^{16,18}O elastic scattering from ^{58}Ni†

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(Received 22 July 1974)

The elastic scattering of $^{18}O+^{58}Ni$ at 63.4 MeV and $^{16}O+^{58}Ni$ at 63, 71.5, and 81 MeV has been studied and optical model fits have been obtained. The data indicate that weakly absorbing optical potentials of the type used in some recent distorted wave Born approximation calculations are inconsistent with back angle elastic scattering. A five-parameter surface transparent optical potential with $a_I < a_R$ has been found which reproduces the elastic scattering over this energy range and appears to be capable of qualitatively reproducing the observed forward peaked and oscillatory transfer reaction angular distributions in this mass region.

[NUCLEAR REACTIONS ^{58}Ni(^{18}O, ^{18}O), $E = 63.4$ MeV, ^{58}Ni(^{16}O, ^{16}O), $E = 63$, 71.5, 81 MeV; measured $\sigma(\theta)$; deduced optical model parameters.]

There has been much interest recently in the so-called "anomalous" angular distributions which sometimes occur in heavy ion transfer reaction data.[1-4] These anomalous angular distributions are oscillatory and forward peaked, as opposed to the relatively structureless bell-shaped angular distributions reported in early heavy ion studies even at energies well above the Coulomb barrier.[5] It has been demonstrated in the case of the ^{48}Ca(^{14}N, ^{13}C) reaction[2,6] that the forward peaking and oscillatory behavior can be reproduced by means of distorted wave Born approximation (DWBA) calculations in which a weakly absorbing optical potential is employed. Since such weakly absorbing optical potentials were consistent with the measured elastic scattering, the explanation seemed reasonable.

However, in previous studies of heavy ion elastic scattering on *sd*-shell nuclei undertaken at Seattle,[7] it was found that a weakly absorbing optical potential tends to predict too much structure in the back angle elastic cross sections. (By back angles we mean those where $\sigma/\sigma_R \lesssim 10^{-2}$.) For this reason it seemed worthwhile to carefully study the elastic scattering for another system which appears to show anomalous angular distributions, namely the $^{16,18}O+^{58}Ni$ system. [The ^{58}Ni(^{18}O, ^{16}O) reaction studied by Auerbach *et al.*[1] at 63.4 MeV was an early example of a forward-peaked transfer reaction angular distribution.] By extending the elastic scattering measurements to more backward angles than were studied previously,[1] we expect to be able to distinguish experimentally between strongly and weakly absorbing potentials. It was also felt worthwhile to examine the behavior of the optical potentials found here in transfer reaction DWBA calculations, to see whether the additional "restriction" of fitting the back angle elastic data would automatically eliminate potentials which (incorrectly) predict structureless bell-shaped transfer reaction angular distributions. These DWBA calculations will be discussed below.

The experiment consisted of measurement of the elastic scattering of $^{18}O+^{58}Ni$ at 63.4 MeV and $^{16}O+^{58}Ni$ at 63, 71.5, and 81 MeV. The data were taken with an array of large area Si(Li) detectors, spaced 1.1° apart in the lab, to scattering angles such that $\sigma/\sigma_R \lesssim 10^{-3}$. Figure 1 shows the observed angular distributions for all four data sets.

Optical model fits to the data have been obtained with a heavy ion version of the optical model code GENOA[8]; the parameters are listed in Table I. Two different types of potentials were found: conventional strongly absorbing (SA) potentials and five-parameter "surface transparent" (ST) potentials. For purposes of comparison, the weakly absorbing (WA) "Brookhaven" potential, obtained by Auerbach *et al.*[1] from fitting the forward-angle $^{18}O+^{58}Ni$ elastic scattering at 63.4 MeV, is included in Table I. In all cases the ^{16}O angular distributions were fitted simultaneously with a single optical potential. Furthermore, the real well depth was arbitrarily fixed at 70 MeV in all parameter searches. [In what follows we will refer to the surface transparent $^{18}O+^{58}Ni$ potential as ST18, and similarly for the other sets. The DWBA calculations described below are labeled in the same manner, e.g., potential set ST18-ST16 refers to a DWBA calculation employing potential ST18 in the ($^{18}O+^{58}Ni$) entrance channel and ST16 in the ($^{16}O+^{60}Ni$) exit channel.]

