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Publication Date

1975-11-01

Submitted to Nuclear Physics A

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November 1975

Prepared for the U. S. Energy Research and
Development Administration under Contract W-7405-ENG-48

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TWO-PARTICLE TRANSFER CONTRIBUTIONS TO ELASTIC AND
INELASTIC HEAVY ION SCATTERING*

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November 1975

Abstract: The contributions of two-particle transfer to elastic and inelastic scattering of heavy ions are treated simultaneously in the coupled channels framework using microscopic transfer form factors. As an example, the reaction $O^{18} ({}^{16}O, {}^{16}O) {}^{18}O(g.s. \text{ and } 2_1^+)$ is investigated at three energies near the Coulomb barrier. The interference between scattering and transfer leads to a consistent interpretation of both elastic and inelastic data. Indirect transfer contributions give relatively small, but non negligible corrections to the direct scattering plus transfer results, removing a previously reported energy dependence of the spectroscopic factor.

*Work supported by the U. S. Energy Research and Development Administration.

[†]Supported in part by the German National Fellowship Foundation.

1. Introduction

The coherent appearance of scattering and particle transfer can occur in heavy ion reactions when the two colliding nuclei differ by only one or a few nucleons, leading to strong interferential oscillations in the angular distributions. A large number of experiments dealing with this process in the elastic channel ¹⁾ have been successfully interpreted using the method of linear combination of nuclear orbits (LCNO) ²⁾ or a coherent addition of the optical model amplitude for elastic scattering and the DWBA transfer amplitude ³⁾. More recently, evidence for particle transfer contributions to inelastic scattering has been found ^{4,5)}. If collective states are populated in the exchange process, the inelastic coupling between ground and excited states and thus, the indirect transfer mechanisms ⁶⁾ can generally not be neglected, and a coupled channel approach is appropriate. We present such a calculation in the no-recoil approximation for the reaction $^{18}\text{O} (^{16}\text{O}, ^{16}\text{O}) ^{18}\text{O} (\text{g.s.}, 2^+)$ at $E_{\text{Lab}} = 24, 28, \text{ and } 32 \text{ MeV}$. Two-neutron transfer can contribute coherently to elastic and inelastic scattering. We compare with the experimental elastic ⁷⁾ and inelastic ⁸⁾ data as well as with previous LCNO ⁷⁾ and DWBA ⁹⁾ calculations for the elastic channel, and determine the importance of indirect transfer contributions.

2. Review of previous analyses

For the $^{16}\text{O} + ^{18}\text{O}$ reaction at energies 24, 28 and 32 MeV we are investigating here, no analysis of the inelastic data of Braun-Munzinger et al. ⁸⁾ has been done yet. Analyses of the elastic data of Gelbke et al. ⁷⁾ were performed by several authors using the LCNO model ⁷⁾,

the DWBA elastic transfer theory in the cluster description ⁹⁾, and, ignoring exchange contributions, the optical model with angular-momentum-dependent absorption ⁹⁾. The latter description is less satisfactory, because it predicts the phase of the oscillations in the angular distributions to be energy dependent, which is in disagreement with the data. The first two models lead to almost identical results reproducing the elastic data. The agreement between the LCNO model, which includes multiple exchange, and the DWBA, where only single-step transfer is considered, indicates that for this reaction, multiple transfer processes are unimportant, so that a first order treatment of the transfer process is appropriate. In the calculations reported in refs. ^{7,9)} a spectroscopic amplitude for the transferred "di-neutron" has been used as a free parameter to fit the magnitude of the elastic transfer process. To obtain a good fit of the backward angle region, the spectroscopic amplitude had to be different at the three energies. It has been suggested that, among other possible explanations, this difference might be due to the neglect of indirect transfer via the ^{18}O (2^+) state ⁷⁾. The LCNO model in the two-state approximation as well as the DWBA treatment both ignore the coupling to excited states, and consequently, indirect transfer mechanisms ⁶⁾ are not considered. We note that in (^{16}O , ^{18}O) reactions on heavier targets, transfer via the ^{18}O (2^+) state as an intermediary was found to be very important ¹⁰⁾.

