Emission of the outer layers by an expanding hot nucleus

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We calculate the hydrodynamical expansion of a hot nucleus. The results indicate that at breakup the excited nuclear system emits its surface region with a relatively high kinetic energy.

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In spite of the efforts made in the last years, it has not been yet possible to ascertain the mechanism(s) by which a nuclear system divides into many fragments after suffering an energetic collision. Such a study is essential, since, in order to extract the much sought-for-information on the nuclear equation of state from multifragmentation data, the process through which the fragments are formed must be previously elucidated.

This situation has led to a profusion of models used to analyze the existing data. Much of the discussion among the supporters of the different models has concentrated on whether the fragments are produced sequentially (evaporation [1] and sequential decay [2,3] models) or almost simultaneously (statistical [4–6], cold fragmentation [7], and percolation [8] models). However, most, if not all, of the models employed to analyze the data make the hypothesis that the nuclear system is in a homogeneous, thermally equilibrated state prior to its breakup. It is obvious that such an assumption also affects strongly the results extracted from the data and should be studied carefully.

A common prediction of the dynamical models proposed so far is that as a consequence of the collision the hot nuclear system formed in it expands considerably. This picture is supported by recent data [9] which show the existence of radial flow in the kinetic-energy distribution of fragments. Such an expansion leads to the appearance of density instabilities, which are presumed to be responsible for the fragmentation of the nucleus [10]. However, it was recently shown that instead of growing indefinitely, as assumed in Ref. [10], these instabilities saturate [11].

One should thus consider the scenario in which the fragment formation process takes place in the presence of density waves, which strongly affect the mass spectra of the fragments emitted [12]. In the present work we show that these waves have also quite noticeable effects on the velocity distribution of the different nuclear regions.

We consider that the expansion is both irrotational and isentropic; i.e., the velocity field can be written in terms of a potential function $\mathbf{v}=-\nabla\phi$, and the entropy per nucleon, $s(\mathbf{r},t)$, is constant both in space and time. The hydrodynamical motion is ruled by the continuity and Euler equations. If we assume, for simplicity, that the proton and neutron densities are identical, they can be written in terms of the nucleon density ρ as

$$\frac{\partial\rho}{\partial t}+\nabla\cdot(\rho\mathbf{v})=0 \tag{1}$$

and

$$\frac{\partial\mathbf{v}}{\partial t}+(\mathbf{v}\cdot\nabla)\mathbf{v}=-\frac{1}{m}\nabla\frac{\delta E}{\delta\rho}\ , \tag{2}$$

respectively, where m is the nucleon mass and the energy functional E is given by [13]

$$E[\rho,s]=E_{\mathrm{Coul}}[\rho]+\int\left[\varepsilon(\rho,s)+\frac{\hbar^2}{2m}\gamma(s)\frac{(\nabla\rho)^2}{\rho}\right]d^3\mathbf{r}\ . \tag{3}$$

Here E_{Coul} is the Coulomb energy of the system. For the energy density ε, we took a Skyrme parametrization

$$\varepsilon(\rho,s)=\alpha(s)\rho^{5/3}+\tfrac{3}{8}t_0\rho^2+\tfrac{1}{16}t_3\rho^{7/3}\ . \tag{4}$$

The expressions for $\alpha(s)$ and $\gamma(s)$ can be found from the results given in Ref. [13]. At entropy densities not too high, e.g., $s\le 2$, they can be approximated by

$$\alpha(s)=\frac{3\hbar^2}{10m}\left[\frac{3\pi^2}{2}\right]^{2/3}\left[1+\frac{5}{3\pi^2}s^2\right]\ , \tag{5a}$$

$$\gamma(s)=\frac{1}{36}\left[1+\frac{4}{3\pi^2}s^2\right]\ . \tag{5b}$$

The parameters t_0 and t_3 are adjusted so as to reproduce the density and binding energy per nucleon of nuclear matter, $\rho_0=0.16\ \mathrm{fm}^{-3}$ and $e_0=-16$ MeV, respectively.

