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TOWARDS A NEW STRATEGY OF SEARCHING FOR QCD PHASE TRANSITION IN HEAVY ION COLLISIONS

A.A.Shanenko, V.D.Toneev

The Hung-Shuryak arguments in favour of searching for deconfinement phase transtion in heavy ion collisions downward from the nominal SPS energy at about $E_{lab} = 30$ GeV/A are reconsidered. Using the recent lattice QCD data and the mixed phase model, it is shown that the deconfinement transition might occur at the energies as low as $E_{lab} = 3$—5 GeV/A. Attention is drawn to the study of the mixed phase of nuclear matter formed in heavy ion collisions in the energy range 2—10 GeV/A.

The investigation has been performed at the Bogoliubov Laboratory of Theoretical Physics, JINR.

О новой стратегии поиска кварк-глюонной плазмы в столкновениях тяжелых ионов

А.А.Шаненко, В.Д.Тонеев

Обсуждаются аргументы Ханг и Шуряка в пользу поиска фазового перехода деконфайнмента в экспериментах по столкновениям тяжелых ионов при энергиях ниже номинальной SPS-энергии, около $E_{lab} = 30$ ГэВ/А. С помощью новых данных решеточной КХД и модели со смешанной кварк-адронной фазой показывается, что искать деконфайнмент нужно при еще более низких энергиях $E_{lab} = 3$—5 ГэВ/А. Подчеркивается перспективность исследований смешанной фазы ядерного вещества в столкновениях тяжелых ионов при энергиях $E_{lab} =$ 2—10 ГэВ/А.

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Over the last ten years, a fundamental QCD prediction of phase transition of hadrons into a state of free quarks and gluons, quark-gluon plasma, has been attacked actively by both theorists and experimentators. Extensive lattice QCD calculations allowed one to specify more accurately the deconfinement temperature, the order of phase transition and their flavor dependence for pure gluon matter and for plasma with dynamical quarks. By now, there is a rather long list of various signatures which can signal us about the quark-gluon plasma formation. Many of these signatures were testified experimentally at CERN SPS with the ^{16}O and ^{32}S 200 GeV/A beams where crucial conditions for deconfinement transition are expected to be reached. Indeed, some predicted effects (for example, strangeness enhancement, J/Ψ suppression, $\phi/(\rho+\omega)$ enhancement) have been observed but their hadronic interpretation cannot be excluded. General belief is that for more definite conclusions *heavier ions* and *higher beam energy* should be used. This is why the experiments with the Pb beam became available at CERN in the fall of 1994 and future experiments at RHIC and LHC are of great interest.

Recently, a new strategy of experimental search for the QCD phase transition in heavy ion collisions has been proposed [1]. As has been noticed long ago [2], the equation of state (EOS) is very «soft» in a narrow range around the critical temperature leading to a significant reduction in *transverse* expansion of the fireball formed in heavy ion collisions. The authors of Ref.[1] have demonstrated that this «softness» of the EOS affects not only the transverse, but also the *longitudinal* expansion, resulting in a longer lifetime of the excited system. Thus, certain observables should exhibit a sharp and specific dependence on the heavy-ion beam energy around this «softest» point having been estimated as located at the energy density $\varepsilon \approx 1.5$ GeV/fm^3 that corresponds to the beam energy $E_{lab} \approx 30$ GeV/A [1]. Therefore, to see the QCD phase transition it is quite promising to go *downward* from the nominal SPS energy.

Estimates cited above were made in a rather simplified model but the authors [1] are confident that even in more sophisticated models the total lifetime should have a maximum (with multiple observable consequences) near the indicated energy region. From our point of view, the implementation of the brilliant idea of the longest-lived fireball has a crucial point: some *formal approximation* of the crossover deconfinement behaviour for *baryon-free nuclear matter* has been used. It is not very clear how well this description corresponds to lattice QCD results. In addition, due to considerable stopping in nucleus-nucleus collisions up to $E_{lab} \approx 200$ GeV/A (especially for heavy systems) there is little hope to create a baryon-free region. In this paper, we shall consider how this longest-lived fireball is sensitive to the details of the EOS used and how it survives in baryon-reached matter inherent in excited nuclear systems formed at energies $E_{lab} \leq 200$ GeV/A. Our analysis is based on the statistical model taking consequently into account the mixed phase in which unbound quarks and gluons coexist with hadrons [3,4,5].

