

Detectability of strange matter in heavy ion experiments

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We discuss the properties of two distinct forms of hypothetical strange matter, small lumps of strange quark matter (strangelets) and of hyperon matter [metastable exotic multihypernuclear objects (MEMO's)], with special emphasis on their relevance for present and future heavy ion experiments. The masses of small strangelets up to $A_B=40$ are calculated using the MIT bag model with shell mode filling for various bag parameters. The strangelets are checked for possible strong and weak hadronic decays, also taking into account multiple hadron decays. It is found that strangelets which are stable against strong decay are most likely highly negatively charged, contrary to previous findings. Strangelets can be stable against weak hadronic decay but their masses and charges are still rather high. This has serious impact on the present high sensitivity searches in heavy ion experiments at the AGS and CERN facilities. On the other hand, highly charged MEMO's are predicted on the basis of an extended relativistic mean-field model. Those objects could be detected in future experiments searching for short-lived, rare composites. It is demonstrated that future experiments can be sensitive to a much wider variety of strangelets. [S0556-2813(97)02905-1]

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I. INTRODUCTION

One of the most fascinating aspects of modern particle physics is the phase transition from hadronic matter to a deconfined strong interacting plasma phase. New forms of matter might be possible [1] and formed during this transition. It has been proposed that the introduction of strange quarks into a plasma with two flavors could lower the Fermi energy of the system and thus the mass of the quark matter. If its mass is lower than the mass of hadronic (hyperonic) matter with the same strangeness fraction, it could not decay (completely) via strong interactions, which means that it would be metastable [2]. If its mass is even lower than non-strange nucleonic matter, quark matter would be the true ground state of nuclear matter [3].

The only way to produce a quark-gluon plasma in the laboratory is by collisions of heavy ions at ultrarelativistic energies. It has been shown that during the stage of coexistence of the two phases the abundantly produced strange and antistrange quarks are distributed asymmetrically between the quark and the hadron phase [4,5]. The strange quarks are enriched in the plasma, thus lowering its mass, whereas the antistrange quarks are found predominantly in the hadronic sector. Radiated pions and kaons carry away entropy and antistrangeness from the system, thus cooling it and charging the quark droplet with net strangeness. This mechanism can lead to the formation of a droplet of rather cold, strange quark matter; a strangelet.

On the other hand, even without a phase transition strangeness and antistrangeness are abundantly produced in heavy ion collisions. Therefore baryonic objects with a high strangeness fraction may be formed; so-called metastable exotic multihypernuclear objects (MEMO's) [6]. They are expected to be bound by energies up to $E_B/A \approx -22$ MeV and

to possess properties quite similar to those of strangelets [7].

There are several experiments under way at the AGS in Brookhaven using forward spectroscopy [8–11] or an open geometry [12] looking for long-lived charged strangelets ($\tau > 10-100$ ns) as a “smoking gun” for the formation of a quark-gluon plasma (QGP). The NEWMASS collaboration (experiment NA52) has recently reported new limits for producing long-lived strangelets ($\tau > 10^{-6}$ s) at the higher bombarding energy of the SPS facility at CERN [13]. The H dibaryon [14] with quark content ($uuddss$), is possibly the lightest strangelet. The search for the H dibaryon in the collisions of heavy ions opened a very active field of research [15]. Most recently experiment E888 at AGS set new limits on the production of the H dibaryon for lifetimes of $\tau > 1$ ns [16]. Also, quite recently, experiment E896 has been approved to look for short-lived H dibaryons in the forward direction [17] sensitive to lifetimes of $\tau \approx 10^{-11}$ s.

Simple coalescence estimates give production probabilities of strange clusters of the order of $10^{3-A_B-|S|}$, where S denotes the strangeness and A_B the baryon number of the cluster [2,18]. Hence, small clusters with $A_B + |S| \leq r + 3$, where r is the sensitivity of the apparatus (presently $r \leq 12$), are most favored for detection. Therefore, if strangelets are formed due to this scenario, baryon numbers of $A_B \leq 12$ are expected. Dynamical calculations with nonequilibrium particle emission suggest also $A_B \approx 10-30$ [5,19] for initial entropies corresponding to AGS and SPS bombarding energies. At higher energy, at the RHIC and LHC colliders, strangelet distillation still works but lower mass numbers of $A < 10$ are expected [20], which might be detectable with the ALICE detector at the LHC [21]. In the following we examine the properties of both forms of strange matter for this mass range, its decay properties, and its detectability for recent and future heavy ion experiments.

II. STRANGELETS

In the present investigation, strangelets are treated as non-interacting fermions within the MIT bag model, filling up the bag with exact single-particle Dirac states following [22,4]. We point out that the simple mass formula of Berger and Jaffe [23] or Fermi gas models including a curvature term [24] are not appropriate for describing the low mass strangelets of interest here as shell effects get crucial for their stability. Similar shell model calculations have been performed recently [25]. The authors consider strong *and* weak decay by nucleon and hyperon emission together and conclude that stable low mass strangelets ($A_B < 100$) exist which have a low (and positive) charge to mass ratio. A detailed inspection of Fig. 2 in [25] shows that strangelets with mass number $A_B = 10$ and $Z = -4$ or $Z = 7$ exist which have a rather high mass to charge ratio contrary to their conclusion. We point out that the procedure of their work is to start in the *absolute minimum* for a given baryon number and then to look for its stability against possible weak and strong decays. Although this investigation is very important, we believe that their finding is not fully consistent with the initial condition of possible strangelet production in relativistic heavy ion collisions. Initially, all kinds of strangelets might be produced with different quark contents. They are decaying first by strong decays (strong hadron emission) and afterwards, if surviving, by weak hadronic decays. In Ref. [25] the authors start only with those strangelets at their minimum value in E/A for a given baryon number A and study the stability of those candidates only. However, it is only the slowest decay, the weak leptonic decay, which ultimately drives a strangelet to its minimum value. For the purpose of detecting strangelets the direct strong decays and weak hadronic decays are now relevant, thus giving rise to a much wider class of possible candidates to be observed (see also the discussion below). In the following we recalculate strangelets for low masses and now check separately for strong and weak hadronic decay starting with all possible combinations and allowing for all kinds of decays.

