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ENERGY DEPENDENCE OF ONE-NUCLEON TRANSFER IN HEAVY-ION COLLISIONS

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Abstract: Single-proton stripping reactions in the collisions $^{16}O+^{208}Pb$ and $^{12}C+^{208}Pb$ at bombarding energies up to 50 MeV per nucleon are analyzed in the semiclassical approximation. Utilizing an energy dependent interaction consistent with the data for proton-nucleus scattering the absolute cross sections are reproduced. A simple estimate of the total reaction cross section for a specific channel in heavy-ion collisions is obtained in a semiclassical description.

NUCLEAR REACTIONS $^{208}Pb(^{16}O, ^{15}N)$, $(^{12}C, ^{11}B)$, $E \approx 100$-800 MeV. Calculated $\sigma(E)$. Semiclassical approximation.

1. Introduction

The transfer of nucleons in heavy-ion collisions between bound states in target and projectile is a non-trivial problem due to the recoil effect. A careful treatment of the recoil is important at high bombarding energy where the wavelength of the relative motion of the ions is small. The semiclassical description is then quite accurate while the standard DWBA treatment becomes cumbersome.

In the semiclassical approximation one may separate the dependence on nuclear structure in terms of single-particle form factors which depend on the local momentum carried by the transferred particle due to the relative velocity of the two ions. The interaction potential appearing in these form factors is the single-particle mean field of the target as seen from the nucleon in the projectile. At low bombarding energies it is therefore the same potential which binds the transferred particle to the target in the final state, while at higher energies it is expected [1,2]) that the nuclear part of this interaction is reduced in the same way as the real part of the optical potential for nucleon–nucleus scattering.

2. Total transfer cross section

In order to obtain the cross section for a specific transfer reaction one usually has to take into account the depopulation to other channels. This is conveniently done in terms of an imaginary part $W(r)$ (the absorptive potential) in the interaction potential between the colliding nuclei. This quantity describes the depopulation mostly to other transfer channels in the grazing region. The depopulation to fusion is included if one neglects all trajectories that pass over the Coulomb barrier in the effective potential for the radial motion (the sum of the interaction potential and the centrifugal potential). While the differential cross section can only be obtained semiclassically by using complex trajectories [3]) the total cross section is rather accurately obtained by integrating over all impact parameters ρ for real trajectories, i.e.

$$\sigma_\beta = 2\pi \int_0^\infty \rho \, d\rho \, P_\beta(\rho) , \tag{2.1}$$

where the probability for populating the channel β,

$$P_\beta(\rho) = p_\beta(\rho) P_0(\rho) , \tag{2.2}$$

is the product of the transfer probability p_β and the probability of remaining in the entrance channel,

$$P_0(\rho) = \exp\left\{\frac{2}{\hbar}\int_{-\infty}^{\infty} dt \, W(r(t))\right\} . \tag{2.3}$$

The time integral is performed along the classical trajectory corresponding to the impact parameter ρ. The transfer probability may be expressed as the absolute square of the amplitude a_β which in first-order perturbation theory (in the prior representation) for a single-particle stripping reaction is given by

$$a_\beta(\rho) = \frac{1}{i\hbar}\int_{-\infty}^{\infty} dt \, \langle \psi_\beta | (U_{1A} - \langle U_{1A} \rangle) \, e^{i\sigma_{\beta\alpha}(\boldsymbol{k})} | \psi_\alpha \rangle \exp\{i[(E_\beta - E_\alpha)t + \gamma_{\beta\alpha}(t)]/\hbar\} , \tag{2.4}$$

where the integral is taken along the classical trajectory. The quantities ψ_α and ψ_β are the single-particle wave functions of the initial and final states in projectile and target, respectively, while U_{1A} is the nuclear-plus-Coulomb interaction of the target on the transferred proton. With E_α and E_β we have indicated the total energies of the entrance and exit channels, respectively. The phase $\gamma_{\beta\alpha}$ depends on the charge and mass transfer while $\sigma_{\beta\alpha}$ depends on the recoil momentum $\boldsymbol{k}$ (for more details cf. refs. [4,5])).

