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SINGLE-PARTICLE AND COLLECTIVE ASPECTS OF THE ABSORPTIVE POTENTIAL FOR HEAVY ION REACTIONS

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The mass dependence of the absorptive potential due to transfer processes is studied for the reactions $^{16,17}O + ^{28}Si$ and $^{16}O + ^{28,29,30}Si$ at 33 MeV. While the system $^{16}O + ^{28}Si$ is very transparent at this bombarding energy a marked increase in the absorptive potential is observed by adding nucleons to either the target or the projectile.

1. INTRODUCTION

The observation, in heavy ion reactions, of anomalously large elastic scattering cross sections (cf. ref. 1 and refs. therein) at scattering angles located in the backward hemisphere provides strong support for the existence of nuclear molecular states (shape isomers). A consensus exists that in these collisions the two nuclei come to very close distances and display a high degree of transparency (cf. e.g. refs. 2-6 and refs. therein). They thus provide information on regions of the ion-ion potential which are usually unaccessible in grazing collisions and on the mechanisms responsible for the depopulation of the entrance channel.

In collisions at energies below 20-30 MeV per nucleon, surface absorption is expected to be dominant. In other words all final channels including fusion are expected to be reached through doorway states excited during the approach of the nuclear surfaces of the two ions[7,8].

The two main components of the imaginary potential at typical grazing distances have been found to arise from single-particle transfer ($W_t(r)$) and inelastic scattering processes ($W_v(r)$). The range of $W_t(r)$ is of the order of 0.6 fm, while that of $W_v(r)$ is only 0.3 fm. The depopulation due to the excitation of rotational bands has to be treated, as a rule, explicitly. In this connection it is interesting to note that anomalously large cross sections in the backward hemisphere have been observed in collisions where one or both partners are deformed. With this proviso it is fair to say that the degree of transparency to be expected in a collision between

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heavy ions is essentially controlled by the strength of $W_t(r)$. At low bombarding energies this strength is a strong function of the nuclear structure.

In the present paper we illustrate this fact by studying the dependence of $W_t(r)$ with mass number for the reaction $^{16}O + {}^{28,29,30}Si$ and $^{16,17}O + {}^{28}Si$ at 33 MeV. In Section 2 the basic expressions needed to calculate $W_t(r)$ are presented. In Section 3 they are applied to the four O+Si reactions mentioned above. The conclusions are collected in Section 4.

2. THE ABSORPTIVE POTENTIAL DUE TO TRANSFER PROCESSES

Through particle transfer reactions the entrance channel is depopulated as a function of time during a heavy ion collision. It is in many cases convenient to describe such depopulation in terms of an imaginary potential. This is possible to the extent that elementary transitions depopulating the entrance channel are independent of each other and that the associated probabilities are small.

Single-particle transfer reactions fulfil these conditions and are the most important elementary transitions in the depopulating process at energies below 20-30 MeV. Multi-nucleon transfer reactions are well described as successive transfer of nucleons, and the correlations neglected in such description are in general not expected to be of significance in the present context.

A local absorptive potential has been derived in ref. 7 making use of the considerations mentioned above. It reads

$$W_t(r) = \sum_{a_1 a_1' \lambda} \left(\frac{a_{tr}(a_1,a_1')}{16\pi^2 |\ddot{r}_0|^2 \hbar^2}\right)^{\frac{1}{2}} g_\lambda(Q) \qquad (1)$$

$$\left\{(2j_1'+1)\ U^2(a_1\ I_A)\ V^2(a_1'\ I_a)\ \left|f_{\lambda 0}^{a_1 a_1'(NS)}(O,r)\right|^2\right.$$

$$\left. +\ (2j_1+1)\ U^2(a_1'\ I_a)\ V^2(a_1\ I_A)\ \left|f_{\lambda 0}^{a_1 a_1'(NP)}(O,r)\right|^2\right\}$$

The single-particle levels connected in the transition are labelled by the quantum numbers $a_1 \equiv (n_1 \ell_1 j_1)$ and $a_1' \equiv (n_1' \ell_1' j_1')$. The quantity $a_{tr}(a_1, a_1')$ is the diffuseness of the associated formfactors. This quantity is on average of the order of 1.2 fm.

