Noncongruence of the QCD phase transition

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Noncongruence

First-order phase transitions (PTs) with more than one globally conserved charge are called *noncongruent* PTs. They differ fundamentally from *congruent* PTs, with only one globally conserved charge, because the concentrations of the charges can be exchanged between the two phases.

The term “noncongruent“ is commonly used for PTs in terrestrial applications with chemically reacting plasmas [2]. Noncongruence is also well known in heavy-ion collisions, nuclear physics and astrophysics [3,4], where usually the terms “Maxwell“ and “Gibbs“ are used instead.

Our study

We investigate the noncongruent features of the QCD PT by using the chiral SU(3) model [5]. We also compare the QCD PT with the nuclear liquid-gas PT, for which we apply the non-linear relativistic mean-field model FSUgold [6]. Coulomb interactions are always neglected.

In heavy-ion collisions, there are always at least two conserved charges, baryon number and isospin or equivalently the charge to baryon ratio Y_Q=Z/A. Thus one can expect that PTs are generally noncongruent. In our study, we consider heavy-ion collisions of symmetric (Y_Q=0.5) and asymmetric nuclei (Y_Q=0.3).

Chiral SU(3) EOS

The chiral SU(3) equation of state (EOS) is an effective quantum relativistic mean-field model, with interactions mediated by meson exchange in a chirally invariant Lagrangian [5]. Quarks (u,d,s) and hadrons (baryon octet) are included as a chemical mixture of quasi-particle degrees of freedom. The coupling constants are fitted to vacuum masses of baryons and mesons, nuclear matter properties, hyperon optical potentials, and lattice data.

The degrees of freedom which are actually populated are regulated by the “Polyakov“ field Φ, appearing in the potential U,

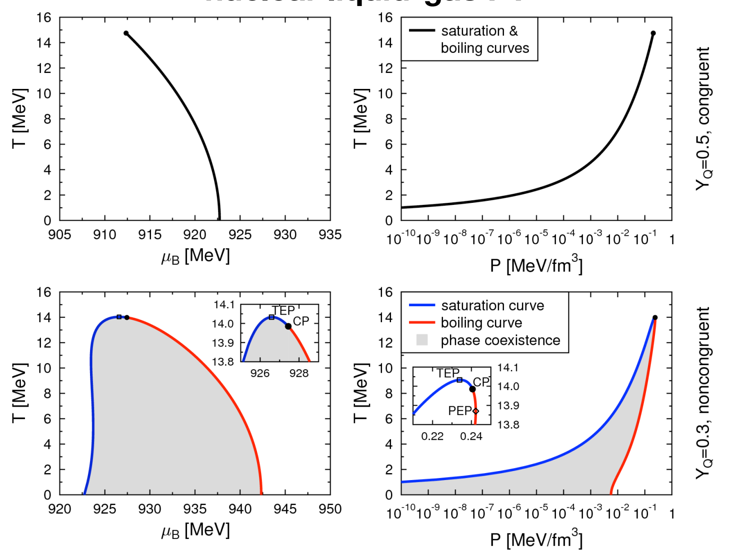
$$U = (a_0 T^4 + a_1 \mu_B^4 + a_2 T^2 \mu_B^2)\Phi^2 \\ + a_3 T_0^4 \ln(1 - 6\Phi^2 + 8\Phi^3 - 3\Phi^4),$$

via its contribution to the masses of baryons and quarks:

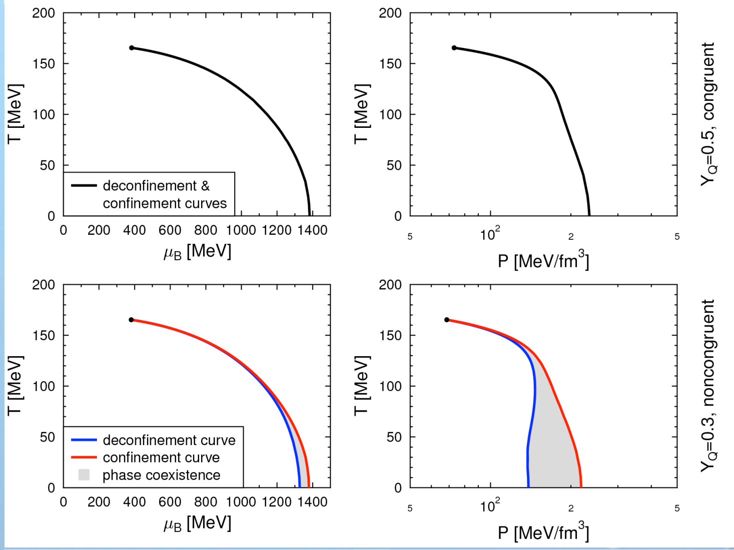
$$M_B^* = g_{B\sigma}\sigma + g_{B\delta}\tau_3\delta + g_{B\zeta}\zeta + M_{0_B} + g_{B\Phi}\Phi^2,$$
$$M_q^* = g_{q\sigma}\sigma + g_{q\delta}\tau_3\delta + g_{q\zeta}\zeta + M_{0_q} + g_{q\Phi}(1-\Phi).$$

Note that at zero temperature, the low density phase contains only hadrons and the high density phase only quarks. At finite temperature, there generally is a mixture of the two.

nuclear liquid-gas PT



QCD PT



Results and discussion

Because of isospin symmetry of the strong interactions, for the symmetric system with Y_Q=0.5 one obtains a congruent PT. This is the behavior of an *azeotropic* substance. The QCD PT in asymmetric systems ($Y_Q\neq$0.5) is noncongruent.

The dimensionality of phase diagrams is different for congruent and noncongruent PTs. In the noncongruent case, phase coexistence lines become phase coexistence regions (e.g., in T-μ, T-P). This also means that an isothermal PT does not have a constant pressure.

For noncongruent PTs, critical points (CPs) do not coincide with (topological) endpoints, such as the temperature (TEP) or pressure endpoint (PEP). This is clearly seen for the nuclear liquid-gas PT. Conversely, for the QCD PT the noncongruent features become vanishingly small around the CP. This can be explained by the high temperatures involved, which reduce the importance of the conserved charges.

We find a principle difference between the liquid-gas and QCD PT: in contrast to the ordinary Van-der-Waals-like PT, the phase coexistence line of the QCD PT has a negative slope in the pressure-temperature plane. This results from a higher entropy in the quark phase compared to the hadronic phase (Clapeyron equation). The QCD PT is not of liquid-gas type because it is “entropic“ and not “enthalpic“ [7].

Critical points and 2-EOS approaches

The chiral SU(3) model gives a continuous transition from hadronic to quark matter above a critical point (CP), and a first order PT below. To obtain such a behavior, it is essential to have both hadronic and quark degrees of freedom within a unified EOS model. With 2-EOS models, where quark and hadronic matter are described with separate Lagrangians, this is impossible, they cannot contain CPs.

References

[1] M. Hempel, V.A. Dexheimer, S. Schramm, I. Iosilevskiy, Phys. Rev. C **88**, 014906 (2013).

[2] I. Iosilevskiy, Acta Phys. Polon. B (Proc. Suppl.) **3**, 589 (2010).

[3] C. Greiner, P. Koch, and H. Stöcker, Phys. Rev. Lett. **58**, 1825 (1987).

[4] N.K. Glendenning, Phys. Rev. D **46**, 1274 (1992).

[5] V. A. Dexheimer and S. Schramm, Phys. Rev. C **81**, 045201 (2010).

[6] B.G. Todd-Rutel and J. Piekarewicz, Phys. Rev. Lett. **95**, 122501 (2005).

[7] I. Iosilevskiy, arXiv:1403.8053 (2014).