In order to solve the hydrodynamical equations, we transform them into an effective Schrödinger equation [14]. To do this we consider the wave function

$$\Psi=\sqrt{\rho}e^{iM\phi/\hbar}\ , \tag{6}$$

with $M=m/[2\sqrt{\gamma(s)}]$ and ϕ the velocity potential, and obtain

$$i\hbar\frac{\partial\Psi}{\partial t}=-\frac{\hbar^2}{2M}\nabla^2\Psi+V(\mathbf{r},t)\Psi\ . \tag{7}$$

The potential in Eq. (7) is given by

$$V(\mathbf{r},t)=\frac{1}{2\sqrt{\gamma(s)}}\left[V_{\mathrm{Coul}}+\frac{\partial\varepsilon(\rho,s)}{\partial\rho}\right]\ , \tag{8}$$

where $V_{\rm Coul}=\delta E_{\rm Coul}/\delta\rho$, and this equation is solved employing numerical methods borrowed from standard time-dependent Hartree Fock calculations [15].

As initial conditions for the nucleon density ρ, we have taken the equilibrium shape, parametrized in a Wood-Saxon form, associated with the given entropy. In this case the density in the nuclear central region is smaller than the unexcited nuclear matter density ρ_0. For the initial velocity field $\mathbf{v}$, we take a uniform radial expansion, so that $\mathbf{v}\propto\mathbf{r}$.

In Fig. 1 we show the nucleon density and velocity field at several times during the expansion of a nuclear system composed of $A=120$ nucleons, in the case of an entropy per nucleon $s=1.7$ and total excitation energy per nucleon $E^*/A=23$ MeV. At $t=0$ the kinetic energy per nucleon associated with the radial expansion is 14 MeV. We note that some time after the beginning of the evolution the nucleon density shows the appearance of waves in the region closest to the surface, with associated disturbances in the velocity field. The connection between these two phenomena follows from the continuity equation. On the other hand, the central region of the nuclear system still retains the characteristics of a uniform expansion, i.e., a rather constant density and a linear radial dependence of the velocity field.

From these results we can calculate the collective velocity distribution of the nucleons which compose the system, dn/dv, at any point during its expansion. This distribution at $t=24$ fm/c is shown as a solid line in Fig. 2. In this figure we also depict, as a reference, dn/dv calculated for the case of the uniform expansion of a nucleus with a Woods-Saxon density profile (dashed line) having the same density and velocity distribution in the central region as our dynamical calculation. For the uniform expansion, dn/dv is dominated by the r^2 geometrical weighting factor, while the dynamical expansion shows a marked structure.

The sharp peaks in dn/dv around $v/c\approx0.16$ are readily associated with the extrema of $v(r)$ in Fig. 1(b). This velocity region corresponds to the radial distance interval 8–11 fm, which is also the position of the large peak in the density [Fig. 1(a)]. The higher number of nucleons with velocities $v/c\approx0.16$ arises, therefore, as a consequence of both the higher than average nucleon density $\rho(r)$ and the plateau in $v(r)$.

It could be interesting to investigate how the appearance of the surface structure in the density profile is related to the properties of nuclear matter. To do this we considered equations of state with compressibilities in the range $K_0\approx200$–400 MeV. This was done by appropriately modifying the $\frac{7}{3}$ exponent of the last term on the right-hand side of Eq. (4). We found that, for fixed excitation energy and entropy, the density at which the structure first appears and its rate of growth both increase with the compressibility. On the other hand, the speed of the surface layer is observed to be approximately independent of K_0 and thus appears not to be related to the speed of sound, which is proportional to $K_0^{1/2}$.

