Undamped Surface Waves in the Scattering of $^{16}O + ^{28}Si$ at $E_{c.m.} = 35$ MeV

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The elastic scattering of $^{16}O + ^{28}Si$ at $E_{c.m.} = 35$ MeV has been measured in the angular range $20° \leq \theta_{c.m.} \leq 180°$. The data exhibit a strongly oscillatory behavior in the region $60° < \theta_{c.m.} \leq 180°$ and a pronounced backward rise up to $d\sigma/d\sigma_{Ruth}(180°) \approx 1.5 \times 10^{-2}$. The structure at backward angles is of the form of a Legendre polynomial $|P_{l=26}(\cos\theta)|^2$, indicating the existence of a partial-wave (orbiting) resonance.

In recent years considerable effort has been put into studies of elastic scattering between heavy ions.[1-3] Except for cases where target and projectile differ only by a few nucleons these investigations have been confined to a limited angular range around the grazing angle. The information on back-angle cross sections for heavy-ion scattering on heavier targets is scarce[4] and no pronounced structures have been observed. It is, however, the large-angle part of the elastic cross section, where diffraction effects are negligible, which is most likely to contain information about the possible existence of phenomena like molecular orbiting on surface-wave resonances.[5-7] Large-angle cross sections, therefore, provide the most sensitive test of heavy-ion optical potentials.

In particular the system $^{16}O + ^{28}Si$ has been extensively studied[8-11] in the forward-angle region ($\theta_{c.m.} < 90°$). From an analysis of the energy dependence of the forward-angle cross section a "unique" energy-independent optical potential was inferred.[9] This Letter presents an investigation of the elastic and inelastic scattering of $^{16}O + ^{28}Si$ at $E_{c.m.} = 35$ MeV over the complete angular range $20° \leq {}_{c.m.} \leq 180°$. The data exhibit pronounded oscillations for scattering angles larger than 60° and a strong backward rise consistent with a resonance in the grazing partial wave.

The experiment used the ^{16}O beam of the State University of New York at Stony Brook FN tandem Van de Graaff facility and the ^{28}Si beam of the Brookhaven National Laboratory tandem Van de Graaff facility. To obtain forward-angle cross sections, 100-$\mu g/cm^2$-thick SiO targets were bombarded with ^{16}O ions and the elastically scattered particles detected using two solid-state ΔE-E telescopes. Backward angles for the reaction $^{28}Si(^{16}O, ^{16}O)^{28}Si$ were measured by bombarding self-supporting Al_2O_3 targets of ~100 $\mu g/cm^2$ thickness with the ^{28}Si beam at an incident energy $E_{lab} = 96.25$ MeV and detecting recoiling ^{16}O ions at forward angles. In the angular range $15° \leq \theta_{lab} \leq 45°$ ($90° \leq \theta_{c.m.} \leq 150°$) the detection system consisted of three standard ΔE-E semiconductor telescopes. For angles $0° \leq \theta_{lab} \leq 15°$ ($150° \leq \theta_{c.m.} \leq 180°$) the ^{16}O ions were identified and their energies measured with a dual-wire proportional counter in the focal plane of the Brookhaven quadrupole–triple-dipole spectrometer. The energy resolution of $\delta E \approx 800$ keV (completely determined by the target thickness) was sufficient to resolve the transitions to the ground state and first excited state in ^{28}Si ($E^x = 1.78$ MeV) which, because of the reaction kinematics, have a separation of ~2.4 MeV in the laboratory system. For angles close to 0° the Si beam was stopped by a Mylar foil of ~25 μm thickness mounted on the focal-plane detector. In all experimental setups the angular resolution was better than 0.5° in the laboratory system.

Relative cross sections were obtained by normalizing on two symmetrically placed monitor counters. The absolute cross-section scale was established to better than 20% accuracy by using solid-state detectors to measure the elastic scattering of $^{27}Al + ^{28}Si$ and $^{16}O + ^{28}Si$ at small angles where the cross section follows the Rutherford law.

