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ABSTRACT

Heavy ion fusion reactions of light and medium systems have been analyzed within a two-step compound model composed of a dinucleus, coupled to particle and break-up channels, as well as to the equilibrated compound nucleus. The fused configuration is reached from the entrance channel only via the dinucleus. The resulting fusion cross sections, defined as the summed particle emission cross sections from the equilibrated system, are in reasonable agreement with the data.

In the last several years heavy ion fusion reactions have attracted considerable interest, both theoretical and experimental[1]. More than half a dozen models have been proposed, ranging from the more sophisticated microscopic, TDHF to simple geometrical parametrizations. Several facts have emerged from these studies, the more important of which is that the simple one-degree of freedom description, usually called the entrance channel model, is not fully adequate. For a recent review we refer the reader to Ref. 1.

In this Letter, we develop a model for heavy ion fusion which incorporates both the entrance channel effects and the compound nucleus characteristics in a consistent way. We feel that a model realistic enought to deal with HI fusion must contain, at least, these effects.

We emphasize at this point that by "entrance channel effects", we do not mean just the restriction imposed through transmission factors calculated with a given entrance channel potential, rather, we also incorporate the effects arising from the formation of an intermediate dinucleus configuration that preceeds the final equilibrated compound nucleus. We allow the HI system to emit particles both from the intermediate stage as well as from the compound nucleus. The dinucleus system is also allowed to break-up into two fragments. The need for such a multi-step description of heavy ion fusion has already been pointed out in previous publications[2,3].

Figure 1 shows the sequence of events that eventually lead to fusion. The coupling between the dinucleus and the compound nucleus is treated statistically within the multi-step compound model of Agassi, Weidenmüller and Mantzouranis[4]. The partial cross section for a transition, leading to particle emission from the compound nucleus is calculated as

$$\sigma_{fi}(J) = \frac{\pi}{k_i^2}(2J+1)\, T_f^{\,c}\, \Pi_{cd}\, T_i^{\,d} \tag{1}$$

where T_i^d is the transmission coefficient describing the formation of the dinucleus from the entrance channel, T_f^c is the corresponding particle emission transmission coefficient from the compound nucleus and π_{cd} is an internal mixing matrix element describing the coupling between the dinucleus and the compound nucleus. The full internal mixing matrix is given by the inverse of

$$\Pi^{-1} = \begin{pmatrix} 2\pi\rho_d\Gamma_d^{\uparrow} + T^{\downarrow} & -T^{\downarrow} \\ -T^{\downarrow} & 2\pi\rho_c\Gamma_c^{\uparrow} + T^{\downarrow} \end{pmatrix} \tag{2}$$

where the internal mixing factor $T^{\downarrow}$ is

$$T^{\downarrow} = (2\pi)^2\sqrt{\rho_c\,\rho_d}\;\overline{V_o^2} \quad , \tag{3}$$

ρ_d and ρ_c are, respectively, the J-dependent density of states of the dinucleus and compound nucleus, $\Gamma^{\uparrow}$ is the escape width, given by

$$\Gamma_d^{\uparrow} = \Gamma_d^{\text{break-up}} + \Gamma_d^{\text{particle}} \tag{4}$$

$$\Gamma_c^{\uparrow} = \Gamma_c^{\text{particle}} , \tag{5}$$

and $\overline{V_o^2}$ is an over all coupling constant, which is taken as a free parameter.

The density of states of the dinucleus is calculated assuming a sticking situation, in the Fermi gas model. ρ_C is the usual compound nucleus density of states. The fusion cross section is calculated from Eq. (1) by summing over all particle emission channels from the compound nucleus and over J. 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 is

$$V(R) = -20.11 \frac{R_1 R_2}{R_1 + R_2}\left(1 + 1.014\left(\frac{N-Z}{A}\right)^2\right) \times$$

$$\times \left[1 + \exp\left(\frac{R - R_o}{0.4454}\right)\right]^{-1} \text{ [Mev]} \tag{6}$$

$$R_{1,2} = 1.2998 A_{1,2}^{1/3} - 0.4286 \; A_{1,2}^{-1/3} \quad \text{[fm]}$$

$$R_o = R_1 + R_2 + 0.29 \quad \text{[fm]}$$

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. 2 that the internal energy of the composite nucleus $\Delta Q = 0.27\ A_{CN}$, that a_d (of the dinucleus) is related to a_c (of the compound nucleus) by

$$a_d \cong 0.2\, a_c \tag{7}$$

implying x = 5.

