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The Observation of Hole States at High Excitation in (p,t) Reactions[*]

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ABSTRACT

A peak about 2 MeV wide is observed at 8 to 9 MeV of excitation in a number of even even tin isotopes and at lower excitation in ^{104}Cd and ^{102}Pd in studies of the (p,t) reaction at 42 and 45 MeV. The excitation energy of the peak centroid and the peak width are observed to increase with increasing neutron number. It is suggested that the peak arises from two neutron pickup from the lower lying filled gpf shell between magic numbers 28 and 50. This explanation is reasonably consistent with the observed excitation energies. In addition, distorted wave born approximation (DWBA) calculations of the angular distributions for two neutron pickup from this shell agree in shape with the data. About 40% to 50% of the predicted total strength is observed experimentally.

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The spreading of simple states into an underlying background of more complex states remains one of the important questions in nuclear physics.[1] One method of studying this problem is by pickup reactions particularly at high excitation energy where the level density is substantial. Neutron hole states with spin-parity $9/2^+$, $1/2^-$ and $3/2^-$ and with significant spectroscopic factors have been observed at about 5 MeV of excitation in the odd tin isotopes in single neutron pick-up reactions.[2,3,4] In the present experiment, which was motivated by a search for high-lying pairing resonances,[5] a peak was observed at an excitation energy of about 8 to 9 MeV in a number of tin isotopes. One plausible explanation for this peak is that it arises from two neutron hole states in the major shell consisting of $1g_{9/2}$, $2p_{1/2}$, $2p_{3/2}$ and possibly $1f_{5/2}$ levels.[6]

Because the pairing-resonances were predicted to occur at $70/A^{1/3}$ MeV, i.e. about 14.1 MeV for ^{122}Sn, the first measurements were carried out using a ^{122}Sn target at a proton bombarding energy of 45 MeV and the tritons were detected in a standard counter telescope consisting of three Si detectors. This arrangement permitted the study of ^{120}Sn up to an excitation energy of about 17 MeV. No structure was observed near 14 MeV but a substantial "bump" was observed around 8.5 MeV excitation.

In order to study this phenomenon in more detail, the $^{122}Sn(p,t)$ reaction was repeated at a proton bombarding energy of 42 MeV using a 50 cm long resistive wire proportional counter backed by a plastic scintillator in the focal plane of the Enge spectrograph. This arrangement gave very clear identification of the tritons but was restricted to measuring a range of triton energies from about 32.5 MeV to 21.5 MeV. Again an enhancement of the cross section was observed near 8.5 MeV in ^{120}Sn, quite consistent with the observations at 45 MeV using the silicon counter telescope. This excluded the possibility that the effect had an instrumental origin. A search of the literature showed that indications of similar structure is present in previously published (p,t) spectra[7,8] but was not discussed.

The (p,t) experiment was continued at 42 MeV on the even tin isotopes, ^{124}Sn, ^{122}Sn, ^{120}Sn, ^{118}Sn and ^{116}Sn. using the Enge spectrograph. The energy resolution was dominated by the target thicknesses which ranged from 0.5 to 5 mg/cm^2. The spectra obtained from these measurements at a laboratory angle of 16° are plotted in Figure 1, using the same absolute energy scale. A peak, about 2 MeV wide at an excitation energy between 8 and 9 MeV is observed in all the Sn isotopes studied. In addition the reactions $^{106}Cd(p,t)$ and $^{104}Pd(p,t)$ were examined. Enhancement was also seen in ^{104}Cd and ^{102}Pd but at a lower excitation energy. In these two cases, fine structure was evident

on top of an overall increase in cross section. In order to check for fine structure in the tin isotopes, a few runs were taken with a 280 μg/cm^2 thick ^{124}Sn target where the energy resolution was about 50 keV FWHM. No fine structure was observed.

The excitation energies of the peaks and the full width at half maximum of the broad structure are given in Table 1. The excitation energy of the peak increases with the addition of neutrons. In addition the width of the peak increases from about 1.9 MeV in ^{114}Sn to 2.7 MeV in ^{122}Sn and the peak becomes more asymmetric for the heavier tin isotopes.

A possible explanation of this feature is that it arises from the pickup of two neutrons from the lower lying, filled, major shell which contains the single particle orbits $1g_{9/2}$, $2p_{1/2}$, $2p_{3/2}$ and $1f_{5/2}$. This explanation is consistent with the observed increase in the excitation with increasing neutron number since, if coupling with other modes is neglected, one must reach deeper below the fermi surface to extract the two neutrons for the heavier isotopes. However coupling to phonon modes has been observed for single neutron hole states at least for f-p shell nuclei[9] and detailed calculations would be required to check the simple assumption made above.

