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A TEST OF COPLANARITY AND FAR-SIDE DOMINANCE IN INTERMEDIATE ENERGY (d,p) AND (p,d) REACTIONS

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In a recently published report[1-2] on the $^{116}Sn(d,p)^{117}Sn$ reaction, it was found that the current model of transfer reactions is particularly poor for well-matched $j_n = \ell_n - \frac{1}{2}$ transitions. This model, based on the distorted wave formalism, treats the deuteron scattering wavefunction adiabatically[3] (to include the effects of S-wave breakup), includes non-locality corrections,[4] and contains both the deuteron S- and D-states through a finite range calculation. The dynamics of (d,p) reactions produced by 80 MeV deuterons makes the reactions coplanar (the neutron orbital angular momentum lies preferentially in the plan defined by the asymptotic deuteron and proton momenta) and far-side dominated, at least insofar as the model calculations are reliable. These dynamics make sufficiently large differences among the various spin-dependent reaction amplitudes that only two are significant away from 0°. This leads to redundancy relations among the spin observables that may be used as a test of the coplanar and far-side dominant features of the distorted wave model.[5]

In the case of the $j^\pi = \frac{7}{2}^+$ transition in $^{116}Sn(d,p)^{117}Sn$, only the deuteron vector (A_y) and tensor (A_{yy}) analyzing powers were available, so only the relationship $A_{yy} = -2 - 3A_y$ could be tested. Although significant deviations were observed beyond the small ones present in the model calculations, it was noted that much of the model difference from this calculation arose from the deuteron D-state. This raised the possibility that the remaining differences could be due to similar contributions from deuteron channel tensor optical potentials or stripping from D-wave breakup states, neither of which is included in the model calculation. These same model calculations also showed that the relationship $3p + 1 = -2A_{yy}$ connecting the deuteron tensor analyzing power with the outgoing proton polarization was relatively free of these complications. To make a useful precision measurement, it is best to measure the analyzing power in the timereversed (p,d) reaction in place of the polarization. For this, a case must be found where a $j_n = \ell_n - \frac{1}{2}$ transition connects the ground states of two stable nuclei, such as ^{66}Zn and ^{67}Zn.

Angular distribution measurements have been made for the cross section and vector and tensor analyzing powers for the ^{66}Zn(d,p)^{67}Zn reaction with 88.0 MeV polarized deuterons, and for the cross section and analyzing power (here quoted as p) for the ^{67}Zn(p,d)^{66}Zn reaction with 91.6 MeV polarized protons. This ground state transition has $J_n = \frac{5}{2}, \ell_n = 3$, one unit of angular momentum smaller than the Sn case.

Figure 1 shows the measured cross section angular distribution, along with calculations that include or omit the deuteron D-state. From the difference between these calculations, we may estimate where tensor potential and breakup effects might appear. The slope of the model calculation differs from the measurements, a fact that may reflect the use of optical potential parameters from the ^{116}Sn(d,p)^{117}Sn calculations of Ref. 1. Clearly

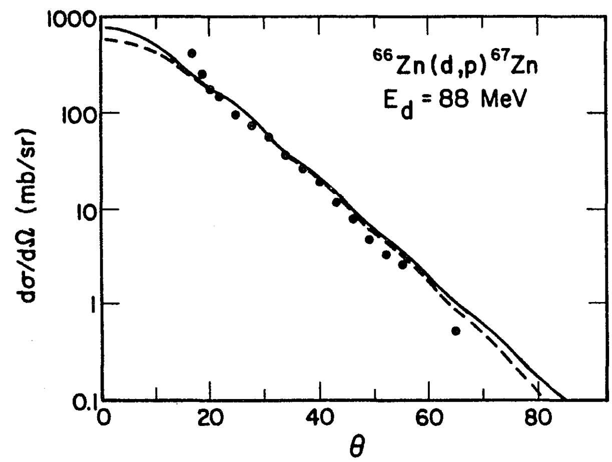

Figure 1. Measurements of the cross section for the ground state transition in ^{66}Zn(d,p)^{67}Zn. The model calculation with the solid (dashed) line includes (omits) the effects of the deuteron D-state.

before any final conclusions are drawn, more appropriate potentials must be obtained.

Like the ^{116}Sn(d,p)^{117}Sn case, a comparison may be made with data for the relationship $A_{yy} = -2 - 3A_y$. So as to compare similar things, the plots in Fig. 2 show A_y and pseudo-A_y ($\widetilde{A}_y$) composed from tensor analyzing power data through the relationship $\widetilde{A}_y = (-2+A_{yy})/3$. These measurements bear a close resemblance to the ^{116}Sn(d,p)^{117}Sn measurements, thus illustrating that the problems with the model calculations transcend any one transition, and are likely to be general features of intermediate-energy (d,p) reactions. The difference, shown in the bottom panel of Fig. 2 as $A_y - \widetilde{A}_y$, is clearly larger than the model value, but a part of it, especially at large scattering angles, is due to effects of the deuteron D-state. The difference, $A_y - \widetilde{A}_y$ is always positive since it corresponds to the presence of a measurable cross section for spin up ($m_d = 1$ relative to the Madison convention y-axis) deuterons.

