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by

M.S. Hussein
Instituto de Física, Universidade de São Paulo

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COHERENT AND STATISTICAL FEATURES OF CHANNEL COUPLING EFFECTS IN HEAVY-ION FUSION REACTIONS*

M.S. HUSSEIN
Instituto de Física, Universidade de São Paulo
C.P. 20516, São Paulo, SP, BRASIL

ABSTRACT

A general discussion of coupled channels effects on the heavy ion compound nucleus formation cross section is presented. Both coherent and statistical features of these effects are considered. Heavy ion fusion reactions are then analyzed within a two-step compound model composed of a di-nucleus configuration, representing overlapping quasimolecular resonances, coupled to particle and break-up channels as well as to an equilibrated compound nucleus configuration. The resulting fusion cross sections, defined as the summed particle emission cross section from the equilibrated compound nucleus, are in reasonable agreement with the data for several systems. The time evolution of the HI system is also briefly discussed.

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I. INTRODUCTION

Heavy ion fusion reactions have created a great amount of interest in the last several years. The popular picture states that at low energies the fusion cross section follows the trend of the total reaction cross section, σ_R exhausting almost all of it (this region is usually referred to as region I). After a certain critical energy, E_c, (of the order of 1.5 E_B, where E_B is the energy corresponding to the height of the Coulomb barrier), is reached, however, as σ_R continues exhibiting its "geometrical" behaviour,

$$\sigma_R = \pi R_B^2 (1 - \frac{E_B}{E}) \quad (1)$$

where R_B is the radius of the Coulomb barrier, the fusion cross section, σ_F, bends down and eventually follows something like

$$\sigma_F = \pi R_c^2 (1 - \frac{E_c}{E}) \quad (2)$$

with $R_c < R_B$ and E_c, is negative for heavy-ion systems and positive for heavier systems. The region where (2) is valid is referred to as region II. Recently, several authors have even suggested a Region III that follows Region II and is characterized by a steep slope. For a review of the subject see the recent article by Birkelund and Huizenga [1].

Most recent publications concerned with heavy ion fusion attempt to answer the following question: is the fact that in region II, $\sigma_F < \sigma_R$ is just telling a trivial fact about unitarity, namely the increasing contribution to σ_R of "direct" processes dominated mainly by deep inelastic reactions or does it contain some more useful information related to the eventually populated compound system?

An answer to this question would lead to a reasonable understanding of the origin of the quantities R_c and E_c and eventually to a deeper understanding of the phenomenon of heavy-ion fusion.

Two distinct interpretations of the heavy-ion fusion cross section in region II exist. The first, the critical distance model, asserts that at higher energies, partial waves that will eventually fuse, have to penetrate, unhindered, up to critical distance, R_c. The threshold energy, E_c, then refers to the value of the interaction potential at this distance. This interpretation is popularly referred to as entrance channel interpretation (ECI). The second approach assumes that the compound nuclear yrast line is responsible for limiting the fusion cross section in region II. A variance of this model, the statistical yrast line [2], assumes that the compound nucleus formed in the fusion process is not in its ground state but rather in an excited state, i.e. where the energy in the compound system is split into two parts, intrinsic excitation par[t] and a rotational part. This last observation is the basis of the shift in the Q-value, ΔQ, discussed by Lee et al.. A refinement of this model, where ΔQ in allowed to depend on the mass number of the compound nucleus har been made in Ref. 3.

We consider both models the entrance channel model and the statistical yrast line model as containing some of the features of the fusion process. But we view both models as extremes, in the sense that in the first, no reference to the compound nucleus is made, whereas in the latter, the fully equilibrated compound nucleus is considered to be explicitly "seen" through the fusion cross section. It is expected that both entrance channel and some aspects of the compound system must be present.

The question one is bound to ask is how to couple both effects? We present below arguments which suggest that a minimal why of achieving this is through the introduction of the dinucleus.