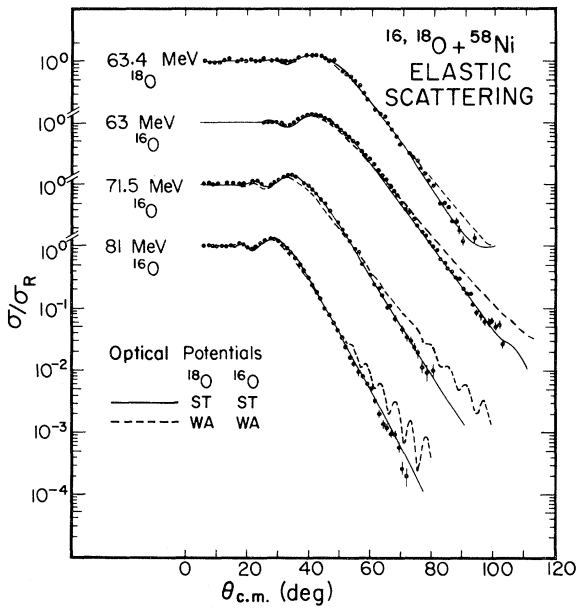

FIG. 1. Angular distributions for $^{18}O+^{58}Ni$ elastic scattering at 63.4 MeV and $^{16}O+^{58}Ni$ elastic scattering at 63, 71.5, and 81 MeV. The solid curves are optical model fits to the data and the dashed curves are predictions of the weakly absorbing Brookhaven potential from Ref. 1.

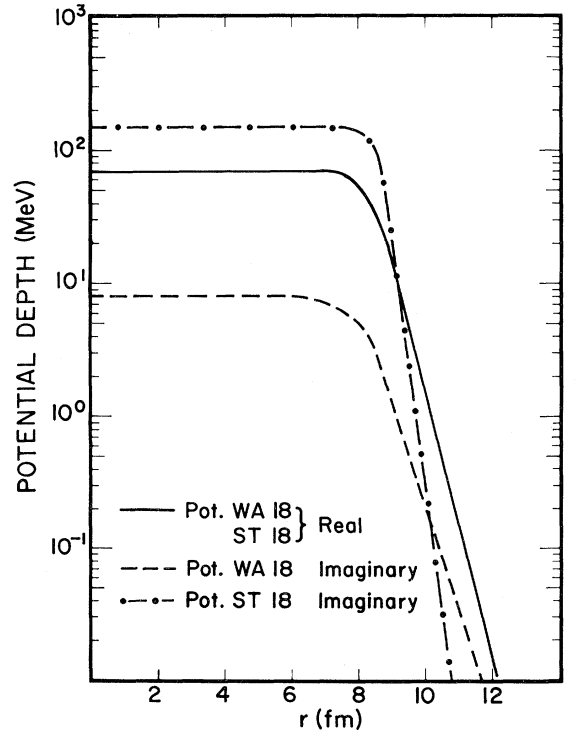

FIG. 2. Geometry for optical potential Sets WA18 and ST18 from Table I. The real geometry is nearly identical for the two cases and is only shown once.

TABLE I. Optical potentials for $^{16,18}O+^{58}Ni$ elastic scattering.

