Giant resonance coupling and l-dependent potentials for ^{16}O

J. P. Delaroche,* M. S. Islam, and R. W. Finlay
Department of Physics, Ohio University, Athens, Ohio 45701
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The effects of giant resonance couplings on the elastic scattering of nucleons from light, spherical nuclei are examined over a wide range of incident energies (18–46 MeV). General trends in the large-angle elastic scattering data for ^{16}O that are poorly described with the conventional optical model are qualitatively reproduced with an uncomplicated picture for the giant states. Comparison is made between this approach and earlier calculations involving giant resonances and l-dependent potentials.

Elastic scattering of nucleons from s-d shell nuclei in the energy region from 20 to 50 MeV has revealed unusual diffractive patterns that cannot be easily described in terms of the traditional optical model potential. For example, a deep minimum in the elastic scattering cross section for ^{16}O appears at around $\theta=130°$. The position of this minimum does not change smoothly with incident energy as it should if it were an ordinary diffraction minimum. This phenomenon has been a challenging problem in nuclear reaction theory for several years, and many interesting explanations have been proposed with varying degrees of success. Mackintosh and Kobos[1] proposed the inclusion of deuteron channels through a p→d coupled-reaction-channel calculation. An explicit angular momentum dependence of the optical model potential was introduced by Mackintosh and Cordero[2] and further developed by Kobos and Mackintosh[3] with specific attention given to this back angle effect in ^{16}O and ^{40}Ca. Fabrici *et al.*[4] have shown that the nondiffractive effect is much more pronounced in spherical nuclei than in deformed nuclei and have shown that coupling to low-lying quadrupole states does not result in good agreement with the data for spherical nuclei such as ^{16}O. Finally, Pignanelli, von Geramb, and De Leo[5] have shown the sensitivity of giant $E2$ and $E3$ resonance couplings on large-angle elastic scattering. The present work is an attempt at a systematic extension of Ref. 5 to ^{16}O covering the same energy range discussed therein for ^{40}Ca.

In the present work, we propose a simple picture of the giant resonance states in ^{16}O and apply this model without adjustment to both neutron and proton scattering data. Positions and strengths of the giant resonances should, of course, be independent of the energy or isospin of the incident particle, and we would prefer to adopt parameters directly from experiment. Unfortunately, the experimental situation is not completely clear. Harakeh *et al.*[6] find evidence from 104 MeV α scattering for considerable isoscalar $E2$ strength between 16 and 26 MeV excitation energy and also for $E0$ strength at 20–25 MeV. Using 45 MeV protons and 60 MeV alpha particles, Buenerd *et al.*[7] find isovector $E1$ and isoscalar $E2$ strength around 24 MeV. In both of these works the familiar difficulty of background subtraction under the giant resonance provides a significant source of uncertainty, but the results are in good overall agreement with the RPA calculations of Wambach *et al.*[8] Information on the isoscalar octupole resonance is sparse, but the RPA calculations of Yadav and von Geramb[9] suggest some concentration of $E3$ strength near 46 MeV.

In the present procedure we seek a distribution of giant resonance strengths in ^{16}O that is consistent with the above, limited information. The sensitivity of the calculated cross sections to the positions and strengths of the giant resonances and to the simultaneous inclusion of couplings to low-lying collective states is examined. The data set includes new measurements of $^{16}O(n,n)$ between 18–26 MeV and the beautifully detailed and precise measurements of $^{16}O(p,p)$ by van Oers and Cameron[10] between 23–46 MeV. Consistency of all calculations with existing values of proton and neutron reaction cross sections as well as neutron total cross sections was required (but not shown).

In all calculations the giant resonances were treated as surface vibrations and the coupled-channel code ECIS79[11] was used. We did not consider it to be clear *a priori* exactly which giant states should be included so isoscalar $E0$, $E2$, and $E3$ and isovector $E1$ modes were considered. It was quickly determined that $E2$ strength between 20–25 MeV had significant effect on the calculation but additional $E1$ strength in this region did not provide substantial additional improvements in the description of the data. It seems likely that we are simulating part of the $E1$ effect in our $E2$ coupling term since the Goldhaber-Teller form factors[12] for these cases have the same radial dependence.

