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Can Momentum Correlations Proof Kinetic Equilibration in Heavy Ion Collisions at 160 AGeV?

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Abstract

We perform an event-by-event analysis of the transverse momentum distribution of final state particles in central Pb(160AGeV)+Pb collisions within a microscopic non-equilibrium transport model (UrQMD). Strong influence of rescattering is found. The extracted momentum distributions show less fluctuations in A+A collisions than in p+p reactions. This is in contrast to simplified p+p extrapolations and random walk models.

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The approach to thermalization in relativistic heavy ion collision has gained a lot of attention in the last year. It has been intensively investigated experimentally and theoretically [1–4]. However, very new event-by-event fluctuation data shed new light onto this topic. Momentum fluctuations are due to the finite particle number and the reaction dynamics. In thermal equilibrium they are connected to the heat capacity of nuclear matter [5]. Additional insight may also be gained by studying particle number fluctuations which are connected to another key quantitity, namely the compressibility of hadronic matter under extreme conditions [6].

In this letter we perform an event-by-event analysis of central ($b<3$ fm) Pb+Pb collisions at 160 AGeV within the Ultra-relativistic Quantum Molecular Dynamics model (UrQMD) [7]. UrQMD is a microscopic hadronic transport approach based on the covariant propagation of mesonic and baryonic degrees of freedom. It allows for rescattering and the formation and decay of resonances and strings. For further details about the UrQMD model, the reader is referred to Ref. [7].

The aim of this investigation is to analyse the fluctuations of event-by-event distributions both in p+p and nucleus-nucleus reactions. One of such distributions is the transverse momentum distribution. It seems obvious that these fluctuations are larger for p+p reactions than for A+A collisions. In p+p reactions, we have strong correlations in particle emissions mainly due to conservation laws [8]. These correlations are, however, reduced in A+A collisions due to the larger amount of energy available in the system and due to rescattering of secondaries. Indeed, UrQMD calculations show these fluctuations to be much smaller in Pb+Pb than in p+p, due to the large amount of meson-baryon (MB) and meson-meson (MM) rescattering. To illustrate this scenario Fig. 1 shows the time evolution of the baryon- (full line) and meson (dotted line) densities in Pb+Pb at 160 AGeV. After 4 fm/c the baryons have complete spatial overlap with the mesons resulting in high scattering rates with secondaries.

For our purpose, it is convenient to introduce the momentum correlation parameter Φ defined as [9]:

$$\Phi := \sqrt{< Z^2 > / < N >} - \sqrt{\overline{z^2}} \quad , \quad \text{with} \quad Z = \sum_{i=1}^{N} z_i \quad , \quad z_i = p_{\perp_i} - \overline{p_\perp} \qquad (1)$$

and $\overline{p_\perp}$ as the particle averaged transverse momentum, $\overline{z}$ denotes the particle averaged z, $< N >$ the average number of particles per event and $< Z >$ is the event averaged Z.

Even though this correlation parameter Φ is not defined in an obvious way (a careful analysis of this quantity is considered in [10]) we make use of it to compare our results to recent investigations [11,12].

This variable Φ can provide insight into the emission dynamics of particles in the course of the collision. The Φ values can best be classified as follows:

1. $\Phi(A + A)/\Phi(p + p) = 1$:

   This indicates that both fluctuations in p+p and A+A are identical. It corresponds to a simple extrapolation of proton-proton collisions to describe A+A. This is done e.g. in the FRITIOF model (see Fig. 2).

2. $\Phi(A + A)/\Phi(p + p) < 1$:

   The emitted particles in A+A are less correlated than they are in p+p. This is the case in thermal models. However, UrQMD shows this behaviour due to the large number of secondary MB and MM collisions (Fig. 2)

3. $\Phi(A + A)/\Phi(p + p) > 1$:

   The momenta of the particles emitted in A+A are more strongly correlated than they are in p+p. This scenario has recently been investigated in the random walk approach [11,13]

The dependence of the correlation variable Φ vs. the number of participants normalized to the proton proton value is shown in Fig. 2 for the UrQMD model (black squares) while the FRITIOF calculation is depicted by full diamonds. The full UrQMD simulation yields a dramatic reduction of the particles momentum correlations when going from p+p to A+A (indicated by *'thermalization?'*). Thus, the UrQMD model belongs to the second of the above discussed models. In contrast, a UrQMD calculation with secondary meson-baryon and meson-meson reactions turned off - i.e. only baryon-baryon collisions can occur - yields a $\Phi(A+A)/\Phi(p+p)$ ratio of one. This is shown as the empty square. Here the Φ value stays compatible with our expectation from the p+p value. This observation is supported by FRITIOF calculations (full diamond), which do not include rescattering of secondaries (see however Ref. [14]). The decrease of the momentum correlation parameter Φ by one order of magnitude when going from p+p to Pb+Pb (or by the inclusion of rescattering) is in line with NA49 data [12].

