Entrance-channel mass-asymmetry dependence of compound nucleus formation time in light heavy-ion reactions

A. Szanto de Toledo

Instituto de Física da Universidade de São Paulo, Departamento de Física Nuclear-Laboratorio, Pelletron, Caixa Postal 66318-05389-970 São Paulo, Brasil

B. V. Carlson

Departamento de Física, Instituto Tecnológico da Aeronáutica, Centro Técnico Aerospacial, 12228-900 São José dos Campos, Brasil

C. Beck

Centre de Recherches Nucléaires, Institut National de Physique Nucléaire et de Physique des Particules-Centre National de la Recherche Scientifique/Université Louis Pasteur, Boîte Postale 28, F-67037 Strasbourg Cedex 2, France

M. Thoennessen

National Superconducting Cyclotron Laboratory and Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824

(Received 28 June 1996)

The entrance-channel mass-asymmetry dependence of the compound nucleus formation time in light heavy-ion reactions has been investigated within the framework of semiclassical dissipative collision models. The model calculations have been applied successfully to the formation of the ^{38}Ar compound nucleus as populated via the ^{9}Be$+^{29}$Si, ^{11}B$+^{27}$Al, ^{12}C$+^{26}$Mg, and ^{19}F$+^{19}$F entrance channels. The shape evolution of several other light composite systems appears to be consistent with the so-called ''Fusion Inhibition Factor'' which has been observed experimentally. As found previously in more massive systems for the fusion-evaporation process, the entrance-channel mass-asymmetry degree of freedom appears to determine the competition between the different mechanisms as well as the time scales involved. [S0556-2813(96)03812-5]

PACS number(s): 25.70.Jj, 25.70.Gh, 25.70.Lm, 24.60.Dr

The occurrence of an asymmetrical fusion-fission process has been identified in light heavy-ion reactions involving dinuclear systems as light as *s*-*d* shell nuclei [1,2]. For such light composite systems, statistically equilibrated compound nuclei (CN) may be expected, if specific phase space conditions are fulfilled [3], to coexist with dinuclear intermediate configurations which lead to binary ''deep inelastic'' collisions with strong and fully energy damping (orbiting), and/or quasimolecular resonant states. Both processes may lead to very inelastic exit channels with ''isotropic'' angular distributions in the reaction plane. This coexistence has been observed experimentally in the formation of the ^{20,22}Ne [4], ^{28}Al [5], ^{36}Ar [6], ^{40}Ca [7], ^{47}V [8], and ^{48}Cr [9] dinuclear systems. In these studies, most of these dinuclear systems were formed via different entrance channels, in order to ascertain whether the CN was playing a key role in the reaction mechanism.

Systematic investigations on the entrance-channel dependence and eventually on the different time scales involved for those strongly damped processes may shed some light on these ambiguities. However in the case of heavier systems ($A_{CN} \lesssim 160$) for which noticeable time differences between the direct component ($\tau \approx 10^{-21}$ sec) and compound component ($\tau \approx 10^{-16}$ sec) have been observed, it has been shown [10] that, depending on the entrance-channel mass-asymmetry parameter $\eta = |(A_{target} - A_{projectile})/(A_{target} + A_{projectile})|$, the time needed for the composite system to evolve until an equilibrated CN has been formed, may vary significantly. In this case, for long CN formation times, the competition between the fusion process and other faster mechanisms may be more important. As a matter of fact, large time differences have been observed in the formation of the ^{164}Yb CN as populated by the asymmetric system ^{16}O$+^{148}$Sm ($\tau \approx 10^{-21}$ sec) or by the more symmetric system ^{64}Ni$+^{100}$Mo ($\tau \approx 10^{-20}$ sec) at $E^*_{CN}=49$ MeV [10]. These time differences are large enough to induce significant divergences in the characteristic features of the CN decay. Very recently [11], similar time differences also have been found in the investigations of a lighter mass region ($A_{CN} = 110$). It was, therefore, quite tempting to investigate this possibility for even lighter dinuclear systems.

