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^{24}Mg($\vec{p}$,d) analyzing-power measurements at 95 MeV

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Analyzing-power angular distributions have been measured for prominent states excited by the ^{24}Mg($\vec{p}$,d) reaction at 94.8-MeV bombarding energy. The distributions for the known low-lying hole states ($E_x < 6$ MeV) exhibit a clear j dependence with characteristic features which are most pronounced near 6° for $l=1$ transitions, and near 35° for $l=2$ transitions. The analyzing powers observed for $l=0$ pickup are strongly oscillatory, reaching a value $\cong 0.9$ near 20°. These measured spin signatures allow the identification of "deep-hole" p states at 8.91-, 9.67-, and 10.57-MeV excitation in ^{23}Mg as $p_{3/2}{}^{-1}$, and of a state at 9.02 MeV as $p_{1/2}{}^{-1}$. Difficulties in reproducing the behavior of the measured cross sections and analyzing powers using standard distorted-wave Born approximation calculations are apparent, particularly for $l=0$ transitions.

NUCLEAR REACTIONS ^{24}Mg($\vec{p}$,d), $E=94.8$ MeV; measured $A(\theta)$. ^{23}Mg levels deduced J; $E_x=0-10.6$ MeV. Enriched targets, DWBA analysis, resolution 70 keV FWHM; $\theta=6-36°$, $\Delta\theta=2$ or 3°.

I. INTRODUCTION

The (p,d) reaction has proven to be a useful spectroscopic tool below about 50-MeV bombarding energy when a simple neutron pickup mechanism is involved. Differential cross section measurements are sensitive to the l dependence of the transfer, and fairly reliable spectroscopic information can be extracted at the lower bombarding energies with the use of DWBA calculations. Furthermore, analyzing-power measurements are sensitive to the j dependence of the transfer.[1] These features have been exploited quite successfully in the past for examining single-hole states of nuclei. There is considerable current interest in studying the extent to which these features of the (p,d) reaction persist at higher bombarding energies where, in particular, the reaction can be useful for identifying "deep-hole" states which are generally inaccessible at the lower energies. Hosono *et al.*[2] have indeed recently noted a clear j dependence in analyzing powers measured for low-lying hole states in $A=12-90$ target nuclei ($1p$ through $2d$ shells) at 65-MeV bombarding energy. In a somewhat higher mass region, the experimental analyzing-power shape at 90 MeV for the ^{90}Zr(p,d) ground state transition has been used to assign unambiguously a spin of $\frac{9}{2}$ to a broad deep-hole structure observed near 5 MeV excitation in ^{119}Sn.[3] Progress in the study of neutron deep-hole strength as measured in (p,d), as well as other (complementary) pickup reactions, has recently been reviewed.[4]

The present paper reports on analyzing-power angular distribution measurements for the ^{24}Mg($\vec{p}$,d)^{23}Mg reaction carried out at the Indiana University Cyclotron Facility (IUCF) at a bombarding energy of 94.8 MeV. Cross-section measurements for the same reaction at the same energy have been reported previously.[5] Of particular interest in the previous work was the identification of four deep-hole p states at excitation energies between 8.91 and 10.57 MeV in ^{23}Mg. When the polarized proton beam became available at IUCF, the present work was undertaken in order to search for spin-dependent signatures of the analyzing powers for the known low-lying $\frac{1}{2}^+$, $\frac{1}{2}^-$, $\frac{3}{2}^-$, $\frac{3}{2}^+$, and $\frac{5}{2}^+$ states of ^{23}Mg. It was hoped that these signatures would then be useful in determining the unknown spins of the deep-hole states. Preliminary reports of the results of the present measurements have been presented previously.[6]

Extensive shell-model calculations have been carried out on $A=23$ nuclei by Chung and Wildenthal,[7] but they have included only even parity states in the basis. Calculations including p states have been carried out by Maripuu[8] for $A=27$ nuclei, which showed that in this mass region $p_{3/2}{}^{-1}$ hole strength would be expected to predominate at excitation energies in the neighborhood of $8-10$ MeV. In the meantime, systematic $(\vec{d},{}^3\mathrm{He})$ analyzing-power measurements at lower energies for several other sd-shell targets[9] were reported which failed to reveal any $p_{1/2}{}^{-1}$ hole strength except in the lowest-lying p state. For these reasons it was anticipated that the four deep-hole p states identified[5] in ^{23}Mg would be spin $\frac{3}{2}$.

