about 50 MeV have been observed with this device.

The first measurements of X_2 have been made with this device over the angular range from 19° to 110°, but analysis has not proceeded to the point where the data can be presented in this report.

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REACTION MECHANISM IMPLICATIONS OF DEUTERON RAINBOW SCATTERING

E.J. Stephenson, J.C. Collins, C.C. Foster, D.L. Friesel, J.R. Hall, W.W. Jacobs, W.P. Jones, M.D. Kaitchuck, and P. Schwandt
Indiana University Cyclotron Facility, Bloomington, Indiana 47405

D.A. Goldberg
University of Maryland, College Park, Maryland 20742

In proton inelastic scattering and proton-induced reactions, the vital information on nuclear structure is carried in the details of the diffraction patterns in the cross section and analyzing power. The same is true for deuteron-induced reactions, except that the diffractive oscillations are frequently much smaller in magnitude, and precise information is therefore harder to extract experimentally. The diffraction pattern is further attenuated at large scattering angles because of the appearance of rainbow scattering. There the values of the vector (A_y) and tensor (A_{yy}) analyzing powers approach unity in the deuteron elastic channel.

While information from the diffraction pattern is disappearing at large angles, the rainbow scattering picture suggests that the reaction mechanism itself has undergone radical change. Since with intermediate-energy deuterons, the spin effects in rainbow scattering are being observed for the first time, it is appropriate to consider the impact of rainbow scattering on the analyzing powers for deuteron-induced reactions. This region may be sensitive to both structure and reaction mechanism in a manner different from scattering at forward angles. It is likely that detailed agreement between theory and experiment will be hard to achieve, since these effects will be superimposed on top of larger effects due to the spin-orbit distortions in the entrance channel.

This contribution describes a series of observations and measurements concerning the implications of rainbow scattering for deuteron-induced reactions.

1. Theoretical Framework. Rainbow scattering takes place in the surface of the nucleus, and thus emphasizes the importance of large angular momentum in the scattering. By expanding the scattering matrix in terms of irreducible spin tensor operators, it is possible to specify in a simple fashion the character of deuteron elastic scattering in the limit of very large angular momentum. In that limit, it may be shown that the scattering matrix commutes with the operator

for spin perpendicular to the scattering plane, so the projection of the deuteron spin along that axis is conserved. This permits the cross section to be decomposed into three independent pieces associated with each projection of the deuteron spin perpendicular to the scattering plane. In the large angular momentum limit, these cross sections are determined solely by the piece of the potential in which the deuteron spin has the corresponding projection along the angular momentum axis. It is this separation of the scattering problem into three pieces which underlies the model of the spin dependence in rainbow scattering.[1)]

Expansion of the scattering matrix in the large angular momentum limit also restricts the sizes of certain tensor analyzing powers. In the absence of tensor potentials, A_{xz} and $2A_{xx} + A_{yy}$ are both zero. All other analyzing powers are influenced to first order by the spin-orbit potential, and may be large.

Work[2)] on this problem was completed while Dr. R.C. Johnson from the University of Surrey (UK) was visiting at IUCF.

2. Tensor Potentials. New optical model calculations were made including the T_R and T_P tensor potentials. These potentials involve the quadratic combination of the deuteron spin with deuteron center-of-mass position and momentum, respectively. The radial dependence of the T_R potential was taken from experiments[3)] at 30 MeV, and the T_P potential was taken from the Pauli- blocking calculations of Ioannides and Johnson.[4)]

The inclusion of these potentials has only a small effect on the vector (A_y) and tensor (A_{yy}) analyzing powers, as shown in Figure 1. Measurements of these analyzing powers will thus be quite useful in determining the central and spin-orbit components of the optical potentials. The effects of tensor

