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$^{18}O(\vec{p},t)^{16}O$ reaction at 90 MeV

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Differential cross sections and analyzing powers were measured for the $^{18}O(\vec{p},t)^{16}O$ reaction at 90 MeV. The angular distributions for six triton groups are compared with calculations performed in the zero-range and finite-range distorted wave Born approximation. The present results were augmented by data available in the literature in order to study the excitation function $\sigma(T_p)$ for the $J^\pi=2^+$ state at $E_x=9.85$ MeV over the range of $T_p=20$ to 90 MeV in comparison with distorted wave Born approximation calculations.

I. INTRODUCTION

In a recent paper[1] we reported on the two-neutron transfer reaction $^{17}O(\vec{p},t)^{15}O$ at 90 MeV for the "simple" case of a transition from a one-particle to a one-hole state. The nuclear wave functions and the scattering potentials were well known in that case. Nevertheless, we experienced some difficulties in reproducing the absolute cross sections and analyzing powers using either the one-step, finite-range (FR) or the second-order, two-step, zero-range (ZR) distorted wave Born approximation (DWBA) calculations. During the course of the measurements we also obtained data for the $^{18}O(\vec{p},t)^{16}O$ reaction whose energy dependence has been investigated previously at lower projectile energies.[2] The addition of our new data gave us the opportunity to study the momentum transfer dependence of the (p,t) cross section over a range more than twice as large as that studied in Ref. 2. A comparison between the ZR DWBA calculations as used in Ref. 2 and the corresponding FR DWBA calculations is made here in an attempt to understand the differences observed between ZR and FR calculations at 90 MeV.

II. EXPERIMENTAL RESULTS

The experiment was performed at the Indiana University Cyclotron Facility by using the quadrupole-dipole-dipole-multipole (QDDM) magnetic spectrometer. Details of the experimental setup are given in Ref. 1. A typical spectrum obtained during the present measurements is displayed in Fig. 1, where six triton groups from the $^{18}O(\vec{p},t)^{16}O$ reaction are clearly observed in the excitation energy range of 5–17 MeV. A gap, as indicated, between 10 and 12 MeV excitation energy resulted at most angles

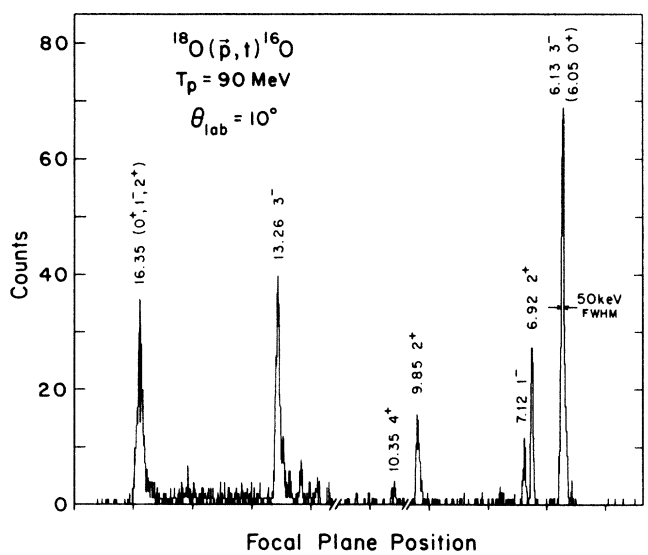

FIG. 1. $^{18}O(\vec{p},t)^{16}O$ spectrum at $\theta_{lab}=10°$. The figure is a composite resulting from three adjacent magnetic field settings of the QDDM magnetic spectrometer. Excitation energies are listed in MeV.

from the two nonoverlapping QDDM magnetic field settings. Figure 1 shows that for the laboratory angle of 10° a state at 10.35 MeV was weakly excited ($d\sigma/d\Omega \simeq 5$ μb/sr, $A_y \simeq 0$). A $J^\pi = 4^+$ state has been reported at this energy.[3] Such a state is expected to be excited very weakly in the one-step pickup reaction from a $J^\pi = 0^+$ nucleus. Although it was seen in the previous (p,t) studies at lower bombarding energies,[2] its cross section declines sharply with increasing T_p and has not been reported for energies above 40 MeV. The unnatural-parity $J^\pi = 2^-$ state at 8.88 MeV was not observed in our experiment ($d\sigma/d\Omega < 1$ μb/sr). This state represents a first-order forbidden transition for (p,t), and its population is expected only if higher order reaction mechanisms and coupling to collective excitations come strongly into play. The decline in the excitation of collective modes with rising projectile energies known from inelastic scattering work might account for the observed absence of this level at 90 MeV projectile energy.