We define the optical model potential as

$$-U(E,r)=V(E,r)+iW(E,r) \ ,$$

where

$$V(E,r)=V_R(E)f(X_R)-V_{so}(\boldsymbol{\sigma}\cdot\mathbf{l})\left(\frac{\hbar}{m_\pi c}\right)^2\frac{1}{r}\frac{d}{dr}f(X_{so}) \ ,$$

$$W(E,r)=W_V(E)f(X_I)-4a_iW_D(E)\frac{d}{dr}f(X_I) \ ,$$

and

$$f(X_i)=[1+\exp(X_i)]^{-1} \ ,$$
$$X=(r-R_i)/a_i \ ,$$

with

$$R_i=r_iA^{1/3}\left(1+\sum_{\lambda,\mu}\alpha_{\lambda\mu}Y_{\lambda\mu}\right) \ ,$$

where $\alpha_{\lambda\mu}$ is related to the vibration amplitude β_λ. The spin-orbit potential was similar to that of Ref. 10 and was not deformed in any of the calculations. We ascribe the same deformation length to all parts of the central potential.

The assumed energy dependences of the real and imaginary well depths require some explanation. First, since the excitation energies of the states under consideration are a large fraction of the incident energy, the channel-energy dependence[13] (CED) of the potentials has been explicitly included. By this we mean

$$U_{cc}(E) = U(E - E_i) \text{ for the diagonal terms}$$

and

$$U_{cc'}(E) = U\left(E - \frac{E_i - E_i'}{2}\right) \text{ for the coupling terms },$$

where E is the incident energy and E_i is the excitation energy of the ith level. The use of this procedure requires the knowledge of V and W at negative energies as well as at all positive energies down to 0 MeV. (Virtual excitation of levels was found to be important in this work just as it is for the evaluation of neutron strength functions for collective nuclei).[14] There is much recent evidence that the optical model potential strengths show anomalous behavior near the Fermi energy, so it would be inappropriate to use a linear extrapolation of V to negative energies from the well-determined values at $E \gtrsim 20$ MeV. The anomaly involves rapid changes in both the strengths and the geometrical parameters of the optical potential in this energy region.[15] As a first attempt to include this effect in ^{16}O, we limit ourselves to variations in strength, choose an average value for the Fermi energy, $\epsilon_F = -8.15$ MeV, and assume that W goes as $(E-\epsilon_F)^2$ times a damping factor that prevents W from becoming unbounded at large E.[16]

For the "Hartree-Fock" component[16] of the real potential, we assume $V_{HF}(E) = V_0 - \alpha E$ with α being close to the value found from a preliminary analysis in which giant resonance coupling is omitted. The amplitude of the anomalous excursion of V from the "Hartree-Fock" value is taken to be about 7% which is less than the ~15% excursion found by Finlay *et al.*[15] for ^{208}Pb, probably because the empirical imaginary potential strength for ^{16}O is only about half that found for ^{208}Pb. We emphasize that this treatment of the Fermi surface anomaly is only a rough approximation that has not been specifically verified for ^{16}O, but we note that distinctly worse results were obtained when an excursion amplitude of either 0 or 15% was chosen.

In covering the entire incident energy region from 18 to 46 MeV, we found that we need at least four pieces of giant resonance: $E2$ at 18, 22, and 24 MeV, and $E3$ at 45 MeV. These states were taken to exhaust 15, 42, 20, and 50% of their respective energy weighted sum rules. These resonance energies and strengths were obtained by trial and error (not by χ^2 minimization), so it is not at all clear that they are the best possible set. They were, however, held constant for all of the subsequent calculations.

