Baryon Stopping as a Probe of Deconfinement Onset in Relativistic Heavy-Ion Collisions

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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 a combined effect of the softest point inherent in an equation of state (EoS) with a deconfinement transition and a change in the nonequilibrium dynamics from hadronic to partonic transport. Thus, this irregularity is a signal from a hot and dense stage of the nuclear collision. In order to illustrate this proposition, 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. It is found that predictions within the first-order-transition scenario indeed reveal an strong irregularity in the incident energy dependence of the form of the net-proton rapidity distributions in central collisions. This behavior is in contrast to that for the hadronic scenario, where the distribution form gradually evolve, displaying no irregularity. The case of the crossover EoS is intermediate. Only a weak irregularity takes place. Experimental data also exhibit a trend of similar irregularity, which is however based on still preliminary data at energies of 20A GeV and 30A GeV.

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I. INTRODUCTION

Onset of deconfinement in relativistic heavy-ion collisions is now in focus of theoretical and experimental studies of relativistic heavy-ion collisions. This problem is one of the main motivations for the currently running beam-energy scan [1] at the Relativistic Heavy-Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) and low-energy-scan program [2] at Super Proton Synchrotron (SPS) of the European Organization for Nuclear Research (CERN), as well as newly constructed Facility for Antiproton and Ion Research (FAIR) in Darmstadt [3] and the Nuclotron-based Ion Collider Facility (NICA) in Dubna [4]. In this paper I would like to argue that the baryon stopping in nuclear collision can be a sensitive probe of deconfinement onset.

In fact, an irregularity in the incident-energy dependence of the baryon stopping is very natural if the system undergoes a phase transition. Let us start with discussion of the conventional (i.e. one-fluid) hydrodynamics, which is applied to the whole process of the nuclear collision, e.g. from its compression stage to the expansion stage up to freeze-out, like it is done in Refs. [5, 6].

The form of the result volume 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. Ref. [7]. 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 [8]. This speculation is very similar to that related to the elliptic flow: a strong elliptic flow results from a strongly deformed almond-shaped initial fireball with the deformation of the resulting momentum distribution of particles being inverse to the spatial deformation of the initial fireball. The physical mechanism here is precisely the same, only the expansion is developed in the transverse direction.

The next question is how this fireball is formed. This is already a matter of dynamics in the early compression stage of the nuclear collision. A softest point [9] characteristic of EoS’s with a phase transition plays an important role in this compression dynamics. The softest point in the equation of state is defined by a minimum in the ratio of the pressure to the energy density at constant specific entropy (i.e. the entropy per baryon): \( P/\varepsilon \). The constancy of \( \sigma \) is required because it is conserved in the ideal hydrodynamics. At the softest point the system exhibits the weakest resistance to its compression as compared with that in adjacent regions of the EoS. In Ref. [9] and subsequent works attention was focused on the softest-point effect on the expansion stage of the collision. In particular, it was argued [9] that at this point the comparatively small pressure prevents a fast expansion and cooling of the system. Here I would like to argue that the same softest point also plays important role during the early compression stage, resulting in extra high energy and baryon densities of the produced fireball.

Let us proceed in terms of the conventional (one-fluid) hydrodynamics. At low energies the softest point is not reached in the collision process, the system remains stiff and therefore the produced fireball is almost spherical.

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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 stats 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, it means a change in cross sections which govern the nuclear stopping power. Therefore, this change also induces a certain irregularity in the stopping power. Only the dip at the midrapidity in ultrarelativistic nuclear collisions has a different origin in the actual case of weak baryon stopping as compared with that in the conventional hydrodynamics. It occurs because the baryon charges of colliding nuclei traverse through each other.

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) employing three different equations of state (EoS): a purely hadronic EoS (hadr. EoS) which was used in the major part of the 3FD simulations so far, and two versions of EoS involving deconfinement. These two versions are 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. [17]. The hadronic EOS possesses no softest point - stiffness of the EoS changes monotonously. Preliminary results of simulations with deconfinement transitions have been already reported in Refs. [18, 19]. There the friction forces for the 2-phase and crossover scenarios were poorly tuned and hence the corresponding simulations poorly reproduced available experimental data. Therefore, the conjecture on an irregular behavior of the net-proton baryon was based on a certain trend of the results of simulations. Here I present calculations with thoroughly tuned friction forces in the quark-gluon phase, which made it possible to reasonably (and often better than in the hadronic scenario) reproduce a great number of observables in a wider (than before) incident energy range 2.7 GeV $\leq \sqrt{s_{NN}} \leq 39$ GeV in terms of the center-of-mass energy. Details of this calculations and results on a great number of bulk observables (rapidity and transverse spectra, flow observables and multiplicities) for various species and a large number of incident energies, their comparison with available data will be reported elsewhere. Here I would like to focus on rapidity distributions of net-protons in central collisions of heavy nuclei in the AGS-SPS energy range. The distribution of net-protons is the best probe of the nuclear stopping in the absence of data on net-baryons.