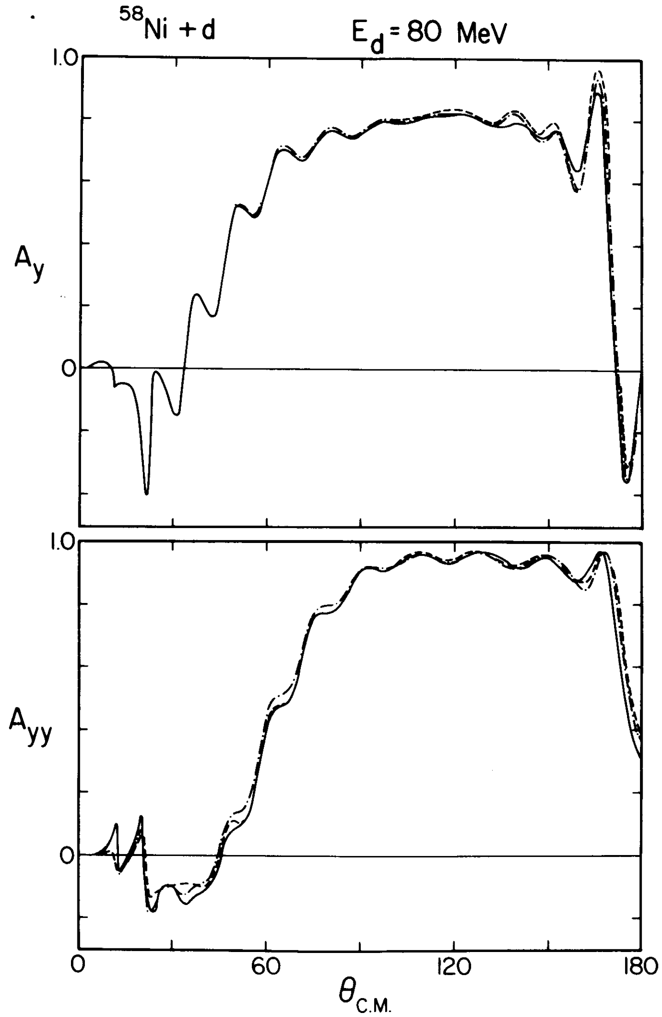

Figure 1. Calculations of the vector (A_y) and tensor (A_{yy}) analyzing powers for deuteron elastic scattering from ^{58}Ni at 80 MeV. The optical potential contains either central and spin-orbit terms only (dashed), or includes a T_R term (dot-dash) or both T_R and T_P (solid).

potentials appear more strongly in A_{xz} and A_{xx}, as shown in Figure 2. By measuring the combination X_2, which is proportional to $2A_{xx} + A_{yy}$, first-order effects of the spin-orbit potential can be eliminated. One notable feature of the calculations for A_{xz} is the very small effect of including the T_P potential, while larger effects are seen in X_2. An experiment including both should provide separate information on the form of the T_R and T_P potential. In addition, when the radius

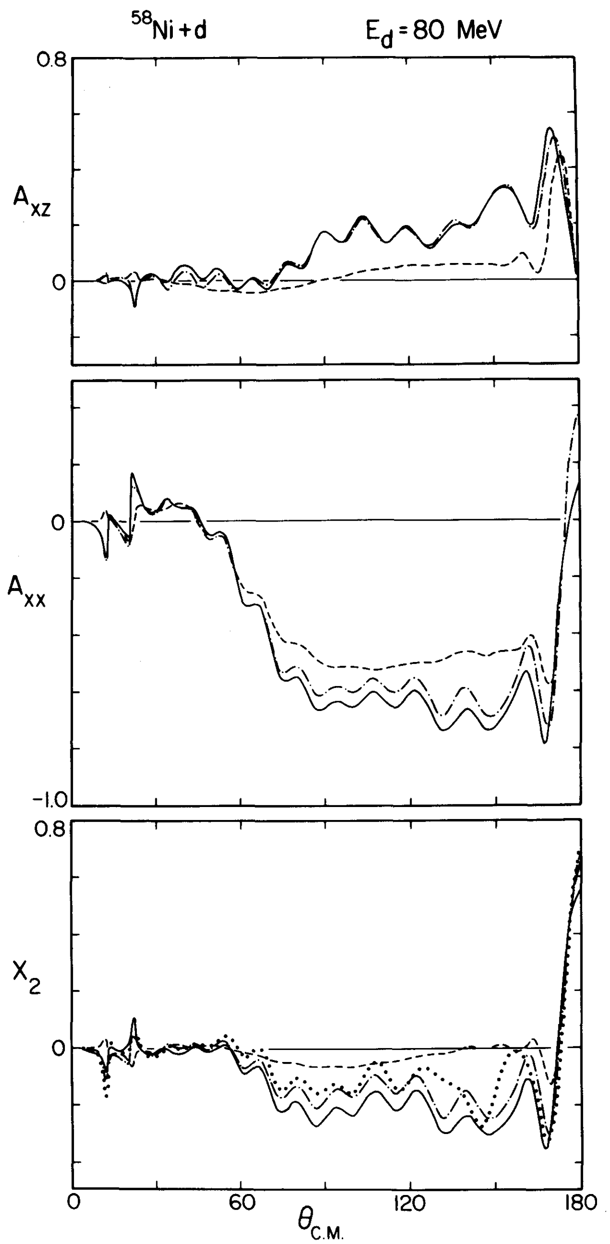

Figure 2. Calculations for three additional tensor analyzing powers (see Figure 1 for details). The dotted curve includes all tensor terms, except that the radius has been substituted for the momentum in the matrix elements of the T_P potential.

is substituted for the momentum in the spin operator for the T_P potential (thus transforming it into a T_R potential), the effect of this potential on the X_2 angular distribution changes sign. This result is in sharp contrast to the work of Goddard,[5] who found these potentials indistinguishable at lower bombarding energies.

