PHYSICAL REVIEW C VOLUME 39, NUMBER 4 APRIL 1989

Phenomenological analysis of $^{10}B+^{16}O$ elastic scattering

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(Received 7 December 1988)

Angular distributions for the elastic scattering of ^{16}O from ^{10}B have been measured at $E_{c.m.}=14.17$, 16.15, and 18.65 MeV over an angular range from 20° to 176°. The angular distributions, which exhibit an oscillatory enhancement of the cross section at backward angles, are described by a scattering matrix parametrization, by adding a very narrow l window to the normal, strong absorption S matrix.

In the scattering of heavy-ion systems in the $1p$ shell, enhancements of the elastic cross sections, with pronounced structures at backward angles, are frequently observed. The strongest "anomalous" back-angle scattering for systems in this mass region has been detected in the $^{12}C+^{16}O$ system[1-4] characterized by two "$n\alpha$-type" nuclei differing by one "α particle." Notwithstanding many "resonancelike" structures in excitation functions which appear correlated in different exit channels[5] in this case, an α exchange process between the two ^{12}C cores has been pointed out as being an important part of the $^{12}C+^{16}O$ interaction responsible for the enhancement and oscillation at backward angles.[6] The back-angle anomaly is still present, although attenuated, in the neighboring $^{11}B+^{16}O$ system.[3,7] No evidence for correlated resonancelike structure has been reported in this case.[8] A one-step elastic transfer process is not a good candidate here for explaining the back-angle enhancement, since the mass difference between ^{16}O and ^{11}B corresponds to three protons and two neutrons. However, interference between an α particle plus proton and ^5Li transfer could occur, as discussed by Schlotthauer-Voos *et al.*[7]

In order to investigate whether the anomalous pattern still persists for a system with a larger nucleon difference for the colliding nuclei, we have measured three complete angular distributions for the $^{10}B+^{16}O$ system for which the mass asymmetry is $3p+3n$. The experimental data were obtained at $E_{c.m.}=14.17$, 16.15, and 18.65 MeV by bombarding a self-supporting 50 $\mu g/cm^2$ ^{10}B target with the ^{16}O beam from the University of São Paulo tandem electrostatic accelerator. Two different experimental setups were used: (1) a ΔE-E silicon surface-barrier detector telescope (13–100 μm) mounted in a 60-cm-diam scattering chamber, and (2) a 38-cm-long position-sensitive gas proportional counter with delay line readout[9,10] at the focal plane of an Enge split-pole spectrograph.[11] The first setup was used for intermediate angle measurements ($40° < \theta_{c.m.} < 100°$) with an angular resolution of $\Delta\theta_{lab}=0.84°$. The focal plane detector was used in detecting scattered ^{16}O at forward angles ($44° < \theta_{c.m.}$) with an angular resolution of $\Delta\theta_{lab}=1.04°$. Also, by detecting recoiling ^{10}B nuclei at forward angles with the magnetic spectrograph, the elastic scattering cross sections at backward angles (up to $\theta_{c.m.}=176°$) were measured. Aluminum absorber foils were mounted in front of the entrance window of the detector to allow the recoil nuclei detection in presence of the intense flux of scattered ^{16}O ions.

The experimental angular distributions (Fig. 1) exhibit a normal Fresnel pattern at forward angles, with small oscillation structures which are related to the grazing angular momentum. The experimental cross sections also exhibit enhancements at backward angles with oscillatory structures similar to those observed in the $^{11}B+^{16}O$ system.[3,7] The cross-section oscillations in the backward region show a larger angular period than those of the forward part. The orbital angular momentum related to this angular period must be smaller than the grazing value. The angular structure at intermediate angles could be interpreted as an interference pattern between two processes.

A simple model was considered for the description of the data using the formalism developed by Frahn.[12] The forward-angle part of the elastic angular distributions was described by a scattering matrix S_0 and the back-angle range by an "anomalous process" matrix $\tilde{S}$. The channel spin of the colliding nuclei was ignored and the scattering amplitude was obtained by a plane-wave expansion, taking the nuclear scattering matrix as a sum of S_0 and $\tilde{S}$.

