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Chiral perturbation theory for pentaquark baryons and its applications

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Abstract

We construct a chiral Lagrangian for pentaquark baryons assuming that the recently found $\Theta^+(1540)$ state belongs to an antidecuplet of SU(3) flavor symmetry with $J^P = \frac{1}{2}^{\pm}$. We derive the Gell-Mann–Okubo formulae for the antidecuplet baryon masses, and a possible mixing between the antidecuplet and the pentaquark octet. Then we calculate the cross sections for $\pi^- p \to K^- \Theta^+$ and $\gamma n \to K^- \Theta^+$ using our chiral Lagrangian. The resulting amplitudes respect the underlying chiral symmetry of QCD correctly. We also describe how to include the light vector mesons in the chiral Lagrangian.

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1. Introduction

Recently, five independent experiments reported observations of a new baryonic state $\Theta^+(1540)$ with a very narrow width < 5 MeV [1–6], which is likely to be a pentaquark state $(uudd\bar{s})$ [7]. Arguments based on quark models suggest that this state is a member of SU(3) antidecuplet with spin $J = \frac{1}{2}$ or $\frac{3}{2}$. The hadro/photo-production cross section would depend on the spin J and parity P of the Θ^+, and it is important to have reliable predictions for these cross sections. The most proper way to address these issues will be chiral perturbation theory.

In this Letter, we construct a chiral Lagrangian for pentaquark baryons assuming they are SU(3) antidecuplet with $J = \frac{1}{2}$ and $P = +1$ or -1. (The case for $J = \frac{3}{2}$ can be discussed in a similar manner, except that antidecuplets are described by Rarita–Schwinger fields.) Then we calculate the mass spectra of antide-

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cuplets, their possible mixings with pentaquark octets, the decay rates of antidecuplets, and cross sections for $\pi^- p \to K^-\Theta^+$ and $\gamma n \to K^-\Theta^+$. Finally we describe how to include light vector mesons in our framework, and how the low energy theorem is recovered in the soft pion limit.

2. Chiral Lagrangian for a pentaquark baryon decuplet

Let us denote the Goldstone boson field by pion octet π, baryon octet including nucleons by B, and antidecuplet including Θ^+ by $\mathcal{P}$. Under chiral $SU(3)_L \times SU(3)_R$ [8], the Goldstone boson field $\Sigma \equiv \exp(2i\pi/f)$, where $f \approx 93$ MeV is the pion decay constant, transforms as

$$\Sigma(x) \to L\Sigma(x)R^\dagger.$$

It is convenient to define another field $\xi(x)$ by $\Sigma(x) \equiv \xi^2(x)$, which transforms as

$$\xi(x) \to L\xi(x)U^\dagger(x) = U(x)\xi(x)R^\dagger.$$

The 3×3 matrix field $U(x)$ depends on Goldstone fields $\pi(x)$ as well as the SU(3) transformation matrices L and R. It is convenient to define two vector fields with following properties under chiral transformations:

$$\begin{aligned} V_\mu &= \frac{1}{2}\left(\xi^\dagger\partial_\mu\xi + \xi\partial_\mu\xi^\dagger\right),\\ V_\mu &\to UV_\mu U^\dagger + U\partial_\mu U^\dagger,\\ A_\mu &= \frac{i}{2}\left(\xi^\dagger\partial_\mu\xi - \xi\partial_\mu\xi^\dagger\right),\\ A_\mu &\to UA_\mu U^\dagger. \end{aligned} \tag{1}$$

Note that V_μ transforms like a gauge field. The transformation of the baryon octet and pentaquark antidecuplet $\mathcal{P}$ including Θ^+ $(I=0)$ can be chosen as

$$\begin{aligned} B^i{}_j &\to U^i{}_a B^a{}_b U^{\dagger b}{}_j,\\ \mathcal{P}_{ijk} &\to P_{abc}U^{\dagger a}{}_i U^{\dagger b}{}_j U^{\dagger c}{}_k, \end{aligned}$$

where all the indices are for SU(3) flavor. The pentaquark baryons are related to $\mathcal{P}_{abc} = \mathcal{P}_{(abc)}$ by, for example, $\mathcal{P}_{333} = \Theta^+$, $\mathcal{P}_{133} = \frac{1}{\sqrt{3}}\tilde{N}^0$, $\mathcal{P}_{113} = \frac{1}{\sqrt{3}}\tilde{\Sigma}^-$, and $\mathcal{P}_{112} = \frac{1}{\sqrt{3}}\Xi^-_{3/2}$. Then, one can define a covariant derivative $\mathcal{D}_\mu$, which transforms as

$$\mathcal{D}_\mu B \to U\mathcal{D}_\mu BU^\dagger, \quad \text{by}$$
$$\mathcal{D}_\mu B = \partial_\mu B + [V_\mu, B].$$

