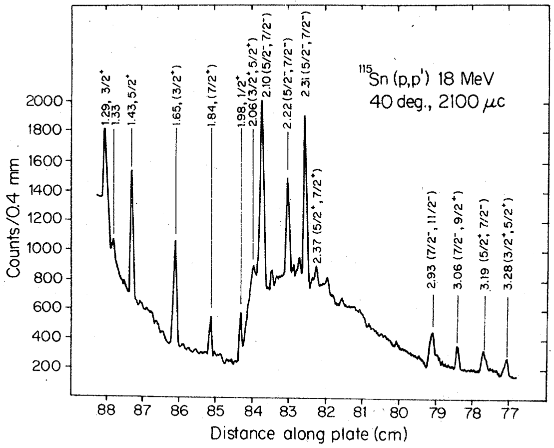

FIG. 1. Energy spectrum at 40 deg (lab) expressed as the distance along the photographic plate for 18 MeV (p,p') on ^{115}Sn. The target was prepared by isotopic separation, implanted into carbon. The peaks are plotted as a sum of counts in 0.4 mm steps but were scanned in 0.2 mm steps. Counts are relative only and cannot be compared between different spectra. The energy resolution is typically 15 keV. The background at low excitation energies is from ^{12}C impurity peaks. The rise in cross section near 2.3 MeV is real and discussed in the text.

case of an evaporated target, particularly for the weaker transitions. Unfortunately, the targets contained a number of light impurities and were very nonuniform so that it was not possible to obtain reliable angular distributions; attempts to normalize the present data to the 2^+ (and 3^-) cross sections measured by (p,p') at 16 MeV (Ref. 7) proved to be unreliable. Consequently, only excitation energies and relative strengths at a fixed angle for a given target nucleus are reported herein. These data, however, are of sufficient quality to reveal the presence of several previously unknown and strongly excited inelastic transitions in the neighborhood of the excitation energy of the octupole states (~2.3 MeV) in the even tins. Indeed, there appears to be no high resolution inelastic data available on separated isotope odd tin targets in the energy region of interest in this paper.

Representative energy spectra are given at forward angles in Figs. 1–3 and at backward angles in Figs. 4–6 for ^{115}Sn, ^{117}Sn, and ^{119}Sn, respectively. The excitation energies given are accurate to ±10 keV for the levels below 2 MeV and ±15–20 keV for the levels above 2 MeV, as the energy resolution was typically 15–20 keV. The broad peaks shown in the spectra are due to elastic scattering from ^{16}O and ^{12}C, although these peaks are not plotted in every spectra. A number of levels near 2.3 MeV in excitation energy are strongly populated in all spectra as shown in Figs. 1–6 and these were generally not known previously. In ^{119}Sn, the ^{12}C elastic peak obscures many of these states at back angles.

The present data are given in Tables I, II, and III for $A = 115$, 117, and 119, respectively, where they are compared with the results of other reactions presumably populating the same final states. The generally large errors given with the quoted peak areas reflect uncertainties in the level of background subtraction which is estimated at ±20%.

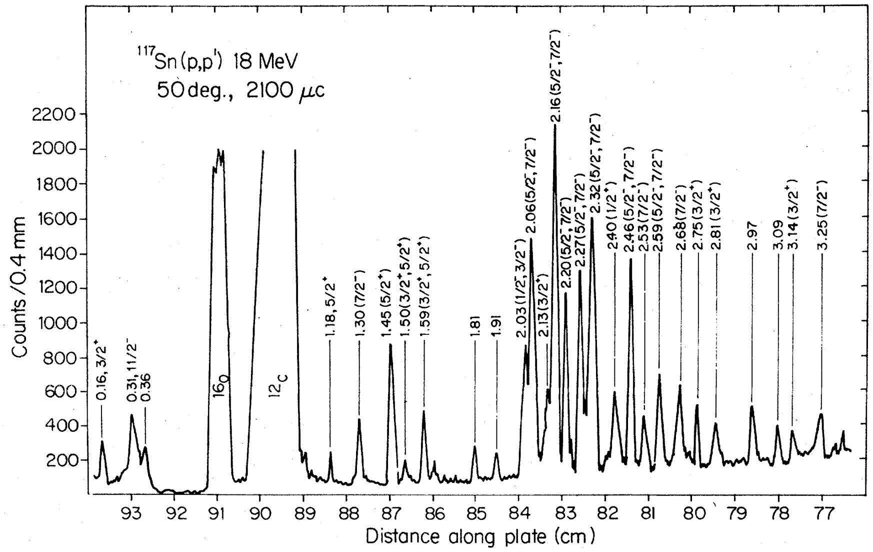

FIG. 2. Energy spectrum for 18 MeV (p,p') on ^{117}Sn at 50 deg (lab). See caption to Fig. 1.

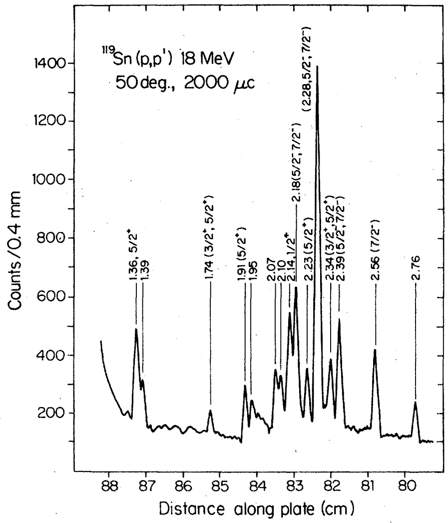

FIG. 3. Energy spectrum for 18 MeV (p,p') on ^{119}Sn at 50 deg (lab). See caption to Fig. 1.

