Spin of deep hole states from $(\vec{p},d)$ reactions

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Analyzing power measurements from the $(\vec{p},d)$ reaction on ^{90}Zr and ^{120}Sn have been made using a 90 MeV polarized proton beam. The spin of the broad structure near 5 MeV excitation energy in ^{119}Sn has been unambiguously determined to be 9/2 from comparison with the empirical analyzing power for the ground state of ^{89}Zr and from distorted wave Born approximation calculations.

[NUCLEAR REACTIONS ^{90}Zr(p,d), ^{120}Sn(p,d) $E=90$ MeV; polarized beam, measured $\sigma(\theta)$, $A_y(\theta)$ DWBA analysis, deduced by J^π, resolution 100 keV.]

In a large number of previous studies of deep-hole states in medium and heavy nuclei, the transferred orbital angular momentum l has been determined from the measurement of the angular distribution. However, the angular distribution is not sensitive to the total angular momentum j of the final state and this assignment has therefore generally been made only on the basis of the theoretical expectation of the position of a particular shell model orbit. Since the predictions of the single particle strength function have been made for definite values of total angular momentum, it is important to determine the j unambiguously.

Distorted wave Born approximation (DWBA) calculations indicate that a strong j dependence is expected for the analyzing power (A_y) of the $(\vec{p},d)$ reaction at incident energies around 100 MeV. At present there is rather little experimental information on this problem. Some A_y measurements for $(\vec{p},d)$ reactions on a few light nuclei at $E_p=65$ MeV have been reported[1] and some unpublished measurements from a few $0s1d$ shell nuclei are available.[2] Measurements at even higher energies from 200 to 400 MeV on ^{13}C also indicate a strong j dependence of the analyzing power.[3] Because of these indications of j dependence and because earlier measurements of the (p,d) reaction at 90 MeV on a series of Sn isotopes showed that deep hole states near 5 and 8 MeV excitation energy were strongly excited,[4] differential cross sections and analyzing powers were measured for $(\vec{p},d)$ reactions on ^{90}Zr and ^{120}Sn using a 90 MeV polarized beam from the Indiana University Cyclotron.

The beam polarization was measured before and after each run using a polarimeter placed in the beam line after the first cyclotron and before injection into the second cyclotron. Earlier measurements had established that there was no loss of beam polarization during the final acceleration stage. The measured polarization in both spin-up and spin-down modes was about 70% and proved to be extremely stable. The spin direction was flipped automatically every minute during the data taking runs to reduce systematic errors. A further check was made by operating two detectors, one on each side of the beam, and equivalent measurements made at the same laboratory scattering angle were in good agreement.

The outgoing particles were detected in a solid state detector telescope consisting of a Si(Li) ΔE detector, an intrinsic Ge(E) detector, and a final veto detector also of germanium. To improve the speed of data collection, particle identification was carried out using Elsint identifier boxes which gave excellent separation between deuterons and tritons. The energy resolution was about 100 keV full width at half maximum. The spectra were calibrated using the (p,d) reactions on ^{58}Ni and Mylar targets.

Deuteron spectra from the ^{90}Zr$(\vec{p},d)^{89}$Zr and ^{120}Sn$(\vec{p},d)$ ^{119}Sn reactions, taken with proton spin up and down, are shown in Fig. 1. These spectra show the strong excitation of the deep hole states in ^{119}Sn near 5.5 MeV and in ^{89}Zr near 4.5 MeV as well as the isobaric analog states (IAS) particularly in ^{89}Zr at an excitation energy near 10 MeV. An inspection of these spectra also shows immediately that the analyzing power is a rather clear indi-

