Interference between Coulomb and Nuclear Excitation in Inelastic Scattering of ^{16}O Ions

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The excitation function for the process ^{58}Ni(^{16}O, ^{16}O′)^{58}Ni* (1.45 MeV) has been measured at 60°, 75°, and 90° lab over the energy range 34–58 MeV. At low energy the cross section rises as expected from Coulomb excitation of an electric quadrupole with a $B(E2)$ value of $(0.066 \pm 0.004)e^2$ b^2. As the energy is increased further, the 2^+ excitation function exhibits a deep valley, due to an interference between Coulomb and nuclear excitations, which is localized over a distance of ~1 F and appears to be correlated with a rise in elastic scattering (relative to Rutherford scattering).

Heavy-ion reactions show promise as a spectroscopic tool for the excitation of high spin states[1] and for the excitation of complex nuclear configurations such as single-particle states coupled to core vibrational states.[2] Because of their strong absorption characteristics, it is also expected that heavy-ion reactions will provide a sensitive probe of the nuclear surface. Hopefully, the success of the distorted-wave Born approximation (DWBA) method in the analysis of light-ion reactions will carry over to heavy-ion reactions and allow their unique features to be exploited. At present, such a program is hampered by ambiguities[3] in the nuclear potential used to generate the incoming and outgoing distorted waves. These ambiguities arise partly from a lack of structure in the elastic scattering of heavy ions from medium-weight nuclei ($A > 30$) and partly from a lack of experimental data covering a wide range of target mass and projectile energy. Since the DWBA method connects nuclear reactions with elastic scattering, it is possible that structure in the reaction cross section will also be helpful in delineating features of the nuclear potential. Of particular interest here is the excitation of quadrupole and octupole vibrational states since, in this case, the perturbing potential is simply related to the nuclear potential. An understanding of such excitations is necessary before the more complicated two-step processes[2] can be treated successfully. For these reasons we have explored the behavior of ^{16}O inelastic scattering to the first 2^+ state in ^{58}Ni, over the energy range 34–58 MeV.

The ^{16}O beams were provided by the Niels Bohr Institute tandem accelerator and focused to a 1-mm-wide by 2-mm-high spot with a divergence less than ±0.1°. The target consisted of 100-μg/cm^2 ^{58}Ni (99.7% pure) sputtered onto an 80-μg/cm^2 carbon backing foil. Charged particles from the target were detected by three 100-μm-thick Si surface barrier detectors located at 60°, 75°, and 90° lab. Brass collimators before the counters limited the solid angles to $\sim 2\times10^{-4}$ sr. An additional Si detector located at 25° lab served to monitor the experiment by means of elastic Rutherford scattering. The electronic pulse-height analyzer was adjusted for 100 keV/channel and the over-all resolution was ~300 keV at 60°, ~350 keV at 75°, and ~400 keV at 90°. Kinematic considerations allowed us to identify the two highest peaks in the spectra as elastic and inelastic (1.45 MeV) scattering of ^{16}O on ^{58}Ni. Data reduction was accomplished off-line by means of a computer controlled display. The software included a peak-fitting routine and a general background routine all controlled by a light pen. The extracted number of counts was converted to absolute cross sections by assuming elastic scattering at the lowest energy (34 MeV) to be pure Rutherford scattering.

In Fig. 1 are shown the resulting excitation functions for elastic and inelastic scattering from the first 2^+ state of ^{58}Ni at 60° lab. The error bars are largely determined by comparing overlapping measurements from two different runs and include statistical uncertainties. An additional absolute error (< 5%), due to the normalization procedure, is not included. At the lower energies, the cross section for exciting the first 2^+ state in ^{58}Ni increases smoothly with energy as expected from Coulomb excitation.[4] The dashed curve in the figure is the calculated Coulomb excitation cross section[5] using a $B(E2)$ value of $0.066e^2$ b^2 which provides the best fit to our data between 34 and 40 MeV. We estimate an error of $0.004e^2$ b^2 due to an uncertainty in our absolute scattering angle. Our $B(E2)$ value may be compared with the value $(0.072 \pm 0.007)e^2$ b^2 from γ-ray yield measurements.[6] Between 42 and 45 MeV, the inelastic cross section is generally higher than predicted by Coulomb excitation. As

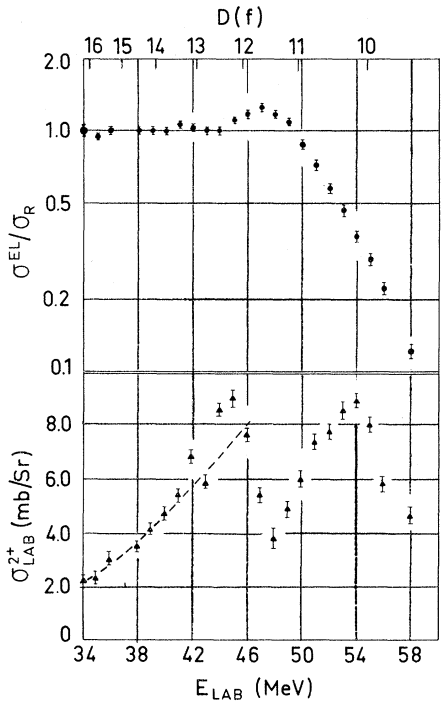

FIG. 1. Upper half of figure, cross section relative to Rutherford scattering as a function of beam energy for the elastic scattering of ^{16}O ions from a ^{58}Ni target at 60° lab. Lower half, the corresponding cross section for inelastic excitation of the 1.45-MeV 2^+ state in ^{58}Ni. The scale at the top shows the classical "distance of closest approach." Dashed curve, calculated cross section for Coulomb excitation for a $B(E2)$ value of $0.066e^2$ b^2.

