A Study of High-Spin States in Light Nuclei with the (^{3}He,p) Reaction

L.H. Harwood and G.M. Crawley

A series of experiments at Berkeley[1,2,3] have yielded what appears to be a set of systematics for the energies of high spin states in light nuclei. In these studies, the (α,d) reaction was used to populate high spin states in the various nuclei. This reaction is very momentum mismatched and tends to selectively populate high spin states. Because of the large negative Q-values for the reactions, high excitation regions of the spectra were not studied. These studies also suffered from poor energy resolution ($\gtrsim$200 keV). We have made a series of measurements of the (^{3}He,p) reaction at $E_{^3He}$=70 MeV on ^{11}B, ^{12}C, ^{13}C, ^{14}N, ^{16}O, ^{18}O, ^{27}Al and ^{28}Si targets in order to extend this earlier work.

The data were taken at the MSU Cyclotron Laboratory. A 70 MeV ^{3}He beam from the MSU Sector-focused Cyclotron was used in all the measurements. The targets were obtained from the laboratory stockpile. None were made specifically for this experiment, so no discussion of their preparation will be given here. The protons were momentum analyzed with an Enge split-pole spectrograph onto a 20-inch long proportional counter with delay line readout. Typical spectra are shown in figure 1. The energy resolution was roughly 90 keV.

One goal of this study was to try to get spin/parity information for some of the states by DWBA analysis of angular distributions. The (α,d) studies made no attempt at such analyses. This type of analysis proved to not be applicable to the present data. Figure 2 compares the angular distributions of the 5.83 MeV 3^- and 6.44 MeV 3^+ states in ^{14}N to the calculated shapes for L=3 and L=2 transfers. Obviously the data for the 5.83 MeV state do not match the curve very well; those for the 6.44 MeV state match quite well. Furthermore, the data for the two states are so similar as to make it hard to say that any differences are significant. Thus, based on the inability of DWBA calculations to consistently predict the shapes of the angular distributions and the similarities of the data to each other, we have concluded that the (^{3}He,p) angular distributions measured in this study cannot yield any spin/parity information. Possibly data at larger angles would have been informative, but the angular distributions were dropping so rapidly that larger angle data would have taken prohibitively long to obtain.

There were some differences between our data and those of the (α,d) studies. For example, where Lu, et al[3] see a single state at 11.95 MeV in ^{15}N, we see a doublet at 11.88 and 11.98 MeV. We note that their $\sim$200 keV energy resolution would not have resolved these states. As seen in Fig. 1, we also observe states in ^{15}N which were previously unreported. They are at 18.66± 0.01, 19.26± 0.02 and 19.80± 0.02 MeV excitation. The (α,d) spectrum does not extend to this excitation range. The ^{12}C(^{3}He,p)^{14}N is very similar to the ^{12}C(α,d) spectrum of Rivet, et al.[2] except we do not observe the 15.0 MeV state. In fact, our spectrum is extremely featureless in that excitation range, as seen in figure 1. Since the (^{3}He,p) reaction can be a T=0 or T=1 transfer, we can explain the observation of the new states in ^{15}N by proposing that they are T=3/2 states, which would be inaccessible in an (α,d) reaction because the latter is a pure T=0 transfer. We as yet have no explanation for why the 15.0 MeV state is populated in the (α,d) reaction but not in the (^{3}He,p) reaction.

Finally, we have studied a number of nuclei to look for any systematics in the spectra. Rivet, et al. and Lu, et al. have proposed that there is a set of states with very simple wavefunctions which occur in a number of nuclei and have "charted" them as a function of the mass of the nucleus. For example, they propose the 9.00 MeV, 13.02 MeV and 0.0 MeV states in ^{14}N, ^{15}N, and ^{26}Al, respectively, are all $(d_{5/2})^2{}_{5^+}$ states, in shell model notation. They contend this explains why these states are populated so strongly in the transfer reactions. Figure 3 shows the binding energies of the most strongly populated two to four states for each nucleus in the present study. For example, we observe strongly populated states in ^{13}C and ^{15}N where the "$(d_{5/2})^2$" line of Rivet, et al. would predict we should see states. Comparisons to shell model predictions will complete the study.

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3. C.C. Lu, et al., Phys. Rev. 186, 1086 (1969).

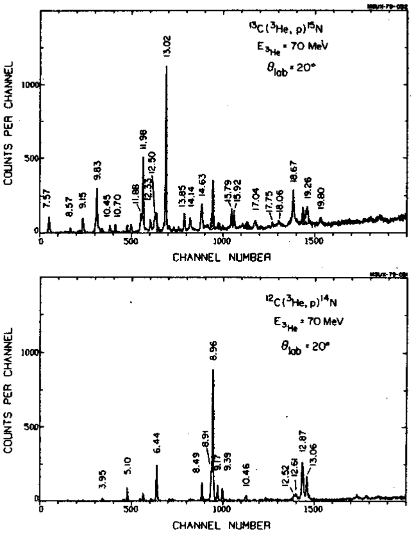


Fig. 1. Spectra of the ^{17}C(He,p)^{14}N and ^{13}C(^{3}He,p)^{15}N reactions at a bombarding energy of 70 MeV and a scattering angle of 20 degrees.

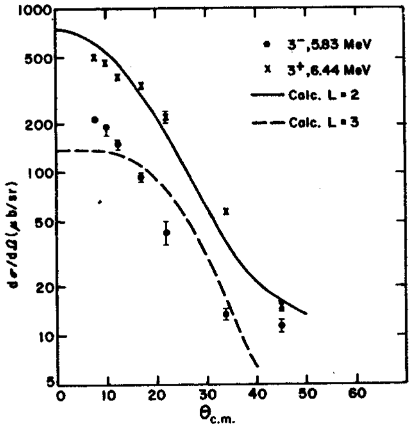


Fig. 3. Angular distributions of the 5.83 and 6.44 states in ^{14}N measured in this study. The data are compared to DWBA calculations for L=3 and L=2 transfers respectively. Note that the data for the two states resemble each other mere than the calculations.

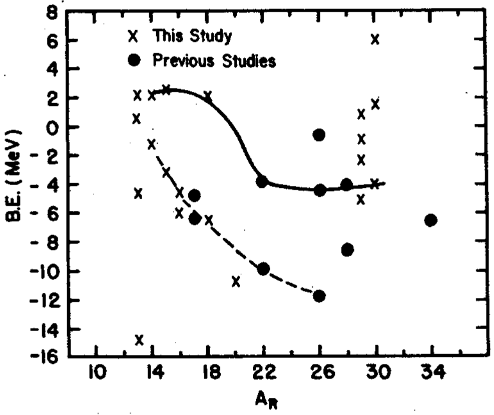


Fig. 3. The binding energies of the states most strongly populated by (^{3}He,p) and (α,d) reactions plotted versers the mass of the residual nucleus. For $A_R \leq 22$ the dashed line passes near the strongest states and the solid curve through the second strongest. For A > 22 the solid curve passes near the strongest state for each nucleus. Crosses indicate states observed by Rivet et al (2) in (α,d) reactions.