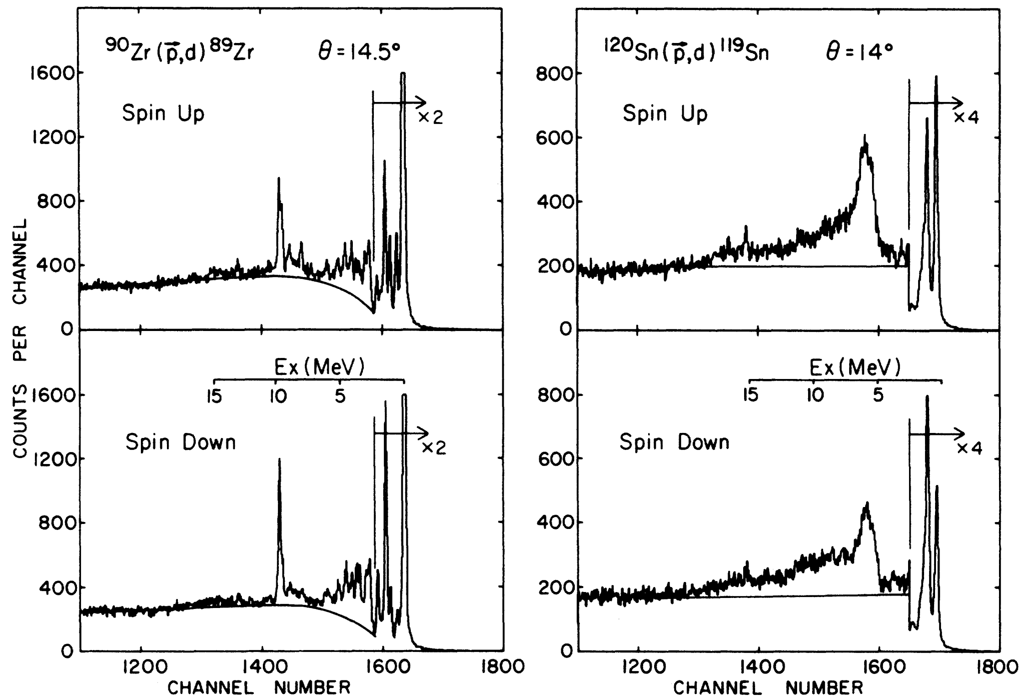

FIG. 1. Deuteron spectra from the ^{90}Zr($\vec{p}$,d)^{89}Zr and ^{120}Sn($\vec{p}$,d)^{119}Sn reactions at 90 MeV bombarding energy taken with proton spin up and proton spin down. The solid lines indicate the background assumption.

cator of total angular momentum at these energies. For example, as one can see from Fig. 1, the low lying $\frac{1}{2}^-$(0.6 MeV) and $\frac{3}{2}^-$(1.1 MeV) states in ^{89}Zr have quite different cross sections for proton spin up and spin down at 14.5°.

The angular distributions of the cross sections on the other hand, shown in Fig. 2 for a few of the low lying states, have a rather steep slope and do not give any clear indication of the j of the final state. The slopes of these angular distributions are different for different l transfers and the $\frac{1}{2}^-$ state has slightly more diffractive structure than the $\frac{3}{2}^-$ state. However the analyzing powers A_y versus scattering angle which are also plotted in Fig. 2 show much more dramatic differences. For example, the A_y's for the two $l=1$ states are completely out of phase and the two $l=4$ states, one in ^{89}Zr and the other in ^{119}Sn, also have substantially different behavior of A_y with scattering angle.

The deep hole states in ^{119}Sn have been analyzed in a number of different ways. A smooth background was drawn under the region as shown in Fig. 1. One analysis consisted simply of slices which divide the region into two pieces, one between 4.5 and 6.5 MeV of excitation energy, and the other over the excitation energy region between 6.5 and 9.0 MeV. Alternately these two regions were fitted by Gaussian peak shapes of width 1.5 and 3.0 MeV, respectively. Since the lower energy peak is rather sharp and quite strongly excited, these two methods gave rather similar results. The analyzing power for the lower energy peak extracted using the former method is shown in Fig. 3(a) together with the empirical A_y for two known $\frac{9}{2}^+$ and $\frac{7}{2}^+$ states, one the ground state of ^{89}Zr and the other in ^{119}Sn(0.09 MeV). The A_y for the $\frac{9}{2}^+$ state gives rather good agreement with the data, which on the other hand is very different from the A_y for the $\frac{7}{2}^+$ state.

Distorted wave born approximation calculations have been carried out using the code DWUCK [5] with finite range corrections primarily to check the sensitivity of the A_y values to changes in target mass and excitation energy. Calculations were carried out for a number of low lying states in ^{89}Zr and ^{119}Sn with known spin as well as for the deep hole states. The first calculations were carried out with standard optical potentials obtained from fitting elastic proton and deuteron elastic scattering.[6,7] The fits to the A_y were substantially improved if the V_{so} in the proton channel was increased by 2 MeV. The optical parameters which gave the best fits are shown in Table I. The calculated angular distributions of the cross sections reproduce the experimental angular distributions reasonably well, perhaps the worst cases being for the two $l=1$ transitions. The spectroscopic factors extracted are given in Table II and are in fairly good agreement with previously reported values. In particular, the spectroscopic factor

