Strange Hadronic Matter

Jürgen Schaffner,[1,2] Carl B. Dover,[1,3] Avraham Gal,[1,2,4] Carsten Greiner,[1,5] and Horst Stöcker[1,2]
[1]*National Institute for Nuclear Theory, University of Washington, Seattle, Washington 98195*
[2]*Institut für Theoretische Physik, J. W. Goethe Universität, Frankfurt, Germany*
[3]*Brookhaven National Laboratory, Upton, New York 11973*
[4]*Racah Institute of Physics, The Hebrew University, Jerusalem 91904, Israel*
[5]*Department of Physics, Duke University, Durham, North Carolina 27706*
(Received 17 March 1993)

In an extended mean field theory, we find a large class of bound multistrange objects, formed from combinations of $\{p,n,\Lambda,\Xi^0,\Xi^-\}$ baryons, which are stable against strong decay. We predict a maximal binding energy per baryon of $E_B/A \approx -21$ MeV, strangeness per baryon $f_s \approx 1-1.2$, charge per baryon $f_q \approx -0.1$ to 0, and baryon density 2.5-3 times that of ordinary nuclei. For $A \geq 6$, we obtain stable combinations involving only $\{\Lambda,\Xi^0,\Xi^-\}$ hyperons.

PACS numbers: 21.80.+a, 13.75.Ev, 21.30.+y

Strangeness (S) remains a largely unexplored degree of freedom in strongly interacting baryonic matter. In addition to ordinary nuclei ($S=0$), there exists a modest body of data on $S=-1,-2$ states involving one or two Λ hyperons bound to a nuclear core [1], but there is no information available on systems with $S \leq -3$. It has been speculated [2,3] that states of quark matter ("strangelets") with large strangeness per baryon ($|S|/A \sim 1$) might be even more stable than normal nuclei. The existence of stable strangelets could have significant ramifications [4], for instance, in astrophysics (nucleosynthesis, cores of neutron stars) and for relativistic heavy ion collisions, where the production of both stable and metastable objects might be enhanced if a transition to quark-gluon plasma takes place [5]. A number of experiments are under way to search for such multistrange objects.

Strangelets [2,3] are hypothetical objects in which the quarks (u,d,s in approximately equal numbers) are confined to a single large bag. In this paper, we consider bound states of hyperons (Λ,Ξ^0,Ξ^-) and nucleons (n,p), where the binding arises from attractive mean fields. In this case, the strange quarks are localized within individual hyperons, which are assumed to retain their identity in the bound system. Hyperons are distinguishable from nucleons, and can occupy shell-model states of the same orbital angular momentum l and total spin j as nucleons. Using an extension of the relativistic mean field (RMF) theory [6-8], we form a succession of multistrange nuclei by occupying the single-particle bound states supported by the mean field. Remarkably, we obtain stable systems which display many of the features of hypothetical strange quark matter (large strangeness fraction $f_s = |S|/A \sim 0.6-1.2$, small net charge fraction $f_q = q/A \sim 0.1$ to -0.1, and densities $\rho \sim (2-3)\rho_0$, where $\rho_0 \simeq 0.16$ fm^{-3} is the density of nonstrange nuclear matter). However, the binding energy per particle E_B/A for multistrange nuclei, limited by the single-particle well depths, is of order -10 to -20 MeV, much less than the Λ-N mass difference of 175 MeV. Thus these objects, while enjoying stability against strong decay, will decay by weak interactions with a typical lifetime $\tau \sim 10^{-10}$ sec or less. Strangelets, on the other hand, could conceivably have much larger binding energy, and also be stabilized against weak decay.

Several earlier calculations [7-11] of strange hadronic matter (SHM) have focused on mixtures of Λ hyperons and nucleons, altogether the role of the heavier Σ and Ξ hyperons in the equation of state of neutron stars has been explored [12,13]. In RMF calculations [7,9,10] with Λ's and nucleons, a variety of multi-Λ hypernuclei were found, with binding per baryon as large as $E_B/A \approx -9$ MeV, and $f_s \leq 0.2$. An example is shown in Fig. 1 for a ^{56}Ni nuclear core plus n_Λ Λ hyperons, using a standard RMF calculation with mean fields generated by scalar (σ) and vector (ω) meson exchange [6]. The filled circles correspond to closed Λ shells with $n_\Lambda = 0,2,8,14$. We have noted a key point, missed in previous work, that for n_Λ greater than some critical number, a system of N's and Λ's collapses via the reactions

