Strangeness instabilities in high energy heavy-ion collisions

A. Lavagno

Department of Applied Science and Technology, Politecnico di Torino, I-10129 Torino, Italy

INFN, Sezione di Torino, I-10125 Torino, Italy

Abstract

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. In this investigation we are going to explore the presence of thermodynamic instabilities and the realization of a pure hadronic phase transition at finite temperature and baryon density nuclear 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. In this context, a phase transition characterized by both mechanical instability (fluctuations on the baryon density) and by chemical-diffusive instability (fluctuations on the strangeness concentration) in asymmetric nuclear matter can take place. In analogy with the liquid-gas nuclear phase transition, hadronic phases with different values of antibaryon-baryon ratios and strangeness content may coexist during the mixed phase. 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.

Introduction

In this contribution, we to study the hadronic equation of state (EOS) at finite temperature and density by means of a relativistic mean-field model with the inclusion Δ-isobars, hyperons and the lightest pseudoscalar and vector meson degrees of freedom and by requiring the Gibbs conditions on the global conservation of baryon number and zero net strangeness.

In Ref. [1], we have studied the presence of thermodynamical instabilities and a subsequent phase transition from nucleonic matter to resonance-dominated Δ matter in a warm and dense asymmetric nuclear medium ($T \leq 50$ MeV and $\rho_0 \leq \rho_B \leq 3\rho_0$). In this paper we plan to extend such a previous investigation in regime of high temperature and dense baryon matter by including the hyperon and Δ-isobar degrees of freedom in an effective relativistic hadronic EOS. By requiring the Gibbs conditions on the global conservation of baryon number and zero net strangeness, we are going to show that the presence of the Δ-isobars can drive to the formation of mechanical and chemical-diffusive instabilities which imply a pure hadronic phase transition with different strangeness content in the mixed phase.

Hadronic equation of state

The relativistic mean-field model (RMF) is widely successful used for describing the properties of finite nuclei as well as hot and dense nuclear matter [2-3].
The Lagrangian for the self-interacting octet of baryons (p, n, Λ, Σ^+, Σ^0, Σ^-, Ξ^0, Ξ^-) can be written as [2]

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

where the sum runs over the full octet of baryons, M_k is the vacuum baryon mass of index k, the quantity $\vec{t}$ denotes the isospin operator that acts on the baryon.
In regime of finite values of temperature and density, a state of high density resonance matter may be formed and the Δ(1232)-isobar degrees of freedom are expected to play a central role [4-5]. In particular, the formation of resonances matter contributes essentially to baryon stopping, hadronic flow effects and enhanced strangeness. The Lagrangian density concerning the Δ-isobars (Δ^{++}, Δ^+, Δ^0, Δ^-) 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 ψ_Δ^ν is the Rarita-Schwinger spinor for the Δ-isobars (Δ^{++}, Δ^+, Δ^0, Δ^-). Due to the uncertainty on the meson-Δ coupling constants, we limit ourselves to consider only the coupling with the σ and ω meson fields, more of which are explored in the literature.
The field equations in a mean field approximation are

$$\begin{aligned} & (i\gamma_\mu\partial^\mu - M_k^* - g_{\omega k}\gamma^0\omega - g_{\rho k}\gamma^0 t_{3k}\rho)\psi_k = 0\,, && (3)\\ & (i\gamma_\mu\partial^\mu - M_\Delta^* - g_{\omega\Delta}\gamma^0\omega)\psi_\Delta^\nu = 0\,, && (4)\\ & m_\sigma^2\sigma + a\,g_{\sigma N}^3\,\sigma^2 + b\,g_{\sigma N}^4\,\sigma^3 = \sum_i g_{\sigma i}\,\rho_i^S\,, && (5)\\ & m_\omega^2\omega + c\,g_{\omega N}^4\,\omega^3 = \sum_i g_{\omega i}\,\rho_i^B\,, && (6)\\ & m_\rho^2\rho = \sum_i g_{\rho i}\,t_{3i}\,\rho_i^B\,, && (7)\end{aligned}$$