The MIT bag model used includes only the quark kinetic energy, the Pauli principle, and confinement. It should not be taken too seriously as it effectively models the features of the QCD at the confinement energy scale. It cannot fix the overall energy scale due to the unambiguity of the bag constant B , which decides whether or not strange quark matter is stable. It does, however, illustrate potentially interesting effects as shell closure effects. Infinite strange quark matter, treated as a gas of noninteracting quarks, is absolutely stable for bag constants of $B^{1/4} \approx 145$ MeV. For bag constants between $B^{1/4} \approx 150 - 200$ MeV strange quark matter is metastable, i.e., it can decay weakly depending on its strangeness content. For larger bag constants strange quark matter is unstable and decays completely via strong reactions into hadrons. Hence, we will discuss our results for various choices of the bag constant, preferably for the case of metastability.

The Dirac equation with a Bogolyubov-type boundary condition reads

$$j_{l_\kappa}(pR) = -\text{sgn}(\kappa) \frac{p}{E + m_i} j_{l_{-\kappa}}(pR) \quad (1)$$

with

$$p = \frac{\omega_{\kappa,\alpha}^i}{R} \quad (2)$$

and the energy

$$E_{\kappa,\alpha}^i = \left[\left(\frac{\omega_{\kappa,\alpha}^i}{R} \right)^2 + m_i^2 \right]^{1/2}. \quad (3)$$

Here m_i denotes the mass of the quark of flavor i . We choose $m_u = m_d = 0$ MeV and $m_s = 150$ MeV. R is the radius of the bag, κ the angular momentum quantum number, and α labels the eigenvalues in the quantum state κ . The total energy is calculated by summing the lowest occupied single particle energies and adding the phenomenological bag energy BV with the volume of the bag V , which has to be chosen such that the inside pressure of the quarks is in equilibrium with the outside vacuum pressure. The term

$$E_{\text{Cb}} = \frac{1}{15} \alpha \frac{(2A_u - A_d - A_s)^2}{R} \quad (4)$$

with the quark number A_i of flavor i accounts for Coulomb corrections. Pressure equilibrium is achieved by minimizing the total energy with respect to the bag radius. This exact result has recently been approximated by curvature contributions to the mass of strangelets [24].

We calculate the binding energy of strangelets for an *arbitrary* number of u , d , and s quarks with $A_B \leq 16$ for a given bag parameter. Afterwards we look for possible strong decays, i.e., single baryon $\{n, p, \Lambda, \Sigma^{+,-}, \Xi^{0,-}, \Omega^-\}$ emission and mesonic $\{\pi^{+,-}, K^{+,-}, K^0, \bar{K}^0\}$ decays (note that kaon decays do not occur in our calculation) extending the ideas already presented in [2] to finite size configuration. Note that for smaller strangelets shell effects are therefore of crucial importance. For example a strong neutron decay of a strangelet

$$Q(A_B, S, Z) \rightarrow Q(A_B - 1, S, Z) + n \quad (5)$$

is allowed if the energy balance of the corresponding reaction is

$$E(A_B, S, Z) > E'(A_B - 1, S, Z) + m_n, \quad (6)$$

where E stands for the total energy of a strangelet. Multiple hadron emission is implemented by considering the combination of hadrons for a given charge $f_z = Z/A_B$ and strangeness fraction $f_s = |S|/A_B$ with the lowest total mass. The possible area for strangelets ($f_s \geq 0$, $f_z \geq -1$, and $f_s + f_z \leq 2$) is divided into nine areas of (free) hadronic matter where seven areas are covered by the possible metastable combinations of three different baryon species as given in Table IV of Ref. [6]. The remaining two are $\{\pi^+ p \Sigma^+\}$ and $\{\pi^- n \Sigma^-\}$ matter. Multiple hadron emission is allowed if

$$E(f_s, f_z) > H(f_s, f_z), \quad (7)$$

where $H(f_s, f_z)$ stands for the lowest mass of hadrons for a given strangeness and charge fraction. Note that the baryon number does not enter here as it is a conserved quantity. In addition, we checked also for the fission of a strangelet into

TABLE I. Candidates of small MEMO's for filled s -shell states. Here we only consider $(pn\Lambda\Xi^0\Xi^-)$ baryons. The double hypernucleus ${}^6_{\Lambda\Lambda}\text{He}$ which was already seen [31] belongs also to this class. Candidates involving Σ baryons are $2(n\Sigma^-\Xi^-)$ and $2(p\Sigma^+\Xi^0)$.

	$2(\Xi^0\Xi^-)$	$2(\Lambda\Xi^0\Xi^-)$	$2(n\Lambda\Xi^-)$	$2(p\Lambda\Xi^0)$	$2(n\Lambda\Xi^0\Xi^-)$	$2(p\Lambda\Xi^0\Xi^-)$	$2(pn\Lambda\Xi^-)$	$2(pn\Lambda\Xi^0)$	$2(pn\Lambda\Xi^0\Xi^-)$
A	4	6	6	6	8	8	8	8	10
Z	-2	-2	-2	+2	-2	0	0	+2	0
S	8	10	6	6	10	10	6	6	10

another strangelet and an arbitrary number of hadrons while conserving charge, strangeness, and baryon number:

$$E(A_B, S, Z) > E'(A'_B, S', Z') + (A_B - A'_B)H(f'_s, f'_z) \quad (8)$$

by three combined loops where $f'_s = (S - S') / (A_B - A'_B)$ and $f'_z = (Z - Z') / (A_B - A'_B)$. This allows, for example, for a combined strong decay of a strangelet emitting a neutron and a pion. It might well be that single hadron decay is not possible while multiple hadron decay is due to shell effects.

Note that this procedure is different from the one used in [25] where mesonic decays and multiple hadron emissions have not been implemented. Nevertheless, the authors allowed also for weak neutron decay which we will discuss later in a wider class (Sec. V) separately.

A strangelet is called *metastable* in the following if its energy lies under the corresponding (free) hadronic matter of the same baryon number, charge, and strangeness, and if it cannot emit a single hadron or multiple hadrons by strong processes as described above. A metastable strangelet can then only decay via weak decays such as the nonleptonic (hadronic) decays. Strangelets which are stable against strong decay but unstable against nonleptonic weak decay will be denoted in the following as *short lived* (see Sec. IV). Estimates of this weak decay rate range from $\tau_{\text{nl}} \approx 10^{-6} - 10^{-5}$ s [26] and $\tau_{\text{nl}} \approx 3 \times 10^{-7}$ s [27] to anything between $\tau_{\text{nl}} = 10^{-5} - 10^{-10}$ s [28]. These estimates were calculated for the process $u + s \leftrightarrow d + s$ in infinite matter and depend sensitively on the difference of the d - and s -quark chemical potentials. For the lightest strangelet, the H dibaryon with quark content $(uuddss)$, one gets a lifetime of about $\tau_{\text{nl}} = 10^{-8} - 10^{-6}$ s depending on its mass [29].