$$\Lambda + \Lambda \rightarrow \Xi^- + p, \quad \Xi^0 + n\,. \tag{1}$$

Because of binding effects, reaction (1) can induce a strong decay of the many-body system, even though the reverse reactions $\Xi N \rightarrow \Lambda\Lambda$ proceed with sizable energy release $Q=28.3$ and 23.2 MeV, respectively, in free space. Therefore, stable SHM necessarily includes a mixture of Λ's and Ξ's, such that the decays of Eq. (1) are Pauli blocked [14] in both directions. For $A=74$, for example, our calculation does not yield a stable $\{^{56}\text{Ni} + 18\Lambda\}$ configuration corresponding to the next closed Λ shell, since such a state is unstable with respect to the processes of Eq. (1). Among the systems with $n_\Xi \neq 0$ shown in Fig. 1, we note two stable states with $A=74$, corresponding to $(n_\Lambda, n_{\Xi^0}, n_{\Xi^-}) = (8,8,2)$ and $(14,2,2)$. These have a different charge and strangeness than the unstable $(18,0,0)$ configuration.

The RMF approach incorporates effective baryon-

0031-9007/93/71(9)/1328(4)$06.00

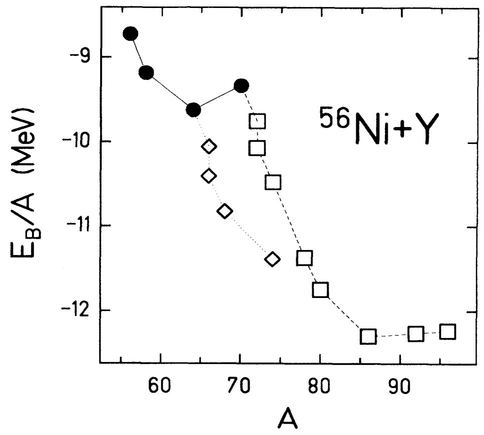

FIG. 1. Binding energy per baryon E_B/A, for model 1 (weak YY interaction) as a function of baryon number A, for bound states of strange hadronic matter consisting of a ^{56}Ni nuclear core plus differing numbers of Λ, Ξ^0, and Ξ^- hyperons. The solid circles represent systems consisting only of the ^{56}Ni core plus Λ's, with $n_\Lambda = 0,2,8,14$. The open diamonds correspond to objects with $n_\Lambda = 8$, to which Ξ hyperons are added ($n_\Xi = 2,4,10$). These are more deeply bound than systems of the same A which have $n_\Lambda > 8$, $n_\Xi = 0$. The open squares have $n_\Lambda = 14$, with $n_\Xi = 2,4,8,10,16,22,26$.

baryon interactions which are adjusted to reproduce the saturation and binding properties of nuclei at normal density, and it is also used to predict the equation of state for denser systems such as neutron stars [6]. These global properties are less dependent than others (for instance, excitation modes) on pion exchange and other correlation effects neglected in the Hartree mean-field approximation employed here. We extend the RMF approach to $S \neq 0$ systems in a controlled fashion, constrained by the observed binding energies of $S = -1, -2$ hypernuclei. A detailed discussion is relegated to Ref. [15]. We consider two models, one with a weak and another with a strong hyperon-hyperon (YY) interaction, denoted as models 1 and 2, respectively. The latter is more in line with the strongly attractive $\Lambda\Lambda$ $^1S_0$ interaction suggested by the few available $\Lambda\Lambda$ hypernuclear events [16]. In model 1, we simply add the $\{\Xi^-, \Xi^0\}$ isospin $\frac{1}{2}$ doublet, coupled to the usual σ and ω isoscalar fields and to the isovector ρ field. For the ω coupling constants g, we use ratios $g_{\omega\Xi} = g_{\omega\Lambda}/2 = g_{\omega N}/3$ given by the constituent quark model [SU(6) symmetry]. The σ couplings are then determined by fitting the Λ and Ξ well depths [1,17] in nucleon matter, $U_\Lambda^{(N)} \approx 30$ MeV and $U_\Xi^{(N)} \approx 28$ MeV. Model 1, which exhibits rather weak YY interactions, nevertheless implies the existence of stable SHM over a wide range of $\{n_p, n_n, n_\Lambda, n_{\Xi^0}, n_{\Xi^-}\}$, typically with large strangeness ($f_s \sim 0.6$), small charge ($f_q \sim 0.1$), and maximum binding energies of order $E_B/A \sim -13$ MeV. The small net charge is due to the tendency of Ξ^-'s and protons to occupy similar orbits so as to minimize the total Coulomb repulsion. This renders it possible for SHM to be stable in the bulk limit ($A \to \infty$), because fission does not occur for large A as in ordinary nuclei. We find that the existence of stable SHM is assured over a wide range of choices for the coupling constants.