where the effective mass of the ith baryon is defined as

$$M_i^* = M_i - g_{\sigma i}\sigma\,. \tag{8}$$

The ρ_i^B and ρ_i^S are the baryon density and the baryon scalar density, respectively. They are given by

$$\rho_i^B = \gamma_i \int \frac{\mathrm{d}^3k}{(2\pi)^3}[n_i(k) - \overline{n}_i(k)]\,, \tag{9}$$

$$\rho_i^S = \gamma_i \int \frac{\mathrm{d}^3k}{(2\pi)^3}\,\frac{M_i^*}{E_i^*}\,[n_i(k) + \overline{n}_i(k)]\,, \tag{10}$$

where $n_i(k)$ and $\overline{n}_i(k)$ are the fermion particle, antiparticle distributions function, given by

$$n_i(k) = \frac{1}{\exp(E_i^*(k) - \mu_i^*)/T + 1}\,, \tag{11}$$

$$\overline{n}_i(k) = \frac{1}{\exp(E_i^*(k) + \mu_i^*)/T + 1}\,. \tag{12}$$

The effective chemical potentials μ_i^* are given in terms of the chemical potentials μ_i by means of the following relation

$$\mu_i^* = \mu_i - g_{\omega i}\,\omega - g_{\rho i}\,t_{3i}\,\rho\,, \tag{13}$$

where t_{3i} is the third component of the isospin of i-th baryon. The baryon effective energy is defined as $E_i^*(k) = \sqrt{k^2 + {M_i^*}^2}$.

Phase transition and stability conditions

We are dealing with the study of a multi-component system at finite temperature and density with two conserved charges: baryon (B) number and zero net strangeness (S) number ($r_S = \rho_S/\rho_B = 0$). For what concern the electric charge (Q), we work in symmetric nuclear matter with a fixed value of $Z/A = 0.5$ and we do not consider fluctuation in the electric charge fraction, due to the high temperature regime. Therefore, Q results to be separately conserved in each phase during the phase transition.
The chemical potential of particle of index i can be written as

$$\mu_i = b_i\,\mu_B + s_i\,\mu_S\,, \tag{14}$$

where b_i and s_i are, respectively, the baryon and the strangeness quantum numbers of i-th hadronic species.
For such a system, the Helmholtz free energy density F can be written as

$$F(T,\rho_B,\rho_S) = -P(T,\mu_B,\mu_S) + \mu_B\rho_B + \mu_S\rho_S\,, \tag{15}$$

with

$$\mu_B = \left(\frac{\partial F}{\partial \rho_B}\right)_{T,\rho_S}\,, \quad \mu_S = \left(\frac{\partial F}{\partial \rho_S}\right)_{T,\rho_B}\,. \tag{16}$$

In a system with N different particles, the particle chemical potentials are expressed as the linear combination of the two independent chemical potentials μ_B and μ_S and, as a consequence, $\sum_{i=1}^N \mu_i\rho_i = \mu_B\rho_B + \mu_S\rho_S$.
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. The phase coexistence is given by the Gibbs conditions [3]

$$\mu_B^I = \mu_B^{II}\,, \qquad \mu_S^I = \mu_S^{II}\,, \tag{17}$$

$$P^I(T,\mu_B,\mu_S) = P^{II}(T,\mu_B,\mu_S)\,. \tag{18}$$

At a given baryon density ρ_B and at a given zero net strangeness density $r_S = \rho_S/\rho_B = 0$, the chemical potentials μ_B are μ_S are univocally determined by the following equations

$$\rho_B = (1-\chi)\,\rho_B^I(T,\mu_B,\mu_S) + \chi\,\rho_B^{II}(T,\mu_B,\mu_S)\,, \tag{19}$$

$$\rho_S = (1-\chi)\,\rho_S^I(T,\mu_B,\mu_S) + \chi\,\rho_S^{II}(T,\mu_B,\mu_S)\,, \tag{20}$$

where $\rho_B^{I(II)}$ and $\rho_S^{I(II)}$ are, respectively, the baryon and strangeness densities in the low density (I) and in the higher density (II) phase and χ is the volume fraction of the phase II in the mixed phase ($0 \leq \chi \leq 1$).

