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Failure of the distorted-wave Born approximation in analysis of the $^{24}Mg(\vec{p},d)^{23}Mg$ reaction at $T_p = 94$ MeV

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We describe a detailed analysis for the $l=0$ transition to the 2.36 MeV $1/2^+$ level in ^{23}Mg where the analyzing powers are large and oscillatory at $T_p=94$ MeV. Distorted-wave Born approximation calculations completely fail to reproduce this behavior. Qualitative agreement is obtained only by introducing a great deal of absorption artifically, e.g., by using a large radial cutoff.

[NUCLEAR REACTIONS $^{24}Mg(\vec{p},d)^{23}Mg$, $E=94$ MeV; calculated analyzing powers including exact finite-range effects, deuteron-tensor interaction in optical potential, explicit treatment of deuteron breakup and multistep processes; calculations also performed with radial cutoffs. Compared with data.]

The distorted wave Born approximation (DWBA) has generally been quite successful in reproducing (p,d) cross sections over a wide range of bombarding energies extending up to $T_p=800$ MeV. Analyzing powers depend more sensitively on details of reaction amplitudes and, not surprisingly, the DWBA does not reproduce these quantities as well, although qualitative agreement is frequently achieved. In many cases, however, agreement is quite poor and can only be improved by arbitrary and physically unjustified adjustment of input parameters, such as potential strengths or geometries. Such troubles are frequently encountered for low angular momentum transfer in light nuclei.[1] The origin of the difficulty is not well understood although the possibilities are myriad. Isolating and identifying these problems would provide guidance for developing and improving theoretical understanding of the (p,d) reaction mechanism.

In the present paper, we report on recent measurements for which the DWBA fails in a most spectacular fashion. Specifically, we will discuss cross-section and analyzing power measurements for the $^{24}Mg(\vec{p},d)^{23}Mg(2.36 \text{ MeV } \frac{1}{2}^+)$ transition at $T_p=94$ MeV.[2] While similar failures have been observed by us for transitions in other light nuclei in this energy regime, this particular one is the most severe and has been the focus of our attention. We have examined the influence on the DWBA of several frequently ignored effects in an attempt to identify the source of the difficulty.

Figure 1 compares the data with "standard" DWBA calculations employing phenomenological proton[3] and deuteron[4] optical model potentials and target wave functions tied to electron scattering densities.[5] Both exact-finite range (calculations performed as in Ref. 6) and zero-range results are shown with cross sections normalized using the theoretical spectroscopic factor of Chung and Wildenthal as reported in Ref. 7. While some differences can be perceived between the calculations, they are insignificant when compared to the discrepancy with the data. The calculations