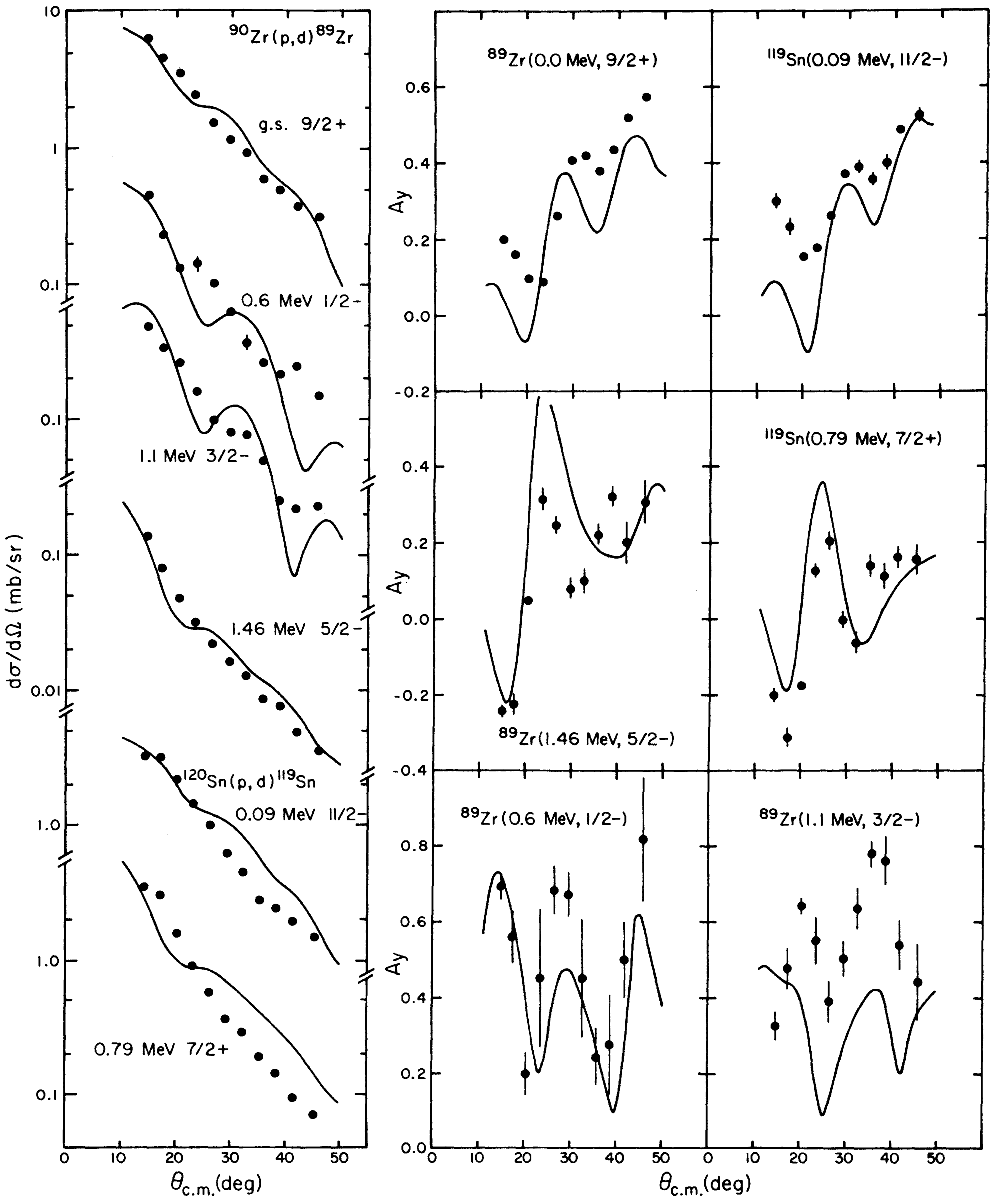

FIG. 2. Angular distributions and analyzing powers for low-lying states in ^{89}Zr and ^{119}Sn. The excitation energies, angular momentum transfer, and spin values are indicated for each state in the figure. Solid lines are DWBA predictions for the indicated l and j values.

TABLE I. Optical parameters used in the analysis of the $(\vec{p},d)$ reaction on ^{90}Zr and ^{120}Sn at 90 MeV bombarding energy.

Channel	V_0 (MeV)	r (fm)	a (fm)	W (MeV)	W_d (MeV)	r_i (fm)	a_i (fm)	V_{so} (MeV)	W_{so} (MeV)	r_{so} (fm)	a_{so} (fm)	r_C (fm)
$p + {}^{90}$Zr	28.2	1.22	0.72	6.9		1.40	0.55	6.0	0.85	1.08	0.66	1.25
$p + {}^{120}$Sr	28.3	1.225	0.728	6.9		1.40	0.56	6.0	0.85	1.09	0.65	1.25
$d + {}^{89}$Zr	71.58	1.25	0.796		18.0	1.23	0.82	6.39		1.34	0.55	1.3
$d + {}^{119}$Sn	72.17	1.25	0.829		16.43	1.223	0.732	5.56		1.275	0.66	1.3

