PROCEEDINGS OF SCIENCE

Strangeness instabilities in relativistic heavy-ion collisions

A. Lavagno[a,b,*]

[a] *Department of Applied Science and Technology, Politecnico di Torino, I-10129 Torino, Italy*
[b] *INFN, Sezione di Torino, I-10126 Torino, Italy*

E-mail: andrea.lavagno@polito.it

In this investigation we are going to show that, similarly to the low density nuclear liquid-gas phase transition, thermodynamic instabilities and, consequently, a pure hadronic phase transition can occur in regime of high temperature and dense baryon matter. The analysis is performed by means of an effective relativistic mean-field model with the inclusion of hyperons, Δ-isobars, and the lightest pseudoscalar and vector meson degrees of freedom. The Gibbs conditions on the global conservation of baryon number and zero net strangeness in symmetric nuclear matter are required. It turns out that a continuous phase transition takes place with two phases at the same baryon and strangeness chemical potentials but with a different content of baryon and strangeness density, altering significantly the baryon-antibaryon and meson-antimeson ratios. Such a physical regime could be in principle investigated in the high-energy compressed nuclear matter experiments where it is possible to create compressed baryonic matter with a high net baryon density.

41st International Conference on High Energy physics - ICHEP2022
6-13 July, 2022
Bologna, Italy

*Speaker

PoS(ICHEP2022)1030

One of the very interesting aspects of high energy heavy-ion collisions experiments is a detailed study of the thermodynamical properties of strongly interacting nuclear matter away from the nuclear ground state and many efforts were focused on searching for possible phase transitions in such collisions [1, 2]. The main goal of this paper is to explore the presence of mechanical instability (due to fluctuations on the baryon density) and chemical-diffusive instability (due to fluctuations on the strangeness concentration) in hot and dense symmetric nuclear matter. The consequent hadronic phase transition results to be characterized by different values of antibaryon-baryon ratios and strangeness content during the mixed phase.

The framework of this investigation is the relativistic mean-field model based on the Lagrangian density for the self-interacting octet of baryons (p, n, Λ, Σ^+, Σ^0, Σ^-, Ξ^0, Ξ^-) [3]

$$\begin{aligned}\mathcal{L}_{\rm octet} =&\sum_k \overline{\psi}_k\,[i\,\gamma_\mu\,\partial^\mu-(M_k-g_{\sigma k}\,\sigma)-g_{\omega k}\,\gamma_\mu\,\omega^\mu-g_{\rho k}\,\gamma_\mu\,\vec{t}\cdot\vec{\rho}^{\,\mu}]\,\psi_k+\frac{1}{2}(\partial_\mu\sigma\partial^\mu\sigma-m_\sigma^2\sigma^2)\\&-\frac{1}{3}a\,(g_{\sigma N}\,\sigma)^3-\frac{1}{4}\,b\,(g_{\sigma N}\,\sigma^4)+\frac{1}{2}\,m_\omega^2\,\omega_\mu\omega^\mu+\frac{1}{4}\,c\,(g_{\omega N}^2\,\omega_\mu\omega^\mu)^2+\\&+\frac{1}{2}\,m_\rho^2\,\vec{\rho}_\mu\cdot\vec{\rho}^{\,\mu}-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}-\frac{1}{4}\vec{G}_{\mu\nu}\vec{G}^{\mu\nu}\,,\end{aligned} \tag{1}$$

where the sum runs over the full octet of baryons M_k is the vacuum baryon mass of index k.

The Lagrangian density for the Δ-isobars can be expressed as [4, 5]

$$\mathcal{L}_\Delta=\overline{\psi}_{\Delta\,\nu}\,[i\gamma_\mu\partial^\mu-(M_\Delta-g_{\sigma\Delta}\sigma)-g_{\omega\Delta}\gamma_\mu\omega^\mu]\psi_\Delta^{\,\nu}\,, \tag{2}$$

where $\psi_\Delta^{\,\nu}$ is the Rarita-Schwinger spinor for the Δ-isobars.

The parameters of the model are fixed to reproduce the properties of equilibrium nuclear matter. In the following we will use the parameters set marked as TM1 of Ref. [3]. On the other hand, there are large uncertainties on the couplings $x_{\sigma\Delta}=g_{\sigma\Delta}/g_{\sigma N}$ and $x_{\omega\Delta}=g_{\omega\Delta}/g_{\omega N}$ between Δs and field mesons. Qualitatively, it has been possible to establish that the Δ-isobars inside a nucleus feel an attractive potential. Due to phenomenological analysis, different experimental constraints on the values of the Δ-meson coupling constants can be obtained [6]. Without loss of generality, we limit our study by fixing $x_{\omega\Delta}=1$ and varying $x_{\sigma\Delta}$ from unity to the value $x_{\sigma\Delta}=1.2$.

