UNIVERSIDADE DE SÃO PAULO

INSTITUTO DE FÍSICA
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O. Civitarese, B.V. Carlson, M.S. Hussein
and A. Szanto de Toledo

Instituto de Física da Universidade de São Paulo
Lab.Pelletron, CP 20516, São Paulo, Brasil

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O.Civitarese(*), B.V.Carlson, M.S.Hussein and A.Szanto de Toledo

Instituto de Física da Universidade de São Paulo
Lab.Pelletron, C.P. 20516, São Paulo, Brasil

ABSTRACT

A systematic analysis of available light- and intermediate-heavy-ion fusion cross section data within the Statistical Yrast Line Model is performed. The intrinsic excitation energy needed for fusion to occur is found to depend linearly on the mass of the compound system. An interpretation of this dependence in terms of multistep processes is suggested.

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(*) Fellow of the CONICET, Argentina. Permanent address, Department of Physics, University of La Plata, Argentina.

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The limitation of the complete fusion (σ_F) cross section as a function of bombarding energy has been the subject of extensive experimental and theoretical investigation[1-3]. In the case of light-heavy-ion collisions at low energies ($E_{CM} < 2\ V_B \equiv$ (height of the Coulomb-Barrier), "Region I"), it is well known that σ_F almost exhausts the total reaction cross section (σ_R)[1-2]. At higher energies ("Region II") the systematic observation of a sudden downward deviation of σ_F from σ_R motivated the development of dynamical models[4,5] as well as several parametrized descriptions of the data[6-8].

The available experimental information has been interpreted by either the entrance channel limitation model[6] or the compound nucleus (C.N) limitation model[7-9]. These models basically describe fusion as a process leading directly from the entrance channel to the compound nucleus.

In this letter we present evidence for the role of intermediate stages in limiting the formation of the compound nucleus.

We base our findings on a systematic analysis of the available data within the C.N. limitation model of Ref. 7. The statistical yrast line (S.Y.L) model introduced in Ref. 7, considers the fusion cross section as limited by an "extra" amount of energy ΔQ which should be added to the C.N. yrast line. The resulting S.Y.L can be interpreted as the beginning of strong absorption into the compound nucleus[7]. Similar restriction on σ_F were introduced in Ref. 8. The ΔQ value proposed in Ref. 7, was found to be independent of the mass, $A_{C.N.}$, of the compound system ($\Delta Q \approx 10$ MeV). In the present work we have extended the analysis of Ref. 7, to all available data on σ_F. Futhermore we have recalculated the S.Y.L directly from the data and have found that it differs from the yrast line of the C.N. by an energy ΔQ, which does depend on $A_{C.N}$. This result should be contrasted with the constant value reported by Lee et al.[7].

In our analysis we have used the expression

$$\Delta Q = E_{CM} + Q - \frac{\hbar^2}{2\mathcal{J}_{C.N}} I(I+1), \tag{1}$$

where E_{CM} is the center of mass energy, Q is the Q-value for the C.N. formation, I is the C.N. angular momentum identified with the critical angular momentum, ℓ_c, extracted from the experimental σ_F (i.e. $\sigma_F = \frac{\pi\hbar^2}{2\mu E_{CM}}(\ell_c + 1)^2$; μ being the reduced mass). In Eq.1, $\mathcal{J}_{C.N}$ is the rigid body moment of inertia given by

$$\mathcal{J}_{C.N} = \frac{2}{5} m r_o^2 \, A_{C.N}^{5/3} \quad , \tag{2}$$

with $r_o = 1.20$ fm and m being the nucleon mass. The best fit to the maximum value of the fusion cross section (σ_F^{max}) was obtained with

$$\Delta Q = 0.27 \; A_{C.N} \; \text{MeV} \tag{3}$$

Our results for σ_F^{max}, obtained with ΔQ of Eq. 3, for a wide variety of systems are shown in Fig. 1. The above result, Eq. 3, clearly, indicates that the amount of energy deposited into the compound system reaches saturation: the intrinsic energy per unit mass approaches a constant value ($\simeq$ 0.27 MeV/A).

We advance the following picture concerning the nature of the C.N configurations that carry the above excitation energy. We assume that ΔQ is distributed among a certain number of excitons, the average value of which, $\bar{n}$, is given by[10,11)]

$$\bar{n} = (2g\Delta Q)^{1/2}, \tag{4}$$

where g is the average level density at the Fermi energy ε_F[11)]

$$g \simeq \frac{\pi^2}{4} \frac{A_{C.N}}{\varepsilon_F}. \tag{5}$$

Using the empirical relation, Eq. 3, we obtain

$$\bar{n} \simeq 0.2 \; A_{C.N} \quad , \tag{6}$$

when the value $\varepsilon_F = 37$ MeV is used. The obtained value of $\bar{n}$, therefore represents the minimum number of excitons which have to be excited in the compound system for fusion to occur. We view the linear dependence of $\bar{n}$ on $A_{C.N}$ as an indication of the importance of the single-particle-degrees of freedom at this stage of the fusion process.