For high bombarding energies the matrix element in (2.4) depends on time not only through the distance $\boldsymbol{r}$ between the colliding ions but also through the momentum $\boldsymbol{k}$ of relative motion carried by the transferred nucleon, i.e.

$$\langle\psi_\beta|(U_{1A}-\langle U_{1A}\rangle)\,e^{i\sigma_{\beta\alpha}(k)}|\psi_\alpha\rangle \sim f(r(t), k_\parallel(t), k_\perp(t)), \tag{2.5}$$

where both the longitudinal and transverse components of $\boldsymbol{k}$ contribute. At low bombarding energies the interaction U_{1A} coincides with the shell-model potential which binds the transferred nucleon to the target in the state $|\psi_\beta\rangle$. At higher energies it is expected [1,2]) that the nuclear part of this interaction is reduced in the same way as the real part of the optical potential for proton-nucleus scattering. Proton scattering data are analyzed by using a nuclear interaction of Woods-Saxon shape with an energy-dependent depth parametrized as

$$U_0(E)=\zeta(E)U_0, \tag{2.6}$$

with

$$\zeta(E)=1-\beta\frac{E}{51\text{ MeV}}, \tag{2.7}$$

where E is the energy of the impinging proton. Values of β in the range $\beta=0.3$–0.5 are quoted in the literature [6]).

With the parametrization (2.6) of the strength of U_{1A} we notice that the real part of the ion-ion optical potential, which is the folding of this interaction with the particle density of the projectile, is reduced by the same law where the energy E is the kinetic energy per nucleon above the Coulomb barrier. This expectation seems to be born out from the experimental data [1]).

With the simple scaling (2.6) also the form factor (2.5) achieves an approximate scaling although the Coulomb component of U_{1A} does not scale with energy. This is because the Coulomb field in U_{1A} is essentially cancelled by the Coulomb field in the average potential $\langle U_{1A}\rangle$, cf. ref. [4]).

3. Numerical calculations

Utilizing an interaction U_{1A} with an energy-dependent depth of the nuclear part (2.6) we have calculated the total cross sections (2.1) for the single-proton stripping reactions from the $^{16}O(1p_{1/2})$ state to the ground state and first excited states of ^{209}Bi as well as from the $^{12}C(1p_{3/2})$ state to the same states in ^{209}Bi. The shell-model used is the one presented in ref. [7]) except that the depths of the nuclear part of the shell-model potentials were adjusted for each level individually to reproduce the experimental binding energies. With dashed curves we present in figs. 1 and 2 the total cross sections as functions of the bombarding energy in comparison with the experimental data of refs. [8-10]) for the $^{16}O+{}^{208}Pb$ reactions and of refs. [11-13]) for the $^{12}C+{}^{208}Pb$ reactions. The calculations have been performed by using the optical model parameters of refs. [8-10]) for the $^{16}O+{}^{208}Pb$ reactions and of refs. [11-14]) for the $^{12}C+{}^{208}Pb$ reactions. We have assumed that the $^{16}O(1p_{1/2})$ state and the $^{12}C(1p_{3/2})$