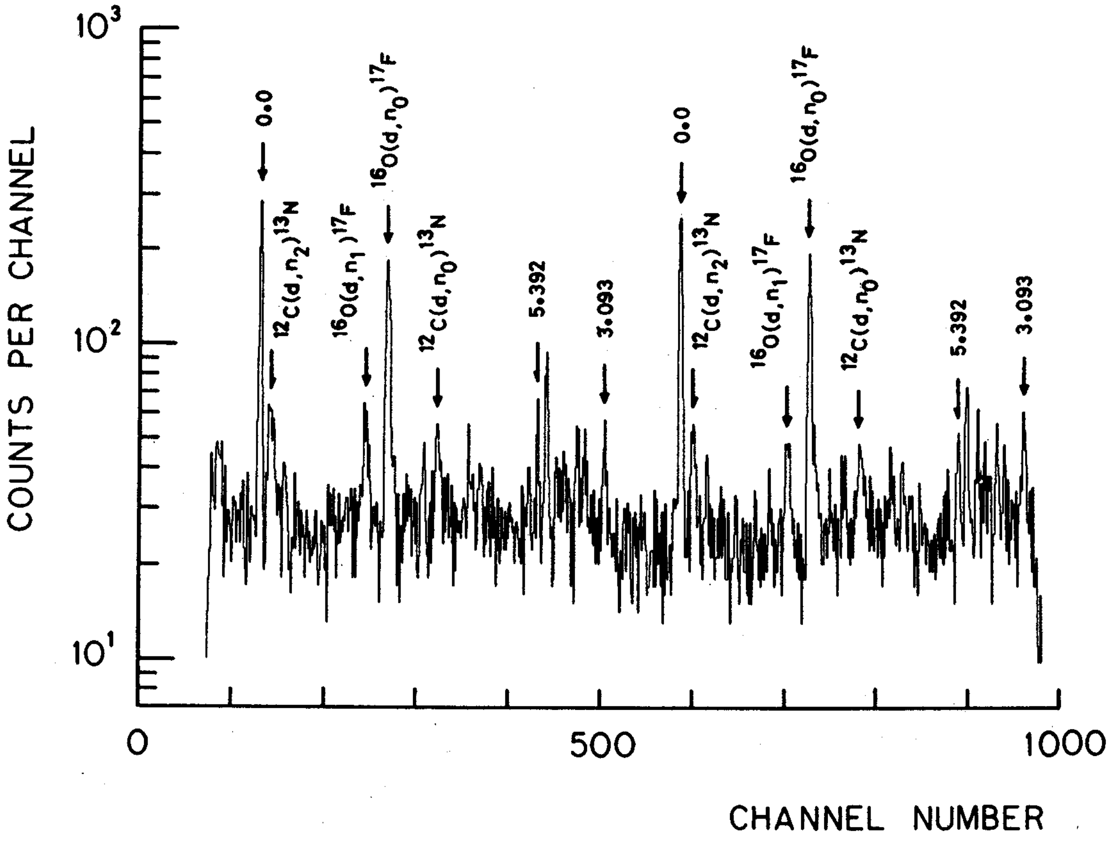
The ^{48}Ca(d,n)^{49}Sc Reaction at 20 MeV; Spectroscopic Factors From the (d,n) and (^{3}He,d) Reactions

Y. Iwasaki,* A. Galonsky, and D.J. Weber+

Proton single particle states have often been studied with the (^{3}He,d) reaction. In order to check the spectroscopic information derived from this reaction, we have performed a (d,n) experiment on ^{48}Ca. This target is doubly magic, and the final nucleus in the reaction, ^{49}Sc, has a series of well-separated proton single-particle states which have been well studied with the (^{3}He,d) reaction.[1]

By using a large liquid scintillation detector[2] at a distance of 34 meters from the target we achieved a neutron energy resolution of about 120 keV with time-of-flight spectrometry.[2] Data were taken at 13 angles from 7.5° to 50°. One of the time spectra is shown in the figure. Up to an excitation energy of 7.1 MeV, thirteen peaks (one a doublet) are resolved.

A standard DWBA analysis using DWUCK 72[3] is in progress. Preliminary analysis shows that derived spectroscopic factors are generally in agreement with those obtained from ^{48}Ca(^{3}He,d) data.[1]



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High-Lying Neutron Hole Strength in Zr, Sn, Te, and Sm Isotopes Via the (p,d) Reaction at 42 MeV

S. Gales[+], G.M. Crawley, D. Weber[++], and B. Zwieglinski[*]

One neutron hole strength distributions in $^{89,91}Zr$, $^{111,115,117,119,121,123}Sn$, $^{121,123,129}Tc$ and $^{143,147,149,151,153}Sm$ nuclei have been investigated between 0 and 12 MeV excitation energy using the (p,d) reaction at 42 MeV incident energy. A similar systematic study has been undertaken via the (^3He,α) reaction at 70 MeV in order to enhance hole components with large angular momentum near the N=82 (Te,Sm) and the N=126 (Pb,Bi) neutron closed shell.[1]

The comparison of such reactions is very useful in order to determine unambiguously the ℓ transfers involved in the neutron pick-up processes. Both different matching conditions and absolute normalizations of the measured cross sections lead to a better determination of the total neutron hole strength concentrated in the "giant resonance" like structure observed in the study of the (p,d) and the (^3He,α) reaction to deep hole states in heavy nuclei.

In order to study a large range of excitation energy with good energy resolution (25 to 35 keV) the outgoing deuterons were detected in the focal plane of a split-pole spectrograph using a 50 cm delay line gas counter. Under such conditions a strong fragmentation of the $1f_{7/2}$ neutron hole strength is observed around 4-5 MeV in $^{89-91}Zn$ isotopes. The "fine structure" evident at about 5.5 MeV in the lighter tin isotopes (^{111}Sn, ^{115}Sn) is clearly confirmed. The (p,d) reaction enhances the ℓ=1 ($2p_{1/2}$, $2p_{3/2}$) part of the inner neutron hole strength in the tin isotopes and this substructure is clearly resolved from the ℓ=4 ($1g_{2/2}$) part of the bump. In addition a broad and weaker bump located around 8-9 MeV in the Sn isotopes is suggested by the present experiments.