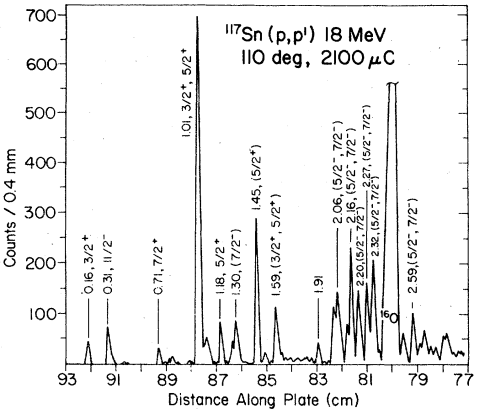

FIG. 5. Energy spectrum for 18 MeV (p,p') on ^{117}Sn at 110 deg. See caption to Fig. 1.

The spectroscopic assignments follow mainly from single-neutron transfer data[8-11] and, for the levels of low excitation (≤2 MeV), from γ-ray studies.[20-23] The levels tentatively identified as $(\frac{5}{2}^-, \frac{7}{2}^-)$ are mainly from the present study applying the supposition that states with a parentage based on the 3^- core $(\frac{1}{2}^+ \times 3^-)$ of the even tins should be strongly excited in (p,p') on the odd tins; in some cases, these assignments agree with those from other studies.[5,6,13]

It is interesting to note that while the energy spectra of ^{117}Sn and ^{119}Sn are similar, that of ^{115}Sn differs in two respects: (1) In the region of excitation energy from 2 MeV, the density of (sharp) states seen in $A = 115$ is about a factor of 2 less than observed in $A = 117$ and $A = 119$. The same qualitative result has been observed in a comparative (p,t) study[14] and, similarly, the level density seen in the $^{115}\mathrm{Sn}(p,d)^{114}\mathrm{Sn}$ reaction is markedly reduced compared to that on the other odd tin targets.[8] These results may be identified with the extra stability of the ^{114}Sn core (as opposed to ^{116}Sn) due to the $g\frac{7}{2}\text{-}d\frac{5}{2}$ subshell closure, an effect which manifests itself in the odd-even mass difference and in the strong excited 0^+ state seen in the $^{112}\mathrm{Sn}(t,p)^{114}\mathrm{Sn}$ reaction[15] and one that is difficult to reproduce theoretically.[1,16] (2) The "background" spectrum in the case of ^{115}Sn in the region of 2 MeV excitation (at 40 deg) looks like an evaporation spectrum, which would certainly be curious in view of the mean c.m. energy of ~13 MeV. The competition between "compound" and "direct" effects in (p,p') on the tin nuclei at bombarding energies ~18 MeV has been discussed elsewhere.[24,25] The energy region corresponding to the "collective" 2^+ and 3^- levels (≤3 MeV) of interest in this experiment is considered, however, to be overwhelmingly a direct process.

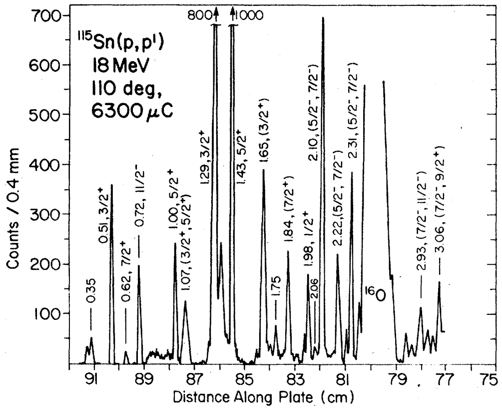

FIG. 4. Energy spectrum for 18 MeV (p,p') on ^{115}Sn at 110 deg. See caption to Fig. 1.

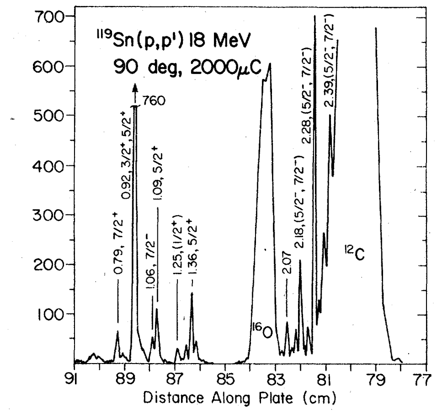

FIG. 6. Energy spectrum for 18 MeV (p,p') on ^{119}Sn at 90 deg. See caption to Fig. 1.

TABLE I. Levels in ^{115}Sn.