For light-heavy-ions, e.g. $^{12}C + {}^{15}N$, expression (6) gives $\bar{n} \simeq 5$. For such a small value of $\bar{n}$ it is known that the ratio between the escape width $\Gamma_{\bar{n}}^{\uparrow}$ and the damping width $\Gamma_{\bar{n}}^{\downarrow}$ is not negligible ($\Gamma_{\bar{n}=5}^{\uparrow} / \Gamma_{\bar{n}=5}^{\downarrow} \simeq 0.1$)[11)]. According to Agassi et al.[11)] this should ensure an intermediate stage sufficiently long-lived to allow pre-equilibrium emission. In contrast, for medium-heavy systems, e.g. $A_{C.N} \simeq 80$ we find $\bar{n} \simeq 16$, which corresponds to a ratio $\Gamma^{\uparrow}_{\bar{n}=16} / \Gamma^{\downarrow}_{\bar{n}=16} \approx 0.01$[11]. This indicates the decreased importance of the intermediate stages and a corresponding reduction of pre-equilibrium emission in heavier system. In this case it is appropriate to relate ΔQ of Eq. 3 to the average internal energy of an equilibrated C.N., thus making valid the concept of a critical temperature for fusion, T_F. Using the relation

$$\Delta Q = a T_F^2 \quad , \tag{7}$$

and taking for the level density parameter $a = A/8$ MeV^{-1}, we find as an average temperature $T_F \approx 1.47$ MeV.

Evidence supporting a description in terms of the exciton model can be found in the statistical analysis of the excitation function for the case of the $^{12}C(^{15}N,\alpha)^{23}Na$ reaction[12] at energies within "Region I". This analysis yields a correlation width $\Gamma \approx 400$ keV together with the smaller one (≈ 70 keV) associated with the equilibrated C.N. Ericson fluctuations[12]. The presence of several distinct correlation widths in a given nuclear reaction may be associated with the existence of several classes of overlapping doorway resonances, that are characterized by different numbers of excitons[13]. The more complicated these classes are (the larger the number of excitons), the smaller the correlation widths and consequently the larger their life-times. From this point of view the value $\Gamma \approx 400$ keV can be associated with a simple "doorway" configuration consistent with $\bar{n} = 5$ excitons; the value estimated for this system in the present analysis. Although the results of Ref. 12 were obtained for

energies below the one corresponding to σ_F^{max}, similar pre-equilibrium features are expected to appear at energies in the vicinity of "Region II"[14]. In such a case the pre-equilibrium emission is expected to be observed in the continuum part of the spectrum. The extension of such a statistical analysis to higher energies and other systems would be of great value.

In conclusion, we arrive at a picture of heavy-ion fusion displaying a clear multistep character. This arises, in part, from the rather weak coupling between the initial configuration of the heavy-ion system in the entrance channel and the final configuration that describes the equilibrated compound system. This picture is in line with the conclusions reached by Mosel[1] and clearly points out for the need of a model for heavy-ion fusion which takes into account explicitly the intermediate stages[15].

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FIGURE CAPTION

Figure 1 - Maximum fusion cross section σ_F^{max} measured for various systems (closed circles). Data were taken from original papers cited in ref. 1, 2, 3, 4). The dashed line is a guide for the eye on the σ_F^{max} calculated for all the systems on the basis of the statistical yrast line model[7] with the parametrization r_o = 1.20 fm and ΔQ = 10 MeV.

The full line joins the σ_F^{max} values obtained in the present work using the dependence $\Delta Q = 0.27\ A_{CN}$. (cf. Eq. 3).

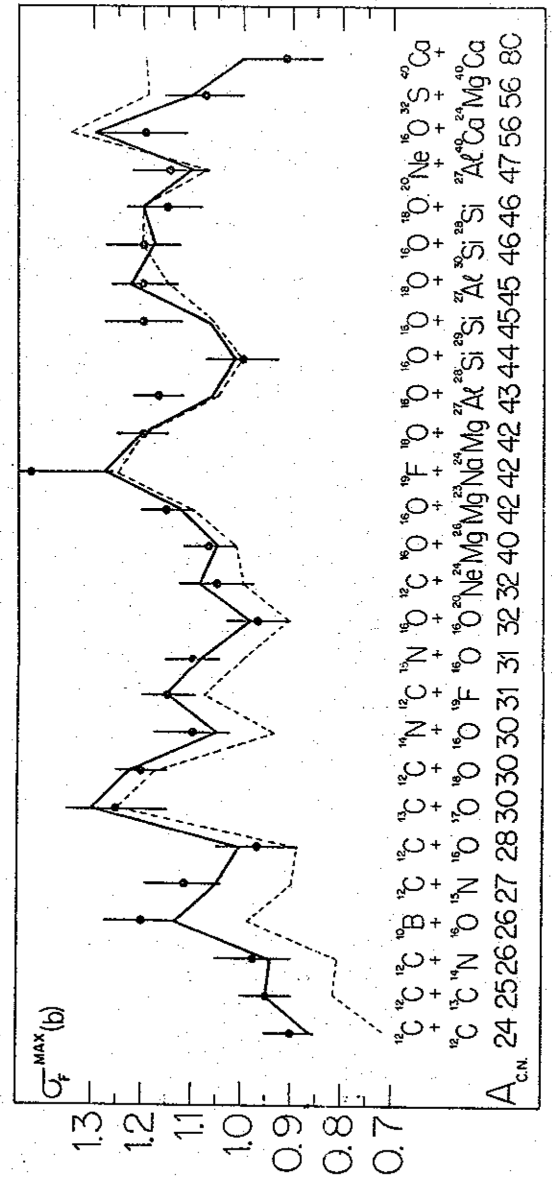

FIGURE 1