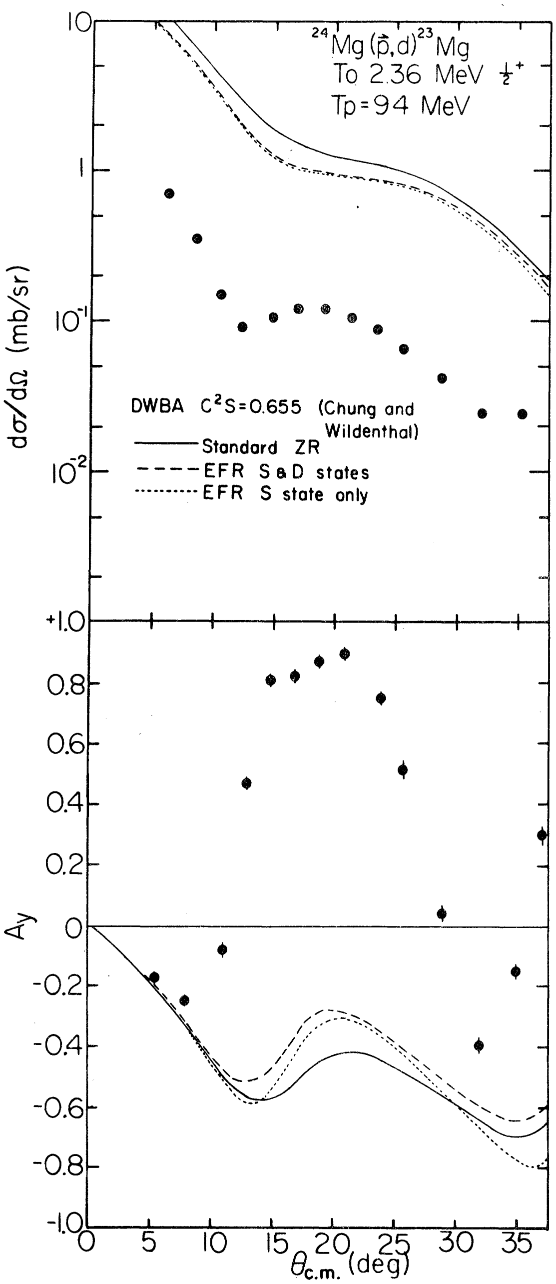

FIG. 1. Zero-range and exact-finite-range DWBA calculations are compared with data.

overestimate the cross sections by at least an order of magnitude and the pronounced oscillatory structure observed in the asymmetry data is in no way reproduced. These discrepancies constitute an extreme failure of the DWBA.

Several sets of optical potentials were tested and while some sensitivity was observed, especially to deuteron potentials, the variations in cross section and A_y were miniscule compared to the discrepancy with the data. Since the transition is an $l=0$ pickup, the nonzero analyzing powers arise solely from the proton and deuteron spin-orbit potentials which contribute almost equally to the calculated A_y. Reasonable variations of these potentials by themselves, including the addition of reasonable imaginary parts,[8] likewise produced small effects.

The influence of a more complicated spin dependence in the deuteron channel was also studied. Figure 2 shows zero-range calculations including a configuration-space tensor interaction, usually designated as T_R, in the deuteron channel. The parameters of T_R were determined by analysis of $d+{}^{12}C$ elastic scattering data at $T=29.5$ MeV (Ref. 9) and, although this extrapolation is likely to be quantitatively unreliable, Fig. 2 shows that the influence of T_R is quite small even when the strength determined in Ref. 9 is arbitrarily doubled.

The effect of the deuteron continuum on (p,d) and (d,p) cross sections has been frequently studied. Approximate treatments—such as the Johnson-Soper prescription[10]—have resulted in improved agreement with cross-section data in many cases. Full coupled-channels formulation of the three-body problem[11,12] is much more difficult and extended comparisons with data have not yet been made. Farrell, Vincent, and Austern[11] suggest that continuum or break-up effects are most pronounced for low partial waves in the nuclear interior. This is just the region emphasized in momentum mismatched reactions such as the one discussed here. We therefore performed coupled channels calculations in the spirit of Ref. 11 using five continuum channels and a separable nucleon-nucleon potential.

The models discussed above treat the system as a neutron, proton, and inert nucleus with the nuclear internal degrees of freedom evident only through the imaginary part of the nucleon-nucleus potential. The solution to this three-body Hamiltonian is expanded in deuteron eigenstates keeping only a few of the lowest partial waves. The different methods differ primarily in their treatment of the continuum states of the deuteron. Johnson and Soper[10] use a single state and the adiabatic approximation while Rawitscher[12] and Farrel *et al.*[11] use finite momentum bins. An alternative solution which we use is to quantize the states in a spherical box of finite but large radius. This method avoids the disadvantages of the binning procedure where one either uses a average energy[12] for the