Exc. (MeV)[a]	Counts(40°)[a]	Exc. (MeV)[d]	j^{π}[d]	$S_j(d,p)$[e]	$S_j(p,d)$[f]	$S_j(d,t)$[g]	$\sigma_T(p,t)$[h]
0.51	550 ± 150[b]	0.50	$\frac{3}{2}^+$	0.62	1.3	0.88	220
0.62	100 ± 50[b]	0.61	$\frac{7}{2}^+$	0.19	6.0	6.3	100
0.72	850 ± 150[b]	0.71	$\frac{11}{2}^-$	0.77	3.6	2.2	50
1.00	430 ± 100[b]	0.99	$\frac{5}{2}^+$	0.12	6.0	4.0	420
1.07	150 ± 50[b]	1.08	$(\frac{3}{2}^+, \frac{5}{2}^+)$				
1.29	900 ± 300	1.28	$\frac{3}{2}^+$	0.029	0.14	0.16	50
1.33	450 ± 150[b]						
1.43	1650 ± 400	1.42	$\frac{5}{2}^+$		0.20	0.21	210
1.65	1150 ± 300	1.64	$(\frac{3}{2}^+)$	0.044	0.17	0.16	70
1.84	550 ± 180	1.85	$(\frac{7}{2}^+)$		~0.2	0.35	100
1.98	850 ± 230	1.97	$\frac{1}{2}^+$	0.082	0.20	0.12	130
2.06	200 ± 60[b]	2.07	$(\frac{3}{2}^+, \frac{5}{2}^+)$	$(\frac{1}{2}^+, 0.45)$[j]	~0.1		
2.10	4200 ± 800		$(\frac{5}{2}^-, \frac{7}{2}^-)$[i]				
2.22	1400 ± 350	$(2.21, \frac{3}{2}^+)$	$(\frac{5}{2}^-, \frac{7}{2}^-)$[i]		$(\frac{3}{2}^+, \sim 0.1)$[j]	$(\frac{3}{2}^+, 0.21)$[j]	
2.31	2500 ± 500	2.30	$(\frac{5}{2}^-, \frac{7}{2}^-)$[i]			$(\frac{5}{2}^-, 0.1)$	
2.37	500 ± 200[c]	2.36	$(\frac{5}{2}^+, \frac{7}{2}^+)$[j]			$(\frac{7}{2}^+, 0.35)$	
2.93	600 ± 200	2.94	$(\frac{7}{2}^-, \frac{11}{2}^-)$[j]	$(\frac{7}{2}^-, 0.64)$			
3.06	350 ± 100	3.06	$(\frac{7}{2}^-, \frac{9}{2}^+)$[j]	$(\frac{7}{2}^-, 0.061)$		$(\frac{9}{2}^+, 0.032)$	
3.19	400 ± 120	3.19	$(\frac{7}{2}^-, \frac{5}{2}^+)$[j]	$(\frac{7}{2}^-, 0.070)$		$(\frac{5}{2}^+, 0.013)$	
3.28	450 ± 140	3.27	$(\frac{3}{2}^+, \frac{5}{2}^+)$				

[a] From present study of 18 MeV (p,p'), Fig. 1. Excitation energies accurate to ±10 keV below 2 MeV and ±(15–20) keV above.

[b] Estimated from systematics at other angles (e.g., Fig. 4).

[c] Close-lying doublet or broad peak.

[d] Average excitation energies and "accepted" j^{π} values from nuclear transfer reactions, augmented by γ decay studies. Uncertain assignments are given in parentheses.

[e] Spectroscopic factors for the (d,p) reaction at 15 MeV, from Schneid *et al.*, Ref. 13.

[f] Spectroscopic factors from the (p,d) reaction at 20 MeV for levels up to 2 MeV, from Fleming (Ref. 8). For higher levels, approximate values obtained from the 30 MeV (p,d) cross sections of Cavanagh *et al.* (Ref. 12), normalized to those of Fleming (Ref. 8).

[g] Spectroscopic factors for the (d,t) reaction at 26 and 52 MeV, from Berrier-Ronsin *et al.* (Ref. 9); average values from both energies are given for the levels below 2 MeV.

[h] Summed 20 MeV (p,t) cross sections (in arbitrary units) from 10–50 deg, from Fleming *et al.*, Ref. 14.

[i] Enhanced population in the present (p,p') study to states with excitation energies in the region of the 3^- level in the even core (2.3 MeV), strongly suggestive of the presence of $(\frac{5}{2}^-, \frac{7}{2}^-)$ levels.

[j] Inconsistent spin assignments from different studies for levels at apparently the same excitation energies.

III. DISCUSSION

There are several important features which emerge from the comparisons presented in Tables I–III. As indicated above, the nuclear structure of levels in the odd-A tins is expected to be predominantly 1 qp for the lowest-lying levels of spin j, with particle-vibration (pv) coupling states of the type $(j \times J)$, where J is the corresponding phonon state (predominantly 2 qp) of the even tin core, becoming increasingly important above ~1 MeV.[16-18] The lowest-lying 1 qp states have spins of $\frac{1}{2}^+$ (g.s.), $\frac{3}{2}^+$, $\frac{7}{2}^+$, and $\frac{11}{2}^-$ due to the "valence" neutron shells $3s\frac{1}{2}$, $2d\frac{3}{2}$, $1g\frac{7}{2}$, and $1h\frac{11}{2}$. The $2d\frac{5}{2}$ shell is mostly filled and only in ^{115}Sn is the first $\frac{5}{2}^+$ level predominantly 1 qp.[8,17,18] These 1 qp levels are generally weakly excited in the present (p,p') study but are seen with relatively large spectroscopic factors in (p,d) and (d,p) studies.[8,13] This is consistent with the occupancies V_j^2 of the shell model orbits involved and is in accord with the expected strong excitation of collective states in (p,p'). It is interesting to note that, of the predominantly 1 qp states, the $\frac{11}{2}^-$ level, identified

TABLE II. Levels in ^{117}Sn.