The measured elastic-scattering angular distribution is shown in Fig. 1. It is seen that the envelope of the ratio of the cross section to the Rutherford cross section, which for angles around the grazing angle $[d\sigma/d\sigma_{Ruth}(\theta = \theta_{gr}) = 0.25]$ expo-

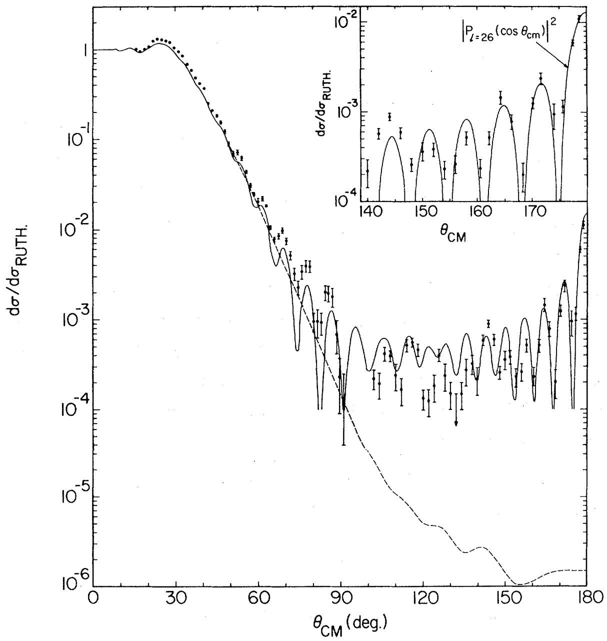

FIG. 1. Elastic-scattering angular distribution of $^{16}O + ^{28}Si$ at $E_{lab} = 55$ MeV. The dashed line is an optical-model calculation using the potential E18 of Ref. 9. The solid line is a Regge-pole calculation described in the text.

nentially decreases with increasing angle, reaches a minimum for angles $\theta_{c.m.} \approx 120°$ and then increases again until $d\sigma/d\sigma_{Ruth}(180°) \gtrsim 10^{-2}$. Superimposed are oscillations which are most pronounced in the regions $65° < \theta_{c.m.} < 90°$ and $140° < \theta_{c.m.} < 180°$. In fact, the latter angular region can very well be described by the square of a Legendre polynomial $|P_{l=26}(\cos\theta)|^2$ as is displayed in the inset in Fig. 1 where the cross section for $140° \leq \theta_{c.m.} \leq 180°$ is compared to $|P_{l=26}(\cos\theta)|^2$. Such behavior is completely unexpected in the framework of optical-model calculations using strongly absorbing optical potentials. This is demonstrated by the dashed curve in Fig. 1, which is the optical-model prediction using the "unique" potential E18 of Ref. 9. The calculation completely fails in reproducing the measured cross section at backward angles. Similar behavior is also found for other optical potentials taken from Refs. 8, 10, and 12.

The $|P_{l=26}(\cos\theta)|^2$ pattern at backward angles is indicative of a process which selectively modifies one (or a few) partial waves. It is interesting to note that $l = 26$ agrees with the grazing angular momentum calculated with the potential of Ref. 9 to within one unit of $\hbar$. This peculiar behavior of the cross section is strongly reminiscent of the glory effect,[5,13] a surface-wave phenomenon which finds its natural description in terms of a surface Regge pole or quasimolecular shape resonance.[6,7,14] In this model, the nuclear part of the elastic S-matrix element is modified according to

$$S_l = S_l^0 \left[1 + i\frac{D(l)\exp(2i\varphi)}{l - l_0 - i\Gamma(l)/2}\right]. \qquad (1)$$