Here, the EOS is the key quantity, and thermodynamic properties of excited matter near QCD phase transtion should be calculated from the first principles and in a non-perturbative manner. At present, such calculations are possible only in terms of lattice QCD. This approach shows that gluonic matter in pure gauge $SU(2)$ and $SU(3)$ theories exhibits a phase transition of the second and first order, respectively (see, for example the review article [6]). For the more realistic case of the $SU(3)$ theory with dynamical quarks recent lattice studies, in contrast with previous results, show that there is a smooth crossover for the quark masses close to the physical ones rather than a distinct phase transition. And nothing is really known for the most important case of the lattice QCD at finite baryon number density [6]. So, statistical models should be invoked to describe thermodynamic properties of the excited nuclear matter. There are many versions of the statistical model (see [7] and references therein) but all of them predict the deconfinement phase transition of the first order and, therefore, do not reproduce the lattice QCD results noted above. The only exception is the statistical mixed phase model of deconfinement having advanced in [3,4,5] which will be used in our consideration.

The main particularity of the approach considered [3,4,5] is taking account of the coexistence of the spatially non-separated hadron phase and quark-gluon plasma. The last is treated as a phase made of unbound «elementary» generic particles (quarks and gluons) while hadrons are considered as quark-gluon clusters. The mixed phase model is based on a general approach [4] to the description of the clustering matter which assumes beforehand the separation of cluster degrees of freedom. Clusters are separated by passing from an exact Hamiltonian to an effective cluster one,

$$H(\psi) \to H_c(\psi_c). \tag{1}$$

Here, ψ is a set of field operators of the generic particles and $\psi_c \equiv \{\psi_{\bar{n}} : 1, 2, \ldots\}$ stands for quasiparticle operators ($n = 1$ corresponds to unbound generic particles, $n > 1$ is for clusters). A large variety of possible clusters creates an enormous number of possible states but realized one will be that corresponding to extremum of the thermodynamic potential calculated with H_c. This results in equations to be somewhat different from the Gibbs conditions for a phase coexistence.

The following very important point should be emphasized. In separating out cluster degrees of freedom and changing $H \to H_c$, the effective cluster Hamiltonian may acquire extra dependence on thermodynamic parameters like temperature T and cluster densities ρ_c:

$$H_c \equiv H_c(\psi_c, T, \rho_c), \qquad \rho_c \equiv \{\rho_n : 1, 2, \ldots\}. \tag{2}$$

The appearance of a density-dependent interaction in (2) is not a surprise for nuclear physics but it is a distinctive feature of this approach as compared to other statistical models [7]*. This fact, however, needs an extreme caution in dealing with the cluster Hamiltonian: both Hamiltonians must be thermodynamically equivalent, i.e., in the thermodynamic limit their thermodynamic characteristics must coincide [8]. These demands of the thermodynamic equivalence and thermodynamic self-consistency impose the following additional conditions on the cluster Hamiltonian:

$$\langle \frac{\partial H_c}{\partial T} \rangle = 0, \qquad \langle \frac{\partial H_c}{\partial \rho_n} \rangle = 0 \tag{3}$$

which essentially define the form of the cluster Hamiltonian. In the mean-field approximation for the cluster Hamiltonian one has [3,4]:

$$H_c = \sum_n \sum_s \int d\mathbf{r}\, \psi_n^+(\mathbf{r}, s)\, (K_n + U_n)\, \psi_n(\mathbf{r}, s) - CV. \tag{4}$$

The presence of non-operator term CV is necessary to satisfy the conditions (3). Here, n enumerates the clusters, s stands for their internal degrees of freedom, $K_n = \sqrt{-\nabla^2 + M_n^2}$ is the kinetic energy and $U_n = U_n(T, \rho_c)$ is a mean-field acting on an n-particle cluster. Unbound particles are treated as trivial clusters with $n = 1$. In the mean-field approximation, the conditions of thermodynamic equivalence (3) are reduced to

$$\frac{\partial U_n}{\partial T} = 0, \tag{5}$$

*Similar situation is met in the case when interaction is taken into account by the excluded-volume method.

i.e., the mean-field $U_n = U_n(\rho_c)$ can depend on temperature only through densities. If free cluster masses M_n are known experimentally or from other calculations, to use approach based on (3), only U_n and C are the quantities which have to be defined, C being able to be found from (2) with known U_n [8].