It is generally believed in the case of light dinuclear systems ($A_{CN} \lesssim 50$) that due to the smaller number of nucleons involved (subsequent smaller moment of inertia) and, due to the typical value of the relaxation time [12], the time scales of the different binary processes involved are strongly compressed. One of the more illustrative examples can be found in the fusion systematics which has been proposed in this mass region [13]. In the discussion of this fusion systematics, a fusion inhibition factor (FIF) has been defined and a clear correlation between this factor and the entrance-channel mass-asymmetry parameter has been established [13]. The FIF reflects the fact that the reaction flux which, after penetrating the fusion barrier at a radius R_B and a barrier height V_B is diverted to other reaction channels than fusion depending on the target plus projectile combination. The FIF which is derived from the reduced fusion cross section $\sigma_{red} =$
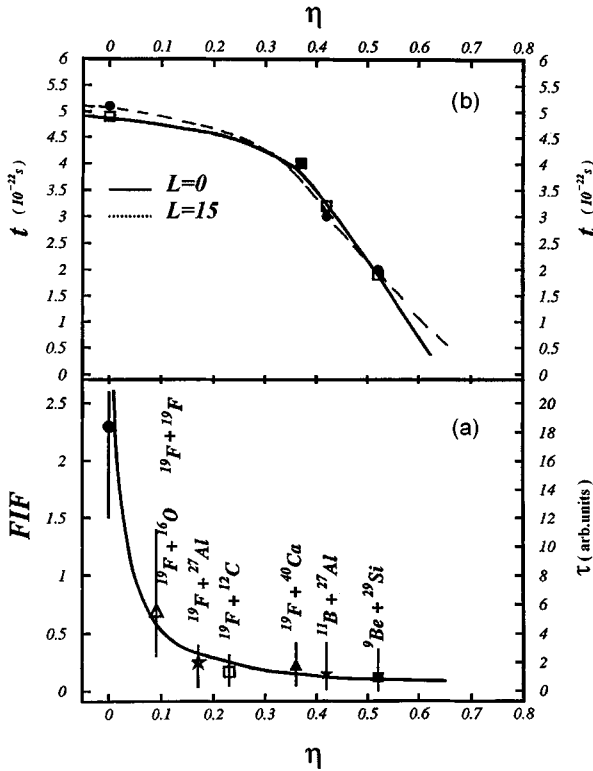
FIG. 1. (a) (Lower) Experimental values for the fusion inhibition factor (FIF) as defined in the text (left scale) for ^{19}F induced reactions and for the ^{38}Ar CN fusion reactions. The solid curve dependence (right scale) of the ''configuration lifetime'' defined in Ref. 13 also is given as a function of the mass asymmetry to guide the eye. (b) (Upper) Time scales predicted by HICOL (see text) for the ^{19}F+^{19}F, ^{12}C+^{26}Mg, ^{11}B+^{27}Al, and ^{9}Be+^{29}Si entrance channels to reach the CN equilibrated shape. The dashed and solid curves (drawn to guide the eyes) represent the cases for L = 0 and L = 15$\hbar$, respectively.

$\sigma E_{\text{c.m.}}$ / πR_B^2, is determined from its deviation from the linear behavior σ_{red}=($E_{\text{c.m.}}-V_B$). The tangent of the deviation angle, defined as the fraction of the flux which penetrates the fusion barrier, but does not lead to CN formation, is defined as the fusion inhibition factor. It has been shown clearly (see Fig. 10 of Ref. [13]) that FIF can be fairly well correlated with the entrance-channel mass-asymmetry. Systems with larger initial symmetries show larger fusion inhibition. Figure 1(a) displays the experimental FIF values (left scale of the lower part of the figure) for light systems [13,14]. It has been suggested that this behavior might be related to the larger time scale needed to reach the equilibrated CN configuration, allowing faster processes to be competitive, although the linear relation is purely suggestive.