Here, S_l^0 is the background S-matrix element for partial wave l. The factor in square brackets describes the resonance in angular momentum space. Here D is the elastic width and Γ is the total width of the resonance while φ is a resonance mixing phase. Following Ref. 14 the l dependence of D and Γ is assumed to be of the form $(1 - |S_l^0|)$. For a description of the background the nuclear S-matrix elements calculated from the potential E18 of Ref. 9 are used. The result of a calculation using the S-matrix elements of Eq. (1) is shown as the solid line in Fig. 1. The parameters used in the resonance term are $l_0 = 24.5$, $D = 0.6$, $\Gamma = 6.0$, and $\varphi = 0$.[15] It is seen that adding a single surface resonance to a background amplitude generated from a strongly absorbing optical-model potential yields a remarkably good description of the data not only in the angular region around 180° but even in the region of the forward-angle oscillations. From this result one may conclude that the backward oscillations correspond to the Regge pole alone while the forward-angle oscillations are due to interference[14] between the Regge pole and the background.

Figure 2 shows the angular distribution for the inelastic scattering to the 2^+, 1.78-MeV first excited state in ^{28}Si. Again a pronounced backward rise of the cross section is visible together with marked oscillations over nearly the full angular range. This backward rise in the inelastic cross section also is not predicted in the framework of a coupled-channels Born-approximation calculation using strongly absorbing potentials. This is shown in Fig. 2 where the dashed line is a coupled-channels calculation[17] using the deformation parameter of Ref. 16 and the potential E18 of Ref. 9 to generate the scattering wave functions. This calculation also clearly demonstrates that the coupling between the ground state and the first excited state in ^{28}Si is not responsible for the observed backward rise in the elastic cross section.

It should be noted that the observed strong backward rise should also be describable in

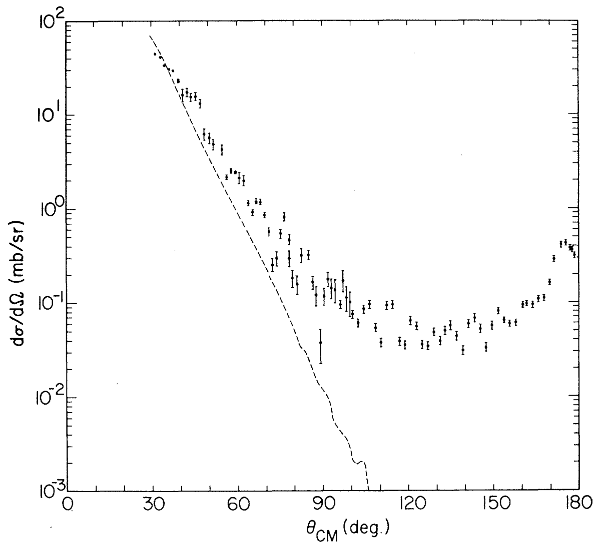

FIG. 2. Inelastic scattering angular distribution for the reaction $^{28}Si(^{16}O,{}^{16}O)^{28}Si(2^+)$ at $E_{lab} = 55$ MeV. The dashed line is a coupled-channels calculation using the optical potnetial E18 of Ref. 9 and the deformation parameters of Gale and Eck (Ref. 16).

terms of an optical potential. For example, surface transparent potentials produce[18] large-angle cross sections as large as observed if the imaginary diffuseness is small enough. However, the $|P_l(\cos\theta)|^2$ characteristic observed at back angles is not reproduced with the potential parameters proposed in Ref. 18. In an attempt to reproduce forward-angle oscillations at $E_{c.m.} = 38.18$ MeV, Shkolnik *et al.*[11] resorted to weakly absorbing potentials with Woods-Saxon geometry and were able to obtain a remarkably good fit for angles $\theta_{c.m.} < 90°$. These potentials, however, predict forward-angle oscillations at $E_{c.m.} = 35$ MeV which are out of phase with our data and neither the phase nor the magnitude of the predicted back-angle structure is in agreement with the present experiment.