In model 2, we incorporate stronger YY interactions, as suggested by the sparse $\Lambda\Lambda$ data [16] and also by a one-boson exchange model [18] consistent with the NN, ΛN, and ΣN scattering data. We estimate, based on this information and the value $U_N^{(N)} \approx 80$ MeV from standard RMF calculations [6,7], potential depths

$$U_\Lambda^{(\Xi)} \approx U_\Xi^{(\Xi)} \approx 2U_\Lambda^{(\Lambda)} \approx 40 \text{ MeV} \qquad (2)$$

for hyperons embedded in hyperon matter at $\rho_\Xi \approx \rho_0$ and $\rho_\Lambda \approx \rho_0/2$. In order to obtain the necessary attraction, we supplement the $\sigma + \omega$ model by a second scalar-vector pair σ^* and ϕ of isoscalar meson fields, which are assumed to couple only to hyperons. For the $\phi(1020)$ couplings, we use the quark model relationships $g_{\phi\Xi} = 2g_{\phi\Lambda} = -2\sqrt{2}g_{\omega N}/3$. For the σ^*, we use the mass of the observed $f_0(975)$ meson, but treat its couplings purely phenomenologically so as to satisfy Eq. (2). This yielded $g_{\sigma^*\Lambda}/g_{\sigma N} = 0.69$, $g_{\sigma^*\Xi}/g_{\sigma N} = 1.25$. We remark that since the YY interaction has been appreciably strengthened in model 2 with respect to model 1, we are not far from reproducing the binding energy of the light system $^{6}_{\Lambda\Lambda}$He [16].

We have investigated models 1 and 2 for a wide variety of SHM configurations based on various doubly magic nuclear cores. Representative results are shown in Figs. 2 and 3, each of which displays three families of stable sequences. The jagged nature of these plots is due to the effects of shell closures, which are superimposed on a smooth A, f_s, or f_q dependence which may be represented by a generalization of the familiar Bethe-Weizsäcker mass formula for nuclei. There is an approximately linear correlation between f_s and f_q, rather similar to the relation $f_q = (1 - f_s)/2$ characteristic of isospin saturated strange quark matter. The approximate parabolic behavior evident in Figs. 2 and 3 near the minima can be parametrized as

$$\begin{aligned} \frac{E_B}{A} &\simeq \left(\frac{E_B}{A}\right)_{\min} + c_s(f_s - f_s^{\min})^2 \\ &\simeq \left(\frac{E_B}{A}\right)_{\min} + c_q(f_q - f_q^{\min})^2 . \end{aligned} \qquad (3)$$

One family of points in Figs. 2 and 3 gives E_B/A for model 2 sequences based on ^{56}Ni ($N = Z = 28$) and ^{180}Th ($N = Z = 90$) cores, as a function of f_s (Fig. 2) or f_q (Fig. 3). We note that E_B/A approaches values as large as $(E_B/A)_{\min} \simeq -22$ MeV, for $f_s^{\min} \simeq 1.1$, $f_q^{\min} \simeq -0.04$, corresponding to systems with more hyperons than nucleons. The ^{56}Ni sequence starts from $f_s = 0$, $f_q = 0.5$, corresponding to a stable core, and extends to systems as large as $A \sim 350$. In contrast, the unstable ^{180}Th core re-

