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Roper mass in chiral perturbation theory

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Understanding the nature of the Roper resonance is of particular interest. Its mass, for example, shows a very unusual pattern: it is lower than the negative parity state $N(1535)$. Also, the Roper is expected to play a role in low energy observables due to its closeness to the nucleon and Delta. We report on a systematic study of the nucleon, Delta, and Roper masses in chiral perturbation theory up to next-to-next-to-leading order. For the first time, the contributions due to the mixing between the nucleon and the Roper allowed by chiral symmetry are taken into account. Recently, several lattice QCD collaborations have reported some results on the Roper mass, assuming this particle is always stable. A chiral extrapolation of these data is also presented as an application of our results.

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1. Introduction

The light-quark spectrum provides a great opportunity to study Quantum Chromodynamics (QCD) in its nonperturbative regime. In particular, the first even-parity excited state of the nucleon, the $J^P = (1/2)^+$ Roper resonance $N(1440)$ or $P_{11}(1440)$, has been a puzzle since its discovery [1]. In the constituent quark model, the Roper, as an S-wave excitation, tends to be above the first odd-parity excited state $N(1530)$ or $S_{11}(1530)$, a P-wave excitation. The recent outburst of interest in lattice QCD (LQCD) has not resolved this puzzle. Several LQCD collaborations have published results for the Roper mass at various values of the pion mass m_π [2, 3, 4, 5, 6, 7]. Except for the χQCD collaboration [6] which finds relatively small masses with a chiral behavior similar to that of nucleons, most of the results are in broad agreement.

Chiral perturbation theory (ChPT), as an effective field theory (EFT) of QCD, provides a model-independent framework [8] to perturbatively explore phenomena at momenta small compared to the typical QCD scale $M_{QCD} \sim 1$ GeV, where chiral symmetry is crucial. Much work has been carried out in ChPT including explicitly pions, nucleons and Deltas — for a comprehensive review, see for example Ref. [9]. In contrast, the next nucleon excited state, the Roper, has received considerably less attention. The Roper-nucleon splitting is still somewhat smaller than M_{QCD} at the physical pion mass, and could decrease towards the chiral limit. Therefore, it can be included as an explicit degree of freedom in ChPT.

The goal of the present work is to initiate a systematic study of nucleon, Delta and Roper properties within ChPT by treating the baryon mass differences in the same footing as the pion mass, and consider momenta $Q \sim m_\pi \sim \delta_{\Delta N} \sim \delta_{RN}$. As a first step, we reconsider the Roper self-energy [10, 11] to next-to-next-to-leading order (NNLO) including explicitly the pion-mass dependence of the mixing between nucleon and Roper. We also calculate the virtual Roper effects on the nucleon and Delta self-energies to the same order.

2. Theoretical Framework

The effective Lagrangian relevant for the chiral corrections to the nucleon, Delta, and Roper self-energies up to NNLO can be split as

$$\mathscr{L} = \mathscr{L}_\pi + \mathscr{L}_{\pi N} + \mathscr{L}_{\pi N\Delta} + \mathscr{L}_{\pi NR} + \mathscr{L}_{\pi\Delta R}, \tag{2.1}$$

which describe interactions among pions, nucleons, Deltas, and Ropers. The explicit expressions of Lagrangian can be found in Ref. [12]. We want to mention that the Roper-nucleon mixing Lagrangian is

$$\mathscr{L}_{\pi NR}^{\text{mixed}} = c_{NR}(\langle\chi_+\rangle\bar{N}R + \text{H.c.}), \tag{2.2}$$

which we kept here explicit in contrast to what is done in Ref. [10]. Due to the mixing of nucleon and Roper, two new diagrams can contribute to the Roper self-energy, and the non-diagonal terms should be included in the baryon mass matrix M_B,

$$M_B = \begin{pmatrix} M_{NN} & 0 & M_{NR} \\ 0 & M_{\Delta\Delta} & 0 \\ M_{RN} & 0 & M_{RR} \end{pmatrix}. \tag{2.3}$$

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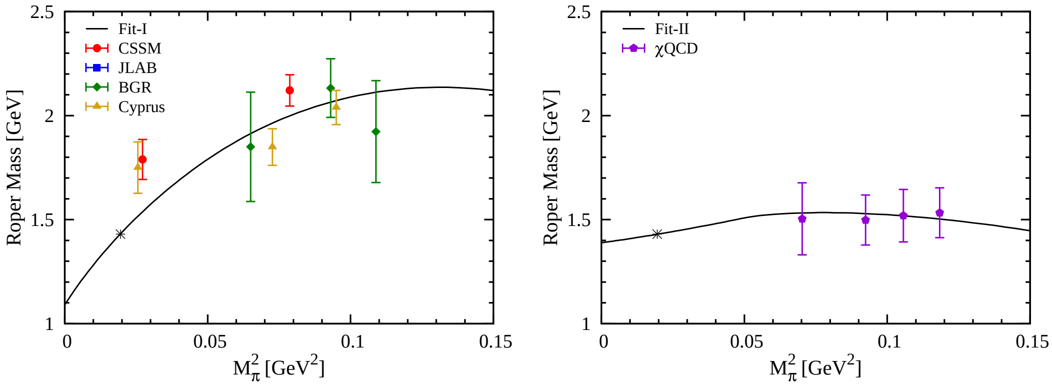

Figure 1: Chiral extrapolation of Roper mass. Left panel and right panel are the results from Fit-I and Fit-II, respectively.

In order to obtain the chiral expansion of baryon masses, one should firstly diagonalize M_B, and, secondly perform the expansion in powers of momentum and pion mass up to NNLO. The details of calculation will be presented in Ref. [12].

3. Chiral extrapolation of Roper mass

Due to the unstable Roper state with $m_\pi \leq 500$ MeV in LQCD, in principle, the lattice Roper mass is not suitable to be studied in ChPT. As a simple application, we perform a tentative study of chiral extrapolation of Roper mass by fitting the corresponding lattice data [1].

Because of the large number of low-energy constants (LECs) appearing in the nucleon, Delta, and Roper masses up to NNLO, we would like to utilize the next-to-leading order (NLO) baryon masses to simultaneously study the lattice data of nucleon, Delta, and Roper masses and their experimental results. The fitting details can be found in Ref. [12]. Here we just present the chiral extrapolation of Roper mass in Fig. 1. The left panel is the results by fitting the Roper masses from the CSSM, JLab, BGR, and Cyprus collaborations (denoted as Fit-I), the right one for the χQCD lattice data (Fit-II). As we expected, the lattice data from the CSSM, JLab, BGR, Cyprus collaborations present a large chiral-log effect, whereas the χQCD results give a mild quark mass dependence of Roper mass. Due to the large difference of the fitted lattice data, the values of LECs related to the Roper, e.g. δ_{RN}, c_{R1}, are very different. Furthermore, the value of $c_{NR} \sim 0$ denotes that the mixed effects of nucleon and Roper are very small at NLO. But, on the other hand, the sizable error of c_{NR} also indicates the mixing effects should be carefully investigated when lattice data of Roper masses becomes available.

4. Conclusion

In this work, the nucleon, Delta, and Roper masses are calculated in chiral perturbation theory up to next-to-next-to-leading order. The effects of the mixing between the nucleon and the Roper

[1] Several similar works have been reported in the study of lattice data of lowest-lying octet and decuplet baryon masses [13, 14, 15, 16].

are taken into account for the first time. Besides, the virtual Roper contribution to the nucleon and Delta masses are evaluated. A tentative analysis of lattice Roper masses is presented.

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