

Baryon stopping signal for mixed phase formation in HIC

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Abstract. It is argued that an irregularity in the baryon stopping is a natural consequence of onset of deconfinement occurring in the compression stage of a nuclear collision. It is an effect of the softest point inherent in an equation of state (EoS) with a deconfinement transition. In order to illustrate this effect, calculations within the three-fluid model were performed with three different EoS's: a purely hadronic EoS, an EoS with a first-order phase transition and that with a smooth crossover transition.

1. Introduction

One of the main goals of the current experiments at RHIC and SPS and forthcoming experiments at FAIR and NICA facilities is to determine a kind of the deconfinement transition in dense baryonic matter and to find the collision energy (thereby the baryonic density) at which this transition starts. In this paper it is argued that the baryon stopping in nuclear collisions can be a sensitive probe of the deconfinement onset. Let us start with discussion in terms of the conventional (i.e. one-fluid) hydrodynamics.

The form of the resulting rapidity distribution of net-baryons depends on the spatial form of the produced fireball. If the fireball is almost spherical, the expansion of the fireball is essentially 3-dimensional which results in a peak at the midrapidity in the rapidity distribution. This statement is a theorem that can be proved in few lines. If a the fireball is strongly deformed (compressed) in the beam direction, i.e. has a form of a disk, its expansion is approximately 1-dimensional that produces a dip at the midrapidity, which is confirmed by numerous simulations, see e.g. [1]. In terms of the fluid mechanics this is a consequence of interaction of two rarefaction waves propagating from opposite peripheral sides of decaying disk toward its center [2].

The formation of this fireball is already a matter of dynamics at the early compression stage of the nuclear collision. A softest point [3] characteristic of EoS's with a phase transition plays an important role in this compression dynamics. At the softest point the system exhibits the weakest resistance to its compression as compared with that in adjacent regions of the EoS. At low collision energies the softest point is not reached in the collision process, the system remains stiff and therefore the produced fireball is almost spherical. As a result, the baryon rapidity distribution is peaked at the midrapidity. When the incident energy gets high enough, the softest-point region of the EoS starts to dominate during the compression stage, the system weaker resists to the compression and hence the resulting fireball becomes more deformed, i.e.



more of the disk shape. Then its expansion is close to the 1-dimensional pattern and, as a result, we have a dip at the midrapidity. With energy rise, the stiffness of the EoS (in the range relevant to compression stage) grows, the system starts to be more resistant to the compression and hence the produced fireball becomes less deformed. The expansion of this fireball results in a peak or, at least, to a weaker dip at the midrapidity as compared to that at the “softest-point” incident energy. With further energy rise, the initial kinetic pressure overcomes the stiffness of the EoS and makes the produced fireball strongly deformed again, which in its turn again results in a dip at the midrapidity.

Thus, even without any nonequilibrium, we can expect a kind of a “peak-dip-peak-dip” irregularity in the incident energy dependence of the form of the net-proton rapidity distributions. Nonequilibrium also contributes to this irregularity. At a phase transformation the hadronic degrees of freedom are changed to partonic ones. In particular, the dip at the midrapidity in ultrarelativistic nuclear collisions occurs because the baryon charges of colliding nuclei traverse through each other rather than results from the 1-dimensional expansion of a disk-like fireball.

It is important to emphasize that the “peak-dip-peak-dip” irregularity is a signal from the hot and dense stage of the nuclear collision.

In the present paper this qualitative pattern is illustrated by calculations within a model of the three-fluid dynamics (3FD) [4] employing three different equations of state (EoS): a purely hadronic EoS [5] (had. EoS) and two versions of EoS involving deconfinement [6]: an EoS with the first-order phase transition (2-phase EoS) and that with a smooth crossover transition (crossover EoS). The softest points in these EoS’s are illustrated in Ref. [7]. The hadronic EoS [5] possesses no softest point, i.e. stiffness of the EoS changes monotonously. Results on the stopping power were reported in Refs. [8] more in detail.

2. Results of simulations

A direct measure of the baryon stopping is the net-baryon (i.e. baryons-minus-antibaryons) rapidity distribution. However, since experimental information on neutrons is unavailable, we have to rely on net-proton (i.e. proton-minus-antiproton) data. Presently there exist experimental data on proton (or net-proton) rapidity spectra at AGS [9] and SPS [10] energies.

Figure 1 presents calculated rapidity distributions of net-protons in central collisions at AGS and SPS energies and their comparison with available data. Difference between protons and net-protons is negligible at the AGS energies. As seen from Fig. 1, the distributions within the first-order-transition scenario indeed exhibit the above-discussed “peak-dip-peak-dip” irregularity in contrast to results obtained within the purely hadronic and crossover scenarios. The experimental distributions exhibit a qualitatively similar behavior as that in the 2-phase-EoS scenario. However, quantitatively the 2-phase-EoS results certainly disagree with data in the energy region $8A \text{ GeV} \leq E_{lab} \leq 40A \text{ GeV}$.