As has been shown in [3,4,5] in the case of the quark-gluon clustering matter, the mean field acting on unbound gluons or quarks, U_1, can be approximated as follows [11]:

$$U_1 = \frac{A}{\rho^\gamma}; \qquad 0 < \gamma < 1 \tag{6}$$

with the total quark-gluon density $\rho = \sum_n n\rho_n$. The presence of ρ in (6) corresponds to the inclusion of the interaction between all components of the mixed phase under discussion. Note that in the situation when hadrons are absent, $\rho_n = 0$ ($n > 1$), expression (6) is the same as was in use in papers [11] to describe the thermodynamic properties of the quark-gluon plasma. Alongside with the mean-field term (6) depending on the constants A and γ, there is also a cluster interaction potential $\Phi_{nm}(r)$ characterizing the interaction strength between clusters having n and m generic particles. In a fusion-decay mechanism of cluster long-ranged interactions it is possible to get [8] a recurrent relation like

$$\Phi_{nm}(r) \sim nm\, \Phi_{\min}(r) \tag{7}$$

and to reduce all unknown interactions to the single interaction potential $\Phi_{\min}(r)$ of the simplest non-trivial clusters (two-gluon glueballs in the ground state or lightest mesons or lightest baryons). In the Hartree approximation to (4), for describing the cluster interactions the only constant

$$\overline{\Phi}_{\min} \equiv \int d\mathbf{r}\, \Phi_{\min}(r) \tag{8}$$

is needed to know. Thus, the Hamiltonian (4) is completely defined and thereby any thermodynamic characteristics of the mixed phase system can be found if three constants A, γ and $\overline{\Phi}_{\min}$ have been fixed (see [3,4,5] for a detail). This 3-parameter set was found by fitting the temperature dependence of energy density and pressure calculated within the lattice QCD for the pure gluonic matter in the gauge $SU(2)$ [9] and $SU(3)$ [10] theories where a fairly good description was achieved for the mentioned thermodynamic quantities [3,4]. It is worth emphasizing that the parameter A depends only on the colour group and γ is constant for all the gauge systems. So, fitting the $SU(3)$ pure gluonic lattice data allows one to fix A and γ parameters and to use them for the $SU(3)$ system with quarks. As to $\overline{\Phi}_{\min}$ in this case, it can be found from a nucleon-nucleon potential by referring to the relation (7). Therefore, there are no free parameters when we proceed to study deconfinement for nuclear matter within the mixed phase model [3,4,5]. Indeed, we have $\gamma = 0.62$, $A^{1/(3\gamma+1)} = 225$ MeV and $\overline{\Phi}_{\min} = 4.1 \cdot 10^{-5}$ MeV^{-2}. With these values of para-