Concerning the fit of the friction force, few comments are in order. The friction in the hadronic phase was estimated in Ref. [20]. Within hadronic scenario (hadr. EoS) we had to enhance this friction in order to reproduce the baryon stopping at high energies [10]. Though such a enhancement is admissible in view of uncertainties of the estimated friction, the value of the enhancement looks too high. Indeed, at $\sqrt{s_{NN}} = 17.3$ GeV, i.e. at the top SPS energy, this enhancement exceeds the factor of 2. In scenarios with deconfinement there is no need to modify the hadronic friction. This can be considered as a theoretical argument in favor of such scenarios.

![FIG. 1: Pressure scaled by the product of normal nuclear density ($n_0 = 0.15$ fm$^{-3}$) and nucleon mass ($m_n$) versus baryon density scaled by the normal nuclear density for three different temperatures $T = 10$, 100 and 200 MeV (bottom-up for corresponding curves).](image-url)
II. EQUATIONS OF STATE

Figure 1 illustrates differences between three considered EoS’s. The deconfinement transition makes a EoS softer at high temperatures and/or densities. The 2-phase EoS is based on the Gibbs construction, taking into account simultaneous conservation of baryon and strange charges. However, the displayed result looks very similar to the Maxwell construction, corresponding to conservation of only baryon charge, with the only difference that the plateau is slightly tilted, which is practically invisible. Application the Gibbs construction in hydrodynamical simulations silently assumes that the inter-phase equilibration in the mixed-phase region is faster than the hydrodynamical evolution. From the practical point of view, this assumption allows us to avoid problems with instabilities in the spinodal region. However, from conceptual point of view this assumption is not obvious. It would be better to consider a finite relaxation time for the inter-phase equilibration as it was proposed long ago [21]. If this relaxation time is short enough, the unstable spinodal region will be still avoided, that is important for the numerical reasons. That is a long-term plan of refining the model. In the present calculations the instantaneous inter-phase equilibration is assumed.

The 2-phase and crossover EoS’s still differ even at very high densities. The latter means that the crossover transition constructed in Ref. [16] is very smooth. The hadronic fraction survives up to very high densities. In particular, this is seen from Fig. 2: the fraction of the quark-gluon phase ($W_{QGP}$) reaches value of 0.5 only at very high energy densities. In this respect, this version of the crossover EoS certainly contradicts results of the lattice QCD calculations, where a fast crossover, at least at zero chemical potential, was found [22]. Therefore, a true EoS is somewhere in between the crossover and 2-phase EoS’s of Ref. [16].

Figure 2 demonstrates that the onset of deconfinement in the calculations happens at top-AGS–low-SPS energies. Similarly to Ref. [23], the figure displays dynamical trajectories of the matter in a central box placed around the origin $r = (0, 0, 0)$ in the frame of equal velocities of colliding nuclei: $|x| \leq 2 \text{ fm}, |y| \leq 2 \text{ fm}$ and $|z| \leq \gamma_{cm} 2 \text{ fm}$, where $\gamma_{cm}$ is Lorentz factor associated with the initial nuclear motion in the c.m. frame. Initially, the colliding nuclei are placed symmetrically with respect to the origin $r = (0, 0, 0)$, $z$ is the direction of the beam. At a given density $n_B$, the zero-temperature compressional energy, $\varepsilon(n_B, T = 0)$, provides a lower bound on the energy density $\varepsilon$, so the accessible region is correspondingly limited. In the case of the crossover EoS only the region of the mixed phase between $W_{QGP} = 0.1$ and $W_{QGP} = 0.5$ is displayed, since in fact the mixed phase occupies the whole $(\varepsilon - n_B)$ region. The $\varepsilon - n_B$ representation is chosen because these densities are dynamical quantities and, therefore, are suitable to compare calcu-
lations with different EoS’s.

