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STRANGE SEA ASYMMETRY IN NUCLEONS*

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We evaluate the medium effects in nucleon which can induce an asymmetry of the strange sea. The short-distance effects determined by the weak interaction can give rise to $\delta m \equiv \Delta m_s - \Delta m_{\bar{s}}$ where $\Delta m_{s(\bar{s})}$ is the medium-induced mass of strange quark by a few KeV at most, but the long-distance effects by strong interaction could be sizable.

The strange content of the nucleon is under particular attention by the high energy physics society recently. Ji and Tang[1] suggested that if a small locality of strange sea in nucleon is confirmed, some phenomenological consequences can be resulted in. The CCFR data[2] indicate that $s(x)/\bar{s}(x) \sim (1-x)^{-0.46\pm0.87}$. Assuming an asymmetry between s and $\bar{s}$, Ji and Tang analyzed the CCFR data and concluded that $m_s = 260 \pm 70$ MeV and $m_{\bar{s}} = 220 \pm 70$ MeV[1]. So if only considering the central values, $\delta m \equiv m_s - m_{\bar{s}} \sim 40$ MeV. In the framework of the Standard Model $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$, we would like to look for some possible mechanisms which can induce the asymmetry.

The self-energy of strange quark and antiquark $\Sigma_{s(\bar{s})} = \Delta m_{s(\bar{s})}$ occurs via loops where various interactions contribute to $\Sigma_{s(\bar{s})}$ through the effective vertices. Obviously, the QCD interaction cannot distinguish between s and $\bar{s}$, neither the weak interaction alone in fact. Practical calculation of the self-energy also shows that $\Delta m_s = \Delta m_{\bar{s}}$. In fact, because of the CPT theorem, s and $\bar{s}$ must be of exactly the same mass.

If we evaluate the self-energy Δm_s and $\Delta m_{\bar{s}}$ in vacuum, the CPT theorem demands $\Delta m_s \equiv \Delta m_{\bar{s}}$. However, when we evaluate them in an asymmetric environment of nucleons, an asymmetry $\Delta^M m_s \neq \Delta^M m_{\bar{s}}$ where the superscript M denotes the medium effects, can be expected. In other words, we suggest that the asymmetry of the u and d quark composition in nucleons leads to an asymmetry of the strange sea.

There exist both short-distance and long-distance medium effects. The short-distance effects occur at quark-gauge boson level, namely a self-energy loop including a quark-fermion line and a W-boson line or a tadpole loop. The contributions of u and d-types of quark-antiquark to the asymmetry realize through the Kabayashi-Maskawa-Cabibbo mixing.

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The calculations at the parton-$W(Z)$ level is trustworthy, because it is carried out in the standard framework which has been proved to be correct. One does not suspect its validity and trusts that this mechanism can cause an asymmetry of the strange sea in nucleons. However, later we will show that it can only result in a δm of order of a few KeV, much below what we need for phenomenology.

Accepting the value of δm achieved by fitting data as about 40 MeV, one has to look for other mechanisms which can bring up larger δm. Obviously the smallness of δm is due to the heavy W or Z bosons in the propagators. and they are responsible for the weak interaction. We would ask if the strong interaction can get involved, if yes, it definitely enhances the δm by orders. However, the parton-gluon interaction cannot lead to the asymmetry, because gluon is flavor-blind. Thus the perturbative QCD where gluons are exchanged between partons does not apply in this case. A natural extension would be that the long-distance interaction may result in a larger asymmetry. It is generally believed that the long-distance effects exist at the quark level, but the realm is fully governed by the non-perturbative QCD, so the question is how to evaluate the long-distance effects.

In fact, Brodsky and one of us proposed a meson-baryon resonance mechanism and they suggested that the sea quark-antiquark asymmetries are generated by a light-cone model of energetically favored meson-baryon fluctuations[3].

We try to re-evaluate the asymmetry from another angle, namely, we consider the interaction of quark(parton)-meson. Here there is a principal problem that the parton picture was introduced for high energy processes where partons are treated massless compared to the involved energy scale. That is an self-consistent picture where the chiral symmetry is respected. Can the picture enclose the quark-meson interaction is still a puzzle. But as the phenomenology suggests, the long-distance strong interaction should apply in this case, there can be possibility to treat the quark-meson interaction as for the constituent-quark-meson interaction, even though at this energy scale (the invariant masses of the mesons) the chiral symmetry is broken. There is another reason to believe the picture that the pseudoscalar mesons π, K etc. are composite of SU(3) quarks and antiquarks, but also are the Goldstine bosons, so they must satisfy the Bethe-Salpeter equation and the Dyson-Schwinger equation simultaneously. The picture may become self-consistent when the non-perturbative QCD effects can be properly regarded. At this stage we just postulate that we can apply the chiral lagrangian to treat the quark-meson interaction where the sea quark(antiquark) and valence quarks are all included.

Many authors employed this scenario to estimate various flavor asymmetries and spin contents[4,5,6], where the sea quarks(antiquarks) make substantial contributions. However, in Ref. 4, the constituent quark mass of 340 MeV was employed, whereas, in Ref. 5, the current quark mass relation $m_s/\hat{m} = 25$ is used where $\hat{m}$ is the mass of the light quarks (u and d). This discrepancy still comes from lack of solid knowledge on the non-perturbative QCD. In our work, we vary the quark masses and see how the numerical values change. Our results indicate that the difference for various quark masses is not too remarkable.

