$^{16}O + ^{40}Ca$ Inelastic Scattering and Direct-Reaction Calculations in Heavy-Ion Scattering

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Inelastic scattering to the lowest 2^+, 3^-, and 5^- states in ^{40}Ca was studied for $^{16}O + ^{40}Ca$ at $E_{lab}(^{16}O) = 60$ MeV. The angular distributions are compared to distorted-wave and coupled-channel Born-approximation predictions. The results show that the effect of the 3^- inelastic excitation on the elastic scattering wave function has to be treated explicitly in order to reproduce the angular distributions. This is particularly evident for the 5^- transition, despite the fact that direct coupling between the 3^- and 5^- states is negligible.

The failure of conventional distorted-wave Born-approximation (DWBA) calculations to describe heavy-ion–induced direct reactions adequately in a large number of cases has led to coupled-channels Born-approximation (CCBA) treatments of such transitions. The major departure from DWBA is the more accurate treatment of the entrance and exit channels by including explicitly couplings to various direct transitions. This has two important consequences. First, it introduces additional transition routes to the same final state. Secondly, it includes the effects of inelastic transitions on the usual optical-model wave function of relative motion. A number of measurements and CCBA calculations have recently demonstrated the importance of the multistep processes in specific cases. On the other hand, the importance of other inelastic channels—in general not directly coupled to the specific transition of interest—on modifying the optical-model wave function has not been clearly demonstrated. In this Letter $^{16}O + ^{40}Ca$ inelastic-scattering data and CCBA analyses are presented which establish that such modifications are important in the specific case investigated and suggest that they are at least partially responsible for the numerous discrepancies reported in comparisons of DWBA calculations and heavy-ion–induced direct-reaction data.

We have measured at an incident energy of 60 MeV the inelastic scattering of ^{16}O on ^{40}Ca leading to the first 2^+, 3^-, and 5^- states in ^{40}Ca, and have extracted angular distributions (Fig. 1). Special emphasis was put on covering a large angular range where, in particular, we extended the measurements to very forward angles since we expected the forward-to-backward cross-section ratio to put serious constraints on reaction-model calculations. Very little experimental information exists on extreme forward-angle inelastic heavy-ion scattering,[1-3] and none for systems with a charge product Z_1Z_2 as large as that for ^{16}O plus ^{40}Ca. The lack of forward-angle inelastic data obviously arises from the experimental difficulties of separating the inelastic transitions from the low-energy tail of the elastic scattering.

In our measurements we used the Argonne split-pole magnetic spectrograph and identified the various reaction products with a position-sensitive ionization chamber[4] in the focal plane. Measurement of the differential energy loss, the total energy, and the position along the focal plane allowed for unambiguous particle identification. The observed energy resolution of less than 100 keV full width at half-maximum (FWHM) was mainly determined by target thickness effects in the 60-$\mu g/cm^2$ ^{40}Ca (>99%) targets deposited on 15-$\mu g/cm^2$ carbon backings. The energy resolution was sufficient to separate the ^{40}Ca (3^-) state at 3.74-MeV excitation energy from the ^{40}Ca (2^+) state at 3.90 MeV. The relative normalization was established by a monitor detector located at $\theta_{lab} = 25°$. Absolute cross sections were obtained by normalizing the elastic scattering to Rutherford scattering at forward angles. To correct for the charge-state fractionation, elastic scattering was measured for the 6^+, 7^+, and 8^+ charge states over the angular range $5° \leq \theta_{lab} \leq 40°$.