An important feature of this conditions is that, unlike the case of a single conserved charge, baryon and strangeness densities can be different in the two phases, although the total ρ_B and ρ_S are fixed [3,6].

For such a system in thermal equilibrium, the possible phase transition can be characterized by mechanical (fluctuations in the baryon density) and chemical instabilities (fluctuations in the strangeness number). As usual the condition of the mechanical stability implies

$$\rho_B\left(\frac{\partial P}{\partial \rho_B}\right)_{T,\rho_C} > 0\,. \tag{21}$$

By introducing the notation $\mu_{i,j} = (\partial\mu_i/\partial\rho_j)_{T,P}$ (with $i,j = B,S$), the chemical stability for a process at constant P and T can be expressed with the following conditions [7,8]

$$\rho_B\,\mu_{B,B} + \rho_C\,\mu_{S,B} = 0\,, \tag{22}$$

$$\rho_B\,\mu_{B,S} + \rho_S\,\mu_{S,S} = 0\,. \tag{23}$$

Whenever the above stability conditions are not respected, the system becomes unstable and the phase transition take place. The coexistence line of a system with one conserved charge becomes in this case a two dimensional surface in (T,P,r_S) space, enclosing the region where mechanical and diffusive instabilities occur.

Results and discussion

By increasing the temperature and the baryon density during the high energy heavy ion collisions, a multi-particle system may take place and the formation antiparticles become much more relevant.
In analogy with the liquid-gas case, we are going to investigate the existence of a possible phase transition in the nuclear medium by studying the presence of instabilities (mechanical and/or chemical) in the system.
The chemical stability condition is satisfied if ($r_S = \rho_S/\rho_B$):

$$\left(\frac{\partial\mu_S}{\partial r_S}\right)_{T,P} > 0 \quad \text{or} \quad \begin{cases} \left(\dfrac{\partial\mu_B}{\partial r_S}\right)_{T,P} < 0\,, & \text{if } r_S > 0\,, \\[2ex] \left(\dfrac{\partial\mu_B}{\partial r_S}\right)_{T,P} > 0\,, & \text{if } r_S < 0\,. \end{cases} \tag{24}$$