The first term in (1) is connected with stripping reactions while the second describes pick-up processes, the functions

$f^{a_1 a_1'}(NS)$ and $f^{a_1 a_1'}(NP)$ being the corresponding single-particle formfactors.

The acceleration $\ddot{r}_0$ at the distance of closest approach for the grazing trajectory can be estimated through the expression $m_{aA}\,\ddot{r}_0 = (2E-E_B)/r_B$ valid for a Coulomb trajectory. The quantities E_B and r_B are the height and the radius of the Coulomb barrier, while E is the bombarding energy in the center of mass system.

The parameters U^2 and V^2 are the spectroscopic factors. Thus

$$V^2(a_1'\ I_a) = \frac{1}{2j_1'+1} \sum_{m_1'} \langle I_a M_a | a^+_{j_1' m_1'}(a_1')\ a_{j_1' m_1'}(a_1') | I_a M_a \rangle$$

$$= \frac{1}{2I_a+1} |\langle I_a \| a^+_{j'}(a') \| I_b \rangle|^2 , \qquad (2)$$

is the probability that the single-particle orbital a_1 is occupied in the nucleus a while the quantity $U^2 = 1-V^2$ is the corresponding probability that it is empty in the target A.

The function $g_\lambda(Q)$ which depends parametrically on the Q-value and on the angular momentum λ transferred in the reaction determines the adiabatic cut-off. That is, it weights the probability with which the different transfer channels contribute to $W_t(r)$. This quantity is the main source of the energy dependence of the imaginary potential, and its value essentially controls the role played by the different contributions to (1).

3. APPLICATIONS

In this section we present the calculations of $W_t(r)$ associated with the reactions $^{16}O + {}^{28,29,30}Si$ and $^{16,17}O + {}^{28}Si$ at 33 MeV. Both the proton and the neutron stripping and pick-up contributions to (1) were considered. The single-particle levels involved in these processes were taken from experiment[9] and are shown in fig. 1. The associated wavefunctions were calculated making use of a standard shell model potential (cf. ref. 8 and refs. therein). In all cases occupancies equal to 1 or 0 have been assumed except for the cases of ^{17}O and ^{29}Si where the last occupied orbit was given a fractional occupancy.

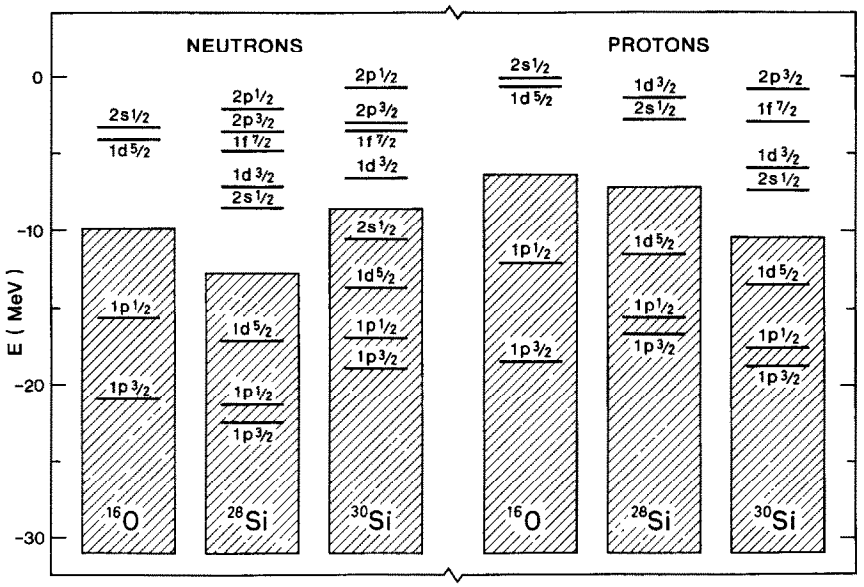

FIGURE 1
The experimental spectrum associated with the single-particle motion of neutrons and protons in ^{16}O and $^{28,30}Si$.

