ACCESSIBILITY OF COLOR SUPERCONDUCTING QUARK MATTER PHASES IN HEAVY-ION COLLISIONS*

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We discuss a hybrid equation of state (EoS) that fulfills constraints for mass-radius relationships and cooling of compact stars. The quark matter EoS is obtained from a Polyakov-loop Nambu–Jona-Lasinio (PNJL) model with color superconductivity, and the hadronic one from a relativistic mean-field (RMF) model with density-dependent couplings (DD–RMF). For the construction of the phase transition regions we employ here for simplicity a Maxwell construction. We present the phase diagram for symmetric matter which exhibits two remarkable features: (1) a "nose"-like structure of the hadronic-to-quark matter phase border with an increase of the critical density at temperatures below $T \sim 150$ MeV and (2) a high critical temperature for the border of the two-flavor color superconducting (2SC) phase, $T_c > 160$ MeV. We show the trajectories of heavy-ion collisions in the plane of excitation energy *versus* baryon density calculated using the UrQMD code and conjecture that for incident energies of $4 \ldots 8\ A$ GeV as provided, *e.g.*, by the Nuclotron-M at JINR Dubna or by lowest energies at the future heavy-ion collision experiments CBM at FAIR and NICA at JINR, the color superconducting quark matter phase becomes accessible.

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Theoretical studies of the QCD phase diagram have predicted a rich structure of nonperturbative phases under conditions of temperatures T below the deconfinement temperature $T_c \sim 180\,\mathrm{MeV}$ found in lattice QCD studies [1] and baryochemical potentials μ_B above $\sim m_N$, where $m_N = 939\,\mathrm{MeV}$ is the nucleon mass. Of particular interest are the questions:

- How does the order and the location of the chiral phase transition depend on temperature, density, size and isospin asymmetry of the system?

- What is the nature of confinement and how does deconfinement occur?

- Can deconfinement and chiral symmetry restoration occur independent from each other at high densities? As a consequence, shall we expect massive deconfined quark matter or chirally symmetric but confined quark matter (quarkyonic matter)?

- Is dense quark matter (color) superconducting? Does confinement preclude color superconductivity? Is there a BEC or rather BCS phase of color superconductivity? What is the critical temperature? Can these phases be created in the laboratory?

The energy scan program of the NA49 experiment has given indications for a phase change at $E \sim 30\,A\,\mathrm{GeV}$, in particular from the peak ("horn") in the K^+/π^+ ratio. Recently, it has been suggested that the "horn" may be the signature of an approximate triple point in the QCD phase diagram [2] where three phases meet: hadronic matter, quarkyonic matter, and a quark–gluon plasma. Experiments of the next generation (NA61-SHINE, low-energy RHIC, CBM and NICA) should, however, take into their focus the possibility that qualitatively new features could be found at still lower energies. This concerns in particular color superconducting quark matter phases like the 2SC phase [3] and the conjectured quarkyonic phase [4]. At the JINR Dubna, the modernized Nuclotron-M and the planned Nuclotron-based Ion Collider facility (NICA) give a unique opportunity to explore the above mentioned region of the phase diagram, and may thus complement alternative programs for systematic studies of heavy-ion collisons in the relevant range of collision energies $2 \leq E \leq 40\,A\,\mathrm{GeV}$.