We show in Fig. 2, a sample of our results obtained with $\overline{V_o^2}$ = 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. The details of these calculation will be published elsewhere[5]. 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^F_{max} and 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 come out quite reasonable, and follow 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. 6.

In conclusion, 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 claculation.

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"[7], in complete agreement with Ohta et al.[8]. Some indirect experimental evidence for the existence of the dinucleus has already been reported[9,10].

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10. It is tempting to suggest that the dinucleus, as it is treated in our model, is a geometrical visualization of overlapping quasi-molecular resonances. As is well known, HI systems such as $^{12}C + ^{12}C$, $^{16}O + ^{12}C$, 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 led to the suggestion that these resonances, which may be isolated in, e.g. $^{12}C + ^{12}C$, at the energies considered, $\frac{E_{CM}}{A} \sim 2\text{-}3$ MeV, become overlapping at higher energies and/or in other systems.

FIGURE CAPTIONS

Figure 1. A schematic representation of the two-step compound fusion process.

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.

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^{max} from the modified statistical yrast line model[2]. The dashed curve is the statistical yrast line model prediction of Ref. 6.

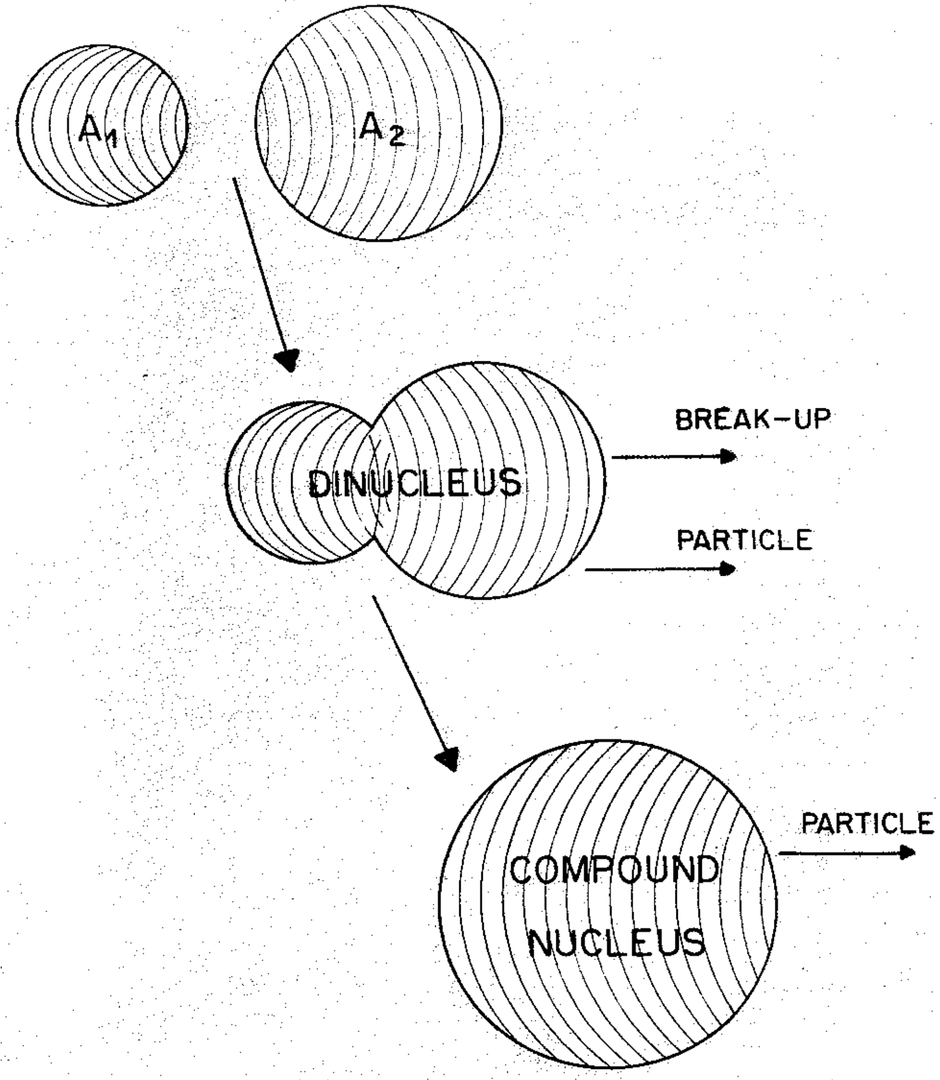

Fig. 1

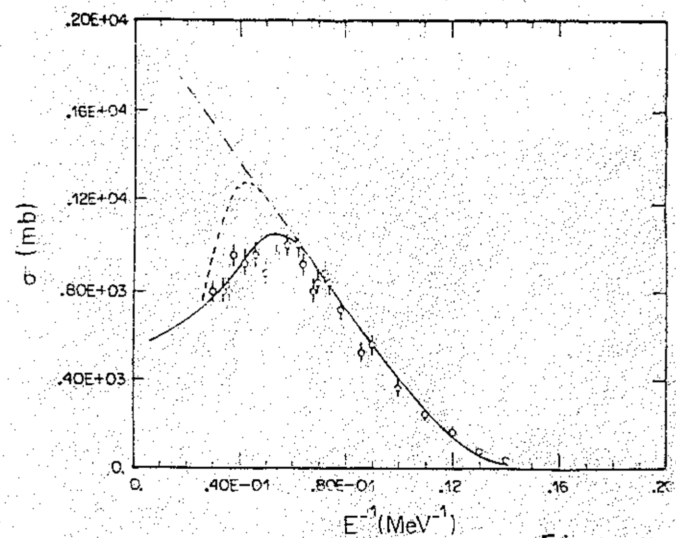

Fig. 2a

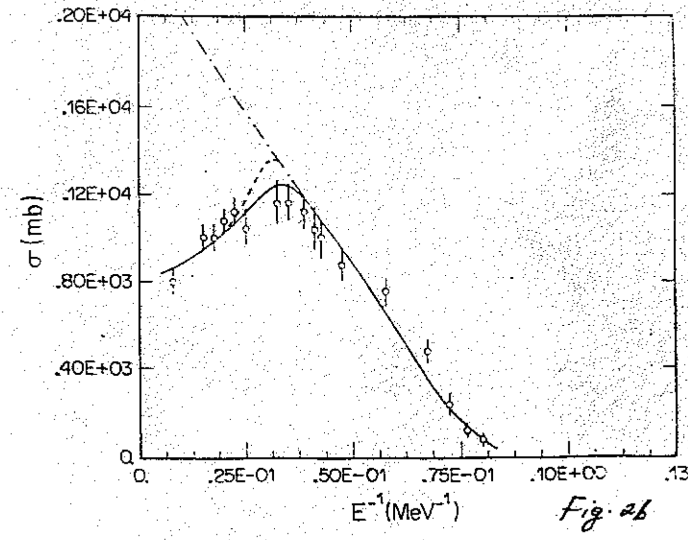

Fig. 2b

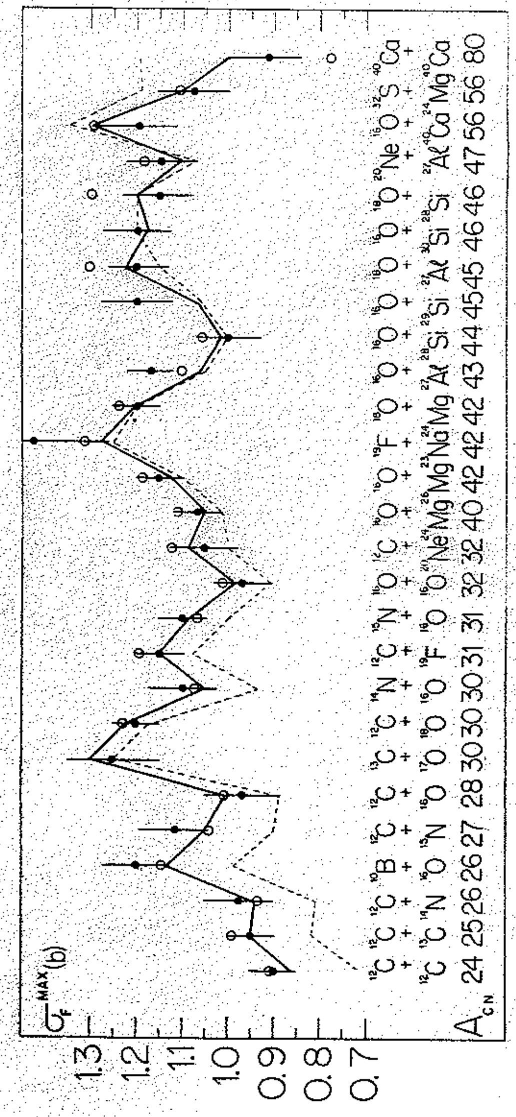

Fig. 3