Set	V (MeV)	r_R [a] (fm)	a_R (fm)	W (MeV)	r_I [a] (fm)	a_I (fm)
			^{18}O			
ST18	70	1.33	0.38	149.0	1.33	0.20
WA18 [b]	70	1.31	0.40	8.0	1.26	0.50
SA18	70	1.16	0.60	39.8	1.16	0.60
			^{16}O			
ST16	70	1.18	0.57	82.1	1.18	0.39
WA16 [b]	70	1.30	0.40	8.0	1.27	0.50
SA16	70	1.19	0.54	18.5	1.19	0.54

[a] $R=r(A_1^{1/3}+A_2^{1/3})$.
[b] Reference 1.

The solid curves in Fig. 1 represent fits to the data using the five-parameter potential sets ST18 and ST16. For these potentials the real and imaginary radii were kept the same and the real and imaginary diffuseness were allowed to vary independently. To emphasize the somewhat unusual geometry of these potentials, Fig. 2 shows a comparison of the Brookhaven $^{18}O+^{58}Ni$ potential (WA18) with that obtained here (ST18). The geometry of the real well is almost the same for the two potentials and is only shown once. As can be seen, Set ST18 is strongly absorbing compared to the Brookhaven potential except at large radii, around 10 fm, where the two potentials are roughly comparable. Thus, at least in the surface region, five-parameter potentials such as Sets ST18 and ST16 are indeed weakly absorbing.

The dashed curves in Fig. 1 refer to predictions of the weakly absorbing Brookhaven potentials WA18 and WA16. As can be seen, these potentials do a reasonable job of fitting the forward angle elastic scattering data at all energies, although they fail rather badly at back angles. This is most obvious at 81 MeV where the predicted oscillations are clearly not present in the experimental data.

In order to investigate differences between these various parameter sets we have repeated some of the DWBA calculations for the $^{58}Ni(^{18}O, ^{16}O)$ reaction at 63.4 MeV using the exact finite-range code LOLA.[9] The calculations were performed with cluster wave functions ($2S$ and $3S$ for ^{18}O and ^{60}Ni, respectively) bound at the appropriate two-neutron separation energies. Some of the results are shown in Fig. 3. We find, in agreement with the Brookhaven results,[1] that strongly absorbing optical potentials of the usual four-parameter type do *not* predict the transfer reaction correctly, giving a bell-shaped angular distribution as op-

posed to the experimentally observed forward peaking. However, five-parameter potentials such as Set ST18-ST16 (with a small imaginary diffuseness) do appear to give more reasonable results in the DWBA calculations. Compared with the predictions of the weakly absorbing four-parameter Brookhaven potential (Set WA18-WA16) we find that both sets predict similar structure (the phase difference will be discussed below) and magnitude (except at the most forward angles), although at more backward angles the pronounced oscillations given with the weakly absorbing potentials are absent when the surface transparent potentials are used. It should be pointed out that the experimental data for the ^{58}Ni(^{18}O, ^{16}O)^{60}Ni(g.s.) reaction are more forward peaked than the calculations shown here. This may be due to the choice of cluster wave functions since the calculation reported by Auerbach *et al.*[1] using a more realistic two-nucleon form factor along with potential Set WA18-WA16 does reproduce the envelope of the data. Furthermore, the calculations of Ref. 1 were done with a no-recoil code. For the purposes of this paper, however, it was not felt to be necessary to reproduce in detail the experimental angular distribution as long as the qualitative agreement between Sets WA18-WA16 and ST18-ST16 holds true. It is also worth noting that, at least in this particular case, one can find rather different optical potentials, e.g., Sets ST18 and SA18, which do an excellent job of fitting elastic scattering data of ^{18}O + ^{58}Ni down to $\sigma/\sigma_R = 10^{-3}$ or below and yet predict very different transfer reaction angular distributions. [At the scale to which Fig. 1 is drawn, the theoretical curves corresponding to the strongly abosrbing potentials SA18 (for 63.4 MeV ^{18}O) and SA16 (for 71.5 MeV ^{16}O) would be indistinguishable from the solid curves over the angular range for which data exist.]

