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Properties of Exotic Matter for Heavy Ion Searches

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Abstract. We examine the properties of both forms of strange matter, small lumps of strange quark matter (strangelets) and of strange hadronic matter (Metastable Exotic Multihypernuclear Objects: MEMOs) and their relevance for present and future heavy ion searches. The strong and weak decays are discussed separately to distinguish between long-lived and short-lived candidates where the former ones are detectable in present heavy ion experiments while the latter ones in future heavy ion experiments, respectively. We find some long-lived strangelet candidates which are highly negatively charged with a mass to charge ratio like a anti deuteron ($M/Z \approx -2$) but masses of A=10 to 16. We predict also many short-lived candidates, both in quark and in hadronic form, which can be highly charged. Purely hyperonic nuclei like the $\Xi\alpha$ ($2\Xi^0 2\Xi^-$) are bound and have a negative charge while carrying a positive baryon number. We demonstrate also that multiply charmed exotics (charmlets) might be bound and can be produced at future heavy ion colliders.

1. Introduction

Heavy ion collisions offer an unique possibility to study the properties of hitherto unknown domains of strongly interacting matter. New forms of matter might be possible [1] and formed during the collision. Strange particles are abundantly produced in central heavy ion collisions at relativistic energy. This opens up the tantalizing scenario of the formation of strange matter either by a quark-gluon plasma [2] or by the coalescence of hyperons [3]. After formation, the system cools down by evaporating baryons and pions via strong interactions (strong decay). At timescales of $10^{-10} - 10^{-5}$ s, the system can decay weakly by emitting a baryon or pion and losing one unit of strangeness (weak hadronic decay). Weak semileptonic decay (emission of electrons and antineutrinos) will appear then at a longer time, maybe 10^{-4} s after the reaction, as it is a three body decay [4]. Most heavy ion experiments searching for strange matter are sensitive to a lifetime of $\tau \approx 50 - 100$ ns [5], i.e. they can probably see strange matter which is stable against weak hadronic decay (long-lived candidates) but not the ones which are only stable against strong decay (short-lived candidates).

In any case, small baryon numbers are expected for the surviving finite multiply strange objects. Hence, shell effects will be important. Two different classes of strange nuggets are possible: either a bag consisting of up, down and strange quarks (strangelets) [6] or a 'nucleus' consisting of nucleons and many hyperons or even of hyperons alone (Metastable Exotic Multihypernuclear Objects, MEMOs) [7]. The former ones are calculated by using the MIT bag model with shell mode filling, the latter ones by using an extended relativistic mean field model. For an overview of the properties of strange matter for heavy ion physics see [8].

In the following two sections, we discuss the properties of both forms of strange matter and the possible long- and short-lived candidates referring to [9]. In the last section, we give an outlook for charmlets at future heavy ion colliders [10].

2. Long-lived candidates: strangelets

Up to now, strange quark matter and strangelets have been studied using the MIT bag model. Whether or not strangelets exist depends crucially on the value of the bag constant which is not known for such strange and big systems. For a bag constant of $B^{1/4} = 145$ MeV, the original value of the MIT bag model fit, strangelets are absolutely stable, for bag constants up to $B \approx 180$ MeV strangelets are metastable, i.e. they can decay by weak interactions, for higher bag constants, as suggested by QCD sum rules or fit to charmonium states, strangelets are unbound. So anything between absolutely stable and unbound is possible. Nevertheless, for the following arguments one needs only three basic assumptions:

(i) Strange quark matter is at least metastable.

(ii) There exists a local minimum for the total energy per baryon of strange quark matter at a finite strangeness fraction $f_s = |S|/A$.

(iii) The relativistic shell model can be used for strangelets.

With these assumptions we predict that there exists a valley of stability at low mass numbers and that these strangelets are highly negatively charged contrary to former findings.