The cross section and analyzing power angular distributions for the six stronger $^{18}O(\vec{p},t)$ groups are displayed in Fig. 2 together with FR and ZR one-step DWBA predictions. The calculations were performed with the codes FRUCK2 and CHUCK3 (Ref. 4) by using the same optical model potentials and bound state geometry parameters as in Ref. 1, and spectroscopic amplitudes for the $^{18}O(\vec{p},t)$ transfer taken from Ref. 5. The doublet at 6.05 and 6.13 MeV, $J^\pi = 0^+, 3^-$, was typically not resolved in our experiment. Where it was partially resolved, the 3^- state dominated by a factor of about 5. The measured excitation

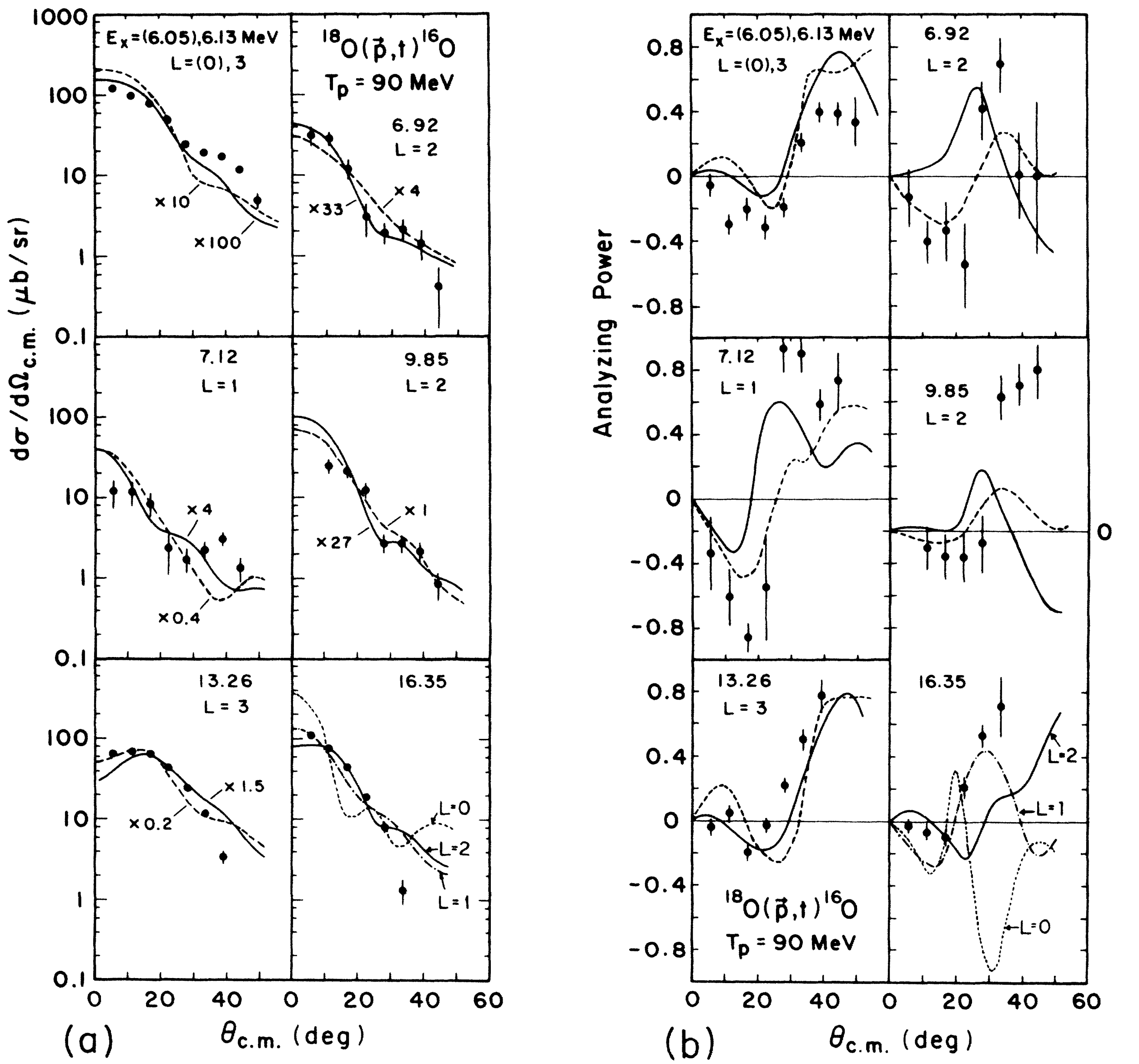

FIG. 2. (a) $^{18}O(\vec{p},t)$ differential cross sections and (b) analyzing powers for the six residual groups of ^{16}O in comparison with calculations in the finite-range (solid lines) and zero-range (dashed lines) distorted wave Born approximation. The normalization factors at the curves are based on spectroscopic factors from Ref. 5. For the group at 16.35 MeV only finite-range calculations are shown for the indicated L values.

energy and the shapes of the angular distributions indicate a predominant $L=3$ component in this transition. The broad group seen at 16.35 MeV appears to be the $(0^+,1^-,2^+)$ multiplet at 16.35 and 16.44 MeV.[3] A $J^\pi=0^+$ state seems to have been observed at 16.33 MeV in an $^{18}O(p,t)$ experiment for 42 MeV projectile energy.[6] Figure 2 displays only FR calculations for $L=0,1,2$ for this latter group. Although the reproduction of the data is at best marginal for any of the L values, the $L=0$ result appears to have the largest discrepancies. Any $L=0$ admixture to this group is therefore assumed to be small.

III. DISCUSSION

The $^{17}O(\vec{p},t)$ analysis[1] had shown significant disagreement between FR and ZR one-step calculations for both