Weak nonleptonic or hadronic decay is implemented by the hadronic decay processes mentioned above allowing for strangeness violation of $\Delta S = \pm 1$. A strangelet stable against all these weak decays can then only decay via leptonic decay of the form $s \leftrightarrow ue^- \bar{\nu}_e$ and $d \leftrightarrow ue^- \bar{\nu}_e$ or via radiative decays through $us \leftrightarrow ud\gamma$. These decay modes are suppressed by the three-body space of the leptonic decay or by the electromagnetic coupling constant of the radiative decay compared to the nonleptonic decays. Both decay modes are supposed to yield similar lifetimes [23] which are then higher than the nonleptonic ones. A strangelet stable with respect to weak hadronic decay but unstable with respect to weak leptonic or radiative decay is called *long lived* (see Sec. V). It lives on the time scale of the weak leptonic decay $\tau = \tau_l$, which has been estimated to be $\tau_l = 10^{-4} - 10^{-5}$ s in infinite matter [2,30,26]. If a strangelet demonstrates to be stable against these decays also, then it can only decay by higher order weak decay ($\Delta S = \pm 2$), which results in lifetimes of days

(see, e.g., the estimate of the $\Delta S = \pm 2$ decay of the H dibaryon [29]). In this case the strangelet would be super long lived.

III. MEMOS

The (multi)strange baryonic objects are treated within the framework of an extended relativistic mean-field theory. Although the application of the mean-field approximation seems doubtful for small systems, it has been shown that the model furnishes quite remarkable results for nuclei with baryon numbers as small as $A_B = 4$ [6]. In addition to the well-known σ and ω meson, strange scalar and vector mesons are introduced; the σ^* and the ϕ meson ($m_{\sigma^*} = 975$ MeV, $m_\phi = 1020$ MeV). The latter couple to strangeness only, thus incorporating the seemingly strong attractive hyperon-hyperon interaction [7].

The vector coupling constants are chosen according to SU(6) symmetry, the scalar coupling constants are fixed to hypernuclear data. Within this model, MEMO's consisting of combinations of $\{p, n, \Lambda, \Xi^0, \Xi^-\}$ baryons demonstrate that they are metastable due to Pauli-blocking effects. They possess binding energies per baryon of $E_B/A_B \approx -22$ MeV, strangeness per baryon of up to $f_s \approx 2$, unusual charge per baryon of $f_z \approx -0.5$ to zero while carrying positive baryon number and baryon densities up to 2.5–3 times that of ordinary nuclei. Metastable clusters of purely hyperonic matter $\{\Lambda, \Xi^0, \Xi^-\}$ have been also predicted [7].

In the following we extend the calculation of [7] to small mass numbers relevant for heavy ion physics. We calculate even combinations of $\{n, p, \Lambda, \Xi^0, \Xi^-\}$ baryons up to a filled s and p shell, i.e., eight baryons of each using model 2 of Ref. [7]. Out of these 3125 combinations we have found 298 configurations, which are bound and metastable. The two smallest systems for $A_B = 4$ are ${}^4\text{He}$ and the corresponding Ξ system, i.e., two Ξ^- and two Ξ^0 . The next heavier ones ($A_B = 6$) are the combinations ${}^6_{\Lambda\Lambda}\text{He}$, $\{2n, 2\Lambda, 2\Xi^-\}$, $\{2p, 2\Lambda, 2\Xi^0\}$, and $\{2\Lambda, 2\Xi^0, 2\Xi^-\}$. Pure Λ or neutron matter is not bound in this model. Nevertheless, we have found some very loosely bound $\{\Xi^0, \Xi^-\}$ systems. The properties of these small MEMO's are summarized in Table I. Other light candidates are discussed extensively in [7], such as ${}^6_{\Xi^0}\text{He}$ and ${}^7_{\Lambda\Lambda}\text{He}$. Note that the double Λ hypernucleus ${}^6_{\Lambda\Lambda}\text{He}$ has already been seen [31], but the event cannot be reinvestigated as the documents disappeared. A discussion about the well-established double hypernucleus ${}^{10}_{\Lambda\Lambda}\text{Be}$ and the hyperon-hyperon interactions can be found in [32].

The binding energy per baryon for these small systems is not more than -16 MeV for baryon numbers less than $A_B \approx 16$. For higher baryon numbers we have found an approximately linear decrease of the binding energy. This fact

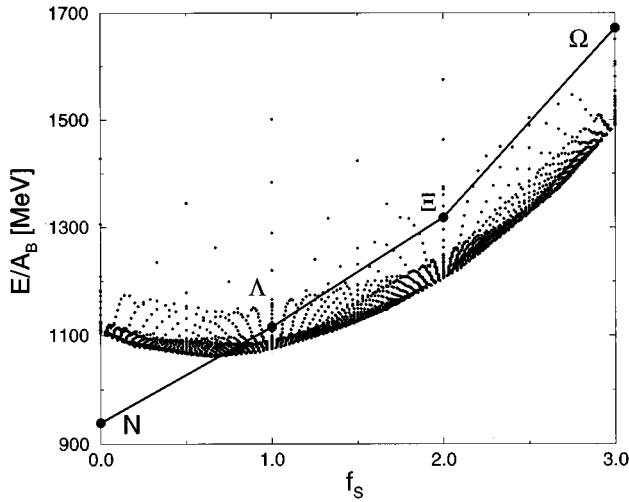


FIG. 1. The energy per baryon E/A_B of all possible strangelets with $A_B \leq 40$ and $N_u = N_d$ for a bag constant of $B^{1/4} = 170$ MeV versus the strangeness fraction f_s . The solid line connects the masses of nucleon Λ , Ξ and Ω and stands for free baryon matter.

is already known from ordinary nuclei. The less bound combinations found are mainly combinations of Ξ^- and Ξ^0 , i.e., pure Ξ matter with only $E_B/A_B \approx -2$ MeV.