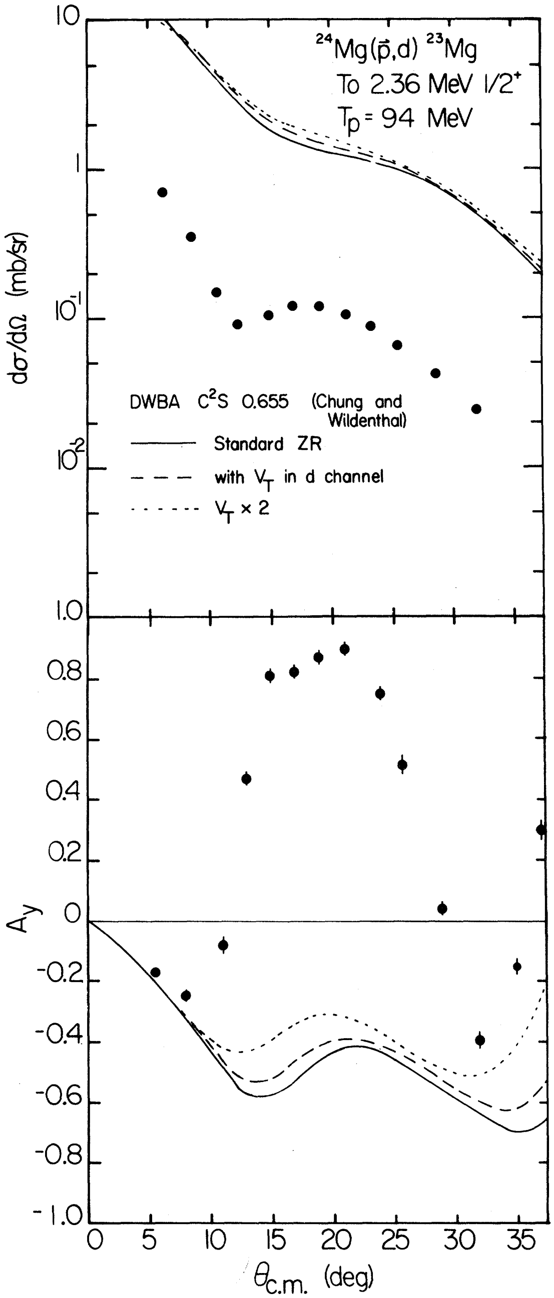

FIG. 2. Zero-range calculations, with and without tensor potentials, in the deuteron channel are compared with data.

bin or a numerically complicated bin integration scheme.[11]

The Hamiltonian for the three-body system is given by

$$H = T_R + T_r + V_{np}(r) + V_n(r_n) + V_p(r_p) , \qquad (1)$$

where T_R and T_r are the kinetic energies of the center-of-mass and internal motion of the deuteron, respectively. The potential $V_{np}(r)$ is chosen to be the separable potential of Yamaguchi[13] and V_n and V_p are the optical potentials of the proton and neutron on the nucleus A at half the deuteron incoming kinetic energy.

The solution to the Hamiltonian is expanded in eigenstates of

$$[T_r + V_{np}(r)]\phi_i(r) = \epsilon_i \phi_i(r) , \qquad (2)$$

$$\Psi(R,r) = \sum_{i=0}^{\infty} \chi_i(R)\phi_i(r) , \qquad (3)$$

where $\chi_0(R)$ for the deuteron ground state has the boundary condition of incoming plane wave plus outgoing scattered wave and $\chi_n(R)$ for $n > 0$ have the boundary conditions of outgoing waves only. The $\phi_n(r)$ are restricted in this work to be only relative s-wave states satisfying a boundary condition $\phi_n(r_{max}) = 0$.

The solution of the Schrödinger equation then reduces to an infinite set of coupled equations of the form

$$(E_i - T_R - V_{ii})\chi_i(R) = \sum_{j \neq i} V_{ij}\chi_j(R) , \qquad (4)$$

where

$$V_{ij} = \langle \phi_i(r) \mid V_n(R + r/2) + V_p(R - r/2) \mid \phi_j(r) \rangle \quad (5)$$

and

$$E_i = E - \epsilon_i . \qquad (6)$$

This set of equations is then truncated to give a finite set of coupled equations which can be solved by usual methods, e.g., by the computer code CHUCK.[14]

The radius r_{max} is chosen so as to give five or six states for the deuteron center-of-mass energy between the zero and maximum energy. The states near zero energy for the center-of-mass motion are found to contribute insignificantly to the elastic scattering. For a total energy of the system of 22 MeV the value of r_{max} was about 24 fm. The comparison of our method with the calculations of Farrel *et al.*[11] gave very close quantitative agreement as shown in Fig. 3.