Exc. (MeV) [a]	Counts (50°) [a]	Exc. (MeV) [d]	j^{π} [d]	$S_j(d,p)$ [e]	$S_j(p,d)$ [f]	$\sigma_T(p,t)$ [g]	$d\sigma(p,p')$ [h]
0.16	530 ± 100	0.16	$\frac{3}{2}^+$	0.66	2.0	110	
0.31	1150 ± 150	0.32	$\frac{11}{2}^-$	0.80	4.4	60	
0.36	600 ± 150 [b]						
0.71	400 ± 150 [c]	0.72	$\frac{7}{2}^+$	0.12	6.2	80	0.26
1.01	10 000 ± 1000 [c]	1.02 [b]	$\frac{3}{2}^+, \frac{5}{2}^+$ [i]	0.063	3.7	280	3.61
1.18	350 ± 90	1.19	$\frac{5}{2}^+$	0.035	2.2	320	1.29
1.30	930 ± 120	1.31	$(\frac{7}{2}^-)$	0.033			
1.45	2060 ± 150	1.46	$\frac{5}{2}^+$	0.024	0.20	220	1.03
1.50	230 ± 80 [b]	1.51	$(\frac{3}{2}^+, \frac{5}{2}^+)$	0.020	0.22		
1.59	1020 ± 130	1.58	$(\frac{3}{2}^+, \frac{5}{2}^+)$	0.006			0.43
1.81	290 ± 90						
1.91	350 ± 110						
2.03	2350 ± 300 [b]	2.01	$(\frac{1}{2}^-, \frac{3}{2}^-)$				
2.06	4300 ± 250 [b]	2.05	$(\frac{5}{2}^-, \frac{7}{2}^-)$ [k]	0.026	$(\frac{1}{2}^+, 0.23)$ [j]		
2.13	1300 ± 200 [b]	2.13	$(\frac{3}{2}^+)$		~0.06		
2.16	6200 ± 300	$(2.15, \frac{3}{2}^+)$ [j]	$(\frac{5}{2}^-, \frac{7}{2}^-)$ [k]	$(\frac{3}{2}^+, 0.005)$ [j]			2.92
2.20	3000 ± 250		$(\frac{5}{2}^-, \frac{7}{2}^-)$ [k]				
2.27	3600 ± 300	2.28	$(\frac{5}{2}^-, \frac{7}{2}^-)$ [k]				3.58
2.32	4600 ± 250	$(2.31, \frac{5}{2}^+)$ [j]	$(\frac{5}{2}^-, \frac{7}{2}^-)$ [k]	$(\frac{5}{2}^+, 0.008)$ [j]	$(\frac{11}{2}^-, \sim 0.4)$ [j]		
2.40	1800 ± 300 [b]	2.39	$(\frac{1}{2}^+)$	0.004			
2.46	3300 ± 300	2.46	$(\frac{5}{2}^-, \frac{7}{2}^-)$ [k]	$(\frac{7}{2}^-, 0.037)$			
2.53	980 ± 280	2.54	$(\frac{7}{2}^-)$	0.018			
2.59	1750 ± 300	2.55	$(\frac{5}{2}, \frac{7}{2}^-)$				1.75
2.68	1300 ± 250	2.68	$(\frac{7}{2}^-)$	0.013			
2.75	600 ± 180	2.77	$(\frac{3}{2}^+)$	0.006			
2.81	480 ± 170 [b]	2.82	$(\frac{3}{2}^+)$		~0.08		
2.97	1000 ± 200						
3.09	520 ± 180						
3.14	500 ± 180	3.11	$(\frac{3}{2}^+)$	0.013			
3.25	750 ± 200 [b]	3.23	$(\frac{7}{2}^-)$	0.12			

[a] From present study, Fig. 2. See also footnote (a), Table I.

[b] Close-lying doublet or broad peak.

[c] Counts estimated from systematics at other angles, e.g., Fig. 5.

[d] See footnote (d), Table I.

[e] Average spectroscopic factors for the (d,p) reaction, from the 15 MeV data of Schneid *et al.* (Ref. 13) and the sub-Coulomb stripping work of Carson and McIntyre, Ref. 11.

[f] See footnote (f), Table I.

[g] See footnote (h), Table I.

[h] Differential cross sections (mb/sr) at 19 deg for 55 MeV (p,p') data, from Yagi *et al.*, Ref. 5.

[i] A close-lying doublet from the γ decay studies of Beery *et al.* (Ref. 23), and Stelson *et al.* (Ref. 22); 1.005 MeV $(\frac{3}{2}^+)$ and 1.020 MeV $(\frac{5}{2}^+)$. The (d,p) and (p,d) reactions preferentially populate the $\frac{5}{2}^+$ (single quasiparticle) level.

[j] See footnote (j), Table I.

[k] See footnote (i), Table I.

only in ^{115}Sn and ^{117}Sn, is the one most strongly excited in (p,p'). In this report, though, the focus is on the collective states of the even-A core, $J = 2^+$ and 3^-. States with a structure $(\frac{1}{2}^+ \times J)$ should be most strongly populated in (p,p') from the $\frac{1}{2}^+$ ground states of the odd-A tins, with (weak-coupling) centroid energies around 1.3 and 2.3 MeV, respectively.

TABLE III. Levels in ^{119}Sn.