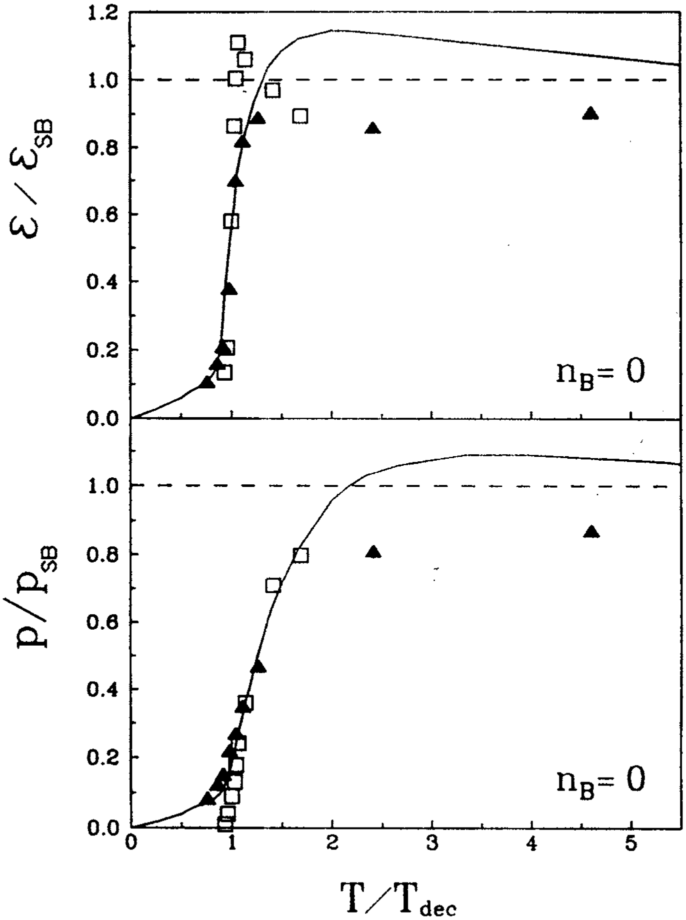

Fig.1. Temperature dependence of energy density and pressure (relative to corresponding values in the Stephan-Boltzmann limit) for $SU(3)$ gauge theory of baryon-free matter with massive dynamical quarks. Curves were calculated within the mixed phase model [3,4]. Triangles and squares are lattice data for the Wilson [12] and Kogut-Susskind [13] scheme of accounting for dynamical quarks, respectively.

meters, the mixed phase model predictions for $SU(3)$ symmetry with two light flavours are shown in Fig.1 for the $n_B = 0$ case.

When confronted with the lattice QCD data for the $SU(3)$ system with two light fermions, the mixed phase model [3,4] gives a very similar temperature behaviour of the energy density ε and pressure p. As follows from these results, the mixed phase model estimates the deconfinement temperature as high as 150 MeV and predicts the crossover-type phase transition (see [3,4,5]) in full agreement with the lattice data. Some overshooting of the model at $T > T_{dec}$ is related to neglecting the negative Coulomb-like term of the quark-gluon interactions. Two different sets of the best available lattice QCD results plotted in Fig.1 correspond to two different schemes to take quarks into account. A peak-like structure of ε near the deconfinement temperature T_{dec} for the Kogut-Susskind scheme [13] seems to be unphysical and related to the problem in the calculations of the pressure that turns out to be vanishing in this case for temperatures below about 0.9 T_{dec}. Indeed, at zero baryon density we have

$$\varepsilon = T\frac{dp}{dT} - p.$$

So, the abnormal rapid increase of the pressure in the vicinity of the deconfinement point has to result in the peak-like behaviour of the energy density in the same region. The quark mass in the Kogut-Susskind calculations amounts to $m_q \approx 0.1T_{dec}$. On the other hand, in the Wilson scheme we do not really know the quark mass used. In this case, the value $m_q \sim T_{dec}$ given in [12] seems to be enormously large because there is good agreement of the Wilson scheme results with the ideal meson gas below T_{dec} [12].

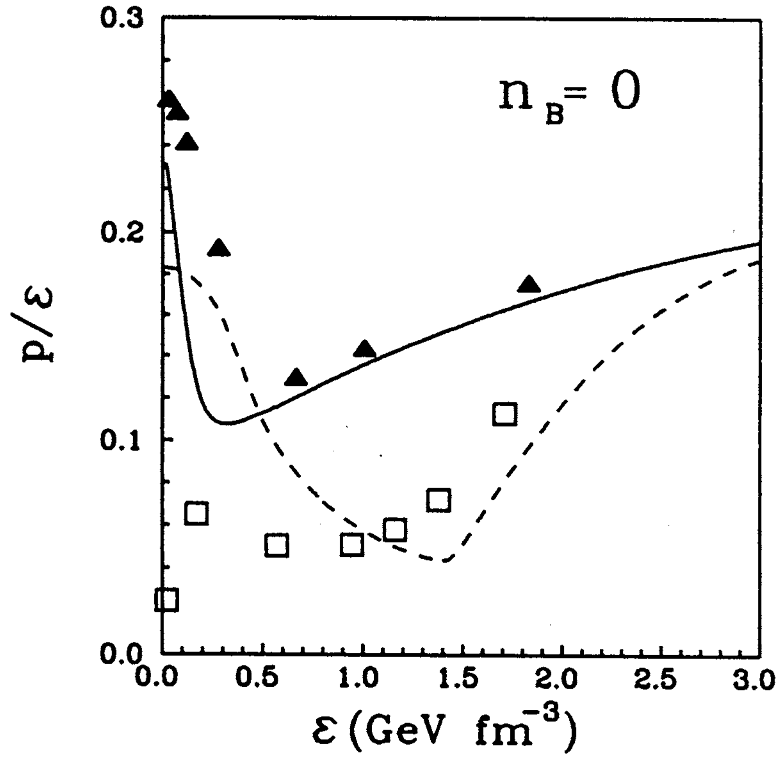

Fig.2. Pressure to energy density ratio versus ε. Notation is the same as in Fig.1. The dashed curve corresponds to the approximation used in paper [1]. Data are given for $\varepsilon > 0.005$ GeV/fm^{-3}