One aim of our analysis is to show that by including the indirect transfer processes in the $^{16}\text{O} + ^{18}\text{O}$ reaction at energies near the barrier, the slight discrepancy between elastic data and calculations ^{7,9)} can

be removed. Our second objective is to obtain a simultaneous fit of both elastic and inelastic data. Our approach is different from another recent coupled channel analysis by Kalinsky et al. ¹¹⁾ of the $^{16}\text{O} + ^{18}\text{O}$ reaction at similar energies. These authors employ the molecular symmetry axis as a reference frame. Therefore, they have to neglect completely the recoil effects as well as the scaling factor that enters the argument of the wave functions in the usual no-recoil limit. We formulate the coupled equations including recoil, although we perform the calculations in the no-recoil limit. In addition, we use two-particle wave functions rather than a cluster description for the calculation of the transfer form factors.

3. Coupled channel calculations

3.1 Outline of the theory

We consider the elastic scattering of projectile A from target nucleus B

$$A + B \rightarrow A + B \quad (1)$$

and the inelastic scattering to excited states of B

$$A + B \rightarrow A + B^*, \quad (2)$$

where

$$B = A + X, \quad (3)$$

so that the core of B is identical to A, and the mass of X small compared to the mass of A. For simplicity, we assume A to have spin zero. Because of the identity of the cores, the transfer of particle(s) X leads into the same elastic and inelastic channels as the ordinary (direct) scattering, and therefore the two processes interfere. Indirect transfer modes such as inelastic excitation and subsequent

transfer (or vice versa), considerably enhance the number of interfering amplitudes. The coordinate system relevant to our calculations is given in fig. 1. We formulate the coupled equations in the source term method ¹²⁾ for the wave functions depending on the radial coordinates R_1 and R_2 , respectively. Because in the reactions we want to investigate, multiple back-and-forth transfer is unimportant (see sect. 2, and ref. ¹¹⁾), we include only first order transfer terms. The S-matrices for scattering and transfer can then be calculated separately. The ordinary scattering amplitude at angle θ interferes with the particle transfer amplitude at $(\pi-\theta)$. The total cross sections in the elastic channel and inelastic channels are computed from the coherent sum of the amplitudes for scattering and transfer, respectively.

The ordinary (direct) elastic or inelastic scattering leading to the ground state of A and B, or an excited state of B, is treated by expanding a solution $\psi_b^{\pi IM}$ of the Schrödinger equation for parity π , total angular momentum I, projection M, and incident particles in channel b, as

$$\psi_b^{\pi IM}(\hat{R}_1, \hat{r}_1) = R_1^{-1} \sum_{b'} u_{b'}^{\pi I}(R_1) \phi_{b'}^{\pi IM}(\hat{R}_1, \hat{r}_1). \quad (4)$$

The indices b, b' denote any channel, including the elastic, which is otherwise referred to as b_0 . Here, b stands for the spin j of nucleus B, and the relative angular momentum ℓ between A and B. The channel functions are defined as

$$\phi_b^{\pi IM}(\hat{R}_1, \hat{r}_1) = [Y_\ell(\hat{R}_1) \phi_j(\hat{r}_1)]_I^M \quad (5)$$

with $\phi_j(r)$ being the internal wave function of nucleus B. The coupled equations for the radial wave functions $u_b(R_1)$, obtained after substitution into $(E - H) \Psi = 0$, and truncation of the problem to the channels of interest are ¹²⁾

$$(T_b + U(R_1) - E_b) u_b(R_1) = - \sum_{b' \neq b} V_{bb'}(R_1) u_{b'}(R_1) \quad (6)$$

with

$$E_b = E - E_B.$$

Here and in the following, the quantum numbers π, I, M are omitted. The right hand side of the coupled equations represents the feeding of channel b by inelastic processes from channels b' , V is the effective interaction ¹³⁾ within the truncated space considered. The parametrization of the off-diagonal matrix elements of V in the collective model is given in section 3.2. The diagonal matrix elements

$$V_{bb}(R_1) = \langle \phi_b | V(A, B) | \phi_b \rangle \equiv U(R_1) \quad (7)$$

are parametrized by an optical potential $U(R_1)$, which is assumed to be channel independent. It differs from the optical potential used to describe elastic scattering because of the explicit consideration of the inelastic coupling.

