Comparison of Heavy-Ion-Induced α Transfer and Backward-Angle Elastic Scattering

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Resonancelike structures are observed at backward angles for elastic scattering of $^{12}C + ^{32}S$ and for the reaction $^{28}Si(^{16}O, ^{12}C)^{32}S$ which are uncorrelated with the ones seen in the system $^{16}O + ^{28}Si$. Analysis of angular distributions indicates that forward α transfer is dominated by partial waves different from those of backward-angle α transfer and elastic scattering in the entrance and exit channels.

Backward-angle excitation functions for the elastic and inelastic scattering of ^{12}C and ^{16}O on ^{28}Si exhibit resonancelike structure.[1,2] Similar structures have also been seen in the forward-[3] as well as backward-angle[4] excitation functions of the α-transfer reaction $^{24}Mg(^{16}O, ^{12}C)^{28}Si$. Two of the questions arising from previous observations are the following: (i) Are these resonances associated with structure in the compound nucleus, and (ii) are the partial waves responsible for the resonances in the elastic entrance and exit channels simply related to the partial waves dominating transfer reactions?

In this Letter we compare backward-angle elastic excitation functions for two systems, $^{12}C + ^{32}S$ and $^{16}O + ^{28}Si$, which lead to the same compound nucleus. To study possible connections between structures in large-angle elastic scattering and the recently observed resonance phenomena in forward-angle α transfer,[3] we have also measured excitation functions at both forward and backward angles for the reaction $^{28}Si(^{16}O, ^{12}C)^{32}S$. Lack of correlations between the resonances observed in the various channels clearly indicates that they are not produced by *common* isolated doorway states. Furthermore, angular distributions measured for the reaction $^{28}Si(^{16}O, ^{12}C)^{32}S$ and for the elastic scattering in entrance and exit channels demonstrate that different partial waves dominate forward- and backward-angle cross sections.

The experiment used the ^{12}C, ^{16}O, ^{28}Si, and ^{32}S beams and the quadrupole–triple-dipole magnetic spectrograph of the Brookhaven National Laboratory tandem Van de Graaff facility. The experimental technique has been described in detail.[1,5] By detecting the outgoing ^{16}O and ^{12}C nuclei, forward-angle cross sections were obtained from the bombardment of 120-μg/cm^2 SiO and 60-μg/cm^2 CdS targets with ^{16}O and ^{12}C ions, while backward angle cross sections were obtained from the bombardment of 100-μg/cm^2 Al_2O_3 and 50-μg/cm^2 C targets with ^{28}Si and ^{32}S ions. The elastic-scattering and forward-angle transfer angular distributions have been measured with an angular resolution of $\Delta\theta_{lab} \leq 0.9°$. The forward-angle excitation function for the α-transfer reaction has been measured with an angular aperture of $\Delta\theta_{lab} = 2.9°$, the angle being adjusted to follow the maximum in the angular distribution around $\theta_{c.m.} = 10°$ (see Fig. 2). All backward-angle excitation functions at $\theta_{c.m.} = 180°$ have been measured with a solid angle of 8 msr.

The elastic excitation functions at $\theta_{c.m.} = 180°$ are presented in Fig. 1. The data for the system $^{16}O + ^{28}Si$ are from Ref. 1. The system $^{12}C + ^{32}S$ exhibits broad structures similar to those observed in the scattering of ^{16}O by ^{28}Si; however, the average cross section is about one order of magnitude smaller and a strong splitting of the gross structure into fine structure is apparent, similar to the fragmentation observed in the scattering of ^{12}C by ^{28}Si.[1] The striking feature of these data is that there is no obvious correlation between the gross structure observed in the two systems. This result, which is consistent with the observation of Clover *et al.*,[6] rules out the resonancelike phenomena being generated by a common doorway state in the compound nucleus.

