HEAVY ION FUSION BELOW THE COULOMB BARRIER: AVERAGE ANGULAR MOMENTA AND FEATURES OF THE EXCITATION FUNCTION*

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Fusion cross sections and mean angular momenta measured for the five systems $^{16}O+^{112}Cd$, $^{28}Si+^{90,100}Mo$ and $^{58,64}Ni+^{64}Ni$ can be explained in the framework of the coupled channels (CC) approach. In particular the influence of 2n-transfer channels with positive Q-values shows up. The direct relation between excitation function and angular momenta has been proved by a simple analytic relation. On this basis a new way for extracting fusion barrier distributions $D(B)$ out of complete angular momentum distributions is presented.

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1. Introduction

During the last few years the interest in subbarrier heavy ion fusion has been renewed by two factors. On the experimental side the investigation of the compound nucleus (CN) angular momentum as a complementary source of information has become more and more important. Mean angular momenta and their energy dependent behaviour and also a few complete angular momentum distributions could be measured, the latter by means of the highly efficient detector arrays which became available in recent years. A summarizing overview is given in reference [1]. On the other hand the distribution of barriers and its extraction from experimental data by the second derivative of the fusion-evaporation excitation function as proposed recently [2] offered a new insight in the underlying structure of the interaction between the processes taking place in heavy ion collisions in the vicinity

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of the Coulomb barrier. *E.g.* a successful application of this method for the deformed ^{154}Sm has reproduced the deformation parameters obtained by nuclear structure experiments [3, 4].

On the basis of the direct relation between the integral fusion cross section $\sigma_{\rm fus}$ and the partial wave transmission coefficient $T(E,\ell)$ [5]

$$T(E,\ell) = \frac{1}{\pi R_b^2}\left[(E - E_{\rm rot})\left.\frac{d(E\sigma_{\rm fus})}{dE}\right|_{E-E_{\rm rot}} + \sigma_{\rm fus}(E - E_{\rm rot})\right] \quad (1)$$

a new method for extracting these structures from experimental data will be proposed in the second part of this contribution. In the first part measured fusion cross sections and mean angular momenta for several systems showing a systematic dependence on the Q-value of 2n-transfer channels will be discussed. The application of equation (1) to those data confirms the validity of this simple approach.

2. Experimental fusion cross sections and mean angular momenta

As reported before [6,7], for the five systems ^{16}O+^{112}Cd, ^{28}Si+^{94,100}Mo and ^{58,64}Ni+^{64}Ni fusion cross sections and mean angular momenta have been measured using the recoil mass spectrometer RMS and, in case of the first system, a simpler electrostatic deflector set-up, together with four (respectively two) 4″×4″ NaI(Tl) detectors. The fusion cross sections have been obtained by the evaporation residues (ER) detected in the focal plane of either instrument normalizing to the Rutherford scattered beam particles. The average γ-multiplicities have been obtained as described in Ref. [8] and references therein. They have been transformed into mean angular momenta using partly the predictions of the evaporation code PACE2 [9] and partly the information on the number of evaporated particles given by the detected ER masses.

The measured fusion cross sections and mean angular momenta are shown in Figs 1–3. They are compared with detailed CC-calculations and the assumptions suggested by the results of the integral cross section measurements (subsection 2.1.) are generally confirmed by the complementary information extracted from the $\langle\ell\rangle$-data (subsection 2.2.).

The systems ^{58,64}Ni+^{64}Ni have been investigated before by Beckerman *et al.* [10]. A comparison with the actual data shows a good agreement for ^{58}Ni+^{64}Ni, whereas in the other case a certain discrepancy remains. The relative behaviour shown by the two systems, however, is qualitatively the same in the present measurements and in Ref. [10].

2.1. Fusion cross sections

The fusion of ^{16}O with ^{112}Cd is not expected to be influenced by strong couplings to degrees of freedom other than the inelastic excitations of ^{112}Cd, because of the rigid structure of ^{16}O and the absence of transfer channels with favourable Q-values. In fact, the measured cross sections can be reproduced by simplified CC calculations using the CCfus code [11] by including only the coupling to the low-lying excitations of the target nucleus, as can be seen in Fig. 1 (a).