The formation of hyperons and Δ-isobars implies a remarkable softening of the Equation of State (EOS) at high density, therefore the considered hadronic EOS does not satisfy the observational existence of neutron stars with masses of about 2 $M_\odot$. However, this problem could be overcome in the scenario of two coexisting families of compact stars, as discussed, for example, in Ref. [6].

The finite temperature and density EOS with respect to strong interaction has to conserve two charges related to baryon number (B) and strangeness number (S). Due to the high temperature involved in this study, we limit to consider symmetric nuclear matter and, for simplicity, we neglect fluctuations on the electric charge.

By assuming the presence of two phases (denoted as I and II, respectively), the system is stable against the separation in two phases if the free energy of a single phase is lower than the free energy in all two phases configuration. In this case the phase coexistence is described by the following Gibbs conditions

$$\mu_B^I=\mu_B^{II}\,,\qquad \mu_S^I=\mu_S^{II}\,,\qquad P^I(T,\mu_B,\mu_S)=P^{II}(T,\mu_B,\mu_S)\,. \tag{3}$$

The mechanical and the chemical (strangeness) stability conditions ($r_S = \rho_S/\rho_B$) are satisfied if [7, 8]

$$\rho_B \left(\frac{\partial P}{\partial \rho_B}\right)_{T,\rho_S} > 0\,, \quad \left(\frac{\partial \mu_S}{\partial r_S}\right)_{T,P} > 0\,. \tag{4}$$

Whenever the above stability conditions are not respected, the system becomes unstable and a binodal surface in (T, P, r_S) space encloses the area where the system undergoes to the phase transition.

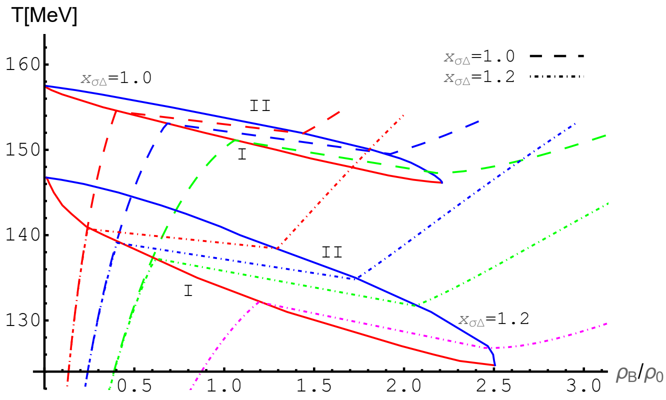

Figure 1: Phase diagrams $T-\rho_B$ (in units of the nuclear saturation density ρ_0) for two values of the coupling: $x_{\sigma\Delta} = 1.2$ and $x_{\sigma\Delta} = 1.0$. Dot-dashed and dashed lines, represent the isentropic trajectories for $S/B = 30, 20, 15, 10$ (red, blue, green and magenta, respectively) for the two coupling ratios $x_{\sigma\Delta}$.

In Fig. 1, we report the phase diagram in the temperature-baryon density plane, for two different Δ-coupling ratios: $x_{\omega\Delta} = 1$ (upper curves) and $x_{\sigma\Delta} = 1.2$ (lower curves). Although the thermodynamic instabilities are already present in the so-called "minimal coupling" choice $x_{\sigma\Delta} = x_{\omega\Delta} = 1$, by increasing $x_{\sigma\Delta}$ and, consequently, the relevance of the Δ-isobar degrees of freedom in the EOS, we observe a remarkable reduction of the critical temperature and an increase of the baryon density range for which the system enters into the thermodynamical instabilities region. This feature has strong consequences especially with regard to the formation of strange baryons and mesons during the mixed phase.