Exc. (MeV)[a]	Counts(50°)[a]	Exc. (MeV)[d]	j^{π}[d]	$S_j(d,p)$[e]	$S_j(p,d)$[f]
0.79	750 ± 150[b]	0.79	$\frac{7}{2}^{+}$	0.10	5.3
0.92	8800 ± 800[b]	0.92	$\frac{3}{2}^{+}, \frac{5}{2}^{+}$[g]	0.008	0.50
1.06	600 ± 200[b]	1.06	$\frac{7}{2}^{-}$	0.034	
1.09	1100 ± 150[b]	1.09	$\frac{5}{2}^{+}$	0.11	4.0
1.25	650 ± 150[b]	1.25	$(\frac{1}{2}^{+})$	0.011	
1.31	250 ± 100[b]	1.31	$(\frac{5}{2}^{+} \geqslant \frac{7}{2})$[h]	$(\frac{5}{2}^{+}, 0.003)$	
1.36	1150 ± 280[c]	1.36	$\frac{5}{2}^{+}$	0.018	1.5
1.39	450 ± 150[c]				
1.74	330 ± 120	1.73	$(\frac{3}{2}^{+}, \frac{5}{2}^{+})$	0.009	24
1.91	500 ± 150	1.91	$(\frac{5}{2}^{+})$	0.008	
1.95	250 ± 150[c]	1.95	$(\frac{3}{2}^{+}, \frac{3}{2}^{-})$[h]	$(\frac{3}{2}^{-}, 0.011)$	$(\frac{3}{2}^{+}, 0.10)$
2.07	570 ± 180[c]				
2.10	470 ± 130[c]				
2.14	1270 ± 250[c]	2.14	$\frac{1}{2}^{+}$	0.011	0.08
2.18	1600 ± 300[c]		$(\frac{5}{2}^{-}, \frac{7}{2}^{-})$[i]		
2.23	580 ± 220	2.25	$(\frac{5}{2}^{+})$	0.003	~0.05
2.28	4300 ± 300		$(\frac{5}{2}^{-}, \frac{7}{2}^{-})$[i]		
2.34	720 ± 230	2.35	$(\frac{3}{2}^{+}, \frac{5}{2}^{+})$	0.017	
2.39	1250 ± 250	2.40	$(\frac{5}{2}^{-}, \frac{7}{2}^{-})$[i]		$(\frac{11}{2}^{-}, \sim 0.2)$
2.56	900 ± 200	2.55	$(\frac{3}{2}^{-}, \frac{7}{2}^{-})$[h]	$(\frac{7}{2}^{-}, 0.047)$	
2.76	420 ± 180				

[a] From present study, Fig. 3. See also footnote (a), Table I.

[b] Estimated from systematics at other angles, e.g., Fig. 6.

[c,d] See footnotes Table I.

[e] Up to 2 MeV, numbers shown are an average of the spectroscopic factors measured by Schneid *et al.* at 15 MeV (Ref. 13) and T. Borello-Lewin *et al.* at 17 MeV (Ref. 10); for levels beyond 2 MeV, the values quoted by T. Borello-Lewin *et al.* are used (Ref. 10).

[f] See footnote (f), Table I.

[g] Very close lying doublet measured in the decay studies of G. Ch. Madueңe *et al.* (Ref. 21) and Stelson *et al.* (Ref. 22); 920.4 keV $(\frac{3}{2}^{+})$ and 921.6 keV $(\frac{5}{2}^{+})$. In the (p,d) and (p,d) reaction, it appears that the $\frac{5}{2}^{+}$ level is preferentially excited.

[h] See footnote (j), Table I.

[i] See footnote (i), Table I.

A. The $(\frac{1}{2}^{+} \times 2^{+})\ \frac{3}{2}^{+}$ and $\frac{5}{2}^{+}$ levels

The situation in ^{117}Sn as revealed by Coulomb-excitation studies[22] is as follows: The 1.005 MeV $(\frac{3}{2}^{+})$ level is predominantly $(\frac{1}{2}^{+} \times 2^{+})$ while the 1.020 MeV $(\frac{5}{2}^{+})$ level contains about 65% of this strength and the 1.45 MeV $(\frac{5}{2}^{+})$ level the remaining 35%. In contrast, the 1.18 MeV $(\frac{5}{2}^{+})$ level has a structure which is predominantely $(\frac{3}{2}^{+} \times 2^{+})$ with ~7% of the $(\frac{1}{2}^{+} \times 2^{+})$ strength. These features are in good agreement with the present (p,p') data. The unresolved 1.005, 1.01, and 1.020 states dominate the spectrum (obscured by the ^{16}O and ^{12}C peaks at 50 deg, Fig. 1, but clearly visible at 110 deg, Fig. 5) with the next most strongly populated level in this energy region being the 1.45 MeV $(\frac{5}{2}^{+})$ state. That the dominant structure of these levels is predominantly $(\frac{1}{2}^{+} \times 2^{+})$ is supported by the fact that the 1.18 MeV level, with a parentage mostly $(\frac{3}{2}^{+} \times 2^{+})$ as deduced from the γ decay studies of Ref. 22, is very weakly excited in the present (p,p') study. At the same time, though, it should be noted that the 1.59 MeV $(\frac{3}{2}^{+}, \frac{5}{2}^{+})$ level is also clearly, albeit relatively weakly, excited in the (p,p'). Both (α,α') (Ref. 6) and (p,p') (Ref. 5) studies at higher incident beam energies reveal the same features, although in the latter study at 55 MeV the 1.18 MeV $(\frac{5}{2}^{+})$ level appears to be much more strongly populated than here at 18 MeV (Table II). In ^{117}Sn then, the essence of the pv coupling picture of $(\frac{1}{2}^{+} \times 2^{+})$ is in reasonably good accord with the experimental results from both

