Multistep α-Particle–Transfer Description of Anomalous Heavy-Ion Elastic Scattering

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A multistep α-particle–transfer picture is used to describe anomalous back-angle elastic scattering of $^{16}O+^{28}Si$. Transfer of two and three α particles is described in a semiclassical treatment of the interplay between absorption and transfer processes. The energy dependence of the anomalous contribution to the elastic S matrix due to these processes is estimated and shown to be consistent with the overall trend of the data.

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It has by now become very clear that several light–heavy-ion systems (e.g., $^{16}O+^{28}Si$, $^{12}C+^{24}Mg$, etc.) exhibit back-angle elastic scattering angular distributions and excitation functions that show[1] marked deviations from the usual "optical" behavior seen in almost all heavy-ion systems. These deviations are a clear manifestation of some specific nuclear structure effects which cannot be accounted for by the usual absorption-refraction picture inherent in a normal optical-model description. The physical origin of these deviations has so far escaped clear identification. For a full discussion of this anomalous behavior in $^{16}O+^{28}Si$ and other "$n\alpha$ nuclei" see the recent review of Braun-Munzinger and Barette.[1]

A conventional resonance interpretation of the gross structure seen in the $\theta=\pi$ excitation function, though seemingly feasible for accounting for some of the features seen in the data, fails when confronted with the full range of phenomena observed. In particular, no clear-cut correlation among the excitation functions of the different channels was seen.

A recent analysis of the data supports, on the other hand, a picture in which the deviation from the E18 optical behavior[2] arises from a localized complex l window. This window contains two components: a dominant parity-independent component and a small, parity-dependent one.[3] Though quite weak this second window does affect rather drastically the elastic scattering in the far back-angle region.

A direct-reaction interpretation involving the implicit consideration of the effect of coupling to several α-particle–transfer channels was shown to be able at least in principle to generate both l-window components.[3] On the basis of the results of Frahn and Hussein[4] it was further suggested in Ref. 3 that the parity-independent contribution to the S matrix could arise from an absorptive two-step α-particle–transfer process, while the parity-dependent term would appear through refractive multi-α-particle transfer, equivalent to an elastic transfer process. These processes are illustrated, for the case of $^{16}O+^{18}Si$, in Fig. 1. The first evidence supporting these α-particle–transfer mechanisms as responsible for these anomalous angular distributions was recently presented in the analysis of 40-MeV $^{12}C+^{24}Mg$ scattering data by Lichtenthaler *et al.*[5] They showed that the influence of the two-step α-particle transfer channel on the elastic scattering could account for the observed oscillations at intermediate angles, where the parity-dependent contribution is expected to be negligible.

In this Letter we present further support for this α-particle–transfer model. In particular we extend the dynamical treatment of Ref. 5 by in-

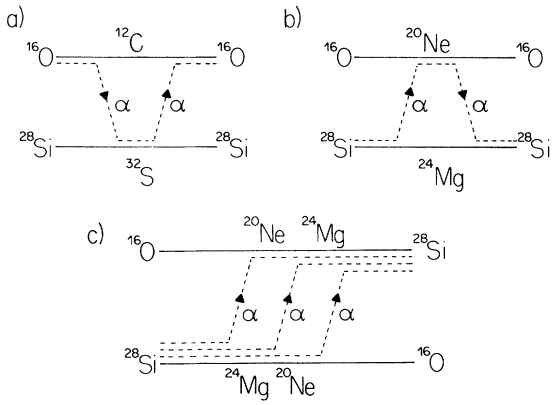

FIG. 1. Coupling schemes used in the discussion. See text for details.

cluding the parity-dependent term in the l window. Special consideration is given to the energy dependence of both the parity-dependent and -independent components, and we show that their behavior agrees with that expected from the average trend of the data.

The elastic S-matrix element corresponding to the lth partial wave may be written as