As for the heavier mass nuclei (Te,Sm), broad structures (Γ≃2-6 MeV) already observed in the study of the (^3He,α) reaction on the same target nuclei are confirmed. However, the spreading of the $1\ g_{g/2}$ and $1\ h_{11/2}$ inner neutron hole states in Te and Sm isotopes appears to be smaller in the (p,d) spectra as compared to the (^3He,α) results. Such preliminary results may indicate the population of large ℓ components (ℓ=4,5) at rather high excitation energy ($Ex \gtrsim 9$ MeV) in the (^3He,α) spectra whereas such strength is much smaller in the (p,d) data.

Figure 1 shows the spectra obtained for the $^{144,148,150,152,154}Sm(p,d)$ reaction at 42 MeV incidental energy. One can notice the low "background" at high excitation energy and the clear enhancement of the "peak" cross section observed at 4.8, 3.6, 2.9, and 2.7 MeV respectively, in $^{147,149,151,153}Sm$ isotopes. A large amount of strength is located in the tail of the main bump and this contribution increases with the mass number A of the target nucleus. This behavior strongly suggests a correlation between the characteristics of the deep-hole states (e.g., Ex, Γ) and the transition between spherical to deformed core states in the Sm isotopes.

DWBA analysis of the angular distributions for both the well separated low-lying states and the fragmented structures are now in progress. A search for a consistent set of optical model parameters in the proton and deuteron channels is being carried out to reproduce the pick-up data in this large range of the mass table (A=90 to 154). In this preliminary stage both exact finite range and adiabatic deuteron break up calculations seem to be needed in order to achieve a consistent description of the individual angular distribution.

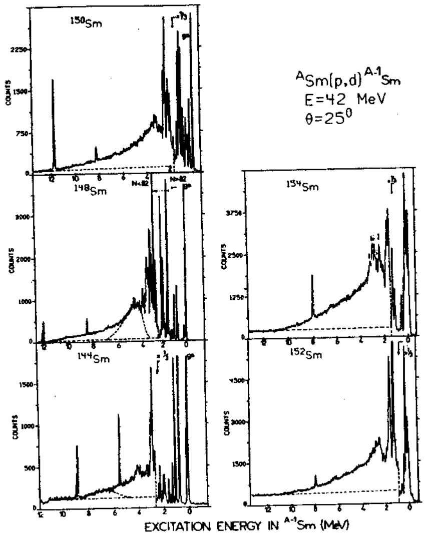

Fig. 1.

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Deep Hole States Observed in One and Two Particle Transfer Reactions on the Sn Isotopes

G.M. Crawley, W. Benenson, S. Gales, D. Weber and B. Zwieglinski

A broad structure has been observed in (p,t) reactions on the even Sn isotopes ^{112}Sn, ^{116}Sn, ^{118}Sn, ^{120}Sn, ^{122}Sn and ^{124}Sn between 7 and 9 MeV excitation energy. A preliminary report of this work has been published as a letter[1] and a more complete discussion was presented earlier this year[2], Both the width and the excitation energy of the observed structure show a very similar A dependence to that observed in (p,d) reactions on the same targets which populate the g9/2 deep hole state (See Fig. 1.) Thus it seems clear that the structure observed in the (p,t) is related to the pickup of at least one particle from a deep lying orbit.

However, it is not clear whether one or both neutrons are picked up from deep orbits. For the case, where both particles leave deep holes, the excitation energy would be about twice the single hole energy minus the interaction energy between the two particles picked up. For the heavier tin isotopes, ^{116}Sn to ^{124}Sn, the difference between twice the g9/2 hole excitation energy and the excitation energy of the bump in the (p,t) spectrum is very nearly constant at about 2.2 MeV. This value is not too different from the pairing energy between particles in the same shell. For example, Broglia and Bes estimate a value of about 1.7 MeV for the pairing energy in this same region. One exception is the much smaller difference of only about 0.75 MeV for the ^{112}Sn target.

If on the other hand one particle is picked up from a valence orbit and one from a deep orbit the excitation energy would be the sum of the hole energy plus the excitation energy of the valence particle minus the interaction energy. The interaction energy would be small in this case since the particles are in widely separated orbits. If an average valence particle energy is about 2.0 MeV, for example in ^{116}Sn (d,t), then the expected bump position in (p,t) would be at 7.2 MeV or less. This is rather lower than the 8 MeV excitation energy observed in the ^{116}Sn (p,t) reaction but does not clearly rule out this possibility. A rather more detailed calculation by Broglia predicts the 0^+ states formed from the g9/2 and p shell holes to occur around 9 MeV which lend support to the ideal that the neutron picked up both come from deep orbits.

A further check on the excitation energy expected for a one-valence deep hole was made using the (p,d) reaction on the odd Sn isotopes ^{117}Sn and ^{119}Sn. A broad structure, similar to that observed for the (p,d) on even Sn targets was observed at an excitation energy of about 7.8 MeV in ^{116}Sn and 8.0 MeV in ^{118}Sn respectively. This indicates that the excitation energy of the one-valence one-deep hole strength in ^{116}Sn and ^{118}Sn is similar to the excitation energy of the structure observed in the (p,t) reactions.

DWBA calculations were carried out using the code DWUCK. Two different assumptions were made in the calculations. In one case both particles were assumed to be picked up from one of the deep hole orbits g9/2 p1/2 or p3/2. In the other case one particle was picked up from a valence orbit either g7/2 or d5/2 and the other particle was assumed to come from the g9/2 orbit.

For the case of both particles picked up from a deep orbit, the angular momentum transfers which are strongest are $\ell=0$, 2, 3, and 5. The $\ell=4$, 6 and 8 transfers are about an order of magnitude weaker. No one transition dominates and the incoherent sum is plotted as a solid curve in Fig. 2 where it is compared with the measured cross section.

For the one valence, one deep hole case, there are no $\ell=0$ transitions of course, and the remaining ℓ transfers are comparable in magnitude. The sum is shown as a dashed curve in Fig. 2. The magnitude of the predicted cross section is more than a factor of two less than for the two deep hole calculations and the experimental cross section is larger than that predicted by about 20%. On the other hand, for the two deep holes, only about 50% of the predicted strength is observed experimentally. Unfortunately no definative conclusions can be drawn from the shapes of the theoretical angular distributions compared with the measured cross section.

If one particle is being picked up from a valence orbit, one might expect the strength to increase as the mass number increases since more particles are present in the valence orbits for the Sn isotopes with larger A. However the peak cross section if fairly constant across the isotopes showing only very slight increase for the ^{118}Sn and ^{120}Sn targets. This would be consistent with picking up two particles from deep orbits since these are presumably full in all the isotopes.

A more complete report of this work is being prepared for publication.