Only expansion stages of the evolution are displayed, where the matter in the box is already thermally equilibrated. Evolution proceeds from the top point of the trajectory downwards. Subtraction of the $n_{n} n_{p}$ term is taken for the sake of suitable representation of the plot. The size of the box was chosen to be large enough that the amount of matter in it can be representative to conclude on the onset of deconfinement and to be small enough to consider the matter in it as a homogeneous medium. Nevertheless, the matter in the box still amounts to a minor part of the total matter of colliding nuclei. Therefore, only the minor part of the total matter undergoes the deconfinement transition at 10.4 GeV energy.

As seen, the deconfinement transition starts at the top AGS energies in both cases. It gets practically completed at low SPS energies in the case of the 2-phase EoS. In the crossover scenario it lasts till very high incident energies. The trajectories for two different EoS’s are nevertheless very similar at displayed energies. Apparently, it happens because the friction in the quark-gluon phase was selected in such a way that both scenarios reasonably reproduce available data at high energies.

III. PROTON AND NET-PROTON RAPIDITY DISTRIBUTIONS

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 [24–27] and SPS [28–31] energies. These data were analyzed within various models [3, 6, 10, 12, 34–40].

Figure 3 presents calculated rapidity distributions of protons (for AGS energies) and net-protons (for SPS energies) and their comparison with available data. Notice that difference between protons and net-protons, as well as a contribution of weak decays to these yields are negligible at the AGS energies, see compilation of experimental data in Ref. [41]. Contribution of weak decays of strange hyperons into proton yield was disregarded in accordance with measurement conditions of the NA49 collaboration. Correspondence between the fraction of the total cross section related to a data set and a mean value of the impact parameter was read off from the paper [33] in case of NA49 data. For Au+Au collisions it was approximately estimated proceeding from geometrical considerations.

As seen from Fig. 3 at lower AGS energies all EoS’s predict the same results, since at these energies only hadronic parts of all EoS’s are relevant, see Fig. 2. Results of the 2-phase EoS start to differ from those of the hadr. and crossover EoS’s beginning from 6.4 GeV: the 2-ph.-EoS distributions reveal a dip at the midrapidity. This dip contradicts the available experimental data and is very robust: variation of the friction in a wide range does not remove this dip. Therefore, it is a direct consequence of the onset of the first-order phase transition, which starts precisely at these energies in the 2-ph.-EoS scenario, see Fig. 2. This dip survives even in one-fluid calculations [3, 6] involving the 1st-order phase transition in spite of immediate baryon stopping inherent in the one-fluid model. In 3FD calculations, this dip changes into midrapidity peak at higher energies (30.4 GeV and 40.4 GeV). With further energy rise ($E_{lab} > 40$ GeV) the midrapidity peak again transforms into a dip, see also Fig. 3. The latter dip is already a normal behavior which takes place at arbitrary high energies, which is associated with growing transparency of the colliding nuclei rather than with production of strongly deformed fireball of completely stopped matter, as it was discussed at the example of the conventional (one-fluid) hydrodynamics. Thus, the “peak-dip-peak-dip” irregularity indeed results from essential interplay between softening of the EoS and incomplete stopping of the colliding matter.

The experimental distributions exhibit a qualitatively similar behavior as that in the 2-phase-EoS scenario: after a plateau or a shallow midrapidity dip at the energy of 8.4 and 10.4 GeV, a well pronounced peak at 20.4 GeV is again observed. However, quantitatively the 2-phase-EoS results certainly disagree with data at 8.4 GeV, 10.4 GeV and 40.4 GeV energies. They also disagree with data 20.4 GeV and 30.4 GeV, which however have preliminary status, and hence it is too early to draw any conclusions from comparison with them. The 2-phase-EoS behavior is in contrast with that for the hadronic-EoS scenario, where the form of distribution in central collisions gradually evolve from peak at the midrapidity to a dip. The case of the crossover EoS is intermediate: only a shallow dip occurs at 10.4 and 15.4 GeV while at 20.4 GeV the distribution looks like a plateau.

