Partial-transparency effects in high-energy collisions of heavy ions

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A model is proposed for heavy-ion collisions at $E_{\rm lab} \sim 1$ GeV/nucleon for the case of an incomplete statistical equilibrium in the highly excited nuclear matter. This approach can reproduce the characteristic double-humped structure of the experimental rapidity distributions of secondary particles.

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Manko and Nagamiya[1] have recently reported a kinematic analysis of experimental data[2] on the emission of protons and composite fragments in nucleus-nucleus collisions at the incident-nucleus energy $E_{\rm lab} = 0.8$ GeV/nucleon. They found that the rapidity distributions of the reaction products with a small transverse momentum have a characteristic double-humped structure. This structure can be seen particularly clearly in the case of composite particles. In the present letter we offer an interpretation of this structure in terms of a partial transparency of the nuclei, which prevents the attainment of a local thermodynamic equilibrium in the course of the reaction.

In our semiphenomenological approach we explicitly allow for a possible incomplete randomization of the initial momentum of the colliding nuclei. This approach is essentially similar to the two-fluid hydrodynamic model[3] but much simpler from the calculation standpoint. As in the firestreak model,[4] we assume that only the overlapping parts of the nuclei interact substantially in the course of the collision. The interaction is broken up into the interactions of individual tubes (streaks) which are positioned opposite each other. The interaction between tubes in the transverse direction is ignored. In contrast with the firestreak model, we do not assume that the matter of the colliding tubes comes to a complete stop in their center-of-mass frame. We assume that the incomplete stopping of the tubes, especially of short tubes, results in a spatial separation of the nuclear matter into two blobs, whose velocities and temperatures are found by a dynamic analysis.

The interaction of the two fluxes of nucleons which have undergone the mutual stopping is described by a relativistic kinetic equation [5,6] using a Fokker-Planck expansion. The use of this approximation is justified by the circumstance that at energies $E_{\rm lab} \sim 1$ GeV the NN cross section is very anisotropic, with small momentum transfers predominant. This situation causes a slow relaxation of the original two-stream deviation from equilibrium of the nucleons, so that we may parametrize their distribution function as the sum of two Maxwellian distributions separated by a distance equal to the average relative velocity of the fluxes. The equations derived for the parameters of the Maxwellian distributions in this approach constitute the system of equations of two-fluid hydrodynamics.

In an effort to formulate a theory in a simpler way, avoiding laborious numerical calculations, we take the approach of studying the time evolution of the tube 4-velocities U^i_α and of their internal energies per particle,[1)] ε_α, averaged over the volumes of the tubes, instead of solving the corresponding hydrodynamic equations. After taking this average, we find $(c = 1)$

$$dN_\alpha / dt = 0, \tag{1}$$

$$N_\alpha d(\epsilon_\alpha U^i_\alpha)/dt = \mp D(t)(\epsilon_p U^i_p - \epsilon_t U^i_t)/(\epsilon_p \epsilon_t), \tag{2}$$

where N_α is the number of particles in tube α, the minus and plus signs (here and below) correspond to the values $\alpha = p$ and t, respectively, and

$$D(t) = \frac{1}{4}[s(s-4m^2)]^{1/2}\sigma_{tr}(s)\int n_p(x) n_t(x) d^3x. \tag{3}$$

Here $n_\alpha(x)$ is the local number density of particles in tube α (in its proper frame), $\sigma_{\rm tr}$ is the transport cross section for NN scattering, m is the mass of the nucleon, $s = m^2(U_p + U_t)^2$, and $x = (t,\mathbf{x})$.

We introduce the average tube rapidities y_α by means of $U^i_\alpha = (\mathrm{ch}y_\alpha, 0, 0, \mathrm{sh}y_\alpha)$, where the z axis coincides with the axis of the tubes.