The two neutron hole states in the tin isotopes should occur at approximately twice the excitation energy of the single hole states observed in the single neutron pick-up experiments (about 11 MeV) minus the energy due to residual interactions between the nucleons. For the pairing interaction, the residual interaction was estimated by Broglia and Bes[5] to be about 1.4 MeV. The observed excitation energy of the peak in the (p,t) spectra of between 8 and 9 MeV is in reasonable agreement with this estimate particularly in view of the uncertainty in the residual interaction. Hopefully the present observations might stimulate theoretical calculations of the expected energies of such states including the variation in excitation energy and width observed from isotope to isotope.

To further test the assumption that the structure observed arises from pickup of two neutrons from the gpf shell, a number of DWBA calculations were carried out using the code DWUCK.[10] Becchetti-Greenlees[11] optical parameters were used to describe the protons, and the triton parameters were taken from a Zr(p,t) experiment with 38 MeV protons.[12] All four orbits, $1g_{9/2}$, $2p_{1/2}$, $2p_{3/2}$ and $1f_{5/2}$, were included and all configurations with spin from 0^+ to 8^+ which could be made by picking up two neutrons from these orbits were calculated. The assumption was made that these orbits were completely full so that the total pickup strength was therefore calculated. The value of D_o^2 was set equal to the value[13] of 22.0 $\mathrm{MeV}^2/\mathrm{fm}^3$ for all states calculated. In other words no dependence of D_o^2 with ℓ or J-transfer was allowed even though such an effect is sometimes observed for lower excited states. For these lower excited states, this variation

of D_o^2 is believed to arise because of the insufficiency of the basis used to describe the low lying states. This problem is less likely to arise for a completely filled shell well below the fermi level.

The results of these calculations for ^{116}Sn(p,t) and ^{122}Sn(p,t) are shown in Fig. 2, together with the experimental angular distribution for the peak observed in these two reactions. In extracting the experimental cross section for the enhanced structure, a straight line background was assumed which matches the non-enhanced regions of the spectrum. This is the conventional approach which has been adopted for extracting broad features in the absence of any model to fit the background. The uncertainties were estimated by a comparison of a number of different attempts to extract the peak area. For both ^{116}Sn(p,t) and ^{122}Sn(p,t) the sum of the theortical predictions for some of the stronger J-transfers is plotted, together with the total summed prediction for all 21 configurations considered. Clearly no single J-transfer dominates the predicted cross section. The total cross section predicted is rather structureless and, for the ^{116}Sn(p,t) reaction, matches the shape of the experimental angular distribution remarkably well. For the ^{122}Sn(p,t) case, the agreement is reasonably good although in this case the data do seem to show more of a decrease at forward angles than is predicted. Since the peak is narrower in the ^{116}Sn(p,t) reaction, the uncertainties in extracting the area from the background are smaller than in the ^{122}Sn(p,t) case.

The absolute magnitude of the predicted summed cross section is about 2.6 times higher than the experimental cross section for the ^{122}Sn(p,t) reaction and about twice as high for the ^{116}Sn(p,t) case. A different set of triton parameters[14] was also tried in the DWUCK calculations. These gave an increase of about 10% in the predicted cross section but made little change in the relative contributions of the various J-transfers. Thus the comparison between theory and experiment appears not to be very sensitive to the choice of optical parameters.

Since the $1f_{5/2}$ orbital is expected to be lower than the $g_{9/2}$ and the p orbitals, a calculation was also made excluding the $f_{5/2}$ level. The summed cross section was decreased about 15 to 20% but the overall shape of the angular distribution was not changed significantly. The calculation was also repeated including only negative parity states since these states arise from a hole in the pf orbitals coupled to one in the g orbital, and as a result are somewhat less strongly bound. Thus negative parity states would be expected to occur at a lower excitation energy. In the ^{116}Sn(p,t) case, the shape of the predicted angular distribution for the negative parity states does not give as good a fit as for the case when all states are included, and at forward angles the experimental cross section is greater than predicted. For ^{122}Sn(p,t) the negative parity prediction is in reasonably good agreement in both shape and magnitude with the experimental angular distribution.

However, in the ^{104}Pd(p,t) reaction, where fine structure is seen, at least one of the resolved peaks which occurs near the middle of the region of enhanced cross section has a clear 0^+ angular distribution. This suggests that there are probably positive parity states also present in the structure observed in the Sn isotopes.

If one assumes the total summed strength is correctly predicted by the DWBA calculation, then the fraction of the total strength observed (50% for ^{116}Sn(p,t) and about 40% for ^{124}Sn(p,t)) is quite large. In the Sn(d,t) reactions about 30% of the $g_{9/2}$ and 20% of the $p_{1/2}$, $p_{3/2}$ sum rule limit is observed experimentally.[2] For the (p,d) reactions[3,4] less than 20% of the sum rule limit is observed. However a recent single proton pickup experiment on the samarium isotopes[15] has observed about 50% of the sum rule limit for the $g_{9/2}$ orbital.