Analyzing-power measurements for $(\vec{p},d)$ are inherently interesting for comparison with DWBA calculations at energies in the 100-MeV range, because they have a much greater sensitivity to details of the reaction amplitudes than do cross-section measurements. Standard calculations have met with limited success, suggesting a poor understanding of certain details of the reaction mechanism and a need for new approaches. An extensive set of calculations in this spirit, carried out by Shepard, Rost, and Kunz for comparison with both the present ^{24}Mg(p,d) analyzing-power and earlier cross-section measurements,[5] is reported elsewhere.[10] A recent paper by Rawitscher and Mukherjee[11] also provides a comparison for the observed $l=0$ cross section angular distributions.

Experimental procedures employed in this work are described in Sec. II. Results obtained for the analyzing-power angular distributions are presented in Sec. III. Section IV provides a discussion of the served spin-dependent signatures, their use in determining the spins of the four deep-hole states, and a comparison of the results with standard DWBA calculations.

II. EXPERIMENTAL PROCEDURE

Polarized protons from an atomic-beam source located in the 800-kV electrostatic terminal at IUCF were accelerated through the injector and main cyclotrons to an energy of 94.8 MeV. Momentum-analyzed polarized beams of $40-100$ nA were focused in a dispersion-matching mode on a 3.62 ± 0.1 mg/cm^2 self-supporting 99.94% enriched ^{24}Mg target. Reaction product deuterons were momentum-analyzed by the quadrupole-dipole-dipole-multipole magnetic spectrometer operated with an acceptance solid angle of 2.31 msr. The overall resolution obtained was about 70 keV full width at half maximum. Typical spectra obtained for the ^{24}Mg$(\vec{p},d)$ reaction for proton beam spin up and spin down are shown in Fig. 1. Each spectrum is a charge-normalized composite obtained using three different magnetic field settings for the spectrometer. Further details of the general experimental arrangement have been described previously.[5]

The spectrometer was operated in a "single-arm" mode, with the $(\vec{p},d)$ analyzing power $A_y(\theta)$ calculated from yields obtained for the two proton spin orientations perpendicular to the reaction plane. The spin was reversed once each minute in order to reduce systematic errors associated with slowly-varying beam parameters. The beam polarization was monitored by a ^{4}He polarimeter, periodically inserted directly after the injector cyclotron ($E_p=8.3$ MeV). The polarization at full energy (94.8 MeV) was checked by carrying out an analyzing-power measurement for elastic scattering on carbon. Within the uncertainties, dominated by counting statistics of older double-scattering measurements,[12] no depolarization caused by acceleration in the main cyclotron could be detected. The same conclusion has been drawn at all other IUCF energies where a comparison has been made.[13] Typical beam polarizations determined from the low-energy polarimeter during this experiment were about $+71\%$ and -68% in the two spin orientations.

III. EXPERIMENTAL RESULTS

Figure 2 shows the analyzing-power angular distributions obtained for known[14] $l=0$ pickup reactions to two low-lying hole states in ^{23}Mg excited by the ^{24}Mg$(\vec{p},d)^{23}$Mg reaction. The transitions show essentially an identical angular distribution for the analyzing power, with a large oscillation reaching nearly 0.9 at about 20° c.m. As is the case for all transitions presented in this work, differential cross-section angular distributions at this same energy, but covering a much larger angular range, have been published previously[5] and are not reproduced here.

