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New results on energy and momentum conservation for particle emission in A+A collisions at SPS energies

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We construct a new, simple model of the heavy ion collision. This model is local in the impact parameter plane and appropriate for the CERN Super Proton Synchrotron (SPS) energy range. It can be regarded as a new realization of the "fire-streak" approach, originally applied to studies of lower energy reactions. Starting from local energy and momentum conservation, we nicely describe the whole centrality dependence of the pion rapidity distribution in Pb+Pb collisions at $\sqrt{s_{NN}}$ =17.3 GeV. In particular we explain the broadening of the pion rapidity distribution when going from central to peripheral collisions. The results of our calculations are compared to experimental data from the NA49 detector at the SPS. We discuss the resulting implications on the role played by energy and momentum conservation for the dynamics of particle production in the heavy ion collision. We conclude that the latter conservation laws play a dominant role in the centrality dependence of the absolute size and shape of pion rapidity spectra. A specific space-time picture emerges, where the longitudinal evolution of the system strongly depends on the position in the impact parameter (b_x, b_y) plane. In non-central collisions we predict the existence of "streams" of excited matter moving very close to the spectator system in configuration (x, y, z) space. This picture is consistent with our earlier findings on the longitudinal evolution of the system as deduced from electromagnetic effects on charged pion directed flow and charged pion ratios.

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1. Introduction

The present short paper is largely based on our recent publication [1] where a much more detailed description of different technical aspects of our work can be found. Below we summarize only the main findings emerging from this work.

The presence of energy and momentum conservation laws at the different stages of the heavy ion collision is evident, but their detailed impact on multiparticle production processes can be far from obvious. In the case of the complex nonperturbative phenomena which underly the bulk of particle production, this impact should be investigated with due care because it constitutes a basis for all further, nontrivial phenomena like quark-gluon plasma formation, as well as the collective expansion of the system up to the final state which is observed in the detector.

Our earlier studies of spectator-induced electromagnetic (EM) effects in A+A collisions at SPS and low RHIC energies brought us information on the longitudinal evolution of the system [2-4]. Consequently we now formulate a simple model with exact local energy-momentum conservation in the initial state of the collision, followed by a simple scheme of subsequent particle (pion) production. We examine the implications of energy-momentum conservation laws for the longitudinal evolution of the presumably deconfined matter created in the collision as a function of its impact parameter. Especially in peripheral collisions, the "hot" system of dense partonic matter located close to midrapidity appears to be accompanied by relatively "colder", but still highly energetic volumes of matter positioned in different regions of the (b_x, b_y) plane and moving with large velocities. We find that the larger is the pion rapidity, the closer is the position of its formation zone to the spectator system which coincides with our observations from EM effects.

Our model is presented in Fig. 1, which illustrates the situation before and after the collision in the top and bottom panels, respectively. Before the collision we have two colliding

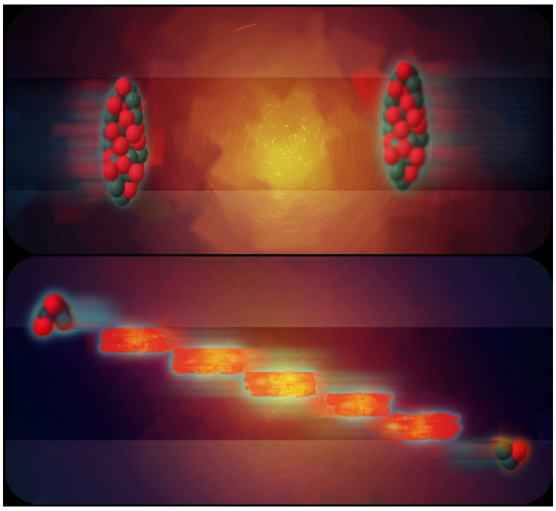

Figure 1: Schematic picture illustrating our model: the 3D nuclear mass distribution is treated assuming local energy-momentum conservation in the impact parameter plane; 1 x 1 fm^2 size elements of both nuclei form "fire-streaks" whose kinematic characteristics are defined by conservation of energy and longitudinal momentum (the plot is taken from [5]).

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nuclei in the overall center-of-mass system. After the collision the nuclear mass, subdivided in 1 x 1 fm^2 "bricks", forms "fire-streaks" [6] of excited and possibly deconfined matter. The rapidity and excitation energy of the fire streaks follows directly from energy-momentum conservation.

2. Pion production in a simple energy-momentum conservation model

For the production of final state pions in A+A collisions, we assume that each fire streak fragments (or freezes-out) independently in its own c.m.s. frame. We use a uniform phenomenological fragmentation function which again fulfills (statistically) energy conservation:

$$\frac{dn}{dy} \sim A \cdot (E_s^* - m_s) \cdot \exp\left(\frac{-[(y-y_s)^2 + \varepsilon^2]^{\frac{n}{2}}}{n\,\sigma_y^n} \right)$$

Here, *dn/dy* is the number of pions produced from a single fire-streak per unit of pion rapidity, y_S is the fire-streak rapidity, E_S^* is its total energy in its c.m.s. frame (that is, its invariant mass). Finally, m_S is the sum of "cold" masses of the two "bricks" of nuclear matter which were designed to form this fire-streak before the collision actually took place, while *A*, *n* and σ_y are free parameters.