In an effort to see which features of the optical potentials used above are responsible for the observed differences in the DWBA predictions we did some model calculations using a surface transparent potential in one channel and a weakly absorbing potential in the other. The results of these calculations are shown in Fig. 4, along with the weakly absorbing prediction from Fig. 3. Here we find that using a surface transparent potential in the entrance channel (dotted curve) returns us to a strong absorption type of angular distribution. This is apparently related to the momentum mis-

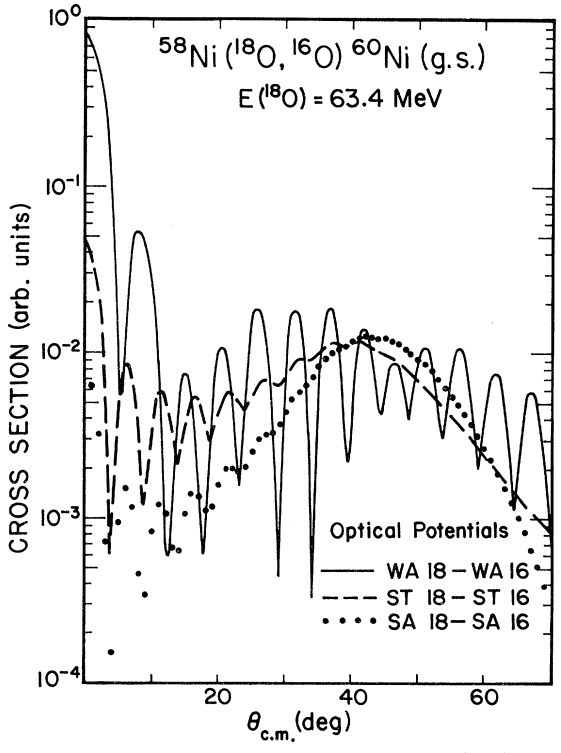

FIG. 3. DWBA predictions for the ^{58}Ni(^{18}O, ^{16}O)^{60}Ni(g.s.) reaction at 63.4 MeV for various optical potentials. The bound states were calculated with $r = 1.15$ fm and $a = 0.50$ fm.

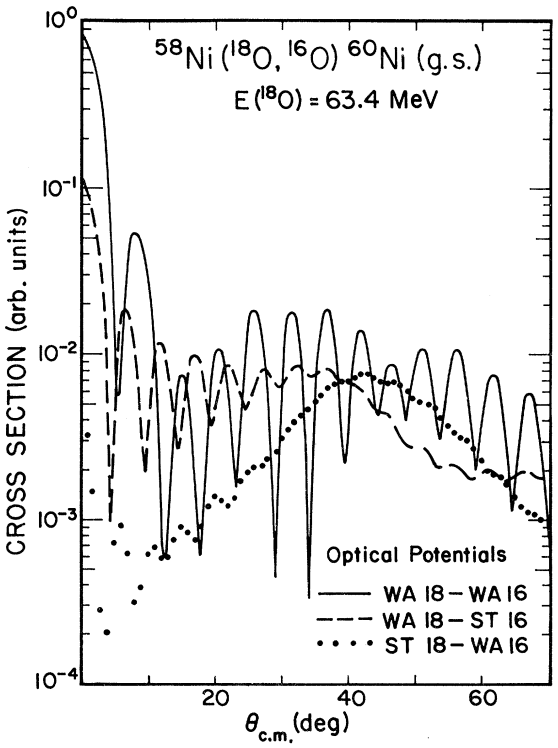

FIG. 4. Additional DWBA predictions for the ^{58}Ni(^{18}O, ^{16}O)^{60}Ni(g.s.) reaction at 63.4 MeV. The bound states were calculated with $r = 1.15$ fm and $a = 0.50$ fm.

match indicated for this choice of potentials. In Fig. 5 the reflection coefficients for the various optical potentials are plotted. As can be seen, for any optical potential which does a reasonable job of predicting the entrance channel elastic scattering the critical angular momentum (where $\eta_l = 0.5$) is $L_c \approx 33$. Using potential WA16 in the exit channel, however, gives $L_c \approx 37$, as opposed to $L_c \approx 35$ for potentials obtained by actually fitting the elastic scattering of $^{16}O + ^{58}Ni$ at about the correct center of mass energy for the $^{58}Ni(^{18}O, ^{16}O)$ reaction ($E_{lab} = 71.5$ MeV).

