Charge Symmetry Breaking in Neutron Matter

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Charge symmetry is one of salient features of nuclear forces. However it is known that the symmetry is slightly broken and only approximate. It has been suggested that charge symmetry breaking (CSB) caused by isospin mixing of two neutral vector mesons can account for most of the difference between the pp and nn scattering lengths. Piekarewicz and Williams proposed a basic mechanism for the isospin mixing of vector mesons[1]. According to this, two vector mesons in different isospin eigenstates undertake transition to each other through a baryon loop. An essential point is the incomplete cancellation between the contributions from a loop with proton and antiproton and one with neutron and antineutron to the transition amplitude. The small mass difference between proton and neutron causes this incomplete cancellation. One can take advantage of this idea to study nuclear medium effect on CSB. The medium effect on the isospin mixing appears through the Pauli principle for nucleons in the intermediate baryon loops and nucleon effective masses, leading to a density-dependent CSB (DDCSB) in nuclear medium.

With the above idea of DDCSB, we have examined the medium effect on the isospin mixing in nuclear matter in the previous work[2]. We found that the density dependence of CSB works in the right direction such that the Okamoto-Nolen-Schiffer anomaly is resolved. A striking feature which we have studied there is that the isospin mixing is rapidly and strongly enhanced as soon as nuclear matter departs from the isosymmetric state. The strong isospin mixing induces large energy increase of nuclear matter and works eventually to restore the minimal isospin symmetry. This motivated us to investigate the medium effect on CSB in neutron matter which has the largest isospin asymmetry. We are due to pursue it in this work.

We use the relativistic model of nuclear matter called QHD II[3]. We modify it such that the model can describe the transition between two vector mesons;

$$\mathcal{L} = \mathcal{L}_{QHD\ II} + \epsilon(n) V_\mu^{(0)} V^{(1)\mu} \ . \tag{1}$$

The first term represents the standard QHD II Lagrangian and the second one induces the mixing between the pure isospin-0 and 1 vector meson fields. The mixing parameter $\epsilon(n)$, which depends on the matter density, can be related with the transition amplitude between the isoscalar- and isovector vector mesons,

$$\mathcal{M}(k;n) = G_0 \Pi^{(V)}(k;n) G_1 + G_0 \Pi^{(T)}(k;n) F_1 \ , \tag{2}$$

where

$$\Pi^{(V)}(k;n) \ = \ -i \int \frac{d^4p}{(2\pi)^4} \mathrm{Tr}[\gamma^0 G(p+k) \gamma^0 \tau_3 G(p)] \ , \tag{3}$$

and the second term originates from the interference between the vector and tensor interactions. This integral does not vanish due to the finite mass difference of the proton and

neutron in nuclear matter. The density dependence of the mixing angle arising from (2) is determined as done in ref. [2]. Then, we shall carry out the mean field calculation for the pure neutron matter with the Lagrangian (1).

We are mainly interested in (i) the nuclear density dependence of the mixing angle, and (ii) the influence of DDCSB due to the isospin mixing on the equation of state of neutron matter. It was found that the isospin mixing is rapidly and strongly enhanced as neutron density increases compared with the normal nuclear matter. Consequently the charge symmetry is broken to large extent in neutron matter as shown in Fig.1, where the mixing angle is defined as $\theta = \tan^{-1}[2\epsilon/(m_1^2 - m_0^2)]/2$. We have seen that DDCSB modifies the energy per nucleon and provides a softer equation of state in Fig.2. As an astrophysical demonstration of DDCSB, we showed that the maximum mass of 'pure' neutron stars is decreased by a sizable amount $\sim 10\%$[1]. This demonstration warns us that, unless one takes DDCSB into account, one cannot apply ordinary nuclear forces to a nuclear system with large isospin asymmetry such as unstable nuclei with large neutron excess. These results are reported in ref. [4].

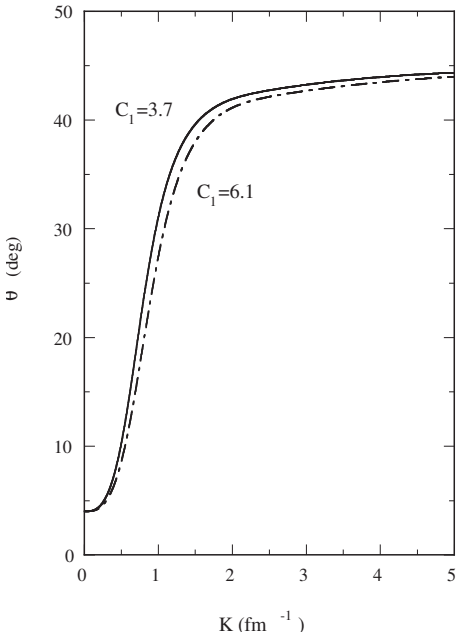

Figure 1: Neutron density dependence of the $\rho - \omega$ mixing angle θ

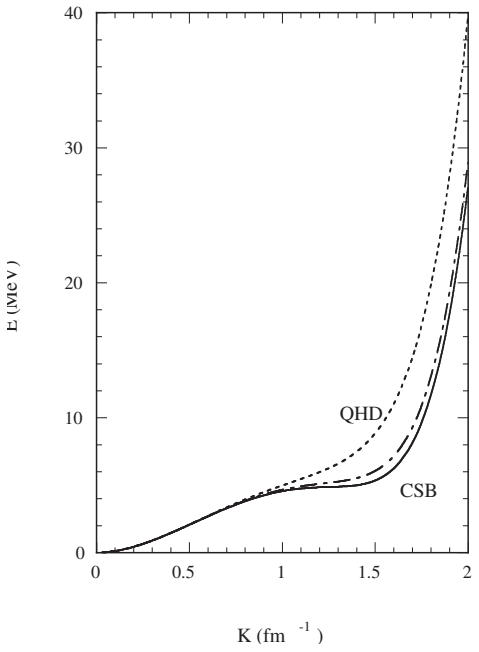

Figure 2: Energy per nucleon as a function of neutron Fermi momentum E

References

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[1] This result would be changed if we took into account the proton degrees of freedom and β equilibrium condition in the realistic neutron star