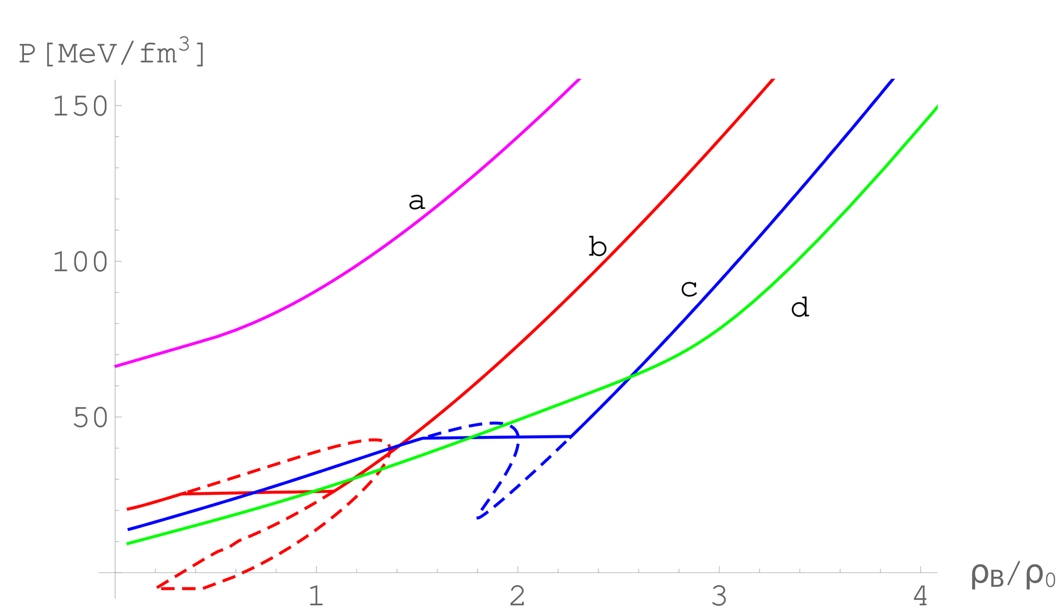

Fig. 1 - Pressure as a function of the baryon density (in units of the nuclear saturation density ρ_0) at different temperatures. The curves labeled a through d have decreasing temperatures: T= 150, 140, 130 and 120 MeV, respectively. In the case b and c, the system is mechanically unstable (dashed lines) and the Gibbs constructions are also shown.

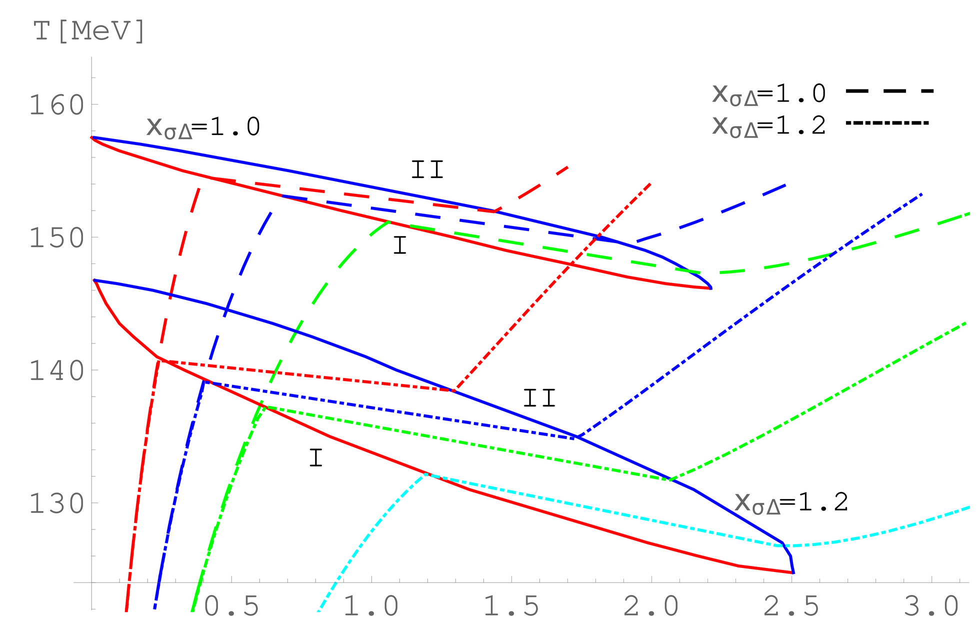

Fig. 2 - Phase diagrams for two values of the coupling: $x_{\sigma\Delta} = 1$ (upper continuous curves) and $x_{\sigma\Delta} = 1.2$ (lower continuous curves). Dashed and dot-dashed lines, represent the isentropic trajectories for S/B = 30, 20, 15, 10 (red, blue, green and light-blue, respectively) for the two coupling constants $x_{\sigma\Delta}$.

Let us observe that the thermodynamic instabilities are already present in the so-called "minimal coupling" choice, assuming the Δ-isobars coupling constants equal to the nucleon one ($x_{\sigma\Delta} = x_{\omega\Delta} = 1$). 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 instability region. Furthermore, along each isentropic trajectory, conserved in a fluid element in the hydrodynamics models, we have in the mixed phase a reduction of the temperature in a wide range of baryon density. This peculiar behavior could be phenomenologically relevant in order to identify such a phase transition in the future compressed baryonic matter experiments [9,10].

