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INDIRECT TRANSITIONS IN TWO-NUCLEON TRANSFER
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ABSTRACT

Two-nucleon transfer reactions between heavy ions are investigated in the coupled channel framework. Indirect transitions through the collective $^{18}\text{O}(2^+)$ state in $(^{16}\text{O}, ^{18}\text{O})$ reactions or their inverse can considerably modify the direct ground state transfer cross sections. Characteristic features of the direct process, the indirect process, and their interference are discussed. Special emphasis is put on the consistency of the parameters with the experimental elastic and inelastic scattering data for the channels involved in the reaction calculations. For the targets nickel and tin, a comparison with the data of various experimental groups is presented.

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1. Introduction

For transfer reactions induced by light nuclides, it has been established that indirect processes involving the inelastic excitation of target or residual nucleus can be an important reaction mode¹). In heavy ion reactions, the large probability of exciting collective states suggests that indirect mechanisms can play an even more important role in the transfer of nucleons between the heavy ions. However, for a long time no strong disagreement between experiments and DWBA calculations of the direct transfer contributions was found. Then, the first theoretical efforts to include higher order transfer processes in a coupled channel formalism were reported^{2,3}). A prediction^{2,4}) based on CCBA calculations in the source term method⁵) was made that indirect modes in the production of the collective $^{122}\text{Sn}(2^+)$ state in the reaction $^{120}\text{Sn}(^{18}\text{O}, ^{16}\text{O})$ can flatten out its cross section through a destructive interference with the direct process, whereas for the corresponding pickup reaction, a constructive interference between direct and indirect modes preserves the usual bell-shape of the $^{120}\text{Sn}(2^+)$ cross section⁶). This has subsequently been confirmed in an experiment at the Berkeley cyclotron⁷). Other experiments and their theoretical analyses gave further indications of the importance of indirect transfer modes in heavy ion reactions. Examples are the $^{144}\text{Nd}(^{12}\text{C}, ^{14}\text{C})$ reaction⁹), where the indirect production of the $^{142}\text{Nd}(2_1^+)$ state leads to a flat, rather than a bell-shaped cross section, or the reaction $^{19}\text{F}(^{16}\text{O}, ^{15}\text{N})^{20}\text{Ne}$, where the strong excitation of the 4^+ level in ^{20}Ne found experimentally¹⁰) provides evidence for a two-step process, because the direct population of this state is improbable for structural reasons.

Recent calculations suggested that the indirect feeding of the ground state through a low-lying collective state of the projectile can strongly modify the cross section. It was indicated that the $^{18}\text{O}(2^+)$ state is an important intermediate state in the $^{122}\text{Sn}(^{16}\text{O}, ^{18}\text{O})$ reaction¹¹⁾, as well as in the $^{62}\text{Ni}(^{16}\text{O}, ^{18}\text{O})$ reaction¹²⁾.

In this work, we present a systematic investigation of the $(^{16}\text{O}, ^{18}\text{O})$ reaction on the targets ^{122}Sn , and $^{60,62,64}\text{Ni}$. We focus on the coupling of the collective $^{18}\text{O}(2^+)$ state. Special emphasis is put on the consistency of the potential parameters, and inelastic form factors entering the reaction calculations, with the experimental data for elastic and inelastic scattering.

The CCBA calculations are outlined in section 2. In section 3, we investigate general features of direct and indirect transfer processes, and their interference, namely the enhancement of forward-angle cross sections, the energy dependence and Q-dependence of direct vs indirect processes, and the possible appearance of secondary peaks. A detailed discussion of the $A+^{18}\text{O}$ reactions, including analyses of elastic and inelastic scattering in the relevant channels, is presented in section 4, followed by a similar discussion for the $^{122}\text{Sn}(^{16}\text{O}, ^{18}\text{O})$ reaction at two different energies at and above the Coulomb barrier, in section 5.

2. Outline of the CCBA-Calculations

In our theoretical treatment of heavy ion transfer reactions

$$A(a,b) B \quad (1)$$

where

$$B = A + x, \quad a = b + x$$

we allow in principle for the inelastic excitation of any of the four nuclei. In the calculations reported here, the transferred particles x are two neutrons, and in most cases only the collective 2^+ state of nucleus $a = {}^{18}\text{O}$ is coupled. The source term method, which is described in detail in refs.^{5,14)} is used to obtain coupled differential equations corresponding to initial, and final partition. Inelastic scattering in the initial partition is described by a set of equations for the radial wavefunctions $u_a^{\pi I}(r_a)$ for each channel a , parity π , and total angular momentum I

$$(T_a - E_a) u_a^{\pi I}(r_a) = - \sum_{a'} V_{aa'}^{\pi I}(r_a) u_{a'}^{\pi I}(r_a) \quad (2)$$

where T_a is the kinetic energy operator, E_a the energy in channel a , and V is the interaction between the two nuclei. Before we discuss the parametrization of the matrix elements of V , we give the equations for the wavefunctions of relative motion $w_b^{\pi I}(r_b)$ for each channel b in the final partition⁵⁾

$$(T_b - E_b) w_b^{\pi I}(r_b) + \sum_{b'} V_{bb'}^{\pi I}(r_b) w_{b'}^{\pi I}(r_b) = \sum_a \rho_{ab}^{\pi I}(r_b) \quad (3)$$