$$S_l = \bar{S}_l + \sum_i W_l{}^i(E), \quad (1)$$

where $\bar{S}_l$ is the "normal strong absorption profile"[6] and the complex functions $W_l{}^i$ represent the windowlike contributions from different processes to the anomalous back-angle enhancement. The explicit forms of these deviations depend on the physical nature of each particular contributing process. In practical applications the terms included in the summation appearing in Eq. (1) are just the dominant ones. In our model we will assume that the dominant channels for the specific case of $^{16}O + {}^{28}Si$ are the two-step α-particle transfer $^{16}O + {}^{28}Si \rightarrow {}^{12}C + {}^{32}S \rightarrow {}^{16}O + {}^{28}Si$ [Fig. 1(a)] and the three-step α-particle transfer $^{16}O + {}^{28}Si \rightarrow {}^{20}Ne + {}^{24}Mg \rightarrow {}^{24}Mg + {}^{20}Ne \rightarrow {}^{28}Si + {}^{16}O$ [Fig. 1(c)]. The choice of this particular two-step process over the other possibility $^{16}O + {}^{28}Si \rightarrow {}^{20}Ne + {}^{24}Mg \rightarrow {}^{16}O + {}^{28}Si$ [Fig. 1(b)] was based on the much larger cross section for the reaction $^{28}Si(^{16}O, {}^{12}C)^{32}S$ than for $^{28}Si(^{16}O, {}^{20}Ne)^{24}Mg$ expected from kinematical considerations and recently confirmed through a comparison between the spectroscopic factors, for the ground state and the first two lowest-lying excited states in both reactions at $E_{lab} = 49.66$ MeV.[7] In Ref. 3 these two processes were represented within the context of Eq. (1) through the forms

$$W_l{}^1(E) = d_1(E)\omega_l, \quad (2a)$$

$$W_l{}^2(E) = d_2(E)(-)^l\omega_l. \quad (2b)$$

The energy dependence of the two "windows" was separated, through their overall strengths $d_1(E)$ and $d_2(E)$, respectively, from their distribution in l space which was assumed to be the same and given by the complex function ω_l.

In Ref. 3 the strengths d_1 and d_2 were rather arbitrarily given an exponential energy dependence chosen to fit the data, while ω_l was chosen to be a symmetrical window function of width $\tilde{\Delta}$ centered at $\tilde{L}$. The energy dependence of both of these parameters was obtained through semiclassical arguments based on the assumption that the processes responsible for this window occur at a fixed distance. It was also shown that, other than the centroid and width, the elastic scattering at large angles is not sensitive to the specific shape of ω_l.

No clear discussion of the physical origin of the l window was presented in Ref. 3, nor was any attempt made to explain the energy dependence utilized. The l dependence, however, can be easily understood as the result of the combined effects of strong absorption, given by $\bar{S}_l$ which cuts off lower angular momenta, and the transfer amplitude which rapidly decreases with increasing l. Such a description of the nature of the l window is based on the perturbative treatment of multistep processes developed in Ref. 4 and subsequently used for the analysis of data in Ref. 5.

A similar data is used in this Letter to obtain the energy dependence of the anomalous window strengths $d_1(E)$ and $d_2(E)$, i.e., both absorption and multiple-transfer amplitudes will be jointly considered.

As a result of the separate l and E dependence of Eq. (2), it is possible to calculate $d(E)$ for any value of l. Semiclassical considerations (optimal l matching) point to the center of ω_l, $\tilde{L}$, as the most suitable choice. For this value of l, we can use Brink's[8] simple transfer theory, as generalized to multistep transfer processes by Kammuri and Matsuoka.[9]

As in Ref. 9, we assume a straight-line trajectory in the transfer region,

$$r(t) = [\tilde{R}^2 + (vt)^2]^{1/2} \approx \tilde{R} + (vt)^2/2\tilde{R}, \quad (3)$$

where $\tilde{R} = 7.36$ fm is the distance of closest approach associated with $\tilde{L}$ (Ref. 3) through a Rutherford trajectory, $v = [2(E - \tilde{E})/\mu]^{1/2}$ is the tangencial velocity at $\tilde{R}$, μ is the reduced mass in the entrance channel, and $\tilde{E}$ is the effective barrier associated with $\tilde{L}$.[9] The semiclassical multistep transfer amplitude $C_{if}{}^{(n)}$ can then easily be calculated along this trajectory. For two-step processes [Figs. 1(a) and 1(b)] and three-step processes [Fig. 1(c)] the results are given, respectively, in Eqs. (4.2) and (4.10) of Ref. 9. The semiclassical calculation of Kammuri and Matsuoka,[9] however, does not include absorptive effects along the trajectory.