The results of this exercise are shown as solid lines in Fig. 1(a) for neutrons and in Fig. 1(b) for protons. Although

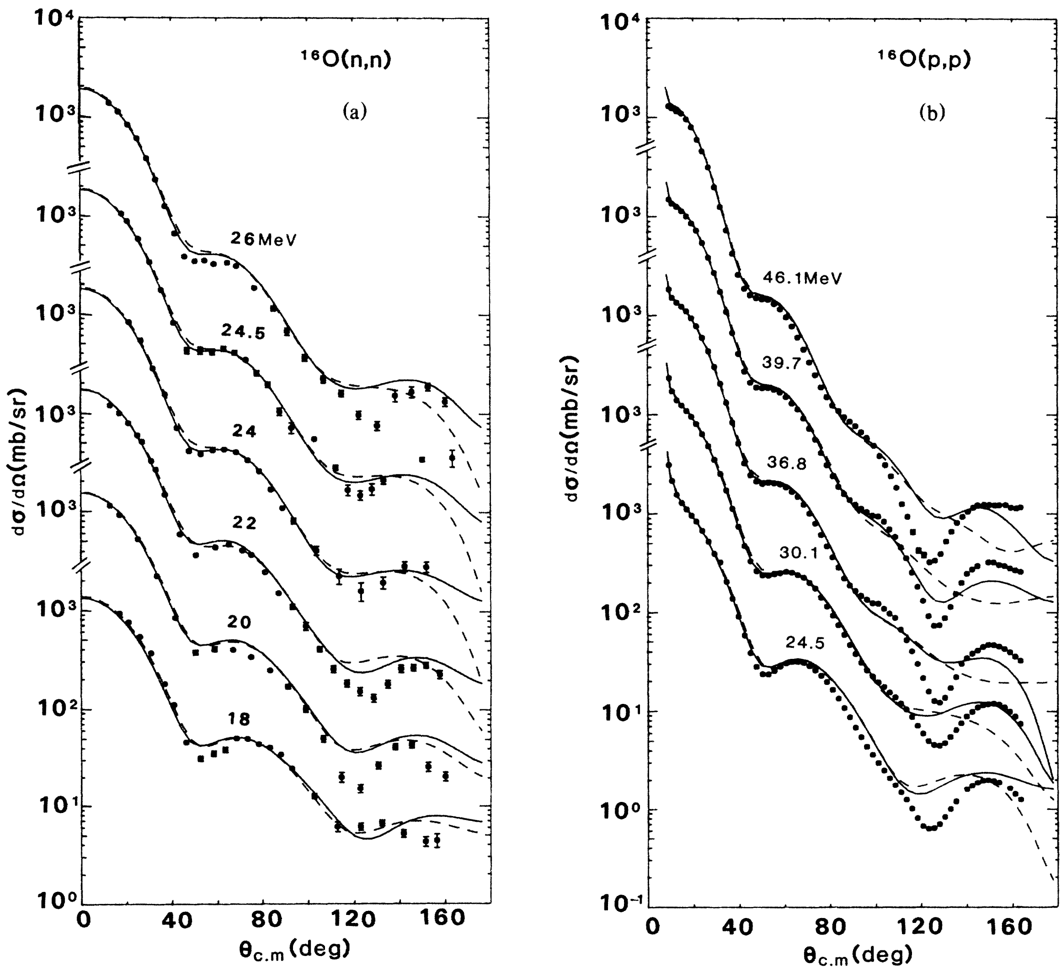

FIG. 1. Elastic scattering of (a) neutrons and (b) protons from ^{16}O. Solid lines are calculations including coupling to the giant resonance states and to the 3^- state at 6.13 MeV. In all cases $\beta_3 = 0.56$. Dashed lines show the effect of excluding the giant resonance couplings.

the predictions are not perfect, they are significantly better than those which can be obtained in an ordinary phenomenological picture, either in a spherical optical model calculation or in a coupled-channel (CC) calculation in which the couplings to giant states are excluded (dashed lines). In particular, the deep backward-angle minimum is predicted at about the right angular position over the entire energy range, and the trend in the calculation for $\theta > 130°$ is generally in phase with the data in contrast with the calculation omitting giant resonance couplings. There is a worsening of the prediction at $E_p = 24.5$ MeV which might be due to existing resonances in the compound system ^{17}F in the vicinity of that energy.