Transfer processes from initial channels a to final channels b are described, to first order in the interaction, by the source term appearing on the right. The structure of the source term was discussed in earlier publications^{5,14)}. In the no-recoil approximation

$$\tilde{r}_a \approx \tilde{R} \quad , \quad \tilde{r}_b \approx \alpha \tilde{R} \quad ,$$

with R connecting the centers of the cores, it becomes particularly simple

$$\rho_{ab}(\alpha R) = \alpha \langle \phi_b(\hat{R}, \tilde{r}') | V | \phi_a(\hat{R}, \tilde{r}) \rangle u_a(R) \quad (4)$$

$$\tilde{r}' = \tilde{r} + \tilde{R}$$

with channel wavefunctions ϕ as defined in ref. ⁵), and the solutions u_a of eq. (2). In the usual no-recoil limit, the scaling factor is $\alpha = A/B$, implying that the transferred particle has negligible mass.

If instead one assumes that the particles are transferred between the mass centers of particles a and B at the edge of these nuclei, then

$$\alpha = r_b/r_a \approx 1.03$$

for the ($^{18}_0, ^{16}_0$) reaction on nickel, or tin. However, the calculations are not very sensitive to a variation of α between the values A/B , and 1.03, if strongly absorbing optical potentials are used. We employ $\alpha = 1.03$. The nuclear matrix elements appearing in the source term, Eq. (4), have radial transfer form factors that are evaluated from the microscopic wavefunctions, and weighted by the product of parentage amplitudes for the nuclei involved, because we use mixed configurations for the nuclear states. The numerical values for the parentage coefficients which are taken from other calculations will be given in section 4 and 5. As for the finite-range interaction, V , that enters the source term, eq. (4), we use the Woods-Saxon potential that binds each of the two neutrons in the heavy nucleus at the average experimental separation energy.

The matrix elements of the interaction V in eqs. (2) and (3) are treated in a phenomenological way, to obtain precise fits of the scattering data in the relevant channels, which is a necessary condition for conclusions about the reaction mechanism. The reduction of the coupled eqs. (2) and (3) to a finite set corresponds to the replacement of the fundamental interaction by complex valued effective interaction¹⁶⁾. The diagonal matrix elements are parametrized by an optical Woods-Saxon potential. Usually the coupling between elastic and inelastic channels for spherical nuclei is sufficiently weak that the potential for pure elastic scattering can be used for the coupled system. However, the excitation of the collective quadrupole state of ^{18}O in a collision with a heavy nucleus is so strong that the elastic potential has to be modified when the coupling is explicitly treated. To search for its parameters in coupled channel calculations, the optical model analysis of ^{16}O scattering (the neighboring spherical nucleus) provides the starting parameters. The potential parameters for inelastic ^{18}O scattering on nickel and tin derived in this way will be given in sections 4 and 5. To treat the vibrational, or rotational, quadrupole excitation of the nucleus "a" (similarly for the other nuclei), the optical potential is expanded about its spherical shape

$$U[r - R(\theta)] = U(r - R) + \sum_{n=1}^{\infty} \frac{(-R_a)^n}{n!} (\beta_2 Y_2(\theta)) \frac{\partial^n U}{\partial r^n} \quad (5)$$

with R_a being the radius of the nucleus a, R the optical model radius, and

$$R(\theta) = R_A + R_a [1 + \beta_2 Y_{20}(\theta)] \quad (6)$$

in the body-fixed coordinate frame of nucleus a. The sum of the radii, $R_A + R_a$ has to be identified with the optical model radius. The deformation parameter β_2 is associated with R_a only, and must be consistent with results derived from other data, such as inelastic proton scattering. The nonspherical parts of the interaction (eq. (5)) give rise to inelastic excitations, and are used to parametrize the nondiagonal parts of the effective interaction. The lowest order term has the radial form

$$F(r) = -\beta_2 R_a \frac{\partial U}{\partial r} \quad (7)$$

If the spherical potential U is of Woods-Saxon type with V , W being the depths of real, imaginary part, respectively, and the geometry of both parts being the same with diffuseness a , and radius R , this can be written as

$$F(r) = e^{i\phi(-\beta_2 R_a)} \sqrt{V^2 + W^2} \frac{df}{dr} \quad (8)$$

$$f(r) = \left[1 + \exp\left(\frac{r - R}{a}\right) \right]^{-1}$$

with the phase ϕ as prescribed by the spherical potential

$$\phi = \text{arctg}(W/V) \quad (9)$$

This parametrization, together with a real Coulomb potential and form factor¹⁶⁾, usually allows for a successful calculation of angular distributions in inelastic heavy ion scattering, although there is no justification for this form from the microscopic theory. Recently, however, it was found that for some cases of light particle excitation,