It is interesting to point out that the Regge-pole description of our data is very similar to a description in terms of the angular-momentum-dependent absorption model.[19] Both models allow the buildup of nearly undamped surface waves traveling around the nuclear surface. Since a Regge-pole expression contains a description of a quasimolecular rotational band,[14] a study of the energy dependence of the oscillatory structure and of the backward-angle cross section might allow a decision as to which of these parametrizations is a more appropriate description of the data.

To summarize, we have for the first time measured the back-angle structure for elastic and inelastic scattering of $^{16}O + ^{28}Si$ at an energy where the grazing angle is $\theta_{c.m.}{}^{gr} \approx 40°$. For both elastic and inelastic scattering the cross sections show strong backward rises. At angles $140° < \theta_{c.m.} \leq 180°$ the elastic-scattering angular distribution oscillates like $|P_{l=26}(\cos\theta)|^2$ showing the existence of a backward glory effect which strongly suggests the extension to a heavier system of the orbiting resonances or molecular structures observed in large-angle elastic scattering of α particles[20,21] or in the elastic scattering of $^{12}C + ^{12}C$, $^{12}C + ^{16}O$ and $^{16}O + ^{16}O$.[22]

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Low-Energy Electron-Nucleus Scattering—a Possible Test for Weak-Interaction Theories

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We investigated the excitation of nuclei by longitudinally polarized electrons in view of parity mixtures of nuclear states. The asymmetry in the cross section for the left- and right-polarized electrons is shown to be already very large at low momentum transfer. In many cases the asymmetries caused by parity mixtures are larger by orders of magnitude compared to the contributions expected from weak Z^0-boson exchange.

For many years intensive studies of weak-interaction processes in nuclei have been done.[1-3] All of these processes are caused by parity-nonconserving forces leading to small admixtures of states of opposite parity. The processes looked for can be roughly divided into two groups: (i) electromagnetic transitions (measurement of circular polarization or asymmetry of γ radiation); (ii) hadronic scattering or decay processes, such as α decay, for example. With the discovery of weak neutral leptonic currents, electron scattering has been investigated theoretically for possible tests of theories of weak neutral currents. Polarized electron-nucleon and electron-nucleus scattering has been considered by Reya and Schilcher[4] and by Feinberg[5] and Walecka,[6] respectively. The left-right asymmetry in the electron scattering was supposed to originate from the interference of interaction processes involving the exchange of a photon and those mediated by a neutral heavy boson (Z^0), as pictured in Fig. 1.

The calculation by Feinberg[5] shows that the expected asymmetry $A(q^2)$ of left- and right-polarized electrons,

$$A(q^2)\equiv\frac{(d\sigma)_R-(d\sigma)_L}{(d\sigma)_R+(d\sigma)_L}, \qquad (1)$$

for the inelastic scattering from nuclei is given by

$$A(q^2)=-1.2\times10^{-4}(1-2\sin^2\theta_W)|q^2|/m_p^2 \qquad (2)$$

if the Weinberg-Salam model is used to describe the process in Fig. 1(b). θ_W is the Weinberg angle, $0.28\leq\sin^2\theta_W\leq0.48$; m_p is the proton mass; and q denotes the four-momentum transfer. The value of the asymmetry given in Eq. (2) is roughly the same for elastic scattering. We realize that in order to obtain sizable values for the asymmetry one has to go to very high momentum transfer. At low momentum transfer the asymmetry

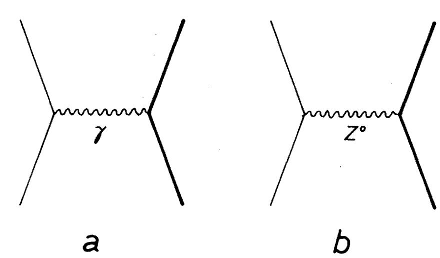

FIG. 1. Interactions between electron and nucleus: (a) electromagnetic one-photon exchange; (b) weak-boson (Z^0) exchange. Both processes (a) and (b) interfere in polarized electron-nucleus scattering.