(p,p') and Coulomb excitation, giving a centroid energy of about 1.2 MeV. The consistency of this picture, however, becomes more uncertain when nuclear transfer data are also considered. As can be seen from Table II, the (p,d) reaction excites the 1.01 and 1.18 MeV levels with comparable strength. Since the occupancy $V_{3/2}{}^2$ expected in the (p,d) is easily satisfied by the 1 qp strength to the 0.16 MeV level,[8] it is reasonable to surmise that the observed population of the 1.01 MeV doublet in the (p,d) is due primarily to the $\frac{5}{2}^+$ (1 qp) level—an interpretation at variance with the previously discussed (p,p') results. On the other hand, the 1.45 MeV ($\frac{5}{2}^+$) level is weakly populated in the (p,d) and this is in accord with the (p,p') results. The (p,t) reaction, a collective excitation process like (p,p'), excites all three $\frac{5}{2}^+$ levels with comparable strength, a result which has been commented upon earlier.[14]

In summary then, there is no simple overall interpretation which emerges from the (low-lying) $\frac{3}{2}^+$ and $\frac{5}{2}^+$ states in ^{117}Sn. Comparisons of the (p,p'), (p,d), and (p,t) results reveal considerable mixing between 1 qp and 3 qp (and higher) degrees of freedom (indicated also by fragmentary strength to higher-lying levels), which requires some detailed theoretical analysis before a more thorough understanding will emerge. The early calculations of Kuo-Baranger[17] and Sorensen,[18] involving just the valence neutron shells but including 3 qp admixtures, generally do not agree well with the (p,d) data for the $\frac{5}{2}^+$ levels[8] and such a limited model space would surely not account for the collective (p,p') and (p,t) cross sections. The realistic Tabakin-interaction (2 qp) calculations of Clement and Baranger[16] include 12 neutron and proton orbits and these provide reasonably good agreement with the relative 2^+ (and 3^-) cross sections in the even-A tins measured by (p,t) (Ref. 14) and (t,p) (Ref. 15) as well as the (p,p') 2^+ inelastic cross sections and spin-flip probabilities at 30 MeV[2]. Similar calculations at 155 MeV for both (p,p') and (α,α') agree with the experimental 2^+ cross sections[4] to within a factor of 3–5, although this lack of agreement may be as much a result of the interaction potential chosen than of the Clement-Baranger wave functions themselves. It is thus not clear if microscopic calculations of this type can account for the collective excitations seen in the *odd-A* tin isotopes, and in particular, if the degree of mixing seen in the $\frac{5}{2}^+$ states can be reproduced.

The situation appears to be somewhat more straightforward in ^{115}Sn and ^{119}Sn, although again considerable mixing is evident in the $\frac{5}{2}^+$ levels. In the former case (Table I and Fig. 4), the 1.00 MeV ($\frac{5}{2}^+$) state is only weakly populated in the (p,p') but strongly in (p,d), consistent with the expectation that it should be primarily a 1 qp state[17,18]; again, this simple interpretation is made slightly nebulous by the (p,t) data, for which the 1.00 MeV level is the strongest transition. However, excitation of this 1 qp level is allowed in the (p,t) reaction and the fullness of the $d\frac{5}{2}$ shell will contribute significantly to the cross section, which is determined by the spectroscopic amplitude

$$B(\tfrac{1}{2},\tfrac{5}{2};2)=\tfrac{5}{6}U^A(\tfrac{5}{2}^+)\times V^B(\tfrac{1}{2}^+)\,.$$

A similar case exists in the (t,p) reaction where the 1 qp $\frac{3}{2}^+$ ground state of ^{121}Sn is one of the strongest states in the spectrum.[19] In (p,p'), the 1.29 MeV ($\frac{3}{2}^+$), 1.43 MeV ($\frac{5}{2}^+$), and 1.65 MeV ($\frac{3}{2}^+$) levels in ^{115}Sn are all strongly excited but relatively weak in the (p,d), being then good candidates for a predominantly $(\frac{1}{2}^+\times 2^+)$ structure. In ^{119}Sn (Table III) there is a very close-lying doublet of 920 keV,[22,23] which deexcitation γ rays following Coulomb excitation[22] characterize as 920.5 ($\frac{3}{2}^+$) and 921.4 ($\frac{5}{2}^+$). As in ^{117}Sn, the $\frac{3}{2}^+$ level is dominantly $(\frac{1}{2}^+\times 2^+)$ but the collective $\frac{5}{2}^+$ strength is somewhat more spread out than in ^{117}Sn, appearing in the 921.4, 1090, and 1354 keV ($\frac{5}{2}^+$) levels with ~55%, 30%, and 20% probability, respectively. These are, indeed, the levels in this energy region most strongly excited in the (p,p'), particularly the 0.92 MeV doublet (Table III and Fig. 6). Levels at 0.95 and 1.35 MeV are also preferentially populated in 34.4 MeV (α,α') studies.[6] In ^{119}Sn then, as in ^{115}Sn, the basic predictions of the pv coupling picture are reasonably well confirmed. The strongest collective level (0.92 MeV) seen in (p,p') and (α,α') (Ref. 6) is very weakly excited in (p,d) contrary to the situation in ^{117}Sn. Mixing with other degrees of freedom is again evident though in the 1.09 and 1.36 MeV levels, which are relatively strongly populated in the (p,p') and, particularly the 1.09 MeV state, in (p,d).[8]