The new information available with the ^{66}Zn(d,p)^{67}Zn measurements consists in a comparison between the outgoing polarization and the tensor analyzing power. This is

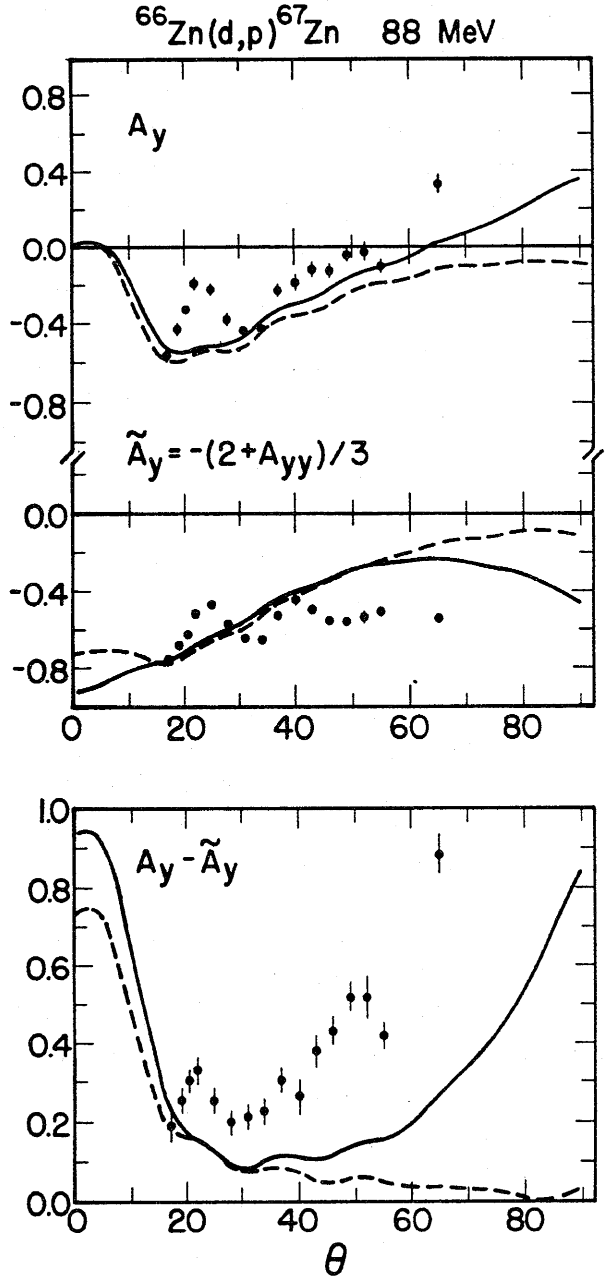

Figure 2. Measurements of the vector analyzing power (A_y), and the tensor analyzing power (A_{yy}) replotted to simulate the vector analyzing power through the formula $\widetilde{A}_y = -(2 + A_{yy}))/3$. In the bottom panel is shown the difference $A_y - \widetilde{A}_y$. The model calculation with the solid (dashed) line includes (omits) the effects of the deuteron D-state.

