Chiral Symmetry Breaking and Stability of Strangelets

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We discuss the stability of the strange matter composed of u, d and s quarks. The strange matter can be stable due to the large number of degrees of freedom including the strange flavor, and could be the real ground state of the QCD matter [1]. Such a state is expected to be found in the early universe, compact stars, heavy ion collisions and so on. The stability of the strange matter discussed by the MIT bag model leads to an idea that the finite size of the strange matter (strangelet) could also exist stably. It could be one of candidates for an origin of the dark matter [1, 2]. However, the previous theoretical researches of the strangelets have neglected some non-perturbative dynamics of quarks.

It was shown that the dynamical breaking of chiral symmetry can lead to the stability of the bulk quark matter regardless of the each flavor by using the NJL model [3]. The stability of the strange matter is determined by the competition between the decrease in the kinetic energy by the large number of the degrees of freedom by s flavor and the increase in the energy by the large mass of the s quarks. In the NJL model, the strange matter cannot be an absolutely stable state, since chiral symmetry in s quarks are not sufficiently restored at the stable density. Being motivated by the stability of the bulk quark matter by [3], we discuss the stability of the strangelets by considering spontaneous chiral symmetry breaking.

We use the NJL model to describe dynamical chiral symmetry breaking. In addition, for the confinement of quarks in the strangelet, we impose a boundary condition on the surface of the strangelet which is used in the MIT bag model [4]. Then, our lagrangian is

$$\mathcal{L} = \bar{\psi}(i\partial\!\!\!/ - m^0)\psi + \frac{G}{2}\sum_{a=0}^{8}\left[\left(\bar{\psi}\frac{\lambda^a}{2}\psi\right)^2 + \left(\bar{\psi}i\gamma_5\frac{\lambda^a}{2}\psi\right)^2\right] - M\bar{\psi}\psi\theta(r-R). \qquad (1)$$

The second term is the four-point quark interaction in the NJL model. λ^a are Gell-Mann matrices normalized by $\mathrm{tr}\lambda^a\lambda^b = 2\delta^{ab}$. The last term, in which M goes to infinity after all the calculations, represents the confinement. R is the radius of the strangelet, which is determined by the energy minimization.

The energy levels of quarks in the strangelet are discretized by the boundary condition. Our interest is in the strangelets with large baryon number, starting from the stability of the bulk quark matter. Since it is rather complicated to calculate many discretized energy levels directly by solving the boundary condition for the large size strangelets, we use an approximation of the multiple reflection expansion (MRE), which takes the boundary condition into quark propagator. The modification of quark propagator is represented by the change of the number density by $\rho_{MRE}(p, m, R)$ in the momentum space [2]. By using the mean field approximation in the NJL interaction and the MRE method, we obtain the energy density,

$$\epsilon = \sum_{f=u,d,s}\left[\nu\int_{\Lambda}^{p_f^F}\sqrt{p^2+m_f^2}\,\rho_{MRE}(p, m_f, R)\frac{p^2dp}{2\pi^2} + \frac{(m_f - m_f^0)^2}{4G}\right] - \epsilon_0. \qquad (2)$$

The dynamical mass m_f of flavor f is obtained by solving the Schwinger-Dyson (S-D) equation $\partial\epsilon/\partial m_f = 0$. The Fermi momentum p_f^F is determined by the quark number density. ϵ_0 is the

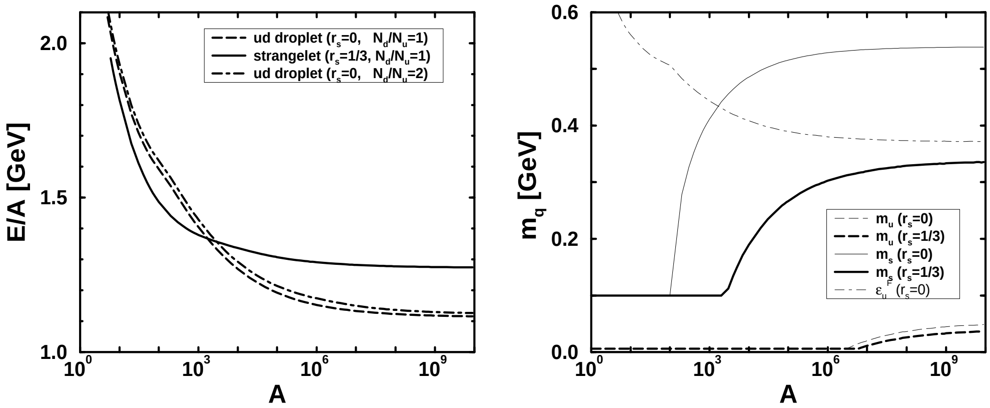

Figure 1: Left: the energy per baryon number in the quark droplet for fixed quark number fraction. Right: the dynamical mass of the quarks and the Fermi energy of u quark in the ud droplet.

energy density in the chirally broken bulk vacuum. The parameters, such as G and Λ and m_f^0, are determined by the properties of hadrons in the vacuum.

The energy per baryon number is used to discuss the stability of the ud matter and the strange matter. We fix the baryon number A and the number fraction of each flavor, e.g. the strangeness fraction $r_s = N_s/3A$, where N_s is the number of s quarks. For a fixed radius of a strangelet, we obtain the dynamical quark mass m_f from the S-D equation. We take a variation of the energy E of the strangelet with respect to the radius, and obtain the energy per baryon number E/A as shown in Fig. 1. In the limit $A \to \infty$, the results coincide with the bulk quark matter by [3].

We see that the strangelets are more stable than the ud droplets for the baryon number $A < 10^3$. This is due to the restoration of chiral symmetry, not only for the u and d quarks, but also for the s quark in the small radius strangelets. The restoration of chiral symmetry of s quarks support the generation of s quarks in the ground state by the β-decay (Fig. 1). The Fermi energy of u quark ϵ_u^F is larger than the s quark dynamical mass m_s in the ud droplets for $A < 10^3$. Therefore s quarks are generated by weak processes $u \to s + e^+ + \nu_e$ and $u + d \to u + s$.

As compared with the nucleon mass $m_N \sim 0.94$ GeV in the ordinary nuclei, the strangelets seem to have a large energy and be unstable. However, once the strangelets are formed as the ground state of the quark droplets, it is expected to take long time to decay to the ordinary nuclear matter due to the multi weak processes.

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