Predictions of different scenarios diverge to the largest extent in the energy region 8.4 GeV $\leq E_{lab} \leq 40$ GeV. Unfortunately data at 20.4 and 30.4 GeV still have a preliminary status and disagree with any considered scenario. Updated experimental results at energies 20.4 and 30.4 GeV are badly needed to pin down the preferable EoS and to check the hint to the zigzag behavior of the type “peak-dip-peak-dip” in the net-proton rapidity distributions.

IV. ANALYSIS OF “PEAK-DIP-PEAK-DIP” IRREGULARITY

In order to quantify the above-discussed “peak-dip-peak-dip” irregularity, it is useful to make use of the method proposed in Ref. [15]. For this purpose the data on net-proton rapidity distributions are fitted by a simple formula

$$
\frac{dN}{dy} = a \exp\left\{(-1/w_s) \cosh(y - y_{cm} - y_s)\right\} + \exp\left\{(-1/w_s) \cosh(y - y_{cm} + y_s)\right\}
$$

(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. The width $w_s$ of the sources can be interpreted as $w_s = \langle \text{temperature} \rangle / \langle \text{transverse mass} \rangle$. If we assume that collective velocities in the sources have no spread with respect to the source rapidities $\pm y_s$. 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. The fit was performed in the rapidity range $|y - y_{cm}| / y_{cm} < 0.7$. The choice of this range is dictated by the data. As a rule, the data are available in this rapidity range, sometimes the data range is even more narrow (80A GeV and new data at 158A GeV [32]). I put the above restriction in order to treat different data in approximately the same rapidity range. Another reason for this cut is that the rapidity range should not be too wide in order to exclude contribution of cold spectators. The fit in the rapidity range $|y - y_{cm}| / y_{cm} < 0.5$ has been also done in order to estimate uncertainty of the fit parameters associated with the choice of fit range.

A useful quantity, which characterizes the shape of the rapidity distribution, is a reduced curvature of the spectrum at the midrapidity defined as follows

$$C_y = \left( y_{cm}^3 \left. \frac{d^3N}{dy^3} \right|_{y=y_{cm}} \right) / \left( y_{cm}^2 \left. \frac{dN}{dy} \right|_{y=y_{cm}} \right) = (y_{cm}/w_s)^2 (\sinh^2 y_s - w_s \cosh y_s) .$$

The factor $1 / (y_{cm} dN/dy)_{y=y_{cm}}$ is introduced in order to get rid of overall normalization of the spectrum. The second part of Eq. (2) presents this curvature in terms of parameters of fit (1). The reduced curvature, $C_y$, and the midrapidity value, $(y_{cm} dN/dy)_{y=y_{cm}}$, are two independent quantities quantifying the spectrum in the midrapidity range. Excitation functions of these quantities deduced both from experimental data and from results of the 3FD calculations with different EoS’s are displayed in Figs. 4 and 5. Notice that a maximum in $y_{cm} (dN/dy)_{cm}$ at $\sqrt{s_{NN}} = 4.7$ GeV happens only because the light fragment production becomes negligible above this energy. The 3FD calculation without coalescence (i.e. without the light fragment production) reveals
FIG. 4: 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) [11] (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 [16]. Upper bounds of the shaded areas correspond to fits confined in the region of $|y - y_{cm}|/y_{cm} < 0.7$, lower bounds – $|y - y_{cm}|/y_{cm} < 0.5$.

FIG. 5: The same as in Fig. 4 but for midrapidity value of the (net)proton rapidity spectrum scaled by $y_{cm}$. The thin long-dashed line corresponds to the hadr.-EoS calculation without fragment production, i.e. without coalescence.

a monotonous decrease of $y_{cm}(dN/dy)_{cm}$ beginning from the lowest energy considered here.

To evaluate errors of $C_y$ values deduced from data, I estimated the errors produced by the least-squares method, as well as performed fits in different the rapidity ranges: $|y - y_{cm}|/y_{cm} < 0.5$ and $|y - y_{cm}|/y_{cm} < 0.7$, where it is appropriate. Problems were met in fitting the data at 80A GeV [31] and the new data at 158A GeV [32]. These data do not go beyond the side maxima in the rapidity distributions. This results in large uncertainty in the parameters. In particular, because of this problem I keep the old data at 158A GeV [28] in the analysis. The error bars present largest uncertainties among mentioned above. The upper errors of 158A-GeV 80A-GeV points results from the uncertainty of the narrow rapidity range. The uncertainty associated with the choice of the rapidity range turned out to be a dominant one in the case computed data. Therefore, in Fig. 4 results for the computed spectra are presented by shaded areas with borders corresponding to the fit ranges $|y - y_{cm}|/y_{cm} < 0.7$ and $|y - y_{cm}|/y_{cm} < 0.5$. In Fig. 5 the midrapidity values of the rapidity spectra were taken directly from experimental data and calculated results. Therefore, only experimental error bars are displayed there.