In the calculations shown in Fig. 1, the only low-lying state included in the CC calculation was the 3^- state at 6.18 MeV. Inclusion of additional low-lying states provides a slight renormalization of the solid-line curves in Fig. 1. Significantly, inclusion of up to nine low-lying states for which we have measured inelastic neutron scattering does not produce improved agreement with the elastic scattering data if the giant states are omitted. It is clearly the coupling to the giant states that produces the favorable shape changes in Fig. 1.

For the proton data between 24 and 40 MeV, fits of the quality given in Fig. 1(b) were obtained only after varying W_D in the exit channel for the virtual excitation of the giant octupole resonances. The resulting values of W_D were (with large uncertainties) systematically larger than expected from typical dispersion theory assumptions about the behavior of W at $E < \epsilon_F$. This is not inconsistent with the results of pickup and stripping to quasibound states[16] but this may only be a partly spurious result of the present approach to the analysis. The effect of inclusion of the giant states is not so dramatic for the neutron data, in part because compound nucleus contributions tend to fill the back-angle minimum for incident energy $\lesssim 22$ MeV.

Rather than asserting the uniqueness of this description of nondiffractive elastic scattering, we now proceed to show the phenomenological equivalence of this model to one familiar alternative approach, i.e., the l-dependent potential model of Kobos and Mackintosh.[3] In Fig. 2 we show the S-matrix elements for elastic scattering versus angular momentum for $E_n = 22$ MeV and $E_p = 40$ MeV. The full lines (dashed lines) are calculations with (without) giant resonance couplings. The net effect of giant resonance couplings seems to be to reduce the S-matrix elements for $l < 6$, which is very similar to the results in Fig. 4 of Ref. 3.

We have shown that coupling to giant resonances, with or without coupling to low-lying states, gives semiquantitative agreement with the nondiffractive behavior in the elastic scattering channel in ^{16}O. Much better agreement (i.e., local fits) could be obtained if the properties of the giant resonances were permitted to depend on incident energy as had been allowed in earlier work.[5] We have chosen not to do that. The locations and strengths of the giant resonances in this picture are consistent both with experiment and with RPA calculations. In the same model, we calculate (p,p') scattering to the continuum[7] with fair success, thus suggesting that the assumed strengths are not unreasonable. Finally, the phenomenological similarity between giant resonance couplings and l-dependent potentials suggested earlier by Pignanelli *et al.*[5] is demonstrated numerically for ^{16}O. There are many limitations to the present picture: A fixed-geometry optical potential was used even near the Fermi surface, a simple form factor was assumed for the excitation of the giant resonances, and the final calculations were not optimized with an automatic coupled-channel search routine. One new feature of the present work that deserves particular emphasis is the sensitivity of the results to virtual excitation of the giant states and thus, to the anomalous behavior of the optical potential near the Fermi surface. Further improvement of the present analysis would require more specific information about the locations and strengths of the giant resonances as well as better guidance from theory concerning the behavior of the ^{16}O optical potential in the vicinity of the Fermi surface.

