Deep hole states observed in (p,t) reactions

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The (p,t) reaction on ^{120}Sn, ^{122}Sn, and ^{124}Sn at a bombarding energy at 89 MeV shows a broad feature similar to the one observed at lower bombarding energy. The excitation energies and widths were consistent with those observed in the earlier experiment. Angular distributions are in good agreement with distorted-wave Born approximation calculations in which two neutrons are assumed to have been picked up from deeply bound orbits.

[NUCLEAR REACTIONS ^{120,122,124}Sn(p,t), $E=89$ MeV; measured levels, Γ, $\sigma(\Theta)$. Enriched targets. DWBA analysis.]

A recent paper[1] claimed to observe deep hole states in the even tin isotopes in (p,t) reactions carried out at a bombarding energy of 42 MeV. The data showed a bump at around 8 MeV excitation with a width which varied from 2 to 3 MeV. This feature was interpreted as arising from the pickup of two neutrons which leave two holes in deep-lying orbits such as the $1g_{9/2}$ and $2p_{3/2}$ or $2p_{1/2}$ subshells. Part of the evidence presented to support this claim was the agreement of the angular distribution of the enhanced structure with the sum of individual ℓ transfers as calculated in the distorted wave Born approximation (DWBA). However, both the experimental angular distribution and the theoretical (summed over ℓ) distributions were quite structureless and decreased rather slowly with angle.

In order to investigate this phenomenon further, the (p,t) reaction was studied on three even-even tin isotopes ^{120}Sn, ^{122}Sn, and ^{124}Sn at a bombarding energy of about 89 MeV using a proton beam from the Indiana University Cyclotron. At this energy, the predicted angular distributions decrease much more rapidly with angle than they do at the lower bombarding energy, particularly for the lower ℓ transfers. In addition, at 89 MeV the angular momentum matching occurs for an ℓ value near six whereas at 42 MeV the favored ℓ transfer is between two and three. Thus, the higher energy experiment was expected to cast some more light on the angular momentum transfer which gives rise to the broad structure.

The observed excitation energy of the peak measured at a different bombarding energy would also be useful in understanding the effect. At 42 MeV, the position of the bump has the same A dependence as that of the $g_{9/2}$ hole observed in one neutron transfer reactions. This relationship should be independent of bombarding energy. On the other hand, if the bump arises from a three body breakup process, it would appear at a different excitation energy at a different bombarding energy.

In order to investigate the triton spectra over a wide range of excitation energies, the tritons were detected in a solid state detector telescope. The telescope consisted of a 2 mm silicon ΔE detector and a 1 cm intrinsic Ge E detector followed by an anticoincidence detector to eliminate elastically scattered protons. The gains of the silicon and Ge detectors were matched using the ratio of the energy needed to produce an ion pair in silicon and germanium. The targets were rolled foils of enriched isotopes as follows: ^{120}Sn(98.4%; 9.90 mg/cm), ^{122}Sn(90.8% 5.30 mg/cm), ^{124}Sn(94.7%; 5.13 mg/cm). The triton spectra were calibrated using the ^{58}Ni(p,t) reaction and the low lying resolved states of the tin isotopes. Unfortunately although the deuteron spectra were taken at the same time, the energy calibration from the deuteron spectra was systematically about 600 keV different from the triton calibration line. A similar effect has been observed in silicon detectors with lower energy particles.[2] As a result, only points from (p,t) spectra were used to calibrate the triton energy scales.

Spectra from the three isotopes taken at a laboratory angle of 25° are shown in Figure 1. The ground state and first excited (2^+) state are quite weakly excited at this angle but a number of states around 4 MeV of excitation show up strongly. In addition, the broad bump observed at 42 MeV bombarding energy is also clearly visible in all three spectra. The increase in width of the peak from ^{120}Sn to ^{124}Sn targets, also observed at lower energy, can be readily observed in these spectra. The excitation energies and widths are compared with the results at lower bombarding energy in Table I and are seen to be consistent. The similarity of the excitation energy observed at different bombarding energies convincingly excludes the possibility of some three body breakup process being responsible for this feature.