As soon as lighter dinuclear systems are considered, the spread in time between the several possible processes is so much reduced that a time measurement might not be sensitive enough to distinguish among them. Therefore time scale measurements in the case of s-d shell composite nuclei as in the cases of the ^{10}B + ^{18}O, ^{11}B + ^{17}O, and ^{19}F + ^{9}Be reactions for which the energy damped binary yields are produced dominantly by CN mechanisms or in the case of the ^{12}C + ^{12}C and ^{12}C + ^{16}O reactions which are capable of showing resonant processes of a quasimolecular nature [3],

may not resolve the doubt whether or not the CN characteristics keep the memory of the entrance channel properties. As a consequence, it is still an open question whether the Bohr hypothesis is valid for very light heavy-ion fusion reactions. Therefore, a clear understanding of the dynamics of the collision is still lacking in this mass region. A detailed study of the shape evolution of the dinuclear system before scission within a fusion-fission process or involving orbiting and quasimolecular mechanisms is highly desirable.

In this paper we will propose a simple investigation of the shape evolution of light dinuclear systems as a function of time for selected incoming angular momenta and given entrance-channel mass-asymmetry parameters. Results are interpreted in terms of a semiclassical dissipative collision model [10,15].

The curve of Fig. 1(a) showing the experimental FIF values [13,14] has been drawn to guide the eye. Its dependence has been defined in [13] by simple calculations of an average ''configuration lifetime'' based on proximity potentials [16] and on the liquid drop model [17]. This behavior indicates that the entrance-channel mass-asymmetry degree of freedom is relevant to establish a dependence of the fusion barrier and ''driving potential'' to asymmetric configurations. This very qualitative result is in quite good agreement with the conclusions reached by Thoennessen et al. [10,11] for heavier compound systems involving equilibration times which differ, however, to a larger extent with the initial projectile + target combinations.

A more complete and sophisticated approach is based on Swiatecki's dissipative dynamical model [18] which assumes full one-body dissipation. This semiclassical model has been applied by using a particle exchange model code HICOL written by Feldmeier [15]. This code [15] is used to follow the evolution of the system towards equilibrium in its collective and thermodynamic degrees of freedom. We assume that the system has reached equilibrium in the shape degree of freedom as soon as its deformation β does not vary significantly as a function of time.

The results for the four different entrance channels leading to the ^{38}Ar CN (at 55 MeV excitation energy) are presented in Fig. 2 for L = 0, 5$\hbar$, 10$\hbar$, and 15$\hbar$, respectively. All these partial waves contribute to the CN formation. It is shown that the most asymmetric entrance channels reach a given stage of equilibrated deformation faster than the symmetric ones, independently of the choice of the impact parameter (angular momentum). Furthermore, it is observed that the asymptotic value expected for the deformation β (t →∞) is, in magnitude, larger with increasing angular momentum, as expected from the Rotating Liquid Drop Model (RLDM) (Ref. [17]). In order to compare the results of the HICOL calculations with that of the crude estimations of the diffusion time and FIF values given in Fig. 1(a), we have calculated the time (t) which is needed to reach a given deformation β (estimated to 80% of the final equilibrium deformation), starting from a given entrance-channel massasymmetry (with L = 0 and L = 15$\hbar$) as shown in Fig. 1(b). It is concluded that the angular momentum does not play a major role in determining the relative drift time of the system and that in the case of a symmetric entrance channel, the system evolves initially very fast, generating a neck and then drifting more slowly. This might not be due essentially to the
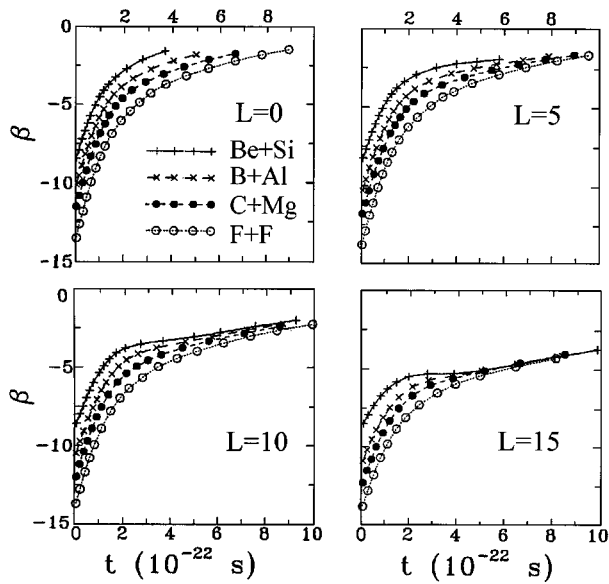
FIG. 2. Time evolution of the nuclear deformation β, estimated to 80% of the final equilibrium deformation, for the $^{19}F + ^{19}F$, $^{12}C + ^{26}Mg$, $^{11}B + ^{27}Al$, and $^{9}Be + ^{29}Si$ entrance channels as predicted by HICOL, for the head-on $L = 0$ collision, and for the $L = 5\hbar$, $L = 10\hbar$, and $L = 15\hbar$ more peripheral collisions.