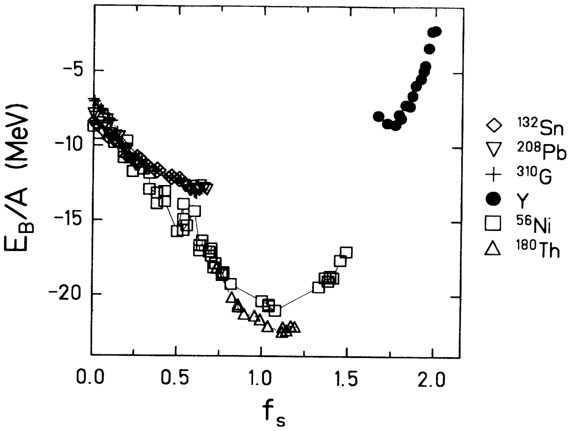

FIG. 2. Binding energy per baryon E_B/A as a function of strangeness fraction f_s for several sequences of SHM based on various nuclear cores as indicated. The superheavy core ^{310}G has $N=184$, $Z=126$, and the symbol Y refers to multihyperon systems containing no nucleons ($N=Z=0$). The calculations for the ^{132}Sn, ^{208}Pb, and ^{310}G cores use model 1 (weak YY interaction), while those for ^{56}Ni, ^{180}Th, and Y use model 2 (strong YY interaction).

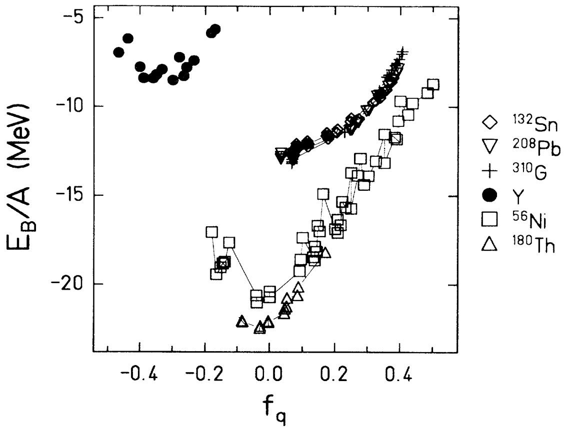

FIG. 3. E_B/A as a function of charge fraction f_q for various sequences of stable SHM. The labeling is the same as in Fig. 2.

quires a large injection of strangeness to stabilize it against baryon emission. In this case, the region of stability extends from $A\simeq330$ ($f_s\simeq0.73, f_q\simeq0.17$) to $A\sim600$.

Another family in Figs. 2 and 3 consists of sequences of stable SHM in model 1, for ^{132}Sn ($N=82$, $Z=50$), ^{208}Pb ($N=126$, $Z=82$), and ^{310}G ($N=184$, $Z=126$) cores. Here, due to the weaker YY interactions, E_B/A achieves values only as large as -13 MeV, with a correspondingly smaller strangeness content ($f_s^{\min}\sim0.6$) and a positive charge ($f_q^{\min}\sim0.1$). A more detailed breakdown of the ^{56}Ni sequence for model 1 is shown in Fig. 1.

A third family of objects is seen as a cluster in the upper-right-hand corner of Fig. 2 and the upper left of Fig. 3. These represent stable aggregates of purely hyperonic $\{\Lambda,\Xi^0,\Xi^-\}$ matter which occurs in model 2 but not in model 1. For such systems, we find E_B/A as large as -9 MeV for $f_s\simeq1.7$ and $f_q\simeq-0.3\pm0.1$. The lightest stable object of this type is likely to be $2\Lambda+2\Xi^0+2\Xi^-$. Purely hyperonic matter, in contrast to SHM in general, is not stable in the bulk limit, because of the Coulomb repulsion generated by the Ξ^-'s.

In summary, we have introduced a strong hyperon-hyperon interaction into the relativistic mean field model, and explored its consequences for the stability of strange hadronic matter. We find a vast array of stable objects composed of $\{n,p,\Lambda,\Xi^0,\Xi^-\}$ baryons, of arbitrarily large baryon number A, very high strangeness content ($f_s>1$), and small net charge (even $f_q<0$). Even if the YY interactions are weakened, as in model 1, these features remain qualitatively valid. The existence of such bound states, and the possibility of stability in the bulk matter limit, may have important consequences for the disposition of the numerous strange particles produced in relativistic heavy ion collisions [19], the strangeness distillation mechanism [5] for the hadronization of quark-gluon plasma, and the equation of state of neutron stars at high density [11-13]. These issues remain to be explored. It may be possible to produce some of the lightest metastable objects envisaged here in the laboratory, by means of high energy heavy ion collisions. Estimates based on a coalescence mechanism [20] yield small, but perhaps measurable production rates, in central Au+Au collisions at 11.7 GeV/c, for the lightest bound Ξ system ${}_{\Xi^0\Lambda\Lambda}^{7}$He. However, a considerable enhancement of the rate may occur if quark-gluon plasma is formed [5,21].

