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Dissipative capture in heavy-ion fusion*

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Energy dissipation during sliding contact is discussed as a fusion limiting mechanism in heavy-ion collisions. A simple model yields a critical angular momentum for fusion in good agreement with the experimental trend of Natowitz after normalization. Estimates of the nuclear viscosity coefficient are in order of magnitude agreement with two available values.

[NUCLEAR REACTIONS, HI fusion Limit calculated from surface friction model. Viscosity deduced from experimental data trend.]

I. INTRODUCTION

A high probability for heavy-ion fusion is found for a variety of targets bombarded by projectiles of moderate mass and energy.[1,2,3] The cross section for compound nucleus formation increases as the energy is raised above the barrier and is a large fraction of the total reaction cross section over an energy interval extending well above the barrier. At some sufficiently high energy, however, the measured fusion cross sections turn down[3] and can become a small fraction of the estimated value.[4]

Two models have been proposed to explain the fusion limit. In the Kalinkin and Petkov[5] model, an arbitrary ellipsoid is assumed for the joined nuclei just after contact. If the potential energy decreases with a decrease in deformation, the nuclei fuse, and if it increases, the nuclei fly apart. The model of Cohen, Plasil, and Swiatecki[6] with later development by Blann and Plasil[7] limits the survival of fused nuclei by fission of the compound system. Formation of a compound nucleus without anomalous inhibition is assumed.

In this paper, a limiting mechanism in the first step of compound nucleus formation is discussed. Spherical nuclei are assumed and it is further assumed that in a collision viscous forces act when nuclear surfaces are in sliding contact. Associated with each nucleus is a well defined moment of inertia.

At first contact between two heavy nuclei in a collision, the nuclear surfaces are assumed to slide with respect to one another. Frictional forces (viscous) clutch the two nuclei, imparting an impulsive torque to each. A dissipation of energy is required for the union (see Fig. 1) to take place and the resultant local heating sets the limit since energy dissipated above a certain value will excite reactions at the surface.

In the next section, a simple clutching model is presented which limits the angular momentum for partial waves which will clutch and subsequently fuse. The experimental trend of Natowitz[3] is reproduced after normalization to one point. An estimate of the viscosity is given in Sec. III. No attempt has been made in this paper to include an energy dependence other than that implicit in the viscosity coefficient.

II. MODEL FOR NUCLEAR CLUTCHING

The possibility of energy transfer between degrees of freedom by forces which are viscous in nature has been reviewed by Swiatecki and Bjornholm.[8] The idea of damping of the collective motion and the heating up of single particle motions is adopted here, but applied at the first contact of the two colliding nuclei.

In the fusion of nucleus A with B, compound system C^* is formed and may subsequently decay by emission of neutron, protons, clusters, or γ rays, or by fission:

$$A+B\rightarrow C^*\rightarrow D+xm+yp+z\gamma\,. \tag{1}$$

In the limit of small values for x and y and small fission probability, complete fusion is approached.

For simplicity the initial spins of nuclei A and B are taken to be 0. Three stages in the formation of compound system C are illustrated in Fig. 1. In stage (1), nuclei A and B are in sliding contact with the moment of inertia $\mathcal{I}_1$ given by the separation of centers and masses. For the Lth partial wave, the angular velocity is ω_1, and similarly for stage (2),

$$L\hbar=\omega_1\mathcal{I}_1=\omega_2\mathcal{I}_2\,. \tag{2}$$

Dissipative forces impart an impulsive torque to the nuclei since the moment of inertia for stage

(2) is larger than for stage (1):

$$\mathcal{I}_2 > \mathcal{I}_1, \quad \omega_2 < \omega_1. \tag{3}$$

The moment of inertia $\mathcal{I}_2$ is that for a rigid rotator with the option to fix the moments of A and B at a fraction (α) of their rigid body values (see Fig. 2). As coalescence proceeds after stage (2), the moment of inertia will, in general, decrease with the corresponding increase in angular velocity.

