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Dissipative processes in light-heavy-ion-induced reactions and their time scales

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Strongly damped exit channels are identified in light-heavy-ion-induced reactions (^{9}Be, ^{10,11}B, ^{18}O+^{10,11}B at $E_{\rm lab} \leq 5$ MeV/nucleon), and their time scales are inferred from the isotropy of the angular distributions. These light compound systems seem able to reach statistical equilibrium within a fraction of a revolution of the dinuclear intermediate configuration. No simple correlation among the inelasticity of the process, mass transferred and "decay angle" is perceived.

Fusion-fission processes and deep-inelastic collisions (DIC) have been extensively investigated in heavy ion reactions.[1,2] These mechanisms are already well characterized and understood. Recently, several authors have extended the investigation, both experimentally and theoretically, to DIC in medium weight heavy-ion systems.[3–6] In these lighter systems, the strong Coulomb focusing, which dominates in heavier systems, is absent and collision trajectories associated with orbiting processes are allowed, leading to angular distributions $d\sigma/d\Omega \propto 1/\sin\theta$ at large angles. This behavior is consistent with the picture of a long-lived dinucleus, formed during early stages of collision, acting as a "doorway" to deep inelastic processes or leading to a fully equilibrated compound nucleus. Through these studies, it has been established that the usual correlations found in heavier systems,[1,2,7] among the inelasticity of the process, the amount of mass transfer of the isotropy of the angular distributions, and the reaction time scale are still present in these medium weight heavy-ion-induced collisons.[5–9] This result may be interpreted in terms of the diffusion of nucleons, between the target and projectile, responsible for the loss of relative kinetic energy (TKEL) whose increment will be intimately related to an increase of the interaction time, leading to an associated increase of the isotropy of the angular distribution. The loss of such correlations is expected to occur in lighter systems where quantal or nuclear structure effects become increasingly more important, rendering the applicability of a full statistical equilibrium distribution, as well as the characterization of relaxation phenomena in "dissipative collisions" questionable.

In this paper, we report on a study of the main characteristics of strongly damped collisions in lighter systems (^{9}Be, ^{10,11}B, ^{18}O+^{10,11}B) which indicates a partial loss of the above-mentioned correlations and establishes an equality in time scale between orbiting and compound nuclear decay. This is partly related to the fact that in such light systems, statistical equilibrium may be reached after a fraction of a revolution of the dinuclear intermediate

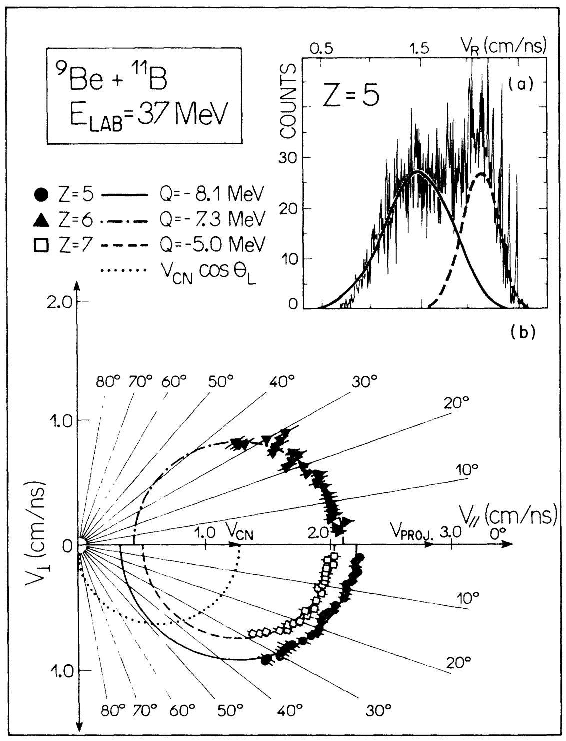

FIG. 1. (a) (insert) Experimental velocity spectrum deduced from the energy spectrum for the boron elements detected from the ^{9}Be+^{11}B reaction at $\theta_{\rm lab}=8°$. The solid line represents a smoothed velocity spectrum predicted by statistical model calculations (code LILITA) for boron evaporation residues. The dashed line represents a fit to the spectrum resultant from the subtraction of the theoretical boron velocity spectrum from the experimental velocity spectrum. (b) Experimental average velocities for $Z=5$, 6, and 7 for the nonfusion components (i.e., dashed line in the inset). The semicircles represent the expected trajectories for binary processes with indicated Q values and for the expected average velocity of evaporation residues (dotted line).

configuration, and to the important fluctuations imposed by nuclear structure on the macroscopic potential-energy surfaces.