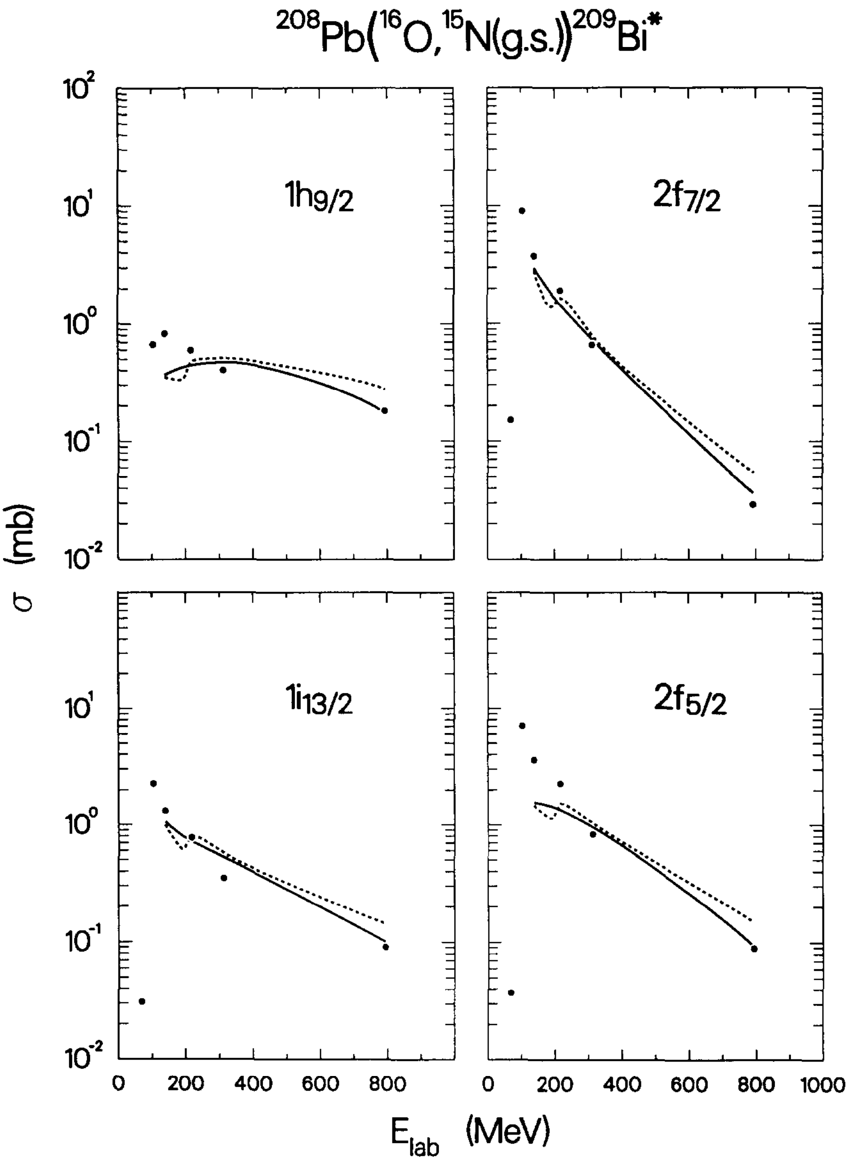

Fig. 1. Total cross sections for the indicated transfer reactions. The shell-model of ref. [7]) is used with the depths of the nuclear part of the shell-model potentials being adjusted for each level individually to reproduce the experimental binding energies. The nuclear part of the interaction U_{1A} has an energy-dependent depth (2.6), $\beta = 0.4$. The $1p_{1/2}$ state in the projectile is completely filled, the spectroscopic factor of the ground state, $1h_{9/2}$, of the target is 0.95, of the $2f_{7/2}$ state it is 0.65, of the $1i_{13/2}$ state it is 0.35, and of the $2f_{5/2}$ state it is 1.00. With dashed curves are shown the cross sections (2.1) calculated by using the optical model parameters of refs. [8-10]), with full-drawn curves are shown the cross sections (2.1) calculated by using the smooth optical potentials, table 1. The experimental data are from refs. [8-10]).