If $\mathcal{I}_A$ is the moment of inertia of nucleus A, the angular momentum impulsively acquired by A during clutching is given by

$$\omega_2 \mathcal{I}_A = \tau \Delta t, \tag{4}$$

where τ is the average torque acting during Δt. To factor out ϵ_1, the energy dissipated in clutching, τ is written

$$\tau = F R_A = \frac{\epsilon_1}{\Delta s} R_A, \tag{5}$$

where F is a force acting tangentially to the surface of nucleus A and R_A is the radius of nucleus A. The sliding distance is Δs, the distance required for clutching to take place.

Substituting, the clutching energy ϵ_1 is given by

$$\epsilon_1 = \omega_2 \mathcal{I}_A \frac{1}{R_A} \frac{\Delta s}{\Delta t}. \tag{6}$$

Using Eq. (2), the result becomes

$$\epsilon_1 = \omega_2 \mathcal{I}_2 \frac{1}{R_A} \frac{\Delta s}{\Delta t} \frac{\mathcal{I}_A}{\mathcal{I}_2} = L\hbar (R_A)^{-1} \frac{\Delta s}{\Delta t} \frac{\mathcal{I}_A}{\mathcal{I}_2}, \tag{7}$$

Since a viscous force is assumed, Δs is expected to be proportional to the relative surface velocity. A convenient form of Δs is given in terms of L by

$$\Delta s = c R_A L, \tag{8}$$

where c is a fitting parameter which depends on the viscosity, the geometric details of the overlap volume, and $\mathcal{I}_A$. A connection to viscosity and a possible energy dependence are discussed in Sec. III. The impulse duration (Δt) is assumed to have the form

$$\Delta t = \frac{\hbar}{E_2}, \tag{9}$$

where E_2 is the rotational energy for stage (2)

$$E_2 = \frac{L^2 \hbar^2}{2 \mathcal{I}_2}. \tag{10}$$

This expression is consistent with that of Sheid, Ligensa, and Greiner[9] in that Δt decreases inversely as the rotational energy increases.

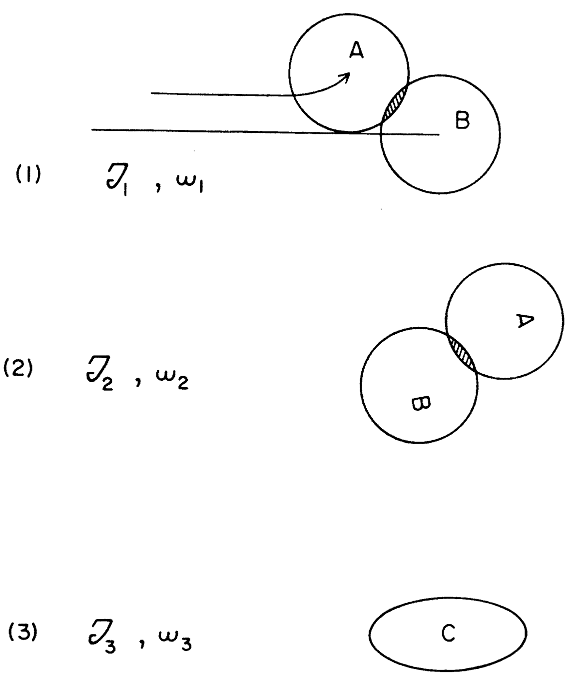

FIG. 1. Three stages of compound nucleus formation in heavy-ion collisions. In stage (1) the nuclei are in sliding contact and the moment of inertia depends on the masses of A and B and distance between centers. In stage (2) the nuclei are clutched (no longer sliding) and the moment of inertia $\mathcal{I}_2$ is that for a rigid rotator which depends on the moments of inertia of A and B, respectively $\mathcal{I}_A$ and $\mathcal{I}_B$, as well as the masses and distance between centers. Stage (3) shows a coalescence to a deformed nucleus with moment of inertia $\mathcal{I}_3$.