The normal scattering matrix S_0 was parametrized by a continuous variable $\lambda=l+\frac{1}{2}$ where l is the angular momentum.[12] Ericson's formula,[13] as described by Frahn *et al.*,[14] is used:

$$S_0(\lambda)=\left[1+\exp\left[\frac{\lambda-\lambda_g}{\Delta}-i\alpha\right]\right]^{-1} . \quad (1)$$

Here, $\lambda_g+i\alpha\Delta$ is the complex cutoff parameter,[13] with λ_g being the real part of the cutoff value. The imaginary parameter α is restricted to values between 0 and $\pi/2$. The "diffuseness" of the scattering matrix is represented

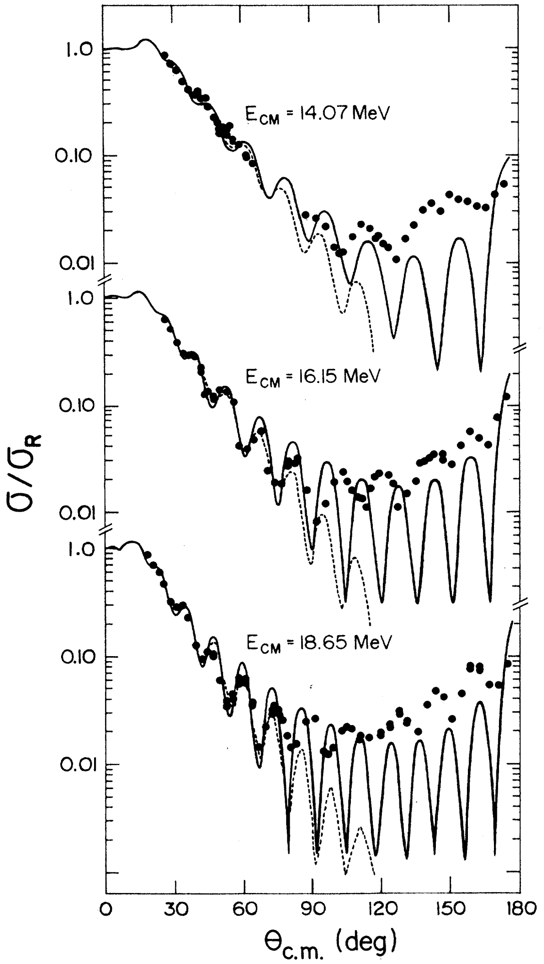

FIG. 1. Experimental angular distributions of $^{10}B+{}^{16}O$ compared to calculated results. The dashed lines were obtained with the normal, strong absorption S matrix, S_0. The solid lines correspond to calculations which include the contributions from the anomalous matrix $\tilde{S}$ as described in the text. The solid and dashed lines overlap for angles smaller than 50°.

by Δ. The energy dependences of λ_g and Δ are taken from semiclassical relations[14] as

$$\lambda_g = A(E-E_0)^{1/2} \tag{2a}$$

and

$$\Delta = \frac{a}{R}\frac{(1-E_0/2E)}{(1-E_0/E)}\lambda_g \ . \tag{2b}$$

The parameters E_0, R, and a (constant with bombarding energy) correspond to the threshold energy, strong absorption radius associated with λ_g, and diffuseness of the colliding system, respectively.

For the anomalous matrix, we have chosen

$$\tilde{S}(\lambda) = d[1-\gamma(-1)^l]\omega(\lambda)\exp(i\Phi) \ , \tag{3}$$

where d is the overall strength, γ is the strength of the parity-dependent part, and Φ a phase between S_0 and $\tilde{S}$. The complex function $\omega(\lambda)$ defines the form of the "anomalous window" in λ space. In the present study, the derivative of Ericson's formula was used for $\omega(\lambda)$:

$$\omega(\lambda) = \frac{1}{2\tilde{\Delta}}[1+\cosh(\mu+i\tilde{\alpha})]^{-1} \tag{4}$$

with

$$\mu = \frac{\lambda-\tilde{\lambda}}{\tilde{\Delta}} \ ,$$

where $\tilde{\lambda}$ is the angular momentum window position, $\tilde{\Delta}$ is the window width, and $\tilde{\alpha}$ is a phase between 0 and $\pi/2$.

The forward part of the angular distributions was described by S_0 by fitting the experimental data, including the higher-energy data obtained by Parks *et al.*[15] (at angles smaller than $\theta_{c.m.} \approx 90°$) at $E_{c.m.} = 20.73$, 25.57, and 30.38 MeV. The following parameters were obtained: $A = 3.95$ MeV$^{-1/2}$, $E_0 = 5.83$ MeV, $R = 7.29$ fm, $a = 0.347$ fm, and $\alpha = \pi/4$. The two independent sets of experimental angular distributions are well reproduced with these parameters for angles less than $\theta_{c.m.} \approx 60°$. However, the lower-energy data ($E_{c.m.} = 10.0$, 11.54, and 12.5 MeV) reported by Krubasik *et al.*[16] are not described by the calculation. The fits at forward angles to our measured cross sections are shown in Fig. 1 by dashed curves.

