DRAFT:

Physics Progress Report:

Strangelet research in ALICE

Theoretical Aspects

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I. INTRODUCTION

The only possibility to study the production of strange matter is in ultra-relativistic heavy-ion collisions. Bound states incorporating strangenes were already predicted in [1]. There, a reduction of the Fermi energy and so of the mass of the quark matter is explained with the presence of strangenes as an additional degree of freedom. How much the mass is lowered with respect to the masses of hadronic or hypreonic matter with the same strangenes content, decides about the possible decay channels and so about the stability of strange matter [2]. Bound states including strangenes were investigated in the framework of the MIT bag model *e.g.* [3,**?**], quark potentials *e.g.* [4], the Skyrme model *e.g.* [5].

Looking at hadronic matter, hypernuclei are already known for some time. There is a close connection between observed double Λ events and the H dibaryon *e.g.* [6]. MEMOs, *i.e.* metastable exotic multihypernuclear objects and purely hyperonic conglomerates of Λs and Ξs as opposed to bags including multiple strange quarks (strangelets) [8] are first mentioned in [7]. Model predictions for bound states of $\Sigma\Sigma$, $\Sigma\Xi$, and $\Xi\Xi$ exist, too [9].

Of course, prior to talking about the stability of any object, it is necessary to think about its production. Commonly, one argues that in an ultra-relativistic heavy-ion collision during the coexistence of the quark-gluon plasma phase and the hadronic phase, strange and antistrange quarks are distributed asymmetrically between the partonic and the hadronic phase [10,11]. Mainly, the strange quarks remain in the plasma whereas the antistrange quarks end up in the hadronic sector. But, even without a phase transition, strangeness and antistrangeness are abundantly produced in ultra-relativistic heavy-ion collisions. For that reason, baryonic objects with high strangeness content could be formed, *i.e.* the MEMOs already mentioned above.

However, there are still large uncertainties in the theoretical predictions. So, we compile here a selection of short overviews about different approaches to the theoretical description of strange matter. We take a glance at its stability, the creation of strange objects in the quark-gluon plasma phase of an ultra-relativistic heavy-ion collision, and also the impact of knowing about the properties of strange matter on other physical fields. We start with a section about the stability of strange matter. Therein, we discuss the importance of its investigation on the example of neutron and quark stars within the Nambu-Jona Lasinio model. In further subsections, we discuss predictions on the stability by calculations within the chiral model and the MIT bag model. In the then following chapter we proceede with the discussion of the formation of strangelets in the quark-gluon plasma. There, we concentrate especially on the strangenes distillation mechanism. In the last chapter briefly we summarize the contents of our essay.

II. STABILITY OF STRANGE MATTER

The experimental strategy for the search for strangelets depends strongly on the lifetime of these objects. Three different scenarios are imaginable:

- Unstable strange quark matter:

  The multy-strange objects have a minimum energy per nucleon higher than that of the hyperons and the nucleons. Thus, they are subject to strong decays into those. Under these circumstances they can only have short lifetimes of arround 10^{-10} to 10^{-5} s.

- Metastable strange quark matter:

  The strangelets or MEMOs would have energies per nucleon that lie between those of the nucleons and those of the hyperons. Thus, the dominant decay mode become weak hadronic decays into pions and nucleons. So they typically live around 10^{-5} and 10^{-4} s.

- Long-lived strange quark matter:

  Lifetimes of more than 10^{-4} s can only be reached if merely weak leptonic decay channels are at hand. This is the case for objects with an energy per nucleon less than that of the nucleons.

In the next subsection we try to motivate the importance of the examination of the stability issue of strange quark matter. In particular, we discuss its impact on the properties of neutron and quark stars.

A. Strange Matter in Neutron and Quark Stars

If ALICE proved the existence of (meta)– stable strange exotic matter it would have an extraordinary impact on the expected properties of neutron stars. [12]: A phasetransition to hypermatter would occure in the interior of neutron stars and a second stable form of neutron stars (hyperstars) with much smaller radii would be possible (see Fig. 1). A collapse to hypermatter in compact stars could create an outburst of gravitational waves which might be detectable in future experiments.