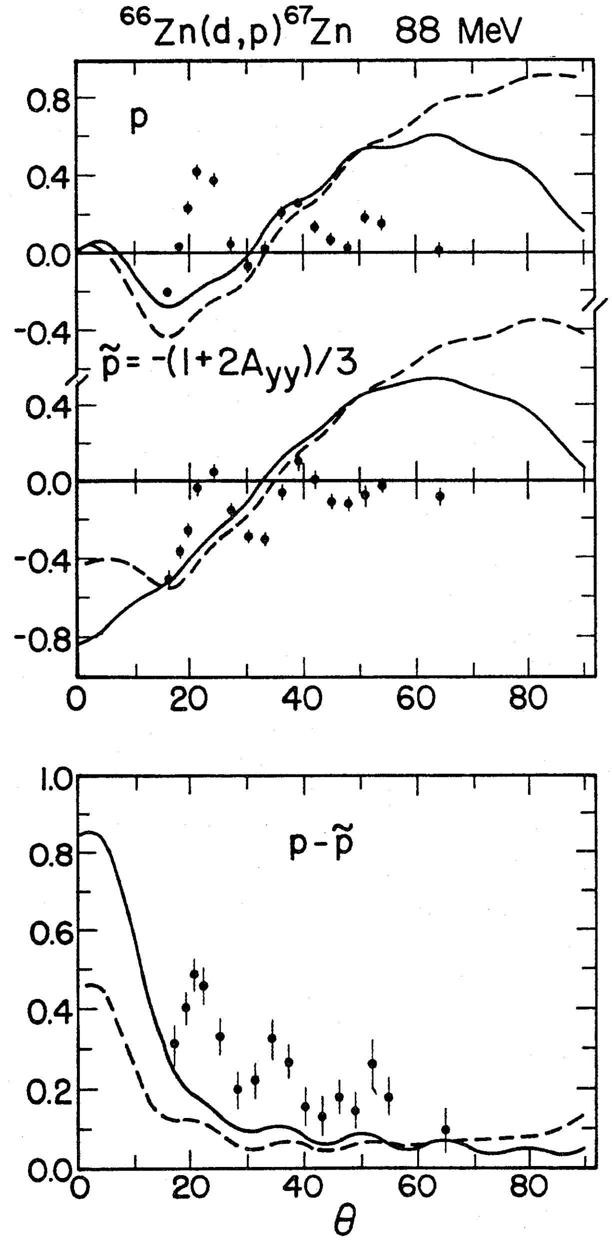

Figure 3. Measurements of the outgoing proton polarization (p), and the tensor analyzing power (A_{yy}) replotted to simulate the polarization through the formula $\widetilde{p} = -(1 + 2A_{yy})/3$. The bottom panel shows the difference $p - \widetilde{p}$. The model calculation with the solid (dashed) line includes (omits) the effects of the deuteron D-state.

shown in Fig. 3 in a fashion similar to Fig. 2. The top panel shows the polarization and its equivalent $\widetilde{p} = -(1 + 2A_{yy})/3$, along with the model calculations. Again, the difference is larger than the model value, as shown by the bottom panel of Fig. 3. In this case, however, the inclusion of deuteron D-state effects makes little difference in $p - \widetilde{p}$. The measured values are also closer to the model calculations than was the case for $A_y - \widetilde{A}_y$, suggesting the tensor potential and breakup effects may still have a role to play in accounting for these differences.

A separate contribution to this report[6] explores the possibility of large near-side amplitudes which are absent in the distorted wave model. Such amplitudes could account for both the deviation in the difference functions and the oscillation pattern clearly present in all three polariztion observables. As plotted in Figs. 2 and 3, all interference patterns have a similar appearance, suggesting a common origin. An analysis similar to that in Ref. 6 also reveals large near-side amplitudes.

For this case, the transfer ℓ_n is one unit smaller than for ^{116}Sn(d,p)^{117}Sn. Here, the difference functions show interference effects where the $A_y - \widetilde{A}_y$ measurements for ^{116}Sn(d,p)^{117}Sn show none.[5] This transition is less well momentum matched at the nuclear surface, hence the model near- and far-side amplitudes are more nearly equal. In this case, it appears that the "missing" amplitude has a far-side piece that creates an interference pattern with the model near-side component in the $p - \widetilde{p}$ angular distribution. The spin-orbit potentials change the location of the resonance singularities in the semi-classical description of Ref. 6, and the measurements of $p - \widetilde{p}$ for this case are the first indication that spin-orbit shifts are measureable for the same "missing" matrix element. These shifts appear in Fig. 3 as a difference in the period of the interference pattern between p or $\widetilde{p}$ and their combination, $p - \widetilde{p}$.

In an effort to improve the model calculation, measurements were recently completed of proton elastic scattering from ^{67}Zn. These are shown in Fig. 4, along with a "best-fit" optical model calculation. The optical potential parameters are given in Table I, and follow the conventions of SNOOPY8. To obtain a correct model calculation for (d,p), we also need a folding model adiabatic potential for the deuteron wave function. Work on this is in progress.

Table I: Optical Potential Parameters for p + ^{67}Zn Elastic Scattering at 91.6 MeV.