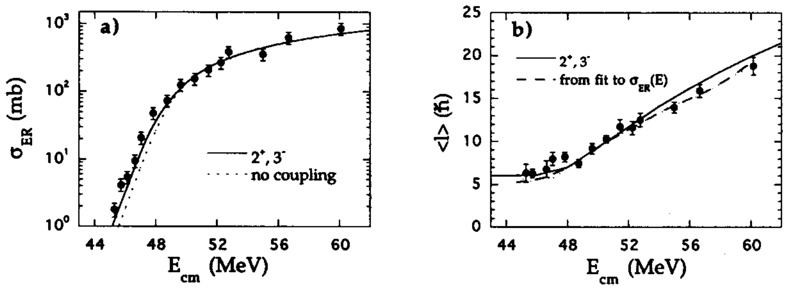

Fig. 1. Fusion-evaporation excitation function (a) and mean angular momenta (b) for the reaction ^{16}O+^{112}Cd. The measured fusion cross sections are compared with the results of CC calculations (see text), and with the no-coupling limit. The mean angular momenta are shown together with the curves obtained from CC-calculations and from a fit to the fusion excitation function (see text).

Inelastic channels are more important for the onset of fusion in the Si-Mo systems. The dashed line in Figs 2 (Ia) and (IIa) has been obtained by coupling the lowest excited states of both target and projectile. In this way the difference between the data and the no-coupling limit (dotted line) is strongly reduced. Although for ^{28}Si+^{94}Mo the remaining discrepancy is smaller, it is obvious that in both cases an additionally enhancing effect is needed to explain the data. One candidate could be the coupling to the transfer of two neutrons which has a positive ground state Q-value in both cases. By coupling an additional channel with the Q-values of the 2n-transfer reactions ^{94}Mo(^{28}Si,^{30}Si)^{92}Mo and ^{100}Mo(^{28}Si,^{30}Si)^{98}Mo of 1.3 MeV and 4.9 MeV respectively, and an adjusted coupling strength of 1.5 MeV, CCfus succeeds fairly well in reproducing the data.

As mentioned above CCfus is a very simplified treatment of the CC problem. It does not take into account mutual or higher-order couplings which play a not negligible role for the fusion enhancement [12], and the importance of nucleon transfer as "doorway-state" can be investigated quantitatively only performing "exact" CC calculations. This was done by Esbensen and Landowne [13] for the systems ^{58,64}Ni+^{64}Ni in order to reproduce the older data by Beckerman *et al.* [10]. The present data in

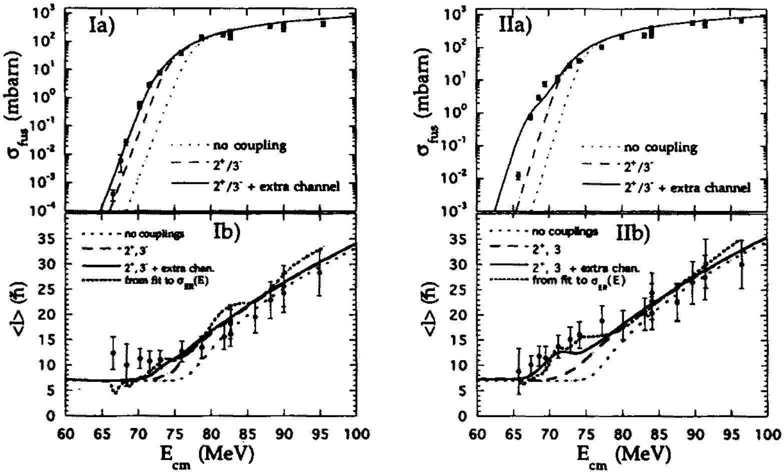

Fig. 2. Fusion-evaporation excitation functions (a) and mean angular momenta (b) for the systems $^{28}Si+^{94}Mo$ (I) and $^{28}Si+^{100}Mo$ (II). The data are compared with the results of CC calculations (see text). The mean angular momenta are compared also with the curve obtained by the first derivative of the fusion excitation function (see text).