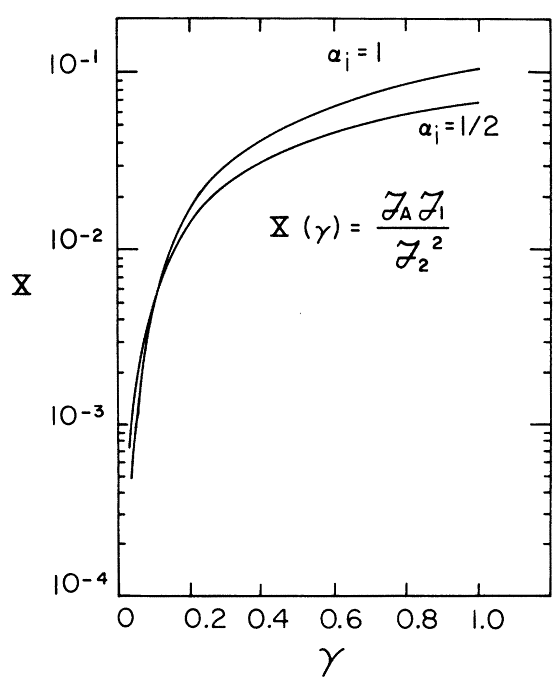

FIG. 2. The quantity $X(\gamma)$ as a function of $\gamma = A/B$ for two values of $\alpha_i = \alpha_A = \alpha_B$.

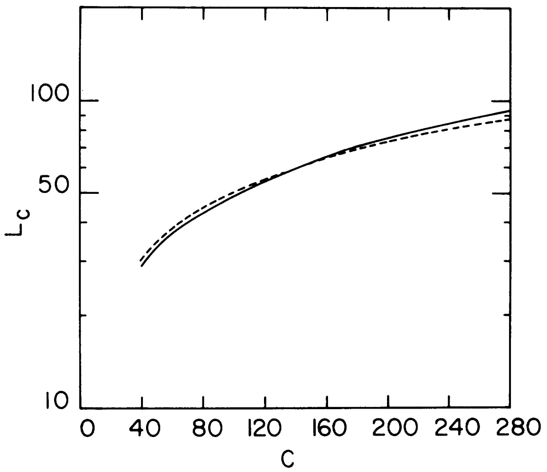

FIG. 3. The critical angular momentum L_c plotted against fused mass C. The dashed line is the experimental trend curve of Natowitz (Ref. 3) and the solid line is calculated for a clutching energy limit $\epsilon_1 = 8$ MeV, $A = 16$ (oxygen projectiles) and normalized at $C = 120$ ($c = 1/236$).

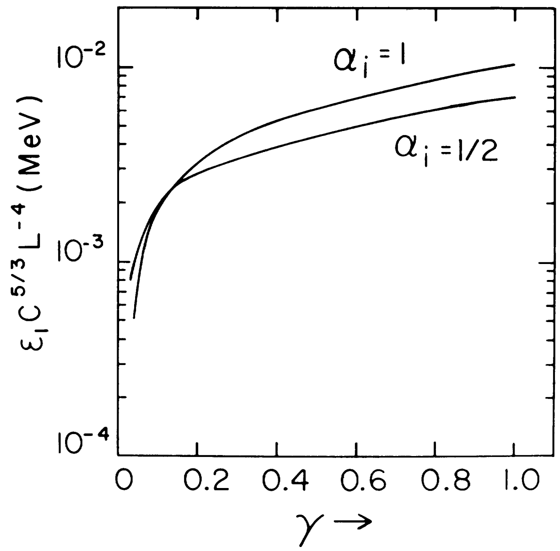

FIG. 4. Plot at $\epsilon_1 C^{5/3} L^{-4}$ against γ for two values of α_i.

