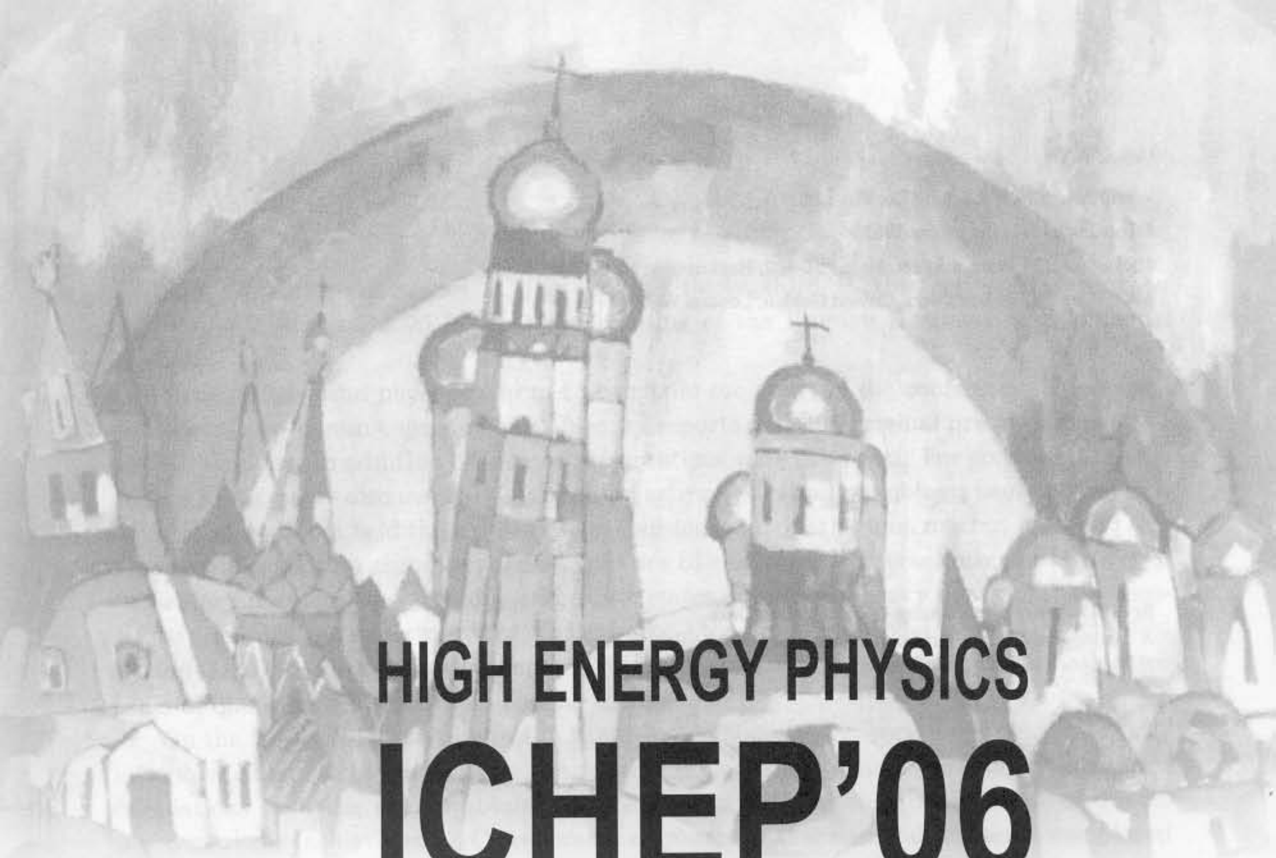

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A SEARCH FOR A MIXED QUARK-HADRON PHASE OF QCD MATTER

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Physics aspects of a JINR project to reach the planned 5A GeV energy for the Au and U beams and to increase the bombarding energy up to 10A GeV are discussed. The project aims to search for a possible formation of a strongly interacting mixed quark-hadron phase. The relevant problems are exemplified. A need for scanning heavy-ion interactions in bombarding energy, collision centrality and isospin asymmetry is emphasized.

Keywords: Phase Transition; Mixed Phase; QCD Matter.