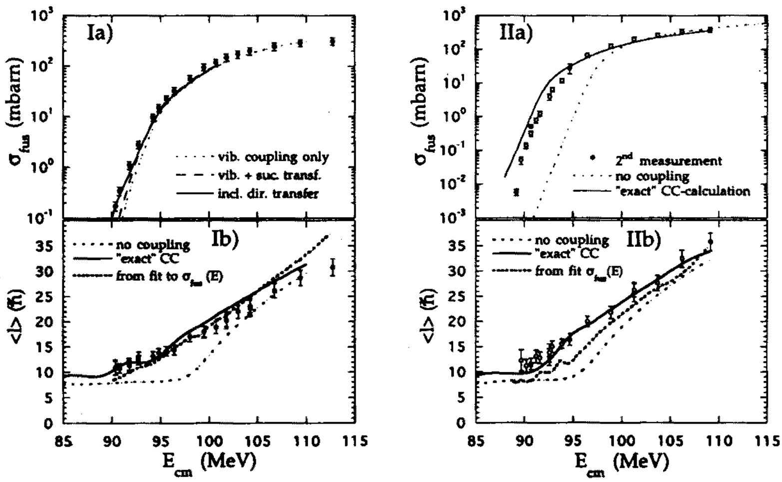

Fig. 3. Fusion-evaporation excitation functions (a) and mean angular momenta (b), for the reactions $^{58}Ni+^{64}Ni$ (I) and $^{64}Ni+^{64}Ni$ (II). The data are compared with CC calculations (see text). The mean angular momenta are compared also with the curve obtained by the first derivative of the fusion excitation function (see text).

comparison with these calculations are shown in Fig. 3. The reaction $^{64}Ni(^{58}Ni,^{60}Ni)^{62}Ni$ delivers an energy excess of 3.9 MeV. Coupling to successive nucleon transfer (dashed line) improves only a little as compared to the coupling to inelastic excitations (dotted line). Only when taking into account also the direct transfer of a neutron pair (full line) the model predictions succeed in reproducing the experimental observations.

The ^{64}Ni+^{64}Ni reaction (Fig. 3 (IIa)) has no transfer channels with positive Q-values. Here the calculations overestimate the data. The reaction has been remeasured in the same run of ^{58}Ni+^{64}Ni at five energies distributed over the whole range. These points (full circles) fall almost exactly on the points of the previous measurement (open circles) and confirm those results. The disagreement between the experimental and calculated values in this case remains an open question, but is not against the trend of the fusion enhancement in relation to the transfer Q-values.

The importance of the transfer channels has been pointed out earlier by various authors [13–15].

2.2. Mean angular momenta

The comparison between the measured $\langle \ell \rangle (E)$ and CCfus calculations for the reaction ^{16}O+^{112}Cd using the same couplings as for the cross sections $\sigma_{\rm fus}(E)$ in Fig. 1 (b) shows a satisfactory agreement. Also the curve obtained from a fit to the fusion excitation function using Eq. (1) confirms the consistency between both independent measurements. The features of this system are discussed in detail in Ref. [6]. Also for the other four reactions where coupling effects are more important a good agreement has been found.

Although we expect from CCfus only a rough estimate, the main features of the Si-Mo systems, as the flattening out of $\langle \ell \rangle (E)$ in the low energy range for ^{28}Si+^{94}Mo and the "bump" in the barrier region for ^{28}Si+^{100}Mo, are at least in a qualitatively good agreement with the data as can be seen from Figs 2 (IIa) and (b).

The "exact" calculations carried out by Landowne [16] for the two Ni-Ni systems using the same couplings as in Ref. [12] for the fusion cross sections show almost no deviation from the data points over the whole energy range. In particular a small hump at the lowest measured energies for ^{58}Ni+^{64}Ni, which is due to the direct 2n-transfer included in the CC-calculations, is consistent with the experiment. The total coupling strength represented by the discrepancy between the no-coupling limit (dashed curve in Figs 3 (Ib) and (IIb)) and complete coupling (solid line) is also found to be realistic in both cases.