MEMO's decay by weak mesonic or nonmesonic decay in analogy to hypernuclear weak decay. The nonmesonic decays of the type $\Lambda N \rightarrow NN$, $\Xi N, \Lambda \Lambda \rightarrow \Lambda N, \Sigma N, \dots$, will play an important role [7]. Due to the high mass differences involved in these decays (about 180–200 MeV) the process is not hindered by Pauli-blocking effects. The first process has been seen in the weak decay of hypernuclei, which decay on the time scale of the lifetime of the Λ , i.e., $\tau_w \approx \tau_\Lambda \approx 10^{-10}$ s. Also the mesonic decay $\Lambda \rightarrow N\pi$ yields similar lifetimes for very light hypernuclei (see, e.g., [33]). We expect that MEMO's will live then on the same time scale, $\tau_{\text{MEMO}} \approx \tau_w$, irrespective of their strangeness content, if they are not bound deeper to create a minimum in the *total* energy at finite strangeness, as is the case for strangelets.

IV. SHORT-LIVED STRANGE MATTER

In the following we will discuss the properties of light strangelets and compare them to those of MEMO's. Figure 1 shows the energy per baryon of all possible quark bags with a baryon number up to $A_B = 40$ as a function of the strangeness per baryon $f_s = |S|/A_B$ for a bag constant of $B^{1/4} = 170$ MeV. We only show bags with equal numbers of up and down quarks. The energetically most favorable combinations always have the same number of up and down quarks since they occupy the same single-particle levels. The Coulomb correction is in the order of some MeV and thus not important in our case.

The solid line connects the masses of the nucleon Λ , Ξ , and Ω . As a first cut for potential candidates, quark bags lying above this line can (and probably will) *completely* decay via strong processes, those lying beneath the line will lead in principle to metastable strangelets. The important point to note here is that any strangelet initially formed with a mass under this line might decay to another strangelet changing baryon number, strangeness, and charge but cannot

decay to a pure hadronic state anymore, simply because of energy conservation. It is remarkable that there exists a quite sharp lower limit of the binding energies: already for bags with $A_B \approx 40$ infinite quark matter is quite a good approximation.

It is clear that this simple version of the MIT bag model is not able to reproduce the hadron spectrum. The masses of the nucleon Λ and Ξ are overestimated, the mass of the Ω is underestimated. To provide a better description of the hadron masses, one-gluon exchange corrections and a zero-point energy term of the form Z_0/R must be taken into account [34]. Strangelets with s states only up to a mass number of $A_B = 6$ have been studied extensively in [35] taking into account colormagnetic and colorelectric corrections. No strangelet has been found to be metastable with the exception of the H dibaryon with $A_B = 2$, $S = -2$, and $Z = 0$. This finding has been confirmed in [22]. Up to now, these corrections can only be applied to quarks sitting in s states. We are not aware of any attempt including these terms for higher shell states also.

For a bag constant of $B^{1/4} = 145$ MeV (not shown) almost all bags are lighter than the corresponding hyperonic matter. After subsequent strong and weak processes the final resulting strangelets thus should have long enough lifetimes to be detectable. Nevertheless, for the situation depicted in Fig. 1 ($B^{1/4} = 170$ MeV) strangelets with a strangeness fraction less than $f_s \approx 0.6$ are less bound than corresponding hyperonic matter (solid line) and hence, they can completely decay strongly into hyperons and nucleons and are not detectable in heavy ion searches. For intermediate strangeness fractions

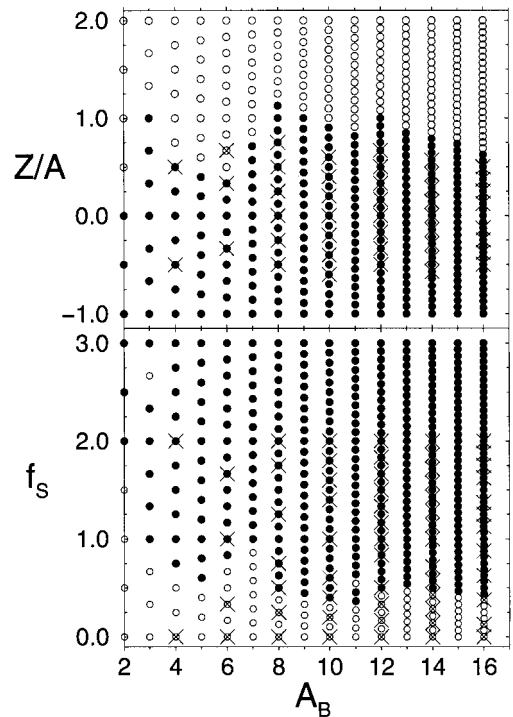


FIG. 2. The strangeness per baryon f_s (lower part) and the charge fraction Z/A (upper part) as a function of the baryon number A_B for short-lived strangelets (dots), unstable strangelets (open circles) for a bag constant of $B^{1/4} = 150$ MeV. The hadronic counterpart, MEMO's, are shown by crosses.

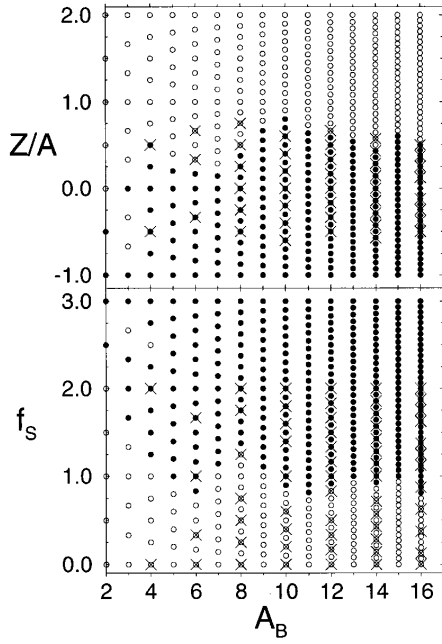


FIG. 3. The same as Fig. 2 for a bag constant of $B^{1/4}=160$ MeV.

only bags with rather large baryon number then can be stable with respect to strong decay. This means that there exists a minimum critical strangeness fraction for which strangelets exist which will depend of course on the bag parameter and baryon number of the strangelet.

The dependence on the baryon number and the bag parameter is illustrated in the following. We have calculated the mass of all possible bags with $A_B \leq 16$, which are most interesting for heavy ion experiments, but with arbitrary numbers of up, down, and strange quarks and various bag parameters. As already stated, we define metastable strangelets as those who are stable against strong decay, while unstable strangelets are not.