The EOS in the form advocated by Hung and Shuryak [1] is represented in Fig.2. Here, all data of Fig.1 are replotted alongside with the curve used in [1] to simulate the crossover transition. As is seen, the p/ε function for *lattice data* themselves shows *a minimum* which is just associated with the «softest» point of the EOS where a fireball of the excited nuclear matter lives for the longest time. In the p/ε representation, the lattice QCD data for two schemes of accounting for dynamical quarks differ very noticeably but result in the same minimum position at $\varepsilon_{sp} \approx 0.5$–$0.6$ GeV/fm^3 which can be reached at the Au beam energies about 3—5 GeV/A. It is noteworthy that this ε_{sp} corresponds to the energy density inside a nucleon, therefore, the system near the «softest» point may be considered as a «big hadron». This value of ε_{sp} is essentially smaller as compared to what is followed from the approximating curve of Hung-Shuryak, $\varepsilon_{sp} \approx 1.5$ GeV/fm^3, corresponding to the beam energy $E_{\rm lab} \approx 30$ GeV/A [1] while the mixed phase model predicts the position of a minimum near $\varepsilon_{sp} \approx 0.3$ GeV/fm^3 which is essentially closer to the lattice results under discussion. Looking at these differences one should keep in mind that the Kogut-Susskind and Wilson schemes predict the deconfinement temperatures as large as 157 [13] and 150 MeV [6]. The mixed phase model gives $T_{\rm dec} = 150$ MeV. Strictly speaking, the Hung-Shuryak approximation does not come from a fit to the lattice QCD data but is a simulation of crossover transition by smoothing out the two-phase bag-model results (for the details on the two-phase bag model see [7]) with the bag constant corresponding to $T_{\rm dec} = 160$ MeV [1].

Note also that the minimum in the approximating Hung-Shuryak curve is seen more distinctly than in the lattice data.

The mixed phase model can naturally be generalized to the case of the non-zero baryon number n_B [5]. As exemplified by the results in Fig.3, the mixed phase model prediction for n_B-dependent pressure coincides with that of the typical nuclear Walecka-like model up

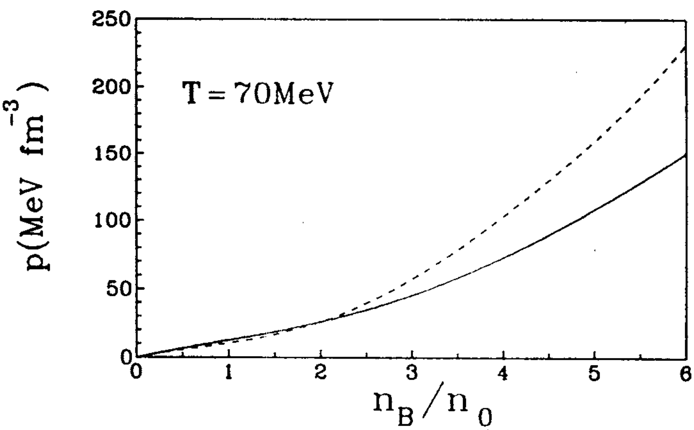

Fig.3. Pressure as a function of the compression ratio for the mixed phase model [5]. The dashed line is calculated within the advanced $\sigma - \omega$ model [14]