In the experiment, ^{10,11}B self-supporting targets were bombarded by ^{9}Be, ^{10,11}B, ^{18}O beams from the University of São Paulo Pelletron Accelerator, with energies 10 MeV $< E_{^9\mathrm{Be}} <$ 40 MeV, 15 MeV $\leq E_{\mathrm{B}} \leq$ 50 MeV, and 20 MeV $\leq E_{^{18}\mathrm{O}} \leq$ 72 MeV. Light charged reaction products and evaporation residues were identified by means of a position sensitive ionization chamber. Angular distributions were measured in steps of 1° along with excitation functions at five forward angles. Fusion and reaction products were distinguished by comparing their energy and inferred velocity spectra to those expected for the evaporation residues and the quasielastically scattered particles[10] [see Fig. 1(a)]. The low-energy side of the spectrum, which is clearly dominated by the compound-nucleus evaporation residues, has been used to normalize the calculated spectra. This procedure decreases the uncertainties in the subtraction procedure.

Some of the systems investigated present significant cross sections diverted to strongly damped binary decay channels. In the case of the ^{18}O+ ^{10}B reaction, using inverse kinematics, a strongly damped component is also observed in the inelastic channels [see Fig. 2(a) and Table I]. In the particular case of the mass symmetric ^{10}B+ ^{10}B reaction and ^{18}O+ ^{10}B mass asymmetric reaction, the exit channels with no charge transfer approximate more closely a 1/sinθ dependence indicating an isotropic angular distribution (see Fig. 2), in contrast to the case of heavy systems.[1,2]

The binary nature of the channels has been clearly established in the $v_{\parallel}$ vs $v_{\perp}$ plots shown in Fig. 1(b) for the ^{9}Be+ ^{11}B system, allowing the extraction of experimental Q values (see Table I). The determination of these Q values demands the knowledge of the mass (A) of the reaction process. However, due to the fact that only their atomic number (Z) was identified, the relation $A = 2Z$ has been used for this purpose. In order to estimate uncertainties in the calculated Q values, the values of A were varied up to ± 2 units, leading to differences in the Q