For the valence and sea quark picture, one has to use the quark distribution function which has obvious statistical meaning. Here instead of the commonly used distribution function, we adopt the distribution with finite medium temperature and density. The temperature involved in the distribution is only a parameter which characterizes the inner motion state of the quarks (valence and sea) and has the order of Λ_{QCD}. In practice, we let the temperature vary within a reasonable range $100 \to 300$ MeV. The advantage of using the finite temperature field theory is obvious. First, the theory is well-established and then the calculations are simple and straightforward.

We are going to employ the familiar formulation of the Quantum Field Theory at finite temperature and density. As well-known, the thermal propagator of quarks can be written as

$$iS_q(k) = \frac{i(\not{k} + m_q)}{k^2 - m_q^2} - 2\pi(\not{k} + m_q)\delta(k^2 - m_q^2) f_F(k \cdot u), \tag{1}$$

where u_μ is the four-vector for the medium and f_F denotes the Fermi-Dirac distribution function

$$f_F(x) = \frac{\theta(x)}{e^{\beta(x-\mu)} + 1} + \frac{\theta(-x)}{e^{-\beta(x-\mu)} + 1}, \tag{2}$$

and $\beta = 1/kT$, μ is the chemical potential. We notice that the first term of Eq. (1) is just the quark propagator in the vacuum. Its contribution to Σ_1 is of no importance to us because this is related to the wave-function renormalization of the quark in the vacuum. We focus on the medium effect, which comes from the second term of Eq. (1). For up and down flavors, we have $n_u - n_{\bar{u}} = 2/V_{eff}$ and $n_d - n_{\bar{d}} = 1/V_{eff}$ in proton while $n_u - n_{\bar{u}} = 1/V_{eff}$ and $n_d - n_{\bar{d}} = 2/V_{eff}$ in neutron.

For the short-distance contribution, the two contributions to the self-energy of s-quark ($\bar{s}$) (a) and (b) are due to the charged current ($W^\pm$) and neutral current respectively, the later is usually called as the tadpole-diagram[7].

The contribution due to the charged current is

$$\Sigma_1^s = \sqrt{2} G_F \gamma^0 L \sin^2\theta_C (n_u - n_{\bar{u}}), \tag{3}$$

where G_F is the Fermi coupling constant, θ_C is the Cabibbo angle. The contribution due to the weak neutral current is

$$\Sigma_2^s = 3\sqrt{2} G_F (-1 + \frac{4}{3} Q^{(s)} \sin^2\theta_W) \cdot \sum_f (T_3^{(f)} - 2Q^{(f)} \sin^2\theta_W)(n_f - n_{\bar{f}}), \tag{4}$$

where $Q^{(f)}$ refers to the charge of corresponding quark (u, d, s). Pal and Pham pointed that the axial part of the neutral current does not contribute[7].

For the long-distance effects, in the calculations, we need an effective vertex for $\bar{s}qM$ where q can be either u or d-quarks and M is a pseudoscalar or vector meson. Here we only retain the lowest lying meson states such as π, K, ρ etc. The effective chiral Lagrangian for the interaction between quarks and mesons has been derived by many authors[8,9].

In terms of these effective vertices, the long-distance medium correction to the mass of strange quark can be evaluated and we obtain

$$\Sigma_3^s = \gamma_0 \frac{f_{kqs}^2}{2} [(n_q - n_{\bar{q}}) + \int \frac{d^3\mathbf{k}}{(2\pi)^3} \frac{M_K^2}{m_s^2 - 2m_s\omega_k - M_K^2} f_F(\omega_k)$$

$$-\int \frac{d^3\mathbf{k}}{(2\pi)^3} \frac{m_k^2}{m_s^2 + 2m_s\omega_k - M_K^2} f_F(-\omega_k)]. \tag{5}$$

In order to avoid the pole in the second term of Eq. (5), we use the familiar Breit-Wigner formulation.

Our numerical results show that for the short-distance effects, $\delta m = 92$ eV $\rightarrow$ 0.8 KeV for proton and $\delta m = 0.38$ KeV $\rightarrow$ 3.0 KeV for neutron, in the range of the effective nucleon radius $R \approx 0.5 \rightarrow 1.0$ fm.

According to the picture of chiral field theory[4,5,6], the effective pseudovector coupling implies $f_{kqs} = \frac{g_A}{\sqrt{2}f}$, where the axial-vector coupling $g_A = 0.75$. The pion decay constant $f_\pi = 93$ MeV, kaon decay constant $f_K = 130$ MeV, for our estimation, an approximate SU(3) symmetry might be valid, so that f can be taken as an average of f_π and f_K. Thus we obtain $\delta m \sim 10 \rightarrow 100$ MeV. One can trust that the order of the effective coupling at the vertices does not deviate too much from this value. More detailed analysis can be found in Ref. 10.

As a summary, we find that an asymmetry of the light quarks in nucleons can induce the expected asymmetry of the strange sea. The short-distance effects are caused by the fundamental weak interactions of the Standard Model, so that the corresponding theoretical estimation of the asymmetry is more reliable, but due to the heavy W(Z) bosons in the propagators, such effects can only result in δm of a few KeV. The main contribution to δm must come from the long-distance strong interaction, if the phenomenological value of δm is about 40 MeV as determined by data. How to correctly evaluate such effects is the key point, even though one can be convinced that the long-distance effects should make a substantial contribution to δm.

In the history, there has been a dispute whether the parton picture and the quark-meson interaction compromise with each other, and if they do coincide, how to properly apply the picture to evaluate phenomenological quantities is still an open problem. In this work, we just calculate the asymmetry of the strange sea by this picture and obtain an estimate which meets the value range from data fitting. Therefore we may consider that this scenario has certain plausibility and its applicability should be further tested in other calculations. The studies along this line are worth more attention, because it is of obvious significance for theory and phenomenological applications.

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