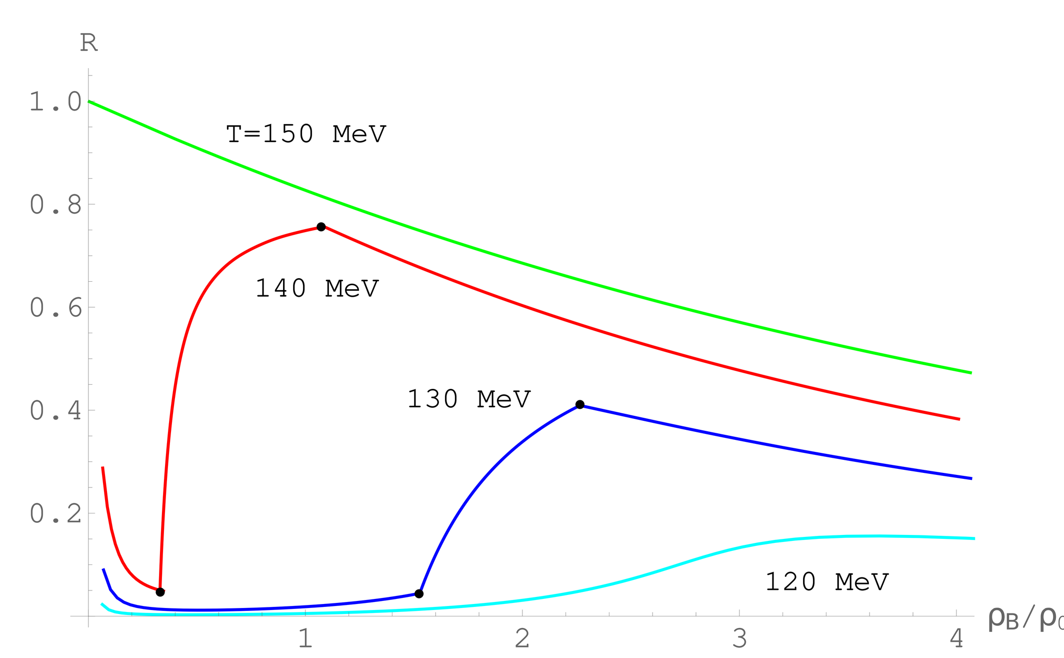

Fig. 3 - Anti-baryon to baryon particle ratio ($R = n_{\overline{B}}/n_B$) as a function of the net baryon density for different temperatures. The dots delimit the regions of mixed phase. The curves relative to T = 120 and 150 MeV correspond to a stable configuration of the EOS.

The main goal of this work it to show the possible presence of thermodynamical instabilities at high temperature and dense nuclear matter, by requiring the global conservation of the baryon number and zero net strangeness. Similarly to the liquid-gas phase transition, mechanical and chemical-diffusive thermodynamic instabilities can be formed but, in the present regime, the corresponding phase transition is driven by a different strangeness content in the mixed phase, instead of a different electric charge fraction.
The introduction of the Δ isobar degrees of freedom plays a crucial role in the realization of the unstable conditions, which are sensible to the values of the meson-Δ coupling constants. We have seen that the thermodynamic instabilities appear in the EOS in a finite range of couplings compatible with different experimental constraints. In this situation, a pure hadronic phase transition takes place, implying a strong enhancement of the anti-baryon to baryon ratios with a consequent formation of $\overline{s}$ quarks, mainly in the baryon sector in the low density phase, and of s quarks, mainly in the meson sector in the high density phase. This phase transition could have, therefore, similar features and signatures to the quark-hadron phase transition with a strangeness distillation effect [11,12].
In the last years, many important progresses have been made in the theoretical modeling of high baryon density nuclear matter with the development of hydrodynamic and microscopic transport models. 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 [13,14]. In particular, the study of the variation of the direct flow at forward rapidity region for different energies beam could reveal a possible phase transition in the high energy heavy-ion collisions.

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