1. Introduction

Over the last 25 years a lot of efforts have been made to search for new states of strongly interacting matter under extreme conditions of high temperature and/or baryon density, as predicted by Quantum Chromodynamics (QCD). These states are relevant to understanding the evolution of the early Universe after Big Bang, the formation of neutron stars, and the physics of heavy-ion collisions. The latter is of great importance since it opens a way to reproduce these extreme conditions in the Earth laboratory. This explains a permanent trend of leading world research centers to construct new heavy ion accelerators for even higher colliding energy.

In JINR there is a modern superconducting accelerator, Nuclotron, which has not realized its planned parameters yet. The Veksler and Baldin Laboratory of High Energy has certain experimental facilities and large experience in working with heavy ions. In [1] a program was proposed for investigating the dense strongly interacting QCD matter, formed in relativistic heavy ion collisions, based on acceleration of heavy ions like Au at the Nuclotron up to the maximal planned energy E_{lab} = 5A GeV. In view of new opened opportunities of the Nuclotron update to increase the bombarding energy up to 10A GeV and to get both Au and U ions with relativistic energies, the relevant physics problems are discussed in this paper.

2. Phase diagrams

A convenient way to present a variety of possible states of strongly interacting matter is a phase diagram in terms of temperature T and baryon chemical potential μ_B (or baryon density ρ_B), as presented in Fig. 1. This picture shows in which region of the diagram the given phase is realized and which colliding energies are needed to populate this region.

As is seen, a system, formed in a high energy collision, is fast heated and compressed and then starts to expand slowly reaching the freeze-out point which defines observable hadron quantities. At the Nuclotron energy E_{lab} = 5A GeV the system "looks" into the mixed phase for a short time, however, uncertainties of these calculations are still large. Note that for E_{lab} =10A GeV these conditions for a phase transition are fulfilled appreciably better. Calculation are carried out for a pure hadronic gas equation of state,

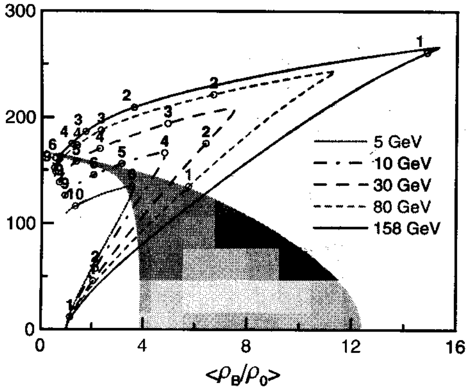

Fig. 1. Dynamical trajectories for central (b = 2 fm) Au+Au collisions in $T - \rho_B$ for various bombarding energies calculated within the relativistic 3-fluid hydrodynamics calculated with hadronic EoS [2]. Numbers near the trajectories are the evolution time moment. Phase boundaries are estimated in a two-phase bag model [3].

and the presence of a phase transition may noticeably change trajectories. In addition, near the phase transition the strongly interacting QCD system behaves like a liquid rather than a gas, as was clarified recently at small μ_B from both quark and hadronic side. As to high μ_B values, it is a completely open question.

One should stress that the presented above dynamical trajectories and boundaries for the first-order phase transition were estimated for a system conserving a single charge, namely the baryonic charge. However, the behavior of this system near the phase transition and particularly within the mixed phase will be qualitatively different if conservation of more than one charge is taken into account [4,5]. So we turn to consideration of effects of additional conservation of the electric charge, or isospin of the system.

We shall characterize the charge asymmetry by the electric-to-baryonic charge ratio $Z/A = \rho_Q/\rho_B$ or by the isospin ratio $x = (\rho_Q - \rho_B)/2\rho_B$ which are related as $x = Z/A - 0.5$. For Au+Au collisions we have $Z/A = 0.4$ or $x = -0.1$.

An essential difference in the first-order phase transition for systems with one and two conserved charges stems from the fact that the phase boundary, which is a line for a single charge conservation, is getting a two-dimensional surface. In the latter case the conserved charges can now be shared by two phases in equilibrium in different concentration in each phase but consistent with the global charge conservation. If this is energetically favored by the internal forces and Fermi energies, then these degrees of freedom will be exploited by the system and will influence thermodynamic quantities.

The boundary surface, so called binodal, may be parameterized in a different way, say as $\{T, \mu_B, \mu_Q\}$, $\{T, \mu_B, x\}$, $\{T, \rho_B, x\}$ or $\{p, \rho_B, x\}$. In Fig.2, some $\{T, \rho_B, x\}$ projections of a hadron-quark phase transition are shown [6].

