SEMICLASSICAL ANALYSIS OF TWO-PARTICLE ELASTIC TRANSFER

E. MAGLIONE [a,b], G. POLLAROLO [c], A. VITTURI[a,d], R.A. BROGLIA [e,f], and A. WINTHER [f]

[a] *Dipartimento di Fisica, I-35131 Padua, Italy*
[b] *INFN, Laboratori Nazionali di Legnaro, I-35020 Legnaro, Padua, Italy*
[c] *Istituto di Fisica Teorica and INFN, I-10125 Turin, Italy*
[d] *INFN, I-35131 Padua, Italy*
[e] *Dipartimento di Fisica and INFN, I-20133 Milan, Italy*
[f] *Niels Bohr Institute, DK-2100 Copenhagen Ø, Denmark*

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Two-particle elastic transfer reactions between heavy ions are studied using the semiclassical approach including both one- and two-step contributions to the two-particle transfer process. Good agreement with the data is obtained with form factors and optical potential calculated from nuclear structure. Because the phases of one- and two-step processes turn out to be very similar it seems, however, difficult to extract, from the interference pattern, clear-cut information on the relative importance of the simultaneous and the successive transfer processes.

The interplay of one- and two-step mechanisms has always been a most crucial and debated aspect in the microscopic description of two-particle transfer reactions between heavy ions [1]. We have shown in a recent paper [2] that with the systematic inclusion of both simultaneous and successive processes one reproduces the absolute magnitude of the cross section associated with the two-particle transfer reactions. One used here transfer amplitudes evaluated semiclassically with local one-particle form factors based on pairing wave functions. The analysis has confirmed previous findings [1] on the dominance of the successive transfer process. One should note, however, that the full calculation and the one including only the one-step contribution lead to similar relative cross sections and also to angular distributions which, although different in magnitude, look alike. This explains why one may use the one-step formalism as a spectroscopic tool in the analysis of two-particle transfer reaction.

A possibility of obtaining information about the relative importance of the two processes is by measuring the phase of the transfer amplitude. This could be done by analysing two-particle elastic transfer reactions such as e.g. $^{16}O+^{18}O$. The oscillatory pattern displayed by the elastic angular distribution at backward angles originates [3] from the interference of the elastic and the transfer amplitudes processes, and should therefore be sensitive to the phase of the transfer amplitude.

The total elastic scattering amplitude is in fact given by

$$f(\theta)=f_{\text{elastic}}(\theta)+f_{\text{transfer}}(\pi-\theta)\ . \qquad (1)$$

The latter amplitude has been evaluated semiclassically for the reaction $^{16}O+^{18}O$ at several bombarding energies according to the formalism given in ref. [2], including both one- and two-step contributions. We just recall that basic ingredients of the calculation are local one-particle transfer form factors and overlaps in the intrinsic frame, defined by the relative ion–ion coordinate, the longitudinal recoil being approximately taken into account through an average phase. The time integrals are carried out over the classical trajectory, further approximated as a parabola around the complex turning point. Six intermediate channels have been used in the intermediate $^{17}O+^{17}O$ mass partition, corresponding to the possible combinations of the three single-particle levels $0d_{5/2}$, $1s_{1/2}$ and $0d_{3/2}$ in ^{17}O. The ground state of ^{18}O is described as a two-particle state outside the ^{16}O

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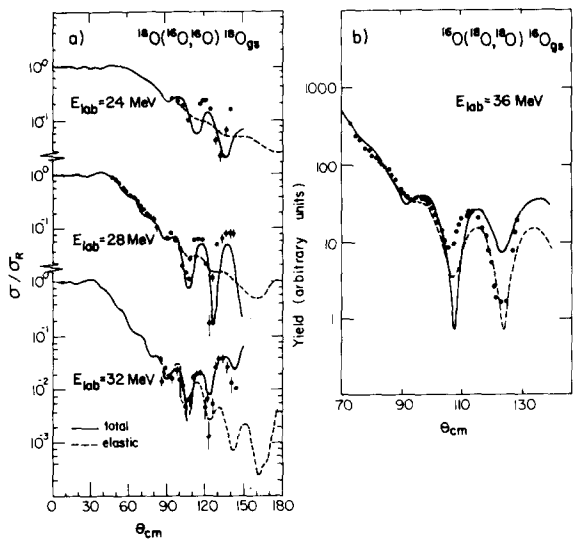

Fig. 1. Elastic angular distributions for the reaction $^{16}O+^{18}O$ at different energies. The experimental data [7,8] are compared with the result of a microscopic calculation, including both one- and two-step two-particle transfer processes, as discussed in the text. Optical-model parameters were also calculated microscopically according to refs. [5,6]. The parameters for the real part are $V=43.24$ MeV, $r_{0v}=1.165$ fm, $a_v=0.605$ fm, while for the imaginary part they are $W=37$ MeV, $r_{0w}=0.97$ fm, $a_w=0.77$ fm at $E=24$ MeV, $W=40.37$ MeV $r_{0w}=0.97$ fm, $a_w=0.81$ fm at $E=27$ MeV, and $W=43.35$ MeV $r_{0w}=0.97$ fm, $a_w=0.83$ fm at $E=32$ MeV. In (a) the dashed curves give the cross sections associated with the "pure" elastic scattering, i.e., neglecting the contribution coming from the transfer process. In (b) the dashed curve gives the cross sections obtained by only including the one-step contribution to the transfer process.

core, with wave function [4] 0.89 $(0d_{5/2})^2+0.396$ $(1s_{1/2})^2+0.223$ $(0d_{3/2})^2$. Finally to generate the elastic WKB phase shifts and to define the classical trajectory we have used the folding potential given in ref. [5] and an energy-dependent imaginary part evaluated according to the microscopic prescription of ref. [6] (cf. figure caption).