Figures 2–4 show the strangeness and the charge fraction versus the baryon number for bag parameters of $B^{1/4}=150$, 160, and 170 MeV, respectively. Dots stand for metastable, open circles for unstable bags, and crosses for small MEMO's. For higher bag parameters, one sees less candidates of metastable strangelets and they are shifted to higher strangeness, higher masses and, more important, to negative charges.

For $B^{1/4}=150$ MeV shown in Fig. 2, metastable strangelets exist for a wide range of charge ($|Z/A| \leq 1$) and strangeness fraction. Only for quite low strangeness fraction $f_s < 0.4$, comparable to the ones of light double Λ hypernuclei, are strangelets unstable with respect to strong decay. This situation changes when looking at the case of $B^{1/4}=160$ MeV depicted in Fig. 3. Nearly no strangelet appears to be metastable with $f_s < 1$ or $Z/A > 0.6$ in the mass range considered here as they are subject to fissioning into nucleons and hyperons. Especially for light systems, the maximum charge is $Z = +2$. This trend is getting even more pronounced for $B^{1/4}=170$ MeV as can be seen in Fig. 4. Only a few of the very light strangelets for $A \leq 6$ remain to be metastable. They are highly negatively charged $Z/A_B < -0.5$ and have a very high strangeness fraction of

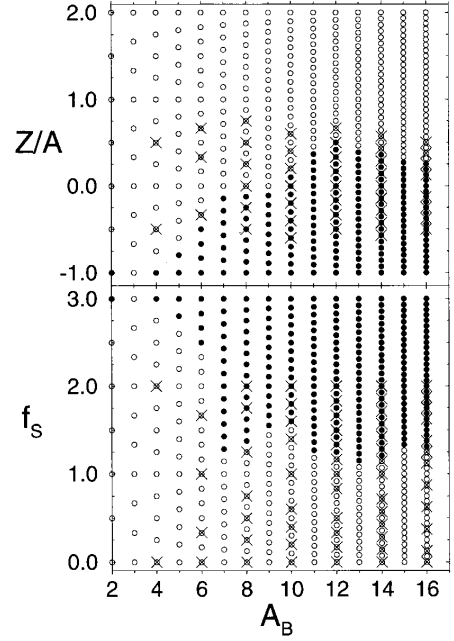


FIG. 4. The same as Fig. 2 for a bag constant of $B^{1/4}=170$ MeV.

$f_s > 2.5$. For higher baryon numbers ($6 < A_B < 16$) no metastable strangelet exists for $f_s < 1$ and $Z/A > 0.5$. Most of the metastable strangelets are found to be highly negatively charged which is contrary to the conclusion drawn in [25]. Here the authors start their consideration in the minimum for a given baryon number due to flavor equilibrium. Nevertheless, a hot strangelet formed in heavy ion collision does not start decaying with flavor changing decays but with strong decays. Our results demonstrate that the cascade of strong decays of a strangelet do not stop in an absolute minimum but in a region allowing for highly charged strangelets.

The hadronic counterpart, MEMO's, are also shown as crosses in Figs. 2–4 for comparison. There are candidates which are highly positively and negatively charged ($-0.6 < Z/A < +0.7$). MEMO's show up where strangelets are unstable and vice versa. There is also a region in the $f_s - Z/A$ plane where both MEMO's and strangelets appear. Here, the energetically least favorable object will decay into the other. A strangelet created in a quark-gluon plasma can then possibly decay into a MEMO via strong interactions. On the other side, MEMO's can coalesce from the hot and hyperon-rich zone of a relativistic heavy ion collision first and form a strangelet which is then detected. The density distributions within both objects resemble each other closely. Transition matrix elements are to first approximation proportional to the overlap of both wave functions. Therefore, the energetically least favorable state may be a doorway state, decaying rapidly into the favorable state. In [36] the decay for a double hypernucleus to a H dibaryon was estimated to happen at $\tau = 10^{-18} - 10^{-20}$ s if the mass of the H dibaryon is close to $2m_\Lambda$. We expect similar time scales for the transition of one form of strange matter to the other if the masses are similar. Of course, this is speculation and cannot be clarified by our present knowledge of strange matter.

V. LONG-LIVED STRANGE MATTER

The properties of strange matter as discussed in the previous section apply for systems living on the time scale of weak interactions, i.e., $\tau_{\text{MEMO}} \approx 10^{-10}$ s and $\tau_{\text{nl}} = 10^{-5} - 10^{-10}$ s. Present experiments are looking for long-lived strangelets $\tau_{\text{exp}} > 10^{-6} - 10^{-8}$ s. They are not able to see MEMO's and possibly most of the strangelet candidates, if the nonleptonic decay is too fast. Nevertheless, it is known that the leptonic decay gives longer lifetimes due to the reduced phase space of the three body decay [2,30,26]. As $\tau_l = 10^{-4} - 10^{-5}$ s in infinite matter, the present experiments are sensitive to strangelets which are stable against weak nonleptonic decay. In the following we study all possible weak hadronic decay for the metastable strangelets such as weak pion, kaon, proton, neutron, Λ , $\Sigma^{+,-}$, $\Xi^{0,-}$, Ω^- decays.

For example, a weak neutron decay of a strangelet (which turns out to be one of the most dominant decay modes)

$$Q(A_B, S, Z) \rightarrow Q(A_B - 1, S - 1, Z) + n \quad (9)$$

happens if the energy balance of the corresponding reaction reads

$$E(A_B, S, Z) > E'(A_B - 1, S - 1, Z) + m_n, \quad (10)$$

where E stands for the total energy of a strangelet. Note that weak neutron decay drives a strangelet to lower strangeness fraction only if the initial strangeness content of the strangelet is $f_s < 1$, but to *higher* strangeness fraction for $f_s > 1$ as the obtained shift in the strangeness content is easily found to read $\Delta f_s = (f_s - 1)/(A - 1)$ and, thus, gets positive.

Multiple hadron emission and fission to another strangelet is also checked in analogy to the strong decays described in Sec. II but now with $\Delta S = \pm 1$. In addition we add the case with $B^{1/4} = 145$ MeV, $m_s = 280$ MeV which are the original MIT values [34].