An angular distribution was measured for the case of the ^{120}Sn(p,t) reaction and is shown in Figure 2. Three angles were measured for the other isotopes and are consistent with the ^{120}Sn case. In extracting the area of the peak, a straight line background was subtracted as indicated in Figure 1. This background rises fairly rapidly at higher excitation energy unlike the background, admittedly covering a smaller energy range, which was observed at the lower bombarding energy. An examination of the two dimensional ΔE-sum display showed that the triton identification was quite clean so that the rising background definitely corresponds to real tritons.

Distorted wave Born approximation (DWBA) calculations were carried out using the code DWUCK.[3] Various sets of proton and triton optical parameters were tried in

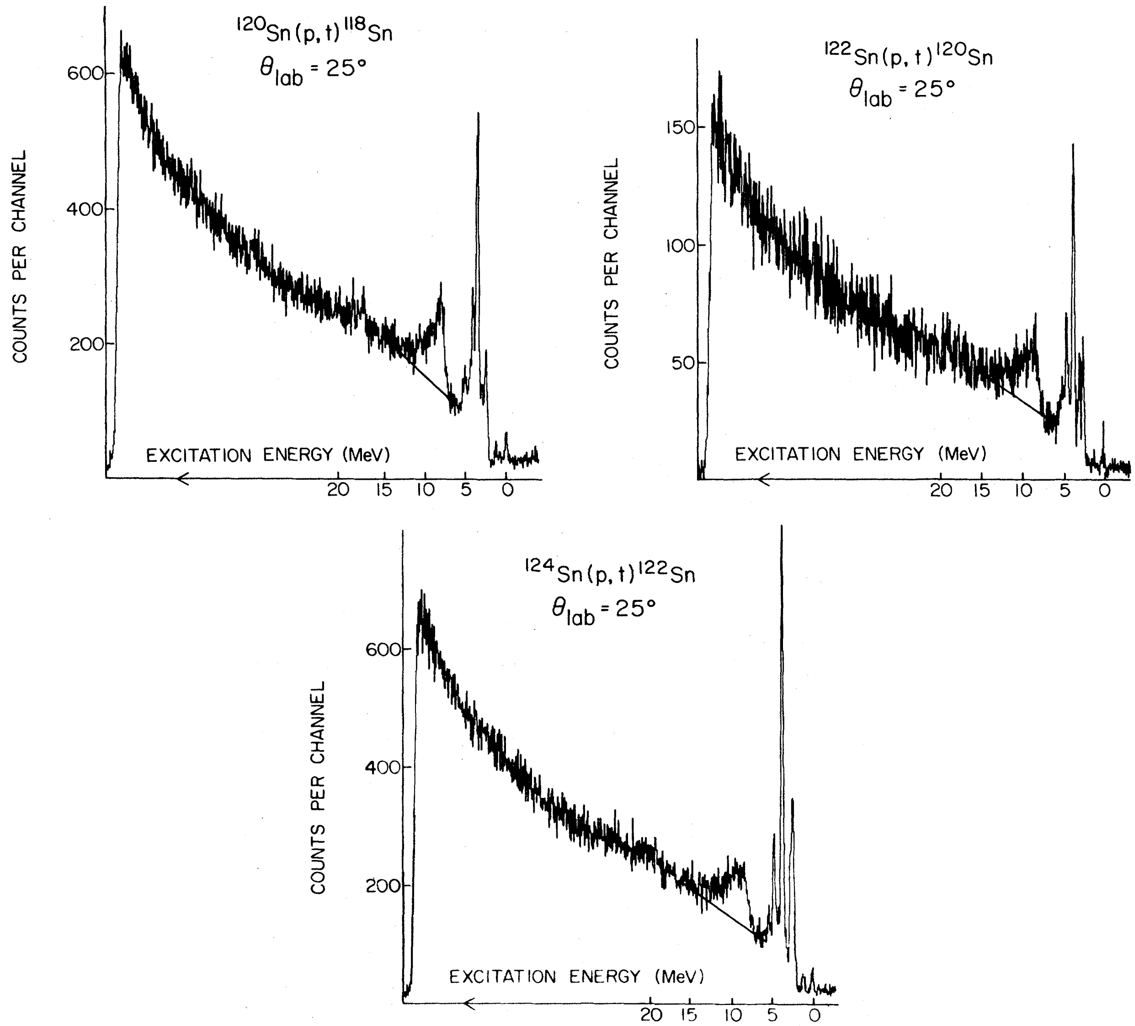

Fig. 1. Triton energy spectra. The excitation energy scale is given for all three residual nuclei. The solid straight lines show the background subtracted in determining the cross section.

Table I. Excitation energies, widths, and cross sections of the broad structure observed in (p,t) reactions on the tin isotopes.

Reaction	E_x (of max. enhancement) (MeV)		(Full width at half max.) (MeV)	
	42 MeV protons	89 MeV protons	42 MeV protons	89 MeV protons
^{112}Sn(p,t)^{110}Sn	7.15 ± 0.10		2.58 ± 0.10	
^{116}Sn(p,t)^{114}Sn	8.00 ± 0.04		1.93 ± 0.07	
^{118}Sn(p,t)^{116}Sn	8.40 ± 0.04		2.12 ± 0.07	
^{120}Sn(p,t)^{118}Sn	8.51 ± 0.04	8.3 ± 0.2	2.16 ± 0.07	2.1 ± 0.3
^{122}Sn(p,t)^{120}Sn	8.53 ± 0.08	8.7 ± 0.2	2.58 ± 0.10	2.7 ± 0.4