A selection of our results is presented in Fig. 2. As a consequence of local energy-momentum

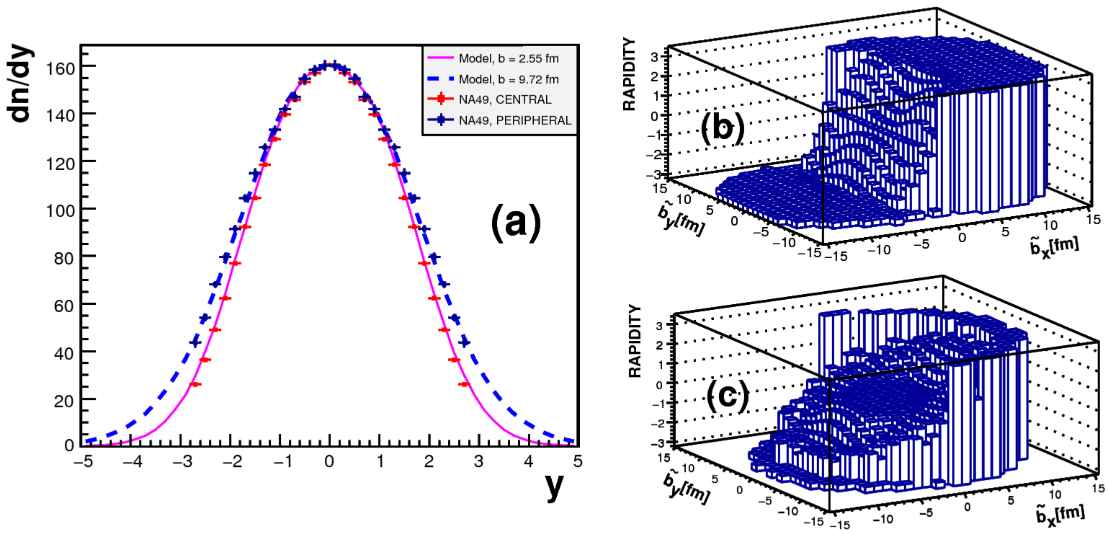

Figure 2: (a) Shape comparison for π^- rapidity spectra in peripheral and central Pb+Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV, measured by the NA49 experiment [7], put together with our model predictions. For peripheral collisions, both experimental data and model results are multiplied up by an arbitrary factor in order to match the distributions in central collisions at *y=0*. **(b)** Distribution of fire-streak rapidity as a function of fire-streak position in the impact parameter plane for peripheral Pb+Pb collisions at impact parameter *b*=9.72 fm. (c) Same for central collisions at *b*=2.55 fm. All the plots are taken from [1].

conservation postulated in our model for the initial stage of the reaction, the deconfined matter contained in the fire-streaks appears to behave differently in peripheral and in central Pb+Pb collisions. As it is apparent in Fig. 2(b), in a peripheral reaction the fire-streaks will "fly away" with large relative rapidities. These will basically extend from target spectator up to projectile spectator rapidity, both represented by large flat surfaces in the figure. On the other hand, in a central collision in Fig. 2(c), a qualitatively similar effect will be present (for the evidently larger participant system), but the overall spread in fire-streak rapidity will be much smaller. Consequently, applying our fragmentation function given above, we obtain final state pion rapidity spectra presented as solid and dashed curves in Fig. 2(a). The predicted narrowing of the pion rapidity spectrum from peripheral to central reactions is fully reproduced by experimental data on Pb+Pb collisions from the NA49 experiment [6]. We note that our model reproduces not only the shape but also the absolute values of the *dn/dy* spectrum as described in [1].

Consequently, we explain both the measured pion multiplicities and the change of shape of pion rapidity spectra as a function of centrality, as a pure result of local energy-momentum conservation!

3. Summary

Below we summarize the basic findings resulting from our study. We proposed a very simple model, uniquely based on a proper description of collison geometry originating from realistic density distributions of the two incoming nuclei. The main assumption of this model was rigorous local energy-momentum conservation for the initially created matter in the transverse (impact parameter) plane. This model explains the whole centrality dependence of negative pion *dn/dy* spectra measured by the NA49 experiment in Pb+Pb collisions at $\sqrt{s_{NN}}$ = 17.3 GeV, also in terms of their narrowing from peripheral to central collisions. This trend is, in our model, a pure consequence of energy and momentum conservation. From the above we conclude that *the longitudinal evolution of the system of hot and dense matter initially created in the heavy ion collision at SPS energies is dominantly defined by conservation laws on energy and momentum*. A natural feature of the resulting picture of the space-time evolution of the system is that the distance between the pion emission site and the spectator system will decrease with increasing rapidity, Fig. 1, which is what we observed from our studies of EM interactions induced by the spectator system on charged pion emission [4].

Acknowledgments

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