	V	r	a
Coulomb		1.25	
Real Central	27.78	1.251	0.694
Volume Imaginary	7.04	1.473	0.604
Real Spin-Orbit	4.941	1.065	0.692
Imaginary Spin-Orbit	−1.099	1.002	0.546

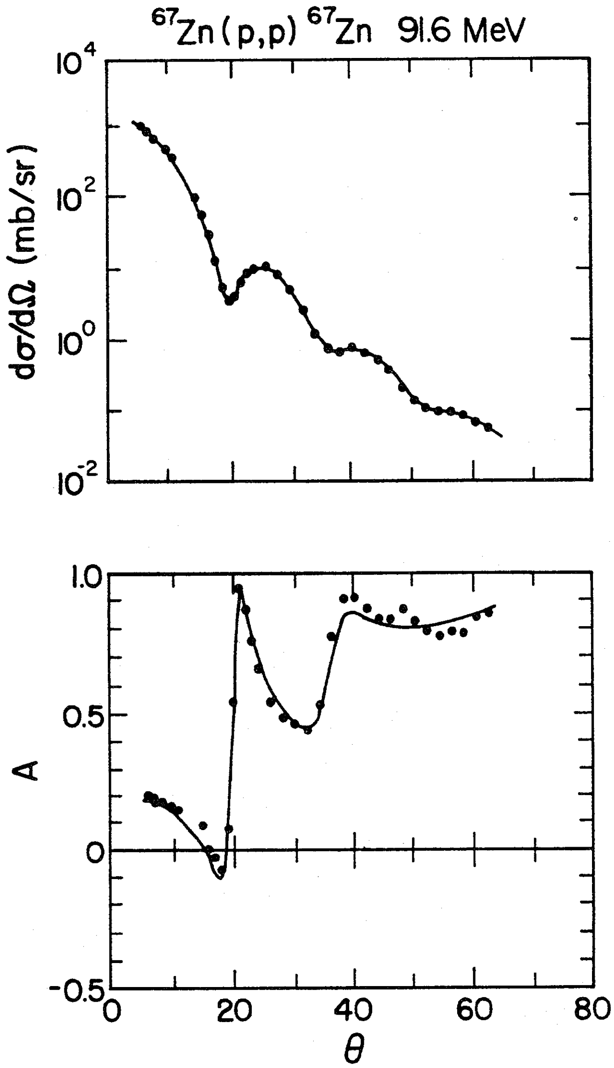

Figure 4. Cross section and analyzing power measurements for p + ^{67}Zn elastic scattering at 91.6 MeV. The calculations represent a "best-fit" optical model.

The discrepancies between model and measurement values of the difference functions, $A_y - \widetilde{A}_y$ and $p - \widetilde{p}$, indicate a significant shortfall of the distorted wave model. Additional evidence from the interference pattern suggests that at least the feature of far-side dominance is incorrect. However, the near-side amplitude may also be coplanar, and in the semi-classical limit of Ref. 6 it is. Work is continuing to understand the characteristics of the additional near-side strength and what physical processes produce it. Until such time as a more complete picture of transfer reactions emerges, the extraction of spectroscopic information based on model calculations is subject to substantial error.

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NATURE OF THE MISSING NEAR-SIDE AMPLITUDE IN CALCULATIONS OF INTERMEDIATE ENERGY (d,p) AND (p,d) REACTIONS

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Model calculations of the cross section and analyzing powers for (d,p) and (p,d) transfer reactions at energies near 100 MeV often bear little resemblance to the measured angular distributions. To provide a basis for a detailed investigation, cross section and analyzing power angular distributions have been made for two time-reverse pairs of reactions, ^{116}Sn(d,p)^{117}Sn with ^{117}Sn(p,d)^{116}Sn (Refs. 1 and 2) and ^{66}Zn(d,p)^{67}Zn and ^{67}Zn(p,d)^{66}Zn (presented elsewhere in this report). These studies find the greatest problems for $j_n = \ell_n - \frac{1}{2}$ transitions, where the presence of a marked interference pattern in the analyzing power angular distributions indicates nearly equal contributions to the reaction amplitude from the far and near sides of the nucleus.[4] In distorted wave Born approximation calculations there is almost no near-side contribution, and the model angular distributions show almost no interference pattern. We have continued to investigate this issue using semi-classical reaction analysis techniques with the intention of extracting a phenomenological extimate of the size and character of the missing near-side amplitude. The data for this investigation come from the $\ell_n = 4, j_n = \frac{7}{2}$ transition in ^{116}Sn(d,p)^{117}Sn.

A semi-classical analysis of the reaction amplitudes may be pursued in this case for two reasons. First, the typical deuteron and proton partial waves that contribute to the stripping or pick-up amplitude are large enough that semi-classical approximations are a useful representation of the reaction. Second, the dynamics of angular momentum matching at the nuclear surface have sufficiently strong effects that only a few of the possible amplitudes contribute significantly to the reaction. This leads in the case of the model calculations to redundancy relations among the polarization observables which are not matched by experiment.[4]

In Fig. 1a, this dynamic selectivity picks out one projection (λ_n) of the transferred neutron's orbital angular momentum. In a model calculation (without spin-orbit distortions for simplicity), this is the maximal projection normal to the asymptotic reaction plane with the sense of rotation commensurate with far-side scattering. Since this is a