the absolute magnitude of the inelastic cross section, as well as the position of the Coulomb-nuclear interference minimum, are not reproduced. An example is the 2^+ excitation of ^{18}O in the scattering from nickel, and tin^{17,18}). The disagreement with the data can be removed by choosing a larger phase ϕ of the nuclear form factor^{12,18}). Although the consideration of simultaneous target and projectile excitation may explain part of the necessity for an additional phase, this seems insufficient to account for the whole effect (see section 4.1). It has been suggested that instead of modifying ϕ , one can introduce an imaginary part in the Coulomb form factor.¹²) This would account for the fact that the imaginary part of the effective interaction, which arises from the truncation of space to a few channels, should not exclusively be attributed to the nuclear interaction (this is also true for the spherical Coulomb potential). However, the required modification of ϕ seems too large to be a pure Coulomb effect, which should also be present in cases of inelastic target excitation. The deviation of ϕ from the value prescribed by eq. (9) seems to indicate that the collective model is not sufficiently accurate for light nuclei like ^{18}O . We mention that inelastic proton or alpha scattering is not very sensitive to ϕ . The reason for the insensitivity is that for protons and alphas, at energies above the barrier, inelastic excitation goes mainly through the nuclear force. In this limit, and to lowest order in the inelastic excitation, the cross section is independent of the phase ϕ . Therefore, the discrepancy between data and macroscopic collective form factors did not become apparent until heavy ion reactions were performed. In this work we use the phase ϕ of the nuclear form factor as a convenient

paramtrization of the inelastic amplitudes which enter the reaction calculations.

An important question is, which states are to be included in the coupled calculations of the two-neutron transfer reactions. In general, one should include the low-lying collective states, for example, the 2^+ states of oxygen and nickel in a ${}^A\text{Ni}({}^{18}_0, {}^{16}_0)$ reaction. Here we want to focus on the modification of the ground state transfer cross sections because of indirect transfer through excited states. Therefore, we couple only such collective states as are populated in the transfer reaction more strongly than the ground state, since only such states are expected to be important intermediate states. For the $({}^{16}_0, {}^{18}_0)$ reactions on ${}^{60}\text{Ni}$ and ${}^{122}\text{Sn}$, this holds for the collective ${}^{18}_0(2^+)$ state at 1.98 MeV. Figure 1 shows as an example the spectrum for the ${}^{60}\text{Ni}({}^{16}_0, {}^{18}_0)$ reaction at about 73 MeV¹⁹⁾. Depending on the scattering angle, the ${}^{18}_0(2^+)$ state is populated up to four times stronger than the ground state in this reaction.

As an aid in the interpretation of the calculated differential cross sections, we consider the quantal analog of the classical deflection function²⁰⁾

$$\Theta(\ell) = \frac{d}{d\ell} (2\delta_{\ell', \ell} + \sigma_{\ell} + \sigma_{\ell'}) \quad (10)$$

with $\sigma_{\ell}, \sigma_{\ell'}$ being the Coulomb phase shifts for incident and exit channels, ℓ the angular momentum of relative motion, and $\delta_{\ell', \ell}$ the phase of the reaction S-matrix,

$$S_{\ell', \ell} = |S_{\ell', \ell}| \exp(2i\delta_{\ell', \ell}) \quad (11)$$

The quantal deflection function (eq. (10)) gives the angle Θ where the largest contribution to the reaction amplitude occurs as a function of ℓ . A plot of $|S_{\ell, \ell}|$ reveals the contributions of different regions of ℓ -space. Different regions in ℓ can be related to their corresponding angular regions in the differential cross section through the quantal deflection function, eq. (10).

3. Characteristics of Indirect vs Direct Transfer Processes, and Their Interference

3.1. Enhanced Forward-Angle Cross Sections

We discuss here characteristic features of direct and indirect transfer processes without going into the detailed parametrization of the calculations, which we defer to section 4. The forward-peaked angular distributions observed in the ground state transfer reaction¹³⁾

$$^{60}\text{Ni}(^{18}\text{O}, ^{16}\text{O})^{62}\text{Ni} \quad , \quad E_L = 65 \text{ MeV} \quad (12)$$

are in sharp disagreement with DWBA calculations that produce a grazing peak in the differential cross section, if a strongly absorbing potential consistent with elastic data is used.

To account for the absence of the expected grazing peak, a weakly absorbing optical potential was proposed¹³⁾, which permitted the survival of penetrating orbits to enhance the forward angle cross section. In disagreement with the data, which show weak oscillations in the grazing region it leads to strong oscillations in the whole angular range, and was latter replaced by a surface transparent potential with a sharp absorptive part, thus removing contributions to the cross section from the nuclear interior²¹⁾. The surface transparent potential given by LeVine et al.²¹⁾ remains unsatisfactory as a phenomenological explanation of the observed effect, because it allows a DWBA fit of the reaction data only for an unrealistically large value of the scaling parameter in the no-recoil approximation. In full recoil calculations the quoted potential does not produce the observed forward cross section^{12,30)}. In addition, surface transparent potentials of this type generally seem to be inconsistent with elastic scattering data²²⁾.

Recently, it was shown that indirect transfer via the $^{18}\text{O}(2^+)$ state which was seen to be strongly populated in the time-reversed reaction on the neighboring nucleus, $^{60}\text{Ni}(^{16}\text{O}, ^{18}\text{O})$, can explain the anomaly seen in the data¹²). Conventional strongly absorbing Woods-Saxon potentials were used in the analysis. Here we discuss in more detail the results, which are shown in fig. 2. The bell-shaped cross section for the direct process is contrasted with the forward-peaked, oscillatory result of the coupled calculation (labelled "direct+indirect"). To be able to show the $^{18}\text{O}(2^+)$ cross section, we have performed the calculation for the reaction time-reversed to the experiment, eq. (12). The only free parameter which is not determined by the elastic and inelastic scattering data (see section 4), or the microscopic wave-functions, is an overall multiplicative factor of the quadrupole transfer form factor. This factor, which is subsequently denoted as "f", is justified because the microscopic calculation does not necessarily yield the correct ratio of transfer form factors to ground, and 2^+ state. For example to account for electromagnetic transitions, effective charges have to be introduced. This factor is chosen to be $f = 2.8$ for the calculations shown in fig. 2, to reproduce the observed forward-angle yield. The $^{18}\text{O}(2^+)$ cross section has not been measured, but see section 4.2 for a discussion of the $^{18}\text{O}(2^+)$ cross section in the experiment on a neighboring nucleus.