In Fig. 2, left panel, we display the anti-baryon to baryon particle ratios as a function of the net baryon density for different temperatures and $x_{\sigma\Delta} = 1.2$. For $T \lesssim 125$ MeV, the system is stable in the phase I, with a low fraction of antiparticles. By increasing the temperature, the system enters in the thermodynamical instability region and a phase transition takes place. In this condition, it occurs a sharp increase of the ratio during the mixed phase (the dots in the figure delimit the first and the second critical baryon density). Finally, for $T \gtrsim 147$ MeV, the system returns stable in an antimatter and Δ-rich phase. Such a feature, almost common to all particles considered, is mainly due to a strong reduction of the (positive) baryon effective mass during the phase transition. In the mixed phase, at a given temperature, we find an analogue remarkable enhancement of the anti-hyperon/hyperon ratio (mainly $\overline{\Lambda}/\Lambda$) with a consequent net formation of $\overline{s}$ quarks in the baryon sector. This behavior is compensated by a sharp reduction of the K^+/K^- ratio in the mixed phase (see Fig. 2, left panel) with an increase of the s quarks mainly in the meson sector, being the system globally at $r_S = 0$.

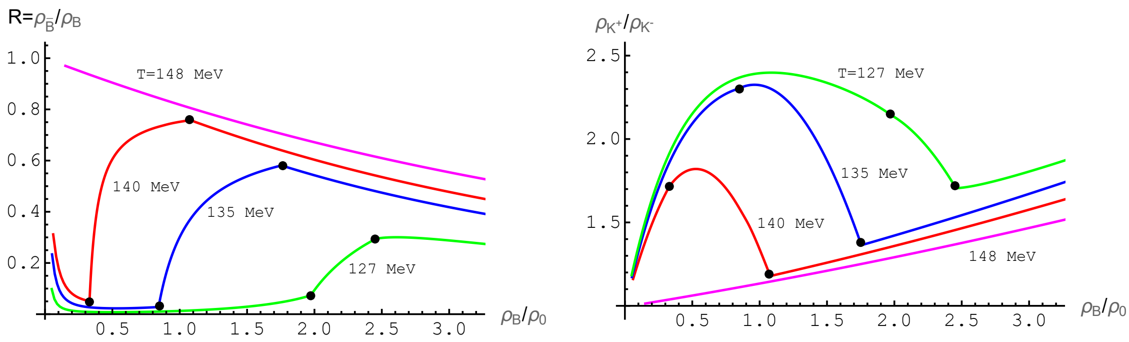

Figure 2: Anti-baryon to baryon particle ratios (left panel) and kaon to antikaon ratios (right panel) as a function of the net baryon density for different temperatures. The dots delimit the regions of mixed phase. The curves relative to $T = 148$ MeV correspond to a stable configuration of the EOS.

In summary, due to a different strangeness content into the instabilities region, in the phase I, at low baryon density and positive strangeness, we have mainly an enhancement of anti-hyperons and, as a counterpart, in the phase II, at higher density and negative strangeness, an enhancement of anti-kaon particles. This feature has strictly analogies to the hadron-quark phase transition where it is possible to realize the so-called strangeness distillation: $\bar{s}$ quarks are foreseen mainly present in the low density hadronic phase and the population of s quarks should be greatly enriched in the higher density quark-gluon phase [9, 10]. Detailed analysis of collective flows, such as directed and elliptic flow, which are sensitive to the early stage of the collisions, can give valuable information about the nuclear EOS and could better discriminate the occurrence and the nature of a first order phase transition in the compressed baryon matter regime [11].

References

[1] C. Spieles, M. Bleicher, *Eur. Phys. J. Special Topics* **229** (2020) 3537 and references therein.

[2] P. Senger (CBM), *Int. J. Mod. Phys. E* **29** (2020) 2030001 and references therein.

[3] Y. Suguhara, H. Toki, *Nucl. Phys. A* **579** (1994) 557.

[4] B.M. Waldhauser et al., *Phys. Rev. C* **36** (1987) 1019.

[5] A. Lavagno, *Phys. Rev. C* **81** (2010) 044909.

[6] A. Drago, A. Lavagno, G. Pagliara, *Phys. Rev. C* **90** (2014) 065809 and reference therein.

[7] H. Müller and B.D. Serot, *Phys. Rev. C* **52** (1995) 2072.

[8] A. Lavagno, D. Pigato, *Phys. Rev. C* **86** (2012) 024917.

[9] C. Greiner, P. Kock, H. Stocker, *Phys. Rev. Lett* **58** (1987) 1825.

[10] A. Lavagno, D. Pigato, *J. Phys. G: Nucl. Part. Phys. G* **39** (2012) 125106.

[11] Y. Nara, T. Maruyama, H. Stoecker, *Phys. Rev. C* **102** (2020) 024913.