The MIT bag model is used here as a guideline only. Fig. 1 shows the energy per baryon number of isospin symmetric strangelets as a function of f_s for $A \leq 40$ for

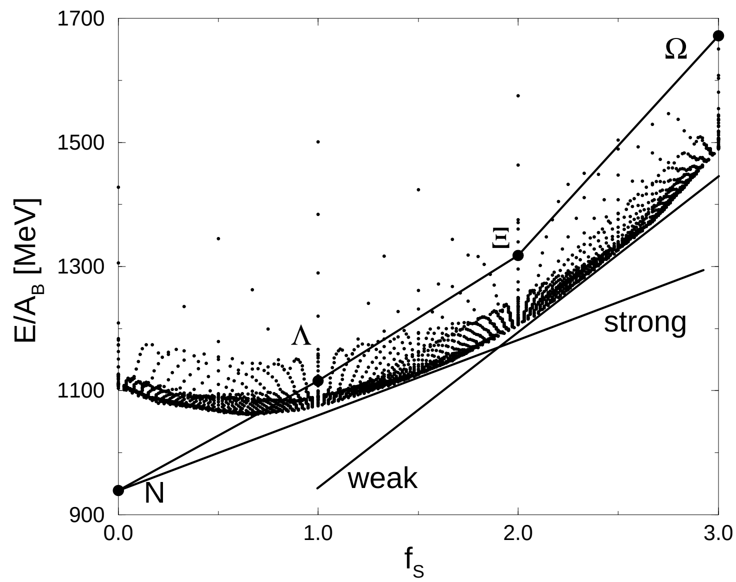

Figure 1. The energy per baryon E/A_B of isospin symmetric strangelets with $A_B \leq 40$ for a bag constant of $B^{1/4} = 170$ MeV versus the strangeness fraction f_s. The solid line connects the masses of nucleon, Λ, Ξ and Ω and stands for free baryon matter.

a bag parameter of $B^{1/4} = 170$ MeV. Now there are three different processes which will shift a strangelet emerging from a heavy ion collisions to a very high strangeness fraction. First, the strangelets sitting above the line drawn between the nucleon and the hyperon masses will decay to a mixture of nucleons and hyperons by strong interactions completely as this is energetically favored. Second, the strangelets located between that line and the tangent construction starting at the nucleon mass (denoted as strong) can decay strongly by emitting nucleons and hyperons. They will be shifted to a higher strangeness fraction until they reach the tangent point at $f_s \approx 1.4$. Third, weak nucleon decay can occur for the strangelets between the former tangent and the other tangent (denoted as weak) starting at the nucleon mass and $f_s = 1$ (as weak interaction change one unit of strangeness) [11]. For a strangelet with $f_s > 1$ the weak nucleon decay will enhance the strangeness fraction as

$$\Delta f_s = \frac{|S|-1}{A-1} - \frac{|S|}{A} = \frac{f_s - 1}{A-1} \quad . \tag{1}$$

Hence, strangelets surviving strong and weak nucleon decay can be sitting at a very high strangeness fraction of $f_s \approx 2.2$ which is the weak tangent point in Fig. 1. For isospin symmetric systems, this large strangeness fraction corresponds to a charge fraction of

$$\frac{Z}{A} = \frac{1}{2}(1 - f_s) = -0.55 \tag{2}$$

which indicates highly charged strange quark matter. This is contrary to the conventional picture that strangelets have a slightly positive charge-to-mass ratio which is the case for strange matter sitting in the minimum of the curve plotted in Fig. 1. But as pointed out before, the combined effect of strong and weak hadronic decay will shift strangelets emerging from a heavy ion collision to much higher values of f_s and therefore to highly negatively charged objects! This was indeed also seen in a dynamical calculation where hadrons were evaporated from a quark-gluon plasma droplet [12].

This simplified picture is only valid in bulk matter. For finite systems, which we are interested in, shell effects will be important. Already in Fig. 1 one sees that shell effects are at the order of 100 MeV per baryon number! Hence, we expect that strangelets with a closed shell can be very deeply bound. These 'magic' strangelets are most likely to be stable against strong and weak hadronic decay modes as their decay products have a much higher total mass. The single particle levels inside a cavity (as for the MIT bag model) or for ordinary nuclei or hypernuclei show the same order of levels for the lowest eigenstates. First, there is a $1s_{1/2}$ shell, then the $1p_{3/2}$ and the $1p_{1/2}$ shells follow. Due to relativistic effects, the spin-orbit splitting is quite sizable for nucleons. As the quarks are much lighter and relativistic effects are even more pronounced, the spin-orbit splitting for quarks is at the order of 100 MeV for very light bags, i.e. on a similar scale as the splitting between the s and p shell. One can put 6 quarks in the s-shell due to the color degree of freedom, then 12 quarks in the $1p_{3/2}$ shell and again 6 quarks in the $1p_{1/2}$ shell. The smallest and most pronounced magic numbers for quarks are then 6, 18, and 24 (the next one would be already at 42).