Does this uncorrelated particle emission indicate global equilibration of the hadronic source? It has been recently adressed that in each single event large fluctuations in energy density and isospin happen [15,16]. This results in non-thermal initial conditions, which can affect the final state of the single event. The information is washed out when one averages over many reactions.

In the present model this effect can be pinned down to be due to the additional MB and MM scattering contributions. In Fig. 3 we have depicted the collision spectra of all particles in central (b<3 fm) Pb+Pb reactions at 160 AGeV. Overall we find ≈1200 baryon-baryon, ≈3400 meson-baryon and ≈2500 meson-meson collisions: Only 17% of all collisions in the Pb+Pb system are due to baryon+baryon extrapolations in the present model. Thus, the Pb(160AGeV)+Pb system reveals a far more complex reaction dynamics than collisions at lower energies or for smaller systems. We propose to study this correlation ratios for different systems (S+S, p+A, impact parameter dependence in Pb+Pb) and different beam energies to disentangle these contributions. Other quantities should also be introduced to analyse the differences between correlations in p+p and A+A [10]. The six times larger number of collisions compared to the B+B extrapolation (or FRITIOF, resp.) leads to less correlated momenta of emitted particles. Therefore, a small Φ value is a necessary, but not a sufficient condition for thermal equilibration. Thus, from the present momentum analysis, on should be careful to draw the conclusion that the system has thermalized at late times in the collision.

We conclude that heavy ion collisions at 160 AGeV, exhibit an intricate interplay between all three collision types (meson-baryon, meson-meson and baryon-baryon). The most important interaction for the p_T distribution is meson-baryon scattering with nearly 50% of all collisions (see also [17]). This leads to particle momentum correlation patterns in strong contrast to simplified p+p and p+A superpositions/extrapolations. The present model predicts the small Φ values as measured in Pb(160GeV)+Pb. We would like to draw the attention of the field to more careful investigation of the hitherto rather unexplored MM and MB reactions.