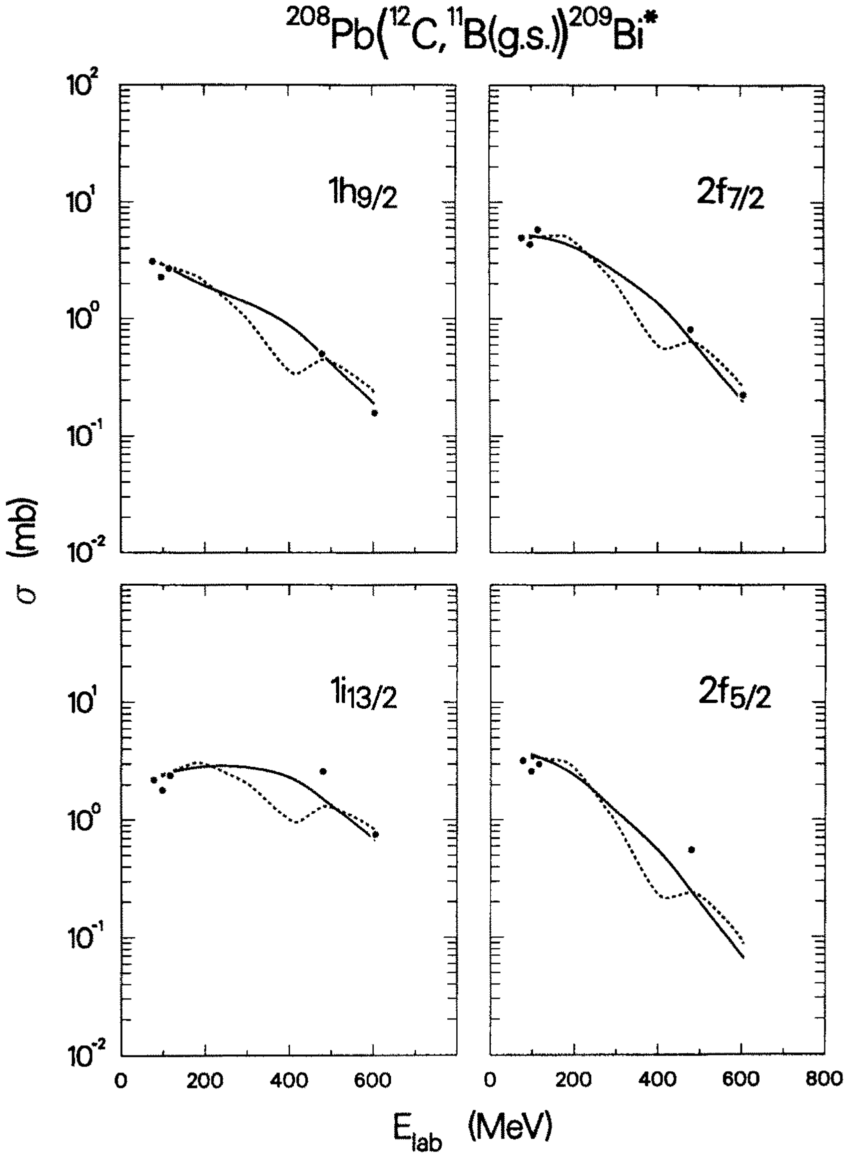

Fig. 2. Total cross sections for the indicated transfer reactions. The shell-model of ref. [7]) is used with the depths of the nuclear part of the shell-model potentials being adjusted for each level individually to reproduce the experimental binding energies. The nuclear part of the interaction U_{1A} has an energy-dependent depth (2.6), $\beta = 0.4$. The $1p_{3/2}$ state in the projectile is completely filled, the spectroscopic factor of the ground state, $1h_{9/2}$, of the target is 0.95, of the $2f_{7/2}$ state it is 0.65, of the $1i_{13/2}$ state it is 0.35, and of the $2f_{5/2}$ state it is 1.00. With dashed curves are shown the cross sections (2.1) calculated by using the optical model parameters of refs. [11-14]), with full-drawn curves are shown the cross sections (2.1) calculated by using the smooth optical potentials, table 2. The experimental data are from refs. [11-13]).

TABLE 1

Woods-Saxon parameters for the absorptive potentials having a smooth energy dependence for the elastic scattering of $^{16}O+^{208}Pb$

	E_{lab} (MeV)	W_0 (MeV)	a (fm)	r_0 (fm)
$^{16}O+^{208}Pb$	138.5	50	0.64	1.179
	192.0	52	0.63	1.179
	216.6	52	0.62	1.179
	312.6	50	0.60	1.179
	793.0	35	0.47	1.179

The corresponding ion-ion potential is the one of ref. [15]) reduced by the scaling factor $\zeta(E)$, $\beta=0.4$, eq. (2.7). The radius parameter is the same for the real and imaginary potentials.

state, from which the protons are being transferred, are completely filled, and we have assumed that the spectroscopic factor for the ground state, $1h_{9/2}$, of ^{209}Bi is 0.95, for the $2f_{7/2}$ state is 0.65, for the $1i_{13/2}$ state is 0.35, and for the $2f_{5/2}$ state is 1.00.