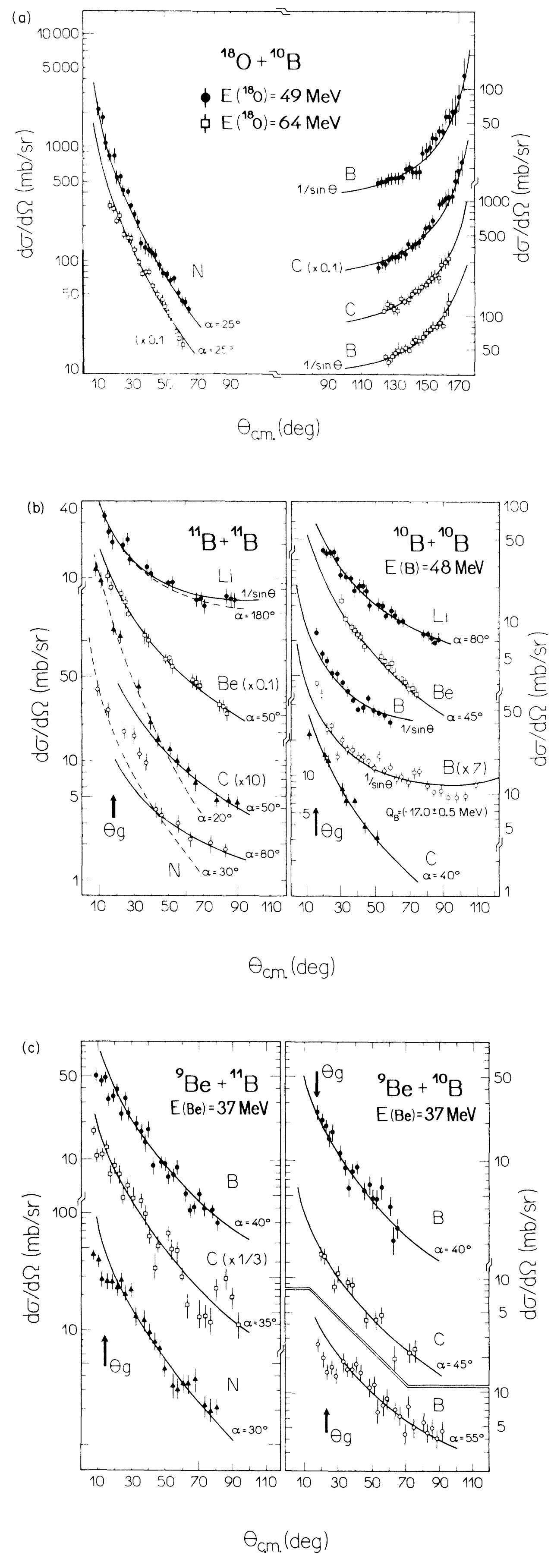

FIG. 2. Angular distributions for targetlike and projectilelike components for the reactions investigated. The solid curves represent fits to expression 1. (a) ^{18}O+ ^{10}B reaction at $E(^{18}\mathrm{O}) = 49$ MeV (solid circles) and $E(^{18}\mathrm{O}) = 64$ MeV (opened squares). (b) Nitrogen and carbon angular distributions measured for the ^{11}B+ ^{11}B reaction at $E(^{11}\mathrm{B}) = 48$ MeV (left-hand side) suggest the contribution of two different processes: A forward peaking indicated by the dashed line and a more isotropic one indicated by the solid line. Components produced in the ^{10}B+ ^{10}B reaction at $E(^{10}\mathrm{B}) = 48$ MeV (right-hand side) are also shown. The boron exit channel is negligible in the ^{11}B+ ^{11}B reaction. For the ^{10}B+ ^{10}B system the angular distribution for a 1-MeV wide bin (centered at the most probable Q_{B} value) is also shown (Ref. 10) (open circles). (c) Reaction products for the ^{9}Be+ ^{11}B reaction (left-hand side) and ^{9}Be+ ^{10}B reaction (right-hand side). To illustrate the dependence of α as with the bombarding energy, an angular distribution for boron ejectiles from the ^{9}Be+ ^{11}B reaction at $E(^{9}\mathrm{Be}) = 16$ MeV (open circles in the lower right-hand side) is also shown. The vertical arrows indicate the value of the entrance channel grazing angle θ_g.

TABLE I. Values obtained for the rotational period T of the dinucleus, estimated lifetime τ_Γ of the compound nucleus, "life angle" α determined from the data, maximum values for the total kinetic energy loss $(\text{TKEL})_{\max} \approx E_{\text{c.m.}} - V_{\text{CB}}$ which, compared to $\langle Q \rangle$, indicates the degree of inelasticity, and experimental average Q values for the significant exit channels (uncertainties are estimated to be ± 1 MeV).

Systems E_{lab} (Mev)	T (10^{-21} s)	τ_Γ 10^{-21} s	Observed exit channel	α (deg)	$(\text{TKEL})_{\max}$ (MeV)	$\langle Q \rangle$ (MeV)
$^{18}O+^{10}B$	2.3	($\simeq$1.5)	B	>180		−14
$E(^{18}O)=64$			C	>180	$\simeq$15	−10
			N	25		−14
$^{10}B+^{10}B$	2.3	($\simeq$1.2)	Li	80		−16
$E(^{10}B)=48$			Be	45	$\simeq$18	−16
			B	>180		−17
			C	40		−12
$^{11}B+^{11}B$	2.2	($\simeq$1.5)	Li	>180		−15
$E(^{11}B)=48$			Be	50	$\simeq$19	−16
			C	50		−10
			N	80		−15
$^{9}Be+^{11}B$	1.8	($\simeq$1.2)	B	40		−8.1
$E(^{9}Be)=37$			C	35	$\simeq$15	−7.3
			N	30		−5.0
$^{9}Be+^{10}B$	2.0	($\simeq$0.9)	B	40	$\simeq$15	−6.6
$E(^{9}Be)=37$			C	45		−6.3