To evaluate the anomalous, energy-dependent strengths $d_1(E)$ and $d_2(E)$ of Eqs. (2) we multiply the amplitudes $C_{ii}{}^{(2)}$ and $C_{ii}{}^{(3)}$ of Ref. 9 by an appropriate absorption factor $A(E)$. This factor is calculated as

$$A = \exp[-\hbar^{-1}\int_{-\infty}^{\infty} W(r(t))dt]. \quad (4)$$

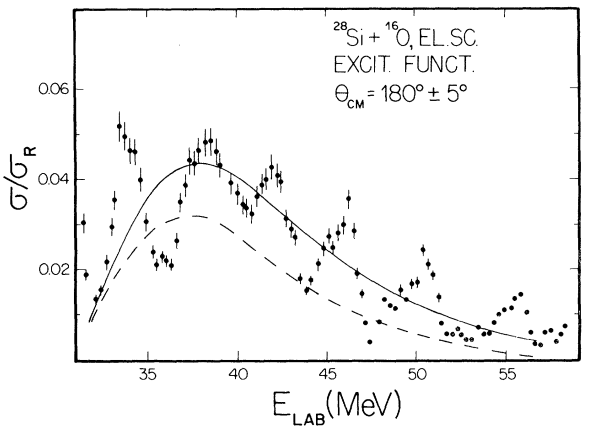

FIG. 2. Strength functions $d_1(E)$ (full line) and $d_2(E)$ (dashed line) calculated as described in the text. Also shown are $180° \pm 5°$ experimental data of Ref. 1. Relative strength of d_1 and d_2 was set arbitrarily.

In the above equation W is the imaginary part of an E18-type potential and $r(t)$ is the straight-line trajectory of Eq. (3). Evaluating the integral we get

$$A = \exp[-\beta/(E-\tilde{E})^{1/2}], \tag{5a}$$

$$\beta = \hbar^{-1} W(\tilde{R})(\pi \tilde{R} a \mu)^{1/2}, \tag{5b}$$

where a is the diffuseness of W. Using for the parameters of W the values given in Ref. 9, we obtain $\beta = 11.4$ MeV$^{1/2}$.

The calculated forms of the energy-dependent strengths, $d_1(E) = A(E) C_{ii}^{(2)}$ and $d_2(E) = A(E) C_{ii}^{(3)}$ for the processes represented in Figs. 1(a) and 1(c), respectively, are shown in Fig. 2. In both cases, only ground states were considered in the intermediate channels. The strength functions $d_1(E)$ and $d_2(E)$ peak at $E_{lab} \cong 38$ MeV in good agreement with the position of the broad structure seen in the average experimental excitation functions. Further, the three-step window $C_{ii}^{(3)}$ has roughly the same shape as $C_{ii}^{(2)}$. This explains why the relative amplitude of the oscillations in the 180° excitation function is more or less uniform throughout the 35–55 MeV laboratory energy range.

The clear windowlike behavior of these strength functions, which may be approximately represented by the expression

$$d(E) = \exp[-\beta/(E-\tilde{E})^{1/2} - \alpha(E-\tilde{E})], \tag{6}$$

is an obvious consequence of the interplay between the two important physical effects represented by $A(E)$ and $C_{ii}^{(n)}$: absorption and the short-range nature of transfer. It is important to recognize that exactly the same kind of interplay is responsible for the l-space localization of the anomalous windows, represented by ω_l, Eqs. (2a) and (2b).

We should emphasize that no attempt has been made in the present work to determine the overall absolute strengths or the phases of these deviations. On the other hand, one expects the *three*-step processes to be much weaker than the *two*-step one. This, however, does not imply that $C_{ii}^{(2)}$ dominates completely the back-angle scattering phenomenon. In the far back-angle region, the contribution of $C_{ii}^{(3)}$ to the elastic scattering amplitude is expected to be enhanced as a result of the fact that the l window attached to $C_{ii}^{(3)}$ contains the even-odd scattering phase $(-)^l$ which cancels a similar phase arising from the Legendre polynomial. This feature has been successfully exploited in Ref. 3.

So far in our discussion we have considered only the ground states in the intermediate channels. The inclusion of excited states is easily done following the same lines, and their overall effects seem to add some strength and would induce a small change in the width.

In conclusion, we have presented in this Letter a simple dynamical model for the anomalous heavy-ion back-angle scattering. Our results indicate clearly that the deviation from the "optical" behavior observed in systems such as $^{16}O + ^{28}Si$ is connected with the couplings to channels reached via multiple α-particle transfers.

It is clear that the many facets of the phenomenon under discussion would require, for their full understanding within this multistep α-particle–transfer picture, more elaborate theoretical and experimental effort. For example, a complete study of the $^{16}O + ^{28}Si$ elastic scattering within the present framework needs data on the reactions $^{28}Si(^{16}O, ^{12}C)^{32}S$, $^{28}Si(^{16}O, ^{20}Ne)^{24}Mg$, and $^{20}Ne(^{24}Mg, ^{24}Mg)^{20}Ne$. We should emphasize that the dynamical model presented in this Letter can be used to study other multistep processes in heavy-ion quasielastic reactions.

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