We solve the coupled equations with the boundary conditions that outgoing (O) and incoming (I) waves ¹²⁾ are present in the elastic channel ($b \equiv b_0$), but only outgoing waves in any inelastic ($b \neq b_0$) channel. The S-matrices $S_{bb_0}^{SC}$ are obtained from the requirement:

$$u_b(R_1) \rightarrow \delta_{bb_0} I_\ell(k_0 R_1) - (k_0/k_b)^{1/2} S_{bb_0}^{SC} O_\ell(k_b R_1) \quad (8)$$

The momentum in the elastic channel is k_0 , in any inelastic channel k_b , and the calculation of the ordinary scattering cross sections from the $S_{bb_0}^{SC}$ is straightforward ¹²⁾. The amplitudes for elastic and inelastic scattering to one excited state of nucleus B, with A remaining in its ground state, are represented respectively by the two graphs in fig. 2 labelled "ordinary scattering (S)". For the transfer process, eq. 6 describes the initial partition, whereas the coupled radial equations for the wave functions $w_b(R_2)$ in exit channels b with the same nuclear states populated as in the ordinary scattering, are ¹⁴⁾

$$(T_b + U_b(R_2) - E_b) w_b(R_2) + \sum_{b' \neq b} V_{bb'}(R_2) w_{b'}(R_2) = \sum_{b'} \rho_{bb'}(R_2). \quad (9)$$

The source term on the right describes the transfer processes from initial channels b' to final channels b

$$\rho_{bb'}(R_2) = R_2 \langle \phi_b(\hat{R}_2, \hat{r}_2) | V(A, X) | \phi_{b'}(\hat{R}_1, \hat{r}_1) \frac{u_{b'}(R_1)}{R_1} \rangle, \quad (10)$$

where all coordinates except R_2 are integrated. Because of the introduction of the source term in the final partition only, the transfer processes are treated to first order. The inelastic coupling, however, is treated to all orders in the effective interaction. Whereas the solution of eq. (9) with eq. (10) implies the correct treatment of recoil terms, we restrict to the "no recoil" approximation to perform the numerical calculation. In the exact expressions

$$\tilde{R}_1 = \frac{A}{A+X} \tilde{R} + \frac{X}{A+X} \tilde{r}_2$$

$$\tilde{R}_2 = \tilde{R} - \frac{X}{A+X} \tilde{r}_2$$

the terms of order $X/(A+X)$ are neglected, to obtain

$$\begin{aligned} R_1 &\approx \alpha_1 & \alpha &= \frac{A}{A+X} \\ \tilde{R}_2 &\approx \tilde{R} \end{aligned} \quad (11)$$

For $X \ll A$, the source term then reads

$$\rho_{b,b}(R) = \langle \phi_b(\hat{R}, r_2) | V(A, X) | \phi_b(\hat{R}, r_1) \rangle \frac{u_b(\alpha R)}{\alpha} \quad (12)$$

If the scaling factor α were absent from the argument of the wave function, u_b , could be replaced by w_b , to obtain a solution of eq. (9) that includes the transfer coupling to all orders. In that case, and with the replacement

$$\phi_b(\hat{R}, r_1) \rightarrow \phi_b(-\hat{R}, r_1) = (-)^{\ell} \phi_b(\hat{R}, r_1)$$

in the source term to account for the exchange symmetry of the cores¹⁵⁾, equations equivalent to the ones of ref.¹⁵⁾ are obtained. Their solution with boundary conditions, expression (8), leads to scattering cross sections already including exchange contributions to all orders. However, the approach reported in ref.¹⁵⁾ does not allow for the inclusion of recoil and, in particular, the scaling factor α in the no-recoil approximation cannot be different from one. Therefore, we calculate the amplitudes for scattering and transfer separately with eqs. (6), (9) to add them coherently.

To obtain the transfer amplitudes, the equations (9) are solved subject to the physical boundary condition that only outgoing waves are present. This yields the S-matrices $S_{bb_0}^{tr}$ for transfer in elastic ($b \equiv b_0$) and inelastic ($b \neq b_0$) channels from

$$w_b(R_2) \rightarrow - (k_0/k_b) S_{bb_0}^{tr} O_{\ell}(k_b R_2). \quad (13)$$

The reaction amplitudes for transfer of particle(s) X from the ground state of nucleus B (channels b_0) to nucleus A, forming again nucleus B (channels b), are labelled "T" in fig. 2. The indirect transfer processes involving intermediate inelastic transitions are labelled "I".