A very characteristic spin signature for $l=1$ transitions at forward angles is observed for the three known $l=1$ transitions to low-lying states of ^{23}Mg, as shown in Fig. 3. The $j=\frac{1}{2}$ transition shows a very pronounced negative analyzing power at the forward angles near 6° c.m., whereas the

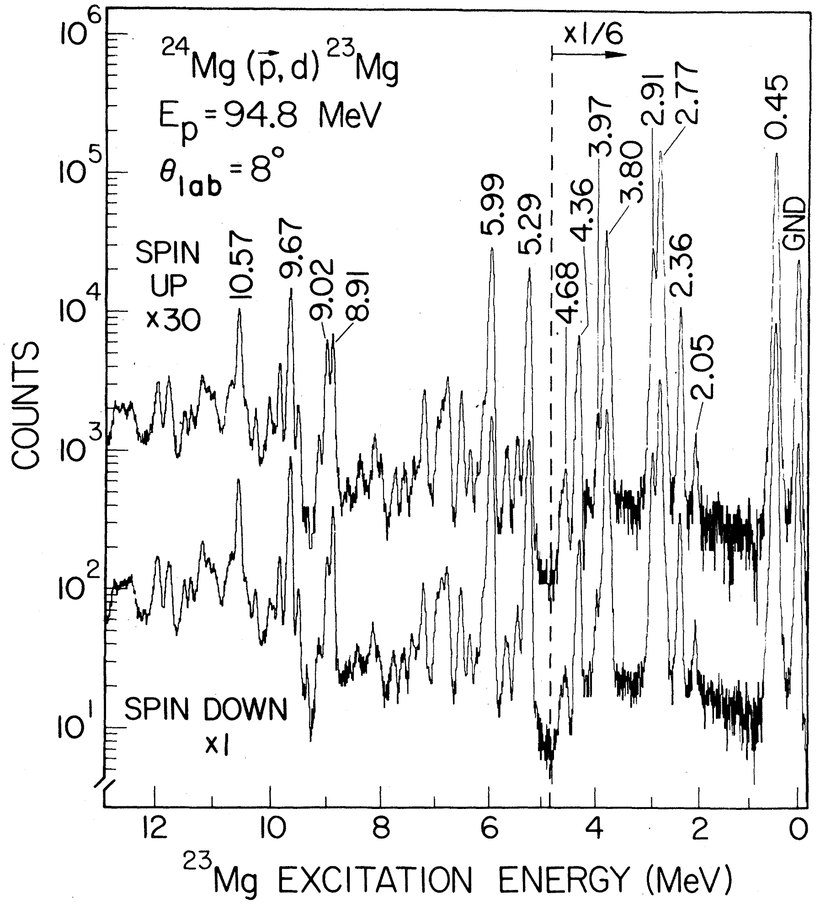

FIG. 1. Composite spin-up and spin-down ^{24}Mg($\vec{p}$,d)^{23}Mg spectra obtained by combining results for three different magnetic field settings at a laboratory angle of 8°. Before plotting, the spin-up spectrum has been multiplied by a factor of 30, and both spectra multiplied by an additional factor of $\frac{1}{6}$ for excitations below E_x=4.8 MeV. The marked difference in analyzing power for $p_{1/2}$ and $p_{3/2}$ transitions at this favored angle can be noted by comparing the spin-up and spin-down yields for the groups corresponding to the deep-hole states at 9.02 and 8.91 MeV, respectively.

$j=\frac{3}{2}$ transitions tend to be slightly positive in this region.

Angular distributions of $A_y(\theta)$ for three known $l=2$ transitions are shown in Fig. 4. Although a substantial j dependence is observed at angles around 35°, little difference in the analyzing power is seen at forward angles between the transitions to the $\frac{3}{2}^+$ ground state and the 0.45-MeV $\frac{5}{2}^+$ state.

Figure 5 shows the analyzing-power angular distributions for three states believed[5] to be excited primarily by two-step processes. The angular distributions are rather featureless and do not exceed 0.3. There is some indication that the two states believed to be $\frac{7}{2}^+$ show a similar behavior for $A_y(\theta)$ which is somewhat different from that of the state believed to be $\frac{5}{2}^-$.

In order to determine the spins of the four deep-hole states between 8.91 and 10.57 MeV in ^{23}Mg previously identified[5] as having $l=1$ character, angular distributions for $A_y(\theta)$ were also measured for transfers leading to these states. Figure 6 shows these four angular distributions superimposed. By comparison with the empirical spin signatures shown in Fig. 3, it is clear that the distribution for the 9.02-MeV state is characteristic of a $j=\frac{1}{2}$ transfer, while the other three correspond to $j=\frac{3}{2}$ transfers.