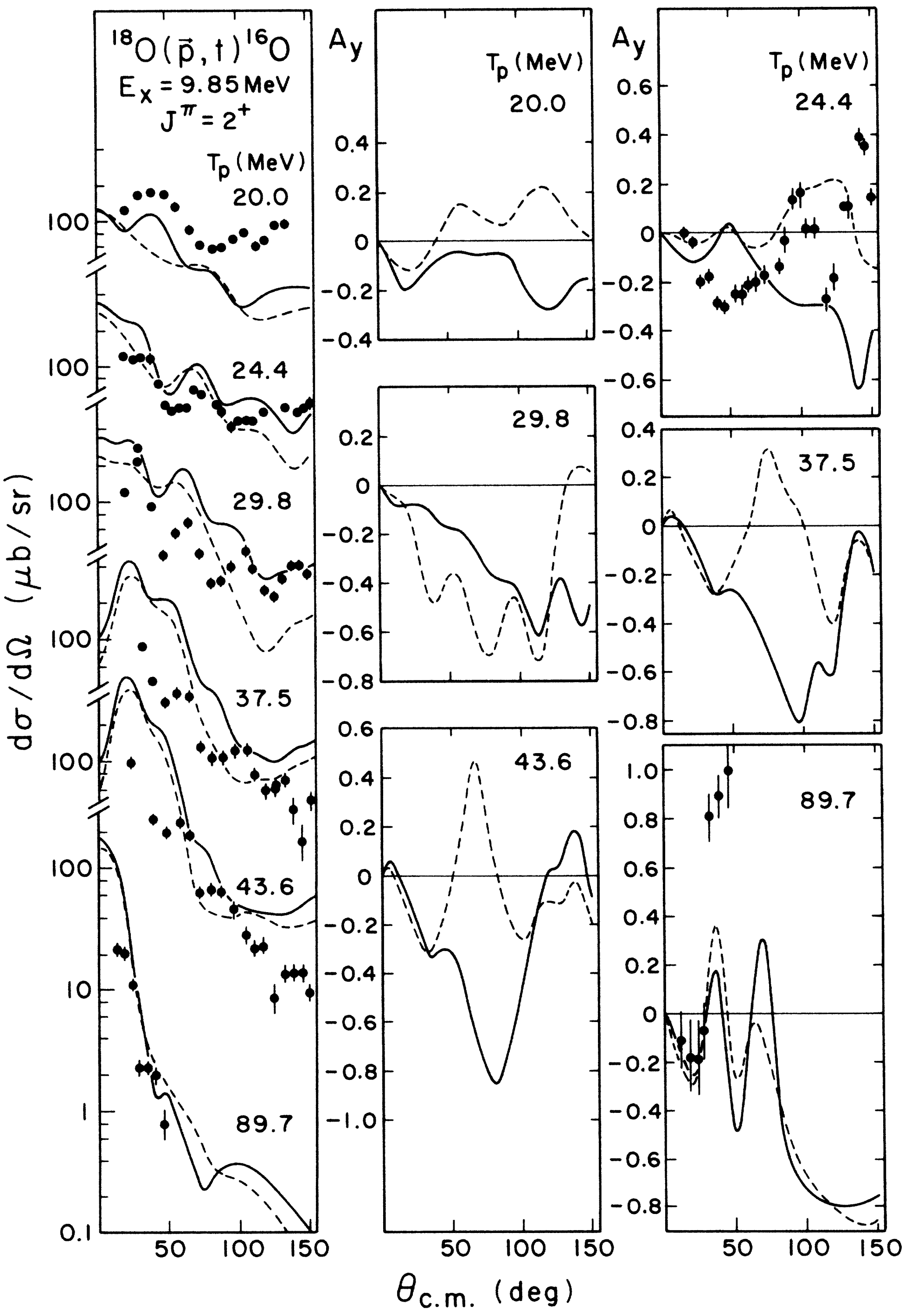

FIG. 3. Differential cross sections and analyzing powers for $^{18}O(\vec{p},t)^{16}O^*(2^+, 9.85$ MeV) at $T_p=20.0$, 24.4, 29.8, 37.5, and 43.6 MeV from Ref. 2, and at $T_p=89.7$ MeV (the present work). The data are shown together with zero-range (dashed lines) and finite-range (solid lines) DWBA calculations (see the text for details). The finite-range curves are consistently multiplied by a factor of 10.

absolute cross sections and analyzing powers, despite the use of equivalent input parameters. Compared to the data, the FR calculations predicted cross sections too small by factors of 2 or more, whereas the ZR results were too high by factors of 4 or more. A similar finding has been reported for the ($\vec{p}$,^{3}He) reaction on ^{24}Mg and ^{28}Si at $T_p=90$ MeV.[7] While obtaining a good reproduction of the shapes of the angular distributions, the authors also encountered large overpredictions in one-step ZR DWBA calculations. For the present ^{18}O($\vec{p}$,t) study, the FR predictions are again too low and the ZR results again relatively too high. The renormalization factors are given in Fig. 2(a). For the $J^\pi=0^+$ target the L transfers are uniquely determined by the final state spins. Hence, failures of the one-step predictions for angular distributions cannot occur because of insufficiently known configuration mixing. The predicted analyzing powers seem to be in slightly better agreement with data for the transitions with $L=3$ than for the other transitions [Fig. 2(b)]. Perhaps this is not surprising, since in the present study momentum and angular momentum mismatch are less serious for $L=3$ than for the smaller L values. In general, the calculations do not satisfactorily reproduce the analyzing power distributions, and large differences also exist between the FR and ZR predictions.