All amplitudes leading to the same final state interfere with each other. The transfer amplitudes, however, have to be evaluated at the correct center-of-mass angle $(\pi-\theta)$, where particle A would be detected after a transfer process, rather than at θ . Because of the symmetry property

$$Y_{lm}(-\hat{R}) = (-)^l Y_{lm}(\hat{R})$$

of the spherical harmonics involved in the calculation of the reaction amplitudes, a total S-matrix can be defined as

$$S_{bb_0} = S_{bb_0}^{sc} + (-)^l S_{bb_0}^{tr} \quad (14)$$

where the + sign arises from the symmetry of the spin zero (boson) cores, and the total cross section for elastic and inelastic scattering with the inclusion of particle transfer can immediately be calculated from the scattering amplitudes constructed with $S_{b_0 b_0}$ and S_{bb_0} ($b \neq b_0$), respectively.

3.2 Details of the calculation

For the scattering of the nuclei $A \equiv {}^{16}\text{O}$ and $B \equiv {}^{18}\text{O}$, we consider the 0^+ ground states of both nuclei, and the first excited collective 2^+ state of ${}^{18}\text{O}$ at 1.98 MeV. To solve the inelastic scattering problem, the off-diagonal matrix elements of the effective two-body interaction V in the coupled equations (6)

$$V_{bb'}(R) = \langle \phi_b | V(A,B) | \phi_{b'} \rangle$$

are expressed in terms of geometrical factors, the interaction strength, and nuclear reduced matrix elements, which are referred to as nuclear form factors for the inelastic transitions ¹³). Using the macroscopic vibrational model, the radial shape of the $J = 2$ inelastic form factor is parametrized, to lowest order, as

$$F_2^{\text{inel}}(R) \simeq \left[-\beta_N R_B (dU/dR) + \beta_C R_C (3/5) Z_A Z_B e^2 * \begin{cases} R^2/R_C^4, & R \leq R_C \\ R_C/R^3, & R \geq R_C \end{cases} \right] \quad (15)$$

with $U(R)$ being the optical potential introduced in eq. (6), R_B the radius of the vibrational nucleus B, and R_C the Coulomb radius. We use $R_B = R_C = 1.2 (B)^{1/3}$. For $B \equiv {}^{18}\text{O}$, the vibrational description is certainly not a very good model. The 2_1^+ state could as well be interpreted as the first excited state of the $K = 0$ rotational band, with 4_2^+ rather than 4_1^+ as its second member. However, the results obtained in a vibrational and a rotational model for ${}^{18}\text{O}(2^+)$ are very similar as long as no higher states are included, the vibrational model yielding slightly better agreement with the data, so that we treat $2^+({}^{18}\text{O})$ as a one-phonon state in all subsequent calculations. We take the Coulomb deformation parameter from ref. ¹⁶) as $\beta_C = 0.3$, whereas $\beta_N = 0.343$ is obtained from a CCBA analysis of forward angle ${}^{18}\text{O} + {}^{16}\text{O}$ inelastic scattering data ⁵), in good agreement with results derived from proton scattering ¹⁷).

The optical potential employed in our calculations is the Woods-Saxon potential "Z" of ref. ¹⁸) with $V = -100$ MeV, $W = -40$ MeV, $r_V = r_W = 1.2$ fm, $a_V = 0.49$ fm, $a_W = 0.32$ fm. Corrections for the explicit treatment of ${}^{18}\text{O}(2^+)$, necessary for more weakly absorbing potentials, have not been made. To compute the two-neutron transfer contributions with the coupled equations (9), we calculate the source terms eq. (12)

$$\rho_{bb'}(R) = \langle \phi_b | V(A, X) | \phi_{b'} \rangle \frac{u_b(\alpha R)}{\alpha}$$

using microscopic two-particle wave functions. The nuclear matrix elements are first rewritten in terms of geometrical factors, and radial transfer form factors $F_J^{\text{tr}}(R)$, which are obtained from evaluation of the matrix elements of the Woods-Saxon potential V that binds the neutrons to the ^{16}O cores¹⁴). With $\rho_{\sim 1}, \rho'_{\sim 1}$ and $\rho_{\sim 2}, \rho'_{\sim 2}$ being the coordinates of the two neutrons in the initial and final partition, respectively, and

$$\rho_{\sim 2} = \rho_{\sim 1} + R$$

these matrix elements read

$$\langle \psi_{J_2 M_2}(\rho_{\sim 2}, \rho'_{\sim 2}) | V(\rho_{\sim 1}) + V(\rho'_{\sim 1}) | \psi_{J_1 M_1}(\rho_{\sim 1}, \rho'_{\sim 1}) \rangle \equiv F_J^{\text{tr}}(R) Y_{JM}^*(\hat{R}). \quad (16)$$