B. The $(\frac{1}{2}^+\times 3^-)\frac{5}{2}^-$ and $\frac{7}{2}^-$ levels

In a similar manner to the $(\frac{1}{2}^+\times 2^+)$ levels above, the $(\frac{1}{2}^+\times 3^-)\frac{5}{2}^-$ and $\frac{7}{2}^-$ (3 qp) states should be preferentially excited (by $L=3$ transitions) in (p,p') reactions on the odd tins. Indeed, at 17.8 MeV bombarding energy,[24] the 3^- cross sections in the even tins are in fact somewhat larger than the 2^+ cross sections, a result confirmed in the present 18 MeV study by spectra taken on an evaporated target enriched in ^{116}Sn. Since the 3^- levels in the even tins lie at an essentially constant excitation energy (in like manner to the 2^+) of ~2.3 MeV, we expect to see the strong population of $(\frac{1}{2}^+\times 3^-)\frac{5}{2}^-$

and $\frac{7}{2}^-$ levels centered around this energy. Such levels are prominent in all three odd tin targets (Figs. 1–6) and constitute probably the most interesting feature of the present data. On this basis, three levels in ^{115}Sn, six levels in ^{117}Sn, and three levels in ^{119}Sn are tentatively identified as $(\frac{5}{2}^-, \frac{7}{2}^-)$ all with centroid energies very near 2.3 MeV. That such levels lie so close together in energy suggests that the coupling to other degrees of freedom is relatively "weak," at least weaker than for the $\frac{3}{2}^+, \frac{5}{2}^+$ levels previously discussed; in the simplest version of this model, however, only two states should have been seen.

A comment on the j^π assignments of Tables I–III (and Figs. 1–6) is germane at this point. The levels below 2 MeV are rather well established but the same statement cannot be made for the levels above 2 MeV. Indeed, there are already several examples of conflicting assignments for levels which appear to be at the same energy. In particular, the $\frac{1}{2}^+$ states near 2 MeV, assigned from nuclear transfer studies,[8-14] all appear to be relatively strongly populated in the present (p,p') study, particularly the 2.14 MeV level in ^{119}Sn, although the corresponding 0^+ levels in the neighboring even-A tins are not populated at all in (p,p').[3] This indicates that probably the same levels are not being excited by the two reactions. It is likely that a number of close-lying levels are being selectively populated by different reactions. Indeed, the situation with regards to level density $\gtrsim 2$ MeV can probably only be clarified by utilizing selective reactions such as (d,t) and $(^3\mathrm{He},\alpha)$ (Refs. 9, 26, and 27) but with very good ($\lesssim 10$ keV) energy resolution.

Most experimental information in the energy region above 2 MeV is available for the levels in ^{117}Sn (Table II) from (d,p),[11,13] (p,d),[8,12] (p,p'),[5] and (α,α') (Ref. 6) reactions. With regard to $(\frac{5}{2}^-, \frac{7}{2}^-)$ states in particular, $\frac{7}{2}^-$ assignments have been made in (d,p) studies to levels at 1.30, 2.05, 2.46, 2.54, 2.68, 3.24, and 3.79 MeV, which correspond rather well to levels we have identified at 1.30, 2.06, 2.46, 2.53, 2.68, and 3.25 MeV. Of these states, only two, the 2.06 and 2.46 MeV levels, are strongly excited in the present (p,p') study. No $\frac{7}{2}^-$ (or $\frac{5}{2}^-$) states have been identified in the (p,d) studies. In the case of the relatively poor energy resolution 55 MeV (p,p') data of Ref. 5, three states have been classified as $(\frac{5}{2}^-, \frac{7}{2}^-)$, corresponding presumably to the levels we identify at 2.16, 2.27, and 2.59 MeV. The 2.16 and 2.27 MeV states are strongly populated in the present study, with the 2.16 MeV level, in fact, being the most intense in this region of the energy spectrum (Figs. 2 and 5). In 34.4 MeV (α,α') scattering,[6] two strong $L=3$ transitions have been reported to levels at 2.10 and 2.40 MeV, which are inconsistent with the present data but presumably can be identified with the 2.16 and 2.46 MeV levels. It is worth pointing out that in the higher energy (p,p') and (α,α') data on ^{117}Sn, with poorer energy resolution of 80 and 180 keV, respectively, at most three $(\frac{5}{2}^-, \frac{7}{2}^-)$ levels are identified, whereas in the present 18 MeV study, six such levels can be characterized on the basis of their strong (p,p') cross sections [additional levels have been assigned $\frac{7}{2}^-$ from (d,p) studies].

