LIGHT PARTICLE EVAPORATION FROM DYNAMICAL SYSTEMS * **

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(Received December 10, 1996)

For the statistical particle-evaporation model to be applicable to particle emission from dynamical time-evolving systems, the system should closely follow the quasistatic path, which represents a sequence of conditional equilibrium shapes. We show that quasifission paths predicted by the one-body dissipation dynamics satisfy this requirement all the way from the contact point to the scission point, excluding short time intervals spent near the contact point (when neck fills in) and during separation (when waist develops).

PACS numbers: 25.70. Gh, 24.75. +i, 25.70. Jj

1. Introduction

The collision of two nuclei at not very large beam energies ($E \leq$ 10–20 MeV/nucleon) proceeds through formation of a rather long-lived (on single-particle scale) composite system, which is often conceived as a liquid drop described in terms of shape, temperature, angular momentum and viscosity. Light particles emitted from the composite system on its way from the contact point to the scission point (in the following we will concentrate on quasifission reactions [1]), are used as a tool to study these macroscopic properties by comparison of measured neutron [2] and light-charged particle [3] spectra and multiplicities with the evaporation (or statistical) model of particle emission.

* Presented at the XXXI Zakopane School of Physics, Zakopane, Poland, September 3–11, 1996.
** Work supported by Grant No. K4L100 from the Joint Fund of the Government of Ukraine and the International Science Foundation, and by Grants No. PB95-1249 from the DGICYT (Spain) and GR94-1022 from the DGR (Catalonia).

The information on macroscopic properties of the composite system is distorted unless the evaporation model takes properly into account large angular momenta and large or even violent deviations from the spherical shape. The problems of adjustment of the evaporation model to these conditions of heavy-ion reactions have been discussed for more than 15 years and are already solved at least in principle [4–6]. An important question which has not been discussed so far, concerns the formulation of the applicability criterion of the statistical model to particle emission from dynamical systems which did not reach thermal equilibrium, and the verification of this criterion for current models of heavy-ion reactions. Our work is intended to fill in this gap.

2. Quasistatic path

The statistical model of particle emission implies that the composite system finds itself in a state of given shape long enough to be able to explore all the phase space available at this shape. This means that our system should be close to so-called conditional thermal equilibrium which differs from the absolute thermal equilibrium in that the nuclear density $\rho(\boldsymbol{r})$ should maximize the entropy S at given value of certain collective coordinate Q of the system. This constraint on Q is needed to keep the system out of the spherical shape. By changing Q one then gets a sequence of conditional equilibrium configurations which we call the quasistatic path.

Let $\widetilde{E}\{\rho\}$ be the energy required to bring the nucleus from its ground state to the nonspherical (and generally rotating) cold state characterized by the spatial density ρ. The hydrodynamic flows in the quasistatic state are absent. Therefore, its thermal energy is equal to the difference between the excitation energy E_x and $\widetilde{E}\{\rho\}$. Then, as seen from the Fermi gas formula for the entropy

$$S = 2\sqrt{a\,(E_x - \widetilde{E}\{\rho\})}\,, \tag{1}$$

one can find ρ of quasistatic state by looking for the conditional minimum of $\widetilde{E}$, because the variation of the level density parameter a with shape is very smooth in comparison to that of $\widetilde{E}$ [7].

In practical terms the quasifission reactions are described by the one-body dissipation model of heavy ion collisions [8] implemented in the code HICOL, while the conditional equilibrium densities can be calculated in the framework of the extended Thomas–Fermi (ETF) model of nonspherical nuclei [9]. With these two models we wish to verify whether the dynamic trajectories in quasifission reactions follow the quasistatic path. The calculations will be done in the $A \approx 160$ mass number region, a subject of current experimental interest [10–13].