It is a well known fact that heavy-ion systems such as $^{12}C+^{12}C$, $^{16}O+^{12}C$ etc., exhibit, in the elastic and compound nucleus (fusion) excitation functions intermediate structure, which is commonly related to the formation of isolated quasi-molecular resonances. It is also a common knowledge that heavier, or structurally more complex systems, do not show this behaviour. One is therefore tempted to suggest that these resonances, which may be isolated in $^{12}C+^{12}C$ etc.,at the energies considered, $\frac{E_{CM}}{A} \sim 2-3$ MeV, become overlapping at higher energies and/or in other systems.

In fact the experience one has gained from studying the dynamics of nuclear reactions over the last thirty years indicates clearly a gradual evolution of these "doorway" resonances, as the energy is increased, from isolated rather widely spaced structures to the overlapping regime, which requires a statistical treatment. Further, quite recently, several authors have suggested that the energy structure seen in the elastic scattering of C+C and O+C may be due to these evolved quasimolecular resonances. In the heavy-ion case one may visualize these resonances geometrically as two sticking nuclei (with a moment of inertia larger than that of the compound nucleus).

It is our aim here to incorporate the overlapping quasimolecular resonances, in the description of heavy-ion fusion processes, commonly discussed within simple models. We visualize the fusion process as in Fig. 1.

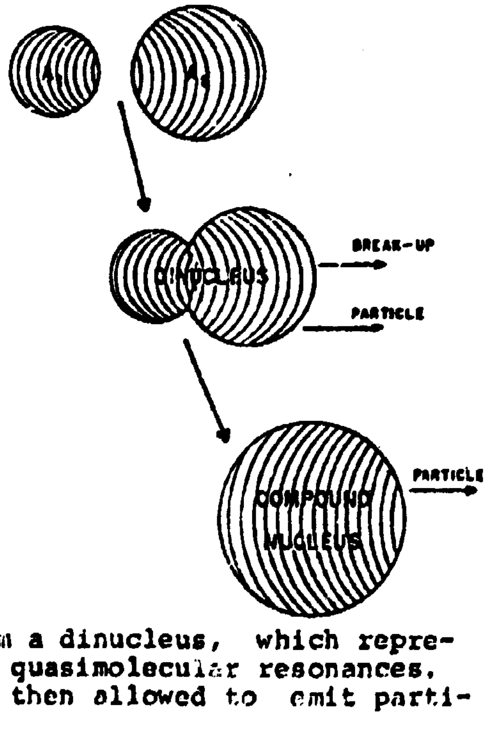


Figure 1.

A schematic representation of the two-step compound fusion process.

The two approaching nuclei, first form a dinucleus, which represents, geometrically, the overlapping quasimolecular resonances. This intermediate composite system is then allowed to emit particles and to break up as well as couple to the equilibrated compound nucleus. There is no direct coupling between the entrance channel and the compound nucleus. The dinucleus acts as a "doorway", and we shall call it such throughout this paper.

The fusion cross section is calculated as the summed "inclusive" cross section for particle emission from the equilibrated compound nucleus. The model we develop below is based on a generalization, to the heavy ion case, of the statistical multiclass compound model of Agassi, Weidenmüller and Mantzouranis [4]. The coupling between the dinucleus and the compound nucleus is treated statistically.

We may, at this point, remind the reader that what we are calling a dinucleus is a two-nucleus configuration which is invariably encountered as an intermediate stage in microscopic, mean field, calculation [5]. Of course, in these theories, which contain only the average mean field effects, one does not obtain the full picture involving the formation and eventual decay of the compound system (namely the exclusive cross section).

For this purpose, a more complicated formulation involving the addition of particle collision effects, is required. In the absence of such theories, one is bound to try other formulations of the problem such as the one alluded to above, which, though necessarily less microscopic, have the merit of being easier to handle theoretically.

Before we present our model, we first give a general discussion of heavy ion fusion reactions affected by direct channel, and multiclass compound, couplings.

