One-body dissipation at intermediate nuclear connection regimes

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We calculate the one-body dissipation function, appropriate for a heavy-ion collision, as a function of the size of the neck connecting the two nuclei.

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The development of a liquid-drop model of nucleus-nucleus collisions has been of invaluable help in the study of the processes that take place in such reactions. Since energy dissipation is a common feature of all heavy-ion reaction mechanisms above the Coulomb barrier, it must be properly included in any realistic nuclear collision model. Due to the long mean free path of nucleons in nuclear matter, one expects that collective energy is dissipated through collisions of the nucleons with the moving nuclear surface region. This idea led to the one-body dissipation model [1], which has been extensively used to understand essential features of heavy-ion collisions [2–6].

The system formed by two heavy ions in collision may be pictured as two approximately spherical volumes joined by a short neck. In this case, the expression for the one-body dissipation function may be written as the sum of two terms. The dissipation that takes place when nucleons in one of the nuclei collide with its surface is described by the so-called wall formula, while the window formula takes into account the energy loss associated to the flux of particles through the neck. Explicit expressions for the one-body dissipation have been obtained only in two limiting cases, namely, for very small and very large neck sizes [2,5].

In order to describe the processes that occur in a heavy-ion collision it is necessary to have expressions for the whole range of neck sizes. This was done by assuming, rather arbitrarily, that the one-body dissipation can be written as an interpolation between the two limiting expressions mentioned above. However, as it is seen in Fig. 1, different authors have adopted very different interpolation recipes [2,4,5].

In this work we determine the dissipation function by direct calculation of the energy exchanged between the nucleons and the nuclear surface, for a schematic geometry appropriate to describe a central heavy ion collision. In order to do this we assume, as in Ref. [1], that the nucleon velocities on each sphere are described by a distribution $f(\mathbf{v})$, which is isotropic and homogeneous in a certain frame of reference, which we call the drift frame. In this frame the nucleon velocity distribution will depend only on the modulus of the nucleon speeds measured in this frame, $\mathbf{v}$. The velocity of the drift frame with respect to the c.m. frame of the whole system, $v_d\hat{\mathbf{z}}$, will be determined later from dynamical considerations.

In Fig. 2 we show the geometry of our system. It is composed by two spherical nuclei, which for simplicity are assumed to be of the same radius R, joined by a cylindrical neck of radius N and length L. The centers of the nuclei approach each other with a relative velocity $2V$. Because of volume conservation, the nuclear radii increase at a rate

$$\dot{R}=\frac{V}{2}(1-\sqrt{1-x^2})\ , \tag{1}$$

where $x=N/R$ and we have neglected the volume of the neck ($L/R \ll 1$).

If we assume that the collisions of the nucleons with the nuclear surface are specular in the local frame of the impact point, then the change in the kinetic energy of the nucleon is given by

$$\Delta E=2mv_s(v_s-v_n)\ , \tag{2}$$

in the frame of reference of the c.m. of the total system. In this equation m stands for the nucleon mass,

$$v_s=\dot{R}+V\cos\vartheta \tag{3}$$

is the radial velocity of the surface at the impact point, and v_n the radial component of the nucleon velocity $\mathbf{v}$. The modulus of the nucleon velocity measured in the

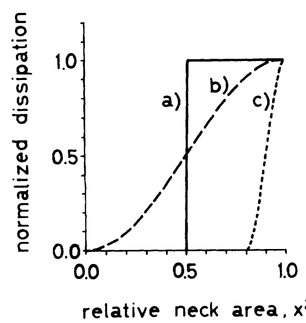

FIG. 1. Different interpolation schemes used for the dissipation function at intermediate connection regimes: (a) Ref. [2]; (b) Ref. [5]; (c) Ref. [4].