The ψ_{JM} are configuration-mixed states

$$\psi_{JM}(\rho, \rho') = \sum_K c_K \chi_{JM}(\rho, \rho')$$

with structure amplitudes c_K of ref.¹⁹) given in table 1, and two-particle states χ_{JM}

$$\begin{aligned} \chi_{JM}(\rho, \rho') = [2(1+\delta_{jj'})]^{-\frac{1}{2}} \sum_{mm'} (jm j'm' | JM) [\phi_j^m(\rho) \phi_{j'}^{m'}(\rho') \\ - \phi_j^m(\rho') \phi_{j'}^{m'}(\rho)]. \end{aligned}$$

The $\phi_j^m(\rho)$ are single particle wave functions of the two s-d shell neutrons in the Woods-Saxon potential V ($r = 1.175$ fm, $a = 0.6$ fm, $V_{\text{so}} = 7.8$ MeV, and the depth being adjusted to bind the neutrons at the average binding energy of the two neutrons in ^{18}O). The ^{16}O core is assumed to be inert, and antisymmetrization between the outer neutrons and the core particles is neglected. An estimate of its influence on the

transfer form factors shows ²⁰⁾ that it has a small effect only for core distances less than six fermi and is therefore completely negligible if strongly absorbing potentials are used.

In the subspace we are considering, three form factors $F_J^{\text{tr}}(R)$ enter the calculation of the source terms, namely for the transitions $0^+ \rightarrow 0^+$, $0^+ \rightarrow 2^+$ (identical to $2^+ \rightarrow 0^+$), and $2^+ \rightarrow 2^+$. We use the same monopole transfer form factor for the $2^+ \rightarrow 2^+$ transfer as for the $0^+ \rightarrow 0^+$ transition. We neglect $J = 2$ and $J = 4$ contributions, which can also connect the 2^+ states. This approximate treatment of the $2^+ \rightarrow 2^+$ transfer has to be improved in cases where indirect transfer turns out to be more important than in the reaction investigated here. While the parametrization of inelastic form factors in the collective model allows for a good fit of inelastic scattering data for collective states by means of adjusting the parameters β_N , β_C , one has to confirm the correct relative sign between (macroscopic) inelastic form factors and (microscopic) transfer form factors. We ensure the correct phase by calculating the sign of the microscopic inelastic nuclear form factor ²¹⁾ in the tail region, with the $^{18}\text{O}(\text{g.s.}, 2)$ wave functions that are used to compute the transfer form factors. The absolute sign of the wave functions given in table 1 leads to consistency with the macroscopic inelastic form factor, eq. (15).

4. Results

Coupled channel calculations for the $^{16}\text{O} + ^{18}\text{O}$ elastic and $^{18}\text{O} (2^+)$ inelastic scattering without and with two-neutron transfer contributions are compared in figs. 3-5 for the three energies $E_L(^{16}\text{O})=24, 28, \text{ and } 32 \text{ MeV}$ where data are available. Potential "Z" (see sect.3.2) is used throughout. Whereas the ordinary elastic and inelastic scattering cross sections show no oscillations at backward angles, the coherent addition of the transfer amplitudes reproduces the oscillatory and backward-rising structure of the data, although the agreement with the (possibly erroneous ²²) inelastic 24 MeV data is not good. Thus, the data for both elastic and inelastic channel find a consistent interpretation, if particle transfer is included.