II. GENERAL CONSIDERATIONS

The total reaction cross may be written as

$$\sigma_R = \frac{k}{E} \langle \psi_k^{(+)} | (-\text{Im}V) | \psi_k^{(+)} \rangle \qquad (3)$$

where V is the optical potential in the elastic channel. The total wave function in the elastic channel is denoted by $\psi_k^{(+)}$. The center of mass energy and the asymptotic wave number are denoted by E and k respectively.

Equation 1 may also be written in terms of partial wave transmission coefficients T_ℓ as follows

$$\sigma_R = \frac{\pi}{k^2} \sum_{\ell=0}^{\infty} (2\ell+1) T_\ell \qquad (4)$$

where

$$T_\ell = \frac{8\mu k}{\hbar^2} \int_0^\infty dr\, |\psi_{\ell,k}(r)|^2 \, |\text{Im}V(r)| \qquad (5)$$

Now the relevance of Eq. (3) to fusion may be made clear by a detailed analysis of ImV. Presumably ImV accounts for compound nuclear absorption + direct processes. In heavy ion systems, however, direct coupling of elastic channel to the compound nuclear states is quite small. It is believed that to populate compound states the system has to first couple to inelastic and transfer channels. This in turn results in an ImV that is basically surface potential.

In the following we formalize the above remarks. We introduce the following projection operators p, q, D_d, and D_c, with p denoting elastic and almost elastic channels (low lying excited collective states), $Q = q+D_c$ the compound nucleus states, D_d denotes the direct doorway subspace: i.e. channels that act as doorways for fusion (giant resonances, transfer channels etc.) and D_c, compound doorway subspace referring to some simple states in the compound system.

We postulate that heavy-ion reactions are characterized by the following important restriction on the coupling

$$H_{pQ} = 0 \tag{6}$$

We call condition (6), the multistep generating condition. Then Feshbach's theory predicts for ImV the following

$$\mathrm{Im}V = \mathrm{Im}H_{pD_d}\mathcal{G}^{(+)}_{D_d}(E)H_{D_dp} \tag{7}$$

where $\mathcal{G}^{(+)}_{D_d}$ is the total Green's function in subspace D_d and describes the propagation of the nuclear system in the space spanned by giant multipole resonances, transfer channels, etc and is given by

$$\mathcal{G}^{(+)}_{D_d}(E) = [E^{(+)} - H_{D_dD_d} - H_{D_dQ}(E - H_{QQ} + \frac{iI}{2})^{-1}H_{QD_d}]^{-1} \tag{8}$$

Since H_{pD_d} and H_{D_dp} are Hermitian, the calculation of ImV is reduced to that of $\mathrm{Im}\mathcal{G}^{(+)}_{D_d}$. Such a calculation would be trivial in the limit of $H_{D_dQ} = 0$ since then the D_d-Hamiltonian operator that appears in the denominator of Eq. (5) becômes Hermitian. For non-Hermitian Hamiltonian, as is the case of Eq. (5), one gets

$$\mathrm{Im}\mathcal{G}^{(+)}_{D_d}(E) = -\pi\sum_i|\tilde{\psi}^{(-)}_{d,i}\rangle\langle\tilde{\psi}^{(-)}_{d,i}| + \mathcal{G}^{(+)+}_{D_d}(E)\,\mathrm{Im}\left[H_{pQ}\frac{1}{E-H_{QQ}+iI/2}H_{Qp}\right]\times\mathcal{G}^{(+)}_{D_d} \tag{9}$$

Therefore σ_R becomes

$$\sigma_R = \frac{k}{E}\pi\sum_i|\langle\psi^{(+)}_{k,i}|H_{pD_d}|\tilde{\psi}^{(-)}_{d,i}\rangle|^2 + \frac{k}{E}\langle\psi^{(+)}_k|H_{pD_d}\mathcal{G}^{(+)+}_{D_d}(E)\times H_{D_dQ}\frac{I/2}{(E-H_{QQ})^2+\frac{I^2}{4}}H_{QD_d}\times\mathcal{G}^{(+)}_{D_d}(E)H_{D_dp}|\psi^{(+)}_k\rangle \tag{10}$$