Figure 2b shows that at forward angles, the differential cross section is dominated by the indirect transfer via $^{18}\text{O}(2^+)$, whereas in the region of the grazing peak, direct and indirect processes have comparable amplitudes, and their destructive interference leads to a

rapid decrease in the cross section beyond the grazing angle, empirically defined by the maximum in the direct cross section. We note that a variation of the scaling parameter α within the range mentioned in section 2 has little effect on the cross section, if the potential is strongly absorbing.

In fig. 3, the S-matrix, its amplitude and the quantal deflection function for the calculations of fig. 2 are shown. The plot of $S_{\ell,\ell}$ in the complex plane reveals that its two-lobed structure is due to the vector addition of a direct part (dashed line) and an indirect part (transfer via $^{18}\text{O}(2^+)$, dotted line) which lie roughly in opposite quadrants. This relative phase is prescribed by microscopic structure of the states. The indirect process is more confined to the low- ℓ region, in agreement with the intuitive picture that indirect processes require a more intimate collision than a one-step process. From the plot of the amplitude of S it can be seen that

(1) the indirect amplitude is attenuated above the peak much faster than the direct. This corresponds to the fact that two form-factors are involved in its calculation, and their falloff at large separation distances causes a rapid damping of the amplitude;

(2) the peak of the indirect amplitude is shifted to a slightly smaller value of ℓ for the same reason; and

(3) the total amplitude is also shifted to a smaller value of ℓ due to the destructive interference between direct and indirect modes (the sign of the interference is determined by the nuclear structure).

For both direct and indirect processes, the peak in the amplitude falls in the region in ℓ -space where the quantal deflection functions exhibit minima due to the nuclear attraction. (This minimum lies very close to the classical orbiting angular momentum. Sometimes referred to as the critical angular momentum.) The localization of the indirect amplitude around the minimum leads to a forward angular distribution of the indirect process which is also very broad because of the dispersion caused by the nuclear interaction for angular momenta around the critical value. For the direct process, the minimum in $\Theta(\ell)$ is less pronounced, and the relatively long, high- ℓ tail in the direct amplitude extends into the flat peak region of $\Theta(\ell)$. Consequently most orbits for the direct process contribute to the grazing angle cross section. For the complete calculation (direct+indirect), the deflection function again exhibits a deep minimum corresponding to the enhancement of the cross section at forward angles.

We note that such "anomalous" angular distributions have also recently been observed²³⁾ in the ($^{16}_0, ^{18}_0$) and ($^{16}_0, ^{14}_0$) reactions on $^{48,42}\text{Ca}$, where they have been accounted for by arbitrary changes of the potential parameters. However, the strong population of several lowlying collective states in these reactions suggests that the forward-peaked angular distributions may be due to higher order processes.

3.2. Energy Dependence

From the discussion in the previous section, it is obvious that the angular distribution of the indirect process should have a strong energy dependence, because the deflection function in the region of the

minimum is sensitive to a variation in energy. At energies below or just above the Coulomb barrier, the minimum in the deflection function vanishes. Rather it is a monotonic decreasing function of ℓ , and consequently, the indirect process is no longer forward-biased. We demonstrate this effect for the $^{62}\text{Ni}(^{16}_0, ^{18}_0)$ reaction at an energy slightly above the barrier.

Figure 4 shows the amplitude of S and the quantal deflection function at the energy of 45 MeV. The parameters for this calculation are the same as in the previous case (see section 4.2 for details). The small preference of the indirect process is clearly exhibited in the plot of the reaction amplitude, but at this low energy, it leads to large-angle scattering, because the deflection function is monotonically decreasing. This can be seen in the calculation of the differential cross section for this case, fig. 5. The indirect process peaks at backward angles, where it interferes destructively with the direct process. The interference causes a minimum in the angular distribution, beyond the grazing angle.

It is interesting to observe that there is an intermediate energy range where both direct and indirect processes have bell-shaped angular distributions. The result of a calculation for the $^{62}\text{Ni}(^{16}_0, ^{18}_0)$ reaction at 60 MeV is shown in fig. 6. Since the complete calculation also exhibits a bell-shaped angular distribution, an experiment performed at this energy would provide a sensitive test of our model.

The energy dependence of the angular distribution for ground state transfer, with the $^{18}\text{O}(2^+)$ state coupled, is shown in fig. 7. The forward peak of the high energy as well as the backward-angle behavior at the low energy are due to the indirect transfer via $^{18}\text{O}(2^+)$. Similar features occur in the $^{16}\text{O}, ^{18}\text{O}$ reaction on tin (section 5), where data at 62 MeV and 104 MeV are available.

