The Mass of Nucleons in a Chiral Quark-Diquark Model

K. Nagata and A. Hosaka

Research Center for Nuclear Physics (RCNP), Ibaraki, Osaka 567-0047, Japan

Recently, a method to study mesons and baryons from the levels of quarks were proposed. This method is inspired from the bosonization of the NJL model. In order to describing baryons, diquark degrees of freedom are included in the NJL model with respecting chiral symmetry. The chiral quark-diquark model is hadronized to study mesons and baryons through the hadronization procedure of path-integral formula. Ebert *et al*[1] and Abu-raddad *et al*[2] formulated the hadronization of the chiral quark-diquark model. They have calculated some quantities for the properties of nucleons. We have also studied the structure of the Nuclear force using the method[3]. In order to describe nucleons, two types of diquarks are needed: Lorentz scalar, iso-scalar type and Lorentz axial-vector, iso-vector type. So far, these works[1, 2, 3], however, included only scalar diquarks. In this brief report, we study the masses of nucleons with including both of two diquarks.

The chiral quark-diquark model is given by

$$\begin{aligned}\mathcal{L} &= \bar{\chi}(i\partial\!\!\!/ - m_q - M)\chi \;+\; D^\dagger(\partial^2 + M_S^2)D + \vec{D}^{\dagger\,\mu}\left[(\partial^2 + M_A^2)g_{\mu\nu} - \partial_\mu\partial_\nu\right]\vec{D}^\nu \\ &+ \tilde{G}\left(\sin\theta\;\bar{\chi}\gamma^\mu\gamma^5\,\vec{\tau}\cdot\vec{D}^\dagger_\mu \;+\; \cos\theta\;\bar{\chi}D^\dagger\right)\left(\sin\theta\;\vec{D}_\nu\cdot\vec{\tau}\,\gamma^\nu\gamma^5\chi \;+\; \cos\theta\;D\chi\right)\,. \qquad (1)\end{aligned}$$

where χ, D, $D^\dagger$ and M are constituent quark, scalar diquark, axial-vector diquark and meson fields, m_q, M_S and M_A are the masses of quarks, scalar diquarks and axial-vector diquarks. Here m_q, M_S and M_A are self-consistently determined in the NJL model, by solving the Gap equation and Bethe-Salpeter equation. $\tilde{G}$ and θ are quark-diquark coupling constant and the mixing angle of scalar and axial-vector diquarks. Baryon fields are introduced as auxiliary fields $B \sim \sin\theta\vec{D}_\nu\cdot\vec{\tau}\gamma^\nu\gamma_5\chi + \cos\theta D\chi$. After integrating out the quark and diquark degrees of freedom, we obtain the meson-baryon Lagrangian[2].

In our model, the self-energy of nucleons are given by Fig. 1. The self-energy diagrams

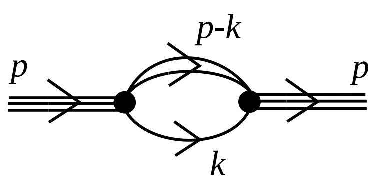

Figure 1: The self-energy diagrams. Single, double and triple lines are quarks, diquarks and nucleons. Blobs denote contact interactions.

are expressed as

$$\mathcal{L}_0 = \bar{B}(p)\left[\cos^2\theta\Sigma_S(p) + \sin^2\theta\Sigma_A(p) - \frac{1}{\tilde{G}}\right]B(p). \qquad (2)$$

Here, we should note that the scalar and axial-vector part have logarithmic and quartic divergences. We employ the Pauli-Villars regularization method in order to maintain important symmetries. The scalar part is regularized by one Pauli-Villars counter term with a cut-off paremeter Λ_S, and the axial-vector part is regularized by two Pauli-Villars counter terms with cut-off parameters $\Lambda_{1,2}$. $\Sigma_{S,A}$ are then decomposed into

$$\Sigma_{S,A}(p) = \Sigma^1_{S,A}(p)p\!\!\!/ + \Sigma^2_{S,A}. \qquad (3)$$

In Eq. (2), B represents the bare nucleon fields. Physical nucleon fields are obtained by the following condition

$$\bar{B}(p)\left[\cos^2\theta\Sigma_S(p)+\sin^2\theta\Sigma_A(p)-\frac{1}{\tilde{G}}\right]B(p) = \bar{B}(p)Z^{-1}(\not{p}-M_N)B(p) \tag{4}$$

$$= \bar{B}_{phys}(p)(\not{p}-M_N)B_{phys}(p). \tag{5}$$

where $B_{phys}=\sqrt{Z^{-1}}B$, and Z and M_N are determined by

$$\begin{aligned} Z^{-1} &= \Sigma_S^1(M_N)+\Sigma_A^1(M_N)+2M_N^2(\Sigma_S^{1\prime}(M_N)+\Sigma_A^{1\prime}(M_N)) \\ &+ 2M_N(\Sigma_S^{2\prime}(M_N)+\Sigma_A^{2\prime}(M_N)), \end{aligned} \tag{6}$$

$$M_N = \left[\frac{1}{\tilde{G}}-\Sigma_S^2(M_N)-\Sigma_A^2(M_N)\right]Z. \tag{7}$$

where primes represents $\partial/\partial p^2$. Solving Eq. (7), we obtain masses of nucleons for various values of $\tilde{G}$ and θ. Results are shown in Fig. 2. We find that as $\tilde{G}$ becomes large, the mass becomes light. This is easily understood from the fact that $\tilde{G}$ is the quark-diquark coupling constant. As $\tilde{G}$ increases, quarks and diquarks are strongly bound, then nucleons become light. On the other hand, as θ increases, the masses become heavy. The reason is that the contribution of axial-vector diquarks are repulsive. The ratio of axial-vector diquarks become large, the repulsion become large and nucleon become heavy.

Since we cannot determine $\tilde{G}$ and θ in this step, we have shown typical values of $\tilde{G}$ and θ to obtain reasonable values of masses. In order to determine these values, we must calculate some other observables, mangentic moments, the axial-coupling constant and so on. Now, we progress such a work.

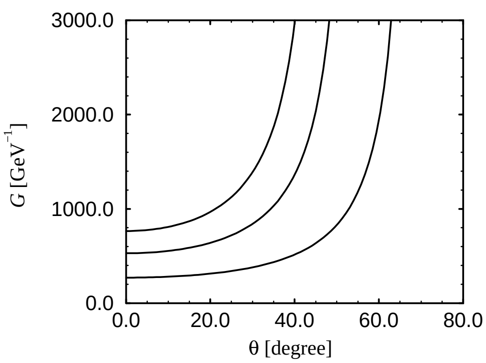

Figure 2: The three curves are for M_N=0.94, 0.80, 0.65 GeV (from bottom to top). Parameters, m_q=0.39, M_S=0.60, M_A=0.90, Λ_S=0.63, Λ_1=0.95, Λ_2=1.0 GeV are used.

References

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