In order to quantify the above-discussed “peak-dip-peak-dip” irregularity, it is useful to make use of the method proposed in Ref. [8]. For this purpose the data on the net-proton rapidity distributions are fitted by the following simple formula

$$\frac{dN}{dy} = a (\exp \{-(1/w_s) \cosh(y - y_s)\} + \exp \{-(1/w_s) \cosh(y + y_s)\}) , \quad (1)$$

where a , y_s and w_s are parameters of the fit. The form (1) is a sum of two thermal sources shifted by $\pm y_s$ from the midrapidity which is put to be $y_{mid} = 0$ as it is in the collider mode. The parameters of the two sources are identical (up to the sign of y_s) because only collisions of identical nuclei are considered. The above fit has been done by the least-squares method and applied to both available data and results of calculations.

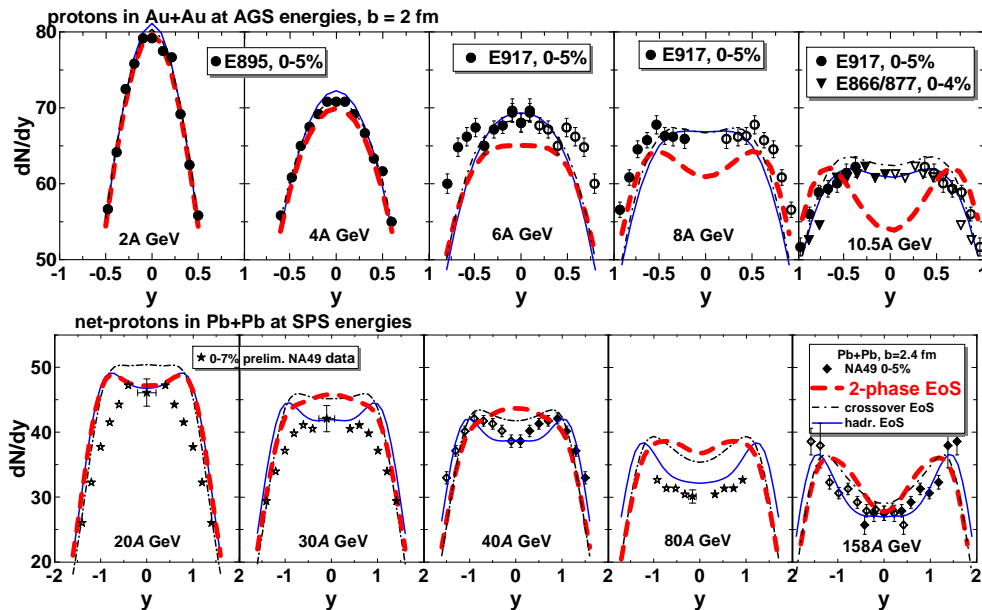


Figure 1. Rapidity spectra of protons for AGS energies (upper row of panel) and net-protons SPS energies (lower row of panels) from central collisions of Au+Au (AGS) and Pb+Pb (SPS). Experimental data are from [9, 10]. The percentage shows the fraction of the total reaction cross section, corresponding to experimental selection of central events.

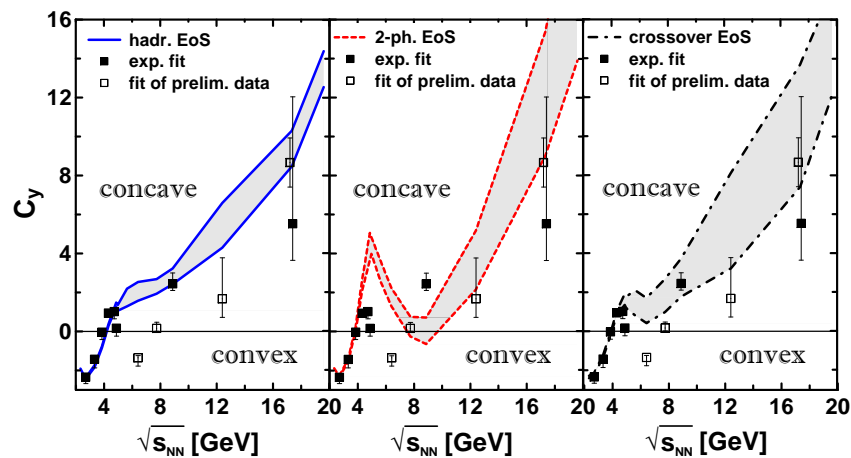


Figure 2. Midrapidity reduced curvature [see. Eq. (2)] of the (net)proton rapidity spectrum as a function of the center-of-mass energy of colliding nuclei as deduced from experimental data and predicted by 3FD calculations with different EoS's: the hadronic EoS (hadr. EoS) [5] (left panel), the EoS involving a first-order phase transition (2-ph. EoS, middle panel) and the EoS with a crossover transition (crossover EoS, right panel) into the quark-gluon phase [6]. Upper bounds of the shaded areas correspond to fits confined in the region of $|y|/y_{\text{beam}} < 0.7$, lower bounds, $|y|/y_{\text{beam}} < 0.5$.