IV. DISCUSSION OF RESULTS

A. Spin assignments

The pronounced negative analyzing power observed for $p_{1/2}$ pickup at very forward angles has

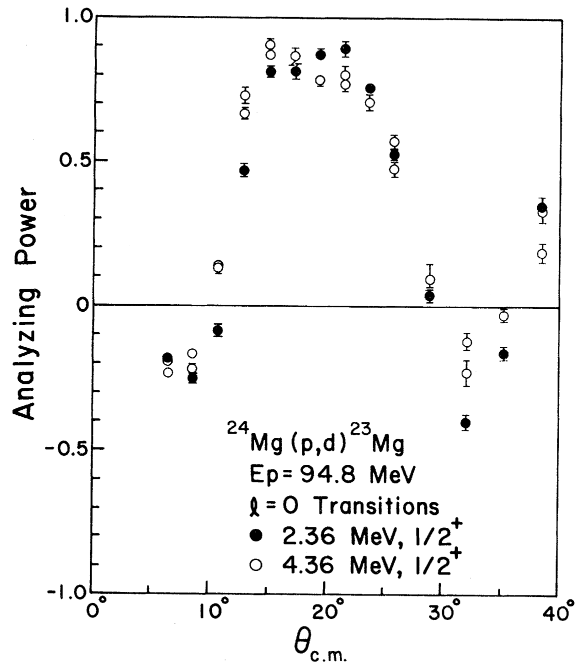

FIG. 2. ($\vec{p}$,d) analyzing-power angular distributions obtained for the two known $l=0$ transitions to low-lying states in ^{23}Mg at 2.36 and 4.36 MeV. Errors shown are purely statistical; where not shown they are smaller than the indicated data points.

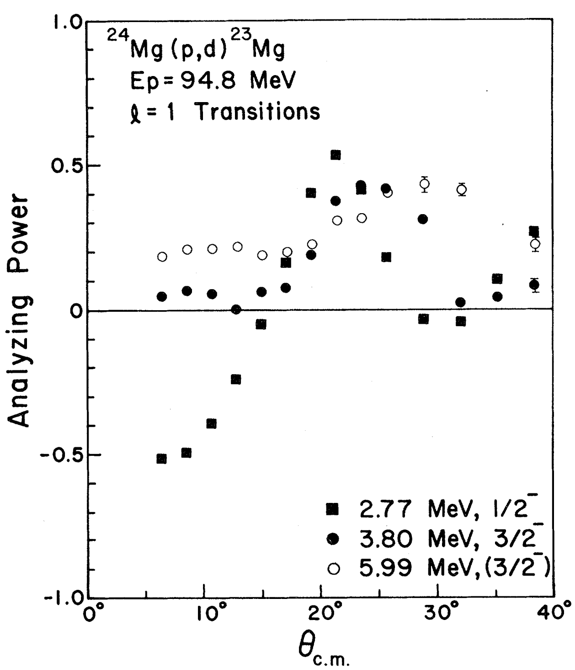

FIG. 3. Analyzing-power angular distributions for the three known $l=1$ transitions to low-lying states in ^{23}Mg at 2.77, 3.80, and 5.99 MeV. The 2.77-MeV state is not fully resolved from a much weaker $\frac{9}{2}^+$ state at 2.71 MeV (Ref. 5).

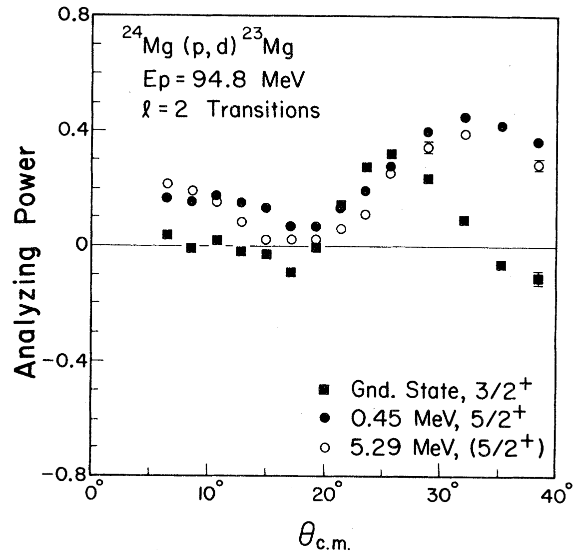

FIG. 4. Analyzing-power angular distributions for three of the four known $l=2$ transitions to the ground state and low-lying states in ^{23}Mg at 0.45 and 5.29 MeV. Results for the $l=2$ transition to the 2.91-MeV state are not shown because they are not considered to be reliable as a consequence of the proximity of the very strong $l=1$ transition to the 2.77-MeV state.