Substituting for Δs and Δt, the expression for the clutching energy for the Lth partial wave becomes

$$\epsilon_1 = L^4 \frac{\hbar^2}{2\mathscr{I}_1} c \frac{\mathscr{I}_A \mathscr{I}_1}{\mathscr{I}_2^2} = L^4 \frac{\hbar^2}{2\mathscr{I}_1} c X(\gamma), \tag{11}$$

where $X(\gamma)$ is the ratio

$$X(\gamma) = \frac{\mathscr{I}_A \mathscr{I}_1}{\mathscr{I}_2^2} \tag{12}$$

and γ is the ratio of mass numbers $\gamma = A/B$. The dependence of $X(\gamma)$ on γ is given in Fig. 2, where α_A and α_B are ratios of the moments of inertia of A and B to their respective rigid-body values. In this form, the clutching energy depends upon the L value of the partial wave, the mass ratio of the colliding particles through the $X(\gamma)$, and the mass of the fused system through $\mathscr{I}_1$. Since the energy ϵ_1 must be dissipated for the Lth partial wave to fuse, an upper bound on ϵ_1 limits the angular momentum value and sets a cutoff of partial waves which can fuse. A value of 8 MeV, the average binding energy, is chosen for the upper limit on ϵ_1.

To test the dependence of the critical angular momentum L on γ, the expression was normalized to Natowitz's experimental trend curve[3] at complete fusion mass 120. An ^{16}O projectile is assumed. The curves in Fig. 3 show a comparison of the clutching model angular momentum limit ($\epsilon_1 = 8$ MeV, $c = (236)^{-1}$, $A = 16$) and the Natowitz curve. For the moments of inertia of nuclei A and B, values of $\frac{1}{2}$ the rigid body values are assumed.[2] If a value of 1 is used, the fit is somewhat poorer. The parameter γ varies over an order of magnitude for the fusion mass range 40 to 280.

III. DISCUSSION

Using the parameters of the fit in Fig. 3, the quantity ($\epsilon_1 C^{5/3} L^{-4}$) is plotted against γ in Fig. 4. The curve suggests that in searches for super heavy elements, the clutching energy will be minimized for a given partial wave where the mass ratio is very asymmetric ($\gamma \ll 1$).

This result is not in agreement with the dependence on γ deduced from the work of Schlotthauer-Voos[10] on the formation of mass 117 by two different pairs of collision partners. A decrease of ϵ_1 as γ increases is found. This disagreement may be due to differences in the values ϵ_1 for the two pairs because of dissimilar reaction Q values. Also, in this simple model, an explicit account of an energy dependence[11] has not been attempted. The limit condition first applies to grazing partial waves as the energy is increased. For higher energies, the momentum exchange along the line of centers may, in terms of this simple model, reduce the sliding distance and raise the critical L value above the limit first encountered at lower energies. This and the apparent velocity dependence of η (discussion follows) deserve further study. In the artifical limit $\alpha_B \rightarrow 0$, $\alpha_A = \frac{1}{2}$, a qualitative change in the dependence of ϵ_1 on γ is induced, i.e., ϵ_1 decreases as γ increases, but this is without justification.

An estimate of the viscosity coefficient η can be obtained from the equation

$$F = \eta \frac{vS}{D}, \tag{13}$$

where S is the area over which the viscous force

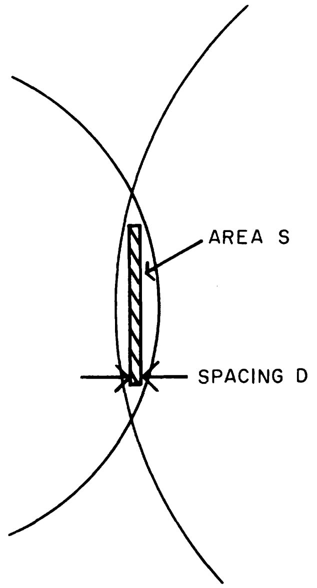

FIG. 5. Volume for viscous interaction of area S and thickness D.