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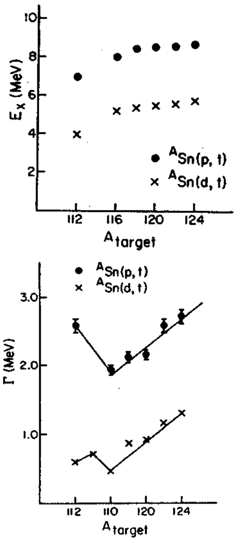

Fig. 1.(a) Excitation energies of the $g_{9/2}^{-1}$ hole state and of the broad structure near 8 MeV observed in the (p,t) plotted va. the A of the tin target isotope.

Fig. 1.(b) Full width half maximum of broad structure observed in (p,t) and (d,t) reactions on the tin isotopes plotted vs. A of the target. The solid lines are only to guide the eye.

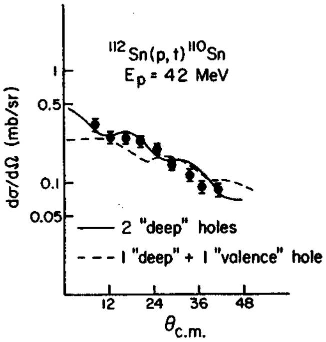

Fig. 2. Angular distribution for the "bump" in the triton spectrum in the reaction ^{112}Sn(p,t)^{110}Sn. The curves are DWBA predictions as discussed in the text. The solid line assumes pickup from two "deep" orbits and the dashed curve pickup from 1 "deep" orbit and 1 "valence" orbit.

Study of the (p,t) Reaction on the Cadmium Isotopes

G.M. Crawley, S. Gales, D. Weber and B. Zwieglinski

In order to further investigate the broad structure observed in the tin isotopes, (p,t) experiments were carried out on a series of even even cadmium isotopes, from A = 106 to A = 116. About 11 to 15 MeV of excitation was observed using a 50 cm Markham-Robertson delay line counter backed by a plastic scintillator placed in the focal plane of an Enge split-pole spectrograph. An energy resolution of 35 KeV FWHM was obtained.

Whereas only one broad state was observed at high excitation in tin, a number of broad features are evident below 15 MeV in all cadmium spectra (Fig. 1) although the one at lowest excitation energy is strongest in all the isotopes. For ^{104}Cd, the lightest cadmium studied, the broad peaks below 8 MeV exhibit considerable fine structure. As in tin, the peaks appear to move toward lower excitation enregy with decreasing target mass. The strongest of the broad states occurs at 7.7 MeV in ^{114}Cd and 6.3 MeV in ^{104}Cd. Since the deep orbits are closer to the fermi level in the Cd isotopes than in the tin isotopes, the fact that the strong broad bump occurs at lower excitation energy in the cadmium isotopes, adds further weight to the agrument that this feature is associated with holes in deep orbits.

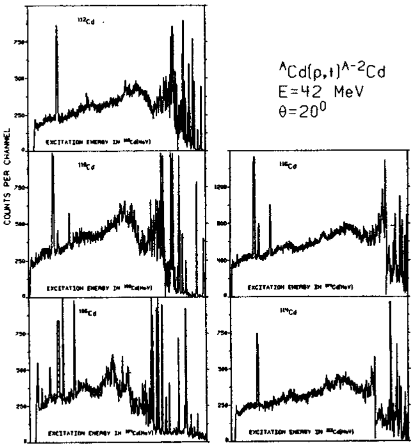

Fig. 1

In addition to the broad features, very little is known about the low lying levels of ^{104}Cd. A mass excess of 83.99 ± 0.21 MeV was obtained in the present work based upon a Q value for the (p,t) reaction of -10.802±0.015 MeV.

Angular distributions for ^{106}Cd (p,t) ^{104}Cd were measured from 8° to 50°. The energy levels of ^{104}Cd observed are shown in Table 1 together with the levels observed in a previous (^{3}He,3nγ) experiment by Hashizume et al. One interesting feature of the angular distribution for a couple of the high lying levels in the region of the bump, is that these appear to have a 0^{+} angular distribution. This would indicate rather directly that two particles are being picked up from the same orbit, supporting the argument that at least some of the strength in the bump arises from picking up two neutrons from deep orbits.

Table 1. Energy levels in ^{104}Cd.

Ex (MeV) from (p,t) expt.	Ex (MeV) from (^{3}He,3nγ) expt.
0.0	0.0
0.665	0.6583
1.507	1.4929
(1.780)	
2.126	(2.1087)
	2.3713
2.445	2.4354
2.587	
	2.871
2.907	2.910
2.997	
3.090	
3.225	3.212
	3.261
3.577	
3.750	
3.793	3.912
5.410	
6.191	

Energy Levels in ^{60}Ni From a Study of the ^{59}Ni(d,p) Reaction

J.A. Nolen, Jr., M.S. Curtin, R.C. Melin, R.M. Ronningen, S. Raman,* and H. Nann**

In order to obtain precise level energies in ^{60}Ni and spectroscopic information for single neutron stripping we have studied the ^{59}Ni(d,p)^{60}Ni reaction at 20 MeV. The protons were detected in the focal plane of the Enge split-pole magnetic spectrograph using both a 50 cm slanted-cathode position-sensitive delay-line proportional counter and nuclear emulsion plates. The counter data were taken in 10° steps from 10° to 50°. The data at 40° are shown in Fig. 1. Two adjacent nuclear emulsion plates (25μ NTB) fronted by 0.0254 mm stainless steel absorbers were used to obtain high-resolution data at 10° and 20°. The data collected on the low-excitation energy plate at 10° are shown in Fig. 2. The resolution was about 15 keV in the counter experiment. The excitation energy range of the plates and counter is about 12 MeV.

The plate data for the lower energies confirms within 1 keV known strongly excited levels below 5 MeV. The plates for the high excitation energy levels are being scanned and the spectra from the counter are being analyzed.