The excitation functions at forward and backward angles for the reaction $^{28}Si(^{16}O, ^{12}C)^{32}S$ are also presented in Fig. 1. Contrary to what has been observed for the system $^{24}Mg(^{16}O, ^{12}C)^{28}Si$,[3]

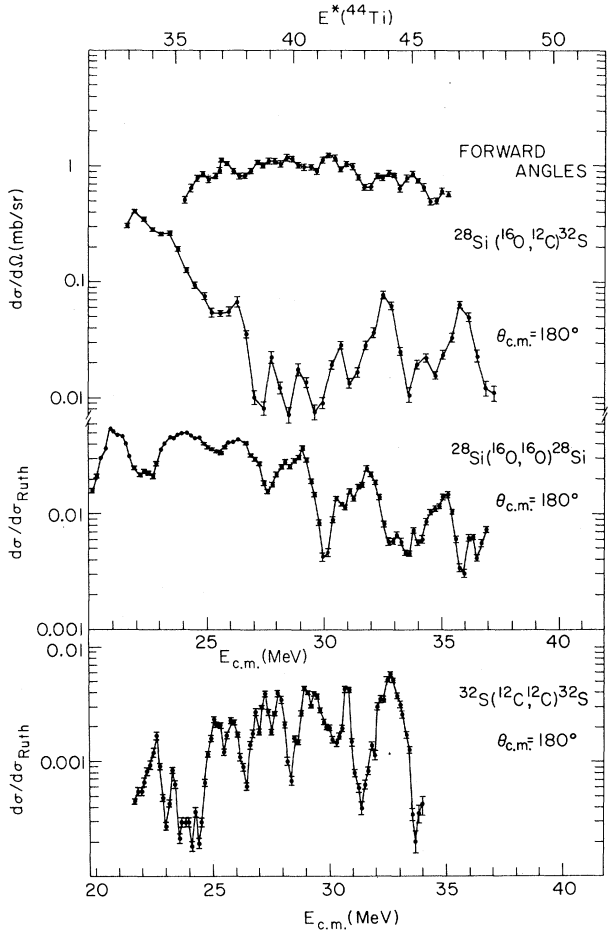

FIG. 1. Excitation function at forward angles and $\theta_{c.m.} = 180°$ for the reaction $^{28}Si(^{16}O, ^{12}C)^{32}S$ and excitation functions at $\theta_{c.m.} = 180°$ for the elastic scattering of ^{16}O on ^{28}Si (data from Ref. 1) and ^{12}C on ^{32}S. The forward-angle excitation function has been measured on the maximum of the angular distribution near $\theta_{c.m.} = 10°$ (see Fig. 2).