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FIGURES

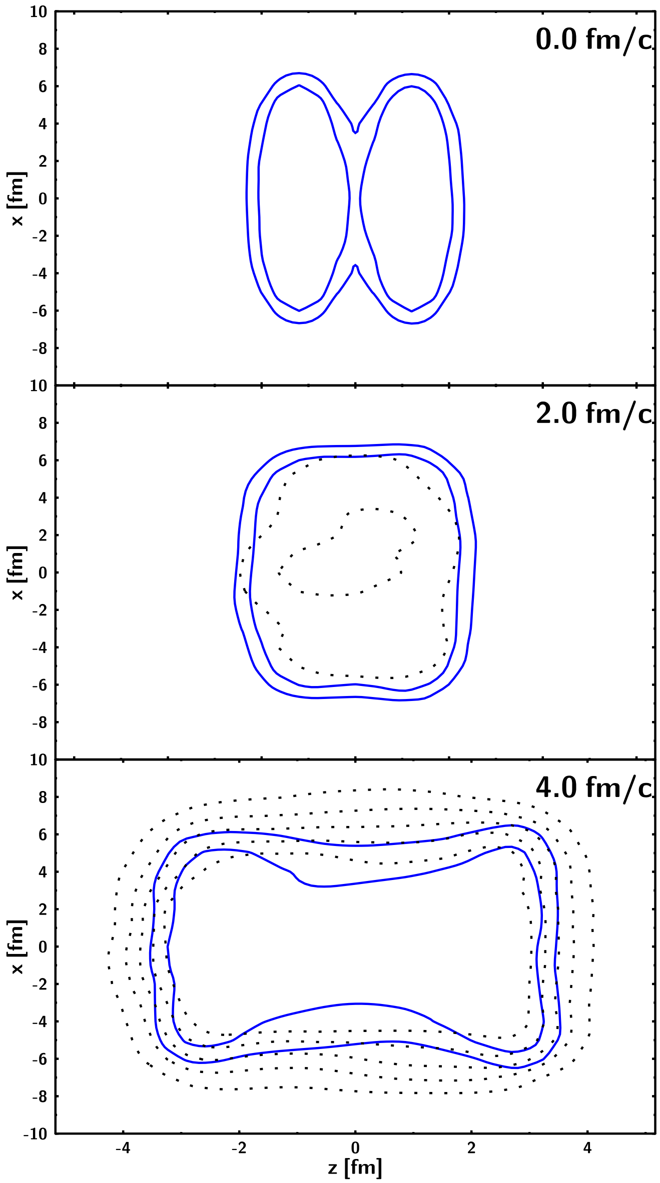

FIG. 1. Time evolution of the baryon- (full line) and meson (dotted line) densities in Pb(160 AGeV)+Pb (b=0 fm) collisions. The equal density lines (in the CMS frame) correspond to ρ_0, $1.7\rho_0$ for baryons and $0.3\rho_0$, $0.6\rho_0$, …, $1.5\rho_0$ for the mesons. The z-axis is along the beam axis, x is the impact parameter direction.

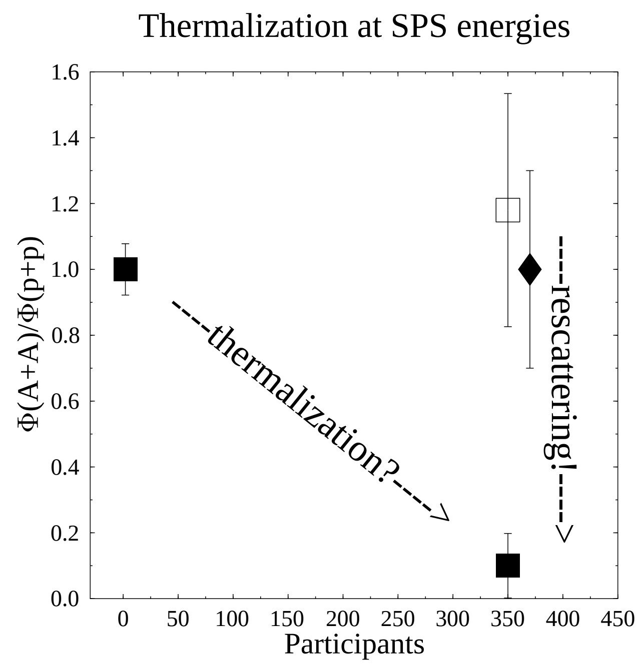

FIG. 2. Normalized Φ values in p+p at 160GeV and Pb+Pb at 160AGeV, b<3 fm. UrQMD calculations with (full squares) and without (empty square) rescattering are compared to FRITIOF calculations (full diamond).

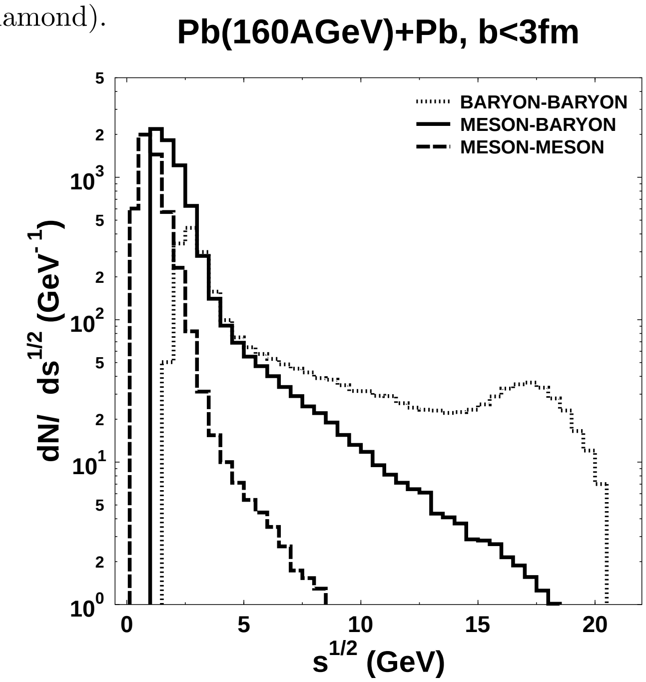

FIG. 3. Collision energy spectra of baryon-baryon (dotted line), meson-baryon (full line) and meson-meson (dashed line) reactions in Pb(160 AGeV)+Pb, b<3 fm.