FIG. 3. Time evolution of the nuclear shapes for the symmetric $^{19}F + ^{19}F$ system and for the most asymmetric investigated system $^{9}Be + ^{29}Si$ for $L = 15\hbar$. The time scale (t) is indicated in units of 10^{-22} sec.

intrinsic diffusion time, but possibly to the available surface energy at this early stage of the collision.

The shape evolution of the ^{38}Ar composite system, predicted by HICOL is depicted in Fig. 3 for both the symmetric $^{19}F + ^{19}F$ and the asymmetric $^{9}Be + ^{29}Si$ entrance channels. We observe that the equilibrium shape, which for these systems is attained within a fraction of a revolution, can be reached even faster for the asymmetric system. Another controversial point in these calculations is that for frontal collisions ($L = 0$), nucleons drift from the light to the heavy fragments. As soon as angular momentum is introduced into the system, it tends to be symmetrically equilibrated. This feature can be well understood in terms of transport phenomena as described, for instance, in the model of the pioneer work of Randrup [19] which was based on the same physical picture. More recently an alternative one-body dissipation model including shell effects has been proposed by Bonasera [20]. It is, however, still difficult to understand that [21,22] from other transport treatments of a similar approach, contradictory conclusions have been advanced in the case of more massive dinuclear systems [22]. Subsequently, the problem that is still open is how in the light dinuclear systems the driving forces are overcome by the centrifugal term.

In conclusion, we have shown qualitatively in this Brief Report that for light heavy-ion fusion reactions, the shape
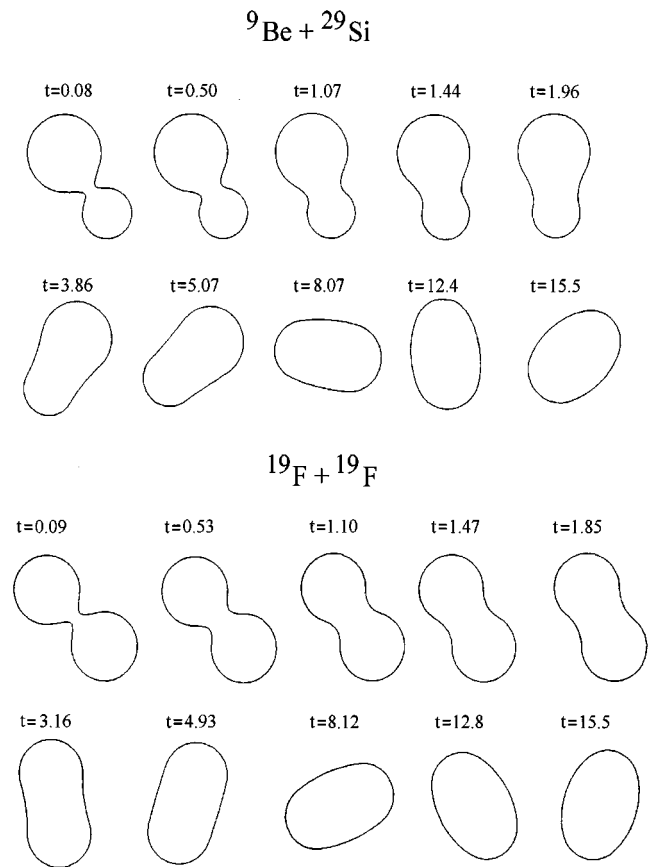
degree of freedom is expected to be equilibrated only within a fraction of a revolution as observed in [4]. As for heavier nuclear systems of the $A_{CN} \approx 110$ and 160 mass regions [10,11], the entrance-channel mass-asymmetry degree of freedom is found to play a key role in the time scale of the fusion process and may determine the degree of competition between fusion and other more peripheral binary processes such as the deep-inelastic orbiting mechanism. Experimental attempts to measure the fission time scales involved in this light-mass region will be soon undertaken.