The ^{24}Mg($\vec{p}$,d) calculations appear in Fig. 4. The dashed curves of Fig. 4 correspond to DWBA calculations using unfolded nucleon-nucleus potentials[15] and are therefore equivalent to the Johnson-Soper method.[10] A folded or Watanabe-type potential[16] was used in the DWBA to generate the dotted curve; this corresponds to a limiting case of the

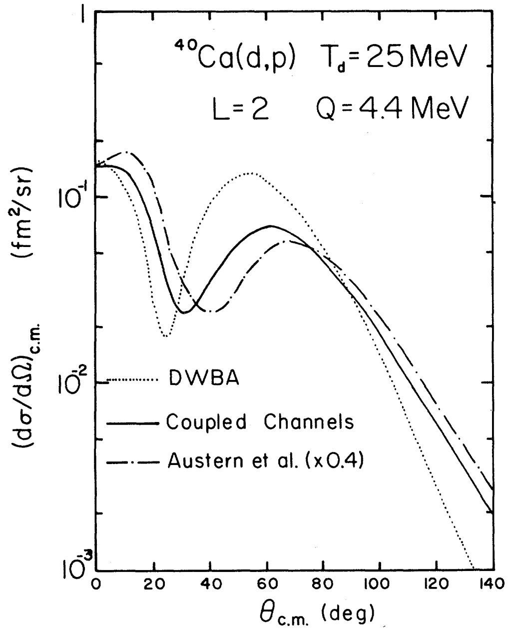

FIG. 3. Comparison of the coupled channels calculations with the DWBA and calculations by Austern *et al.* (Ref. 11). The Austern *et al.*, result has been renormalized to agree with the coupled channels calculation at 0°.

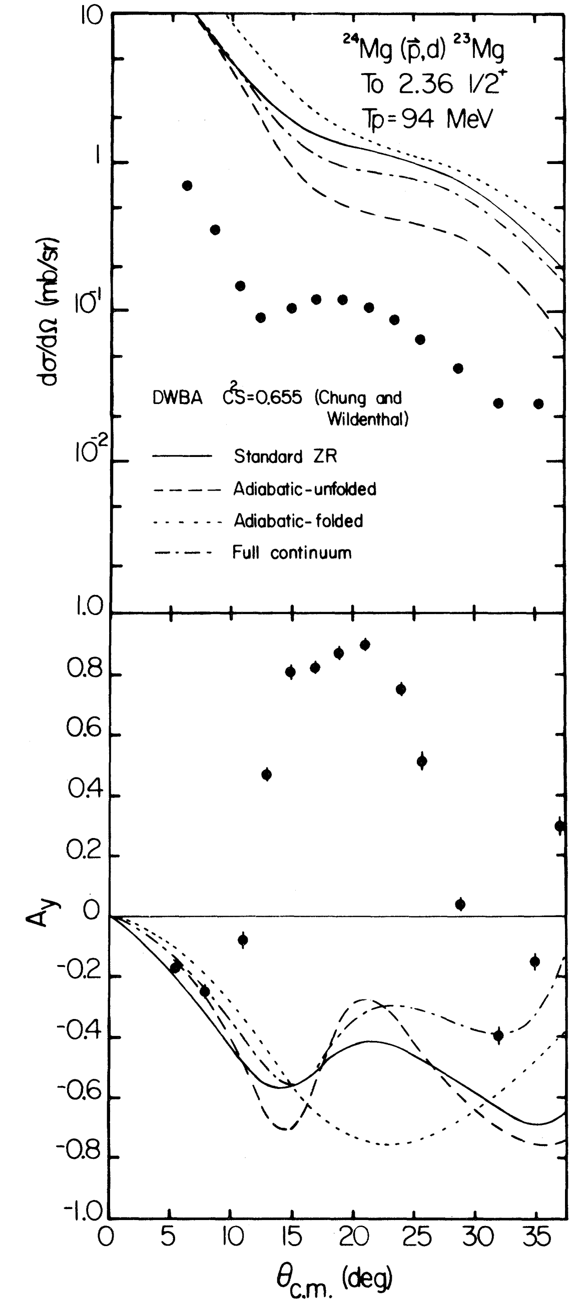

FIG. 4. DWBA calculations with and without continuum contributions are compared with data. See text for explanation.

