Isospin dependence of the critical quark-deconfinement densities

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We explore the dependence of the critical density, separating hadronic matter from a mixed phase of quarks and hadrons, on the ratio Z/A. We use both the MIT bag model and the Color Dielectric Model to describe the quark dynamics, while for the hadronic phase we employ various relativistic equations of state. We find that, if the parameters of quark models are fixed so that the existence of quark stars is allowed, then the critical density drops dramatically in the range $Z/A \sim 0.3$–0.4. Moreover, for $Z/A \sim 0.3$ the critical density is only slightly larger than the saturation density of symmetric nuclear-matter. This opens the possibility to verify the Witten-Bodmer hypothesis on absolute stability of quark matter using ground-based experiments in which neutron-rich nuclei are tested.

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Hadronic matter is expected to undergo a phase transition into a deconfined phase of quarks and gluons at large densities and/or high temperatures. On very general grounds, the transition's critical densities are expected to depend on the isospin of the system. Up to now, experimental data on the phase transition have been extracted from high-energy scattering of almost isospin-symmetric nuclei, having a proton fraction $Z/A \sim 0.4$–0.5. The analysis of observations of neutron stars, which are composed of β-stable matter for which $Z/A \lesssim 0.1$, can also provide hints on the structure of extremely asymmetric matter. No data on the quark deconfinement transition is at the moment available for intermediate values of Z/A. Recently it has been proposed by several groups to produce and study unstable neutron-rich nuclei (for a updated review of the status of these projects see e.g. [1, 2]). As we will show, these new experiments open the possibility to explore in laboratory the isospin dependence of the critical densities.

The information coming from experiments with ultra-relativistic heavy ions is that, for symmetric or nearly symmetric nuclear matter, the critical energy density must be considerably larger than nuclear matter energy density at saturation. Concerning non-symmetric matter, general arguments based on Pauli principle suggest that the critical density decreases with Z/A. We want to study in particular the range $Z/A \sim 0.3$–0.4, which can be explored in radioactive nuclear beam facilities. Here and in the following we are mainly interested in the critical density separating pure hadronic matter from a mixed phase of hadrons and quarks. The second critical density, separating the mixed phase from the pure quark matter phase, is in general reachable only in high energy experiments, while we are mainly interested in intermediate energy experiments.

A sistematic study of the isospin dependence of the critical densities has been performed up to now, to our knowledge, only by Mueller [3]. In that paper only one set of model parameters values is explored. The conclusion of [3] is that, moving from symmetric nuclei to nuclei having $Z/A \sim 0.3$, the critical density is reduced by roughly 10%. In this Letter we will explore in a more sistematic way the model parameters. In particular we will be interested in those parameters sets which would allow the existence of quarks stars [4, 5], i.e. parameters sets for which the so-called Witten-Bodmer hypothesis is satisfied [6, 7]. According to that hypothesis, a state made of an approximately equal number of up, down and strange quarks can have an energy per baryon number E/A smaller than that of iron ($E_{Fe} \approx 930$ MeV). To satisfy the Witten-Bodmer hypothesis, strong constraints on quark model parameters have to be imposed. For instance, using the MIT bag model, the so-called pressure-of-the-vacuum parameter B must have a very small value, $B^{1/4} \sim 140$–150 MeV [8]. Assuming the Witten-Bodmer hypothesis to be true, ordinary nuclear matter would be metastable. In order not to contradict the obvious stability of normal nuclei, quark matter made of only two flavors must not be more stable than iron. As we shall see, slightly more strict boundaries on parameters' value can be imposed by requiring not only iron, but also neutron rich nuclei like e.g. lead, to be stable. If the Witten-Bodmer hypothesis is satisfied, self-bound stars entirely composed of quark matter can exist [4, 5, 9]. Recently several analysis of observational data have emphasized the possible existence of compact stars having very small radii, of the order of 9 kilometers or less [10, 11, 12, 13]. The most widely discussed possibility to explain the observed mass-radius relation is based on the existence of quark stars. It is therefore particularly interesting to envisage laboratory experiments testing the possible signatures of model parameters values that would allow the existence of these extremely compact stellar objects. What we are proposing in this Letter is to use radioactive nuclear beams to this purpose.

It is rather unlikely, at least in the near future, that neutron rich nuclei obtainable in radioactive nuclear beam facilities can be accelerated at very large energies, much larger than 1 GeV per nucleon. The scenario we would like to explore corresponds therefore to the situation realized in experiments at moderate energy, in which the temperature of the system is at maximum of the order of few tens MeV. In this situation, strange quarks cannot be produced and we need only to study the deconfinement transition from nucleonic matter into up and down quark matter.

