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Parity doubling of baryons in a chiral approach with three flavors

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Abstract

We formulate a set of mass relations for the baryon octet and decuplet with positive and negative parity in terms of the order parameter of QCD chiral symmetry. The Gell-Mann–Okubo mass formula and Gell-Mann's equal spacing rule hold manifestly in this approach. Thermal masses of the baryons are calculated in the mean field approximation for various pion masses, and the results are compared with the recent lattice studies. A general trend of the nucleon, Δ and Ω parity-doublers seen in the available lattice data can be understood qualitatively. Expected mass modifications of other strange baryons are also given with the physical and heavier pion masses.

Keywords: Parity doubling; Chiral symmetry breaking

1. Introduction

Modifications of hadron properties in a hot/dense medium have been explored as one of the key issues in the context of QCD phase transition expected in heavy-ion collisions and in the interior of compact stars [1]. As chiral symmetry becomes restored, the hadron spectra with opposite parity are expected to be degenerate. Yet, it remains unclear to what extent they would influence over bulk thermodynamics and experimental observables.

Recently, the first systematic study of thermal masses of the octet and decuplet baryons with positive and negative parity has been carried out in $N_f = 2 + 1$ flavored lattice QCD [2]. The

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temperature dependence of the nucleon, Δ and Ω masses were extracted from temporal correlators, and they obviously exhibit the parity doubling structure. The ground-state mass with positive parity is rather stable against temperature, whereas the mass of the negative parity partner drops substantially toward the chiral crossover temperature. Although the simulations in [2] have been performed with a relatively large pion mass, $m_\pi \sim 400$ MeV, this is a clear signature of the partial restoration of chiral symmetry in the baryonic sector.

In chiral approaches, a non-vanishing nucleon mass which stays finite in chiral restored phase is introduced via so-called mirror assignment of chirality in the parity doublet model [3–5]. The model has been applied to hot and dense baryonic matter and neutron stars [6–9,12,10,11,13–17] as well as the phenomenology in vacuum [18–21].

The two-flavored physics with parity doubling has been rather extensively studied, whereas the studies with three flavors remain quite limited. In particular, a systematic study of the in-medium masses of the octet and decuplet states is still missing. In this paper, we start with the general SU(3) Lagrangian and deduce a complete set of the mass relations in the parity doubling scenario, in a manifestly consistent manner with the celebrated Gell-Mann–Okubo mass formula and Gell-Mann's equal spacing rule. We also study the thermal behavior of the baryon masses in a self-consistent chiral approach under the mean field approximation. For qualitative comparison to the lattice data [2], we demonstrate the calculations with the physical and heavier pion masses.

2. Octet and decuplet baryons

Introducing an octet g_8 and a singlet g_1 coupling constants, the general SU(3) interaction Lagrangian with a meson field Φ is given by [22,23]

$$\begin{aligned}\mathcal{L}_{BB\Phi} &= -\sqrt{2}g_8\alpha \mathrm{tr}\left[\bar{B}\left[\Phi, B\right]\right] \\ &- \sqrt{2}g_8(1-\alpha)\left(\mathrm{tr}\left[\bar{B}\left\{\Phi, B\right\}\right] - \frac{2}{3}\mathrm{tr}\left[\bar{B}B\right]\mathrm{tr}\left[\Phi\right]\right) \\ &- \frac{g_1}{\sqrt{3}}\mathrm{tr}\left[\bar{B}B\right]\mathrm{tr}\left[\Phi\right] ,\end{aligned} \tag{1}$$

where α is known as the $F/(F+D)$ ratio. Masses of the baryon octet are generated when an octet of scalar fields get condensed,[1] and *all of them* depend on the light-quark σ_q and the strange-quark condensates σ_s. As suggested in [24], there exists a special set of the parameters, $(\alpha, g_1) = (1, \sqrt{6}g_8)$, which leads to the nucleon mass depending only on the σ_q.

The extension to the parity doublet picture is carried out following [18]. The chiral invariant mass m_0 of two fermions ψ_1 and ψ_2 is introduced as

$$\mathcal{L}_{\mathrm{inv}} = m_0 \mathrm{tr}\left[\bar{\psi}_1\gamma_5\psi_2 - \bar{\psi}_2\gamma_5\psi_1\right] . \tag{2}$$

In the physical basis, the nucleon masses with positive and negative parity are found as

$$m_{N_\pm} = \sqrt{\alpha_N^2\sigma_q^2 + m_0^2} \mp \beta_N\sigma_q , \tag{3}$$

where α_N and β_N are the nucleon coupling constants to the scalar mesons. The decuplet baryons are introduced as the Rarita–Schwinger fields, and the delta masses are given in a similar fashion [4,5]:

[1] For details of the scalar vacuum expectation matrix staying invariant via a nonlinear transformation, see Appendix of [23].