Directed Flow of Baryons in Heavy-Ion Collisions^G

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The collective motion of nuclear matter observed in heavy-ion interactions is essentially caused by the pressure gradients arising during the time evolution in the collision, and hence opens a promising way for obtaining information on the equation of state (EoS) and, in particular, on a possible phase transition. We analyze the collective motion of nucleons from high-energy heavy-ion collisions within a relativistic two-fluid model for different equations of state [1].

Our consideration is essentially based on the recently proposed Mixed-Phase (MP) model [2]. The underlying assumption of the MP model is that unbound quarks and gluons *may coexist* with hadrons forming a *homogeneous* quark/gluon–hadron phase. Since the mean distance between hadrons and quarks/gluons in this mixed phase may be of the same order as that between hadrons, the interaction between all these constituents (unbound quarks/gluons and hadrons) plays an important role and defines the order of the phase transition. For the case of quarks of two light flavors at zero baryon density ($n_B = 0$), the MP model is consistent with lattice QCD data providing a continuous phase transition of the cross-over type with a deconfinement temperature $T_{dec} = 153$ MeV. In a two-phase approach based on the bag model a first-order deconfinement phase transition occurs with a sharp jump in energy density ε at T_{dec} close to the value obtained from lattice QCD. A particular feature of the MP model is that, for $n_B = 0$ the *softest point* of the EoS, defined as a minimum of the function $p(\varepsilon)/\varepsilon$, is not very pronounced and located at comparatively low values of the energy density: $\varepsilon_{SP} \approx 0.45$ GeV/fm^3, which roughly agrees with the lattice QCD value. In contrast, the bag-model EoS exhibits a very pronounced softest point at large energy densities $\varepsilon_{SP} \approx 1.5$ GeV/fm^3.

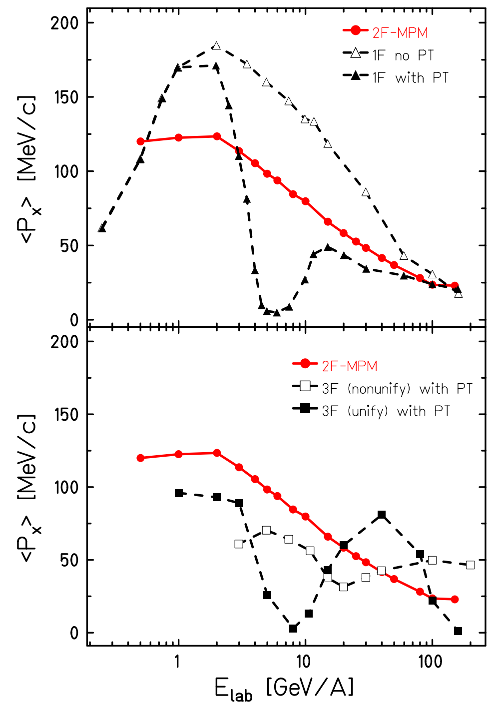
We have studied experimental consequences of these differences in EoS within the hydrodynamic approach. We use the 3D relativistic two-fluid model with a finite stopping power [3]. These two fluids, initially associated with target and projectile nucleons, are described by a set of hydrodynamic equations with the coupling term, which characterizes friction between the counter-streaming fluids. The friction term originates from both elastic and inelastic NN collisions and gives rise to a direct emission of mesons in addition to the thermal mesons in the fluids [3].

The average directed flow is defined by

$$\langle P_x \rangle = \frac{\displaystyle\int dp_x dp_y dy\; p_x \left(E\frac{d^3N}{dp^3} \right)}{\displaystyle\int dp_x dp_y dy \left(E\frac{d^3N}{dp^3} \right)} ,$$

where the integration in the c.m. system runs over the rapidity region $[0, y_{cm}]$. The calculated excitation functions for $\langle P_x \rangle$ of baryons within different models are shown in the figure for $Au{+}Au$ collisions at the impact parameter $b = 3$ fm. As shown in the upper panel, conventional one-fluid (1F) hydrodynamics for pure hadronic matter [4] results in a very large directed flow due to the inherent instantaneous stopping of the colliding matter. This instantaneous stopping is unrealistic at high beam energies. If the deconfinement phase transition (PT), based on the bag-model EoS [4], is included, the excitation function of $\langle P_x \rangle$ exhibits a deep minimum near $E_{lab} \approx 6$ A·GeV, which is a manifestation of the strong softest-point effect in the bag-model EoS.

The result of two-fluid (2F) hydrodynamics with the MP EoS noticeably differs from the one-fluid calculations. After a maximum around 1 A·GeV, the average directed flow decreases slowly and smoothly. This difference is caused by the fact that the softest point of the MP EoS is washed out for $n_B \gtrsim 0.4$ and also by dynamical reasons, i.e. the finite stopping power and direct



pion emission change the evolution pattern. The latter point is confirmed by comparison to three-fluid calculations with the bag EoS [5] plotted in the lower panel of the figure. As seen, the minimum of the directed flow excitation function, predicted by the one-fluid hydrodynamics with the bag EoS, survives in the three-fluid (nonunified) regime, but its value decreases and its position shifts to higher energies. If one applies the *unification procedure* of [5], which favors fusion of two fluids into a single one, and thus making stopping larger, three-fluid hydrodynamics gives results, which are very similar to those of the one-fluid model, and predicts in addition a bump at $E_{lab} \approx 40$ A·GeV.

Recent experimental results confirm that the excitation function of the directed baryonic flow is a smooth function in the 2-8 A·GeV energy range [6], which is in agreement with our MP EoS.

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