The question to be asked is whether the ZR-FR discrepancies encountered here are related to the projectile energy and can be observed more universally. Pignanelli et al.[2] investigated the dependence of the ^{18}O(p,t) reaction on momentum transfer in comparison with one-step ZR DWBA calculations. In the excitation region of Ref. 2 that overlaps with our work only the $J^\pi=2^+$ state at 9.85 MeV was well resolved. Hence, we reproduced the ZR calculations of Ref. 2 for this state and extended them to the higher bombarding energy. We also performed the corresponding FR calculations. The global optical model parameter sets P7H6 from Ref. 2 which were obtained from elastic scattering analyses were used in all calculations. Figure 3 displays the two sets of calculations in comparison with the data for the different projectile energies. Shape differences between the ZR and FR curves occur throughout the region covered by the data with a slightly better reproduction of the relative cross sections by the FR calculations. We note that the ZR and FR calculations require renormalization factors that differ substantially from 1.0, and from each other.

The measured excitation function $\sigma(T_p)$ for the 9.85 MeV state is compared to the ZR and FR predictions in Fig. 4. Due to the smaller angular range of the 90-MeV data, the FR calculation was normalized to the data at forward angles and integrated over the same range as the data of Ref. 2 in order to obtain σ. The error introduced by this procedure was estimated to be small, assuming a reproduction of the shape of the angular distribution within 20%. As the authors of Ref. 2 pointed out, the shape of the ZR curve can be understood in terms of a dependence of the DWBA cross sections upon the matching of momentum and angular momentum. For a given Q value, and target-projectile combination, good matching conditions exist for at most one projectile energy. As can be seen in Fig. 4 both DWBA codes produce a similar dependence on T_p. However, the FR results are almost an order of magnitude smaller than the ZR results over the entire energy range. The fact that the FR DWBA produces a similar $\sigma(T_p)$ curve as the ZR DWBA implies that the introduction of finite-range interactions and replacement of the point-triton by an extended object as described by the Tang-Herndon form factor[8] does not greatly effect the momentum-transfer dependence predicted by the DWBA.