We find that the strangelets mainly decay via weak pion or baryon emission. In a very few cases weak multiple hadron emission is possible. We have also checked the case $B^{1/4} = 180$ MeV but none of the strangelets are stable with respect to weak hadronic decay. Nevertheless, for the other cases we found some candidates. The remaining long-lived strangelets are shown in Fig. 5. Surprisingly, we find some long-lived strangelets with quite low mass numbers for all cases considered here. They are lying on a chain which starts from the triple magic strangelet ($6u6d6s$) where all quarks fill up the $1s$ state—due to its symmetry character it is also called the quark α [37]. The “valley of stability” starting at the quark α continues then towards negative charges by add-

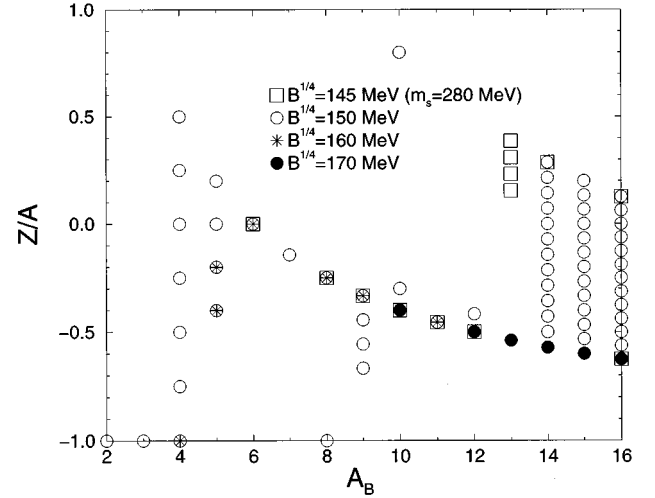


FIG. 5. The charge fraction Z/A for long-lived strangelets, which are stable against nonleptonic weak decay, for different choices of the bag parameter. The case for the original MIT parameters ($B^{1/4} = 145$ MeV, $m_s = 280$ MeV) is also shown.

ing one unit of negative charge when going to a higher mass number. The reason for the stability line is a pronounced shell effect. These strangelets mainly have a closed s shell for the u quarks and a closed s , $p3/2$, or $p1/2$ shell for the s quarks. Then the d quarks added result in the chain seen in Fig. 5. This rule is less stringent for the case $B^{1/4} = 150$ MeV as many strangelets demonstrate to be long lived. For the case $B^{1/4} = 145$ MeV strangelets with a closed $p3/2$ shell for the u quarks also appear resulting in the positively charged candidates at $A_B = 13, 14$. Due to the higher strange quark mass of $m_s = 280$ MeV strangelets with high strangeness fraction are less stable and only the $1s$ shell for the s quarks are filled here. Also for $B^{1/4} = 150$ MeV there are several cases with a filled $p3/2$ shell for the u quarks, such as $A = 10$, $Z = +8$ ($18u6d6s$). The candidates shown for $A_B \leq 6$ have to be taken with some care as colormagnetic and colorelectric terms are not included in the present investigation. If included, they appear to be not stable at all [35,22] and can decay to ordinary hadrons via strong interactions. The lightest long-lived candidates for $A_B \geq 6$ are summarized in Table II. We add also the candidates which can only decay by weak multiple hadron emission as the decay is suppressed by phase space. Actually, we find only one additional strangelet of this type.

The most promising candidates are for $A_B = 10$, $Z = -4$, for $A_B = 12$, $Z = -6$, and for $A_B = 16$, $Z = -10$, which appear in all the cases studied here. Note that the first candidate is

TABLE II. Some candidates for long-lived strangelets with $A \geq 6$ which are stable against weak nonleptonic decay. Case I: $B^{1/4} = 145$ MeV, $m_s = 280$ MeV; case II: $B^{1/4} = 150$ MeV, $m_s = 150$ MeV; case III: $B^{1/4} = 160$ MeV, $m_s = 150$ MeV; case IV: $B^{1/4} = 170$ MeV, $m_s = 150$ MeV.

A	6	7	8	8	9	9	10	10	11	12	12	13	13
Z	0	-1	-8, -3 ^a	-2	-4, -5, -6	-3	-4	-3, +8	-5	-6	-5	-7	+2, 3, 4, 5
case	I-III	II	II	I-III	II	I-III	I-IV	II	I-III	I-IV	II	II-IV	I

^aThis candidate can decay via a weak multiple decay.

triple magic ($6u6d18s$ or $6u18d6s$).

The question of why mainly *negatively* charged strangelets appear to be stable against weak hadronic decay (and also already, to a somewhat lesser extent, against strong hadronic decay) arises. The reason is twofold. (a) Strangelets with a rather low strangeness fraction (and correspondingly positive charges) are decaying strongly by fissioning into nucleons and hyperons as discussed in the last section. As $Z/A > 0$ follows model independently from $f_s < 1$ for isospin saturated matter this will always happen if there is a minimum energy for strangelets at high strangeness fraction. Still, in addition, any strong decay by emitting a neutron [see Eq. (5)] (or a proton) will enhance the relative strangeness content of the remaining strangelet by an amount $\Delta f_s = f_s / (A - 1) > 0$ shifting it to a higher strangeness fraction f_s which thus can exceed 1. (b) It is easier for positively charged strangelets to decay via, e.g., weak proton decay. The charge reverse reaction would be a weak neutron decay accompanied by π^- emission which is less favorable. In general, (the dominant) weak nucleon decay [see Eq. (9)] will drive strangelets with $f_s > 1$ to a higher strangeness fraction and hence to higher negative Z/A ratios.

These two reasons should be generally valid if the masses of finite droplets of SQM follow a distribution close to that shown in Fig. 1. Although calculated within the MIT bag model, we believe that a similar distribution would, in principle, also show up when applying other bag models (and fixing the same overall energy scale within the appropriate parameters). In this sense our major result, i.e., the tendency of short-lived and long-lived metastable strangelets to exist preferably as a slightly or highly negative exotic state of matter, should be seen to be valid on more general grounds.

We emphasize again that a long-lived strangelet is trapped in a deep local, but not global, minimum where it can only decay further via weak semileptonic and radiative decay. We have checked the stability with respect to these two decays. In only two cases did a strangelet demonstrate to be stable against these decays: this is the quark α for $B^{1/4} = 150$ MeV and $B^{1/4} = 160$ MeV, and the strangelet ($6u6d3s$) with $A_B = 5$, $Z = +1$ for $B^{1/4} = 150$ MeV. They would live on the timescale of days as only weak decays with $\Delta S = \pm 2$ are allowed. Due to its nonzero charge only the latter would be visible in a heavy ion experiment. Nevertheless, the colormagnetic term is repulsive for these multiquark states. For the quark α , the colormagnetic term is about $+150$ MeV/A without symmetry-breaking effects, i.e., half the mass splitting of the nucleon and Δ . Therefore, the colormagnetic interaction would shift the mass above the mass of 6Λ 's. Then, the quark α is simply a resonance.