For the sake of comparison between dynamic and quasistatic paths we introduce the elongation coordinate $D_{\rm mm}$ and the neck coordinate $R_{\rm neck}$. In HICOL the approximation of constant density is used and the profile function $y(z)$ of the composite system is parameterized by two spheres smoothly connected by a second order curve [14]. For these so-called Blocki shapes we define $D_{\rm mm}$ as a distance between the mass centers of the two parts of the nucleus on both sides of the plane $z = z_{\rm m}$, where $z_{\rm m}$ is the mean value of the left and right matching points, and identify $R_{\rm neck}$ with $y(z_{\rm m})$.

The ETF calculations are confined to the mass and axially symmetric (about the z axis) density distributions $\rho(r, z)$, where $r = \sqrt{x^2 + y^2}$ and x, y, z are the cartesian coordinates. In this case $D_{\rm mm}$ and $R_{\rm neck}$ are given by

$$D_{\rm mm} = \frac{8\pi}{A} \int_0^{\infty}\int_0^{\infty} z\, \rho(r, z)\, r\, dr dz \tag{2}$$

and

$$R^2_{\rm neck} = \frac{2}{\rho_0} \int_0^{\infty} r\, \rho(r, z = 0)\, dr\,. \tag{3}$$

The definition (3) of the neck radius has been obtained from the requirement that the nucleus with the constant density ρ_0 and the geometrical neck radius equal to $R_{\rm neck}$ will have the same number of particles in the cross section of its neck as the nucleus with the distributed density. In the following ρ_0 in (3) will be identified with the one used in HICOL, namely $\rho_0 = A/(\frac{4}{3}\pi R_0^3)$ where $R_0 = 1.18 \times A^{\frac{1}{3}}$ fm.

3. Numerical illustration

The projection of the quasistatic path on the elongation-neck plane for ^{160}Yb, which represents the composite system in the ^{60}Ni + ^{100}Mo collision, is shown in Fig. 1. The calculations have been performed for a realistic Skyrme interaction, namely SkM* [15]. The ETF energy density incorporates second-order gradient corrections with spin–orbit and effective mass terms [15], which are very important in describing the nuclear surface. From the ETF-SkM* functional, we obtain fully self-consistent nuclear densities by solving the associated variational equations in cylindrical coordinates, with imposing a given value of the quadrupole moment Q_2 [9]:

$$Q_2 = \frac{2\pi}{A} \int_0^{\infty}\int_{-\infty}^{\infty} \left[2z^2 - r^2\right] \rho(r, z)\, r\, dr dz\,. \tag{4}$$

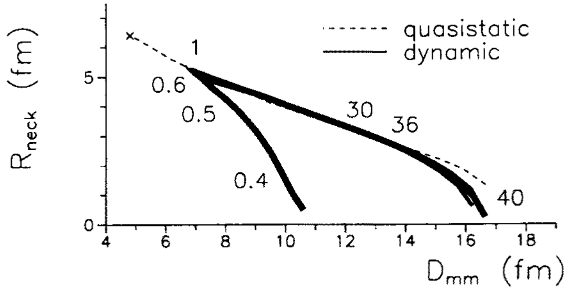

Fig. 1. Dynamic (for $J = 70, 75, 80, 85, 90, 95, 100, 105\,\hbar$) and quasistatic (for $J = 86\,\hbar$) paths in the ^{60}Ni + ^{100}Mo collision at 10 MeV/nucleon are shown by solid and dashed lines, respectively. The spherical shape is shown by a cross. Numbers along the dynamic path indicate the time in units of 10^{-21}s for the $J = 86\,\hbar$ path.

The quasistatic path shown in Fig. 1 is calculated with accounting for the rotational energy with rigid-body moments of inertia and angular momentum $J = 86\,\hbar$, which represents the mean angular momentum for the quasifission window $J = 70$–$103\,\hbar$ found in Ref. [16] for a similar reaction to ours. We found that the quasistatic path only slightly depends on the angular momentum. When one goes from $J = 86\,\hbar$ to $J = 0\,\hbar$ the quasistatic $D_{\rm mm}$ and $R_{\rm neck}$ change only by a small fraction, of 0.1 fm at most.