In summary, enhanced strength has been observed near 8-9 MeV excitation energy in (p,t) reactions on the tin isotopes and also at lower excitation in ^{104}Cd and ^{102}Pd. The angular distribution of the peak agrees in shape with a DWBA prediction assuming two neutron pick-up from the gpf shell. About 40 to 50% of the total strength predicted is observed experientally. If this is the correct explanation for the enhanced cross section, there remains the problem of why this strength should be concentrated within a few MeV of excitation.

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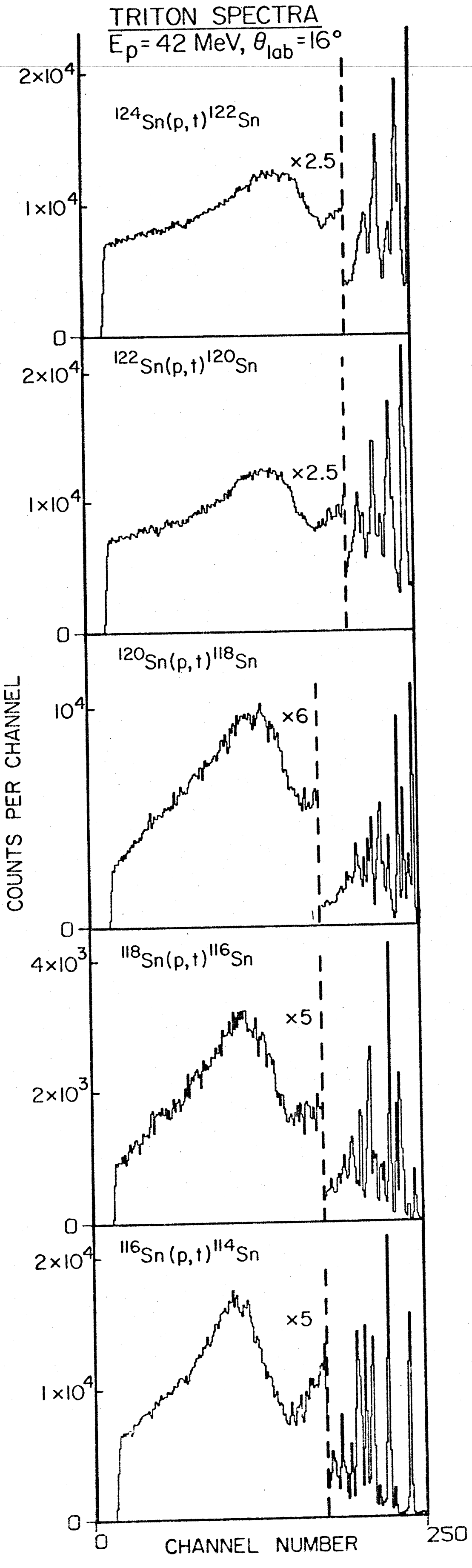
TABLE I.