^{124}Sn(p,t)^{122}Sn	8.65 ± 0.08	8.7 ± 0.2	2.72 ± 0.10	2.9 ± 0.5

Table II. Optical parameters[a] used in the DWBA calculations.

Protons	V(MeV)	r_o(fm)	a(fm)	W_s(MeV)	W_D(MeV)	r_I(fm)	a_I(fm)	V_{so}(MeV)	W_{so}MeV)	r_{so}(fm)	a_{so}(fm)
Set(1)[b]	28.10	1.240	0.817	7.45	0.0	1.457	0.460	2.89	1.95	1.110	0.533
Set (2)[c]	28.56	1.210	0.770	7.40	0.0	1.400	0.538	4.23	1.02	1.066	0.623
Set (3)[c]	28.15	1.212	0.757	6.34	0.0	1.456	0.438	3.15	1.83	1.080	0.564
Tritons											
Set (1)[d]	160.2	1.20	0.672	23.39	0.0	1.095	0.931				
Set (2)[e]	123.0	1.12	0.837	20.50	0.0	1.240	0.828				

[a]See Ref. 3.
[b]From Ref. 4.
[c]From Ref. 5.
[d]From Ref. 6.
[e]From Ref. 7.

these calculations. One set of proton optical parameters were taken from a paper of Kwiatkowski and Wall[4] for 100 MeV protons on ^{120}Sn and two sets were taken from the survey by Nadasen et al.[5] Triton parameters were taken from the work of Shepard et al.[6] describing the (p,t) reaction on ^{208}Pb at 80 MeV and a somewhat different set from a paper describing 71 MeV ^{3}He scattering from ^{60}Ni by Fulmer and Hafele.[7] The various parameter sets are listed in Table II.

All possible configurations of two holes in the 4 orbits $1g_{9/2}$, $2p_{1/2}$, $2p_{3/2}$ and $1f_{5/2}$ were included in the calculations. These orbits were all assumed to be completely full so that unit spectroscopic amplitude was assigned to each configuration. The same normalization factors, including setting $D_o^2 = 22.0 \times 10^4$ MeV^2 fm^3 were used in the 89 MeV calculations as were used at lower energy.[8]