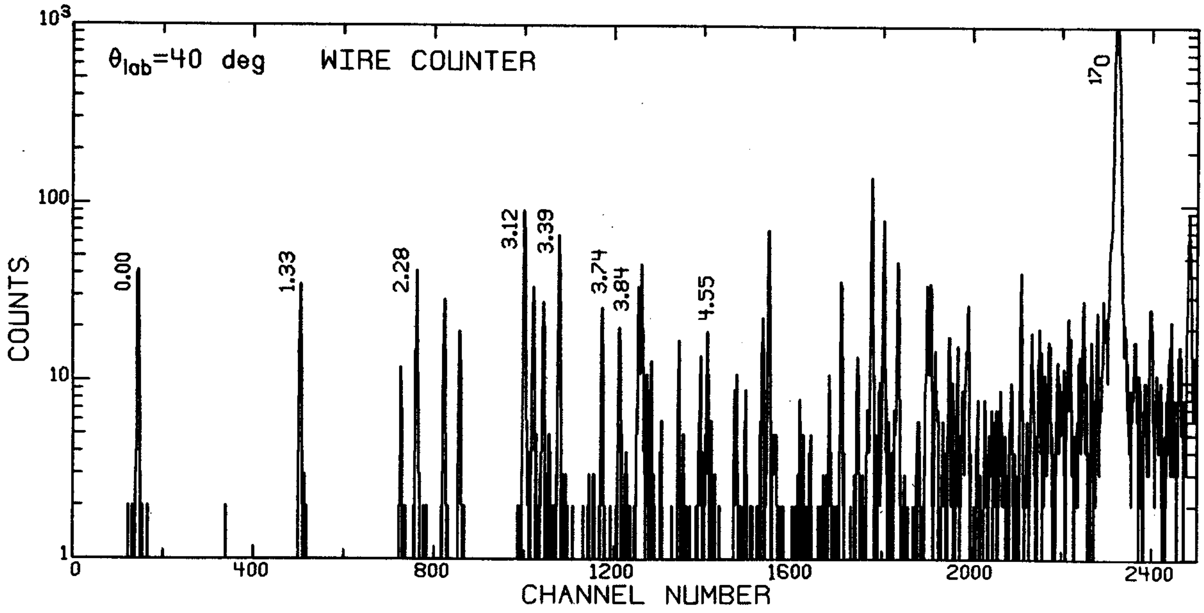

Fig. 1.

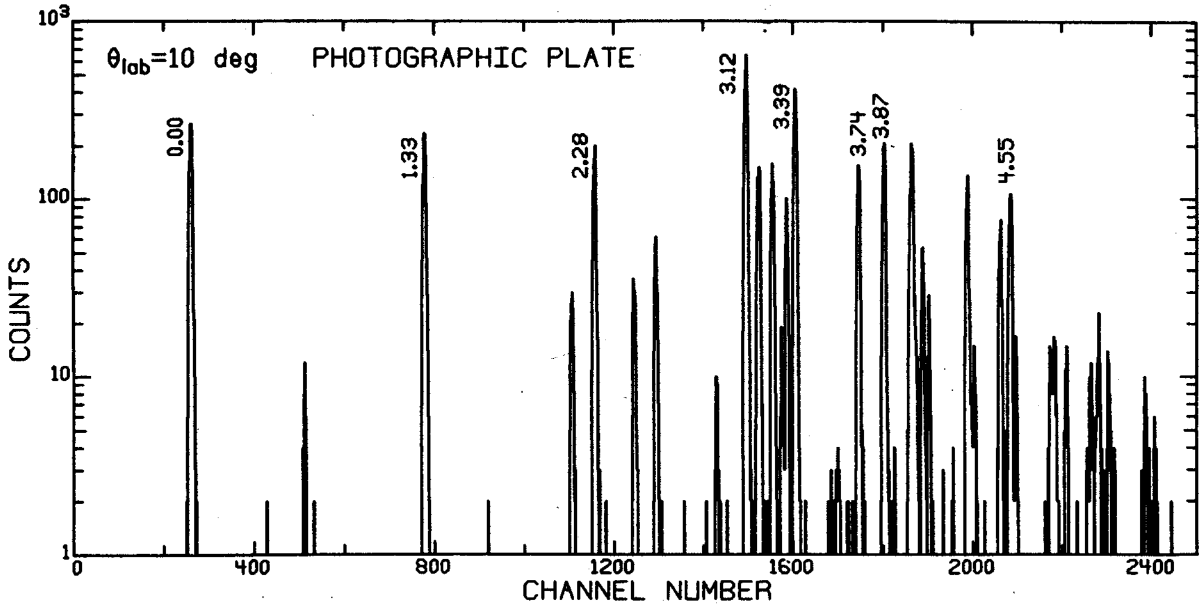

Fig. 2.

"The ^{206,204}Pb (p,α) ^{203,201}Tl Reactions At 35 MeV"

D. Weber, G.M. Crawley, and P.A. Smith$^+$

The level structure of the thallium nuclei provides a useful test both for full shell model studies and for simpler calculations based upon the weak and intermediate coupling schemes. The three hole nucleus ^{205}Tl was recently studied[1] via the ^{208}Pb(p,α) reaction at 35 MeV.

This work was continued with studies of the ^{206}Pb(p,α) ^{203}Tl and ^{204}Pb(p,α) ^{201}Tl reactions at 35 MeV. These data provide further tests of shell model theories farther from the closed shell. It is also of interest to check the validity of a weak coupling picture for these nuclei. As a result of the increasing number of possible phonons in lead with increasing neutron deficiency, the weak coupling picture is not expected to be too successful for these lighter thallium isotopes.

A beam of 35 MeV protons from the Michigan State University Cyclotron was used to bombard a 150 μg/cm^2 target of isotopically enriched ^{206}Pb evaporated onto a 20 μg/cm^2 carbon backing and a 300 μg/cm^2 target of isotopically enriched ^{204}Pb evaporated onto a 30 μg/cm^2 carbon backing. The reaction products were detected after analysis by an Enge Split pole spectrograph on a Markham-Robertson delay line counter[2] backed by a plastic scintillator. A number of spectra were taken on photographic emulsions together with spectra for the ^{93}Nb(p,α) ^{90}Zr reaction. The low lying levels of thallium whose energies were well determined from γ studies and the known levels of ^{90}Zr were used to calibrate the thallium spectra. Typical ^{201}Tl counter spectra with an energy resolution of 35 keV FWHM are shown in figure 1. As with the previously reported ^{205}Tl data, the low-lying low spin states are strongly forward peaked while numerous peaks above 2 MeV excitation emerge at backward angles.

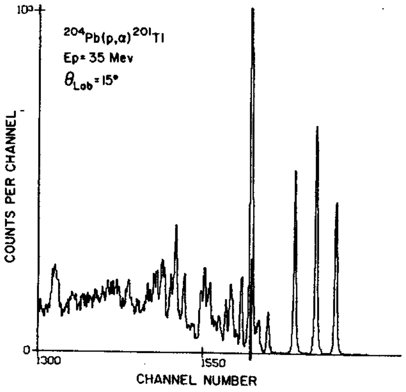

Fig. 1.

About 51 levels of ^{203}Tl and 45 levels of ^{201}Tl were observed in the present study. Angular distributions for a number of these states were obtained and spin assignments were made on the basis of the angular distributions.

Cluster model DWBA calculations provided excellent fits to the data using the optical model parameters of reference 1.