It is interesting to study now the detectability of these long-lived strangelets in heavy ion collisions especially for $A_B > 6$. All recent experiments searching for strangelets are sensitive to composites with lifetimes of $\tau > 10 - 100$ ns except for experiment NA52 with $\gamma\tau > 10^{-6}$ s.

Experiment E814 [8] was looking for positively charged strangelets with $0.1 < Z/A < 0.3$, $A_B > 10$. Their limit on the production of a strangelet in a single event was 1.2×10^{-4} for multiply charged strangelets. Experiment E886 was set up to $0 < A/Z < 14$ yielding a much higher sensitivity of down to 10^{-7} /event [11]. An open geometry is used by experiment E864 which reported new limits for $Z = +1, +2$

and a wide range of mass $A_B > 10$ of about $10^{-5} - 10^{-6}$ /event just recently [12]. According to Fig. 5 these experiments could see the positively charged candidates for $B^{1/4} = 145$ MeV ($m_s = 280$ MeV) at $A_B = 13, 14, 16$ and the ones for $B^{1/4} = 150$ MeV at $A_B = 14 - 16$.

The high sensitivity experiment E858 [9] was looking in the range $-1 < A/Z < -7$ and no strangelet was found with a sensitivity of $10^{-9} - 10^{-10}$ /event. Also the follow-up experiment E878 [10] using the gold beam did not see any evidence for unusual composites with $|Z| \leq 3$ on the level of 10^{-7} /event. Nevertheless, these experiments were measuring at zero degree and were not measuring at midrapidity for $A_B > 8$ [10]. Hence, they are only sensitive to e.g., the candidate $A_B = 7$, $Z = -1$ for the case $B^{1/4} = 150$ MeV and for the other charged candidates at $A_B < 6$ for $B^{1/4} = 150, 160$ MeV.

Unfortunately, none of these experiments has set limits so far for the other candidates in the valley of stability, such as $A_B = 10$ and $Z = -4$ and for higher negative charges. While finishing this work, new results from E886 were published which give limits for negatively charged strangelets down to 10^{-8} /event, but unfortunately for $|Z| < 4$ only [11]. Experiment E864 has given new limits for $Z = -1, -2$ from their newest run for masses of $A = 5$ up to $A = 100$ [38]. Most recently, experiment NA52 presented new limits for negatively charged strangelets with a sensitivity down to $10^{-8} - 10^{-10}$ /event for $M/|Z| = 10 - 40$ [13]. However, their limit for the above mentioned strangelets with $M/|Z| \approx 2$ is much less, about $10^{-6} - 10^{-7}$ /event. Moreover, results were presented for rigidities of $p/Z = 40, 100, 200$ GeV only, while NA52 can cover the range of $p/Z = 5 - 200$ GeV. Midrapidity is reached for $M/Z \approx p/9Z$ [13] corresponding to $M/Z = 4.4$ GeV for the lowest rigidity of $p/Z = 40$ GeV measured so far. Lower rigidities are therefore probing strangelets with lower M/Z and NA52 would be sensitive to the negatively charged strangelet candidates proposed here.

VI. SUMMARY

We have studied the properties of both forms of finite multiple strange systems, strangelets, and MEMO's using the MIT bag model and the relativistic mean-field model, respectively. We demonstrate that short-lived strangelets ($\tau \approx 10^{-10} - 10^{-5}$ s) and MEMO's ($\tau \approx 10^{-10}$ s), which are stable against strong decays, have unusual charge to mass ratios. Contrary to previous findings, strangelets are most likely highly negatively charged not slightly positively charged. We also found strangelets which are stable against weak hadronic decay, i.e., they live on a timescale of $\tau \approx 10^{-4} - 10^{-5}$ s. These long-lived candidates are lying in a valley of stability which is due to pronounced shell effects. The valley of stability starts at the quark α ($6u6d6s$) and continues by adding one unit of negative charge, i.e., $(A, Z) = (8, -2), (9, -3), (10, -4), (11, -5), \dots$. The candidates for $A = 10 - 16$ are found for a bag constant of $B^{1/4} < 180$ MeV. We do not see any long-lived strangelet for higher values of the bag constant. We did not take into account the colormagnetic interaction between the quarks but it might result in other interesting stable states with a nonzero spin.

The present investigation seems to indicate that the search

for highly charged strange matter would be far more promising than hitherto recognized. Most search experiments are, however, designed to detect only particles with small charge-to-mass ratio. But long-lived positively charged strangelets seems to exist only for $A_B > 12$ and very low bag parameters. The most interesting long-lived strangelets found have a mass of about $A = 10 - 16$ and a charge of $Z = -4$ to $Z = -10$. The production limits given so far do not probe these candidates. Experiment E864 is sensitive to highly negative charged strangelets with $A_B \geq 10$. Plans to reanalyze the data and to extend the sensitivity in this domain in future runs are therefore most interesting [39].

On the other hand, experiments looking for short-lived strange matter will be able to see a much wider variety of combinations of charge and mass. Recently, experiment E896 started looking into this rich domain of short-lived composites for the H dibaryon [17] but other composites with low mass-to-charge ratios might be also accessible. Short-lived strange matter, either in the form of metastable strangelets or MEMO's, demonstrate that they are also highly negatively charged which opens the possibility for measuring their formation with an extremely low background from antinuclei. These metastable composites can be detected by a cascade of weak decays and by their unusual charge and mass. Measuring single and double Λ hypernuclei will set limits on the production possibility of MEMO's. This limit can possibly also be applied for strangelets as

MEMO's can decay to them via strong decay and serve as a doorway state. On the contrary, if MEMO's are found they will set stringent limits on the existence of strangelets for the same charge, strangeness, and mass and will give a new impetus for our understanding of the strong interactions between baryons in general.

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[†]Deceased.