the beam energy is increased further, the inelastic cross section successively drops to a minimum near 48 MeV, rises to a second maximum near 54 MeV, then falls monotonically as the energy is increased above 54 MeV. The structure found here is much more pronounced than previously observed[7] in inelastic α-particle scattering. In particular, the interference minimum near 48 MeV, relative to Coulomb excitation, is much deeper than a similar effect found in α-particle inelastic scattering from cadmium[8] or from germanium.[9]

Elastic scattering, shown in the upper portion of Fig. 1, displays the familiar behavior. Up to about 44 MeV, the elastic scattering appears to be predominantly Rutherford scattering. The region between 44 and 49 MeV is characterized by a bump where the cross section rises to values some 20% greater than Rutherford scattering. This feature of elastic scattering occurs in the same energy region as the deep valley in inelastic scattering. Above 49 MeV, the elastic cross

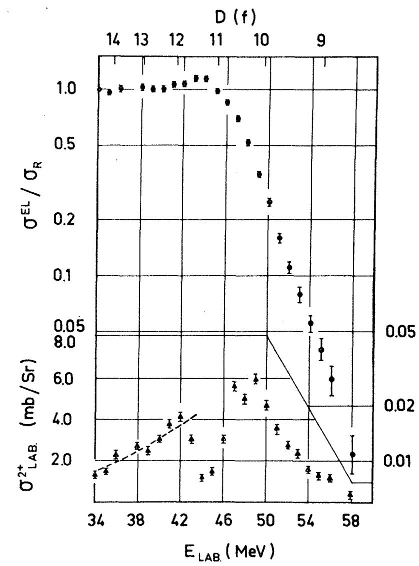

FIG. 2. Same as Fig. 1, but for 75° lab.

section drops exponentially because of the dominance of absorption processes.

At the top of Fig. 1 is a distance scale in terms of the classical "distance of closest approach" for a Rutherford orbit calculated from

$$D = \frac{0.72 Z_1 Z_2}{E}\,\frac{A_1 + A_2}{A_2}\,[1 + \operatorname{cosec}(\tfrac{1}{2}\theta)], \tag{1}$$

where Z_1, A_1 and Z_2, A_2, are the charge and mass of the beam and target, respectively, E is the lab energy of the beam in MeV, θ is the c.m. scattering angle, and D is given in units of fermis. The use of an orbit description seems reasonable since the de Broglie wavelength of the ^{16}O beam is ~0.2 F and $2\pi D/\lambda \simeq 50$. On the basis of this distance scale, the interference minimum near 11.5 is located far out on the nuclear surface [e.g., $r_0(A_1^{1/3} + A_2^{1/3}) = 8.0$ F for $r_0 = 1.25$ F] and is confined to a region which is ~1 F wide.

The data obtained at 75° and 90° are shown in Figs. 2 and 3, respectively. The data at both these angles show the same general structure as the 60° data (Fig. 1), but displaced in energy in such away that the interference minimum occurs at about the same distance of closest approach at all the angles.

The general features of these data can be understood by a semiclassical treatment of the excitation process in terms of Coulomb effects, nuclear effects, and an effect due to the interference between Coulomb and nuclear forces.[10] The amplitude for inelastic scattering can, in first-or-

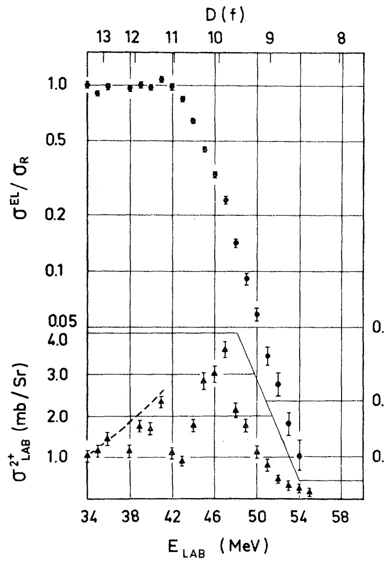

FIG. 3. Same as Fig. 1, but for 90° lab.

der perturbation theory, be expressed as

$$f = i(f_C + f_R) + f_I, \qquad (2)$$

where f_C, f_R, and f_I (which are all real) are the amplitudes for excitation by the Coulomb field, by the real nuclear field, and by the imaginary (absorptive) nuclear field, respectively. The inelastic cross section is then given by

$$\sigma_{2^+} \propto |f|^2 = (f_C + f_R)^2 + f_I^2. \qquad (3)$$

As the Coulomb field is repulsive and the real nuclear field is attractive, f_C and f_R have opposite signs.

The Coulomb field dominates elastic and inelastic scattering at low energies and large distances ($D > 13$ F). At higher energies (smaller distances) the nuclear field changes faster than the Coulomb field and the valley observed near $D = 11.5$ F in the 2^+ excitation function is due to a destructive interference between the Coulomb amplitude f_C and the nuclear amplitude f_R. At even higher energies and smaller distances ($D < 10$ F), nuclear absorption dominates and both cross sections fall off exponentially, but the excitation probability σ_{2^+}/σ_{el} is still increasing. We have both semiclassical and DWBA calculations in progress to try and understand these effects in detail.

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