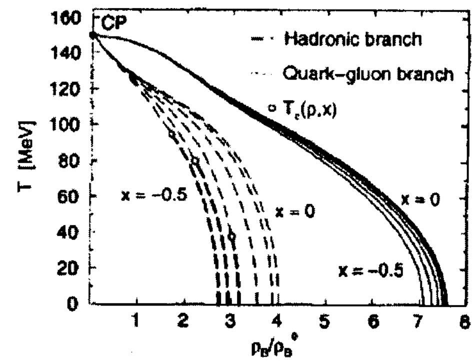

Fig. 2. Projections of the boundary surface on the (ρ_B, T) plane at different x. The isospin ratios are $x = 0, -0.1, -0.2, -0.3, -0.4, -0.5$, starting from the right. The boundaries of the mixed phase with the quark and hadron phase are plotted as solid and dashed lines, respectively [6].

It is seen that, for example, in symmetric matter at $T = 0$ the baryon density ranges along $3.5\rho_0$ between the onset and completion of the transition. For $x = 0$ the hadron boundary is close to that in Fig.1. This mixed phase domain becomes even larger in density for iso-asymmetric systems. Another important observation is that the density at the onset (i.e. hadronic side of the phase boundary at the transition density ρ_c) decreases with increasing isospin asymmetry. If one compares points for $x = 0$ and $x = -0.2$ at $T = 0$, a decrease is $\delta\rho_B \approx 0.5\rho_0$. But this effect is practically absent for $T \gtrsim 120$ MeV.

A more realistic description of the hadronic phase, which takes into account the baryon density dependence of hadron masses and coupling constants [7], was used for the results presented in Fig.3. The general trend of curves is quite similar to that in Fig.2 but now the values of transition densities are higher though the same bag constant $B^{1/4}$ =187 MeV was used in both the calculations [6,7].

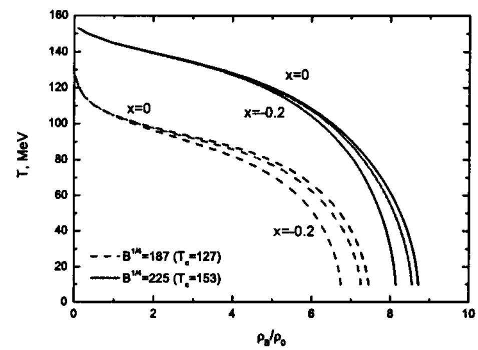

Fig. 3. Hadron boundary of the mixed phase at different x [8]. The isospin ratios are $x = 0, -0.1, -0.2$, starting from the right. Hadronic phase is described within the relativistic mean-field approach with density-dependent hadron masses and coupling constants [7]. The results are given for two values of the bag constant: $B^{1/4}$ =187 (dashed lines) and 225 MeV (solid lines).

Even noticeably stronger reduction of the transition density with increasing neutron fraction is predicted by the Catania group [9] for $T = 0$. It was demonstrated that ρ_c depends appreciably on poorly known properties of EoS at high baryon densities. This statement is illustrated in Fig.4. Quite low values of the transition densities originate from small values of the bag constant used, $B^{1/4} = 140 - 170$ MeV. This choice is argued by the following Witten hypothesis [12]: a state made of an approximately equal number of u, d, s quarks can have the energy per baryon number smaller than that for Fe; therefore, the quark matter is absolutely stable and purely quark stars may exist. This hypothesis put strong constraints on quark model parameters: The bag model parameter B should be small [12]. Today the existence of pure quark stars is not excluded but is rather considered as an exotic case.

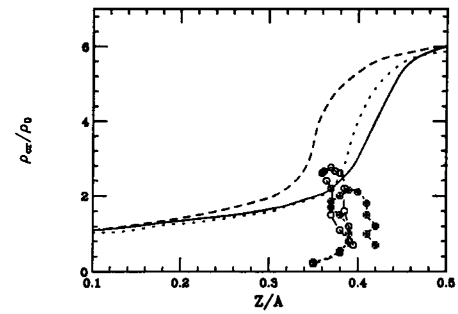

Fig. 4. Variation of the transition density with the proton fraction at $T = 0$ for various EoS parameterizations of the relativistic mean-field theory: Dotted, dashed and solid lines correspond to the GM3 version [10], to an additional inclusion of non-linearity in ρ interaction [11] and to an extra term describing the interaction of the isovector δ-meson [9], respectively. The points represent the dynamical trajectory in interaction zone during semi-central ^{132}Sn + ^{132}Sn collisions at 1A GeV (circles) and at 300A MeV (crosses) [9].