The properties of quark stars, calculated within a chiral quark model (NJL), was found to be strongly dependent on the ratios of the coupling constants characterizing the vector and scalar 4–fermion interaction, $\xi \equiv G_V/G_S$ [13]. On the one hand, it was found that for $\xi \gtrsim 0.4$ the stars near to the maximum mass have a large admixture of strange quarks in their interiors, on the other hand the properties of quark stars with $\xi \gtrsim 1$ show behaviors typical for neutron stars. Therefore, the ALICE results would be important for any realistic neutron and quark star calculation.

In the following subsection, we discuss the predictions of a chiral model concerning the stability of strange matter.

B. Stability of Strange Matter within the Chiral Model

Using a hadronic chiral $SU(3) \times SU(3)$ mean-field model [16,17], the stability of strange hadronic matter is investigated. This model describes the properties of infinite nuclear matter and the known hyperon potentials, finite nuclei and hypernuclei satisfactorily [16–18]. In the following we will consider two different parameter sets which both describe well the infinite nuclear matter and finite nuclei properties as stated above. They differ in the treatment of the baryonic resonances which leads to a different behaviour of the masses of the spin-3/2 resonances. While in case 1 the masses of these resonances stay above the masses of the hyperons, in case 2 the strange resonance masses drop below the octet hyperon masses.

In Figure 2 we plot the predicted energy per particle for different baryonic densities as a function of net-strangeness f_s for the two cases. Both figures show that in the chiral $SU(3) \times SU(3)$ model strange hadronic matter is only stable for small net-strangeness. Furthermore, both calculations predict the nuclear matter saturation point to be the energetically most favorable state. But the results differ concerning the metastability of strange hadronic matter. While in the first case even metastable strange hadronic matter does not occur, in case 2 metastable strange hadronic matter is predicted to be formed for high densities and high net-strangeness. This results from the lower masses of the strange baryon resonances in case 2, which corresponds to more attraction and therefore stronger binding in the system. In summary this shows that calculations in a chiral $SU(3) \times SU(3)$ hadronic mean-field model do predict strange hadronic matter not to be absolutely stable. Furthermore metastable strange hadronic matter occurs in this model only if the strange baryon resonances feel much more attraction in the nuclear medium than the corresponding octet-hyperons.

In the subsequent part of this essay, the results concerning the stability of strange matter obtained by the MIT bag model are discussed.

C. Stability of Strange Matter within the MIT Bag Model

Strangelets have also been studied within the MIT bag model. In [14,15] the masses of stranglets up to $A_B = 40$ are calculated in the framework of the MIT bag model. Under these circumstances, those strangelets which are stable against strong decay should be highly negatively charged. It is also possible that they are stable against weak hadronic decays. However, in this case their masses and charges would rather be high. These candidates are situated in a valley of stability created by pronounced shell effects. This valley starts at the quark α (6u6d6s) and continues by adding units of negative charge. However, colormagnetic interactions between the quarks have not been taken into account. Doing so might modify the picture. The findings in [14,15] could be interpreted so that the search for highly charged matter would be far more promising than thought up to now. Long-lived positively charged strangelets seem to exist only for $A_B > 12$ and very small bag parameters. Here, one would have to look at the region $A = 10 - 16$ and $Z = (-4) - (-10)$

In [14,15] also MEMOs are condsidered using a relativistic mean-field model. In this context, it is predicted that the existence of highly charged objects of this kind could be proved by looking after short-lived, rare composites. If their existence could be proved experimentally there would arise stringent limits for the properties of strangelets of the same mass, strangeness, and charge. Also MEMOs could serve as a doorway state for the production of strangelets via strong decays.

In the section to come, we talk about production mechanisms of (multi-)strange objects from the quark-gluon plasma.

III. STRANGE MATTER FORMATION IN THE QUARK GLUON PLASMA

A very important aspect of the physics of strangeness is the understanding of the mechanism of production of bound states. In the following subsection, we will introduce the commonly accepted picture of strangeness distillation.