The DWBA calculations (Fig. 1) were performed with the program PTOLEMY[5] using optical-model parameters (Table I) obtained from a fit to the elastic-scattering angular distributions. In all calculations macroscopic collective form factors were employed with charge deformation lengths δ_C taken from measured $B(E\lambda)$ values (Table II). The nuclear deformation lengths δ_N were left as free parameters to reproduce the magnitude of the cross sections at forward angle, as done in light-ion studies. The deduced values of δ_N agreed very well with those from light-ion measurements (Table II). The shapes, however, do not reproduce the experimental data. In particular, while the 2^+ angular distribution is reason-

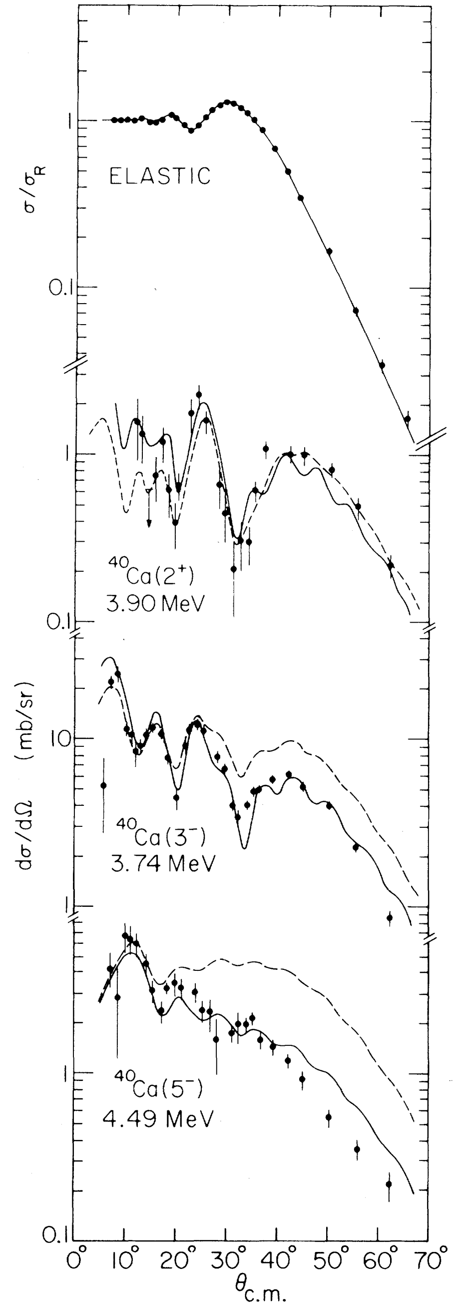

FIG. 1. Elastic- and inelastic-scattering angular distributions for $^{16}O + ^{40}Ca$ to the lowest 2^+, 3^-, and 5^- states in ^{40}Ca. The dashed lines are DWBA and the solid lines are coupled-channels calculations as discussed in the text.

ably well described, the 3^- and especially the 5^- angular distributions are not reproduced by the calculations. These results were found to be independent of optical-model parameters; i.e., all parameter sets which fit the elastic scattering

TABLE I. Optical-model parameter sets used in the DWBA and coupled-channels calculations as discussed in the text. The optical potential $V(r)$ of the Woods-Saxon shape is given in terms of the listed parameters by the following expressions:

$$V(r) = -V_0[f(r, R_r, a_r)] - iW_0[f(r, R_i, a_i)],$$

$$R_r = r_{0r}(A_1^{1/3} + A_2^{1/3}),$$

$$R_i = r_{0i}(A_1^{1/3} + A_2^{1/3}),$$

$$f(r, R, a) = \{1 + \exp[(r - R)/a]\}^{-1}.$$

Potential	V_0 (MeV)	r_{0r} (fm)	a_r (fm)	W_0 (MeV)	r_{0i} (fm)	a_i (fm)
DWBA	14.6	1.373	0.515	7.3	1.381	0.441
Coupled channels	14.6	1.373	0.515	6.35	1.267	0.674

equally well yield essentially equivalent inelastic-scattering predictions, very much in the same way as observed in single-nucleon transfer.[6] In the case of the 2^+ state the Coulomb excitation contribution is comparable to the nuclear excitation, whereas for the other two transitions the Coulomb excitation is small (3^-) or virtually nonexistent (5^-) in comparison to the nuclear excitation. Hence the shapes of the 3^- and 5^- angular distributions are practically unaffected by variation of δ_N in any reasonable range of values.