The most striking feature of all results is a sharp decrease of the transition density ρ_c which takes place in the range $Z/A \sim 0.3\div0.45$, though the size of the reduction effect and its position on the Z/A axis, as is seen in Fig.4, are strongly model dependent. Nevertheless, application of neutron-rich heavy ions seems to be very perspective to study the mixed QCD matter at energies even lower than the project Nuclotron energy 5A GeV. Dynamical trajectories presented in Fig.4 show that the phase boundary may be reached at energies as low as 1A GeV.

As follows from Figs.2-4, the most fa-

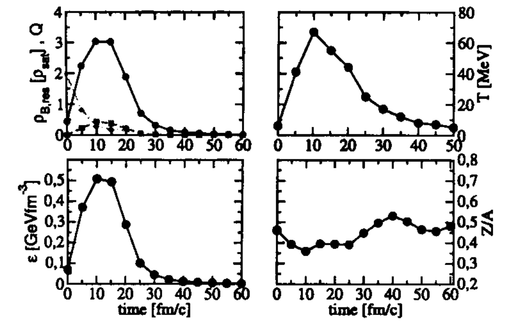

Fig. 5. Time evolution of thermodynamic quantities inside a cubic cell of 2.5 fm wide, located in the center of mass of the system, is shown for semi-central $^{238}U - ^{238}U$ collisions at E_{lab} =1A GeV with b =7 fm. Baryon density, temperature, energy density and proton fraction are presented. Different curves in the upper-left panel are: *black dots* – the baryon density in ρ_0 units; *grey dots* – the quadruple momentum in momentum space; *squares* – the resonance density [9].

vorable temperatures for this reduction effect are in the range $T \lesssim 80$ MeV. It is well known that in central collisions of relativistic heavy ions the growth of the density $\rho_B > 3\rho_0$ with the energy increase is accompanied by the appropriate rise in temperature $T \gtrsim 100$ MeV. Available stable nuclei cover only a very narrow region in isospin asymmetry $Z/A \approx 0.39 \div 0.40$ exhausted by the $^{238}_{92}U$ and $^{197}_{79}Au$ isotopes, respectively, what embarrasses checking the boundary reduction effect. The use of the long-lived $^{195}_{79}Au$ isotope (τ_{life} ~150 days) allows one to move towards neutron-poor side of the boundary till Z/A =0.41. Some possibility to get lower temperatures and to extend the reached isospin asymmetry region is opened by study of semi-central rather than central collisions as is illustrated in Fig.5

It is noteworthy that after about 10 fm/c the quadruple momentum is almost vanishing and a nice local equilibration is achieved. At this beam energy the maximum density coincides with reaching the thermalization. Then the system is quickly cooling while expanding. In Fig.5 one can see that rather exotic nuclear matter is formed in a transient time of the order of 10 fm/c, having the baryon density around $3\rho_0$, the temperature 50 – 60 MeV, the energy density 500 MeV fm^{-3} and the proton fraction between 0.35 and 0.40. So the local neutron excess well inside the estimated mixed phase region may be even higher than that in colliding nuclei (note that for ^{238}U the isospin symmetry ratio is Z/A =0.387).

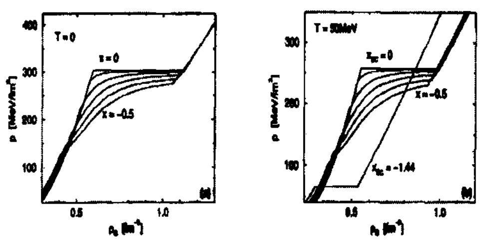

Fig. 6. Isoterms for different values of x at $T = 0$ (left panel) and T = 50 MeV (right panel). The isospin ratios are $x = 0, -0.1, -0.2, -0.3, -0.4, -0.5$ from top to bottom [6].

The $\{p, \rho_B, x\}$ projections of EoS corresponding to the Maxwell construction are given in Fig.6 for two isotherms. In accordance with the result familiar from the behavior of the systems with one conserved charge, for symmetric matter ($x = 0$) the pressure stays constant within the mixed phase. In contrast, at $x < 0$ the pressure changes during the transition increasing with the baryon density. This change of the pressure throughout the phase separation in asymmetric systems is an indication of a smoother transition than in symmetric systems as was first noted in the context of neutron star calculations [5]. Certainly, such behavior of pressure may crucially affect the evolution of two colliding nuclei.