values up to ± 1 MeV. These uncertainties will not affect the conclusions drawn in the present work.

The associated orbiting characteristic of these reaction channels can be further confirmed by the Wilczynski diagrams[2] for the energy relaxed components which describe the angular evolution of the total kinetic energy (TKE) available in the exit channel and displays a ridge which converges, at large angles, to TKE values equivalent to the outgoing channel Coulomb barrier, suggesting scattering to negative angles. This behavior is characteristic of a strongly damped process.[1,2] A typical example can be found in Fig. 3.

The experimental angular distributions for all the reaction products were fitted within the framework of the Regge-pole model[7]

$$\frac{d\sigma}{d\Omega} = \frac{c}{\sin\theta_{\text{c.m.}}}\left[\exp\left(-\frac{\theta_{\text{c.m.}}}{\omega\tau}\right)+\exp\left(-\frac{2\pi-\theta_{\text{c.m.}}}{\omega\tau}\right)\right], \tag{1}$$

which describes the decay of a rotating dinucleus with an angular velocity $\omega = \hbar l/(\mu R^2)$ where μ represents the system reduced mass, l its angular momentum [which has been set equal to the critical angular momentum for fusion (l_c)], and R represents the distance between the two centers of the dinucleus. Small values of the "life angle" $\alpha = \omega\tau$ are associated with the occurrence of a fast process, leading to forward peaked exponential angular distributions, whereas large values, comparable to the dinucleus rotation period T, reflect the tendency towards orbiting, and leads to decay probabilities which are isotropic in the reaction plane and are represented by angular distributions $d\sigma/d\Omega \propto 1/\sin\theta$. Experimental values of the life angle α, extracted in the present study,[11] are indicated in Fig. 2. The inferred lifetime of the dinuclear system $\tau = \alpha/\omega$ and its rotational period $T = 2\pi/\omega$ are to be compared to the compound-nucleus lifetime $\tau_\Gamma = \hbar/\Gamma$ where Γ represents its decay width. Value for Γ, estimated on the basis of empirical expressions,[12] are confirmed by several measurements quoted in the literature[12,13] for similar light systems (see Table I).

It is interesting to observe, that although the nuclear systems under study in the present work are quite light, the time scale arguments commonly used to assess the applicability of statistical equilibrium description are still valid. This requires that the time interval between formation and decay of the compound nucleus is long enough to allow it to reach thermal equilibrium. The typical τ_Γ values, listed in Table I, have to be greater than the characteristic time τ_n for the nucleonic degree of freedom

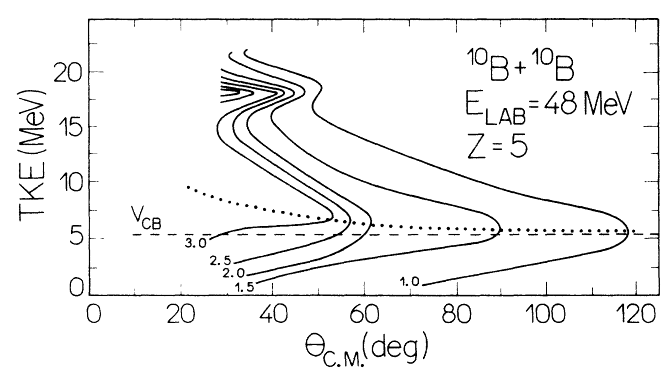

FIG. 3. The Wilczinsky diagram for the boron products in the $^{10}B+^{10}B$ reaction at 48 MeV (contours represent constant cross sections values as indicated in units of mb/sr MeV). The dotted line describes the ridge trajectory and the dashed line indicate the asymptotic energy for the $^{10}B+^{10}B$ system which is equal to the Coulomb barrier, V_{CB}.