As has been pointed out in the case of light ion reactions,[10] the effect of a momentum mismatch is to broaden the DWBA reaction amplitudes in L space. That this occurs in the case of potential Set ST18-WA16 can be seen by looking at the magnitudes of the reaction amplitudes obtained in the present DWBA calculations. These are plotted in Fig. 6 for the various optical potential sets considered here. The reaction amplitudes for the Set ST18-WA16, i.e., for the DWBA calculation using Set ST18 in the entrance channel and Set WA16 in the exit channel, are reduced in magnitude and considerably broader in L space, in agreement with the light ion predictions of Ref. 10. The effect of such a change in width on the predicted angular distribution is illustrated in Fig. 7, where we have parametrized the reaction amplitudes by a Gaussian in L space centered at $L = 35$ (with phases similar to those obtained from the actual DWBA calculations). As the full width at half-maximum of the Gaussian is changed from $\Gamma = 10$ to $\Gamma = 4$, the character of the predicted angular distribution changes from semiclassical to "anomalous."

As is obvious from a consideration of Fig. 5, a momentum mismatch and hence a smooth angular

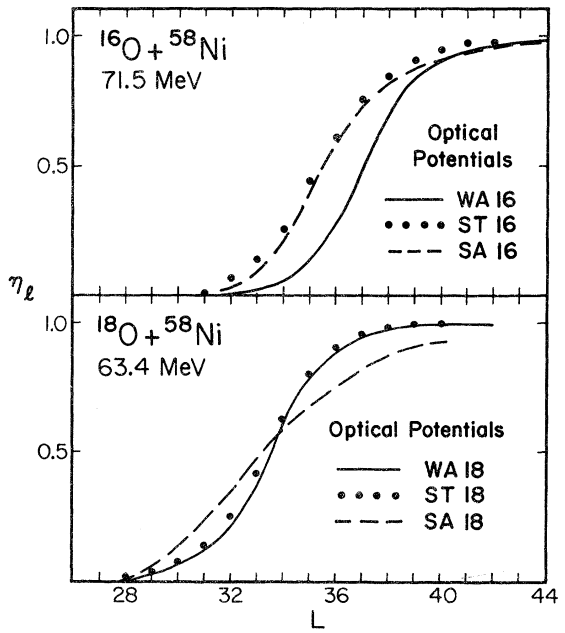

FIG. 5. Reflection coefficients for various $^{18}O + ^{58}Ni$ and $^{16}O + ^{58}Ni$ optical potentials.