3. The distribution of barriers $D(B)$

The method proposed in Ref. [2] for extracting the barrier distribution directly from experimental data uses the second derivative of the function $E \times \sigma_{\text{fus}}$. Therefore very precisely measured fusion cross sections are needed ranging from above the highest to below the lowest barrier. This calls for time consuming and, with respect to the beam-evaporation residue (ER) separation and background suppression, difficult measurements. Moreover large error bars are systematically obtained with increasing energy and the resulting distribution is badly defined at higher energies. Using the relation between the transmission and the reflection coefficients

$$T_\ell = 1 - R_\ell . \tag{2}$$

Leigh *et al.* [17] showed that under certain conditions the barrier distribution can be obtained by the first energy derivative of the quasi-elastic scattering cross section $\sigma_{\text{q-el}}(E)$. A necessary condition for this approach is, however, that the inelastic reaction channels must follow Rutherford orbitals to avoid partial-wave mixing for different reaction types contributing to the quasi-elastic yield. This is not the case *e.g.* for nucleon transfer as pointed out by the authors themselves. The deflection function can differ strongly between transfer and elastic scattering.

In recent years the investigation of complete angular momentum distributions has become possible by means of efficient multiplicity filters partly combined with high-resolution γ-detector-arrays and/or in combination with other particle and CN triggers as ion-optical beam-separators or recoil mass spectrometers. The measured γ-multiplicity distribution can be transformed into relative partial-wave cross section distributions

$$\sigma_\ell(E) = T(E,\ell)(2\ell+1)\pi\lambda\!\!\!^{-2}, \tag{3}$$

where $\lambda\!\!\!^{-}$ is the DeBroglie wavelength of the system. The basic assumption leading to equation (1) [5]

$$T(E,\ell) = T(E - E_{\text{rot}}, \ell = 0), \tag{4}$$

allows the transformation of the angular momentum distribution into the transmission function $T(E)$ assigning to each angular momentum ℓ the corresponding energy $E - E_{\text{rot}}(\ell)$ and normalizing $\sigma_\ell(E)$ to the geometrical partial wave cross section $(2\ell+1)\pi\lambda\!\!\!^{-2}$. Evaluating equation (1) and (3) and comparing the result with the barrier distribution from Ref. [2] one obtains the relation

$$D(B) = \frac{1}{\pi R^2}\frac{d^2 E\sigma_{\text{fus}}}{dE^2} = \frac{1}{(2\ell+1)\pi\lambda\!\!\!^{-2}}\frac{d\sigma_\ell}{dE}. \tag{5}$$

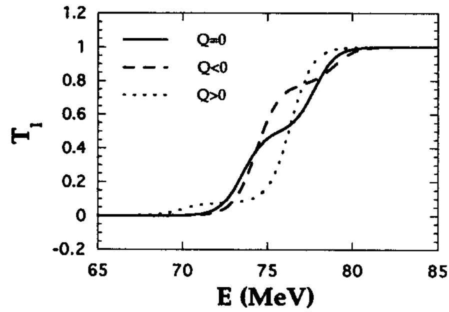

Fig. 4. Theoretical transmission functions for the reaction ^{28}Si+^{100}Mo for coupling one channel with various Q-values (see text).

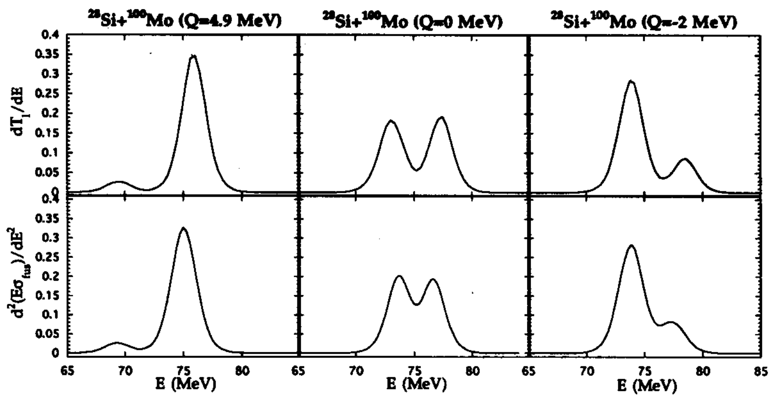

Fig. 5. Comparison of theoretical barrier distributions obtained by the first derivative of complete angular momentum distributions (upper row) and by the second derivative of the fusion excitation function. The three cases of positive (left), negative (right) and zero (center) Q-value are shown.