In our analysis we have explored various hadronic and quark models. Concerning the hadronic phase, we have used the relativistic non-linear Walecka-type models of Glendenning-Moszkowski (GM1, GM2, GM3) [14]. We have also explored the possibility of enhancing the symmetry repulsion at high baryon density introducing a coupling to a charged scalar δ-meson. As remarked in Ref.[15], this is fully in agreement with the spirit of the effective field theories, and of course with the phenomenology of the free nucleon-nucleon interaction. For the quark phase we have considered the MIT bag model at first order in the strong coupling constant α_s [8] and the Color Dielectric Model (CDM) [16, 17]. In the latter, quarks develop a density dependent constituent mass through their interaction with a scalar field representing a multigluon state. After having chosen a model for the hadronic and for the quark EOS, the deconfinement phase transition is then described by imposing Gibbs equilibrium conditions [18]. This technique can be considered as an effective way to describe the multi-quark correlations which generate the hadronization process in a more microscopic approach.

In Fig. 1 we show the critical density ρ_{cr} separating nuclear matter from quark-nucleon mixed phase, as a function of the proton fraction Z/A. The figure has been obtained using GM2 (GM1) parametrization for the hadronic phase and the MIT bag model without gluons (with gluons and $\alpha_s = 0.3$) in the upper and lower window, respectively. The most striking feature of the results shown in Fig.1 is the sharp decrease of ρ_{cr} in the range $Z/A \sim 0.3$–0.4. The lower curves in each window correspond to parameters' values satisfying the Witten-Bodmer hypothesis. In the latter case, and for $Z/A \sim 0.3$, the critical density is of the order of ρ_0. This opens the possibility to test the deconfinement transition in low energy experiments, such as the one performed in future RNB facilities.

The main features of Fig.1 can be easely understood if one recalls that we are investigating situations in which the minimum of pure quark matter EOS is at an energy just above or just below the minimum of the hadronic matter EOS. The first scenario is the one in which the absolute minimum of E/A, for a given value of Z/A, corresponds to the quark matter EOS (this situation corresponds to very small values of the parameter B, e.g. $B^{1/4} = 148$ MeV in the top panel of Fig.1). In this case, the deconfinement transition starts at very small densities, smaller than nuclear matter saturation density. The numerical determination of these densities is rather delicate and we limit ourself to indicate with vertical arrows in Fig. 1 the behaviour of the critical density for a given value of B. If the value of B is further reduced, the ver-

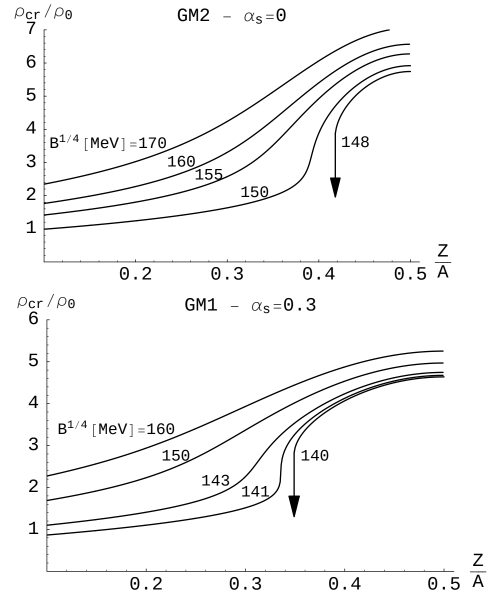

FIG. 1: Transition densities separating hadronic matter from mixed quark-hadron phase. In the upper panel the GM2 parametrisation [14] has been used for the hadronic EOS and the MIT bag model without gluon exchange has been used for the quark EOS. In the lower panel, GM1 parametrisation [14] for the hadronic EOS and MIT bag model with perturbative exchange of gluons with $\alpha_s = 0.3$. The arrows indicate that the transition density drops to very small values and the parameter $B^{1/4}$ cannot be further reduced. ρ_0 is the nuclear matter saturation density.