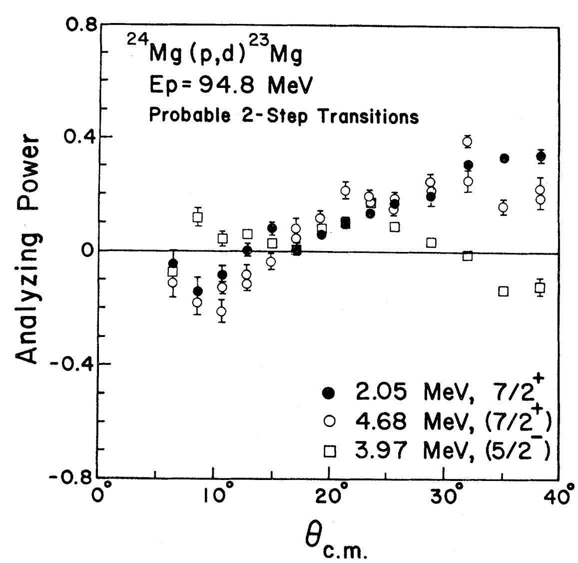

FIG. 5. Analyzing-power angular distributions for transitions to the known $\frac{7}{2}^+$ 2.05-MeV state, and to the probable $\frac{7}{2}^+$ state at 4.68 MeV and the probable $\frac{5}{2}^-$ state at 3.97 MeV. Cross-section angular distributions (Ref. 5) are indicative of two-step or $l>2$ transitions to these states.

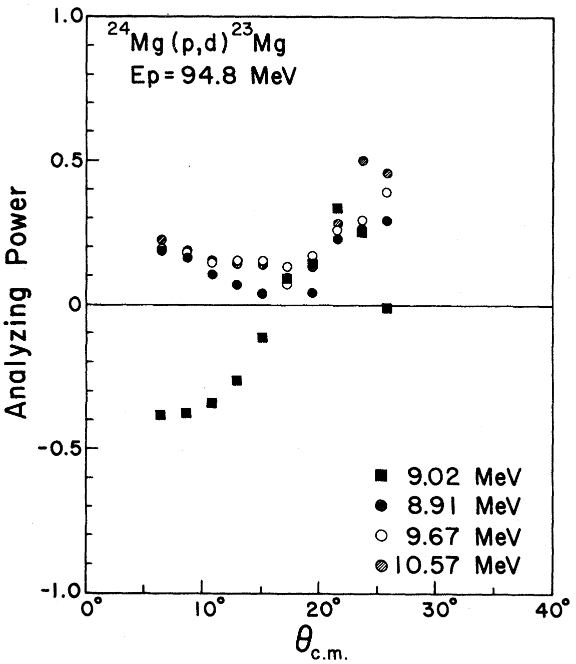

FIG. 6. Analyzing-power angular distributions obtained for $l=1$ transitions to deep-hole states between 8.91 and 10.57 MeV in ^{23}Mg. All but the 9.02-MeV state exhibit the $j=\frac{3}{2}$ pickup signature shown in Fig. 2, while the 9.02-MeV state clearly shows a $j=\frac{1}{2}$ pickup character.

also been observed in this energy range with a ^{13}C target at $E_p=123$ MeV at IUCF (Ref. 15) and with ^{13}C and ^{16}O targets at $E_p=200$ MeV at TRIUMF.[16] Subsequent to the present measurements, the same feature has also been observed[17] with ^{60}Ni and ^{88}Sr targets at $E_p=95$ MeV. This j-dependent signature for $l=1$ transitions is particularly advantageous because it is very distinctive at the forward angles, where the cross section is largest and the signature most easily measured.