As it has been demonstrated in [5, 6] the coupling to the Polyakov loop increases the critical temperature for the 2SC phase to the order of the deconfinement temperature $T_{2SC} \sim 150\,\mathrm{MeV}$, see the left panel of Fig. 1. In that figure, we show a modern QCD model phase diagram based on a quark matter EoS from a three-flavor NJL model with selfconsistent quark masses and diquark gaps [7–10], generalized here by the coupling to the Polyakov-loop potential to suppress unphysical quark degrees of freedom.
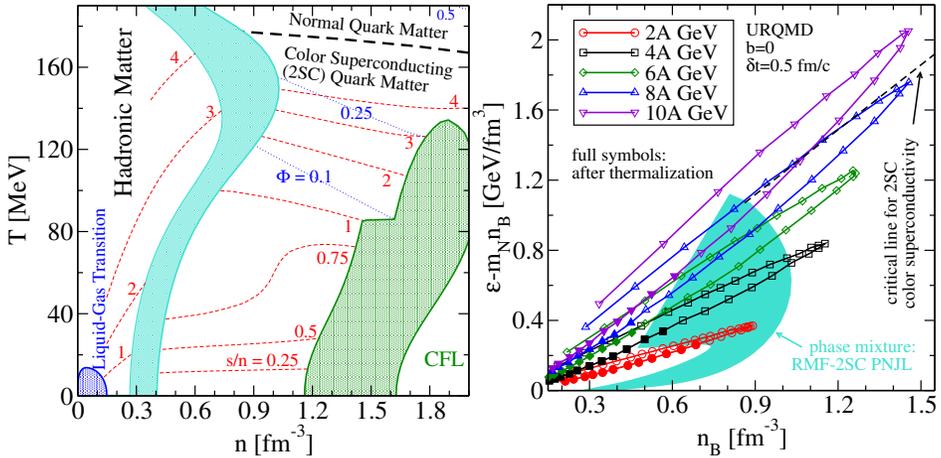
Fig. 1. Left panel: QCD model phase diagram with mixed phase regions corresponding to the first order phase transitions: nuclear liquid-gas (blue), hadron–quark matter (turqoise), 2SC–CFL quark matter (green). The transition from color superconducting (2SC) quark matter to normal quark matter is of second order (dashed line). Right panel: trajectories of central ($b = 0$) heavy-ion collisions at different energies in the excitation energy-density plane overlayed to the hadronic matter–2SC quark matter mixed phase region of the model-QCD phase diagram. The hatched region indicates the mixed phase. The dashed line denotes the critical line for 2SC color superconductivity.

The hadronic phase is modeled with a density-dependent relativistic mean-field approach [11] which also describes the nuclear liquid-gas phase transition with a critical point, see the blue hatched region in Fig. 1 (left panel). The hadron-to-quark matter transition is obtained from a Maxwell construction with a mixed phase coexistence region shown by the turqoise hatched region. The unusual nose-like shape of this region is due to the Polyakov-loop potential which suppresses the quark pressure at finite temperatures below the deconfinement temperature, but not at $T = 0$. At low temperatures, the appearance of the diquark condensate shifts the chiral restoration transition to rather low densities, of the order of 2–3 n_0, $n_0 = 0.16 \, \text{fm}^{-3}$.

In order to answer the question of the accessibility of these novel phases of dense QCD matter, we have examined the trajectories of the Lorentz contracted central region of central Au–Au collisions of given energies in the range $2 < E < 10 \, A \, \text{GeV}$ from UrQMD simulations, see the right panel of Fig. 1. The hatched region corresponds to the mixed phase of hadronic and 2SC quarkyonic matter for the parametrization of the PNJL model without vector mean field. The dashed line denotes the critical line for

2SC color superconductivity. We conclude from this figure that for energies $4 < E < 8\, A\,\mathrm{GeV}$, which presently are in reach with the Nuclotron-M facility, one may expect to enter the 2SC color superconducting quark matter phase with restored chiral symmetry and strong color correlations due to a low Polyakov-loop meanfield $\Phi < 0.25$, indicating a quarkyonic phase [12]. The exploration of the transition from color superconducting to normal quark matter and finally the ceasing of the mixed phase at the QCD critical point would require energies beyond $10\, A\,\mathrm{GeV}$, aimed to be reached at NICA.

Finally, let us discuss two ideas for the experimental identification of the chiral restoration and the color superconductivity transition which should be considered when planning experiments and in particular when designing the multi-purpose detector (MPD) system.

1. An enhancement of the two-photon invariant mass spectrum in the mass range $M_{2\gamma} \sim 300\,\mathrm{MeV}$, from the decay of the sigma meson which should become a long-lived "sharp" resonance when chiral symmetry gets restored and the dominant two-pion decay channel gets closed [13, 14]. This signal shall also prevail in the hypothetic quarkyonic phase and more traditional estimates of the two-photon spectrum within the ordinary NJL model would have to be revised within the PNJL model.

2. An enhancement of the lepton-pair invariant mass spectrum when approaching the critical temperature for color superconductivity from above (precursor effect [16]) which should eventually turn into a resonance-like structure when entering the 2SC phase, due to additional contributions to the diquark–antidiquark annihilation diagrams (generalized Aslamasov–Larkin and Maki–Thompson diagrams) containing anomalous propagator contributions.

In conclusion we would like to stress that our modern QCD model phase diagram suggests that new dense quark matter phases (color superconductor and quarkyonic matter) are accessible already at the present Nuclotron-M energies and that both the study of the transition to normal quark matter and the vanishing of the mixed phase at the QCD critical endpoint will require higher energies than presently available at the Nuclotron-M but are attainable in the planned FAIR-CBM and NICA-MPD experiments.

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