Since experimental data at AGS and RHIC energies were taken from Au+Au collisions while at SPS the Pb+Pb collisions were studied, the calculations were performed respectively for Au+Au ($b = 2$ fm) and Pb+Pb ($b = 2.4$ fm) central collisions. In fact, at the same incident energy the computed results for Pb+Pb collisions at $b = 2.4$ fm are very close to those for Au+Au at $b = 2$ fm. Therefore, the corresponding irregularity of the energy dependence of the fit parameters is negligible.

The irregularity in data is distinctly seen here as a zigzag irregularity in the energy dependence of $C_y$. Of course, this is only a hint to irregularity since this zigzag 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 zigzag irregularity (left panel of Fig. 4) as that in the data fit, while the hadronic
FIG. 6: The same as in Fig. 5 but for midrapidity values of the net-proton (left panel) and proton (right panel) rapidity spectrum in conventional representation, i.e. without scaling. Experimental data are from collaborations E895 [24], E877 [25], E917 [26], E866 [27], NA49 [28–32] and STAR [43].

scenario produces purely monotonous behavior. The crossover EoS represents a very smooth transition, as mentioned above. Therefore, it is not surprising that it produces only a weak wiggle in $C_y$.

This zigzag irregularity of the first-order-transition scenario is also reflected in the midrapidity values of the (net)proton rapidity spectrum (Fig. 5). In the conventional representation of the data without multiplying by $y_{cm}$, the irregularity of the $(dN/dy)_{cm}$ data is hardly visible (Fig. 5). Moreover, the difference between predictions resulted from different EoS’s is also scarcely discernible. Thus, the scaled representation of Fig. 5 serves as a zoom revealing differences. In Fig. 6 not only net-protons but also proton midrapidity values are displayed in a wider energy range. However, results for top energy $\sqrt{s_{NN}} = 62.4$ GeV are very approximate, since more accurate computation requires unreasonably high memory and CPU time. As seen, a visible difference between net-protons and proton data, as well between predictions of hadronic EoS and EoS’s with deconfinement starts only at RHIC energies. Similar (but based on different, double-gaussian fit) analysis was performed in Ref. [12]. It found no irregularities in excitation functions of the corresponding parameters, in particular, because the analysis of Ref. [12] was restricted to energies $E_{lab} \geq 20A$ GeV.

As it was pointed out in the introduction, the “peak-dip-peak-dip” irregularity is very natural in a system undergoing a phase or crossover transition. First, it is associated with the softest point of a EoS. Therefore, it is not surprising that the irregularity is weaker in the crossover scenario than in the first-order-transition one. Indeed, the softest points in the crossover EoS is less pronounced than in the first-order-transition one [17]. There is no softest point in the hadronic EoS and hence there is no irregularity.

The second reason of this irregularity is a change in the nonequilibrium regime. The 3FD model takes into account the leading nonequilibrium of the nuclear collision associated with a finite stopping power of the nuclear matter. It simulates the finite stopping power by means of friction between three fluids. Naturally, this friction changes when deconfinement happens. In the case of the crossover scenario this change in the friction is very smooth. Therefore, it does not contribute to the irregularity. At the same time this change in the friction enhances the irregularity in the first-order-transition scenario. As it was demonstrated in Ref. [18], if the same friction is used in both phases, the reduced curvature calculated with the 2-phase EoS reveals a wiggle behavior in $C_y$ but with considerably smaller amplitude as compared with zigzag in actual calculations with different frictions in different phases. These different frictions appear quite naturally in the 3FD model. The hadronic friction was estimated in Ref. [20] and works well at lower AGS energies. Therefore, there are no reasons to modify it. The partonic friction, while not microscopically estimated, is fitted to reproduce data at high incident energies. This is a reason to believe that it is a proper choice.