We identify the first term in Eq. (10) with genuinely direct processes (including deep inelastic processes). The second term of the right-hand side of Eq. (10) is identified with fusion. Notice however, that the coupling between the elastic channel and the compound nucleus is indirect and explicitly given by the effective coupling interaction

$$H_{pD_d}\mathcal{G}^{(+)}_{D_d}H_{D_dQ}$$

There are two features of "channel" coupling effects, which can be seen in Eq. (7). First, the direct channel coupling effects, appearing through the generalized entrance channel wave function,

$$\mathcal{G}^{(+)}_{D_d} H_{D_d P} |\psi_k^{(+)}>$$

(which may be written as $\sum_{D_d} |\psi_{D_d}^{(+)}>$), can cause two distinct changes in σ_F depending on the energy. At sub-barrier energies, these effects result in an overall enhancement of fusion, as they cause an over all reduction in the height of the Coulomb barrier [6] (this can be understood by representing the channel effects through an effective polarization potential, whose imaginary part decreases with decreasing center of mass energy and accordingly, through a dispersion relation argument its real part become more attractive, undering the height of the effective barrier lower). At higher energies, on the other hand, the direct channels, with ever increasing number, simply complete with fusion in the distribution of the incoming flux.

The second feature is connected with the compound system itself. In Eq. (7) the compound system is referred to through the operator

$$H_{D_d Q} \frac{I/2}{(E-H_{QQ})^2 + \frac{I^2}{4}} H_{QD_d}$$

Usually, when one takes only the equilibrated compound system into account (only q), this quantity is taken as function, the imaginary potential representing C.N. formation. In general, when several distinct classes of compound states are considered, one has to deal with a matrix "potential" which takes into account explicitly the coupling among these different classes (e.g. D_c and q), and their subsequent decay into the different open channels.

III. THE MODEL

From the results of the previous section, we have for the "fusion" cross section ($\sigma_R - \sigma_D$)

$$"\sigma_F" = \frac{k}{E} <\psi_k^{(+)}| H_{PD_d} \mathcal{G}^{(+)^+}_{D_d}(E) H_{D_d Q} \frac{I/2}{(E-H_{QQ})^2 + \frac{I^2}{4}} H_{QD_d} \mathcal{G}^{(+)}_{D_d} H_{D_d P} |\psi_k^{(+)}> \tag{11}$$

It is emphasized here that the above expression for "σ_F" is too inclusive to be associated with σ_F extracted from evaporation residue measurements. There are processes included in the above expression, which are not really fusion events; such as an intermediate compound stage (the dinucleus of Fig. (1) representing the D_c space in our general formulation) that decays before the equilibrated configuration is reached. Further in our formulation below, we represent all the direct doorway contribution exemplified by

$$\mathcal{G}_{D_d} H_{D_d P} |\psi_k^{(+)}>$$

by an effective entrance channel, through an appropriate changes in the interaction to be used.

To explicitly take into account the effect of the break up of dinucleus, in Q, we certainly have to calculate from a statistical stand point (see below) the transition from the generalized entrance channel to a final decay channel opened to the equilibrated compound system. For this purpose we use the formulation of multistep compound processes developed by Agassi, Weidenmüller and Mantzouranis (AWM). AWM write the cross section for the transition $i \to f$ as

$$\sigma_{f \leftarrow i} = \frac{\pi}{k^2}(2J+1) \sum_{a,b} T_f^a \pi_{ab} T_i^b \tag{12}$$

where the transmission coefficient, T_c^b, now describes the probability of the channel c to form states of class b in the composite system. The factor π_{ab} describes the transitions among the classes of states of the composite system and can be defined by