The resulting imaginary potentials $W_t(r)$ are displayed in fig. 2. As was already observed in refs. 5-8, 10, in the case of the reaction $^{16}O + ^{28}Si$ all transfer channels are essentially closed, and the associated absorptive potential at the grazing distance is very weak ($\lesssim 0.02$ MeV). This result implies that the system $^{16}O + ^{28}Si$ is rather transparent, and is at the basis of the phenomenon of backward rise observed in the associated elastic scattering angular distribution.

A major change in $W_t(r)$ takes place when adding nucleons to either target or projectile. In the case of the reactions $^{16}O + ^{28,29,30}Si$ these changes can be qualitatively described in terms of the Nilsson model[11].

The nucleus ^{28}Si is strongly deformed (oblate $\beta \approx -0.4$). A schematic representation of the associated level scheme is shown in fig. 3. Both single-proton (π) and single-neutron (ν) transfer reactions between ^{16}O and ^{28}Si are strongly hindered at 33 MeV. In fact, the most favourable transitions which correspond to

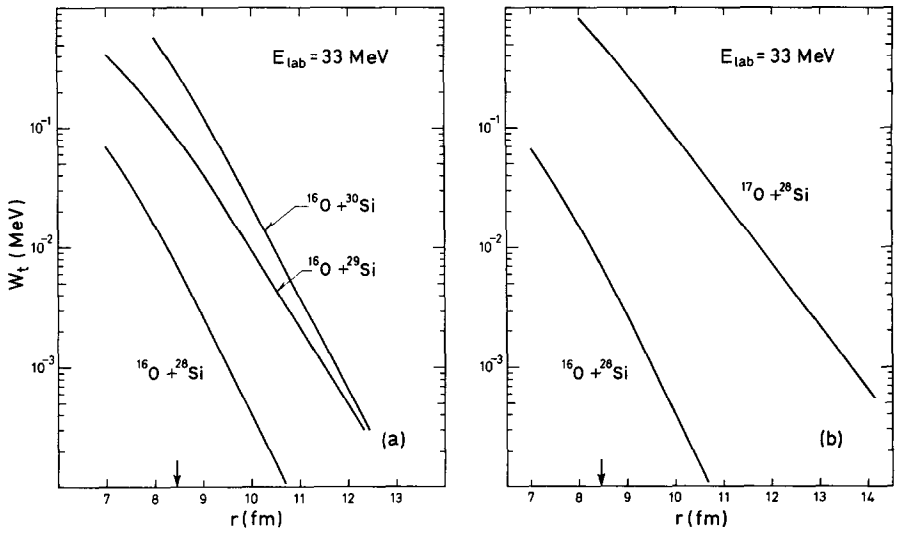

FIGURE 2
Absorptive potential arising from particle transfer processes associated with the reactions (a) $^{16}O + ^{28,29,30}Si$ and (b) $^{16,17}O + ^{28}Si$, at a bombarding energy of 33 MeV.

the stripping processes $1p_{1/2} \rightarrow 2s_{1/2}$, $1d_{3/2}$, $1f_{7/2}$ ($Q \approx -9$ MeV (ν,π)) display g-values of the order of 10^{-2} .

The situation is drastically changed in the case of the reaction $^{16}O + ^{29}Si$. A neutron can now easily be transferred from target to projectile ($2s_{1/2} \rightarrow 1d_{5/2}$, $Q \approx -4$ MeV , $g \approx 0.3$) leading to a major increase in the absorptive potential as compared to the previous case (cf. fig. 2).