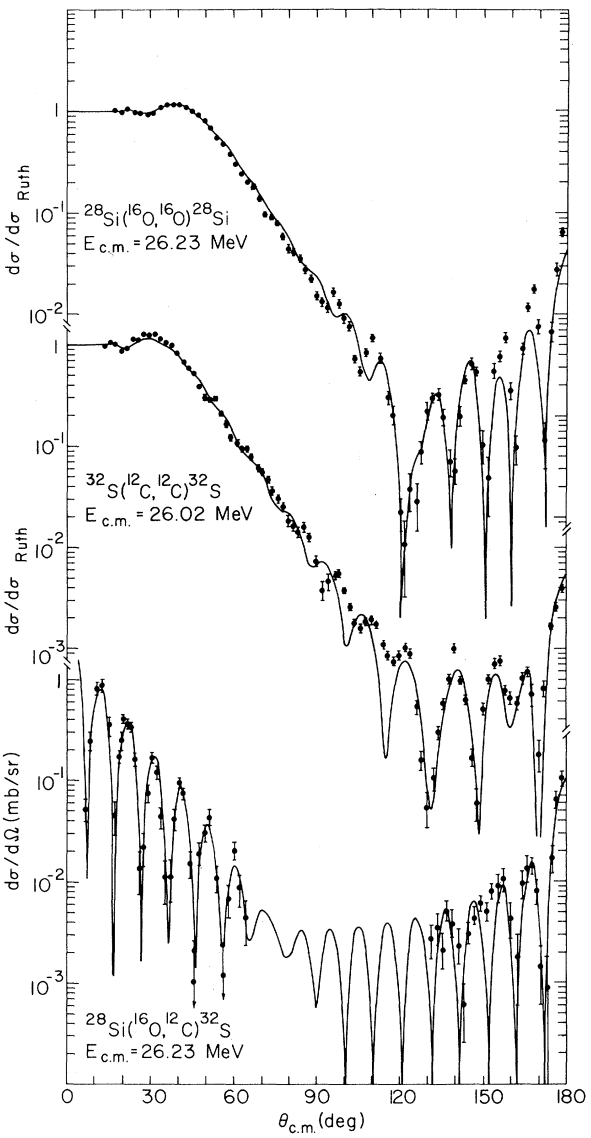

FIG. 2. Angular distributions for the reaction $^{28}Si(^{16}O, ^{12}C)^{32}S$ and the entrance- and exit-channel elastic scattering at $E_{c.m.}(^{16}O + ^{28}Si) = 26.23$ MeV. The solid lines on the elastic-scattering angular distributions are calculations based on a Regge-pole parametrization with the parameters $l_0 = 16.06$, $\Gamma = 0.13$, $D_0 = 0.026$, and $\varphi = 45°$ for the system $^{16}O + ^{28}Si$ and $l_0 = 14.85$, $\Gamma = 1.7$, $D_0 = 0.7$, and $\varphi = 90°$ for the system $^{12}C + ^{32}S$. The line on the transfer angular distribution is an evaluation based on a modified Strutinski parametrization described in the text with the parameters $l_1 = 17.9$, $\Delta_1 = 2.3$, $\theta_1 = 1°$, $l_0 = 17.0$, $\Gamma = 0.15$, $D = 0.05$, and $\varphi = 0$.

no strong gross structure is observed in the present data at forward angles. However, the excitation function for α transfer at backward angles exhibits strong structures which, surprisingly, are not obviously correlated with either the structures observed in forward-angle transfer or backward-angle elastic scattering in the entrance or exit channel. Rather, a common feature of the excitation functions for α transfer and for elastic scattering of $^{12}C + ^{32}S$ is the presence of an intermediate-width structure ($\Gamma_{c.m.} < 500$ keV). The lack of correlation between the various excitation functions suggests that the observed gross structures are caused by entrance- or exit-channel effects.

In order to study further the connection between forward-angle α transfer and backward-angle scattering we have measured angular distributions for forward- and backward-angle α trans-

fer and the elastic scattering in the entrance and exit channels, at $E_{c.m.}(^{16}O+^{28}Si) = 26.23$ MeV. The energy chosen corresponds to a maximum in the excitation function for the system $^{16}O+^{28}Si$. The data are presented in Fig. 2. Consistent with previously published investigations of these reactions,[2,5,6] the elastic-scattering angular distributions exhibit strong oscillations and a rise at backward angles. At forward angles, the angular distribution of the transfer reaction exhibits very pronounced oscillations in agreement with the measurements of Peng *et al.*[7] The envelope of the transfer angular distribution falls off exponentially with increasing angle, but the most remarkable aspect of the transfer angular distribution is the rise of the cross section at backward angle by about two orders of magnitude, with a strongly oscillatory pattern. Such a backward-angle rise is very surprising for a heavy-ion transfer reaction where core exchange effects[8] are expected to be negligible.[9]

In order to determine the partial waves which dominate the elastic scattering at backward angles, we used the Regge-pole parametrization of Braun-Munzinger *et al.*[5] and McVoy.[10] The nuclear part of the elastic S matrix is given by

$$S_l = S_l^0[1 + iD_l e^{2i\varphi}/(l - l_0 - i\Gamma/2)], \quad (1)$$

where S_l^0 is the background S-matrix element for partial wave l, Γ and $D_l = D_0(1 - S_l^0)$ are the total and elastic widths, l_0 is the real part of the Regge pole, and φ is a mixing phase. Consistent with Ref. 5, the background was calculated from potential E18 of Cramer *et al.*,[11] which gives a good description of forward-angle elastic scattering of $^{16}O+^{28}Si$ over a large energy range. The results of these calculations are presented in Fig. 2. We feel that a cautious estimate of the uncertainties associated with the choice of background asserts $15.6 < l_0 < 17.0$ for $^{16}O+^{28}Si$ and $14.4 < l_0 < 15.3$ for $^{12}C+^{28}Si$.

To shed more light on the connection between α transfer at forward angles and backward-angle scattering we have determined the dominant transfer partial wave at forward angles by using the Strutinsky[12] parametrization. Since this parametrization, however, fails to reproduce the observed backward rise we have modified the transfer amplitude in a similar manner as in the elastic-scattering analysis; the transfer S matrix then takes the form

$$S_l = \exp\left(2i\theta_1 l - \frac{(l-l_1)^2}{\Delta_1^2}\right)\left(1 + i\frac{D_l e^{2i\varphi}}{l - l_0 - \Gamma/2}\right), \quad (2)$$

where l_1 is the dominant partial wave at forward angles and l_0 determines the backward angles. The resulting calculation gives a good description of the angular distribution using $l_1 = 18$ and $l_0 = 17$. Note, however, that the value of l_0 is not precisely determined since the angular distribution does not exhibit a pure $P_l^2(\cos\theta)$ pattern at backward angles (see Fig. 2). This value of l_1, which is very well defined from the structure in the angular distribution at forward angles, is considerably larger than the partial waves dominating the backward-angle elastic scattering, again indicating that there is no clear connection between forward-angle transfer and backward-angle scattering.