$$\pi_{ab}^{-1} = \delta_{ab} 2\pi\rho_a(\Gamma_a^{\uparrow} + \Gamma_a^{\downarrow}) - T_{ab}^{\uparrow} - T_{ab}^{\downarrow} \tag{13}$$

where

$$2\pi\rho_a \Gamma_a^{\downarrow} = \sum_b T_{ab}^{\downarrow} \tag{14}$$

and

$$2\pi\rho_a \Gamma_a^{\uparrow} = \sum_c T_c^a \tag{15}$$

The factor $T_{ab}^{\downarrow}$ describes the internal mixing among classes a and b and is defined to be

$$T_{ab}^{\downarrow} = 2\pi\rho_a \overline{V^2}_{ab} 2\pi\rho_b \tag{16}$$

The external mixing among the classes a and b due to open channels is described by $T_{ab}^{\uparrow}$. We neglect this, taking $T_{ab}^{\uparrow} = 0$.

We can also define a partial cross section

$$\sigma_{fi,ab} = \frac{\pi}{k^2}(2J+1) T_f^a \pi_{ab} T_i^b \tag{17}$$

which can be interpreted as the cross section for channel i to form states of class b, and latter decay from class a to channel f. Note that if we take $T_{ab}^{\downarrow} = 0$ as well as $T_{ab}^{\uparrow} = 0$, π_{ab} is diagonal and the corresponding cross section separates into a sum of independent contributions from each of the classes.

In our model [7], we postulate the existence of a class of overlapping doorway states and a class of compound nucleus states. We assume that the doorway states can decay by breakup or particle emission. We write the corresponding transmission coefficients as T_b^d and T_p^d, respectively. We further assume that the compound nucleus can decay by particle emission only, so that $T_p^c \neq 0$ while $T_b^c = 0$. We can then write the escape width for the compound nucleus as

$$2\pi\rho_c \Gamma_c^{\uparrow} = \sum_p T_p^c \tag{18}$$

while the escape width for the doorway states is

$$2\pi\rho_d\Gamma_d^{\dagger} = 2\pi\rho_d\Gamma_{d,p}^{\dagger} + 2\pi\rho_d\Gamma_{d,b}^{\dagger} = \sum_p T_p^d + \sum_b T_b^d \tag{19}$$

For the mean square matrix element in the internal mixing factor, we take an extremely simplified form of that used by Agassi et al. [4]

$$\overline{V_{dc}^2} = \frac{\overline{V_o^2}}{\sqrt{\rho_d\rho_c}} \tag{20}$$

The inverse dependence on the densities of states of the mean square matrix element is consistent with the increasing complexity of the states and their diminishing overlap with increasing excitation energy. It is also consistent with the smooth energy dependence expected of its sum over final states. The constant $\overline{V_o^2}$ is treated as a free parameter to be adjusted in conjunction with the ion-ion interaction in the effective entrance channel.

The dinucleus level density has the form [8]

$$\rho_d(\varepsilon,J,R) = \frac{\pi^{7/2}}{72}\left(\frac{\mu R^2}{\mathcal{J}_T(R)}\right)^{3/2}\left(\frac{A^2}{A_1A_2}\right)(CA)\left(2\frac{\mathcal{J}_1}{\mathcal{J}_T(R)}J+1\right) \times \left(2\frac{\mathcal{J}_2}{\mathcal{J}_T(R)}J+1\right)\frac{(cA\varepsilon)^{17/4}}{(cA\varepsilon)+2(A/A_2)^2)^3(cA\varepsilon+2(A/A_2)^2)^3} \times \exp\left[2\sqrt{CA\varepsilon}\right] \tag{21}$$

where A is the total mass number, $\mathcal{J}_i$ is the moment of inertia of fragment i and $\mathcal{J}_T(R)$ is that of the total composite system,

$$\mathcal{J}_T(R) = \mu R^2 + \mathcal{J}_1 + \mathcal{J}_2 \tag{22}$$

To eliminate the radial dependence of the dinucleus level density we assume that the system will prefer the radius that maximizes the density of states. We thus choose R_J by maximizing the excitation energy and minimizing the effective potential energy.