Adding a second neutron to ^{28}Si leads to ^{30}Si a nucleus which is essentially spherical. This change in shape is associated with an important rearrangement in the single-particle levels. It is now very favourable to transfer nucleons from the $1p_{1/2}$ orbital of ^{16}O to the $2s_{1/2}$ level of ^{30}Si as this orbital has increased its binding energy by few MeV. However, this can only be done with protons because the $2s_{1/2}$ (ν) orbital is now fully occupied. The g-value associated with the $1p_{1/2}$ $(\pi) \rightarrow 2s_{1/2}$ (π) transition is ≈ 0.4 . Non-negligible contributions arise also from the transfers $1p_{1/2}$ $(\pi) \rightarrow 1d_{3/2}$, $1f_{7/2}$ (π) . The resulting

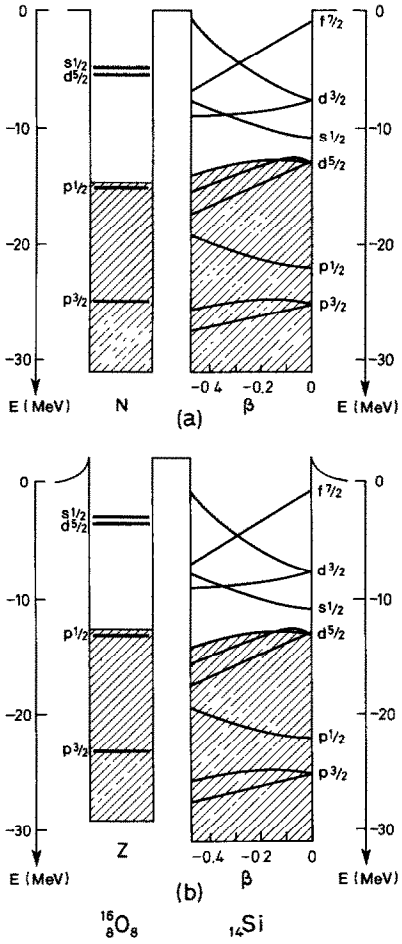

FIGURE 3
Schematic representation of the distribution of both neutron (a) and proton (b) single-particle levels in ^{16}O and ^{28}Si at the grazing distance where the transfer process is expected to take place. The levels of ^{28}Si are displayed as a function of the deformation parameter β and only for negative values. In (b) the shift in the single-particle levels takes into account the contribution to the effective Q-value of the change in the Coulomb barrier due to the transfer of charge.

absorptive potential (cf. fig. 2) is thus essentially due to the proton degrees of freedom. It is noted that in the present case one has to add to $W_t(r)$ and absorptive component $W_v(r)$ arising from the excitation of surface vibrations of ^{30}Si.

As seen from fig. 2(a) the absorptive potential connected with the $^{16}O + ^{29}Si$ reaction displays a larger diffusivity than the corresponding quantity associated with the $^{16}O + ^{28,30}Si$ reactions. This result reflects the rather small binding energy the $2s_{1/2}$ (ν) orbital has in ^{29}Si and the fact that the formfactor

associated with the $^{29}Si(2s_{1/2}) \rightarrow {}^{16}O(1d_{5/2})$ pick-up reaction is essentially controlled by the tail of that orbital.

The change observed in W_t when adding a neutron to the projectile (cf. fig. 3(b)) is directly related to the easiness with which a neutron can then be transferred from the $1d_{5/2}$ orbit of ^{17}O to the different orbits lying above the Fermi surface in ^{28}Si.

The main uncertainties affecting the results presented above stem from the poor knowledge of the strength distribution of single-particle levels in both targets and projectiles. Another source of error is related to the fact that very few transitions contribute to the quantities displayed in fig. 2. On the other hand the expression (1) was derived assuming many weak independent contributions.

4. CONCLUSIONS

A marked change is observed in the absorptive potential associated with the reactions $^{16,17}O + {}^{28}Si$ and $^{16}O + {}^{28,29,30}Si$. They can be simply related to the distribution of single-particle levels around the Fermi surface of both O and Si . In particular the rearrangement of the Nilsson levels taking place because of the phase transition occurring between ^{28}Si (oblate) and ^{30}Si (spherical) is reflected in the different degree of transparency displayed by the $^{16}O + {}^{28}Si$ and the $^{16}O + {}^{30}Si$ systems.

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