A. Strangelet Formation by the Strangeness Distillation Mechanism

To estimate the fluctuations possible in heavy-ion collisions at the LHC, let us consider a recent Pb+Pb calculation performed at $s^{1/2} = 6500$AGeV with FRITIOF 7.02. The probability distribution for non zero net-baryon number fluctuations at midrapidity is plotted in Fig. 3 within bins of one unit of rapidity width. This probability is defined for single events, and shows rapidity density deviations from the average value $< dN/dy >$. Bins between $-3 < y < 3$ have been taken into account. The probability for fluctuations $N_B - < N_B >$ being larger than ± 20 is about 15 %. The asymmetry of the histogram results from the fact that fluctuations may be different for positive and negative deviations around a non zero average rapidity density.

Consider a hadronizing QGP-droplet with net-strangeness zero surrounded by a layer of continuously evaporates hadrons (they undergo the freeze-out). Assume the two phases to be in perfect mechanical, chemical and thermal equilibrium. Now, rapid kaon emission leads to a finite *net* strangeness of the expanding system [10]. As shown in Fig. 4, this results in an enhancement of the s-quark abundance in the quark phase. Prompt kaon (and, of course, also pion) emission cools the quark phase, which then may condense into metastable or stable droplets of strange quark matter.

At collider energies, the midrapidity region is expected to be characterized by rather low net-baryon densities even when taking fluctuations into account. How can one expect to create stable strangelets with baryon density of $\rho > \rho_0$?

In the last section, we conclude with a short summary.

IV. SUMMARY

In the present essay a short overview over theoretical approaches to two important aspects of the physics of strangeness is given. First, we considered the question of stability of (multi-)strange bound states. After that, we had a short glance at the production of strange matter in an ultra-relativistic heavy-ion collision. In the section about the stability, we discussed investigations of that issue within the Nambu-Jona-Lasinio, the chiral, the MIT bag, and the relativistic mean-field model. In the subsequent chapter we mainly focused on the idea of strangeness distillation. Generally, it can be said, that the answers to the questions posed in this field are rather non-uniform. So, more effort on the theoretical side as well as detailed experimental investigations are needed in order to clarify the picture.

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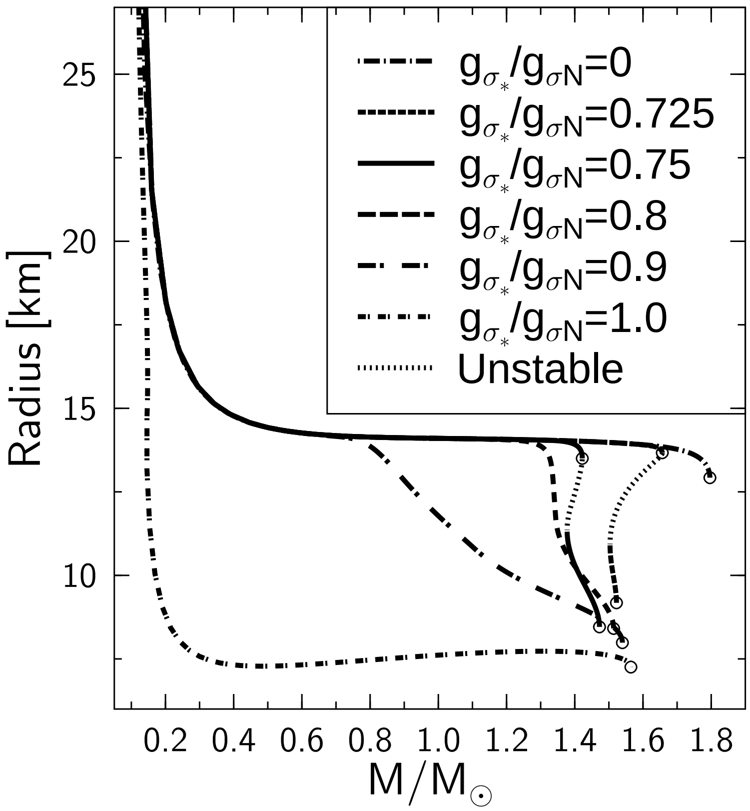

FIG. 1. Mass-radius relation for neutron stars with a highly attractive hyperon-hyperon interaction, where g_{σ^*} is the coupling constant of the hyperons to the σ^* meson . For the cases $g_{\sigma^*}/g_{\sigma N} = 0.725$ and 0.75, we see a twin-star behavior, i.e. two neutron stars with identical masses but different radii are possible. Absolute stable strange hadronic matter ($g_{\sigma^*}/g_{\sigma N} = 1.0$) is characterized by rather small radii of about $R \approx 7$ km.