To obtain the correct backward angle cross sections in the calculations with exchange, we have to apply a common normalization constant $N = 6.3$ to all transfer amplitudes at the three energies, corresponding to an absolute normalization of the backward angle cross section of about a factor five. The necessity of this normalizing factor is not surprising, because we evaluate the microscopic transfer form factors in a restricted configuration space (the s-d-shell), and perform a no-recoil calculation. The absolute magnitude of the transfer amplitudes turns out to be sensitive to the scaling factor α that enters the argument of the radial wave functions in the no-recoil approximation. Calculations with $\alpha = 1$ (as implied in the calculations reported in ref. ¹¹) lead to backward angle cross sections that are about two times larger than the ones computed with the value $\alpha = 16/18$ as prescribed by the relationship of the coordinates. However, the possibility

of adjusting α to obtain the correct magnitude of the backward angle cross sections cannot replace a full recoil calculation. We use $\alpha = 16/18$ in our calculations, and normalize the transfer amplitudes to the experimental data. We mention that in a recent DWBA calculation²³⁾ for the elastic 28 MeV case, the absolute magnitude of the backward angle cross section in the no-recoil approximation is in better agreement with the data. This is due to the introduction of an effective binding energy for the computation of the single particle states, which is different from the experimental separation energy, causing an enhancement of the transfer form factor tail. In this calculation, the inclusion of linear recoil terms was shown to enhance the transfer cross section by about a factor of two above the no-recoil result.

In addition to the overall normalization, the ratio of quadrupole to monopole transfer form factors calculated from the wave functions given in table 1 is slightly enhanced by a factor of 1.3, to give a better account for the observed relative magnitude of inelastic and elastic cross sections at backward angles. This is well within the uncertainties of the wave functions, which also do not reproduce the electromagnetic transition rates correctly. We emphasize, however, that these two adjustments are common to all of the calculations with particle transfer, so that the results shown in figs. 3-5 are obtained with the same set of input parameters, only the energy being different. In contrast, the DWBA calculations for the elastic channel reported in refs. ^{7,9)} required different spectroscopic amplitudes for the transferred neutron cluster in order to account for the magnitude of the backward angle cross sections. The discrepancy is removed by means of the inclusion of indirect transfer mechanisms involving the $^{18}\text{O} (2^+)$ state, as can be seen by comparing

figs. 6 and 7, where results with and without indirect transfer are shown for two different energies. Whereas in the 28 MeV case, the magnitude of the elastic cross section is hardly modified at backward angles, the indirect transfer contributions (I) cause a considerable reduction at 32 MeV, allowing for the use of the same normalization constant. In addition, the calculated inelastic cross sections are in better agreement with the data, when the indirect transfer modes are included. Of course, these results remain to be confirmed in full recoil calculations.

Although the consideration of inelastic coupling and consequently, of indirect transfer modes, turns out to be necessary for the detailed reproduction of the experimental cross sections, their effect is not as drastic as reported in our investigations of (^{16}O , ^{18}O) reactions on heavier targets 10), again with the coupling of the $^{18}\text{O}(2^+)$ state. One reason for this is that the ratio of one-step and indirect transfer amplitudes, which peak at different regions in ℓ -space, is sensitive to the Q-value of the reaction 6). In a large-Q situation, the one-step transitions are more strongly suppressed compared to the indirect ones, which take place closer to the nucleus, and thus the relative importance of one-step compared to indirect reaction amplitudes decreases as the Q-value departs from its optimum. Consequently, in the elastic transfer case with $Q = 0$, the one-step transfer is not suppressed. Another reason is that the transfer form factors eq. (16) depend on the structure of the target, and are therefore different for (^{16}O , ^{18}O) reactions on different targets.

Like the authors of ref. 23) we failed to reproduce satisfactorily the elastic higher energy data for the $^{18}\text{O} + ^{16}\text{O}$ reaction using several

potentials, including weakly absorbing ones, which allow for a good fit of the elastic and inelastic forward angle region. Although reasonable fits to the inelastic data were obtained using the same parameters as in the low energy cases, figs. 3-5, the interferential structure in the elastic channel could not be reproduced due to a very strong dependence on the optic parameters, and the occurrence of diffractive oscillations. This situation in the elastic channel, already reported by Reisdorf et al. ²³), is not significantly improved by the inclusion of the indirect transfer mechanisms.

5. Summary

We have performed coupled channel calculations in the no-recoil approximation for the elastic and inelastic scattering $^{18}\text{O}(^{16}\text{O}, ^{16}\text{O})^{18}\text{O}$ (g.s. and 2^+) including two-neutron transfer contributions, which are described using microscopic transfer form factors. For three energies near the barrier, we have obtained reasonable fits to both elastic and inelastic data, confirming their interpretation as being due to the interference of scattering and transfer mechanisms.