The various sets of optical parameters gave rather similar predicted cross sections in both shape and magnitude. Since the proton parameters are rather similar, very little variation was expected or observed except for a slight difference in the slope of the angular distribution backward of 30°. The two sets of triton parameters are somewhat different and did give a greater difference in the predicted angular distribution. The shaded area in Figure 2 indicates the extremes of the predicted summed angular distributions using the different parameter sets. Some of the individual ℓ transfer calculations using the Nadasen proton parameters (Set 2) and the Shepard triton parameters are shown in Figure 2. The solid line is the incoherent sum of all the ℓ transfers, normalized to the data. The rapid decrease of the cross section with increasing angle predicted by the calculation, especially for the small ℓ transfers, explains why the ground states (0^+) and first excited states (2^+) are so weakly excited at 25°

Even though the experimental angular distribution and the theoretical predictions have a very different slope than at lower energy, the predictions are generally quite consistent with the data, especially considering the uncertainty in the triton parameters. This agreement adds further support to the assumption that the bump observed in (p,t) arises from the pickup of two particles from deep-lying orbits. However the normalization of the experimental and theoretical cross section shown in Figure 2 is now a factor of 0.18 instead of the factor 0.48 needed at 42 MeV bombarding energy. The normalization factor at 42 MeV which arises in making the zero range approximation ($D_o^2 = 22.0 \times 10^4$ MeV^2 fm^3) was chosen to give reasonable agreement with data taken mainly near 40 MeV. A different factor might well be needed at the higher bombarding energy for which very little data is presently available. A recent report of (p,t) studies on

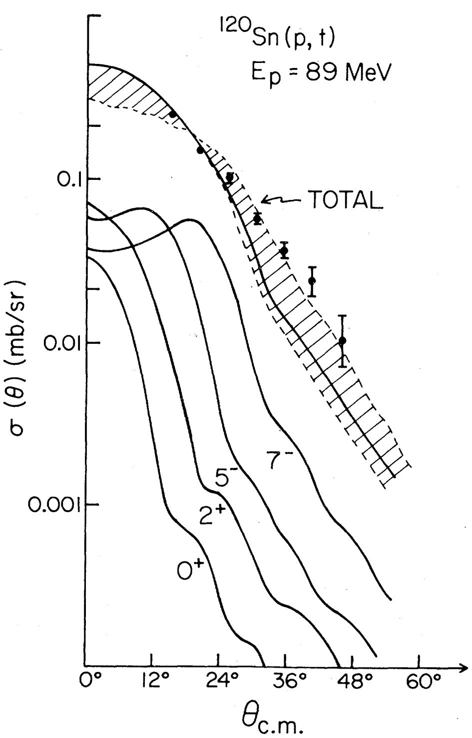

Fig. 2. Angular distirubions for the ^{120}Sn(p,t)^{118}Sn reaction. The curves are DWBA calculations for pickup to the states with J^π as shown. The solid curve is the sum of all the expected strength normalized by 0.18 as described in the text. The shaded area illustrates the spread of the predicted cross section using different optical parameter sets.

^{12}C, ^{54}Fe, and ^{208}Pb at 80 MeV bombarding energy finds[6] enhancement factors which differ by factors of between 4 and 12 for the ground state transitions in ^{54}Fe and ^{208}Pb from 40 MeV. Thus the factor of three difference in normalization between 42 and 89 MeV observed in the present experiment is quite consistent with the general systematics of (p,t) reactions at higher energies. One can tentatively conclude that within the uncertainties in the normalization, which require further systematic studies, the strength observed is the same at 89 MeV as at 42 MeV.

In summary, (p,t) measurements at 89 MeV bombarding energy on the isotopes ^{120}Sn, ^{122}Sn and ^{124}Sn add support to the earlier results obtained at a lower bombarding energy with a very different experimental arrangement. The feature observed is consistent in excitation energy and width at the two bombarding energies. In addition the angular distribution at 89 MeV for ^{120}Sn (p,t) is fitted quite well in shape by a DWBA calculation similar to one which also fits the lower energy data. The strength observed at higher energy is also consistent with the lower energy data provided the larger normalization factors observed in other experiments in this energy and mass region can be applied also to the present experiment.

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