coupled channels calculations where only the deuteron bound state contribution is retained. Examination of the calculated analyzing powers displayed in Fig. 4 shows that, as asserted in Ref. 11, the Johnson-Soper prescription yields a better approximation to the full calculation than the Watanabe model although no distinct preference can be inferred from the cross sections. In any case, no matter how the break-up contributions are treated, Fig. 4 shows that they do not appreciably improve agreement with the data.

^{24}Mg and ^{23}Mg are known to be strongly deformed nuclei. Consequently, relatively large multistep contributions are possible in single nucleon transfer reactions. These effects have been examined in detail for the ^{24}Mg(d,t) and ^{24}Mg$(d,{}^3$He$)$ reactions by Nelson and Roberson.[17] We have used their amplitudes generated from shell model or band-mixed, rotational-model analyses in a coupled-channel Born approximation (CCBA) extension of the DWBA to assess the influence of two-step contributions. The dashed curves of Fig. 5 are typical of the resulting calculations. No significant effect is observed. The dotted curves of Fig. 5 were obtained by arbitrary adjustment of amplitude to give maximum cancellation of one- and two-step contributions. Cross-section normalization is arbitrary. Although the agreement with the A_y data is much improved, it should be noted that the adjusted amplitudes are quite unrealistic—the ratio $C^2S(2^+\rightarrow 1/2^+)/C^2S(0^+\rightarrow 1/2^+)$ is 160 times greater for the dotted curves than for the dashed—and that the cancellation which gives this improvement is quite delicate.

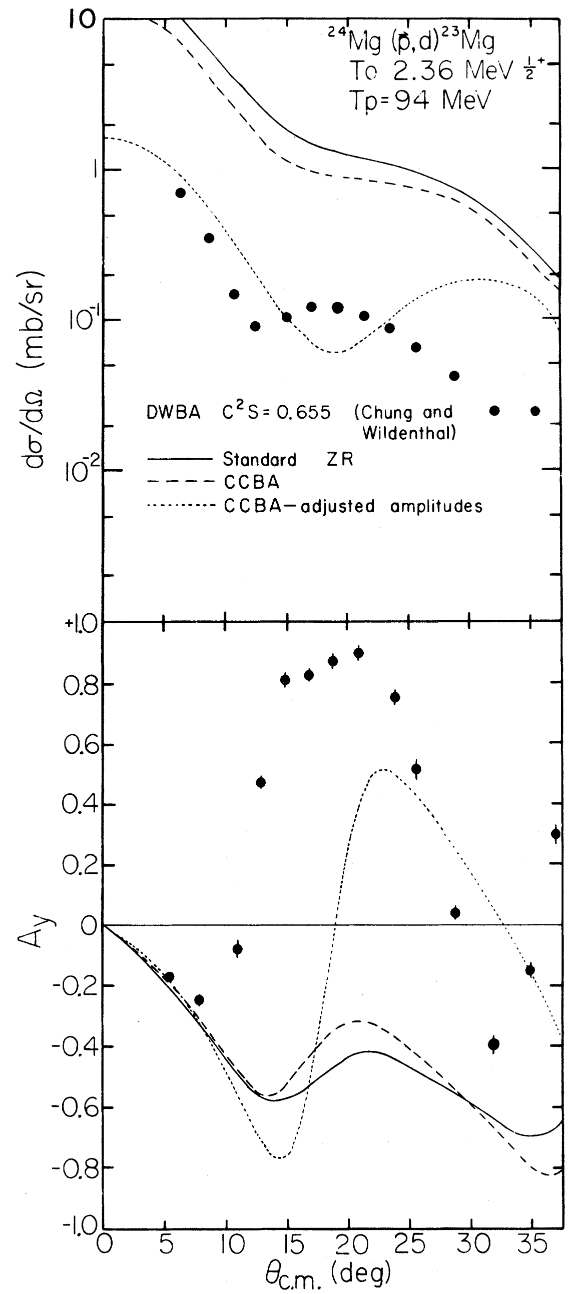

FIG. 5. Calculations with and without two-step contributions are compared with the data. Note that cross-section normalization for the dotted curve is arbitrary.