A useful quantity, which characterizes the shape of the rapidity distribution, is a reduced

curvature of the spectrum at midrapidity defined as follows

$$C_y = \left(y_{\text{beam}}^3 \frac{d^3 N}{dy^3} \right)_{y=0} / \left(y_{\text{beam}} \frac{dN}{dy} \right)_{y=0} = (y_{\text{beam}}/w_s)^2 (\sinh^2 y_s - w_s \cosh y_s), \quad (2)$$

where y_{beam} is the beam rapidity in the collider mode. The second part of Eq. (2) presents this curvature in terms of parameters of fit (1). Excitation functions of C_y deduced both from experimental data and from results of the 3FD calculations with different EoS's are displayed in Fig. 2. To evaluate errors of the C_y values deduced from data, errors produced by the least-squares method were estimated. The uncertainty associated with the choice of the rapidity range turned out to be the dominant one for the C_y quantities deduced from simulation results. Therefore, in Fig. 2 results for the curvature C_y are presented by shaded areas with borders corresponding to the fit ranges $|y| < 0.7 y_{\text{beam}}$ and $|y| < 0.5 y_{\text{beam}}$.

The irregularity in data is distinctly seen here as a wiggle irregularity in the energy dependence of C_y . Of course, this is only a hint to irregularity since this wiggle is formed only due to preliminary data of the NA49 collaboration. A remarkable observation is that the C_y excitation function in the first-order-transition scenario manifests qualitatively the same wiggle irregularity (middle panel of Fig. 2) as that in the data fit, while the hadronic scenario produces purely monotonous behavior. The crossover EoS represents a very smooth transition, therefore, it is not surprising that it produces only a weak wiggle in C_y .

3. Conclusions

In conclusion, the irregularity in the baryon stopping is a natural consequence of deconfinement occurring at the compression stage of a nuclear collision and thus is a signal from the hot and dense stage of the nuclear collision. It is an effect of the softest point of a EoS. As it was demonstrated in Ref. [11], this irregularity is a very robust signal of a first-order phase transition that survives even under conditions of a very limited acceptance. Updated experimental results are badly needed to analyze a trend of the “peak-dip-peak-dip” irregularity. It would be highly desirable if new data are taken within the same experimental setup.

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References

- [1] Russkikh V N, Ivanov Y B, *Phys. Rev. C* **76** (2007) 054907.
- [2] Landau L D and Lifshitz E M, “*Fluid Mechanics*” (Pergamon Press, Oxford, 1979).
- [3] Hung C M and Shuryak E. V., *Phys. Rev. Lett.* **75** (1995) 4003.
- [4] Ivanov Yu B, Russkikh V N, and Toneev V D, *Phys. Rev. C* **73** (2006) 044904.
- [5] Galitsky V M and Mishustin I N, *Sov. J. Nucl. Phys.* **29**, 181 (1979).
- [6] Khvorostukhin A S, Skokov V V, Redlich K, and Toneev V D, *Eur. Phys. J. C* **48** (2006) 531.
- [7] Nikonov E G, Shanenko A A and Toneev V D, *Heavy Ion Phys.* **8** (1998) 89.
- [8] Ivanov Y B, *Phys. Lett. B* **690** (2010) 358; *Phys. At. Nucl.* **75** (2012) 621; *Phys. Lett. B* **721** (2013) 123; *Phys. Rev. C* **87** (2013) 064904.
- [9] Klay J L *et al.* [E-0895 Collaboration], *Phys. Rev. C* **68** (2003) 054905; Barrette J *et al.* (E877 Collaboration), *Phys. Rev. C* **62** (2000) 024901; Back B B *et al.*, (E917 Collaboration), *Phys. Rev. Lett.* **86** (2001) 1970; Stachel J, *Nucl. Phys.* **A654** (1999) 119c.
- [10] Appelshäuser H *et al.* (NA49 Collaboration), *Phys. Rev. Lett.* **82** (1999) 2471; Anticic T *et al.* (NA49 Collaboration), *Phys. Rev. C* **69** (2004) 024902; Alt C *et al.* (NA49 Collaboration), *Phys. Rev. C* **73** (2006) 044910; Blume C (NA49 Collaboration), *J. Phys.* **G34** (2007) S951; Anticic T. *et al.* [NA49 Collaboration], *Phys. Rev. C* **83** (2011) 014901; Alt C *et al.* [NA49 Collaboration], *Phys. Rev. C* **68** (2003) 034903.
- [11] Ivanov Y B and Blaschke D, *Phys. Rev. C* **92** (2015) 024916.