The optical potentials used in the calculations presented in figs. 1 and 2 by dashed curves are obtained by the various experimental groups by fitting the available data for the elastic angular distributions. These potentials do not possess a smooth behaviour as a function of the bombarding energy. Therefore, we made an attempt to use the (energy independent) ion-ion potential of ref. [15]), which is a folding potential, reduced by the scaling factor $\zeta(E)$. A search was performed for Woods-Saxon shaped absorptive potentials which together with this ion-ion potential fit the elastic data reasonably well and do have a smooth behaviour as a function of bombarding energy. In tables 1 and 2 we give the Woods-Saxon parameters of these absorptive potentials. In figs. 3 and 4 the elastic angular distributions calculated in the standard optical model by using the code PTOLEMY [16]) on the basis of these

TABLE 2

Woods-Saxon parameters for the absorptive potentials having a smooth energy dependence for the elastic scattering of $^{12}C+^{208}Pb$

	E_{lab} (MeV)	W_0 (MeV)	a (fm)	r_0 (fm)
$^{12}C+^{208}Pb$	96.0	38	0.67	1.178
	180.0	66	0.52	1.178
	300.0	60	0.45	1.178
	420.0	37	0.48	1.178
	480.0	33	0.52	1.178
	604.8	30	0.60	1.178

See footnote to table 1.

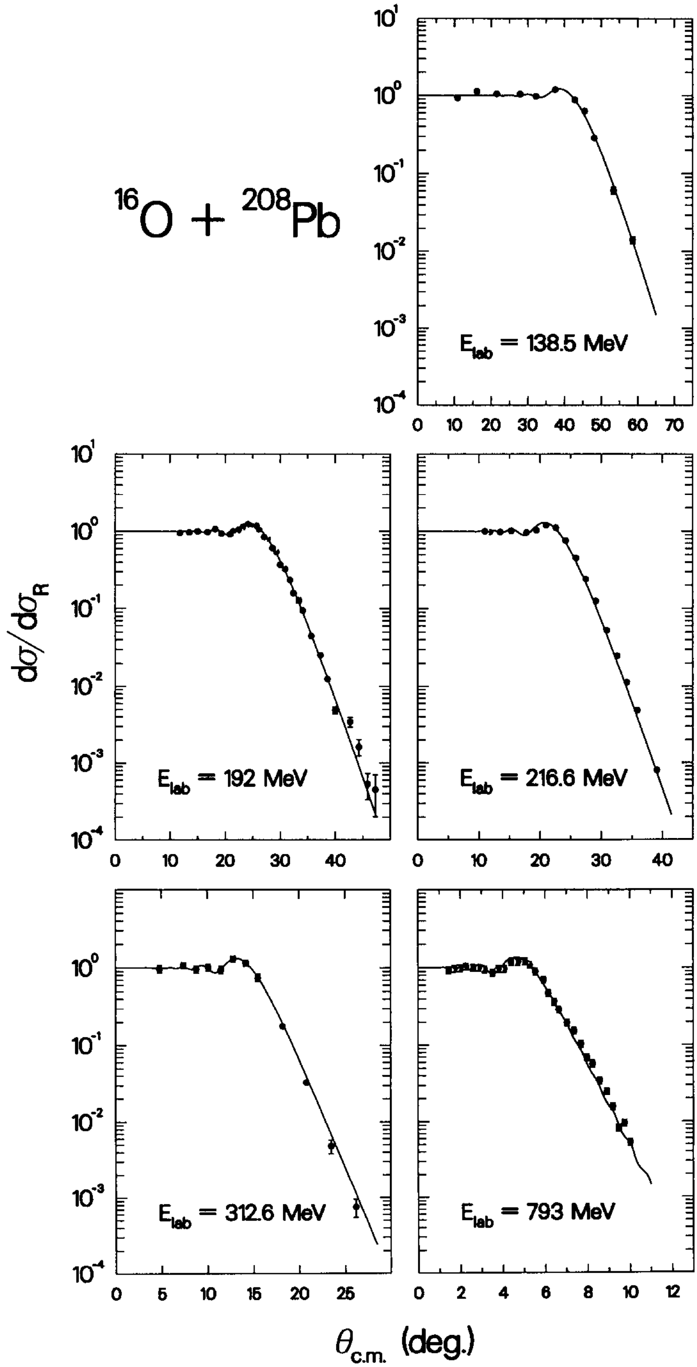

Fig. 3. The ratio of the elastic to the Rutherford angular distribution for the scattering of ^{16}O on ^{208}Pb at different bombarding energies indicated in the separate plots. The curves are calculated in the standard optical model with the ion-ion potential of ref. [15]) reduced by the scaling factor $\zeta(E)$, $\beta = 0.4$, eq. (2.7), and the absorptive potentials of table 1. The data points are from refs. [8-10]).