3.3. Q-Dependence

It has been pointed out that the indirect amplitudes are not suppressed as strongly as the direct in unfavorable Q situations, and a simple classical argument for this behavior has been given⁴). Changes in the angular distributions in transfer reactions on a series of isotopes may therefore be accounted for by the change in Q. We investigate this for the $(^{18}\text{O}, ^{16}\text{O})$ reactions on $^{58,60,62}\text{Ni}$ at 65 MeV, with the coupling of the $^{18}\text{O}(2^+)$ state. The Q-value changes from 4.3 MeV (heavy isotope) to 8.2 MeV. The transfer form factors do not differ very much in the tail region over this range of isotopes, because their slope is determined mainly by the wavefunctions of the two neutrons in oxygen, where they are less strongly bound ($E_B = -12.2$ MeV, compared to -16.5 MeV in ^{64}Ni , and -20.4 MeV in ^{60}Ni). The enhancement factor for the quadrupole transfer form factor over the values calculated microscopically is taken to be the same for all three isotopes. Thus the differences in the angular distributions for direct and indirect process mainly reflect a Q-value dependence. This was checked by using identical transfer form factors, potentials and inelastic form factors for the three cases.

The results for separate calculations of direct and indirect processes are shown in fig. 8. The indirect mode is less strongly suppressed over the whole angular range than the direct, but the difference is not pronounced enough to produce a significant change in cross section for the full calculation (direct+indirect) over the range of isotopes considered. If such a change is observed, it must be due to an additional structure effect. For example, the relative strength of the monopole and quadrupole transfer form factor may change from one isotope to another, probably in a smooth way. The full calculations will be compared with the experimental data in section 5.

3.4. Secondary Peaks

If the amplitudes for direct and indirect processes become comparable in magnitude, and interfere destructively, it is possible that the interference minimum is followed by a secondary peak. An example for the possible occurrence of a secondary peak are the $^{62}\text{Ni}(^{18}\text{O}, ^{16}\text{O})$ reactions at 65 MeV, in particular, on ^{62}Ni . We calculate the differential cross section for the time-reversed reaction to be able to show the $^{18}\text{O}(2^+)$ cross section, fig. 9. Three different strengths of the quadrupole transfer form factor produce different interference characteristics of direct and indirect modes. With a form factor as calculated from the microscopic wavefunctions, the ground state cross section is bell-shaped. It becomes more forward-peaked, with a pronounced interference minimum and a second peak, for an enhanced Q2-form factor. The value of $f = 2.8$ that produces the secondary peak is the same as required in the $^{62}\text{Ni}(^{16}\text{O}, ^{18}\text{O})$ case to produce the observed forward-peaking. It would be very interesting to

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perform the $^{64}\text{Ni}(^{16}\text{O}, ^{18}\text{O})$ experiment and (1) to measure the $^{18}\text{O}(2^+)$ cross section, (2) to measure the forward angle region more carefully, and (3) to decide whether an interference minimum, and a secondary peak do occur.

4. The $A+2$ Ni($^{16}\text{O}, ^{18}\text{O}$) Reactions

4.1. Inelastic Channels

In sections 4 and 5, we present comparisons of our calculations with the available experimental data of elastic and inelastic scattering in the energy range under consideration, and the ($^{18}\text{O}, ^{16}\text{O}$) or ($^{16}\text{O}, ^{18}\text{O}$) reactions on nickel and tin. The Brookhaven data²⁴⁾ for the elastic scattering of ^{16}O from $A+2$ Ni at about 60 MeV are used to obtain parameters for a Woods-Saxon potential in an optical model search. The results, together with the energy of the elastic scattering experiment, are given in table 1. For the $^{18}\text{O} + A$ Ni channels, the $^{18}\text{O}(2^+)$ state is included in the coupled calculations. The collective model form factor in a vibrational coupling scheme, with the phase ϕ as a free parameter, is used together with the Coulomb quadrupole deformation $\beta_2^C = 0.3$ as derived from the $B(E2)$ values of ref.²⁵⁾, and the same values $\beta_2^N = 0.3$ for the nuclear deformation. These deformations are to be associated with a radius of $R_a = 1.2(18)^{1/3}$. Four parameters of a Woods-Saxon potential, and the phase of the nuclear form factor are adjusted to optimize the coupled channel fit of the 63 MeV data taken at Munich¹⁸⁾, fig. 10. The dotted curve for $^{18}\text{O} + ^{58}\text{Ni}$ shows that calculations with a phase as prescribed by the potential parameters fail to reproduce the data. This is also true for surface transparent potentials of the type given in ref.²⁶⁾ that have a large imaginary part. It is interesting that different phases ϕ are required for the three nickel isotopes. This apparently reflects the different collectivity of $^{58,60,62}\text{Ni}$, and suggests that the explicit inclusion of the simultaneous excitation of oxygen and

nickel would partially remove the necessity to modify ϕ from the collective model value. It has been reported, however, that simultaneous target and projectile excitation does not explain the principal discrepancy between data and collective model¹⁷). The parameters for the $^{18}\text{O} + {}^A\text{Ni}$ channels are given in table 1, and enter the reaction calculations, together with those for the $^{16}\text{O} + {}^{A+2}\text{Ni}$ channels, without any modification.

4.2. Two-Neutron Transfer Reaction

For the CCBA-calculation of the two-nucleon transfer cross sections ${}^{A+2}\text{Ni}(^{16}\text{O}, ^{18}\text{O})$, microscopic transfer form factors are evaluated as described in ref. ⁴). We use the Woods-Saxon interaction in the heavy nucleus, rather than in oxygen as usual. This affects the absolute normalization of the differential cross section, but the difference is slight. The parentage amplitudes, table 2, are calculated using the wavefunctions of ref. ²⁸).