As with ^{205}Tl, a weak coupling scheme for an $s_{1/2}$ proton hole coupled to collective states of lead properly predicts the low lying spectrum of ^{203}Tl although the centroids of the resultant doublets again are predicted about 400 keV above their observed energies. Many of the levels excited through the ($\vec{t}$,α) reaction[3] are also seen strongly in (p,α), evidence in support of the crude "Spectator model", which assumes that the two neutrons are transferred coupled to zero angular momentum.

The low lying states of ^{201}Tl are quite similar to those of ^{205,203}Tl and except for a depression by ~ 500 keV, again fit well into a weak coupling picture. Once again a number of low lying low spin states excited in stripping reactions and seen in the decay of ^{201}Pb, those at 1.098, 1.157, 1.239, and 1.420 MeV, do not appear in the (p,α) spectra. In this case, no ($\vec{t}$,α) data can be obtained for comparison, removing an important test of the importance of the transferred neutrons in the (p,α) reaction. A large number of (13/2, 15/2) and (15/2, 17/2) spin assignments have been made, including one at 1.923 MeV, roughly 400 keV lower in excitation than any similar state seen in the heavier isotopes of thallium. Two possible L=9 transfers are observed between 3.6 and 3.8 MeV but with peak cross sections of only 5 μb/sr.

In summary, a good correspondence exits for states in ^{205}Tl, ^{203}Tl and ^{201}Tl below about 1.5 MeV excitation. Between 1.5 and 2.0 MeV, states with 5/2 or 7/2 spin assignments dominate the spectra. Above about 2.0 MeV, there is little correspondence between levels, including those of high spin. States involving L=9 transfers below 2.6 MeV, which cannot be explained by a weak coupling scheme, appear in all three isotopes. Among states with the highest spin, j $\geq$ 19/2, there is an apparent fragmentation of strength. Levels involving L=10 or 12 transfers are weaker in ^{201}Tl than in ^{205}Tl and may increase in number as some of them may be too weak to be observed in ^{203}Tl and ^{201}Tl. The neutrons apparently play an important part in the (p,α) reaction.

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Quartet-plus-Doublet Interpretation of the Excited-Core States in ^{63}Cu

Y. Iwasaki and G.M. Crawley

Experimental data of the reactions ^{63}Cu(p,p')^{63}Cu and ^{65}Cu(p,t)^{63}Cu at E = 40 MeV[1,2] have been analyzed to obtain information on excited-core states in ^{63}Cu. Octupole states that were observed in the ^{63}Cu(p,p')^{63}Cu reaction were interpreted in terms of a weak-coupling quartet-plus-doublet model.[3] A quartet arises from the coupling of a collective state of the core ^{62}Ni with the $2p_{3/2}$ proton orbital, and a doublet from the coupling with the $2p_{1/2}$ proton orbital. Further comparative study of the ^{63}Cu(p,p')^{63}Cu and ^{65}Cu(p,t)^{65}Cu data have shown that the quartet-plus-doublet pattern exists consistently also for quadrupole and hexadecapole excited-core states. Fig. 1 shows the excitation strengths of quadrupole states. The states at E_x = 0.67, 0.96, 1.33, and 2.01 MeV are the $1/2^-$, $5/2^-$, $7/2^-$, and $3/2^-$ members of the quartet $2p_{1/2} \otimes 2_1^+$ (core). The states at E_x = 1.41 and 1.55 MeV are the $5/2^-$ and $3/2^-$ members of the doublet $2p_{1/2} \otimes 2_1^+$. Fig. 2 shows the excitation strengths of octupole states. The states at E_x = 3.32, 3,48, 3.72, and 3.84 MeV are the members of the quartet $2p_{3/2} \otimes 3_1^-$.[3] The states at E_x = 3.81 and 3.89 MeV are the members of the doublet $2p_{1/2} \otimes 3_1^-$.[3] The state at E_x = 2.51 MeV requires a special consideration.[2,3] Fig. 3 shows the excitation strengths of hexadecapole states. The states at E_x = 2.21, 2.34, 2.54 and 2.68 MeV are the members of the quartet $2p_{3/2} \otimes 4_1^+$. The states at E_x = 2.85 and 2.88 MeV are the members of the doublet $2p_{1/2} \otimes 4_1^+$. The persistent occurrence of the quartet-plus-doublet pattern is evidence that the mixing between different multiplets (in particlular, multiplets corresponding to different collective states of the core) is weak, and that the ground states of ^{63}Cu and ^{65}Cu have considerable amplitudes of the component $2p_{1/2} \otimes 2_1^+ \, _{3/2}$. A detailed account of the above results will be published soon.[2]

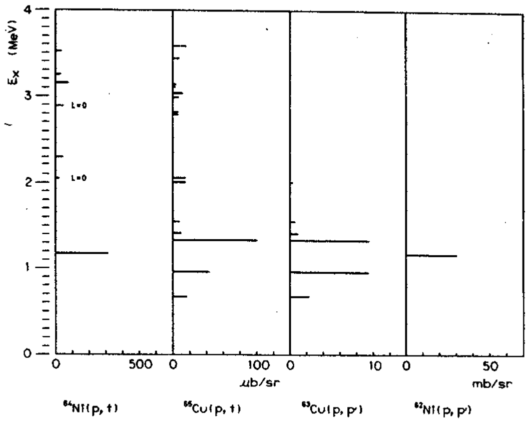

Fig. 1. Excitation strengths of quadrupole states. Solid segments denote pure quadrupole transitions, dashed segments quadrupole-plus-monopole transitions, and dotted segments pure monopole transitions.

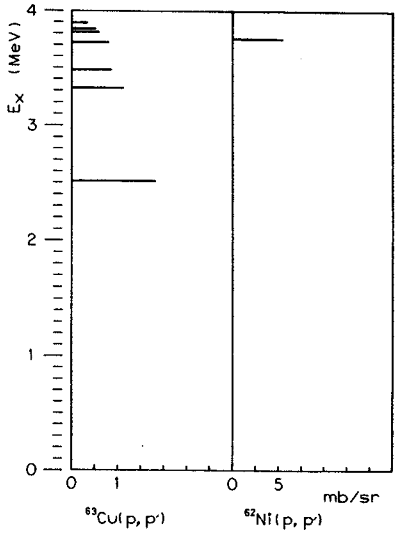

Fig. 2. Excitation strengths of octupole states.