Chiral symmetry is explicitly broken by nonvanishing current-quark masses and electromagnetic interactions. The former can be included by regarding the quark-mass matrix $m = \mathrm{diag}(m_u, m_d, m_s)$ as a spurion with transformation property $m \to LmR^\dagger = RmL^\dagger$. It is more convenient to use $\xi m\xi + \xi^\dagger m\xi^\dagger$, which transforms as an SU(3) octet. Electromagnetic interactions can be included by introducing photon field $\mathcal{A}_\mu$ and its field strength tensor $F_{\mu\nu} = \partial_\mu\mathcal{A}_\nu - \partial_\nu\mathcal{A}_\mu$:

$$\partial_\mu\Sigma \to \mathcal{D}_\mu\Sigma \equiv \partial_\mu\Sigma + ie\mathcal{A}_\mu[Q, \Sigma], \tag{2a}$$

$$V_\mu \to V_\mu + \frac{ie}{2}\mathcal{A}_\mu\left(\xi^\dagger Q\xi + \xi Q\xi^\dagger\right), \tag{2b}$$

$$A_\mu \to A_\mu - \frac{e}{2}\mathcal{A}_\mu\left(\xi^\dagger Q\xi - \xi Q\xi^\dagger\right), \tag{2c}$$

where $Q \equiv \mathrm{diag}(2/3, -1/3, -1/3)$ is the electric-charge matrix for light quarks $(q = u, d, s)$.

Now it is straightforward to construct a chiral Lagrangian with lowest order in derivative expansion. The parity and charge-conjugation symmetric chiral Lagrangian is given by

$$\mathcal{L} = \mathcal{L}_\Sigma + \mathcal{L}_B + \mathcal{L}_\mathcal{P}, \tag{3}$$

where

$$\mathcal{L}_\Sigma = \frac{f_\pi^2}{4}\mathrm{Tr}\left[\mathcal{D}_\mu\Sigma^\dagger\mathcal{D}^\mu\Sigma - 2\mu m\left(\Sigma + \Sigma^\dagger\right)\right], \tag{4a}$$

$$\begin{aligned} \mathcal{L}_B = {} & \mathrm{Tr}\,\bar{B}(i\not{\mathcal{D}} - m_B)B + D\,\mathrm{Tr}\,\bar{B}\gamma_5\{\not{A}, B\}\\ & + F\,\mathrm{Tr}\,\bar{B}\gamma_5[\not{A}, B], \end{aligned} \tag{4b}$$

$$\begin{aligned} \mathcal{L}_\mathcal{P} = {} & \bar{\mathcal{P}}(i\not{\mathcal{D}} - m_\mathcal{P})\mathcal{P} + \mathcal{C}_{\mathcal{P}N}(\bar{\mathcal{P}}\Gamma_P\not{A}B + \bar{B}\Gamma_P\not{A}\mathcal{P})\\ & + \mathcal{H}_{\mathcal{P}N}\bar{\mathcal{P}}\gamma_5\not{A}\mathcal{P}, \end{aligned} \tag{4c}$$

where P is the parity of Θ^+, $\Gamma_+ = \gamma_5$, and $\Gamma_- = 1$, and $m_\mathcal{P}$ is the average of the pentaquark decuplet mass.

The Gell-Mann–Okubo formulae for pentaquark baryons will be obtained from

$$\mathcal{L}_m = \alpha_m\bar{\mathcal{P}}\left(\xi m\xi + \xi^\dagger m\xi^\dagger\right)\mathcal{P}. \tag{5}$$

Expanding this, we get the mass splittings $\Delta m_i \equiv m_i - m_\mathcal{P}$ within the antidecuplet:

$$\Delta m_\Theta = 2\alpha_m m_s, \tag{6a}$$