The results of the calculation are shown together with the data [7], in fig. 1. To evidence the effect of the interference with the transfer process , the cross sections generated by the "pure" elastic process are also shown, as dashed curves, in fig. 1a. The overall agreement with the data is quite satisfactory, in view of the absence of any adjustable parameter or scaling factor, both in the optical potential and transfer couplings.

We now turn to the question of the competition between one- and two-step processes. As an example, in fig. 1b the results obtained in the full calculation are compared with those obtained by only considering the one-step contribution. One can see in the figure that maxima and minima in the angular distribution, although different in magnitude since the amplitudes for the two-step process are larger than the ones associated with the one-step, are not significantly shifted with respect to each other. This is because the two amplitudes turn out to have a phase difference of only a few degrees. Such a result may be understood recalling that the second-order transfer amplitude can be expressed in terms of the one-particle transfer amplitudes (which in turn have the same phases as the simultaneous two-particle amplitudes) in the form

$$a^{(2)}=\tfrac{1}{2}\sum_\gamma a_\gamma a_\gamma^* + \frac{i}{2\pi}\mathscr{T}\int_{-\infty}^{+\infty}\frac{dQ}{Q}\sum_\gamma a_\gamma(Q_\gamma-Q)a_\gamma(-Q_\gamma+Q)\,. \qquad (2)$$

Because of the pairing energy, the effective Q-values Q_γ associated with the intermediate channels are, even for the ground state of the intermediate odd–odd system, always negative. In order to observed marked interference effects one has to use low bombarding energies where the elastic cross section for larger than 90° has a magnitude comparable to the transfer cross section for less than 90°. Furthermore, elastic transfer has only been measured for light ions. Under these circumstances there will be a strong Q-value mismatch and the principal part integral becomes the dominant contribution. This feature makes it difficult at the present time to use the phase as a probe for discriminating among the competing reaction mechanisms.

As a check of the validity of the semiclassical evaluation of the transition amplitudes and of the use of local one-particle transfer form factors as well as of the approximate treatment of recoil, we have used the same approach to describe one-particle elastic transfer reactions. We have selected two cases of elastic scattering, namely those associated with the reactions $^{12}C+^{13}C$ and $^{16}O+^{17}O$. In the former case we have assumed a $(0p_{1/2})\rightarrow(0p_{1/2})$, $\lambda=0$, transfer process interfering with the "pure" elastic scattering, while in the latter we have used a $(0d_{5/2})\rightarrow(0d_{5/2})$

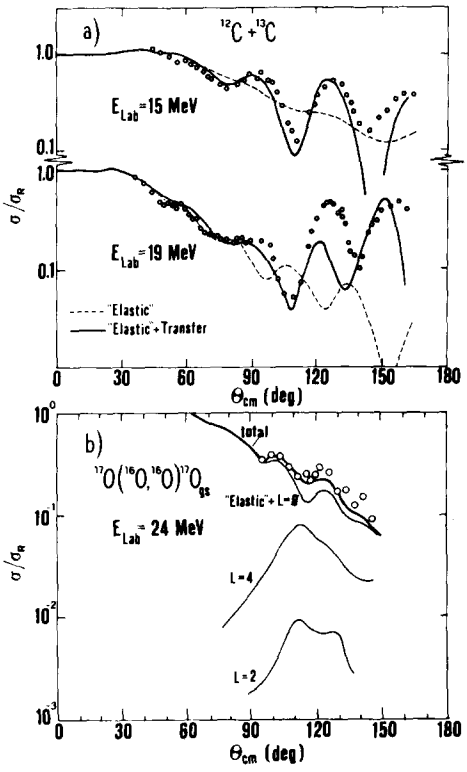

Fig. 2. Calculated elastic angular distributions for the reactions $^{12}C+^{13}C$ and $^{16}O+^{17}O$, compared with the experimental data [9,10]. In (a) the dashed curves give the result obtained in the "pure" elastic scattering. In (b) the different incoherent contributions associated with angular momentum transfer $\lambda=0$, 2 and 4 are also separately shown

transition, with the $\lambda=0$ contribution interfering with the elastic and the $\lambda=2$ and $\lambda=4$ contributions adding incoherently to the cross sections. In both cases spectroscopic factors equal to unity have been assumed, and standard optical potentials as given in refs. [9,10] have been used. The results of the calculations are displayed in fig. 2 and describe the overall trend of the data in much the same way as the quantal analysis [9,10] already published.

We can summarize this note by stating that a quantitative microscopic description of two-particle elastic transfer between heavy ions can be obtained in the semiclassical approach including the contributions due to the one- and two-step two-particle transfer process. However, the large negative Q-values associated with the intermediate channels give rise to similar phases for the associated amplitudes, thus making it difficult to extract from the angular distribution information concerning their relative phase.

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