This reaction turns out to be an example where the consideration of indirect transfer modes leads to relatively small, but non negligible corrections to the direct scattering plus transfer results. Because of these corrections, it is possible to use a common normalization constant for the elastic and inelastic transfer amplitudes at the three energies, thus removing the discrepancies previously reported ⁷) for the elastic transfer cases.

We point out that indirect processes in elastic and inelastic transfer will be more important in reactions where the populations of

ground and excited states differ substantially, so that the feeding of the more weakly populated states by indirect processes via strongly populated ones becomes an important excitation mode. Also, the inelastic coupling can be considerably stronger than in the reaction investigated here, which enhances indirect processes. An example is the recently measured $^{16}\text{O} + ^{20}\text{Ne}$ scattering 24) to the rotational states of ^{20}Ne . In this reaction, a DWBA treatment of the elastic alpha transfer may no longer be applicable, because the strong inelastic coupling can produce important indirect alpha transfer contributions to the backward angle cross section.

One of the authors (G.W.) wants to thank the German National Fellowship Foundation for financial support, and the Nuclear Theory Group at the Lawrence Berkeley Laboratory for their hospitality.

TABLE 1. Configuration amplitudes c_K of the oxygen wave functions (ref. ¹⁹) used in the finite range calculation of the transfer form factors.

	g.s.	2_1^+
$(1d_{5/2})^2$	0.8907	-0.6794
$(1d_{3/2})^2$	0.2230	-0.1034
$(2s_{1/2})^2$	0.3964	
$(1d_{5/2} \ 2s_{1/2})$		-0.6736
$(1d_{5/2} \ 1d_{3/2})$		-0.1596
$(1d_{3/2} \ 2s_{1/2})$		0.2205

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FIGURE CAPTIONS

Fig. 1. The system of coordinates used in the calculations.

Fig. 2. Diagrams representing the amplitudes considered in our calculation of elastic and inelastic $^{16}\text{O} + ^{18}\text{O}$ scattering. Wavy lines indicate scattering interaction (treated to all orders), straight lines with arrows two-neutron transfer (first order treatment). Symbols for the nuclear states are

$$\text{—————} A \equiv ^{16}\text{O}(\text{g.s.}), \text{=====} B \equiv ^{18}\text{O}(\text{g.s.}), \text{|||||} B^* \equiv ^{18}\text{O} (2^+).$$

Fig. 3. Computed elastic and inelastic $^{16}\text{O} + ^{18}\text{O}$ cross sections for ordinary scattering (S) are compared with results where, in addition to the scattering, particle transfer (T) plus indirect particle transfer (I) are included. The data are from refs.^{7,8}). Oscillations in both elastic and inelastic channel are identified as being due to the interference of scattering and transfer. Here and in all subsequent calculations, the transfer amplitudes are normalized by a common factor of 6.3. Potential "Z" (see section 3.2), is used. The center-of-mass energy is 12.71 MeV. Error bars on the inelastic data show statistical errors only.

Fig. 4. As fig. 3, but $E_L(^{16}\text{O}) = 28$ MeV, corresponding to $E_{\text{c.m.}} = 14.82$ MeV. Error bars not shown.

Fig. 5. As fig. 3, but $E_L(^{16}\text{O}) = 32$ MeV, corresponding to $E_{\text{c.m.}} = 19.06$ MeV. Error bars not shown.

Fig. 6. For the 28 MeV case, the coherent sum of ordinary scattering (S), calculated in the CCBA, plus one-step particle transfer (T), are compared with the full-coupling situation including indirect transfer modes (I). Inclusion of process (I) results in relatively small

modifications.

Fig. 7. As fig. 6, but for the 32 MeV case. Indirect transfer processes (I) lead to a stronger reduction of the backward angle cross section at the higher energy. The same normalization constant for the transfer amplitudes as in the 24, 28 MeV cases accounts for the observed cross sections, if the indirect transfer is included.

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Fig. 1

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Fig. 2

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Fig. 3

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Fig. 4

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Fig. 5

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Fig. 6

XBL 7510-8444

Fig. 7

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