The coupled-channels calculations were performed with code CHUCK.[7] The explicit coupling and backfeeding of specific transitions change the elastic-scattering predictions, and consequently a modified optical potential has to be used which simultaneously gives the proper inelastic and elastic scattering. It was found that only the 3^- state is coupled strongly enough to modify the elastic scattering significantly. Thus in the iterative procedure which was used, the imaginary part of the optical potential was modified so as to reproduce the elastic scattering in a coupled-channels calculation involving only the ground state and the 3^- state. The modified potential is listed in Table I. It should be noted that while the 3^- coupling gives the most important change in the elastic-scattering calculations, other channels (i.e., 2^+ and 5^-) have small but noticeable effects. For reasons of transparency and also of limited computational capability, we only take the dominant 3^- contribution into account at this point.

The deformation lengths were chosen in the same manner as for the DWBA calculations; i.e., from experimental $B(E\lambda)$ values (δ_C) and as free

TABLE II. $B(E\lambda)$ values and nuclear deformation lengths for states in ^{40}Ca obtained from various reactions.

J_i^π	J_f^π	Transition energy (MeV)	$B(E\lambda)$ ($e^2\cdot$fm$^{2\lambda}$)	δ_C (fm)	δ_N (pp') [a] (fm)	δ_N $(\alpha\alpha')$ [b] (fm)	δ_N $(\alpha\alpha')$ [c] (fm)	δ_N (^{13}C,^{13}C$'$) [d] (fm)	δ_N This work DWBA (fm)	δ_N This work CC (fm)
0^+	3^-	3.737	2.06×10^4 [e]	1.79	1.36	1.36	1.50	1.05	1.27	1.08
0^+	2^+	3.904	85 [e]	0.47	0.42	0.55	0.55	0.41	0.42	0.41
0^+	5^-	4.492	2.7×10^6 [e]	1.22	0.86	0.73	1.01	0.45	0.90	0.54
3^-	5^-	0.755	13.2 [f]	0.27	···	···	···	···	···	0.27

[a] Ref. 6.
[b] Ref. 7.
[c] Ref. 8.
[d] Ref. 3.
[e] Ref. 9.
[f] Ref. 10.

parameters to reproduce cross-section magnitudes (δ_N). Despite the complicated nature of the coupling, the predicted shapes were again insensitive to values of δ_N for the range of values found to reproduce the overall cross-section magnitude. For the 3^--5^- coupling, the nuclear and the Coulomb deformation lengths were set equal and taken from the measured $B(E2)$ value. All parameters are listed in Table II. Shown as solid lines in Fig. 1 are the results of the coupled-channels calculation, coupling simultaneously 2^+, 3^-, and 5^- states to the ground state. As can be seen there is good overall agreement between calculation and data.

More instructive than this general agreement is a study of the individual contributions in the coupled-channel calculations as shown in Fig. 2. In particular we want to discuss the inelastic scattering to the 5^- state where the changes from DWBA are most drastic, although improvements are evident for all transitions. One immediately finds that the direct coupling between 3^- and 5^- states has a negligible influence on both the magnitude and the shape of the angular distributions. This is also true for the backfeeding of the 2^+ and 5^- states to the ground state. Reorientation effects are found to have only minor influence on the shapes of the angular distributions. The calculated reorientation for the 5^- state, for example, with an intrinsic deformation equal to the one deduced from $B(E2, 3^-\to5^-)$, changes the shape of the angular distribution less than by the differences observed in Fig. 2. We are left then with a situation in which the strong coupling of one state (3^-) to the ground state alters the distorted waves in such a way as to affect drastically the excitation to another independent (i.e., not directly coupled) state (5^-).