In ^{115}Sn and ^{119}Sn, fewer $(\frac{5}{2}^-, \frac{7}{2}^-)$ levels can be identified on this basis. In ^{115}Sn (Figs. 1 and 4, and Table I), three strong peaks stand out in the region of 2.3 MeV and hence are assumed to be characterized by $L=3$ transitions. Of these, only the 2.31 MeV level had previously been assigned, as $\frac{5}{2}^-$ in a 23 MeV (d,t) study.[9] A tentative $(\frac{7}{2}, \frac{9}{2}^-)$ assignment from γ-ray studies[21] to a level at 1.79 MeV is not seen in the present work. Again there are conflicting j^π assignments to levels of presumably the same energy. In particular, the 2.22 MeV level that we characterize as $(\frac{5}{2}^-, \frac{7}{2}^-)$ on the basis of its (p,p') cross section has been identified as $\frac{3}{2}^+$ in pickup reactions.[9,12] Lacking reliable angular distributions in the present study means, of course, that the $(\frac{5}{2}^-, \frac{7}{2}^-)$ assignments made herein cannot be definitive. Nevertheless, they would appear to be rather well founded on the basis of expected pv coupling states in the same energy region. Levels near 3 MeV, which are reported to have fragmentary $\frac{7}{2}^-$ strength in (d,p) studies,[13] are only seen weakly in the present work. In ^{119}Sn, the spectrum is again different. One transition, 2.28 MeV, dominates the energy region of the anticipated $L=3$ strength (Figs. 3 and 6), although the 2.18 and 2.39 MeV levels are also relatively strongly populated and hence can also be assigned $(\frac{5}{2}^-, \frac{7}{2}^-)$. Of these, only the 2.39 MeV level has previously been reported in transfer reactions, but tentatively assigned therein as $\frac{11}{2}^-$.[12] A level at 2.56 MeV is also relatively strongly populated in the present study, which would be consistent with a possible $\frac{7}{2}^-$ assignment from (d,p) studies.[10,13] In 34.4 MeV (α,α'), two strong $L=3$ transitions have been reported[6] to levels at 2.25 and 2.50 MeV. As in ^{117}Sn, there is poor correspondence with the present excitation energies (Table III) but presumably these states can be identified with the strong 2.28 MeV level and the 2.56 (or 2.39?) MeV level. Levels excited by (d,p) beyond 3 MeV,[10,13] and which are assigned either as $\frac{3}{2}^-$ or $\frac{7}{2}^-$, are not seen in the present study. Generally less strength was observed in this region in ^{119}Sn than in ^{117}Sn or ^{115}Sn.

At this time, there are no comprehensive theoretical calculations of *negative* parity states in the odd tin isotopes. There is only one low-lying 1 qp state of negative parity, $h\frac{11}{2}$, which as previously mentioned, appears to be the strongest 1 qp state populated in the present (p,p') study. In the pv coupling picture, one expects then a low-lying $\frac{7}{2}^-$ level to arise from the coupling $(h\frac{11}{2}\times 2^+)$, which should lie at an (unperturbed) excitation energy of ≈1.5 MeV for $A = 115$–119. Calculations of such a multiplet structure $(\frac{7}{2}^-, \frac{9}{2}^-, \frac{11}{2}^-, \frac{13}{2}^-, \frac{15}{2}^-)$ have been reported by Sorensen[18] and by DeBarros *et al.*[28] The latter calculation, in particular, finds good agreement in the calculated spectroscopic factors for the first $\frac{7}{2}^-$ transition seen in (d,p) studies, which provide a measure of the degree of mixing with the $f\frac{7}{2}$ single-particle component. These levels are found to lie in ^{117}Sn and ^{119}Sn at 1.30 and 1.06 MeV, respectively. In first order, such pv coupling states would not be populated in (p,p') from the $\frac{1}{2}^+$ g.s. of the odd-A tins. In higher order the g.s., might contain 3 qp terms also from mixing with $(j\times 2^+)$ states which would permit direct excitation of other multiplet.

In ^{115}Sn, the lowest-lying $\frac{7}{2}^-$ (or $\frac{5}{2}^-$) level reported to date is the one we have identified at 2.10 MeV, which is the most strongly excited in the (p,p') spectrum (Figs. 1 and 4) and hence could not possibly qualify as an $(h\frac{11}{2}\times 2^+)$ state. On the other hand, coupling of the 1 qp states with the 3^- core vibration $(j\times 3^-)$ would produce four $(\frac{5}{2}^-, \frac{7}{2}^-)$ configurations for $j=\frac{1}{2}^+, \frac{3}{2}^+, \frac{5}{2}^+$, and $\frac{7}{2}^+$. Considering the $(2^+\times h\frac{11}{2})$ coupling also, one obtains an additional $\frac{7}{2}^-$ level for a total of nine such states, which is generally in good agreement with the number of experimental levels. There are eleven such states in ^{117}Sn, and using the (d,p) results of Refs. 10 and 13, fourteen candidates are known in ^{119}Sn, some of which have conflicting spin assignments. In ^{115}Sn, however, only eight such levels have been identified, considering also the (d,p) results of Ref. 13. It is, of course, the $(\frac{1}{2}^+\times 3^-)$ admixtures into these states that one expects to excite in the (p,p') reaction. To our knowledge, no calculations of this nature have been carried out. These are clearly necessary if the present (p,p') results, as well as the earlier (d,p) results, are to be understood. Finally, it should be noted that the $f\frac{5}{2}$ and $f\frac{7}{2}$ single-particle orbitals are expected from shell model calculations to lie about 5 MeV above the Fermi surface in the tin nuclei. The presence of significant strength in the (d,p) reaction as low as 2 MeV in the odd tins must be considered as due to mixing of these orbits from the next shell with the 3 qp states formed from pv coupling. The excitation of these high-lying f orbitals has been seen in the (t,p) reaction.[15]

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