The rainbow scattering region provides a reaction mechanism that has changed enough to make the effects of tensor potentials completely different from the observations at lower energies. In this region, the T_R and T_P potentials have distinct effects on the tensor analyzing powers, and their spin dependencies are distinguishable.

Measurements of X_2 may be made directly with a tensor (P_{yy}) polarized beam and out-of-plane scattering (ϕ = 54.7°). This experiment is in progress. Measurements of A_{xz} require precession of the deuteron spin axis so that it is no longer transverse to the beam direction.

3. Extreme Values of the Scattering Matrix. The measurements of A_y reported in the elastic-scattering section of this report are the largest values of A_y ever observed for deuteron scattering. Several extremes of the A_{yy} tensor analyzing power have been located, but these are easier to achieve since only one relation among elements of the scattering matrix must be satisfied.[6] To obtain $A_y = \pm 1$, two conditions must be fulfilled simultaneously. If they are, the scattering matrix is completely determined, with the overall magnitude obtained from the cross section. In particular, if $A_y = 1$, then $A_{yy} = 1$, $A_{xx} = A_{zz} = -1/2$, and $A_{xz} = X_2 = 0$. The observation of an extreme value for the vector analyzing power would thus preclude any observation of other effects in the analyzing powers.

The values for elastic scattering, however, only come close to unity. However, constraints may be obtained on the size of other analyzing powers. If $A_y = 1 - \varepsilon$, where ε is small, then $A_{yy} > 1 - 3\varepsilon$ and $|A_{xz}| < 3\sqrt{\varepsilon/2}$. These constraints are independent of the configuration or spin structure of the final state.

4. Transfer Reactions. In the rainbow model of deuteron scattering, deuterons emerging at large angles originate primarily from rays passing by the far side of the nucleus. This spatial localization permits an analysis to be made in which the momentum transfer and spin transfer in the exchange of nucleons can be matched in an unambiguous way.

During the experiments on elastic scattering, the $^{58}Ni(d,t)^{57}Ni$ reaction was investigated briefly. A sketch of the matched condition for spin up deuterons is shown in Figure 3. Momentum matching requires the transferred neutron to be travelling colinearly with the deuteron, thus giving it angular momentum parallel to the deuteron spin. The neutron spin must be anti-parallel to match to the spin-1/2 triton, so spin-up deuterons pick up neutrons preferentially from J = L - 1/2 single particle states. This situation reverses with the direction of deuteron spin. At large scattering angles we should find that J = L + 1/2 states have negative vector (A_y) analyzing powers while those for J = L - 1/2 states should be positive. A similar rule may be made for $(\vec{d},p)$ and $(\vec{d},n)$ reactions, with the sign of the analyzing power reversed.

Figure 4 shows the analyzing powers for four of the low-lying states in ^{57}Ni. We see that all the analyzing powers are positive. So the selection against spin-down deuterons provided by the rainbow mechanism in the entrance channel overrides even strong spin and momentum selection rules. The weak remnant of these rules can be seen in the observation that the

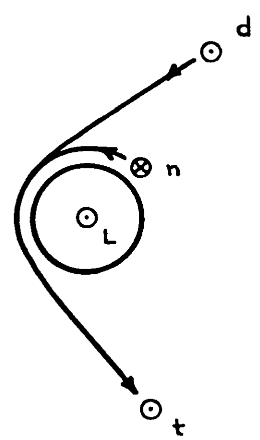

Figure 3. Diagram showing the preferred trajectory and spin configuration for the $(\vec{d},t)$ reaction with spin-up deuterons.