The dynamic paths of the ^{60}Ni + ^{100}Mo composite system found from HICOL at $E = 600$ MeV for $J = 70$–$105\,\hbar$ are also shown in Fig. 1. In few units of 10^{-22}s they join the quasistatic path to closely follow along it during much longer periods. At the moment of joining, the neck just filled

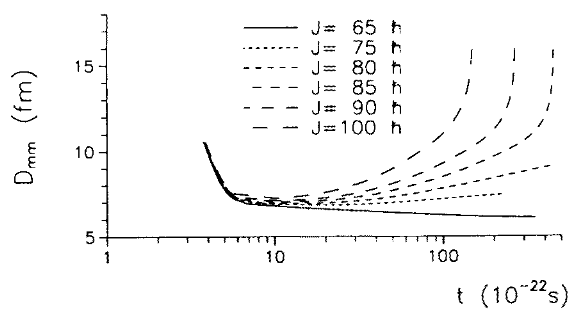

Fig. 2. Time dependence of $D_{\rm mm}$ for the reaction ^{60}Ni + ^{100}Mo at $E = 600$ MeV and $J = 65$–$100\,\hbar$ predicted by the HICOL one-body dissipation code.

in, and individual temperatures and angular velocities of two nuclei became approximately equal. On the approach to the scission point the dynamic trajectories start to progressively deviate from the quasistatic one and yield a thinner neck at the same value of elongation.

Although, as seen from Fig. 1, quasifission paths at different angular momenta are very close to each other, the time spent on this path is strongly changing from one J to another. For example, from the time dependence of $D_{\rm mm}$ depicted in Fig. 2, one can estimate that this time decreases from 4.5×10^{-20} s to 1.5×10^{-20} s when J increases from $85\,\hbar$ to $100\,\hbar$.

We performed the calculation of the $J = 86\,\hbar$ quasistatic path with the constraint on the moment of inertia I, instead of Q_2. The path in the $(D_{\rm mm}, R_{\rm neck})$ space turned out to be almost the same as that we had found with the Q_2 constraint: the differences in $R_{\rm neck}$ are not larger than $\sim$1%. Imposing the I constraint one not only obtains the same values for Q_2 as with the Q_2 constraint, but also finds that the hexadecapole moment Q_4 along the path is very similar. This means that also the nuclear shapes must be equivalent with the I or Q_2 constraint.

The dynamic paths have been found to be rather stable against variation of excitation energy and mass asymmetry. This follows from our dynamic calculations performed for the same system but at the beam energy of 1200 MeV, and at 480 MeV for a beam of ^{48}Ca on an ^{112}Sn target.

4. Conclusion

Strong deviations of the dynamic shapes from quasistatic configurations in the contact and scission phases make inapplicable the particle evaporation model at these two stages of quasifission reaction. Since the composite system spends only a small part of its time in these stages, however, the deviations should not lead to a sizable bias in macroscopic characteristics of the composite system deduced from the particle-fragment coincidence spectra by the particle evaporation model.

The fact that nuclear systems driven by the one-body dissipation dynamics spend most of their time moving along the quasistatic path (which seems to be independent on the specific form of the constraint used to find it) can be regarded as generalization of the compound nucleus concepts [17] to the nucleus–nucleus collisions in which the composite system never reaches the equilibrium shape.

Small sensitivity of quasistatic and dynamic paths on J and high stability of dynamic paths towards variations of E and (to some extent) of mass asymmetry should lead to great simplifications in studies of characteristic times of quasifission reactions by particle evaporation. Indeed, for large variety of projectile-target combinations, beam energies and impact parameters one can use the same set of shapes, moments of inertia, level density parameters, light-particle separation energies and emission barriers.

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