Along with pressure, the temperature as well as the baryonic and electric chemical potentials do not remain constant within the mixed phase. This behavior is responsible for disappearance of the entropy discontinuity at the given p and x as pictured in

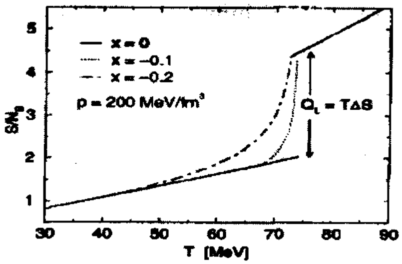

Fig. 7. Entropy per baryon as a function of temperature at the constant pressure for various isospin ratios [6]. For the case $x = 0$ the latent heat Q_L is shown.

Fig.7. This fact gave grounds for author [6] to claim that in the iso-asymmetric matter the first-order phase transition is smoothed and becomes the second-order phase transition. One should note that in spite of such behavior of the entropy, the first derivative of the thermodynamic potential with respect to temperature at the constant chemical potentials (i.e. locally in the μ_i space) suffers a jump, what is evidence of the first-order phase transition in iso-asymmetric matter. In the mixed phase the first derivatives of the thermodynamic potential have discontinuity in the $\{T, \mu_1, ..., \mu_n\}$ representation but they are continuous in the $\{T, \rho_1, ..., \rho_n\}$ one. That is the direct consequence of the Gibbs phase-equilibrium conditions [4] from which follows that in the first representation the every point of the n-dimensional mixed phase surface maps unambiguously on the $\{T, \mu_1, ..., \mu_n\}$ space. Evidently, it is not the case in the $\{T, \rho_1, ..., \rho_n\}$ representation as illustrated in Fig.8. Due to that the volume fraction of the second phase $\lambda \equiv \frac{V_{II}}{V}$ jumps when the system enters in the mixed phase, if the first representation is used, while it does not in the second representation. Any extensive thermodynamic quantity A will follow this behavior of λ since $A = \lambda A_{II} + (1-\lambda) A_I$.

As was noted above, the presence of two conserving charges in the $\{T, \mu_B, \mu_Q\}$ representation changes dimensionality of the two-phase coexistence surface for the first-order phase transition. Namely, the one-dimensional line for the case of a single conserving charge transforms into a two-dimensional (or n-dimensional) (hyper)surface if two (or n) charges are conserved [4], see Fig.8. Therefore, the manifold of critical points, that by definition is the boundary of the mixed phase where the system suffers the second order phase transition, also changes sufficiently: From two isolated points defining the limited line of the mixed phase it transforms into a one-dimensional curve ($(n-1)$-dimensional (hyper)surface) being a boundary of two-dimensional (n-dimensional) coexistence (hyper)surface. The different topologies of the mixed phase states may result in different important consequences.

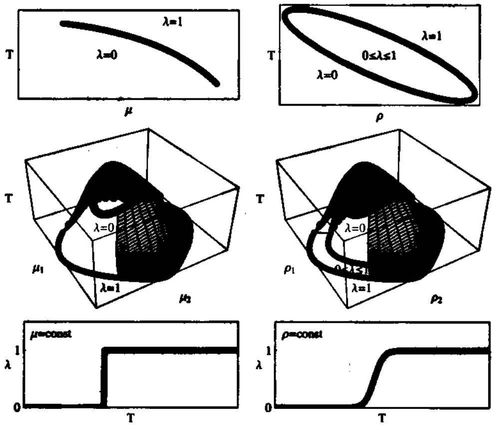

Fig. 8. Schematics view on the mixed phase boundaries in the $\{T, \mu\}$ (on left) and $\{T, \rho\}$ (on right) representations. Boundaries for a system conservation of a single charge (top), two charges (middle) as well as the volume fraction (bottom) are presented.