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- [1] A. R. Bodmer, Phys. Rev. D **4**, 1601 (1971).
 [2] S. A. Chin and A. K. Kerman, Phys. Rev. Lett. **43**, 1292 (1979).
 [3] E. Witten, Phys. Rev. D **30**, 272 (1984).
 [4] C. Greiner, H. Stöcker, and P. Koch, Phys. Rev. Lett. **58**, 1825 (1987); C. Greiner, D. H. Rischke, H. Stöcker, and P. Koch, Phys. Rev. D **38**, 2797 (1988).
 [5] C. Greiner and H. Stöcker, Phys. Rev. D **44**, 3517 (1991).
 [6] J. Schaffner, C. Greiner, and H. Stöcker, Phys. Rev. C **46**, 322 (1992).
 [7] J. Schaffner, C. B. Dover, A. Gal, C. Greiner, and H. Stöcker, Phys. Rev. Lett. **71**, 1328 (1993); J. Schaffner, C. B. Dover, A. Gal, D. J. Millener, C. Greiner, and H. Stöcker, Ann. Phys. (N.Y.) **235**, 35 (1994).
 [8] E814 Collaboration, J. Barrette *et al.*, Phys. Rev. B **252**, 550 (1990); F. Rotondo *et al.*, Nucl. Phys. B, Proc. Suppl. **24B**, 265 (1991).
 [9] E858 Collaboration, M. Aoki *et al.*, Phys. Rev. Lett. **69**, 2345 (1992); H. Crawford *et al.*, Nucl. Phys. B, Proc. Suppl. **24B**, 251 (1991).
 [10] E878 Collaboration, D. Beavis *et al.*, Phys. Rev. Lett. **75**, 3078 (1995).
 [11] E886 Collaboration, A. Rusek *et al.*, Nucl. Phys. **A585**, 59c (1995); Phys. Rev. C **54**, R15 (1996).
 [12] E864 Collaboration, J. Sandweiss *et al.*, Nucl. Phys. B, Proc. Suppl. **24B**, 234 (1991); F. Rotondo, talk given at the *Quark Matter Conference '96*, Heidelberg [Nucl. Phys. A (to be published)].
 [13] NA52 (NEWMASS) Collaboration, K. Borer *et al.*, Phys. Rev. Lett. **72**, 1415 (1994); F. Dittus *et al.*, Nucl. Phys. **A590**, 347c (1995); G. Appelquist *et al.*, Phys. Rev. Lett. **76**, 3907 (1996); R. Klingenberg (private communication); talk given at the *Quark Matter Conference '96* [12].
 [14] R. L. Jaffe, Phys. Rev. Lett. **38**, 195 (1977); **38**, 617(E) (1977).
 [15] C. B. Dover, Nucl. Phys. **A450**, 95c (1986); C. B. Dover, P. Koch, and M. May, Phys. Rev. C **40**, 115 (1989), and references therein.
 [16] J. Belz *et al.*, Phys. Rev. Lett. **76**, 3277 (1996).
 [17] H. Crawford (private communication); talk given at the *Quark Matter Conference '96* [12].
 [18] R. Mattiello, C. Hartnack, A. v. Keitz, J. Schaffner, H. Sorge, H. Stöcker, and C. Greiner, Nucl. Phys. B, Proc. Suppl. **24B**, 221 (1991); M. Sano and M. Wakai, Czech. J. Phys. **42**, 1239 (1992); A. J. Baltz, C. B. Dover, S. H. Kahana, Y. Pang, T. J. Schlagel, and E. Schnedermann, Phys. Lett. B **325**, 7 (1994); L. Gerland, C. Spieles, M. Bleicher, P. Papazoglou, J. Brachmann, A. Dumitru, H. Stöcker, W. Greiner, J. Schaffner, and C. Greiner, *Proceedings of the International Conference on Relativistic Aspects of Nuclear Physics*, Rio de Janeiro, 1995, edited by T. Kodoma, *et al.* (World Scientific, Singapore, 1996), p. 437.
 [19] H. W. Barz, B. L. Friman, J. Knoll, and H. Schulz, Nucl. Phys. B, Proc. Suppl. **24B**, 211 (1991).
 [20] C. Spieles, L. Gerland, H. Stöcker, C. Greiner, C. Kuhn, and J. P. Coffin, Phys. Rev. Lett. **76**, 1776 (1996); C. Spieles, M. Bleicher, L. Gerland, H. Stöcker, and C. Greiner, in *Proceedings of the International Conference on Nuclear Physics at the Turn of the Millennium: Structure of Vacuum and Elementary*

- Matter*, George, South Africa, 1996, edited by W. Greiner and H. Stoecker (World Scientific, Singapore, 1996).
- [21] ALICE Technical Proposal, Report No. CERN/LHCC 95-71.
- [22] E. Farhi and R. L. Jaffe, Phys. Rev. D **30**, 2379 (1984).
- [23] M. S. Berger and R. L. Jaffe, Phys. Rev. C **35**, 213 (1987); **44**, 566(E) (1991).
- [24] J. Madsen, Phys. Rev. Lett. **70**, 391 (1993); Phys. Rev. D **47**, 5156 (1993); **50**, 3328 (1994).
- [25] E. P. Gilson and R. L. Jaffe, Phys. Rev. Lett. **71**, 332 (1993).
- [26] P. Koch, Nucl. Phys. B, Proc. Suppl. **24B**, 255 (1991).
- [27] H. Heiselberg, Phys. Scr. **46**, 485 (1992).
- [28] J. Madsen, Phys. Rev. D **47**, 325 (1993).
- [29] J. F. Donoghue, E. Golowich, and B. R. Holstein, Phys. Rev. D **34**, 3434 (1986).
- [30] H. Heiselberg, J. Madsen, and K. Riisager, Phys. Scr. **34**, 556 (1986).
- [31] D. J. Prowse, Phys. Rev. Lett. **17**, 782 (1966).
- [32] A. R. Bodmer and Q. N. Usmani, Nucl. Phys. **A468**, 653 (1987); R. H. Dalitz, D. H. Davis, P. H. Fowler, A. Montwill, J. Pniewski, and J. A. Zakrzewski, Proc. R. Soc. London, Ser. A **426**, 1 (1989).
- [33] J. J. Szymanski *et al.*, Phys. Rev. C **43**, 849 (1991), and references therein.
- [34] T. DeGrand, R. L. Jaffe, K. Johnson, and J. Kiskis, Phys. Rev. D **12**, 2060 (1975).
- [35] A. Th. M. Aerts, P. J. G. Mulders, and J. J. de Swart, Phys. Rev. D **17**, 260 (1978).
- [36] B. O. Kerbikov, Sov. J. Nucl. Phys. **39**, 516 (1984).
- [37] F. C. Michel, Phys. Rev. Lett. **60**, 677 (1988).
- [38] J. L. Nagle, Ph.D. thesis, Yale University, 1997; (private communication).
- [39] J. Sandweiss (private communication).