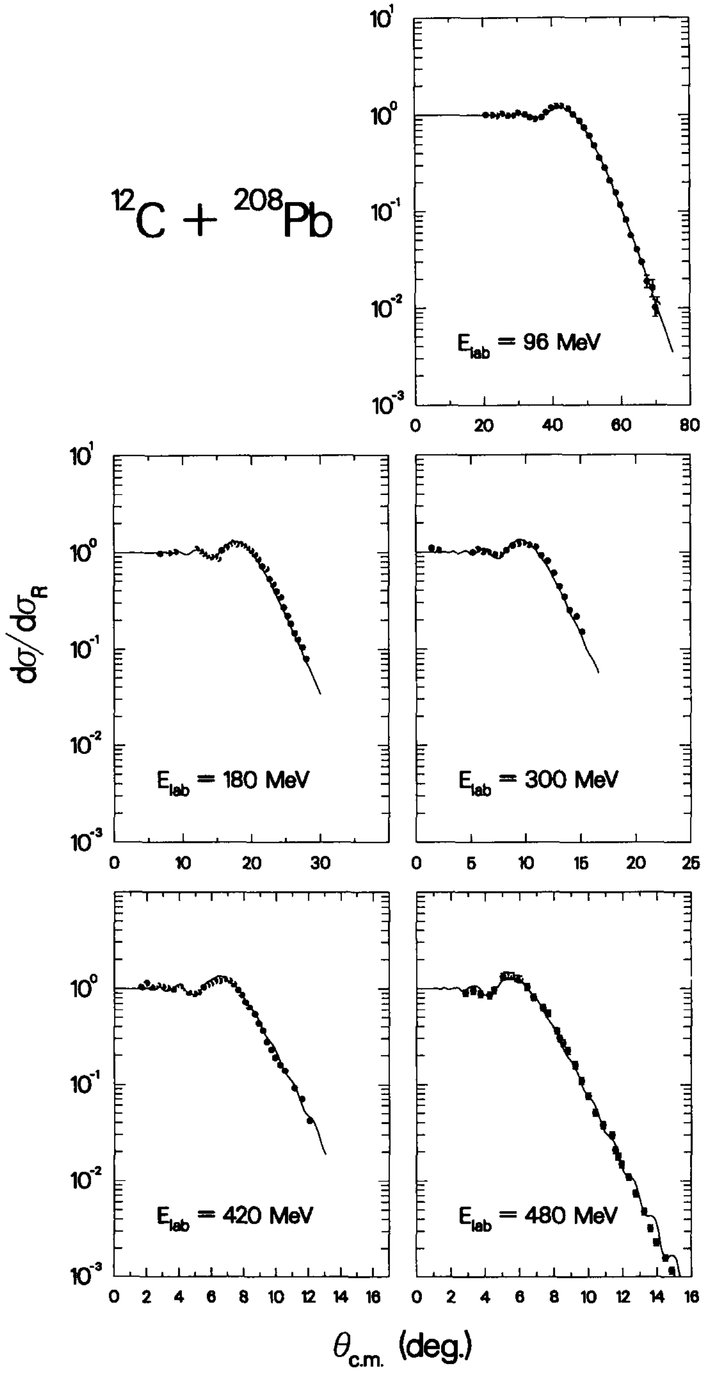

Fig. 4. The ratio of the elastic to the Rutherford angular distribution for the scattering of ^{12}C on ^{208}Pb at different bombarding energies indicated in the separate plots. The curves are calculated in the standard optical model with the ion-ion potential of ref. [15]) reduced by the scaling factor $\zeta(E)$, $\beta = 0.4$, eq. (2.7), and the absorptive potentials of table 2. The data points are from refs. [11-14]).

optical potentials are shown in comparison with the experimental data. The absorptive potential at a bombarding energy of 604.8 MeV for the $^{12}C+^{208}Pb$ reaction is obtained by extrapolation - there are no data for the elastic angular distribution at this energy. Finally, we present in figs. 1 and 2 with solid curves the total cross sections (2.1) for the indicated transfer reactions calculated by using the smooth optical potentials. The discrepancies we observe at low energies for the $^{16}O+^{208}Pb$ reactions is a well known problem that may be ascribed to higher order processes [17]).