We would like to thank Wick Haxton and the other members of the National Institute for Nuclear Theory at the University of Washington for their hospitality during our visits to Seattle. This collaborative effort was initiated during Program 8 at the Institute. One of us (A.G.) was partially supported by an award of the Alexander von Humboldt Foundation and by the Basic Research Foundation of the Israel Academy of Sciences and Humanities. Another (C.G.) is supported by a Feodor Lynen fellowship of the AvH-Stiftung. The efforts of C.G., J.S., and H.S. were supported in part by the Gesellschaft für Schwerionenforschung, the Deutsche Forschungsgemeinschaft via Graduiertenkolleg Theoretische und Experimentelle Schwerionenphysik, and the Bundesministerium für Forschung und Technologie. This manuscript has been authored under Contract No. DE-AC02-76-CH00016 with the U.S. Department of Energy.

[1] R. E. Chrien and C. B. Dover, Annu. Rev. Nucl. Part. Sci. **39**, 113 (1989).

[2] E. Witten, Phys. Rev. D **30**, 272 (1984).

[3] E. Farhi and R. L. Jaffe, Phys. Rev. D **30**, 2379 (1984); **32**, 2452 (1985).

[4] *Proceedings of the International Workshop on Strange Quark Matter in Physics and Astrophysics*, edited by J. Madsen and P. Haensel [Nucl. Phys. (Proc. Suppl.) **24B**, 1-299 (1991)].

[5] C. Greiner, D. H. Rischke, P. Koch, and H. Stöcker, Phys. Rev. D **38**, 2797 (1988); C. Greiner and H. Stöcker, Phys. Rev. D **44**, 3517 (1991).

[6] B. D. Serot and J. D. Walecka, Adv. Nucl. Phys. **16**, 1 (1986).

[7] M. Rufa *et al.*, Phys. Rev. C **42**, 2469 (1990).

[8] J. Schaffner, C. Greiner, and H. Stöcker, Phys. Rev. C **46**, 322 (1992).

[9] M. Rufa, H. Stöcker, J. Maruhn, P.-G. Reinhard, and W. Greiner, J. Phys. G. **13**, 143 (1987).

[10] J. Mares and J. Žofka, Z. Phys. A **333**, 209 (1989).

[11] H. A. Bethe, G. E. Brown, and J. Cooperstein, Nucl. Phys. **A462**, 791 (1987).

[12] J. Ellis, J. I. Kapusta, and K. A. Olive, Nucl. Phys. **B348**, 345 (1991).

[13] N. K. Glendennning, F. Weber, and S. A. Moszkowski, Phys. Rev. C **45**, 844 (1992).

[14] The possibility of stabilizing Ξ's in light systems by Pauli blocking was discussed in Ref. [8]. We find that the lightest stable system including a Ξ is $_{\Xi^0\Lambda\Lambda}^{\;\;\;\;7}$He (^{4}He $+2\Lambda+\Xi^0$). In contrast, systems with Σ's are generally not stable in RMF calculations, since the substantial energy release $Q \approx 75$–80 MeV in reactions such as $\Sigma N \rightarrow \Lambda N$ or $\Sigma\Xi \rightarrow \Lambda\Xi$ cannot be overcome by binding effects.

[15] J. Schaffner, C. B. Dover, A. Gal, C. Greiner, D. J. Millener, and H. Stöcker (to be published).

[16] R. H. Dalitz *et al.*, Proc. R. Soc. London A **426**, 1 (1989); C. B. Dover, D. J. Millener, A. Gal, and D. H. Davis, Phys. Rev. C **44**, 1905 (1991).

[17] C. B. Dover and A. Gal, Ann. Phys. (N.Y.) **146**, 309 (1983).

[18] M. M. Nagels, T. A. Rijken, and J. J. deSwart, Phys. Rev. D **12**, 744 (1975); **15**, 2547 (1977). These papers define model D, in which the $^1S_0$ YY interactions are all comparable and strongly attractive.

[19] O. Hansen, Comments Nucl. Part. Phys. **20**, 1 (1992).

[20] C. B. Dover, A. J. Baltz, S. H. Kahana, Yang Pang, and T. Schlagel, in Proceedings of the Workshop on Heavy Ion Physics at the AGS (HIPAGS), MIT, January, 1993 (to be published).

[21] H. Crawford, M. Desai, and G. L. Shaw, Phys. Rev. D **45**, 857 (1992).