Figure 11 shows as an example the transfer form factors for ${}^{62}\text{Ni}(^{16}\text{O}, ^{18}\text{O}_{\text{g.s.}, 2^+, 4^+})$. The CCBA calculations are then performed as described in section 2, and the S-matrices are used to evaluate the differential cross sections. Coupled calculations for three nickel isotopes are compared with the data (for ${}^{62,64}\text{Ni}$, on the time-reversed reactions), and the bell-shaped direct transition. The calculations for ${}^{62,64}\text{Ni}$ are the same as the ones in sections 3.1 and 3.4. All microscopic quadrupole transfer form factors have been multiplied by a common factor ($f = 2.8$). This yields consistency with the forward-peaked ${}^{62}\text{Ni}$ ground state transfer data, although there are still problems in the agreement with the phase of the oscillations

in the angular distribution. For the ^{64}Ni case, the pronounced secondary peak is shown, and the data suggest its possible occurrence. Different quadrupole transfer form factors, however, can lead to completely different ground state transfer cross sections as discussed in section 3.4, so that the $^{18}\text{O}(2^+)$ data are needed to make a more precise prediction about the ground state angular distribution. For ^{60}Ni , the $^{18}\text{O}(2^+)$ cross section has been measured, and our calculation fails to explain its angular dependence. The ratio of 2^+ /g.s. cross sections at an intermediate angle $\theta_{\text{c.m.}} \approx 30^\circ$ of about 3.8 is reproduced, which gives confidence that the modification of the ground state transfer cross section through the indirect mode is predicted correctly. The most natural explanation for the failure to reproduce the forward-peaked shape of the $^{18}\text{O}(2^+)$ cross section is that we neglect the coupling to higher states, which may modify the 2^+ cross section in the same way as the ground state is modified by transitions through the 2^+ . A possible candidate is the $^{18}\text{O}(4_1^+)$ state, which is the main contribution to the peak at 3.5 MeV in the energy spectrum, fig. 1. A coupled calculation with the inclusion of the 4^+ state, however, is insufficient to remove the discrepancy. Of course, there may be other reasons for the disagreement, including the coupling to additional states.

5. The $^{122}\text{Sn}(^{16}_0, ^{18}_0)$ Reaction

5.1. Inelastic Channels

Experimental data for the $^{18}_0(2^+)$ inelastic scattering from tin are only available for ^{120}Sn at 72 MeV¹⁸⁾. Our coupled channel analysis is performed as in the nickel cases. The required modification of the phase ϕ of the inelastic nuclear form factor is not as large as in the nickel case, see fig. 13. We give the potential and deformation parameters for this calculation in table 3, together with those derived from an optical mode search on the elastic $^{16}_0 + ^{122}\text{Sn}$ data¹⁸⁾ at the corresponding energy of 73.95 MeV. These potentials and deformations are used in the $^{122}\text{Sn}(^{16}_0, ^{18}_0)$ reaction calculation at 62 MeV and 104 MeV (see following section). For these reaction calculations, we will allow for a variation of the phase ϕ with energy.

5.2. Two-Neutron Transfer Reaction

We perform a CCBA-calculation for the $^{122}\text{Sn}(^{16}_0, ^{18}_0)$ reaction at an energy just above the barrier, 62 MeV, with the $^{18}_0(2^+)$ state coupled. At this energy, the ground state data for the time-reversed reaction are available²⁹⁾. An overall enhancement of $f = 1.3$ of the quadrupole transfer form factor over the result of the microscopic calculation with the wavefunctions reported in refs. ^{27,28)} yields the best agreement with the data, fig. 14. Larger enhancement factors would destroy the fit to the ground state data. We use a phase $\phi = 33^\circ$. As in the $(^{16}_0, ^{18}_0)$ reaction on nickel at low energy, the cross section is modified at backward angles due to the coupling of $^{18}_0(2^+)$.

At the energy of 104 MeV, where a forward-biased indirect transition can be expected according to the discussion in sections 3.1 and 3.2, we can compare with both ground state, and $^{18}\text{O}(2^+)$ state data. The bell-shaped differential cross sections are compared with our calculation in fig. 15 for two values of the phase of the inelastic nuclear form factor. The dotted curves are calculated using $\phi = 45^\circ$ as determined from the 72 MeV scattering data.

Figure 16 shows a comparison of DWBA and CCBA calculations, and the separately calculated direct, and indirect cross sections. Although the coupling of the $^{18}\text{O}(2^+)$ state causes a considerable enhancement of the forward-angle yield relative to the grazing cross section, at this energy it is not sufficiently strong to produce a forward-peaked cross section. The indirect transition at this energy has a flat, forward-biased cross section, as in the reaction on nickel at 65 MeV. At an intermediate energy of 74 MeV, both direct and indirect transitions have bell-shaped angular distributions, but no data are available.

6. Summary

Our investigation of ($^{16}_0, ^{18}_0$) reactions on $^{60,62,64}_{28}\text{Ni}$, and $^{122}_{50}\text{Sn}$ for energies at and above the Coulomb barrier shows that indirect transitions can produce important contributions to two-particle ground state transfer cross sections. The important intermediate state included in the coupled channel calculations is the collective $^{18}_0(2^+)$ state at 1.98 MeV, but other excited states may have to be considered in future calculations to achieve a self consistent model of these reactions.