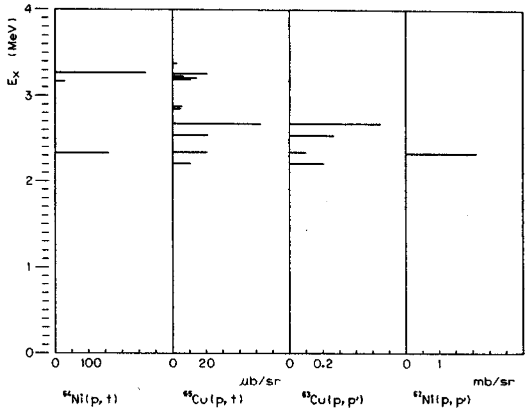

Fig. 3. Excitation strengths of hexcdecapole states.

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Deep Hole States in Two Particle Transfer Reactions at 90 MeV Bombarding Energy

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The purpose of this experiment was to further explore the broad structure observed in (p,t) reactions in the tin isotopes at a bombarding energy of 42 MeV.[1] The experiment at IUCF was carried out in two runs in June and Dec. 1978 using the 90 MeV proton beam. A Si(ΔE) and intrinsic-Ge(E) detector telescope was used to detect the tritons. Deuteron spectra from the (p,d) reaction were recorded simultaneously. Elastic protons were excluded using a veto detector. Spectra were obtained from targets of ^{144}Sm, ^{124}Sn, ^{122}Sn, ^{120}Sn, ^{94}Mo, ^{90}Zr, and ^{58}Ni. An angular distribution of the (p,t) and (p,d) reactions from 15° to 45° was measured on the ^{120}Sn target.

Structure similar to that observed at lower bombarding energy was clearly observed in the triton spectra on the Sn isotopes as shown in Fig. 1. Broad features were also observed in the spectra from the other isotopes studied except for the case of ^{58}Ni. The (p,d) spectra, also displayed in Fig. 1, showed a very clean excitation of the single hole states in the tin isotopes as well as the higher lying analogue states. Higher lying states were also observed in most of the isotopes studied. Perhaps the best example was the ^{90}Zr(p,d) reaction (a spectrum at 25° is shown in Fig. 2) where $g_{9/2}^{-1}$, $f_{5/2}^{-1}$, $f_{7/2}^{-1}$, and three $T_>$ analogue states were observed. In addition, a broad peak can be seen at around 15 MeV excitation which might correspond to holes in the 2s1d shell.

Comparison of the measured angular distribution with the theoretical predictions from a DWBA calculation should help cast further light on the nature of these features at high excitation energy. A report of this work is being prepared for publication.

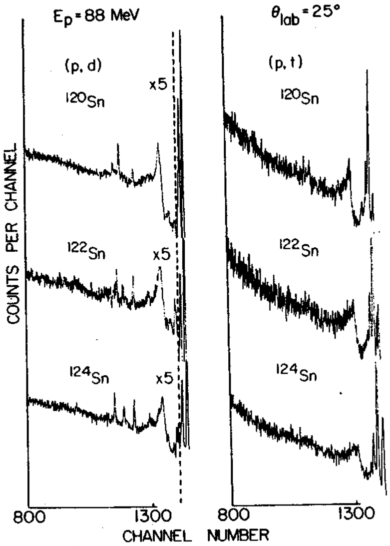

Fig. 1. Spectra of deuterons and tritons at a laboratory angle of 25° from bombardment of tin isotopes with 88 MeV protons. Strong excitation of the $g_{9/2}$ hole is observed near channel 1350 in the (p,d) spectra. A broad feature near channel 1300 is also observed in the triton spectra.

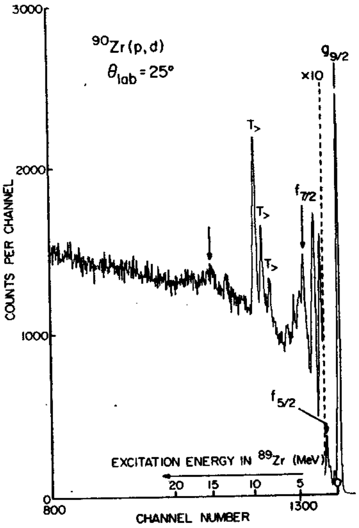

Fig. 2. Spectra of deuterons from the ^{90}Zr(p,d) reaction at a bombarding energy of 88 MeV. Excitation of hole states below 5 MeV of excitation are marked as well as three strong $T_>$ states. A broad structure near 15 MeV excitation (marked by an arrow) could be due to holes in the 5d shell.

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L=2 Amplitude in the (p,t) Transition Between the Ground States of Odd-Proton Nuclei Having the Same Spin-Parity

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In the (p,t) transition between the ground states of odd-proton nuclei having the same spin-parity J^{π}, transition amplitudes with transferred angular momenta L=0, 2, ---, 2J - 1 are allowed by the general conservation laws of spin and parity. In the particle-core-coupling model[1,2] of an odd-proton nucleus in a spherical region, the most dominant configuration (the zeroth-order component) in the ground-state wave function is the one having the core in its ground state and the odd proton in an orbital with the spin-parity J^{π}. The next dominant configurations (the first-order components) are the ones having the core in its first excited state with spin-parity 2^+ and the odd proton in appropriate orbitals. If the single-step two-neutron-transfer mechanism is assumed, the odd proton is a spectator. The most dominant term (zeroth-order term) in the (p,t) transition amplitude is the L=0 amplitude that connects the zeroth-order component $[J^{\pi} \otimes 0_1^+ \text{ (target core)}]_{J^{\pi}}$ of the target ground-state wave function with the zeroth-order component $[J^{\pi} \otimes 0_1^+ \text{ (residual core)}]_{J^{\pi}}$ of the residual ground-state wave function, and the next dominant terms (first-order terms) are the L=2 amplitude connecting the zeroth-order component of the target ground state with the first-order component $[J^{\pi} \otimes 2_1^+ \text{ (residual core)}]_{J^{\pi}}$ of the residual ground state, and the L=2 amplitude connecting the first-order component $[J^{\pi} \otimes 2_1^+ \text{ (target core)}]_{J^{\pi}}$ of the target ground state with the zeroth-order component $[J^{\pi} \otimes 0_1^+ \text{ (residual core)}]_{J^{\pi}}$ of the residual ground state. Since the transition amplitudes with different L's contribute incoherently to cross sections, and since the L-2 amplitude is relatively large at the angular positions of the minima of the L=0 angular distribution, the L=2 contributions to differential cross sections fill in the valleys of the L=0 angular distribution. Therefore, the angular distribution for the ground-state (p,t) transition between odd-proton nuclei with the same spin-parity J^{π} have shallower minima compared with that for the ground-state transition between the corresponding core nuclei. Such an effect was observed for a few cases.[3,4] A comparison of the angular distributions for the ground-state transitions between odd-proton nuclei and between the corresponding core nuclei gives information on the sizes of the components $[J^{\pi} \otimes 2_1^+ \text{ (target core)}]_{J^{\pi}}$ and $[J^{\pi} \otimes 2_1^+ \text{ (residual core)}]_{J^{\pi}}$.