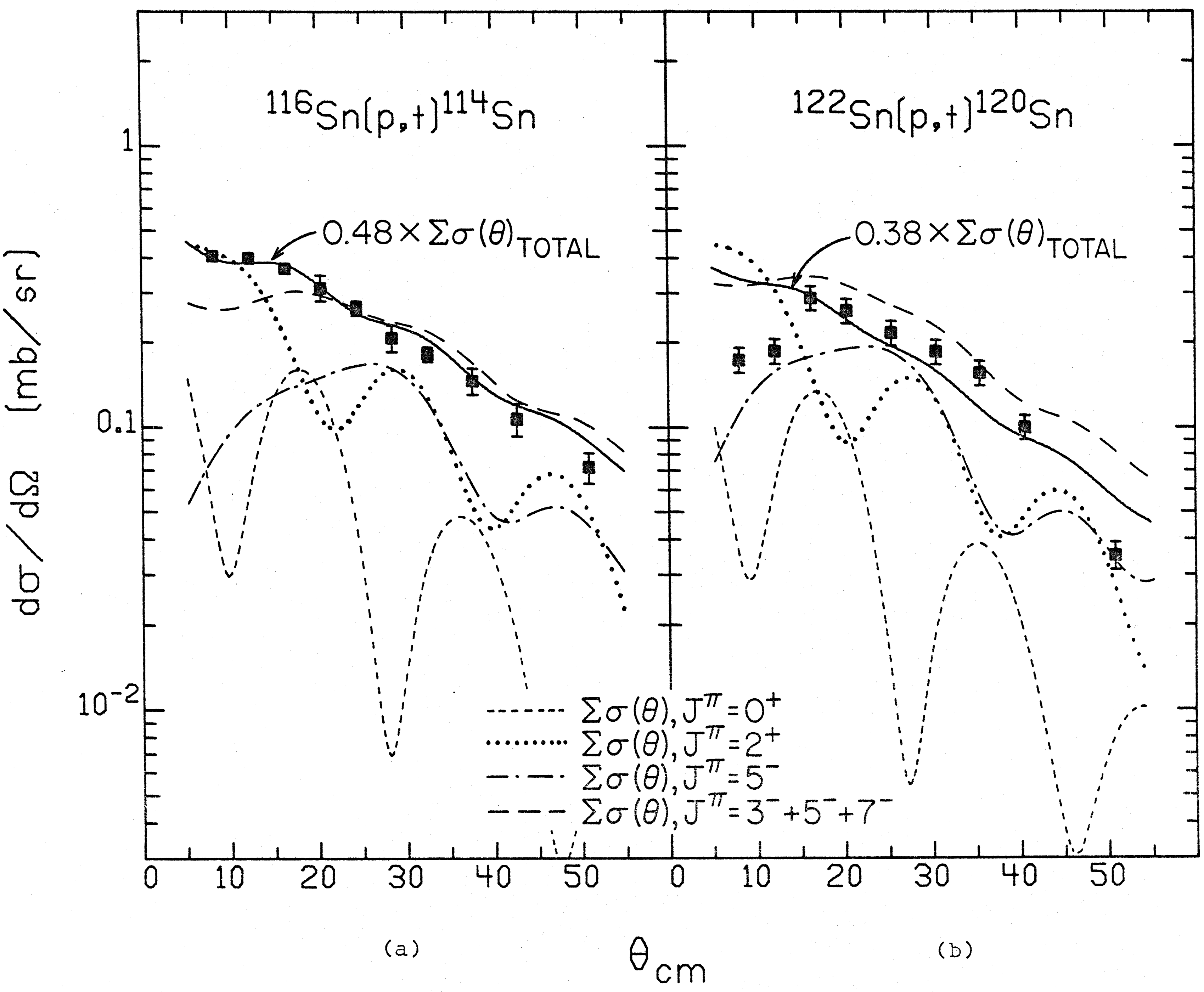
Reaction	E_x of Maximum enhancement (MeV)	Full Width at half Maximum (MeV)
$^{116}Sn(p,t)^{114}Sn$	8.00±0.04	1.93±0.07
$^{118}Sn(p,t)^{116}Sn$	8.40±0.04	2.12±0.07
$^{120}Sn(p,t)^{118}Sn$	8.51±0.04	2.16±0.07
$^{122}Sn(p,t)^{120}Sn$	8.53±0.08	2.58±0.10
$^{124}Sn(p,t)^{122}Sn$	8.65±0.08	2.72±0.10

Figure Captions

FIG. 1.--Triton spectra from the (p,t) reaction on some even-even isotopes of tin at a laboratory angle of 16°. The proton bombarding energy was 42 MeV. The absolute energy scale is the same for all of the spectra.

FIG. 2.--Angular distribution for (a) $^{116}\mathrm{Sn}(p,t)^{114}\mathrm{Sn}$ and (b) $^{122}\mathrm{Sn}(p,t)^{120}\mathrm{Sn}$ for the "peak" in the triton spectrum at an excitation energy of about 8 MeV. The curves are DWBA calculations as outlined in the key. Only the total predicted cross section (solid curve) has been normalized to the data.


TRITON SPECTRA
E_p = 42 MeV, θ_{lab} = 16°
^{124}Sn(p,t)^{122}Sn
×2.5
^{122}Sn(p,t)^{120}Sn
×2.5
^{120}Sn(p,t)^{118}Sn
×6
^{118}Sn(p,t)^{116}Sn
×5
^{116}Sn(p,t)^{114}Sn
×5
2×10^4
1×10^4
0
10^4
4×10^3
2×10^3
COUNTS PER CHANNEL
CHANNEL NUMBER
0
250



^{116}Sn(p,t)^{114}Sn
^{122}Sn(p,t)^{120}Sn
$0.48 \times \Sigma\sigma(\theta)_{TOTAL}$
$0.38 \times \Sigma\sigma(\theta)_{TOTAL}$
$\Sigma\sigma(\theta), J^{\pi} = 0^{+}$
$\Sigma\sigma(\theta), J^{\pi} = 2^{+}$
$\Sigma\sigma(\theta), J^{\pi} = 5^{-}$
$\Sigma\sigma(\theta), J^{\pi} = 3^{-} + 5^{-} + 7^{-}$
$d\sigma / d\Omega$ (mb/sr)
1
0.1
10^{-2}
0
10
20
30
40
50
0
10
20
30
40
50
(a)
(b)
θ_{cm}