to come to equilibrium. This time τ_n represents the time needed by nucleons to suffer a sequence of collisions before kinetic energy is distributed among all the nucleons in a random way. According to the temperature dependent relation proposed by Bertsch,[14] values of the order of $\tau_n \sim 2\times 10^{-22}$ s are obtained, satisfying the relation $\tau_\Gamma > \tau_n$. Furthermore, many examples can be found in the literature[15] confirming the adequacy of the statistical model in the description of the decay, via emission of light particles, of equilibrated compound nuclei as light as the ones investigated in the present work. The fact that in some cases $\tau_\Gamma \leq T$ indicates that statistical equilibrium may be reached within one or a fraction of a revolution.

From the above discussion it is possible to visualize the dinucleus acting as a doorway to both processes observed, i.e., complete fusion and strongly damped binary processes.[16,17]

As far as the correlations in observables seen in DIC mentioned earlier are concerned, experimental values for the life angle, listed in Table I, indicate that in some cases, higher values of α are associated with exit channels with less mass rearrangement in contrast to the case for heavier systems (see Fig. 2). This can be clearly seen in the beryllium and boron exit channels in the B+B reactions and in the boron and carbon exit channels in $^{18}O+^{10}B$ reaction which show isotropic angular distributions. On the other hand, ejectiles originating from a larger mass transfer can present an exponential angular distribution with $\alpha \sim 30°-40°$ leading to reaction times of the order of 5×10^{-22} s.

The simple diffusion models[1,2] relate the average mass transfer (ΔM) to the reaction time (t) according to the following expressions:[18]

$$\Delta M = \tfrac{1}{2}(\bar{\eta}-\eta_0)(A_{\text{target}}+A_{\text{projectile}}) \qquad (2)$$

and

$$\bar{\eta} = \eta_0 - \frac{D\bar{V}'(\bar{\eta})t}{T}, \qquad (3)$$

where η_0 corresponds to the entrance channel mass asymmetry, $\bar{V}'(\bar{\eta})$ represents the corresponding "driving force," T the nuclear temperature, and D the diffusion coefficient. These models describe satisfactorily[2] strongly damped processes in heavy-ion collisions and are based on *smooth* shell corrected liquid-drop potentials $\bar{V}(\bar{\eta})$.[1,2] For light systems, however, these potentials describe only average behaviors, neglecting the very important fluctuations, imposed by the nuclear structure, which give rise to important modifications in the configurations transition rates (along the mass asymmetry degree of freedom).

Due to the fact that the transition rates can fluctuate significantly from one mass to the next, a light dinucleus can evolve along the mass asymmetry axis in a manner that deviates qualitatively from the behavior expected in heavier systems.

A more precise treatment of the mass transfer would require returning to the original discrete mass and charge master equation[2,9-14,17] from which the diffusion equation was, in principle, derived.[19]

In summary, we have identified in this work strongly damped exit channels in light-heavy-ion-induced reactions characterized by orbiting trajectories. The small equilibration time necessary to distribute the relative energy among the few nucleons which constitute the composite systems, allows a statistical equilibrium to be reached within a fraction of a revolution. In contrast to the situation for heavier systems, no simple correlation was found among inelasticity, the mass transfer, and reaction time. It is suggested that the explicit consideration of the fluctuations of liquid-drop potentials may lead to the understanding of these dissipative processes in light-heavy-ion-induced reactions.

Furthermore, the present work establishes an equality in time scale between orbiting and compound nuclear decay which may stimulate a conceptual discussion of fusion-fission processes in such light systems.

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[11]It is known that for symmetric and close to symmetric systems transfer and pickup at backward and forward c.m. angles, respectively, are not distinguishable. In the present work, the choice between these two processes have been based on kinematical considerations, i.e., favorable Q values, etc.

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