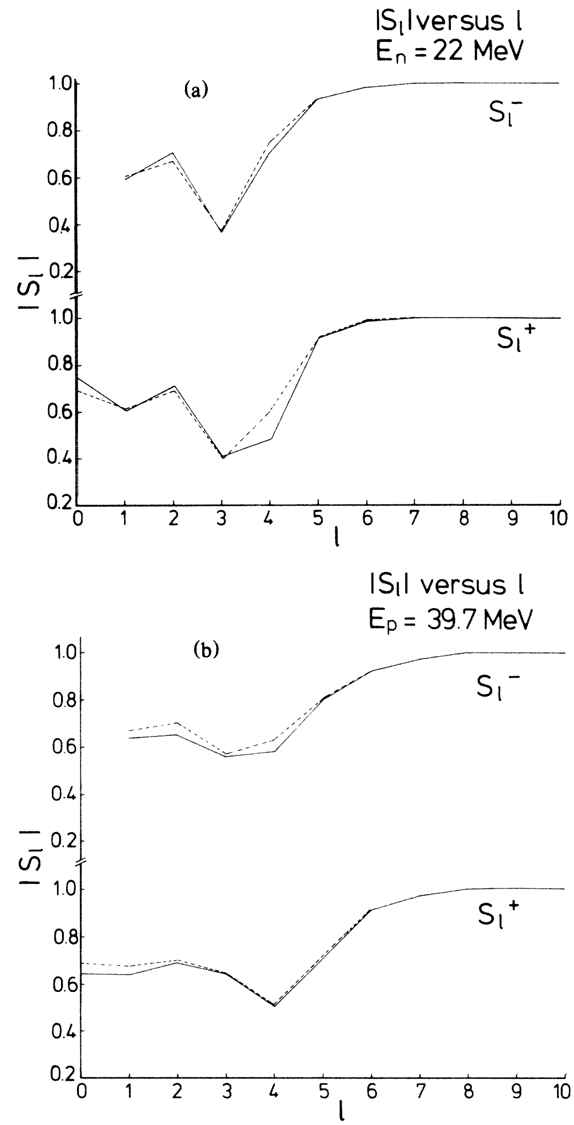

FIG. 2. S-matrix elements for $j = l \pm \frac{1}{2}$ for (a) 22 MeV neutron and (b) 40 MeV proton scattering from ^{16}O. Solid (dashed) lines show the effects of including (excluding) giant resonance couplings.

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*Permanent address: Service de Physique Neutronique et Nucleaire, Centre d'Etudes de Bruyeres-le-Chatel, B.P. No. 12, 91680 Bruyéres-le-Chatel, France.

[1]R. S. Mackintosh and A. M. Kobos, Phys. Lett. **62B**, 127 (1976).

[2]R. S. Mackintosh and L. A. Cordero-L., Phys. Lett. **68B**, 213 (1977).

[3]A. M. Kobos and R. S. Mackintosh, J. Phys. G **5**, 97 (1979).

[4]E. Fabrici *et al.*, Phys. Rev. C **21**, 830 (1980).

[5]M. Pignanelli, H. V. von Geramb, and R. G. De Leo, Phys. Rev. C **24**, 369 (1981).

[6]M. N. Harakeh *et al.*, Nucl. Phys. **A265**, 189 (1976).

[7]M. Buenerd, P. Martin, P. de Saintignon, and J. M. Loiseaux, Phys. Rev. C **14**, 1316 (1976).

[8]J. Wambach, F. Osterfeld, J. Speth, and V. A. Madsen, Nucl. Phys. **A324**, 77 (1979).

[9]H. L. Yadav and H. V. von Geramb, Phys. Rev. C **14**, 1369 (1976).

[10]W. T. H. van Oers and J. M. Cameron, Phys. Rev. **184**, 1061 (1969).

[11]J. Raynal (unpublished).

[12]G. R. Satchler, Nucl. Phys. **A195**, 1 (1973).

[13]A. S. Meigooni, R. W. Finlay, J. S. Petler, and J. P. Delaroche (unpublished).

[14]B. Buck and F. Perey, Phys. Rev. Lett. **8**, 444 (1962).

[15]R. W. Finlay, J. R. M. Annand, J. S. Petler, and F. S. Dietrich, Phys. Lett. **155B**, 313 (1985).

[16]C. Mahaux and H. Ngo, Nucl. Phys. **A378**, 205 (1982).