In summary, DWBA calculations based on distorted waves that were fitted by elastic scattering fail to reproduce the 3^- and 5^- inelastic angular distributions. Coupled-channel calculations provide an adequate description of the data. The success of the coupled-channel calculations is mainly due to the modification of the elastic-scattering distorted waves by the explicit coupling of other direct channels, primarily the strongly excited 3^- state. This is, in particular, evident for the excitation to the 5^- state, whose direct coupling to the 3^- state is negligible. This behavior is in contradiction to the assumption generally made in DWBA that in a direct-reaction calculation for

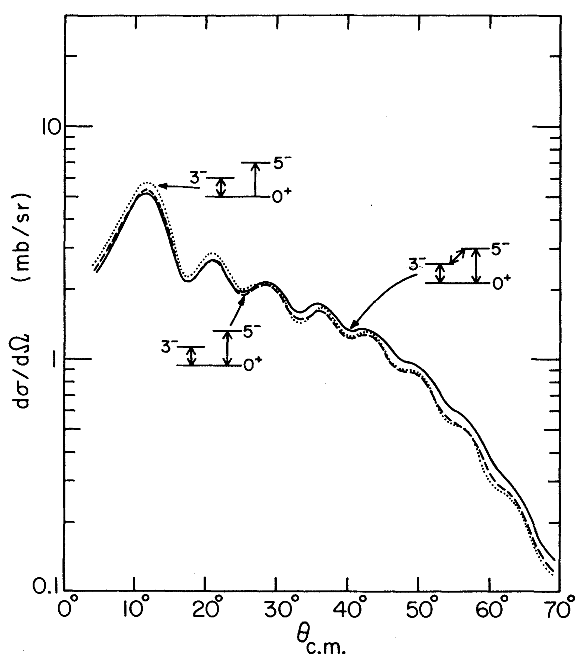

FIG. 2. Coupled-channels calculations for the inelastic excitation of the lowest 5^- state in ^{40}Ca. The excitation diagrams schematically depict the coupling treated in the different calculations. For more detail see text.

a given transition all other non-directly-coupled channels can be treated through an average absorptive potential. This seems of particular importance in view of the failure of DWBA in many heavy-ion transfer calculations. The *ad hoc* changes made in many cases in optical-model parameters in order to reproduce transfer data through DWBA calculations may find a natural explanation in the phenomenon observed in this work.

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Heavy-Ion Inelastic Scattering to Giant Resonances

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Inelastic ^{12}C and ^{14}N scattering experiments have been performed on ^{90}Zr and ^{208}Pb at $E_{^{12}\mathrm{C}}=120$ MeV, and on ^{40}Ca, ^{90}Zr, ^{197}Au, ^{208}Pb, and ^{209}Bi at $E_{^{14}\mathrm{N}}=161$ MeV. Giant resonances are observed in all spectra. An angular distribution has been measured on a ^{208}Pb target, for which distorted-wave Born-approximation analysis is presented.

The investigation of the nuclear continuum with various probes, including electromagnetic interactions and nuclear scattering, has brought about a great deal of results of major importance[1-3] on the collective modes of oscillation of highly excited nuclei. So far, the scattering studies of giant resonances (GR) have used mostly electrons, protons, and strongly absorbed composite projectiles (d, ^{3}He, ^{4}He).[1] The proper selectivity of the probe, due to the properties of the projectile-target interaction, makes it possible to excite the various (J^π, T) modes[1] in different ways. From this standpoint, inelastic scattering of heavy ions seems to offer interesting prospects. The angular-momentum-matching conditions, favoring large L transfer, can be used to search for new collective modes and to study those already known. It is generally assumed that the background, underlying the resonances in light-particle scattering spectra, is generated by quasifree (projectile, projectile-particle) and precompound emission processes; it could also include some strongly damped giant multipole strength.[4] Heavy-ion inelastic scattering is like-