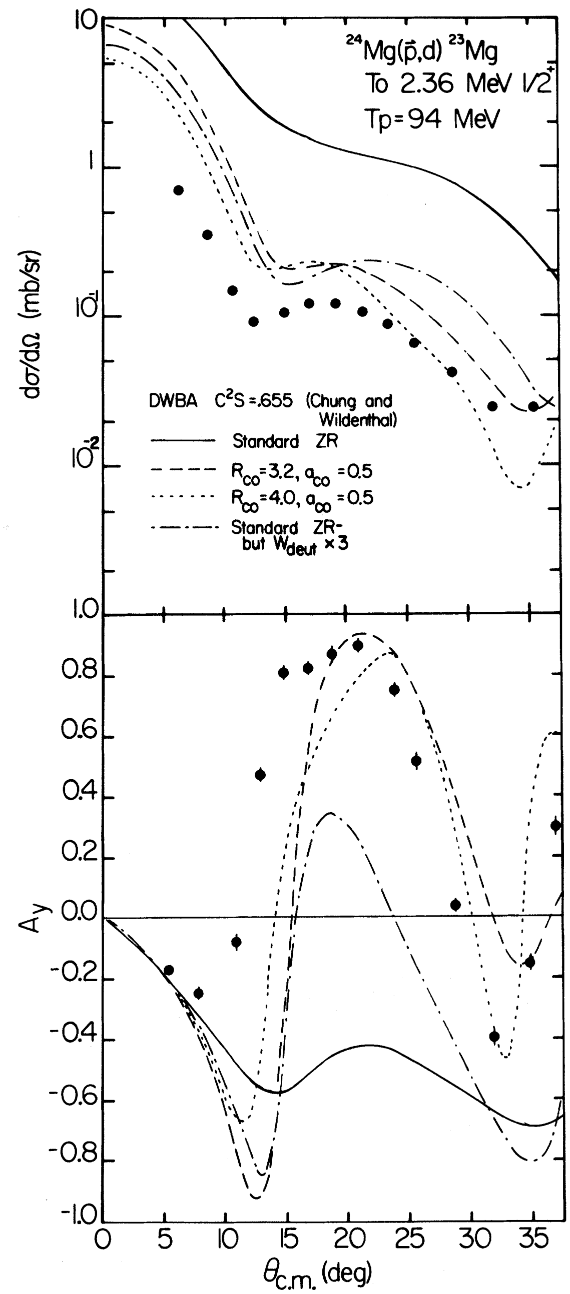

FIG. 6. Zero-range DWBA calculations with and without surface localization are compared with the data. The dashed and dotted curves reflect the use of cutoffs. The dashed-dotted curve reflects the use of increased deuteron absorption.

The highly oscillatory A_y angular distribution observed in the ^{24}Mg($\vec{p}$,d) reaction is qualitatively similar to that observed for elastic scattering of strongly absorbed particles which can qualitatively be described using strong absorption models which exploit the localized nature of the reaction.[18] We used several means of artifically introducing such localization into the DWBA calculations. All gave similar results and resulted in vastly improved agreement with the data. Examples appear in Fig. 6, where the dotted and dashed curves were obtained by multiplying the form factor by

