The effect of Dirac sea in the chiral sigma model for nuclear structure

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The chiral sigma model provides good saturation property for nuclear matter and produces the magic number 28 by pionic correlation in finite nuclei[1]. However, the magic number appears at N=18 instead of N=20 because the incompressibility is too large (K=650[MeV]) in this model. There are several possibilities to solve this problem, such as treatments involving the effect of the Dirac sea, the parity projection, the Fock term, and others. Here, we study the effect of the Dirac sea in the chiral sigma model for nuclear structure. The chiral sigma model is a renormalizable model, and it is important to include the Dirac sea in this model. In the non-chiral model (Walecka model) it is known that the contribution of the Dirac sea is about 10% to 20% and reduces the incompressibility. We try to include the Dirac sea within relativistic Hartree approximation in the chiral sigma model[2]. At the first, we calculate these diagrams shown in Figure 1. Figure 1 (a) is a divergence diagram and Figure 1 (b) is

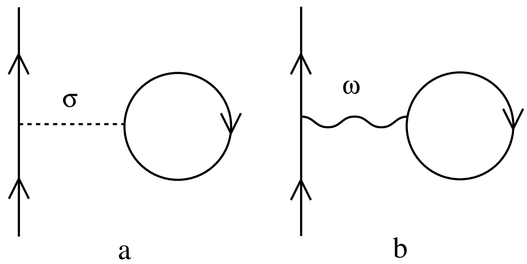

Figure 1: **Second-order tadpole contributions to the baryon propagator**

a finite one. This procedure is not self-consistent, however, where the background particles are noninteracting. We take the relativistic Hartree approximation (RHA) for the nucleon propagator. The nucleon propagator with the RHA has the four divergence diagrams. We must remove these divergence by adding the counter terms. Because the chiral sigma model has the chiral symmetry, the counter terms need to respect the symmetry[3].

$$\delta\mathcal{L}_{CTC} = aM^2(\sigma^2+\pi^2) + b(\sigma^2+\pi^2)^2 + c(\partial_\mu\sigma\partial^\mu\sigma + \partial_\mu\pi\partial^\mu\pi). \qquad (1)$$

We obtain the counter terms with the chiral symmetry, but the counter terms remain arbitrary and the total effective potential has the instability[4]. In addition, the effective mass of sigma meson increases as the density increases. As a result, a mean field of sigma meson becomes very small so that an attractive force is very small.

We suppose the new chiral symmetric renormalization (NCSR) which includes the higher-order counter terms of sigma and pi mesons.

$$\begin{aligned}\delta\mathcal{L}_{CTC}^{NCSR} &= aM^2(\sigma^2+\pi^2) + b(\sigma^2+\pi^2)^2 \\ &+ \frac{c}{M^2}(\sigma^2+\pi^2)^3 + \frac{d}{M^4}(\sigma^2+\pi^2)^4 + e(\partial_\mu\sigma\partial^\mu\sigma + \partial_\mu\pi\partial^\mu\pi). \end{aligned} \qquad (2)$$

Using these counter terms, we take the adequate renormalization conditions. With this renormalization, we can remove both the arbitrariness and the divergence. As a result, the total effective potential becomes stable. We can include the Dirac sea in the chiral sigma model. As shown in Figure 2, the instability from the nucleon loop contribution becomes very

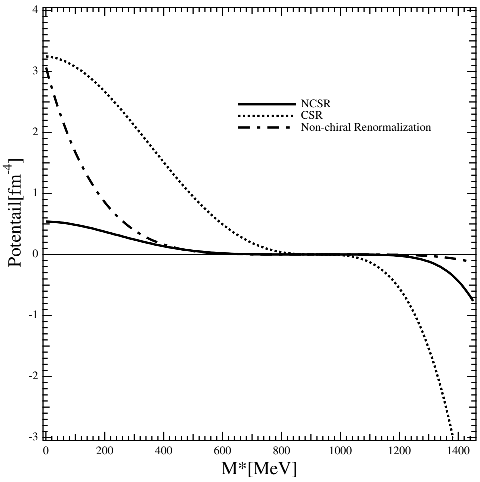

Figure 2: **The contribution of the nucleon loop as a function of the effective mass of nulceon.**

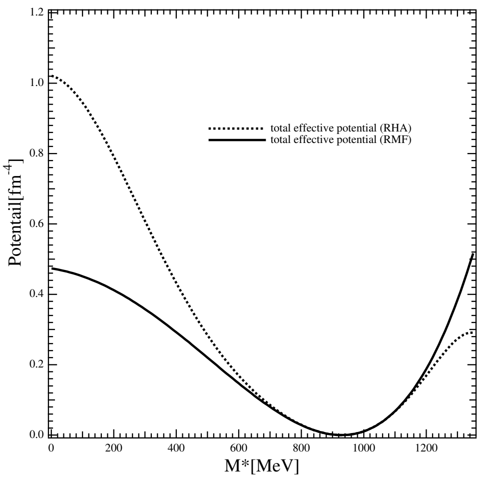

Figure 3: **The effective potential as a function of the effective mass of nulceon.**

soft, and the energy contribution is similar to that of the non-chiral renormalization (in the Walecka model) within the physical effective mass (about from 500[MeV] to 800[MeV]). We expect the similar contribution of Dirac sea in the Walecka model. In addition, the potential at $M^* = 0$ becomes smaller than others so that we can discuss the restoration of the chiral symmetry. Using this renormalization scheme, we obtain the stable effective potential which has a minimum point as shown in Figure 3.

We purpose the new chiral symmetric renormalization. This renormalization scheme has the higher-order terms of sigma and pi mesons. We need these terms to renormalize completely the non-linear sigma meson interactions. Now we include the contribution of the nucleon loop, but have not included that of the boson loop yet. As a next step, we include the loop corrections from both the nucleon and bosons. Because we include the counter terms which have the higher-order terms of scalar mesons, we should include the higher-order terms of scalar mesons to the chiral sigma model. It is known that the incompressibility decreases in a phenomenological model[5]. Now we reconstruct the chiral sigma model which includes the effect of the Dirac sea.

References

[1] Y. Ogawa, H. Toki, S. Tamenaga, H. Shen, A. Hosaka, S. Sugimoto, K. Ikeda, Prog. Theor. Phys. **111** (2004), 75.

[2] B. D. Serot and J. D. Walecka, in advances in Nuclear Physics, ed. J. W. Negele and E. Vogt (Plenum Press, New York, 1986), vol. 16, p.1.

[3] T. Matsui and B. D. Serot, Ann. of Phys. **144** (1982), 107.

[4] J. Boguta, Nucl. Phys. **A501** (1989), 637.

[5] P. K. Sahu and A. Ohnishi, Prog. Theor. Phys. **104** (2000), 1163.