Studying isospin asymmetric systems reveals another important effect. The weak nucleon decay by emitting a proton carries away positive charge. Nevertheless, the neutron does not carry away negative charge if it is not accompanied by a π^-. But this decay is suppressed by the mass of the pion and the phase space of the three body final state. Therefore, a strangelet stable against weak nucleon decay is most likely to be negatively charged.

Let us look now for strangelets which have closed shells for all three quark species with a negative charge and a high strangeness fraction as these are the most likely candidates. The first magic strangelet is the quark alpha with 6 quarks of each quark species at $A = 6$ which has zero charge [13]. The magic strangelets with a high strangeness fraction and a negative charge are then at $A = 10$, $Z = -4$ (with 6 up, 6 down and 18 strange quarks), $A = 12$, $Z = -6$ (with 6 up, 6 down and 24 strange quarks), $A = 14$, $Z = -8$ (with 6 up, 18 down and 18 strange quarks), and $A = 16$, $Z = -10$ (with 6 up, 18 down and 24 strange quarks). One sees a correlation, that adding two units of baryon number decreases the charge by two. Note that these strangelets have a rather high and negative charge fraction of $Z/A \approx -0.5$ very similar to an antideuteron but with a much higher mass and charge! These strangelets constitute a valley of stability which is due to pronounced shell effects.

This picture holds, i.e. these candidates remain, also within an explicit calculation using the MIT bag model with shell mode filling [9]. We calculated the masses of strangelets with all possible combinations of up, down and strange quarks up to a baryon number of $A = 30$. Then we look for possible strong decays as the emission of baryons (p,n,$\Lambda, \Sigma^-, \Sigma^+, \Xi^-, \Xi^0, \Omega^-$) and mesons (pions and kaons) by calculating the mass difference between the strangelet and its possible decay products. For the strong interactions, we also allow for multiple hadron emission, like the strong decay of a strangelet via a neutron and a pion, and the complete evaporation to hadrons. For example, the strong proton decay $Q' \to Q + \mathrm{p}$ is checked by

$$M(A, S, Z) < M(A-1, S, Z-1) + m_p \tag{3}$$

where $M(A, S, Z)$ stands for the mass of the strangelet for a given baryon number, strangeness and charge. Afterwards we check for weak hadronic decay, the single emission of baryons and mesons within the same procedure simply by changing one unit of strangeness in the final products. The weak proton decay $Q' \to Q + \mathrm{p}$ is now checked by

$$M(A, S, Z) < M(A-1, S \pm 1, Z-1) + m_p \tag{4}$$

where we allow for both strangeness changing processes of $\Delta S = \pm 1$. This calculation has been done for several bag parameters. We choose a strange quark mass of $m_s = 150$ MeV if not otherwise stated. The value of $B^{1/4} = 145$ MeV and $m_s = 280$ MeV is taken from the original MIT bag model fit to the hadron masses.

The candidates which are stable against strong and weak hadronic decay are plotted in Fig. 2 in a scatter plot as a function of their baryon number and charge fraction. In all the parametrizations shown, we find the candidates at $A = 10$ with $Z = -4$, at $A = 12$ with $Z = -6$, and at $A = 16$ with $Z = -10$. We do not find any candidates for a bag parameter of $B^{1/4} = 180$ MeV or higher as strange quark matter starts to get unstable.

As expected and outlined before, the main strangelets stable against strong and weak decay are lying in the valley of stability and are highly negatively charged. This finding is contrary to the common belief that strangelets have a small positive charge and will have serious impact on present heavy ion searches for strange matter. In principle, these experiments are able to measure these highly charged candidates also, but have focussed so far on candidates with a small charge and/or a high mass [14, 15].