In conclusion, we have shown that excitation functions for three reactions leading to the same composite system have no obvious correlation, thus ruling out explanation of the observed structures in terms of a common isolated doorway state in the compound nucleus. Rather, the doorway configuration must be specific to the reaction channels. This is corroborated by the fact that the angular distributions are dominated by different partial waves for transfer and elastic scattering.

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Ambiguities in Pion-Nucleus Optical Potentials and the Determination of Neutron Radii

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The $\pi^{\pm}$-^{48}Ca elastic scattering data are shown to be reproduced with a wide range of rms neutron radii if the optical-model parameters are suitably adjusted. The corresponding total cross sections vary significantly.

It has long been expected that any difference between the proton and neutron distributions in nuclei will lead to corresponding differences in $\pi^{\pm}$-nucleus differential[1] and total[2] cross sections in the energy region dominated by the (3, 3) πN resonance. This is because at these energies $\sigma(\pi^+p)\simeq 3\sigma(\pi^+n)$, so that the π^+ mainly "sees" protons and, by symmetry, the π^- mainly sees neutrons. With the aid of recent data[3,4] for ^{40,48}Ca, we have now found that if both differential- and total-cross-section data are fully analyzed, the ambiguities are reduced in extracting radial parameters.

Electron and proton scattering experiments[5] indicate that in ^{40}Ca the rms proton and neutron radii, r_p and r_n, are nearly equal; also, $r_p(^{48}\mathrm{Ca})\simeq r_n(^{40}\mathrm{Ca})$. Hartree-Fock calculations[6] give $\Delta r_n = r_n(^{48}\mathrm{Ca}) - r_n(^{40}\mathrm{Ca}) = 0.31$ fm; however, scattering of 79-MeV α particles[7] indicates $\Delta r_n = 0.08\pm 0.08$ fm, and 1-GeV proton scattering[8] gives 0.16 ± 0.02 fm. Generally, in neutron-rich nuclei, measured neutron radii are smaller than the Hartree-Fock predictions.[9]

Two $\pi^{\pm}$ experiments have been done on ^{40,48}Ca, yielding somewhat different conclusions about Δr_n. Jakobson *et al.*[3] performed measurements at the Clinton P. Anderson Meson Physics Facility (LAMPF) at several energies of the differences in the total cross sections, $\Delta\sigma^{\pm}=\sigma_T^{\pm}(^{48}\mathrm{Ca}) - \sigma_T^{\pm}(^{40}\mathrm{Ca})$. They adjusted the radial parameters in an optical-model calculation to obtain a fit and concluded that the rms neutron radii differ by $\Delta r_n = 0.14\pm 0.05$ fm. At the Swiss Institute for Nuclear Research, Egger *et al.*[4] measured elastic scattering over a range of angles at 130 MeV. They associated the minima with nuclear radii via a black-disk model, and found that the π^- radius exceeded the π^+ radius by 0.21 fm for ^{40}Ca, and by 0.51 fm for ^{48}Ca. They ascribed the ^{40}Ca difference to Coulomb effects, and assumed that the additional radius difference of 0.3 fm in ^{48}Ca is due to a larger neutron radius. They state that these results are consistent with the Hartree-Fock predictions[6] but not those of Jackson *et al.*[3]

One problem in interpreting both of these experiments is that some knowledge of the optical potential is required. Jakobson *et al.*[3] used optical-model parameters based on free-πN data; these parameters reproduce the general features of pion scattering in this energy region, and, as they noted, their analysis is relatively insensitive to the values of the parameters as long as they are the *same* for both ^{40}Ca and ^{48}Ca. In the elastic scattering experiment,[4] the "blackness" of the nucleus is needed to associate the disk radius R with a neutron radius. If the medium is made more absorptive, the absorptive region will move further out into the nuclear surface; since the black-disk diffraction minimum occurs at $2kR\sin(\theta/2)=3.83$, θ decreases as the imaginary part of the optical potential increases. The same effect occurs if the potential is made