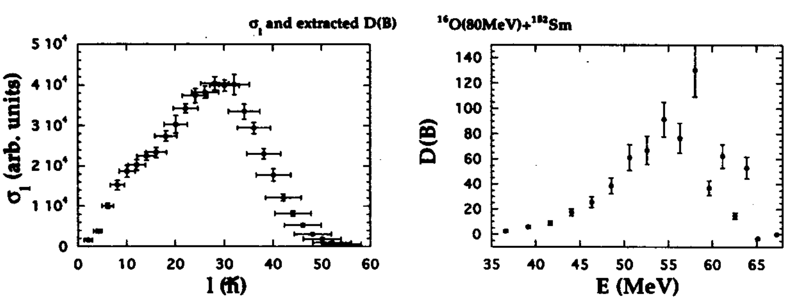

Fig. 6. Measured angular momentum distribution of ^{16}O+^{152}Sm [18] and extracted barrier distribution (see text).

In this way $D(B)$ can be obtained from a complete angular momentum distribution deriving it once. It covers an energy range from $E - E_{\rm rot}(\ell_{\rm max})$ to E. For a medium mass system as ^{28}Si+^{100}Mo at an energy above the barrier and a reasonable maximum angular momentum of $55\hbar$ this corresponds to an energy difference of $\Delta E = 27$ MeV. This includes the total barrier range yielding a complete barrier distribution from only one measured angular momentum distribution. We have applied this method to angular momentum distributions calculated with CCfus [10]. The transmission functions for the three cases of coupling one channel with $Q = 0$, $Q > 0$ and $Q < 0$ are shown in Fig. 4. In Fig. 5 the resulting barrier distributions are compared with the second derivative of fusion excitation functions generated with the same parameters. The reaction ^{28}Si+^{100}Mo was chosen only to fix the mass frame. The good agreement between both approaches confirms their consistency which is implicitly given by the CC-model.

Finally a first application of this method to the angular momentum distribution of ^{16}O+^{152}Sm (deformed) measured by Wuosmaa *et al.* [18] shows (Fig. 6) a barrier distribution similar to what Wei and Leigh *et al.* [3,4] obtained for ^{16}O+^{154}Sm as expected for a prolate deformed nucleus.

4. Summary and conclusions

I have reported on the measurement of fusion cross sections and average angular momenta for the five target-projectile combinations ^{16}O+^{112}Cd, ^{28}Si+^{94,100}Mo and ^{58,64}Ni+^{64}Ni. A good overall consistency between CC-calculations and data has been found in almost all cases. Only in the case of ^{64}Ni+^{64}Ni the theoretical predictions overestimate the experimental fusion cross sections. The main features of the average angular momentum distribution $\langle\ell\rangle(E)$ predicted by the CC-model as the barrier "bump" and the asymptotic limit at energies far below the barrier have been observed. Indications about the important role that 2n-transfer channels play for the onset of fusion have been found, together with a systematic Q-value dependence.

I have presented a new method for the extraction of barrier distributions $D(B)$ from experimental data via the first derivative of complete angular momentum distributions. This method is consistent with the one proposed by Rowley *et al.* [2] as shown by the comparison of both approaches for simplified CC-calculations with the code CCfus [10]. A first application to experimental data from Ref. [18] for ^{16}O+^{152}Sm shows a structure similar to that expected for a deformed nucleus. These results encourage the application of the method to other cases as a further test of the coupled channels model. Some refinement taking into account the variation of form and position of the barrier with increasing angular momentum is still needed.

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