Note, that this calculation does not include colormagnetic and colorelectric interactions between the quarks. These interactions have been studied for the candidates at $A \leq 6$ in the s-shell only [16]. It was found, that the colormagnetic interaction is mainly repulsive and results in unbound systems. Especially the quark alpha was found to be unbound by 0.9 GeV. The only exception is the H dibaryon which is slightly bound

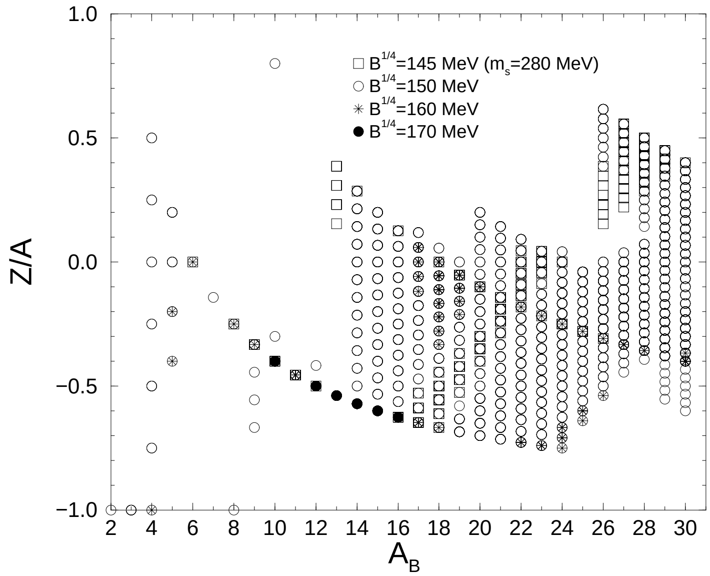

Figure 2. The charge fraction Z/A for long-lived strangelets, which are stable against strong and weak hadronic decay, for different choices of the bag parameter. The case for the original MIT bag model parameters ($B^{1/4} = 145$ MeV, $m_s = 280$ MeV) is also plotted.

when including the colormagnetic term. These corrections might also change then the overall picture at $A > 6$. But this will only be the case if the corrections are larger than the shell effects of about 100 MeV.

3. Short-lived candidates: MEMOs

Going back in the timescale of an heavy ion reaction as outlined in the introduction, one comes to the domain of short-lived strange matter which lives as short as the hyperons ($\tau \approx 10^{-10}$ s). Multiply strange nuclear systems can be formed by coalescence of hyperons after a heavy ion collision [3]. Indeed, we demonstrated within an extended relativistic mean field model that MEMOs might exist [7] and that they are even more bound than ordinary nuclei due to the strongly attractive interaction between the hyperons [17]. Nevertheless, the hyperon potentials are not high enough to overcome the mass difference to the nucleons. Hence, MEMOs can decay weakly on the timescale of the free hyperon weak decay and are short-lived. Of course, this picture will change if the hyperon-hyperon interaction is strong enough to create a local minimum in the total energy per baryon at large strangeness fraction which can not be ruled out by our present poor knowledge of multi hypernuclear properties.