From system (1), (2) we can easily derive equations for the evolution of the relative velocity, $V_{\rm rel} = \mathrm{th}(y_p - y_t)$, and of the internal energies of the fluxes, ε_α (in the approximation $\varepsilon_\alpha - m \ll m$):

$$\frac{dV_{rel}}{dt} = -\frac{\sigma_{tr}}{2} V^2_{rel}\left(\frac{1}{N_p} + \frac{1}{N_t}\right)\int n_p(x) n_t(x) d^3x, \tag{4}$$

$$N_\alpha \frac{d\epsilon_\alpha}{dY} = \frac{N_p N_t}{N_p + N_t}\frac{m^2}{1-Y^2}\left[\frac{1}{\epsilon_\alpha}(1-Y) \mp \frac{\epsilon_t - \epsilon_p}{\epsilon_p \epsilon_t}\right], \tag{5}$$

where $Y = \mathrm{ch}(y_p - y_t)$.

Solving these equations, we can relate the initial (0) and final (f) values of the rapidity difference,

$$\text{th}\,\frac{(y_p - y_t)_f}{2} = \text{th}\,\frac{(y_p - y_t)_0}{2}\exp\left(-\frac{l_p + l_t}{\lambda_T}\right), \tag{6}$$

and we can find an expression for ε_α as a function of $(y_p - y_t)_f$:

$$(\epsilon_\alpha - m)_f = \frac{m l_p l_t}{(l_p^2 + l_t^2) + 2 l_p l_t Y_f}\left\{(Y_0 - Y_f) \mp \frac{l_p - l_t}{l_p + l_t}\left[Y_f + \left(\frac{l_p}{l_t}\right)^{\mp 1}\right] A(Y_0, Y_f)\right\}, \tag{7}$$

$$A(V_0, Y_f) = \sqrt{2}(Y_f - 1)^{1/2}\left[\text{arctg}\left(\frac{Y_0 - 1}{2}\right)^{1/2} - \text{arctg}\left(\frac{Y_f - 1}{2}\right)^{1/2}\right]. \tag{8}$$

Here $l_{p,t}$ are the lengths of the interacting tubes, normalized to the normal nuclear density $n_0 = 0.15\ \text{fm}^{-3}$, and $\lambda_T = 2/(n_0 \sigma_{tr})$ is the effective stopping length (a parameter of the model). To determine each rapidity y_α we must supplement (6) with the momentum conservation law: $l_p \varepsilon_p \text{sh} y_t + l_t \varepsilon_t \text{sh} y_t = \text{const}$.

The inclusive cross sections for proton emission have been calculated from the geometric considerations of the firestreak model.[4] The presence of Δ particles and π mesons in each blob is taken into account by incorporating their corresponding contributions to the equation of state, $\varepsilon_\alpha(T)$, of the nuclear matter.[7,8] We note that if the stopping of the interacting tubes is substantial $(l_p + l_t \gg \lambda_T)$ the predictions of our model become the same as those of the firestreak model.[4]