[1] A. Szanto de Toledo, M.M. Coimbra, N. Added, R.M. Anjos, N. Carlin, L. Fante, Jr., M.C.S. Figuera, V. Guimaraes, and E.M. Szanto, Phys. Rev. Lett. **62**, 1255 (1989).

[2] C. Beck and A. Szanto de Toledo, Phys. Rev. C **53**, 1989 (1996).

[3] C. Beck, Y. Abe, N. Aissaoui, B. Djerroud, and F. Haas, Nucl. Phys. **A583**, 269 (1995); Phys. Rev. C **49**, 2618 (1994).

[4] A. Szanto de Toledo et al., Phys. Rev. C **42**, R815 (1990).

[5] R.M. Anjos et al., Phys. Rev. C **48**, R2154 (1993).

[6] A. Glaesner, W. Dünnweber, W. Hering, D. Konnerth, R.

Ritzka, R. Singh, and W. Trombik, Phys. Lett. **169B**, 153 (1986).

[7] A. Ray, D. Shapira, J. Gomez del Campo, H.J. Kim, C. Beck, B. Djerroud, B. Heusch, D. Blumenthal, and B. Shivakumar, Phys. Rev. C **44**, 514 (1991).

[8] C. Beck, B. Djerroud, F. Haas, R.M. Freeman, A. Hachem, B. Heusch, A. Morsad, M. Vuillet-A-Cilles, and S.J. Sanders, Phys. Rev. C **47**, 2093 (1993).

[9] A.T. Hasan *et al.*, Phys. Rev. C **49**, 1031 (1994); K. Farrar *et al.*, *ibid.* **54**, 1249 (1996).

[10] M. Thoennessen, J.R. Beene, F.E. Bertrand, C. Baktash, M.L. Halbert, D.J. Horen, D.G. Sarantites, W. Spang, and D.W. Stracener, Phys. Rev. Lett. **70**, 4055 (1993).

[11] M. Thoennessen, E. Ramakrishnan, J.R. Beene, F.E. Bertrand, M.L. Halbert, D.J. Horen, P.E. Horen, P.E. Mueller, and R.L.

Walker, Phys. Rev. C **51**, 3148 (1995).

[12] G. Bertsch, Z. Phys. A **289**, 103 (1978).

[13] R.M. Anjos *et al.*, Phys. Rev. C **42**, 354 (1990).

[14] E.M. Szanto (private communication).

[15] H. Feldmeier, Rep. Prog. Phys. **50**, 915 (1987).

[16] J. Blocki, J. Randrup, W.J. Swiatecki, and C.F. Tsang, Ann. Phys. (N.Y.) **105**, 427 (1977).

[17] S. Cohen, F. Plasil, and W.J. Swiatecki, Ann. Phys. (N.Y.) **82**, 557 (1974).

[18] W.J. Swiatecki, Phys. Scr. **24**, 113 (1981).

[19] J. Randrup, Ann. Phys. (N.Y.) **112**, 356 (1978).

[20] A. Bonasera, Phys. Rev. C **34**, 740 (1986).

[21] L. Tassan-Got and C. Stephan, Nucl. Phys. **A524**, 121 (1991).

[22] H. Madani, A.C. Mignerey, A.A. Marchetti, A.P. Weston-Dwakes, W.L. Kehoe, and F. Obenshain, Phys. Rev. C **51**, 2562 (1995).