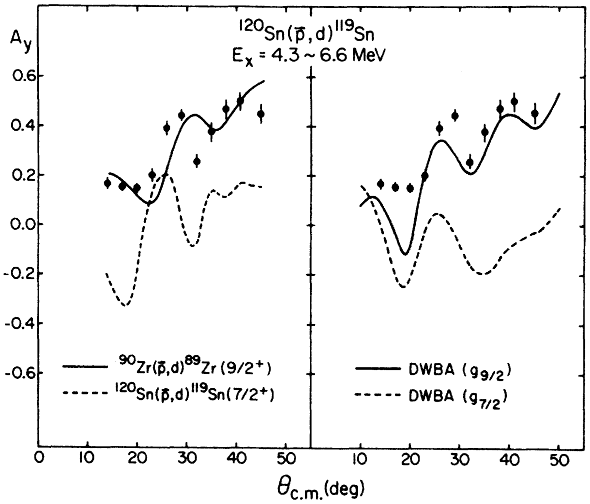

FIG. 3. (a) Analyzing power $A_y(\theta)$ versus angle for the broad peak observed between 4.3 and 6.6 MeV excitation energy in ^{119}Sn. The solid and dashed curves are, respectively, the empirical A_y obtained for the known $E_x = 0.0$, $J^\pi = \frac{9}{2}^+$ ground state of ^{89}Zr and the $E_x = 0.79$ MeV, $J^\pi = \frac{7}{2}^+$ level in ^{119}Sn. (b) Same as (a) except that the solid and dashed curves are now the DWBA prediction for the analyzing power assuming $j = \frac{9}{2}$ (solid and $j = \frac{7}{2}$ (dashed).

for the deep holw state of ^{119}Sn, agrees with measurements from (d,t) (Ref. 8) and (^{3}He,α) (Ref. 9) reactions and implies a rather tight localization of the $\frac{9}{2}$ strength.

The calculated A_y's are shown as solid lines in Fig. 2. Reasonable fits are obtained for the $p_{1/2}$ (0.595 MeV, ^{89}Zr) and $g_{7/2}$(0.79 MeV, ^{119}Sn) transitions. The calculations also reproduce the experimental data fairly well for the $g_{9/2}$(g.s., ^{89}Zr) and $h_{11/2}$(0.09 MeV, ^{119}Sn) transitions except for the forward angles. However, for the $p_{3/2}$(1.1 MeV, ^{89}Zr) and $f_{5/2}$(1.46 MeV, ^{89}Zr) transitions, somewhat worse fits are obtained. The calculated A_y for the analog states around 9 MeV excitation in ^{89}Zr are also in good agreement with experiment. Thus, in general, conventional DWBA calculations

TABLE II. Results of the analysis of the ^{90}Zr($\vec{p}$,d) and ^{120}Sn($\vec{p}$,d) reactions.

Residual nucleus	E_x (MeV)	nlj	C^2S This work	(^{3}He,α)	(p,d)
^{89}Zr	0.00	$1g_{9/2}$	8.90	8.00[a]	5.10[b]
	0.59	$2p_{1/2}$	0.75	1.70	0.99
	1.10	$2p_{3/2}$	1.20	2.48	2.30
	1.46	$1f_{5/2}$	2.9	2.50	1.5
^{119}Sn	0.00	$1h_{11/2}$	2.60	3.50[c]	
	0.79	$1g_{7/2}$	4.60	6.00	
	4.3–6.6	$1g_{9/2}$	2.20	2.18	

[a]Reference 10.
[b]Reference 11.
[c]Reference 8.

reproduce the A_y, as well as the differential cross sections, reasonably well at an incident energy of 90 MeV.

The results of DWBA calculations of the A_y's for a j of $\frac{9}{2}$ and $\frac{7}{2}$ are plotted in Fig. 3(b) together with the measured A_y for the hole state at around 5 MeV. The $\frac{9}{2}$ calculation gives quite a good fit to the data except at forward angles, the same angular region which gives problems for calculations of the low lying states. However the $j = \frac{7}{2}$ calculation is very different from the measured A_y again implying strongly that the deep hole state near 5 MeV is indeed $j = \frac{9}{2}$.

In conclusion, analyzing power measurements from the ($\vec{p}$,d) reaction at 90 MeV appear to give an excellent measurement of the spin of final states. In particular, when applied to the state populated with an $l = 4$ angular momentum transfer at 5 MeV in ^{119}Sn, both a comparison with empirical A_y's for known states and with DWBA calculations indicate that the spin of this state is indeed $\frac{9}{2}$.

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