Once the nuclear system has considerably expanded, it is expected to break into many pieces. The kinetic energies of these fragments should reflect the details of the

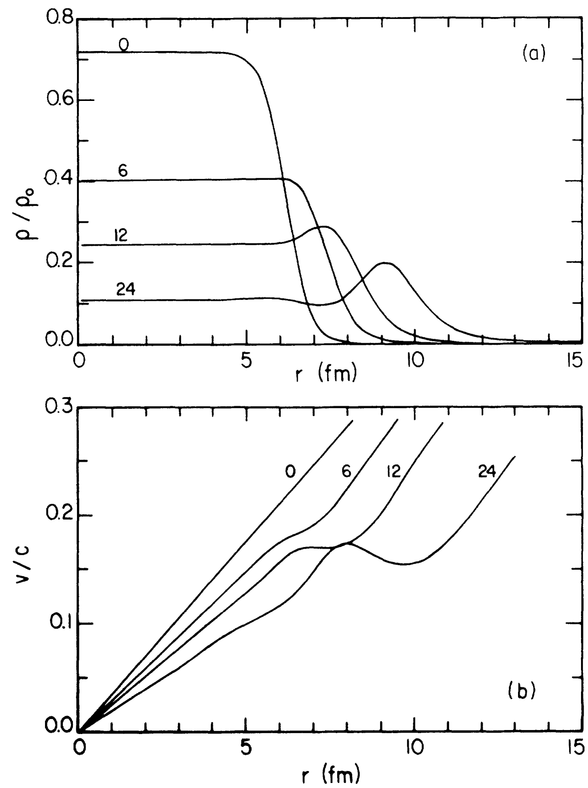

FIG. 1. Time evolution of (a) the nucleon density and (b) velocity field. The numbers labeling the curves indicate the time, in units of fm/c, since the beginning of the evolution. See text for additional details.

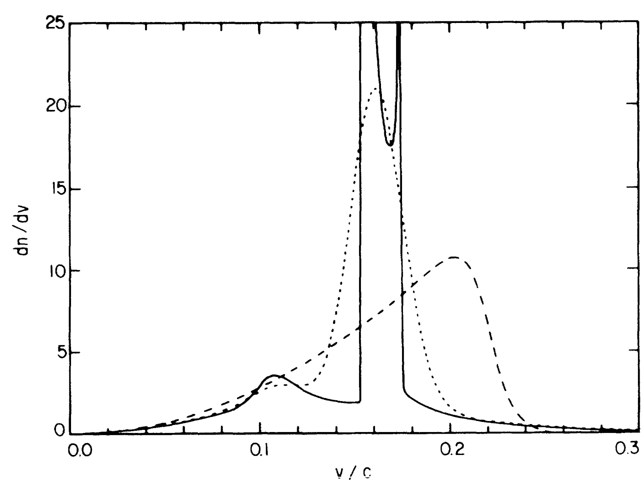

FIG. 2. Distribution of nucleons (in units of A/c) according to their velocities at time $t=24$ fm/c. The solid line shows the result of the hydrodynamical expansion, the dotted line represents a smoothing of the previous result due to the thermal velocity distribution of the nucleons, and the dashed line represents the distribution resulting from a uniform expansion. See text for more details.

collective velocity field at breakup. We expect, therefore, that marked features such as the ones appearing in our dynamical calculation of dn/dv should be present in the fragment kinetic-energy distribution.

One should keep in mind that fragments form through coalescence of the nucleons inside finite regions of the nuclear system. As consequence, the resulting collective velocity of a fragment is an average of those of the individual nucleons from which it was formed. The effect of this coalescence process should be to make the velocity spectrum of fragments smoother than the collective nucleon velocity distribution. This is qualitatively exemplified by the dotted line in Fig. 2, which shows the result of convoluting the original nucleon velocity spectrum with a Maxwell distribution of width of $0.02c$.

In conclusion, the hydrodynamical model clearly predicts that the expansion leads to the appearance of a large density peak in the surface region, which acquires an almost uniform velocity. It appears, thus, that during the dissociation process following an energetic heavy-ion collision, the nucleus emits first its outer layers, with a relatively high kinetic energy. It is interesting to remark that indications supporting the existence of such effects have been found recently [16]. The data available are scarce, however, and so more work is needed to ascertain this claim. On the theoretical side, we believe that the stochastic nucleation model presented in Ref. [17], extended so as to include not only the information on the nucleon density distribution as in Ref. [12], but also their momentum distribution, should be an adequate treatment of fragment formation. The generalization of this model is presently underway.

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