acts, v is the relative velocity between two surfaces bounding the viscous fluid, and D is the spacing between the two surfaces (see Fig. 5). Multiplying Eq. (13) by Δs, using $(\Delta s)F=\epsilon_1$, and letting $v=\Delta s/\Delta t$, η becomes

$$\eta=\frac{\epsilon_1 D}{(\Delta s/\Delta t)\Delta sS}\,. \qquad (14)$$

Curves for two sets of values of D and S selected to represent extreme geometries are shown in Fig. 6. The viscosity η is plotted against $\Delta s/\Delta t$, average relative velocity of the nuclear surfaces during clutching. The dependence of the curves on the velocity parameter is consistent with the low temperature, high collective excitation mode discussed by Immele.[12]

The viscosity plot $\eta(B)$ in Fig. 6 ($D=0.1$ fm, $S=3$ fm^2) approximately corresponds to a contact surface radius of 1 fm for an oxygen projectile (radius 3 fm) which is the particle used in the calculations shown in Fig. 3. The range of values for this geometry is in agreement with the order of magnitude estimate of 10^{-23} MeV sec fm^{-3} obtained by Weiczorek.[13] The range of values for curve $\eta(A)$ is larger because of the choice of geometry and it is in order of magnitude agreement with the estimate by Sierk and Nix[14] of $\eta\approx 7\times 10^{-22}$ MeV sec fm^{-3}. For that matter, so is curve $\eta(B)$ for small values of $\Delta s/\Delta t$.

Although an energy dependence has not been explicitly included, it is implicitly incorporated in

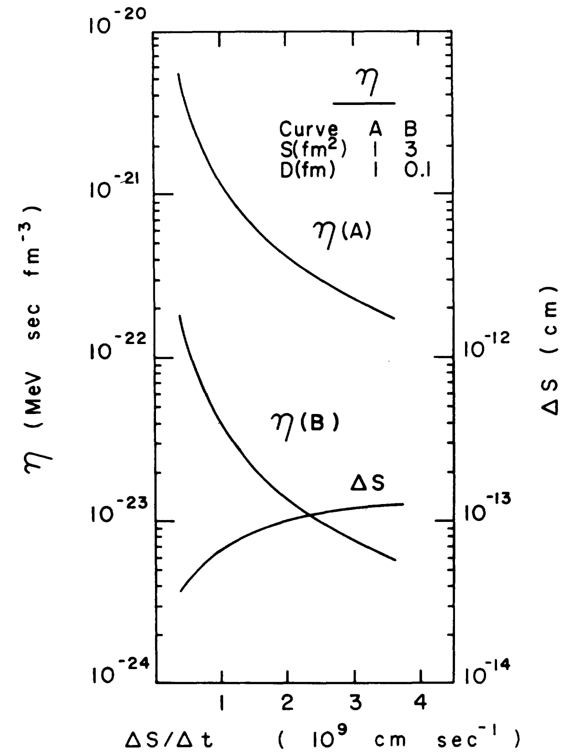

FIG. 6. Viscosity coefficient for two interaction volumes given by S and D plotted against the average relative surface velocity $\Delta s/\Delta t$. The sliding distance Δs is also shown.

that the average relative surface velocity varies with γ over the range of the experimental trend curve. The dependence of the viscosity η on the average relative surface velocity suggests that the rate of energy dissipation may decrease for grazing collisions of higher partial waves. Two possible effects yield opposite results. First, as the value of η decreases, the heating would not be as localized with the more uniform "heating" allowing a higher limit on ϵ_1. In this case, higher partial waves would contribute to the fusion cross section, i.e., an increase in the critical L value. Second, the necessary clutching may not be achieved due to the decrease in the viscosity. The model is too crude and data too sparse to discriminate between the two choices, but the experimental work of Natowitz[11] suggests that the former is the case.

Other fusion limiting mechanisms may provide the bound for certain pairs of colliding nuclei at given energies. Additional experiments and model development are needed to determine the applicability domains of the several limiting mechanisms.

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