We take the effective potential for partial wave J to then be

$$V(J) = \left[V(R_J) + \frac{\hbar^2 J(J+1)}{2\mathcal{J}_T(R_J)}\right]\Big|_{min} + \frac{\hbar\omega(R_J)}{2} \tag{23}$$

The term $\frac{\hbar\omega}{2}$, proportional to the curvature of the potential, is added to take into account the minimum energy of the fragments trapped in the potential well. The final form of the doorway level density is then given by Eq. (21) evaluated at R_J with

$$\varepsilon = E - V_{min}(J) \tag{24}$$

The transmission coefficients were calculated, using the Hill Wheeler form, with a global real potential of the Wood-Saxon type, whose parameters were adjusted, together with $\overline{V_o^2}$, to give the best account of the data for a large variety of light heavy and medium heavy systems. The adjusted nucleus-nucleus potential, describing the effective entrance channel is,

$$V(R) = -20.11\frac{R_1R_2}{R_1+R_2}(1+1.014(\frac{N-Z}{A})^2) \times$$
$$\times \left[1+\exp(\frac{R-R_0}{0.4454})\right]^{-1} [\mathrm{MeV}] \tag{25}$$
$$R_{1,2} = 1.2998A_{1,2}^{1/3} - 0.4286A_{1,2}^{-1/3}[\mathrm{fm}]$$
$$R_0 = R_1 + R_2 + 0.29[\mathrm{fm}]$$

The partial wave fusion cross section, obtained from Eq. (17) looks like

$$\sigma_F^J = \frac{\pi}{k^2}(2J+1)\frac{2\pi\rho_c\Gamma_c^{\uparrow}T^{\downarrow}T_0^d}{2\pi(\rho_d\Gamma_d^{\uparrow}+\rho_c\Gamma_c^{\uparrow})T^{\downarrow}+(2\pi\rho_c\Gamma_c^{\uparrow})(2\pi\rho_d\Gamma_d^{\uparrow})} \tag{26}$$

The complete fusion cross section is calculated from Eq. (26) by summing over all J.

IV. RESULTS

To simplify the calculation, we have considered explicitly only the collective (rotational) degrees of freedom in constructing the level density of states of the dinucleus. To partially take into account the intrinsic degrees of freedom, we merely adjust the level density parameter a (which appears in the Fermi gas formula as $e^{2\sqrt{aE^*}}$) to be $\frac{A}{8x}$, with x being a parameter. Usually x = 1. Here, we find, motivated by the result of Ref. 3 that the internal energy of the composite nucleus $Q = 0.27\ A_{CN}$; that a_d (of the dinucleus) is related to a_c (of the compound nucleus) by

$$a_d = 0.2\ a_c \tag{27}$$

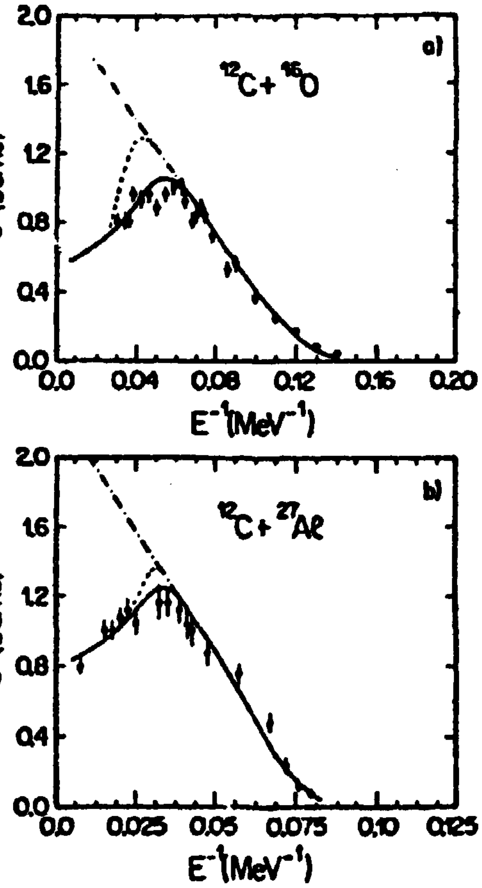
implying x = 5.