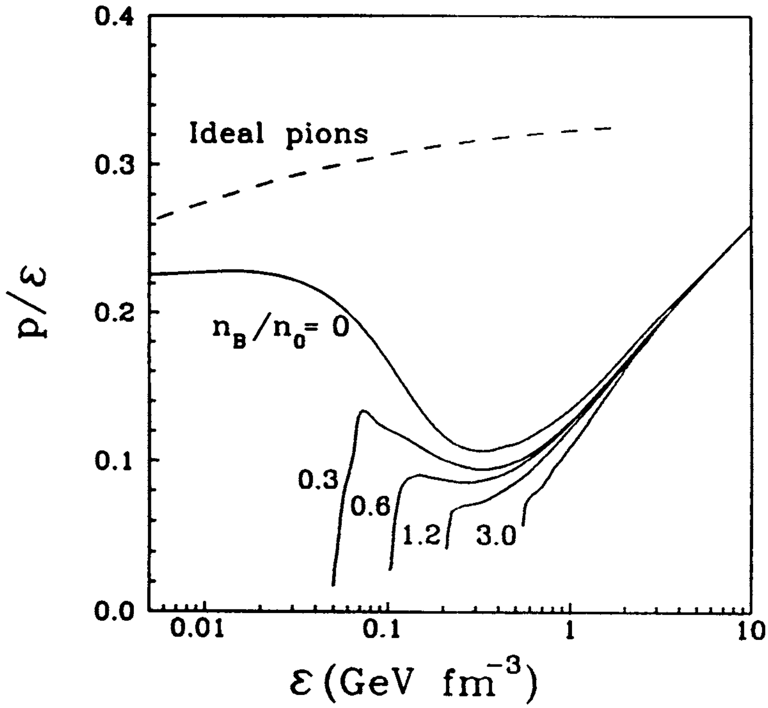

Fig.4. p/ε representation of EOS for baryonic matter predicted by the mixed phase model [5]. Numbers near the curves show the baryon density in units of normal nuclear density. The case of ideal pion gas is given by the dashed line

to $n_B \approx 3n_0$. At higher baryon densities, the mixed phase model gives lower values of pressure due to a quark admixture. As to the predicted energy density, the difference between these models is even smaller.

As is seen in Fig.4, the p/ε-function changes drastically with increasing the baryon density of a system: the «softest» point minimum is washed out at $n_B \approx n_0$ though its position ε_{sp} stays really at the same place. So, we arrive at somewhat controversial conditions: to reach the «softest» point for observing the longest-lived fireball in heavy ion collisions one should go *downward as far as moderate energies* $E_{\rm lab} \approx$ 3–5 GeV/A but high baryon density of a fireball formed at these energies will suppress the «softest» point effect. To see how the lifetime of a fireball will change with the beam energy, one needs detailed dynamical calculations with EOS of the mixed phase model. It is of interest to note that this EOS is quite different from EOS for pure hadronic phase as illustrated in Fig.4 by the case of ideal pion gas.

Concluding one should note that the lattice QCD data do really predict a minimum in the p/ε representation of EOS whose position ε_{sp} according to [1] defines the beam energy at which the fireball formed has the longest lifetime. This representation is essentially more sensitive to a detail of the lattice calculations and to their approximations as compared to standard thermodynamic quantities $\varepsilon(T)$ and $p(T)$. The formal simulation of the EOS with a crossover in [1] results in the «softest» point location $\varepsilon_{ps} \approx 1.5\ \mathrm{GeV/fm^3}$ which is noticeably higher than the lattice value $\varepsilon_{ps} \approx 0.5\ \mathrm{GeV/fm^3}$. The mixed phase model [3,4,5] describing the order and temperature of the deconfinement QCD transition for $n_B = 0$ predicts $\varepsilon_{ps} \approx 0.3\ \mathrm{GeV/fm^3}$ which is close to lattice data and, generally speaking, the agreement may be improved by a more accurate treatment of cluster interactions. All this implies that the proposed beam-energy tuning [1] for identification of deconfinement transition should be done at rather moderate energies 3—5 GeV/A, if ever, rather than around $E_{\mathrm{lab}} \approx 30$ GeV/A. The mixed phase model predicts also a strong dependence of EOS on the baryon density of the system: a minimum of the p/ε function is washed out for $n_B > n_0$. Since the state with ε_{sp} is a transitional one, we expect that the change in the fireball lifetime with E_{lab} will not be as large as in [1]. More definite conclusions can be done only after detailed dynamical calculations*. Nevertheless, we would like to draw attention to heavy ion collisions at moderate 2—10 GeV/A energies for studying the mixed phase of hadronic matter. As has been shown above, a pure hadronic EOS is quite different from the EOS predicted by the mixed phase model near the «softest» point. It is of interest that a possibility of forming the mixed quark-hadron phase at energies $E_{\mathrm{lab}} > 2$–10 GeV/A has been noted earlier in [15] but from a completely different point of view. On the other hand, some enhancement of Λ-hyperon production as a specific plasma formation signature has been observed at as low energy as 3.5 GeV/A at Dubna [16].

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*These calculations within a hydrodynamic model are in progress now.

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