V. CONCLUSION

An irregularity in the baryon stopping is a natural consequence of deconfinement occurring in the compression stage of a nuclear collision. It is a combined effect of the
softest point of a EoS and a change in the nonequilibrium regime from hadronic to partonic one. It is important to emphasize that this irregularity is a signal from the hot and dense stage of the nuclear collision.

Of course, this irregularity does not directly indicate deconfinement, i.e. transition to quark-gluon degrees of freedom. It only indicates softening of the EoS (occurrence of the softest point) in a certain domain of the phase space. In principle, this softening may happen due to other reasons rather than onset of deconfinement. Nevertheless, I reason in terms of the deconfinement because this softening is associated with its onset in the considered EoS’s.

In order to illustrate this irregularity, calculations within the 3FD model were performed with three different equations of state, i.e. with a purely hadronic EoS [11], and also with two versions of EoS involving deconfinement [10]; an EoS with the first-order phase transition and that with a smooth crossover transition. The crossover transition constructed in Ref. [10] is very smooth. The hadronic fraction survives up to very high energy densities. In this respect, this version of the crossover EoS certainly contradicts results of the lattice QCD calculations, where a fast crossover, at least at zero chemical potential, was found [22]. Therefore, a true EoS is somewhere in between the crossover and 2-phase EoS’s of Ref. [10].

It is found that predictions within the first-order-transition scenario reveal a “peak-dip-peak-dip” irregularity in the incident energy dependence of the form of the net-proton rapidity distributions in central collisions. At low energies, rapidity distributions have a peak at the midrapidity. With the incident energy rise it transforms into a dip, then again into a peak, and with further energy rise the midrapidity peak again change into a dip, which already survives up to arbitrary high energies. The behavior the type of “peak-dip-peak-dip” in central collisions within the 2-phase-EoS scenario is very robust with respect to variation of the model parameters in a wide range. This behavior is in contrast with that for the hadronic-EoS scenario, where the distribution form gradually evolve from peak at the midrapidity to a dip. The case of the crossover EoS is intermediate. Only a weak wiggle of the type “peak-dip-peak-dip” takes place.

Experimental data also reveal a trend of the “peak-dip-peak-dip” irregularity in the energy range 8 A GeV ≤ E_{lab} ≤ 40 A GeV, which qualitatively similar to that in the first-order-transition scenario while quantitatively differ. However, the this experimental trend is based on preliminary data at energies of 20 A GeV and 30 A GeV. In general, predictions of different scenarios diverge to the largest extent in the energy region 8 A GeV ≤ E_{lab} ≤ 40 A GeV. Therefore, updated experimental results at energies 20 A and 30 A GeV are badly needed to pin down the preferable EoS and to check the hint to the zigzag behavior of the type “peak-dip-peak-dip” in net-proton rapidity distributions. Moreover, it would be highly desirable if new data in this energy range are taken within the same experimental setup and at the same centrality selection. Hopefully such data will come from new accelerators FAIR at GSI and NICA at Dubna.

In order to quantify the observed “peak-dip-peak-dip” irregularity, the analysis of the distribution shape proposed in Refs. [18, 19] was applied. This method is based on calculation of the reduced curvature of the spectrum at the midrapidity C_y. In terms of C_y the irregularity in data is distinctly seen as a zigzag irregularity in the energy dependence of C_y. The energy location of this zigzag anomaly coincides with the previously observed anomalies for other hadron-production properties at the low SPS energies [44, 46]. A remarkable observation is that the C_y energy dependence in the first-order-transition scenario manifests qualitatively the same zigzag irregularity, as that in the data fit, though quantitatively does not reproduce the data fit. The hadronic scenario produces purely monotonous behaviour. The crossover EoS represents a very smooth transition, as mentioned above. Therefore, it is not surprising that it results in only a weak wiggle in C_y.

Here the distribution of net-baryons was discussed because net-baryons have advantage of being confined by the baryon number conservation. In general, an analysis of the form of particle spectra looks very promising. For instance, in Ref. [44] it was proposed to analyze the incident-energy dependence of the width of pion rapidity distributions. This width can be associated with the sound velocity in the dense stage of the reactions. It is found that the sound velocity has a local minimum (indicating a softest point in the EoS) in the range of √s_{NN} = 4-9 GeV, which coincides with the range of the “peak-dip-peak-dip” irregularity discussed in this paper and that of the previously observed anomalies for other hadron-production properties [45, 46].

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