We show in Fig. 2, a sample of our results obtained with $\overline{V_0^2}\pi$ = 21.5 MeV. The drop in σ_F, seen in what is called Region II, is attributed, within our model, to the increased importance of the dinucleus break-up channel. We have repeated the calculation to more than twenty systems, obtaining an overall reasonable agreement with the data. We may mention that the energy corresponding to maximum fusion cross section is systematically well predicted. Further, the feature of the σ_F vs E_{CM}^{-1} that depends on the entrance channel, and which is reflected by positive, null or negative values of $V_{critical}$ [1], is nicely predicted by our model (e.g. for $^{12}C + ^{16}O$, $^{16}O + ^{27}Al$ and other light heavy systems have $V_{cr} < 0$ while $^{16}O + ^{40}Ca$ or $^{40}Ca + ^{40}Ca$ exhibit $V_{cr} \geq 0$).

The contribution of particle emission from the dinucleus (doorway) configuration is shown in Fig. 2, summed to σ_F (dashed line). We see clearly that this effect is mostly important in the region of maximum σ_F. This implies that pre-equilibrium particle emission should be reasonably copious at these energies. Further, there seems to be a clear connection between the value of σ_{max}^F and

Figure 2.

σ_F for the systems $^{12}C + {}^{16}O$ (Fig.2a) and $^{12}C + {}^{27}Al$ (Fig. 2b). Full curve corresponds to our calculated σ_F. Dashed curve represents $\sigma_F + \sigma_{pre}$. The dashed dotted curve is the total reaction cross section, calculated from the entrance channel transmission coefficient. The data points were collected from Ref. 1.



the cross sections for dinucleus particle emission (pre-equilibrium) σ_{pre}; the larger σ^F_{max}, the smaller σ_{pre}.

For completeness, we show in Fig. 3, the calculated values of σ^F_{max} for 24 systems. Our result comes out quite reasonable, and follows closely the trend of the data and the empirically determined σ_F^{max} of Ref. 2. For comparison, we show in the same figure the prediction of the statistical yrast line model of Ref. 2.

The fact that the general trends of the fusion excitation functions are reasonably well predicted by our model, using the global entrance channel potential plus an average dinucleus - compound nucleus mixing parameter, for more than twenty HI systems, clearly indicates that the most important features of the dynamics are adequately taken into account in the present calculation.

The crucial new ingredient is the presence of the dinucleus, which acts as a "doorway" to fusion. The explicit consideration of the competition between fusion on the one hand and doorway break-up and particle emission channels on the other hand is an important feature of our model, which helps account naturally and consistently for the downward drop of σ_F in Region II seen in light-heavy ion systems, avoiding thus the introduction of a "Region III" [9], in complete agreement with Ohta et al. [10]. Some indirect experimental evidence for the existence of the dinucleus has already been reported [11].