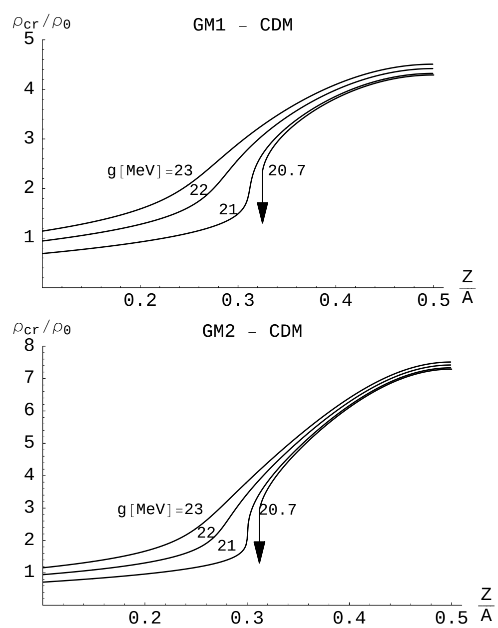

FIG. 2: Similar to Fig.1. The quark EOS has been computed using the Color Dielectric Model [19]. The parameter g regulates the coupling between quarks and a scalar multigluon field, see text.

tical arrow shifts towards larger values of Z/A and therefore cannot correspond to a physically acceptable situation, since it would imply deconfinement into two flavor quark matter at low densities, even for almost symmetric nuclei. In particular we can exclude parameter's values for which the dramatic drop in the critical density takes place for $Z/A \geq 0.4$. In this way we define a *minimal* value of, e.g., parameter B of the MIT bag model. Notice that the limit on the value of the model parameters we get in this way is (slightly) more restrictive than the one generally adopted and based on the stability of Fe against decay into two flavor quark matter.

The second situation is the one in which the minimum of the quark EOS lies slightly above the hadronic minimum, as e.g. for $B^{1/4} = 150$ MeV in the top panel of Fig.1. In this situation the deconfinement transition starts at a density slightly smaller than the one corresponding to the minimum of the quark EOS. The critical density cannot be further reduced, since at even smaller densities the energy E/A in the quark phase rises dramatically, both in the MIT bag model and in the CDM, and therefore no mixing of hadronic matter with quark matter is possible at those densities. It is also important to notice that both in the MIT and in the CDM model, the position of the minimum of E/A is near the value of nuclear matter saturation density when the energy of the minimum is near to the one obtained from the hadronic EOS [19].

Finally, when the value of B is further increased, the minima of the hadronic and of the quark EOS become more and more separated, the dependence of the critical density on the Z/A fraction reduces progressively, and a situation similar to the one discussed in Ref.[3] is reached.

In Fig.2 the same analysis is performed using the CDM for the quark EOS, obtaining results similar to those of Fig.1. In Fig.3 the effect of the exchange of the charged δ meson is also considered [15]. The δ-exchange potential provides an extra isospin dependence of the EOS, and its effect shows up in a further reduction of the critical density in the region $0.3 \lesssim Z/A \lesssim 0.4$. We would like to remark that the NLHρ parametrisation gives results very similar to those obtained using the GM3 parameters set.

Let us now comment on the physical relevancy of the dramatic reduction of the critical density in neutron rich nuclei. Since in these nuclei neutrons presumably occupy an extended area around the core of the nucleus (neutron skin), the density of the very neutron-rich part can be considerably smaller than ρ_0. We cannot therefore expect to find a direct signal of deconfinement in the structure of these nuclei, but we can look for precursor signals. In particular, we can expect that the formation of clusters containing six or nine quarks will be enhanced due to the reduction of the critical deconfinement density. This enhancement can in turn be intepreted as a modification of single-nucleon properties due to the nuclear medium. The experimental search of effects like the one we are discussing here has a very long story, which includes the discovery of the EMC effect [20], that is the non trivial difference between free-nucleon and nuclear structure functions, for which many interpretations have been proposed (for a review see [21]). In particular, models for the EMC effect invoking the formation of multi-quark clusters have been [22, 23] and are still quite popular [24]. The decrease of the deconfinement critical density obtained in our analysis suggests a dependence of the EMC effect on the isospin, since the probability of forming virtual multiquark bags is enhanced in neutron rich nuclei. This dependence would add to the non-isoscalarity effect originated by the different structure functions of protons and neutrons, generally considered in the analyses [25]. A full account of non-isoscalarity corrections arizing from genuine nuclear physics effects has been attempted in [26, 27], and seems to be necessary in the light of the preliminary analysis of CHORUS data on deep inelastic scattering off a Pb target [28].