The outstanding problems involved in understanding the hadron-quark matter phase transition, aside from the description of these phases themselves, are related to the geometric structure of the mixed phase and its evolution with varying the relative fraction λ of phases. If one of the conserved charges is the electric charge, a geometric structure in the mixed phase is expected. The nucleation mechanism for cluster formation (say, quark drops in the hadron environment) is dominant in the metastable region of the first-order phase transition and formation of the mixed phase influenced by finite size effects due to nonvanishing surface tension at the interface between the hadronic and quark matter and the Coulomb energy of the formed drops. The geometric structure of the mixed phase was studied in some detail for neutron star matter (see the review-article [13]) but for nuclear matter uncertainties are rather large.

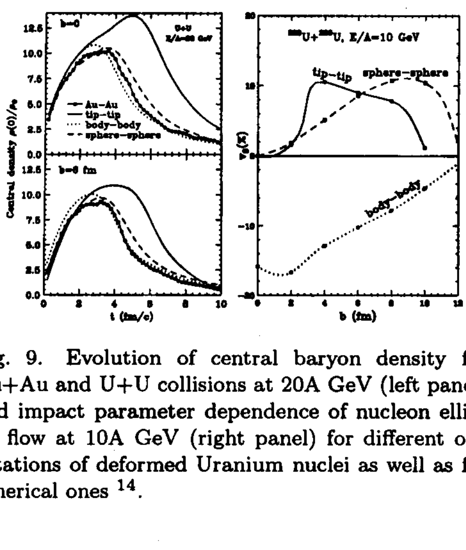

Fig. 9. Evolution of central baryon density for Au+Au and U+U collisions at 20A GeV (left panel) and impact parameter dependence of nucleon elliptic flow at 10A GeV (right panel) for different orientations of deformed Uranium nuclei as well as for spherical ones [14].

As is clearly seen, the value of the density at which the mixed phase can be reached becomes larger, if the finite size effects are taken into consideration. This increase due to finite-size effects is larger for smaller values of the bag constant B (compare with results in Fig.3). Nevertheless, a strong dependence of the transition energy on Z/A survives even in this case [9].

Besides the isospin there is yet another nuclear parameter which may influence evolution of a colliding system. It is the nuclear shape. It was noted earlier [14,15] that deformation and orientation affect compression, elliptic flow and particle production for collisions of Uranium nuclei. As seen from Fig.9, the compression in the tip-tip U+U collisions is about 30% higher and the region with $\rho > 5\rho_0$ lasts approximately 40% longer than in the body-body collisions or spherical U+U collisions. Moreover, the nucleon elliptic flow has some unique features which in principle may allow one to disentangle these two orientations [a]. Such situation is valid for the energy range 1-20A GeV [14] but uncertainties are still large [15].

A particular property of the mixed phase is the so-called distillation effect: While the total charge is conserved, its distribution between two phases is different. The structure of the mixed phase is especially rich and complicated if the conservation of the baryon number, electric charge and strangeness are taken into consideration simultaneously. The distillation effect is expected to result in certain observable effects as discussed in [16,17].

Similarly to the general situation with searching for a quark-gluon plasma in ultrarelativistic collisions, there is no single crucial experiment which unambiguously solves the problem. It is quite evident that direct information on the mixed phase may be obtained only by means of weakly interacting photon and lepton probes.

3. Conclusions

A study of the phase diagram of strongly interacting QCD matter in the domain populated by heavy-ion collisions with the bombarding energy $\lesssim$ 10A GeV and a search for manifestation of the mixed phase formation seem to be a very attractive task. The use of the isospin asymmetry as an additional conserving parameter to characterize the created hot and dense system draws new interest in this problem. Unfortunately, the available theoretical predictions are strongly model

[a] We are thankful to N. Xu for drawing our attention to this issue.

dependent giving rather dispersive results. There are no lattice QCD predictions for this highly nonpertubative region. So much theoretical work should be done and only future experiments may disentangle these models.

A JINR Nuclotron possibility of accelerating heavy ions to the project energy of 5A GeV and increasing it up to 10A GeV will enable us to effort a unique opportunity for scanning heavy-ion interactions in energy, centrality and isospin asymmetry of the system to search for the mixed phase of QCD matter. All this gives a chance to address experimentally many recent problems within the next several years before the FAIR GSI accelerator comes into operation. Being supplemented by scanning in the isospin asymmetry parameter, as discussed in the present paper, the proposed research program at the Nuclotron [1] may be considered also as a pilot study preparing for subsequent detailed investigations at SIS-100/300 [18] and as an integral part of the world scientific cooperation to study the energy dependence of hadron production properties in nuclear collisions.

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