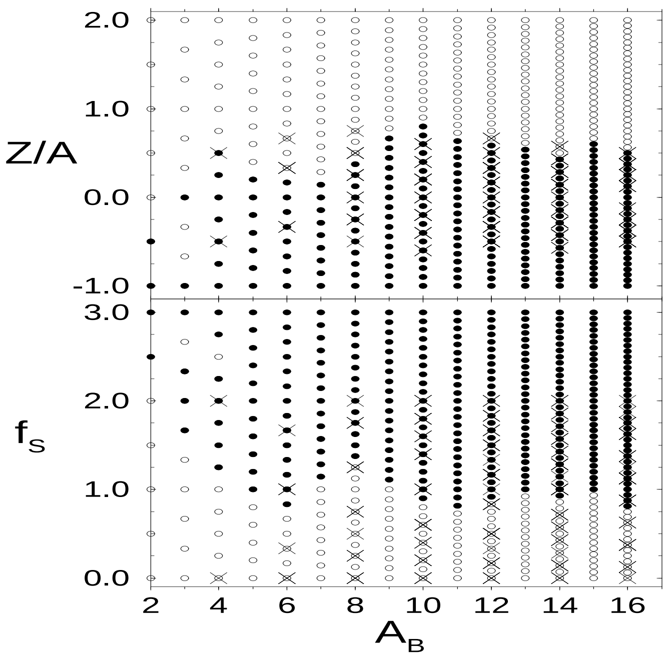

Figure 3. The strangeness per baryon f_s (lower part) and the charge fraction Z/A (upper part) as a function of the baryon number A_B for short-lived strangelets (dots) and unstable strangelets (open circles) for a bag constant of $B^{1/4} = 160$ MeV. The hadronic counterparts, MEMOs, are shown by crosses.

MEMOs have quite distinct properties, they can be negatively charged while carrying a positive baryon number due to the negatively charged hyperons, the Σ^- and the Ξ^-. There exists certain classes of MEMOs: Pauli-blocked systems consisting of $\{$p,n,$\Lambda, \Xi^0, \Xi^-\}$ baryons, mixed nucleon and hyperon systems of e.g. $\{$n,$\Sigma^-, \Xi^-\}$ or $\{$n,$\Lambda, \Xi^-\}$ baryons, and purely hyperonic matter of $\{\Lambda, \Xi^0, \Xi^-\}$ baryons. Very exotic candidates like the alpha particle in the hyperon world, the $\Xi\alpha$ with two Ξ^0 and two Ξ^-, have been predicted to be bound. Other light candidates are the combinations $\{2\mathrm{n}, 2\Lambda, 2\Xi^-\}$, $\{2\mathrm{p}, 2\Lambda, 2\Xi^0\}$, $\{2\Lambda, 2\Xi^0, 2\Xi^-\}$. Pauli-blocked candidates like ${}^{6}_{\Xi^0\Xi^0}$He and ${}^{7}_{\Lambda\Lambda\Xi^0}$He. are discussed in [18].

MEMOs compete with strangelets as they are of similar strangeness content. We calculated light MEMOs up to a closed p-shell and checked for metastability (strong decay). We analyzed the strangelet candidates without the weak hadronic decay, i.e. allowing for the strong decay only. The short-lived candidates for MEMOs and strangelets for a bag constant of $B^{1/4} = 160$ MeV are shown in Fig. 3 in a scatter plot as a function of strangeness fraction f_s, charge fraction Z/A and baryon number A.

As can be seen, there are many more short-lived candidates than long-lived. Light MEMOs can have very unusual charge fractions between $Z/A = \pm 0.6$ indicating a rich structure of strange hadronic matter. Strangelet candidates also cover a wide range of charge fraction but are mainly located at negative charge. This comes from the strong decay which shifts strangelets to higher strangeness fraction and to negative charge. There are MEMOs and strangelets with the same strangeness content and baryon number. Here, the energetically least favourable object can decay into the other via strong interactions. A strangelet created in a quark gluon plasma can then possibly decay into a MEMO. Or vice versa, MEMOs can coalesce from the hot and hyperon-rich zone of a relativistic heavy ion collision first and then they form a strangelet.

Presently, there are only experiments designed to look for long-lived composites with a lifetime of $\tau > 50$ ns except for the H dibaryon searches (see e.g. [14, 15]). Designing an experiment for short-lived composites is challenging but planned for future colliders [19] and can reveal the possibly rich structure of strange matter.

4. Outlook: charmlets

With the advent of heavy ion colliders, a new degree of freedom opens: charm. About ten charm-anticharm pairs are expected in a central collision of gold nuclei at $\sqrt{s} = 200$ GeV at the Relativistic Heavy Ion Collider (RHIC) in Brookhaven [20]. In the following we discuss briefly the properties of multiply charmed quark bags and their production possibility as outlined in [10].

It is known from charmonium spectra, that charm quarks have a quite large and attractive interactions which comes from the Coulomb-like colorelectric term of the one-gluon exchange potential. Indeed, the colorelectric term gets stronger with increasing quark mass while the colormagnetic term decreases with the quark mass. Note, that the overall one-gluon exchange in bulk is repulsive for massless quarks but gets attractive for heavy quarks.