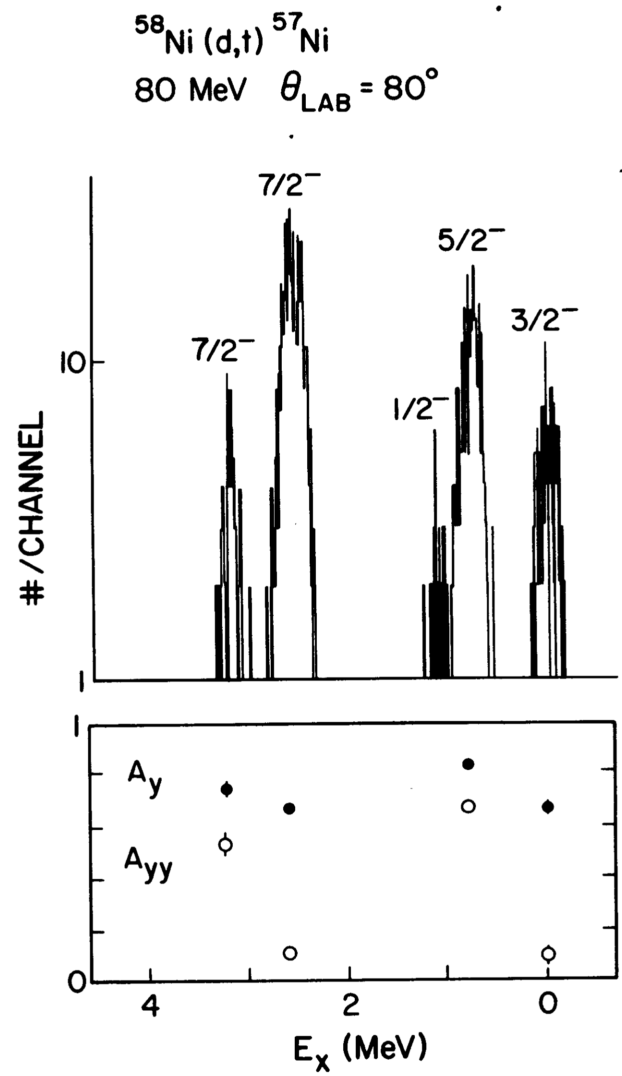

Figure 4. A spectrum and analyzing power measurements for some of the strong, low-excitation states in the $^{58}Ni(\vec{d},t)^{57}Ni$ reaction.

analyzing powers for the $5/2^-$ transition are more positive than for the strong $7/2^-$ and $3/2^-$. The second $7/2^-$ state is weak and may not proceed in one step.

One striking result is that the rainbow mechanism has less influence on A_{yy}, so that this analyzing power shows stronger variations with structure. This result is consistent with the observation of small tensor analyzing powers in the continuum (reported in a separate contribution to this report). It may thus be worthwhile to investigate more thoroughly the use of tensor analyzing powers to extract structure information. This may provide in some cases particularly clean signals, as has been recently noted for $(\vec{d},\alpha)$ reactions at lower energies.[7]

5. Other Rainbow Projectiles. The spin dependence of rainbow scattering was first observed for deuterons because of the availability of polarized beams of intermediate energies. However, rainbow effects are common in the scattering of helium and lithium isotopes. So it is clear that strong saturation of the analyzing powers will be observed there as well at energies in excess of 25 MeV/A. This should be especially true for ^{3}He and ^{3}H, where the spin-orbit potential is already known to exceed the expectations of a simple folding-model prescription.

At the same time, proton elastic scattering exhibits large, positive values of the vector analyzing power while the cross section exhibits a diffractive pattern at all angles. In an optical-model calculation, the features of rainbow scattering (a large-angle cross section enhancement followed by a smooth exponential decline with angle) can be recovered by reducing the strength of the imaginary potential. Increasing the strength quickly drives the analyzing powers to near zero. Thus the positive-going rise in the analyzing power may be interpreted as a remnant of rainbow scattering, which is almost extinguished by the imaginary part of the proton-nucleus interaction.

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ELASTIC SCATTERING OF 178 MeV ALPHA PARTICLES FROM ^{58}Ni AND ^{208}Pb

W.D. Ploughe and J.W. Kerns
The Ohio State University, Columbus, Ohio 43212

W.W. Jacobs and P. Schwandt
Indiana University Cyclotron Facility, Bloomington, Indiana 47405

The differential cross sections for elastic scattering of 178 MeV alpha particles from ^{58}Ni and ^{208}Pb were measured using the QDDM spectrograph. Isotopically enriched targets of ^{58}Ni (thickness 8 and 28 mg/cm^2) and ^{208}Pb (12 mg/cm^2) were used. Over the angular range $8° < \theta_{lab} < 70°$ covered, the measured cross sections span over eight orders of magnitude.

Initial attempts to reproduce the data with a phenomenological optical-model potential taken from the literature are shown in Figs. 1 and 2. The curves