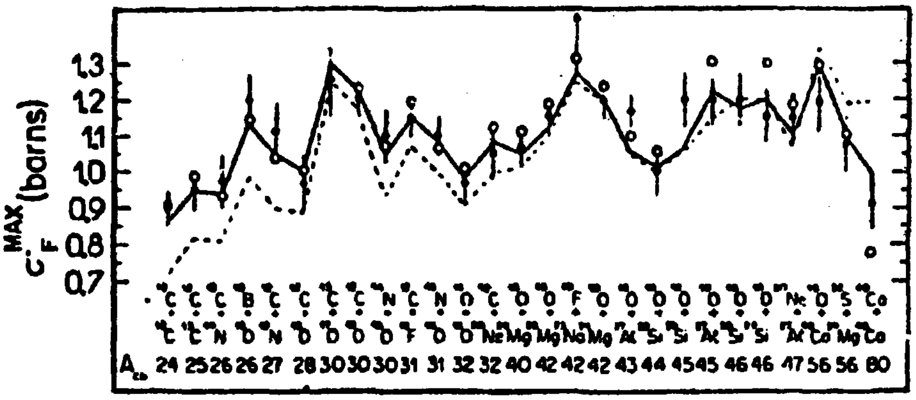


Figure 3

Maximum fusion cross section σ_F^{max} measured for various systems (closed circles). Data were taken from original papers cited in Refs. 1 and 5. The open circles are our calculated σ_F^{max}. The full curve is the empirically found σ_F from the modified statistical yrast line model [3]. The dashed curve is the statistical yrast line model prediction of Ref. 2.

V. TEMPORAL EVOLUTION AND CORRELATION WIDTHS

An important feature of a multi-step compound process is the overall temporal evolution of the system. Once the compound system is formed, its time evolution represented by $A(t)$ (see below), can be easily found by Fourier transforming the multiclass compound S-matrix correlation function [12]. *In the eigenclass* representation [13], which diagonalizes π (Eq. (3)) we have, following McVoy and Tang [14]

$$A(t) = a_+ e^{-\lambda_+ t} + a_- e^{-\lambda_- t} \tag{28}$$

where $\lambda_\pm$ are the eigenvalues of the matrix $\rho^{-1/2}\pi\rho^{-1/2}$, namely

$$\lambda_\pm = \frac{\Gamma_c+\Gamma_d}{2} + \left(\sqrt{\frac{\rho_d}{\rho_c}} + \sqrt{\frac{\rho_c}{\rho_d}}\right)\overline{V_o^2} \pm \sqrt{\left(\frac{\Gamma_c-\Gamma_d}{2}\right)^2 + \left(\overline{V_o^2}\right)^2} \tag{29}$$

The λ_+ and λ_- have very simple physical meaning; they correspond, respectively, to the correlation length (inverse life time) of the doorway (dinuclear) and compound nucleus configurations [12]. The coefficients a_+ and a_-, are "eigenclass" cross sections, both having the one-class Hauser-Feshbach form [14]. We shall not dwell on the calculation of these cross sections, but rather concentrate on the, more interesting, correlation widths, λ_+ and λ_-.

We recall at this point, that these widths have recently been extracted, through a generalized Ericson analysis of the type proposed in (12), for the system $^{15}N + ^{12}C \to \alpha + ^{23}Na$ [15] and using the spectral density method, for the system $^{16}O + ^{12}C \to \alpha + ^{24}Mg$ [16].

From our results of Section IV, we have extracted the correlation widths of the doorway configuration, λ_+ and for the equilibrated system, λ_-. We have chosen the process $^{16}O + ^{12}C \to \alpha_0 + ^{24}Mg$, for definiteness. We have found that if we maintain the value of $\overline{V_0^2}$, in the coupling, equal to 21.5 (MeV) we obtain a reasonable value for λ_- ($\sim$ 70 keV), however, λ_+ comes out extremely large. This shows that the lifetime of the dinuclear system is very short. According to the findings of Ref. 3, λ_+ for $^{16}O + ^{12}O \to \alpha + ^{24}Mg$ is about 250 keV and varies slowly with increasing excitation energy. To get the expected values of λ_+ and λ_- (70 and 250 keV, respectively) we had to reduce $\overline{V_0^2}$ by a factor 10^4! The resulting fusion cross sections, however come out in disagreement with the data.

The above findings clearly indicate that our model, though fully adequate for the description of heavy ion fusion as well as the angular distribution of emitted particles [8], cannot simultaneously describe the time evolution of the system. Presumably the details of the equilibration process, which are not fully accounted for in our model, is the necessary missing ingredient! This may necessitate the inclusion of other classes of compound configurations.

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