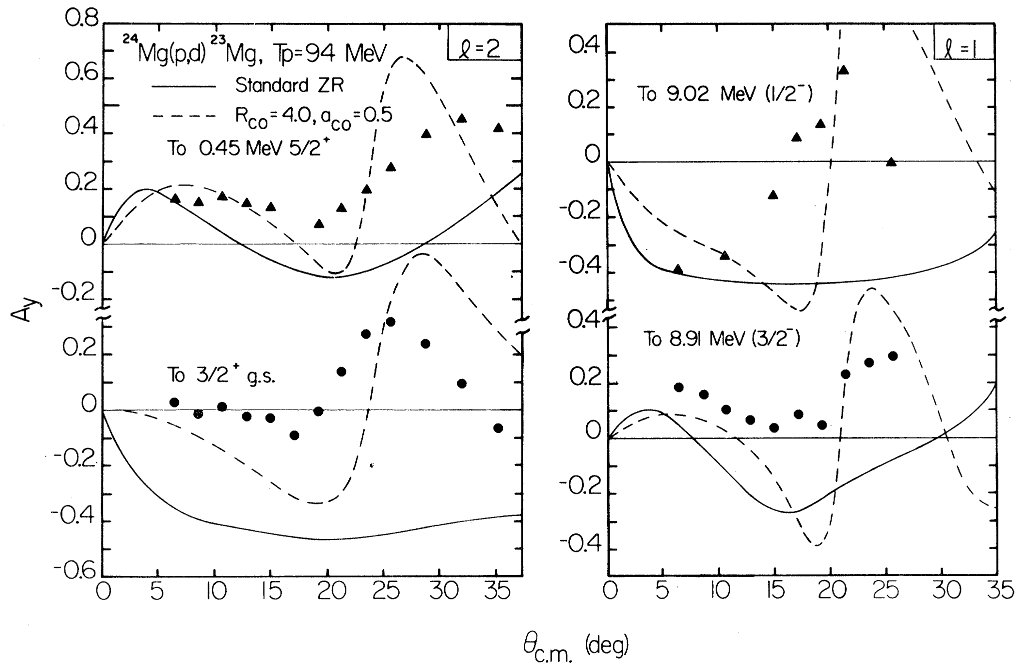

FIG. 7. Zero-range DWBA calculations with and without surface localization are compared with the data. The dashed and dotted curves reflect the use of cutoffs. The dashed-dotted curve reflects the use of increased deuteron absorption.

$$f(r)=1-\{1+\exp[(r-R_{co})/a_{co}]\}^{-1}$$

with $a_{co}=0.5$ fm and $R_{co}=3.2$ and 4.0 fm (or $1.11\times 24^{1/3}$ and $1.39\times 24^{1/3}$), respectively. In effect this amounts to a smoothed lower radial cutoff with cut-off parameters arbitrarily chosen to give the vastly improved agreement with the A_y data shown in the bottom half of Fig. 6. Not surprisingly, a similar effect can be achieved by greatly increasing absorption in the optical potentials. This is illustrated by the dashed-dotted curve in Fig. 6 which was generated using ZR DWBA without a cutoff, but with the imaginary deuteron potential strength increased by a factor of 3. The top of Fig. 6 shows that the cutoff chosen to give optimum agreement with the A_y data also greatly improves agreement with the measured cross sections. Figure 7 indicates that measured A_y values for strong $l=2$ and $l=1$ transitions are also much better reproduced. Cross section calculations using the Chung and Wildenthal spectroscopic factors are also in better agreement.

Such general improvement using cutoffs suggests that delicate cancellations between one- and two-step amplitudes are not responsible for the poor agreement between the DWBA and experiment for the ^{24}Mg($\vec{p}$,d)^{23}Mg(2.36 MeV $\frac{1}{2}^+$) reaction. It does suggest that the cutoffs are mocking up important physical effects neglected in the DWBA even when the many refinements discussed above are included. The calculations are obviously very sensitive to the contributions from the nuclear interior and apparently the DWBA—even in its more refined formulations—does not treat these contributions correctly. In the present case, this incorrect treatment results in catastrophic disagreement with experiment. The physics which underlies the apparent suppression of interior contributions in the present case should be embodied in an improved reaction theory.

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