We have discussed several general features of direct and indirect processes. Their energy dependence can be understood through their localization in ℓ -space, with the aid of the quantal deflection function. For sufficiently high energy, the indirect process has a flat, and forward-biased angular distribution. The destructive interference with the direct mode, which has a bell-shaped angular distribution, provides a physical explanation for the forward-peaked cross sections seen in the ($^{18}_0, ^{16}_0$) reactions on the light nickel isotopes. We have also discussed the different Q -dependence of direct and indirect modes, and the possible occurrence of secondary peaks by means of their destructive interference. A comparison with experimental data from various groups has been presented, and the consistency of all parameters entering the reaction calculations with the available elastic and inelastic scattering data has been emphasized. The problem of reproducing the inelastic scattering data for projectile excitation have been discussed, and solved in a phenomenological way. The physical basis for this effect still remains to be clarified.

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Table 1. Woods-Saxon potential parameters used in CCBA-calculations of $A+2\text{Ni}(160,180)$, nuclear and Coulomb deformations (to be associated with $R = 1.2(18)^{1/3}$), phase of the nuclear inelastic form factors, and energies for the fits to elastic, inelastic scattering data.

Channel	$-V$ (MeV)	$-W$ (MeV)	r (fm)	a (fm)	$\beta_2^N(^{18}\text{O})$	$\beta_2^C(^{18}\text{O})$	ϕ (deg)	E_{Lab} (MeV)
$^{16}\text{O} + ^{60}\text{Ni}$	70	25	1.208	0.54				61.41
$^{16}\text{O} + ^{62}\text{Ni}$	70	25	1.201	0.54				60.99
$^{16}\text{O} + ^{64}\text{Ni}$	70	25	1.225	0.54				60.60
$^{18}\text{O} + ^{58}\text{Ni}$	70	45	1.200	0.56	0.3	0.3	90	63
$^{18}\text{O} + ^{60}\text{Ni}$	70	45	1.205	0.56	0.3	0.3	70	63
$^{18}\text{O} + ^{62}\text{Ni}$	70	45	1.220	0.56	0.3	0.3	80	63

Table 2. Parentage coefficients entering the calculation of the transfer form factors in the $A+2\text{Ni}(^{16}\text{O}, ^{18}\text{O})$ reactions.

	$(^{60}\text{Ni}, ^{58}\text{Ni})$	$(^{62}\text{Ni}, ^{60}\text{Ni})$	$(^{64}\text{Ni}, ^{62}\text{Ni})$	$(^{16}\text{O}, ^{18}\text{O} \text{ g.s.})$	$(^{16}\text{O}, ^{18}\text{O}_{2+})$	$(^{16}\text{O}, ^{18}\text{O}_{4+})$	
$(1g_{9/2})^2$	0.2742	0.4088	0.5635	0.8907	-0.6794	0.9463	$(1d_{5/2})^2$
$(2p_{1/2})^2$	-0.4146	-0.5171	-0.5715	0.2230	-0.1034		$(1d_{3/2})^2$
$(1f_{5/2})^2$	-0.6233	-0.8905	-1.0054	0.3964			$(2s_{1/2})^2$
$(2p_{3/2})^2$	-0.8872	-0.7232	-0.5963		-0.6736		$(1d_{5/2}2s_{1/2})$
					-0.1596	0.3233	$(1d_{5/2}1d_{3/2})$
					0.2205		$(1d_{3/2}2s_{1/2})$

Table 3. Potential parameters for the $^{122}\text{Sn}(^{16}_0, ^{18}_0)$ reactions, deformations, phase of nuclear form factor, and energy of fit to elastic, inelastic scattering data.

Channel	-V (MeV)	-W (MeV)	r (fm)	a (fm)	$\beta_2^N(^{18}_0)$	$\beta_2^C(^{18}_0)$	ϕ (deg)	E_{Lab} (MeV)
$^{16}_0 + ^{122}\text{Sn}$	90	51.3	1.18	0.583				73.95
$^{18}_0 + ^{120}\text{Sn}$	90	55.0	1.20	0.570	0.3	0.33	45	72.0

Figure Captions

- Fig. 1. Energy spectrum for the reaction indicated (Ref. ¹⁹). The population of the low-lying collective 2^+ state of the ejectile ^{18}O exceeds the population of the ground state.
- Fig. 2. (a) Solid lines are differential cross sections from a coupled calculation where both 0^+ and 2^+ state of oxygen are fed via direct transfer, and indirect transfer through the other state. dotted curves represent direct transfer, with the inelastic coupling included. A common normalizing factor 1.6 is used. The ground state data are for the time reversed reaction at the energy of $E_L = 65 \text{ MeV}$ (ref. ²¹)).
- (b) The bell-shaped direct transition (dotted curve) leading to the ground state of oxygen and nickel is compared with the forward-peaked indirect transition through the collective $^{18}\text{O}(2^+)$ state (solid curve). The forward-angle cross section is dominated by the second order process. The parameters for the calculations shown in figs. 2a and 2b are given in section 4.
- Fig. 3. S-matrix, amplitude of S and quantal deflection function for the ground state transfer calculations of 70.7 MeV shown in fig. 2. The complete S is to high accuracy the vector sum of direct and indirect terms (note the different normalization factors). The indirect process occurs at smaller values of ℓ than the direct. The deflection function exhibits a minimum.