A less optimum j-dependent signature is observed for the $l=2$ transitions, since the major difference in the analyzing powers (in the angular range measured) occurs at about 35° c.m., where the differential cross sections are down by a factor of 10 relative to the peak cross section near 10° c.m. (Ref. 5). Nevertheless, the behavior of $A_y(\theta)$ in this region for known $l=2$ transfers[14] supports the j assignment[18] of $\frac{3}{2}^+$ and $\frac{5}{2}^+$ for the states at 2.91 and 5.29 MeV, respectively.

The $p_{3/2}{}^{-1}$ assignments for the 8.91-, 9.67-, and 10.57-MeV deep-hole states in ^{23}Mg, inferred from the empirically observed j dependence for low-lying states, suggests a concentration of $p_{3/2}{}^{-1}$ strength in this region of excitation energy, which is consistent with the predictions of a shell-model calculation[8] for the nearby mass $A=27$. This calculation, however, predicts little $p_{1/2}{}^{-1}$ strength at this high an excitation, and hence it is a bit surprising that $A_y(\theta)$ for the 9.02-MeV state clearly shows a $p_{1/2}{}^{-1}$ signature. More significant are the results at lower energies of a set of systematic ($\vec{d}$,^{3}He) analyzing-power measurements by Mairle *et al.*[9] for other sd-shell targets [leading to mirror residual nuclei from (p,d) studies] which fail to reveal any $p_{1/2}{}^{-1}$ strength except in the lowest-lying p state.

These same four deep-hole states have been studied at IUCF using the ^{24}Mg(d,t) reaction at $E_d=76$ MeV.[19] It is interesting to note that in the observed spectrum for the mirror reaction ^{24}Mg(d,^{3}He), which was studied simultaneously, the only sharp high-lying ^{23}Mg state for which there is *no* obvious mirror counterpart (in excitation energy and relative strength) is the 9.02-MeV $p_{1/2}{}^{-1}$ state. This result is thus consistent with the failure of Mairle *et al.*[9] to see significant $p_{1/2}{}^{-1}$ strength except in the lowest-lying p state excited in their ($\vec{d}$,^{3}He) survey. It is a bit of a puzzle to understand why the (p,d) and (d,t) reactions populate a component of $p_{1/2}{}^{-1}$ neutron hole strength in this region of excitation of ^{23}Mg whereas the expected corresponding proton hole component is not observed at or near the same excitation in the mirror nucleus by the (d,^{3}He) reaction with a similar concentration of strength.

B. Comparison with DWBA calculations

The present ^{24}Mg($\vec{p}$,d) analyzing-power measurements, taken together with the previous cross-section measurements,[5] provide very useful results for comparison with DWBA calculations. We show in Fig. 7 a set of "standard" zero-range predictions for the analyzing powers for the lowest-lying $l=0$, 1, and 2 transitions, carried out using the distorted-wave code DWUCK4.[20] The proton and deuteron parameters were taken from Nadasen *et al.*[21] and Daehnick *et al.*,[22] respectively. It is clear from Fig. 7 that the standard DWBA predictions do not reproduce the experimental analyzing powers for any of the l transfers studied at this energy. Only a rather vague qualitative description of the $l=1$ and $l=2$ data is given, with the signs and oscillatory phases of the forward-angle analyzing powers being roughly correct for all transitions except the $d_{3/2}$ neutron pickup to the ground state. The $l=0$ prediction does not reproduce the large oscillation from 10–30° c.m. in either sign or magnitude. The