Several points might contribute to the findings described above. First, as shown in a recent study[9] on the (p,d) reaction at 800 MeV, the momentum-transfer dependence of the ZR normalization D_0 can be large. Using a plane wave Born approximation, Smith et al.[9] qualitatively demonstrate for the deuteron case that the D-state contribution produces notable differences in the projectile Fourier transform $D(q)$. They show that, even with finite-range corrections, the ZR normalization $D_0=D(q=0)$ is valid only for $q \ll 1.0$ fm^{-1}. At higher momentum transfers the effective $|D_0|$ is considerably smaller than at $q=0$. Hence, the calculated cross sections are smaller, too. Similar arguments may readily apply to the triton case, i.e., with increasing momentum transfer

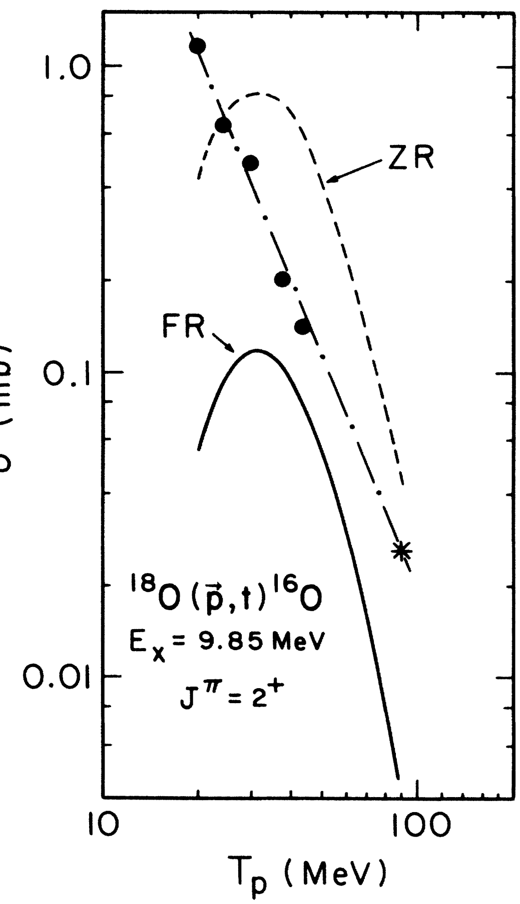

FIG. 4. ^{18}O($\vec{p}$,t)^{16}O*(2$^+$, 9.85 MeV) excitation function $\sigma(T_p)$ together with finite-range (solid line) and zero-range (dashed line) DWBA predictions. The filled circles represent data from Ref. 2; the asterisk is the result of the present work.

the (p,t) normalization will also become sensitive to the detailed structure of the triton and, generally speaking, this means a decrease of $|D_0|$.

Second, the underprediction of the $^{18}O(p,t)$ cross sections by FR calculations could stem from an omission of important sequential transfer channels in the reaction mechanism. Second-order ZR DWBA calculations[1] for $^{17}O(\vec{p},t)$ and other studies of two-nucleon transfer reactions[10–13] have shown that such two-step channels can be of the same strength as the one-step (p,t) channel. However, for the $^{18}O(\vec{p},t)$ reaction two-step calculations are difficult to compute because of the larger configuration space involved. Since the "simple" $^{17}O(\vec{p},t)$ case had already given problems for the second-order ZR DWBA calculations, they were not attempted in the present work.

Finally, the failure of both the ZR and FR DWBA calculations to reproduce the excitation function $\sigma(T_p)$ might indicate a more general problem with the DWBA. Whether omission of second-order effects or insufficient knowledge of wave functions and form factors causes the problem remains to be investigated.

IV. CONCLUSION

This study of the $^{18}O(\vec{p},t)$ reaction was performed in order to cross check the results obtained from the $^{17}O(\vec{p},t)$ DWBA analysis. The possibility of an inclusion of earlier work at lower projectile energies was thought to provide a useful way of discussing which problems are intrinsic to the description of the reaction mechanism versus those associated with a particular bombarding energy regime. Inadequacies of the DWBA for the (p,t) reaction were observed over the entire energy range, indicating that is necessary to improve our understanding of the basic reaction mechanism.

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