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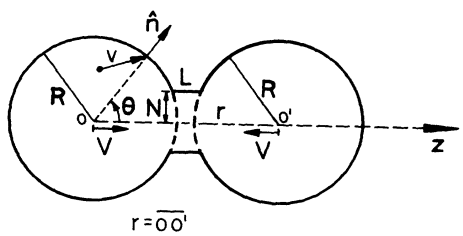

FIG. 2. Shape parametrization of the nuclear system.

drift frame, v', and the angle of incidence of the nucleon on the nuclear surface, χ, measured in the same frame, are related to v_n through

$$v_n = v_d \cos\vartheta + v' \cos\chi \ . \tag{4}$$

In order to calculate the energy exchanged per unit time in these collisions, $\dot{Q}_{\rm wall}$ we integrate ΔE, given by Eq. (2), times the collision rate, over all incidence directions χ and impact points ϑ, and average over the nucleon velocity distribution, which is uniform in the drift frame. After performing these integrations we have

$$\dot{Q}_{\rm wall} = \frac{\pi}{6} \rho m R^2 V(V - v_d) \bar{v}'(1 + \sqrt{1 - x^2})^3 \ , \tag{5}$$

where $\bar{v}'$ stands for the mean value of the modulus of the nucleon velocity in the drift frame. For the window dissipation we consider the relative velocity between the nucleon distributions in the two nuclei, $2v_d$, and obtain

$$\dot{Q}_{\rm window} = \pi \rho m R^2 v_d^2 \bar{v}' x^2 \ . \tag{6}$$

In order to determine the drift velocity v_d we follow the prescription of Ref. [1] appropriate for the case of a central collision. Namely, the square of the normal distance between an element $d\sigma$ of the nuclear surface at a time $t + \delta t$, $\Sigma(t + \delta t)$ and the corresponding element of the surface $\Sigma(t)$ translated a distance $v_d \delta t\, \hat{z}$, integrated over the surface of the whole system, should be minimum.

In our case this means that we should minimize

$$\int_{-1}^{\sqrt{1-x^2}} [\dot{R} + (V - v_d)\cos\vartheta]^2 \sin\vartheta \, d\vartheta \tag{7}$$

with respect to v_d. This results in the following expression for v_d:

$$v_d = V \left[1 - \frac{3}{4} \frac{x^2[1 - \sqrt{1 - x^2}]}{1 + (1 - x^2)^{3/2}} \right] , \tag{8}$$

which is plotted in Fig. 3(a). Substituting Eq. (8) into Eqs. (5) and (6) we obtain $\dot{Q} = \dot{Q}_{\rm wall} + \dot{Q}_{\rm window}$, which is plotted in Fig. 3(b), where it is also compared with the limiting expressions of Refs. [2,5].

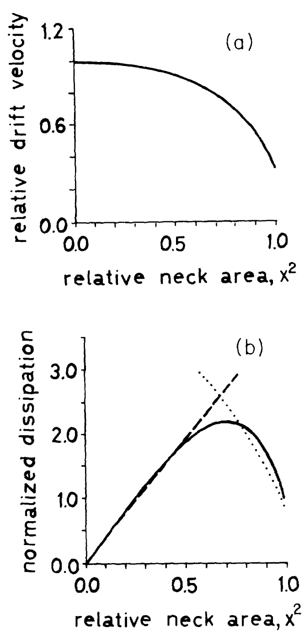

FIG. 3. (a) The relative drift velocity v_d/V as a function of the relative cross sectional area of the neck $x^2 = (N/R)^2$; (b) the normalized dissipation function $\dot{Q}/\pi\rho m R^2 V^2 v'$ (solid line) compared with the small (dashed) and large (dotted) neck size limiting cases.

We note that the calculated drift is quite close to V for values of the relative cross section of the neck $x^2 < 0.5$. For this reason the dinuclear limit constitutes a good approximation for this range of neck sizes. At higher values of the neck parameter neither of the two limiting expressions appears to be adequate, and it is interesting to note that not even an interpolation between these expressions appears to work in this case.

As a final comment we would like to remark that the results presented here were obtained under the assumption that the nucleon velocity distribution is isotropic and homogeneous in the drift frame of reference. Considering that little is presently known about the properties of a three-dimensional time-dependent billiard such as the one used to model our system, we think that the validity of this hypothesis should be carefully investigated.

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