We consider the case of the transitions ^{65}Cu(p,t_0)^{63}Cu and ^{64}Ni(p,t_0)^{62}Ni. Both the ground states of ^{63}Cu and ^{65}Cu have $J^{\pi} = 3/2^-$, and are generally considered to have similar structures. According to a conventional calculation[2] in the particle-core-coupling model, the ground-state wave function of ^{63}Cu has the most dominant component $[3/2^- \otimes 0_1^+ \text{ (residual core)}]_{3/2^-}$ with an amplitude of 0.9221 and the next dominant component $[3/2^- \otimes 2_1^+ \text{ (residual core)}]_{3/2^-}$ with an amplitude of -0.3264. If this wave function is employed for both the ground states of ^{63}Cu and ^{65}Cu, and the pure L=0 and L=2 transition matrix elements are derived from the ^{64}Ni(p,t)^{62}Ni data at E = 40 MeV,[5] and if the matrix element for the L=2 transition ^{62}Ni(0_1^+) → ^{64}Ni(2_1^+) is roughly equal to that for the L=2 transition ^{64}Ni(0_1^+) → ^{62}Ni(2_1^+),[6] the cross section ratio of the first peak to the second minimum of the angular distribution for the ^{65}Cu(p,t_0)^{63}Cu transition is predicted to be smaller than that for the "core" transition ^{64}Ni(p,t_0)^{62}Ni by about 60%. Such a difference in the first-peak-to-second-minimum ratio is not observed experimentally.[7] This means that the L=2 amplitude in the transition ^{65}Cu(p,t_0)^{63}Cu is far smaller than predicted by the conventional particle-core wave function,[2] and in turn that the amplitude of the component $[3/2^- \otimes 2_1^+ \text{ (target core)}]_{3/2}$ or $[3/2^- \otimes 2_1^+ \text{ (residual core)}]_{3/2}$ is far smaller in absolute value than -0.3264. Thus a constraint on the ground-state wave function of ^{63}Cu or ^{65}Cu is obtained. If the component $[3/2^- \otimes 2_1^+]_{3/2^-}$ is smaller, some component(s) must be larger to keep the ground-state wave function normalized. A large $[1/2^- \otimes 2_1^+]_{3/2^-}$ is proposed to give a basis for the quartet-plus-doublet interpretation of excited-core states in ^{63}Cu.[7,8]

The above argument, however, neglects the geometrical aspect[9] of the nucleus-dependence of the (p,t_0) angular distribution. This point requires further investigation.

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Study of the (p,t) reaction on ^{174}Yb at E_p = 38 MeV

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Data of (p,t) reactions on well deformed nuclei have been reported at E_p = 19 MeV[1] and E_p = 52 MeV.[2] Furthermore, measurements on the ground state (p,t) transitions in the region of N = 11 - 146 have been recently performed at E_p = 52 MeV,[3] and the results have shown that the transition strengths in the region of well deformed nuclei are small, and a remarkable change of the cross sections is observed at N = 116. The primary motivation for the present ^{174}Yb (p,t) ^{172}Yb experiment is to compare the transition strengths of the ^{174}Yb (p,t), ^{182}W (p,t) and ^{194}Pt (p,t) reactions at E_p = 38 MeV and to investigate the energy dependence of the reaction mechanism comparing the data at E_p = 38 MeV with those at 19 MeV and 52 MeV.

The ^{174}Yb (p,t) ^{172}Yb reaction has been studied at the proton energy of 38 MeV with a 300 μg/cm^2 target enriched to 99% in ^{174}Yb evaporated on a carbon film with a thickness of 200 μg/cm^2. Triton spectra were measured with a delay-line position-sensitive proportional counter at the focal plane of the Enge split-pole magnetic spectrograph. Angular distributions for 20 peaks up to 2540 keV excitation energy have been measured and are shown in Fig. 1. Relative summed cross sections for the levels of the ground state rotational band are shown in Table I for the ^{174}Yb (p,t) ^{172}Yb reaction at E_p = 38 MeV together with those at E_p = 19 MeV and those for the ^{156}Gd, ^{170}Yb, ^{174}Hf and ^{182}W (p,t) reactions at E_p = 52 MeV. At E_p = 38 MeV, the cross section for the 2^+ state is smaller than that for the 4^+ state in contrast to the results at E_p = 19 MeV and 52 MeV. With a view to accounting for this apparent anomaly, DWBA and CCBA calculations are being performed.

The cross sections for the ^{182}W (p,t) and the ^{194}Pt (p,t) reactions were also measured at the angular positions of the first peak of the L = 0 angular distribution at E_p = 38 MeV and were found to be about 1.3 times and 2.3 times as large as the cross section for the ^{174}Yb (p,t) reaction, respectively. This result shows the same trend as observed at E_p = 52 MeV.[3]

Table I. Relative summed cross sections for the levels of the ground state rotational band.

Energy	38 MeV	19 MeV ref. 1	52 MeV ref. 2			
Target Nucleus	^{174}Yb	^{174}Yb	^{156}Gd	^{170}Yb	^{174}Hf	^{184}W
0^+	1.0	1.0	1.0	1.0	1.0	1.0
2^+	0.174	0.324	0.39	0.37	0.29	0.20
4^+	0.223	0.090	0.048	0.16	0.15	0.15
6^+	0.042	0.018	0.083	0.025	0.029	0.16

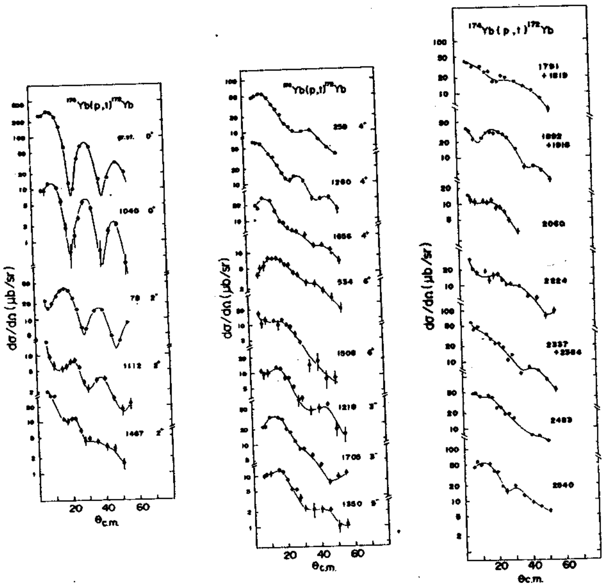

Fig. 1. Angular distributions for low-lying levels. The solid curves are drawn to guide eyes.

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