The differential cross sections for transfer were calculated in the DWBA by the code PTOLEMY for a few examples employing the smooth optical potentials and the scaling mentioned above. The results compared well with the experimental angular distributions and also with the semiclassical results for the total cross sections.

At the lowest bombarding energies we might have used the absorptive potentials calculated according to ref. [18]) taking into account inelastic excitations and transfer of nucleons between bound states in projectile and target, eventually with the recoil corrections of ref. [4]). These absorptive potentials together with the ion–ion potential of ref. [15]) give an accurate description of the elastic angular distributions at low bombarding energy where the absorption is governed by the reactions mentioned above due to the Q-value windows for such processes. At higher bombarding energies, however, the transfer to bound states becomes weaker and one should take into account the depopulation due to transfer to states in the continuum. Besides these mean field effects also the effect of two-body scattering to large angles should be taken into account [19]). For low bombarding energy the absorption due to such processes is small due to Pauli blocking. However, as the relative velocity of the colliding ions increases, the mean field of the target acting on the projectile becomes smaller, and this volume part of the imaginary optical potential, characteristic for nuclear matter, increases and one should include it in a proper description of the reaction.

4. Simple estimate

The total cross section for a specific channel β which is given by the expression (2.1) can be written as an integral over the distance of closest approach r_0 by using the classical equation

$$\frac{Z_a Z_A e^2}{r_0} + U^N(r_0) + \frac{\rho^2}{r_0^2} E_{c.m.} = E_{c.m.}, \tag{4.1}$$

where $E_{c.m.}$ is the center-of-mass energy and U^N the ion–ion potential while Z_a and Z_A are the charge numbers of projectile and target, respectively. Utilizing (4.1) we may thus write

$$\sigma_\beta = \pi \int_{r_{min}}^{\infty} \frac{r_0\, dr_0}{E_{c.m.}} \left[2E_{c.m.} - \frac{Z_a Z_A e^2}{r_0} - r_0 \frac{\partial U^N}{\partial r} - 2U^N(r_0) \right] P_\beta(r_0). \tag{4.2}$$

The function $P_\beta(r_0)$ shows a well-defined maximum. It is according to (2.2) the product of the transfer probability in first-order perturbation theory

$$p_\beta(r_0) = p_\beta(R)\exp\left(-\frac{r_0 - R}{a}\right) \tag{4.3}$$

and the probability of remaining in the entrance channel which we may write

$$P_0(r_0) = \exp\left\{\sqrt{\frac{8\pi a}{\hbar^2 \ddot{r}_0}}\, W(r_0)\right\}. \tag{4.4}$$

This expression is obtained from (2.3) by using a second-order expansion of $r(t) = r_0 + \frac{1}{2}\ddot{r}_0 t^2$ and the exponential form

$$W(r) = W(R)\exp\left(-\frac{r - R}{a}\right) \tag{4.5}$$

for the absorptive potential. The diffuseness parameters in (4.3) and (4.5) are usually quite similar, $a \approx 0.6$ fm.

With the form (4.3) and (4.5) we find that $P_\beta(r_0)$ shows a maximum at the point $r_{\max}$ where

$$P_0(r_{\max}) = 1/\mathrm{e}\,, \tag{4.6}$$

i.e. where

$$W(r_{\max}) = -\sqrt{\frac{\hbar^2 \ddot{r}_0}{8\pi a}}\,. \tag{4.7}$$

We may here estimate $\ddot{r}_0$ by the value

$$\ddot{r}_0 = \frac{2E_{\text{c.m.}} - E_{\mathrm{B}}}{m_0 r_{\mathrm{B}}} \tag{4.8}$$

for a pure Coulomb scattering where E_{B} is the height and r_{B} the radius of the Coulomb barrier while m_0 is the reduced mass of target and projectile. For a given $W(r)$ one may thus easily estimate $r_{\max}$ and calculate $p_\beta(r_{\max})$. The fact that in practice this number is usually smaller than unity is the reason that first-order perturbation theory (or DWBA) is applicable for the description of many transfer reactions. The distances $r_0 < r_{\max}$ where perturbation theory breaks down are irrelevant because of the strong absorption.