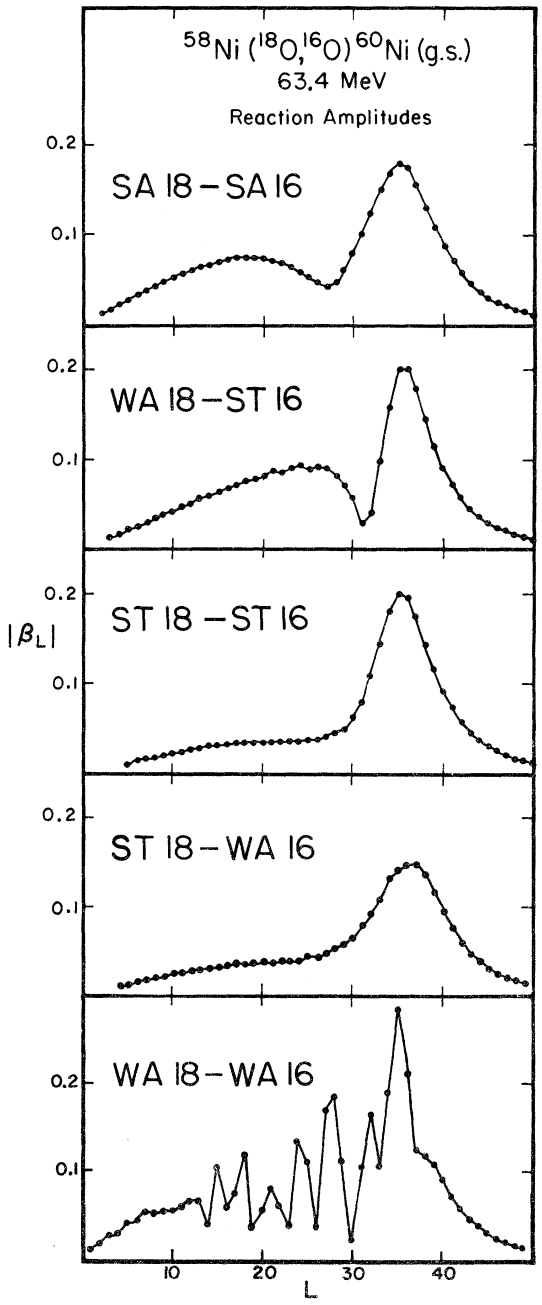

FIG. 6. DWBA reaction amplitudes for the $^{58}Ni(^{18}O, ^{16}O)^{60}Ni$(g.s.) reaction at 63.4 MeV for various optical potentials.

distribution would also seem necessary in the case of potential Set WA18-WA16. However, as Fig. 6 shows, the reaction amplitudes in this case are very irregular in L space. Thus, while there are in fact contributions from a wide range of L values, a few particular ones dominate the cross section, namely $L = 34-36$ and $L = 27-29$. The dominance of the $L = 34-36$ contribution is the reason for the continued "wiggles" in the predicted angular distributions of Ref. 1, since we approach an angular distribution of the type $J_0^2(L\theta)$ when only a few L values are involved. The contribution from the lower partial waves near $L = 28$ (which is well below the grazing angular momentum) is actually important to the cross section. From Fig. 3 or 4 one can see a shift in phase at forward angles between the predictions of the Brookhaven potential (WA18-WA16) and those from potentials which are strongly absorbing in the nuclear interior (ST18-ST16 or WA18-ST16). Using a lower L cutoff for the various cases at $L = 30$ gives no major changes except for the WA18-WA16 case, where eliminating the $L = 27-29$ contribution shifts the forward-angle phase into agreement with the strong absorption predictions.

Aside from the momentum mismatch aspects of these various potential sets, there remain the appreciable differences between DWBA calculations using strongly absorbing potentials and those using

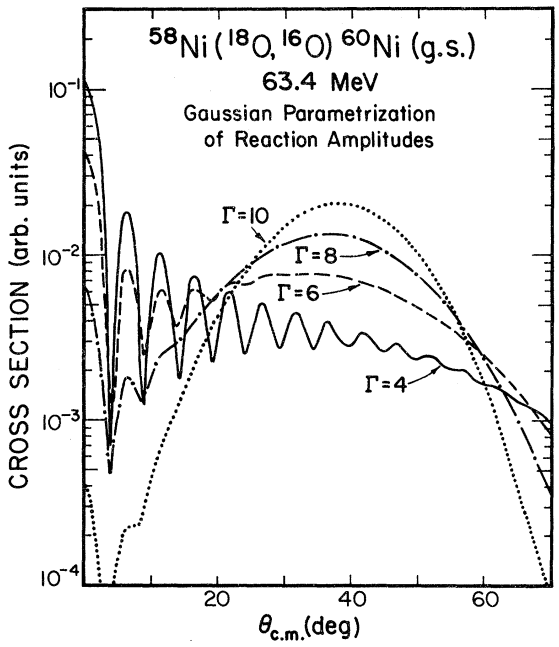

FIG. 7. Predicted angular distributions obtained from a Gaussian parametrization of the DWBA reaction amplitudes. The full width at half-maximum of the Gaussian, Γ, is indicated for each curve.