Another effect is that the colormagnetic term for light quarks (here up, down and strange quarks) can be enhanced by the presence of charm quarks. As the light quarks do not need to be in a colorless state anymore, a preferred combination of color and spin can be found which has a more attractive colormagnetic interaction. For example, a system of one up, down and strange quark (uds) can now be in a color octet state for a charmlet like {udsccc}. Compared to a color singlet state (the Λ), the colormagnetic term can be more attractive by 110 MeV in the SU(3) flavor symmetric case [21] (note that the one-gluon exchange interaction energy is –14 for the flavor singlet, not –65/3 as given in the table by Jaffe).

Fig. 4 shows the area of bound charmed strange matter with respect to hadron emission by strong interactions as a function of strangeness fraction f_s and charm fraction $f_c = |C|/A$. The bag parameter has been chosen to be $B^{1/4} = 235$ MeV, i.e. pure strange matter is unbound. Still one finds a bound area of charmed strange matter which increases when increasing the strong coupling constant α_c for the one-gluon

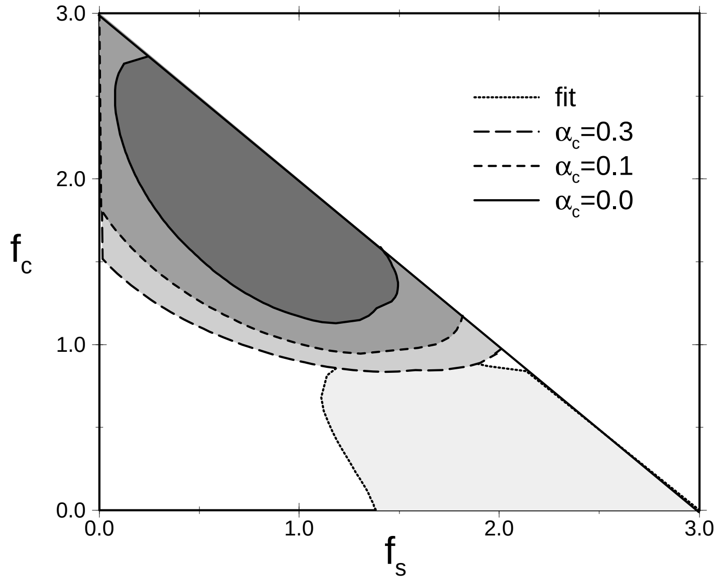

Figure 4. The area of bound strange and charmed matter as a function of strangeness fraction $f_s = |S|/A$ and charm fraction $f_c = |C|/A$ for various bag parameters. The case for a fit to the hadron spectra including charmed hadrons is also shown and is the shaded area at the lower right side.

exchange.

We modified the bag model to include heavy quarks by including the colorelectric term in the same way as the colormagnetic one and are able to fit the masses of the hadrons including charm on the level of a few percent. The area of bound charm strange matter for this case is also shown and denoted as fit. Nevertheless, the bag model gives such a high α_c coupling constant, i.e. larger than $\pi/8$, that the one-gluon exchange is a nonperturbative correction and the pressure for the massless quarks gets negative. Hence, the bag model parameters fitted to hadrons can not be applied for bulk matter, also for charmed matter.

Furthermore, we studied finite systems of multiply charmed exotics. The binding energy is calculated for colormagnetic and colorelectric interactions up to $A = 4$ (see [10] for details). We find, that charmlets can be bound by 100 to 200 MeV in SU(3) flavor symmetry. Their charges ranges from $Z = -4$ to $Z = +4$, again they can be highly charged. The production of charmlets is estimated by using a coalescence model and the momentum distribution of charm quarks using the HIJING model. The production rates for double charmed (about 10^{-2} per event) and maybe even for triple charmed (10^{-5} per event) are high enough to be seen at future experiments at RHIC. The main challenge here is again the lifetime of charmlets: as they are so heavy, they decay on the lifetime of the charmed hadrons, i.e. $\tau \approx 10^{-13}$ s. A silicon vertex detector is needed to possibly detect these charmed exotics which will be available in the future at the STAR detector at RHIC and at the detector ALICE at the Large Hadron Collider (LHC) in CERN [19].

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