In most collisions between heavy nuclei the distance $r_{\max}$ is outside the orbiting radius r_{g} determined by the point where the square bracket in (4.2) vanishes. We may then neglect the variation of this quantity and substitute it by $2E_{\text{c.m.}} - E_{\mathrm{B}}$ as was done in the estimate (4.8) of $\ddot{r}_0$. For the lower integration limit $r_{\min}$ one should use the orbiting radius r_{g}. However, in most cases this lower limit is not important due to the strong absorption at small distances. Neglecting also the linear dependence on r_0 (substituting it by $r_{\max}$) one may evaluate the integral choosing $R = r_{\max}$ with the result

$$\sigma_\beta = \pi a r_{\max} \frac{2E_{\mathrm{c.m.}} - E_{\mathrm{B}}}{E_{\mathrm{c.m.}}} p_\beta(r_{\max}) . \tag{4.9}$$

At low bombarding energies with rather light ions it may happen that the distance $r_{\max}$ is inside the orbiting radius, i.e. in a region where deep inelastic reactions or fusion will take place. One may in this case estimate the total cross section by assuming that

$$U^{\mathrm{N}}(r) = U^{\mathrm{N}}(R) \exp\left(-\frac{r-R}{a}\right) \tag{4.10}$$

and using $x = \exp\{-(r_0 - R)/a\}$ as a variable. One finds, using $r_{\min} = r_{\mathrm{g}}$ and neglecting the linear dependence on r_0 (substituting it by R),

$$\sigma_\beta = \pi a R p_\beta(R) \frac{(2E_{\mathrm{c.m.}} - E_{\mathrm{B}})^2}{-(R/a-2)U^{\mathrm{N}}(R) 2E_{\mathrm{c.m.}}} g(q) \tag{4.11}$$

with

$$g(q) = 2q[1 - q(1 - \mathrm{e}^{-1/q})] , \tag{4.12}$$

where

$$q = \sqrt{\frac{\hbar^2 \ddot{r}_0}{8\pi a}} \frac{R/a - 2}{2E_{\mathrm{c.m.}} - E_{\mathrm{B}}} \frac{U^{\mathrm{N}}(R)}{W(R)} . \tag{4.13}$$

In the rare cases in light nuclei with small W one may find $q \gtrsim 1$. One would then choose $R = r_{\mathrm{g}}$ implying that

$$q = -\sqrt{\frac{\hbar^2 \ddot{r}_0}{8\pi a}} \frac{1}{W(r_{\mathrm{g}})} . \tag{4.14}$$

In the usual case where $q < 1$ (and $g(q) \approx 2q$) the expression reduces to (4.9) when we choose $R = r_{\max}$.

For a strictly exponential ion-ion potential the orbiting phenomenon would be present at all bombarding energies. Since, in fact, the nuclear attractive force reaches a maximum at the sum of the nuclear radii, the maximum in the effective potential for the radial motion disappears above the so-called critical energy [20]). In such situations the absorption is strong ($q < 1$) so that the total transfer cross section does not depend on the lower integration limit, and (4.9) remains approximately valid.

The accuracy of the formulae (4.9) and (4.11) has been checked. There exist analytical expressions for the evaluation of the transfer probability $p_\beta(r_{\mathrm{B}})$, cf. refs. [4,21]). The formulae of ref. [4]) are rather accurate at energies below 50 MeV per nucleon, and so are the results by Brink *et al.* [21]) at higher energies, when the trajectory of relative motion can be approximated by a straight line.

5. Conclusion

It has for some time been a puzzling problem that standard DWBA calculations were not able to reproduce the absolute cross sections for the single-proton stripping reactions for the collision of ^{16}O on ^{208}Pb at all bombarding energies [8-10]) while for the corresponding $^{12}C+{}^{208}Pb$ transfer reactions the absolute values were reproduced [11-13]). However, it is the conclusion of the present investigations that taking into account an energy dependence (eq. (2.6)) of the depth of the nuclear part of the interaction U_{1A} together with a consistent use of spectroscopic factors for the individual states at all bombarding energies and for all reactions lead to absolute agreement with the data.

In a semiclassical formalism we have furthermore derived a simple estimate of the total cross section for a specific reaction channel in heavy-ion collisions, e.g. single-particle transfer. Also a quantitative description of the maximum of the reaction probability as a function of the distance of closest approach or impact parameter is obtained.

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