five-parameter surface transparent or four-parameter weakly absorbing potentials. We have shown that these differences are related to the narrow region in L space which contributes to the DWBA reaction amplitudes in the case of weak surface absorption such as given by potentials WA18, ST18, and ST16. This sharpness in L space (or lack thereof) can also be seen directly in the elastic scattering reflection coefficients shown in Fig. 5. The strongly absorbing potential SA18, for example, is very broad in L space compared to the other ^{18}O potentials and allows a number of L values to make nonnegligible contributions to the DWBA cross sections. This would lead to the prediction that those DWBA calculations done using potential SA18 in the entrance channel will always result in a bell-shaped angular distribution, as is indeed correct. On the other hand, one can see in Fig. 5 that all of the ^{16}O potentials, including the strongly absorbing potential SA16, have a similar width in L space. Thus, we would not expect that the DWBA calculations would be so sensitive to the use of potential SA16 rather than ST16 in the exit channel. This is borne out by a comparison of calculations using potential sets ST18-SA16 and ST18-ST16, both of which give very similar results.

In conclusion, our study of ^{16,18}O elastic scattering on ^{58}Ni indicates that a weakly absorbing potential of the type used in some recent DWBA calculations[1] is not consistent with the back angle elastic data. However, a "five-parameter" surface transparent potential with a rather sharp imaginary diffuseness is capable of reproducing the elastic scattering over a wide energy range and appears to be capable of reproducing (qualitatively) the observed forward peaking and oscillatory nature of the transfer reaction angular distributions in this mass region. Furthermore, the five-parameter potentials found in this study are able to explain forward-peaked angular distributions without requiring important (and possibly unrealistic) contributions from the nuclear interior. It has been shown that the angular distribution predicted for the ^{58}Ni(^{18}O, ^{16}O)^{60}Ni(g.s.) reaction does depend strongly on the optical potentials used, even though the parameters studied give identical fits to measured elastic scattering data down to $\sigma/\sigma_R = 10^{-3}$ or below. The type of angular distribution one gets depends on the width of the DWBA reaction amplitudes in L space. This width can in turn be correlated to the elastic scattering results in terms of momentum mismatch (in some cases), and also in terms of the width in L space of the elastic reflection coefficients. We should emphasize that the back angle elastic data investigated here are sensitive to the same range of L

values as are the transfer reaction data and are therefore very useful in resolving many (but not all) of the optical model ambiguities found when only forward-angle elastic scattering data are considered. It has sometimes been argued that it is incorrect to use back angle elastic scattering data in obtaining optical parameters for use in DWBA calculations. However, we feel that the *whole* angular range should be utilized. Light ion reactions have defined the rules of the DWBA game, namely to generate the distorted waves from potentials which fit the elastic scattering. Insofar as one can obtain (as was done here) a good fit to the back angle elastic data without sacrificing a fit to the forward angle region, this should give a "better" i.e., less ambiguous, potential than one obtained from forward angle data only. Even if the back angles do contain contributions from other processes, it may still be preferable to "renormalize" the optical potential to account implicitly for these effects, which are also presumably occurring (and being ignored) in the reaction calculations. Since the optical model description of elastic scattering is a better theory (having fewer assumptions) than DWBA, the latter should be used to distinguish optical potentials *only* when they do equally well at predicting all available elastic data. It is generally believed[11] that reducing the imaginary diffuseness compared to the real diffuseness is probably mocking up some other effect, such as L dependence in the imaginary potential. However, we do not feel that the present data are capable of resolving this point unambiguously.

We would like to thank Professor J. S. Blair and Professor R. Vandenbosch for their comments and suggestions.

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†Work supported in part by the U. S. Atomic Energy Commission.

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