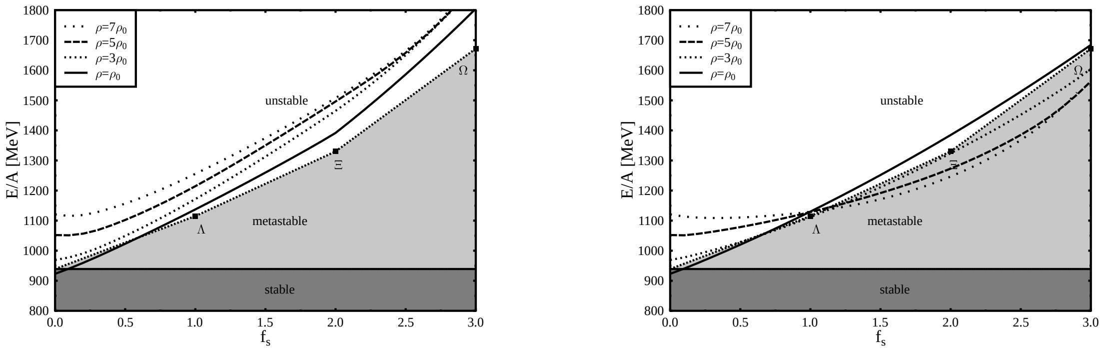

FIG. 2. Energy per particle of strange hadronic matter for different densities as a function of strangeness fraction f_s. The left picture corresponds to case 1, where the masses of the baryon resonances stay above the corresponding hyperon masses at high densities. The right picture represents case 2. Here the strange resonance masses drop below the octet masses. The stability of strange hadronic matter is not affected by this difference but the metastability. While in case 1 no metastable strange hadronic matter is predicted in case 2 strange hadronic matter at high density and net-strangeness can only decay by weak processes.

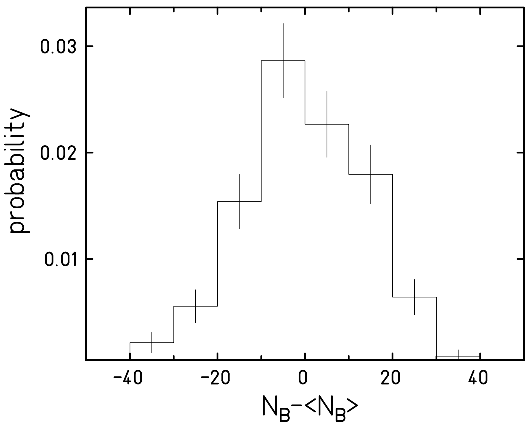

FIG. 3. Probability distribution for net-baryon number fluctuations at mid-rapidity within bins of one unit of rapidity width,for the Pb + Pb system at $\sqrt{s}_{NN} = 6.5$ TeV

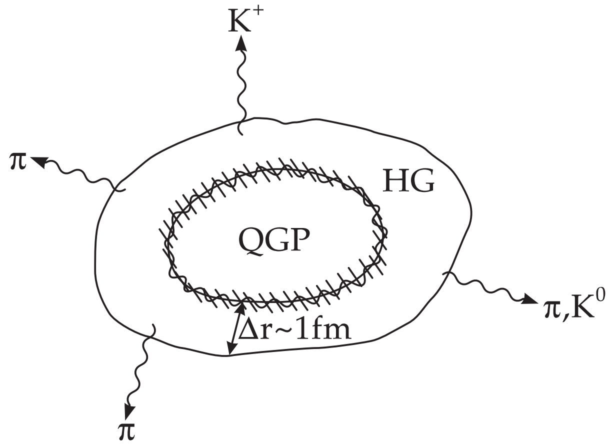

FIG. 4. Hadron gas surrounds the QGP at the phase transition. Particles evaporate from the hadronic region. New hadrons emerge out of the plasma by hadronization.