Fig. 4. Amplitude of S and quantal deflection function at the lower energy of 45 MeV where $\Theta(\ell)$ is monotonic. The small- ℓ preference of the indirect process leads to large-angle scattering.

Fig. 5. CCBA-calculations as in fig. 2, but at the lower energy of 45 MeV. The indirect process increases at backward angles and interferes destructively with the direct mode.

Fig. 6. At the intermediate energy of 60 MeV, the angular distributions for both direct and indirect processes exhibit a bell-shape. The calculation is as for figs. 2 and 5.

Fig. 7. Energy dependence of the $^{62}\text{Ni}(^{16}\text{O}, ^{18}\text{O})$ angular distribution, with the inclusion of indirect transfer via $^{18}\text{O}(2^+)$.

Fig. 8. (a) The dependence of the direct reaction $^A\text{Ni}(^{18}\text{O}, ^{16}\text{O})$ on the mass number A . Strongly absorbing potentials are used, the parameters are given in section 4. The variation in shape and absolute magnitude of the differential cross section is almost purely due to the change in Q -value.

(b) As fig. 8(a), but for the indirect transfer via the collective 2^+ state of the projectile ^{18}O . Again the dependence on A reflects mainly the dependence on Q , if the transfer form factors described in the text (sections 3.3 and 4.2) are used. Note that the indirect process is less suppressed by a large Q -mismatch than the direct one.

- Fig. 9. The coupled channel calculations show the possibility for a secondary peak to occur due to the interference of direct and indirect processes. Example is the $^{64}\text{Ni}(^{16}\text{O}, ^{18}\text{O})$ reaction. Three different strengths for the quadrupole transfer form factor are shown. Data are from the time-reversed reaction¹³⁾.
- Fig. 10. Coupled channel calculations for the inelastic scattering of ^{18}O from three nickel isotopes leading to the ground state of both nuclei, and the 2^+ state of oxygen, are compared with the data of ref. ¹⁸⁾. The phase ϕ of the nuclear form factor is indicated. The dotted curve shows the result obtained in the usual collective model. Parameters are given in table 1.
- Fig. 11. Transfer form factors for transfer from the ground states of ^{16}O and ^{62}Ni to ground, 2_1^+ , and 4_1^+ state of ^{18}O calculated with the parentage coefficients of table 2.
- Fig. 12. The $(^{16}\text{O}, ^{18}\text{O})$ reaction on three nickel isotopes at energies above the barrier, with the indirect transfer mode via the $^{18}\text{O}(2^+)$ state coupled (solid curves). Dotted curves are calculated differential cross sections for the direct transitions only using the same strongly absorbing potentials, with the inelastic excitation included. Parameters are given in table 1. The absolute normalization is 1.6 for the first two cases, 3.5 for the third case. Data are from refs. ^{13,21)}.

Fig. 13. Coupled channel calculations for the inelastic scattering of ^{18}O from ^{120}Sn leading to the ground state of both nuclei, and the 2^+ state of oxygen, are compared with the data of ref. ¹⁸). The phase 45° of the nuclear form factor gives slightly better agreement than the collective model phase (dotted curve). Parameters are as in table 3.

Fig. 14. (a) The $^{122}\text{Sn}(^{16}\text{O}, ^{18}\text{O})$ reaction at an energy slightly above the barrier. The inclusion of indirect transfer via $^{18}\text{O}(2^+)$ in a coupled calculation (solid curves) at this energy modifies the result of the direct calculation only at backward angles. The normalization of all curves is 9.8, parameters are given in table 3. Data are for the time-reversed reaction, ref. ²⁹).

(b) For the ground state transfer, the direct transition is compared with the indirect one via $^{18}\text{O}(2^+)$. The indirect process, which is forward-biased at sufficiently high energy, has vanishing forward-angle cross section at this low energy, and falls off slowly towards backward angles.

Fig. 15. Coupled calculations for $^{122}\text{Sn}(^{16}\text{O}, ^{18}\text{O})$ at 104 MeV are compared with the data of ref. ⁷). The parameters yielding the dotted curves are as in table 3, with a phase 45° of the inelastic nuclear form factor as determined from the fit of the inelastic 72 MeV data. A phase of 75° leads to a good fit of the data (refs. ^{7,11}) for both ground state and $^{18}\text{O}(2^+)$. All curves are normalized by 2.1.

Fig. 16. The result of fig. 16 (solid curve, left) for the reaction indicated is compared with the DWBA result for the same potentials, and separate calculations for direct and indirect transfer modes are shown (right). At this energy, the indirect process has a broad, forward-biased cross section, the direct process a bell-shaped one. Note the enhancement of the forward-angle relative to the grazing cross section, when the indirect mode is included.

XBL 7510-8602

Fig. 1

XBL 7512-9887

Fig. 2

XBL 767-3236

Fig.3

$^{62}\text{Ni} (^{16}\text{O}, ^{18}\text{O}) E=45 \text{ MeV CCBA}$

XBL 767-3237

Fig. 4

XBL 767-8919

Fig. 5

XBL 767-8920

Fig. 6

XBL 767-8921

Fig.7

Fig. 8

XBL 7512-9880

XBL 7512-9881

Fig. 9

NBL 7511-9614

Fig. 10

XBL7511-9532

Fig. 11

XBL 7512-9888

Fig. 12

XBL 7512-10122

Fig. 13

YBL 7512-10125

Fig. 14

XBL 7512-10123

Fig. 15

XBL 7512-10121

Fig.16

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