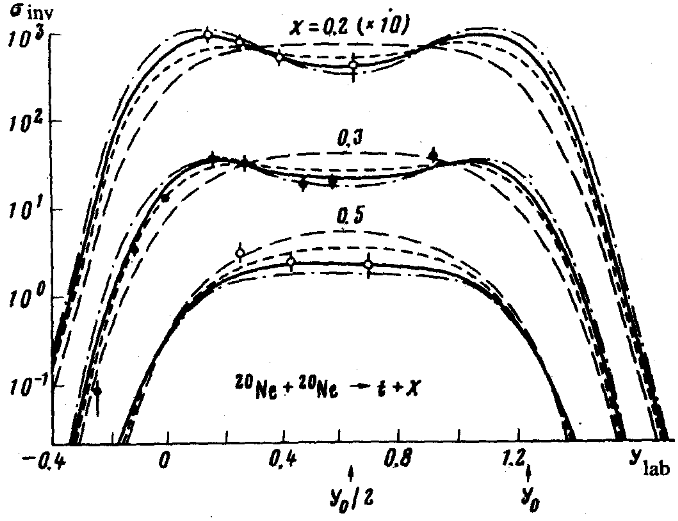

FIG. 1. Invariant cross sections for the emission of tritons (in units of millibarns per GeV^2 per second) in the reaction 20$_{\text{Ne}}$ + ^{20}Ne at $E_{\text{lab}} = 0.8$ GeV/nucleon. Here y_0 is the initial rapidity of the incident nucleus. Points—experimental data[1]; curves with long dashes—$\lambda_T = 0$; curves with short dashes—$\lambda_T = 6$ fm; solid curves—8 fm; dot-dashed curves—10 fm.

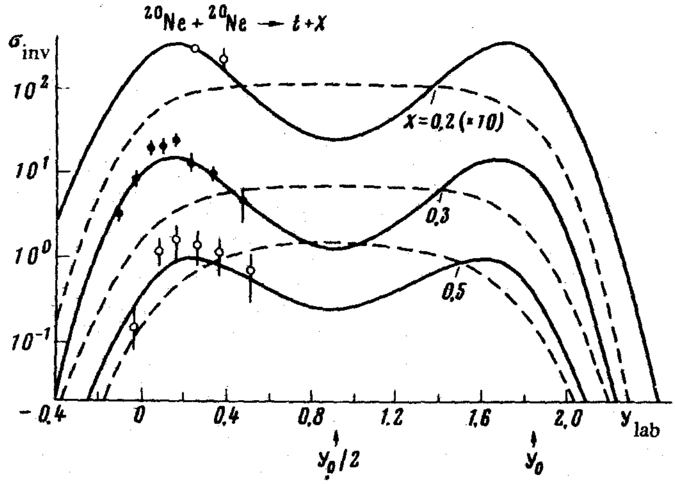

FIG. 2. The same as in Fig. 1, but for $E_{lab} = 2.1$ GeV/nucleon. Points—experimental data[11]; dashed curves—$\lambda_T = 0$; solid curves—14 fm.

The cross sections for the emission of composite particles (deuterons and tritons) are calculated from the coalescence model,[9,10] which agrees well[2] with experimental data. The experimental coalescence coefficients are taken from Ref. 2. Figures 1 and 2 show the invariant proton-emission cross sections $\sigma_{inv} = d^2\sigma/pdE$ in the reaction $^{20}Ne + {}^{20}Ne$ as functions of the longitudinal rapidity $y_{lab} = \frac{1}{2}\ln(E + p_\parallel)/(E - p_\parallel)$ at fixed values of the dimensionless transverse momentum $x = p_\perp/m_t$.

It can be concluded from these calculations that the double-humped structure observed experimentally in the rapidity distributions of the secondary particles cannot be reproduced by the standard firestreak model ($\lambda_T = 0$); it is apparently necessary to allow for a partial transparency of the colliding nuclei in order to explain this structure. The results show that the experimental data at $E_{lab} = 0.8$ GeV/nucleon are described best for all combinations of colliding nuclei with the value $\lambda_T = 8$ fm. This value of the stopping length agrees with that estimated from the vacuum NN cross sections. At the energy $E_{lab} = 2.1$ GeV/nucleon the optimum value turns out to be $\lambda_T = 14$ fm. The calculations show that the double-humped structure in the distributions becomes fainter when we select central collisions or as we move to heavier nuclei (the transparency effects have essentially disappeared at $E_{lab} = 0.8$ GeV/nucleon in the reaction $U + U$). It follows from this new model that "fast" and "slow" sources (in the sense in which these terms are used in Ref. 1) are formed predominantly in peripheral collisions of nuclei, while a "moderate" source is formed preferentially in central collisions. For this reason, we should observe a correlation between the particles from the fast and slow sources.

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[1)]The subscript $\alpha = p,t$ specifies that the tube initially belongs to the incident nucleus or to the target nucleus, respectively.

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