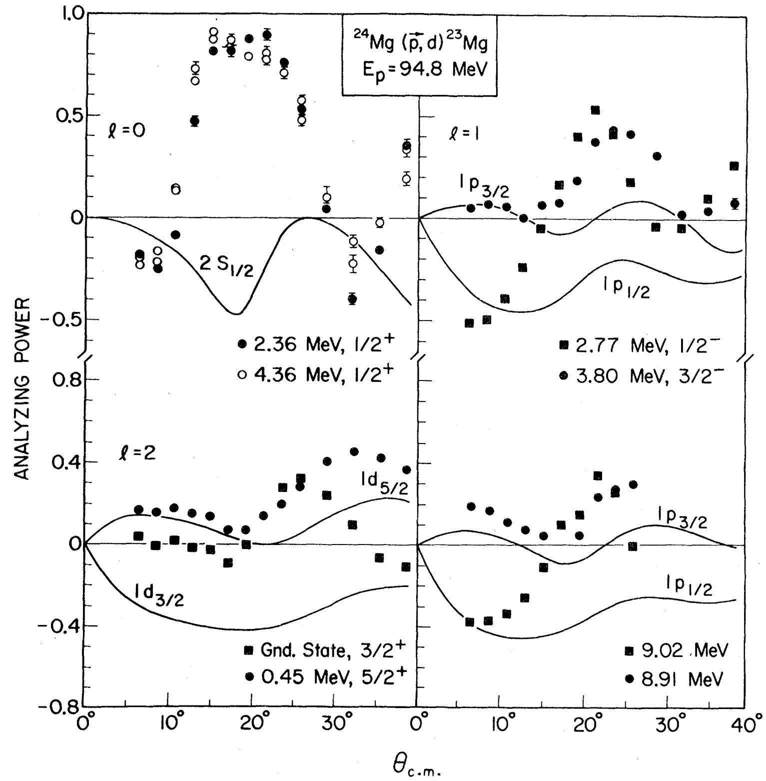

FIG. 7. Comparison of analyzing-power measurements for sample $l=0$, 1, and 2 transitions to low states in ^{23}Mg with standard DWBA calculations using proton and deuteron optical potentials from Nadasen *et al.* (Ref. 21) and Daehnick *et al.* (Ref. 22), respectively. Calculations for two deep-hole p states at 8.91 and 9.02 MeV in ^{23}Mg are also shown.

$l=0$ transitions are especially important for DWBA studies, since the analyzing powers would be zero in the absence of spin-dependent distortions. Furthermore, these transitions should be very sensitive to the effects of the nuclear interior.

Shepard, Rost, and Kunz[10] have carried out very extensive DWBA analyses of these results, with special emphasis on the $l=0$ transitions. These calculations included a number of refinements over the standard zero-range DWBA calculations shown in Fig. 7, including the use of exact finite range, a configuration-space tensor interaction in the deuteron channel, coupled-channels calculations with deuteron continuum contributions, and the introduction of two-step contributions. None of these calculations produced agreement with the pronounced oscillation of the experimental $l=0$ analyzing power, and in general all overpredicted the observed cross section by up to an order of magnitude. Qualitative agreement for both the analyzing power and cross section could be obtained only by the arbitrary introduction of a smoothed lower radial cutoff or by greatly increasing the absorption in the optical potentials. Rawitscher and Mukherjee[11] have also made an independent calculation of the effects of deuteron breakup on the predicted $l=0$ cross section without removing the discrepancy. These theoretical studies clearly indicate that the contributions from the nuclear interior are not being treated correctly with present DWBA methods, even in the most refined formulations to date. New theoretical approaches to the analysis of (p,d) reactions in the 100-MeV range appear to be required. For example, some preliminary success appears to have been obtained recently by applying the methods of Dirac phenomenology to these processes.[23]

V. CONCLUSIONS

The results of this experiment show that $(\vec{p},d)$ analyzing-power measurements at bombarding energies near 100 MeV can serve as a very useful spin analyzer in light nuclei due to the characteristic j dependence observed for $l=1$ and $l=2$ transitions.

These measurements can be particularly useful in establishing the systematics of the $p_{1/2}^{-1}$ and $p_{3/2}^{-1}$ deep-hole states in *sd*-shell nuclei, and hold the potential for similar studies in other parts of the periodic table. In this experiment three known deep-hole p states in ^{23}Mg at 8.91-, 9.67-, and 10.57-MeV excitation were identified as having $p_{3/2}^{-1}$ character, while one at 9.02-MeV excitation was rather unexpectedly found to have a $p_{1/2}^{-1}$ hole structure.

It is also apparent from this experiment and an extensive subsequent DWBA analysis by Shepard *et al.*[10] that analyzing-power measurements can provide stringent additional experimental tests of the (p,d) reaction mechanism at intermediate energies. It appears that contributions from the nuclear interior must be treated more carefully, particularly for low l transitions, and this may require completely new theoretical approaches.

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