For the backward part of the angular distributions, described by the anomalous matrix $\tilde{S}$, the following values for the parameters have been obtained from fits to the experimental data: $\tilde{A} = 3.83$ MeV$^{-1/2}$; $\tilde{E}_0 = 6.89$ MeV; $\tilde{R} = 6.19$ fm; $\tilde{\alpha} = \pi/2$; $d = 0.2$; $\gamma = 0.2$. Because of the limited energy range of the experimental data, $\tilde{\Delta}$, d, and γ were kept constant. Several values for the phase parameter Φ between S_0 and $\tilde{S}$ were tried but better results were obtained with $\Phi = 0.0$. The results of the calculation are represented by the solid curves in Fig. 1. The global pattern of the experimental angular distributions is reasonably described by this simple model, although the deep minima, predicted by the calculation, are not present in the experimental data. The present calculation, however, did not take into account the spin of ^{10}B. Due to the narrow l window, essentially only one P_l term in the plane-wave expansion appears in the anomalous amplitude. With the inclusion of the target spin in the calculation, other P_l terms weighted by angular momentum coupling coefficients would contribute to the plane-wave expansion, leading presumably to less pronounced minima at large angles in the angular distributions.

The semiclassical radius ($\tilde{R}$) associated with $\tilde{\lambda}$ is about 1.1 fm smaller than the strong absorption radius (R) while the nuclear "diffuseness" associated to the window width, $\tilde{\Delta}$, is around 0.19 ± 0.01 fm, which seems to indicate that the mechanism responsible for the anomalous elastic scattering is localized at a very narrow region of the nuclear surface. Both threshold energies (E_0 and $\tilde{E}$) are smaller than the Coulomb barrier ($V_C = 7.90$ MeV) at the strong absorption radius. The threshold energy for the anomalous process is 1.06 MeV higher than that of the normal process. The parity-dependent parameter γ, while small compared to the overall strength parameter

d, is crucial to reproduce the pattern of the angular distributions at intermediate angles, thereby suggesting the possible presence of an exchange process.[14]

In conclusion, enhancement of the elastic cross sections at backward angles has been observed in the present experiment for one more system of $1p$-shell nuclei with a large mass asymmetry, which shows very similar structures to those observed for the $^{11}B+^{16}O$ and $^{10}B+^{14}N$ systems.[3,7,17] For the last system, it has been shown[17] that a one-step process involving the transfer of an alpha particle accounts for the back-angle cross sections up to $\theta_{c.m.}=160°$, but is not able to explain the results at larger angles, close to 180°. Preliminary results of similar calculations carried out for the present system,[18] in which a ^6Li cluster is supposed to be transferred, do not reveal a good agreement with the back-angle scattering data.

Other transfer processes such as a sequential transfer of a deuteron and an alpha particle with a $^{12}C+^{14}N$ intermediate state might, however, be present. The strong population of the $^{12}C+^{14}N$ channel observed in our data[18] and also by Ischenko *et al.*[19] at lower energies seems to support this hypothesis. Also, the narrow l window in $\tilde{S}$ which comes out of the present analysis points to the presence of localized processes.[14] The multiple exchange of nucleons between target and projectile also cannot be excluded. In this respect, it could be useful to investigate the energy dependence of the l window over a wider energy interval. Presumably, physical mechanisms by which the required S-matrix structures are generated could be tested. Also, such phenomenological analysis, if extended to other $1p$-shell systems (and over a wider energy range) might possibly reveal, through a comparison of the fitted parameters, overall features of the enhancement of the cross sections at large angles.

Thanks are due to M. S. Mansueto and J. G. Pacheco for their assistance in taking the data and to R. Donangelo, L. F. Canto, and M. S. Hussein for informative discussions. We are also grateful to K. W. Kemper for providing us with the tabular data of the results from Ref. 15. This work was supported in part by Conselho Nacional de Desenvolvimento Cientifico e Tecnológico (CNPq), by Financiadora de Estudos e Projetos (FINEP), and by Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP).

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