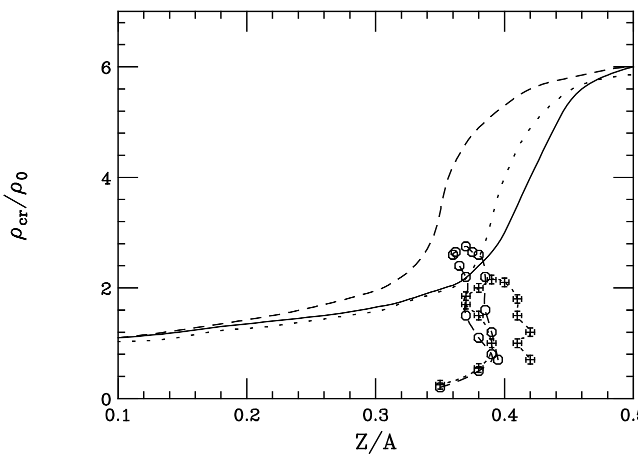

FIG. 3: Variation of the transition density with proton fraction for various hadronic EOS parametrisations. Dotted line: GM2 parametrisation [14]; dashed line: NLHρ parametrisation [15]; solid line: NLH$(\rho+\delta)$ parametrisation [15]. For the quark EOS, the MIT bag model with $B^{1/4}$=150 MeV and α_s=0 has been used. The points represent the path followed in the interaction zone during a semi-central ^{132}Sn+^{132}Sn collision at 1 A.GeV (circles) and at 300 A.MeV (crosses).

A more direct way to explore the reduction of the deconfinement critical density would be to test the EOS of matter via scattering of two neutron rich nuclei. This possibility is based on the analysis of intermediate-energy heavy-ion collisions, as discussed in Refs.[29, 30, 31, 32, 33], and references therein.

To check the practical feasibility of such an experiment, we have performed some simulations of the ^{132}Sn + ^{132}Sn collision (average Z/A=0.38) at various energies, for semicentral impact parameter, b=6 fm, just to optimize the neutron skin effect in order to get a large asymmetry in the interaction zone. We have used a Relativistic Transport Code [34], adoptining the same effective interaction [15] of the $NLH(\rho+\delta)$ EOS of Fig.3 to compute the critical deconfinement density (solid line). In Fig.3 the paths in the $(\rho, Z/A)$ plane followed in the

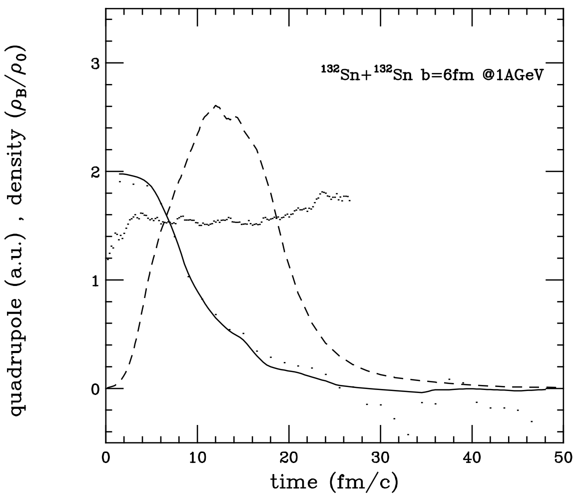

FIG. 4: Time evolution of the quadrupolar momentum in momenta space (solid line) and of the density (dashed line). The simulation examines the after-scattering thermalisation inside a cubic cell 2.5 fm wide, located in the center of mass of the system.

c.m. region during the collision are reported at energies of 300 A.MeV (crosses) and 1 A.GeV (circles). We see that already at 300 A.MeV we are reaching the border of the mixed phase, and we are well inside it at 1 A.GeV. In order to be sure that we are really testing the Nuclear Matter EOS, which is an equilibrium property, we have performed a check of the local thermalization in correspondence of the high baryon density regions reached during the collision. In Fig.4 we show that indeed, when the maximum density is reached ($\rho \sim 2.6\rho_0$) the quadrupole momentum of the nucleon momentum distribution has dropped to $\sim 10\%$ of its initial value, a signal that the system has indeed thermalized.

The use of an harder hadronic EOS for symmetric matter at high density would correspond to a even more favourable situation than the one presented in Fig.3, as shown in the examples of Fig.1. Moreover the use of neutron-richer nuclei would allow to test the EOS at smaller values of Z/A. To this purpose, the most promising nuclei are the ones near the r-process path, in particular for neutron numbers near the magic values N=82 or 126. In these regions, the proton fraction is as low as 0.32–0.33 and these nuclei could be studied in future experiments with neutron-rich beams [35].

In conclusion, our analysis supports the possibility of observing precursor signals of the transition to a mixed quark-hadron phase in the collision, central or semi-central, of exotic (radioactive) heavy ions in the energy range of a few hundred MeV per nucleon. A possible signature could be revealed through an earlier softening of the hadronic EOS for large isospin asymmetries, and it would be observed e.g. in the behaviour of the collective flows for particles having large transverse momentum.

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