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Excited baryons from the FLIC fermion action

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Masses of positive and negative parity excited nucleons and hyperons are calculated in quenched lattice QCD using an $\mathcal{O}(a^2)$ improved gluon action and a fat-link clover fermion action in which only the irrelevant operators are constructed with fat links. The results are in agreement with earlier N^* simulations with improved actions, and exhibit a clear mass splitting between the nucleon and its parity partner, as well as a small mass splitting between the two low-lying $J^P = \frac{1}{2}^-$ N^* states. Study of different Λ interpolating fields suggests a similar splitting between the lowest two $\frac{1}{2}^-$ Λ^* states, although the empirical mass suppression of the $\Lambda^*(1405)$ is not seen.

1. INTRODUCTION

The study of baryon excitations provides valuable insight into the forces of confinement and the nature of QCD in the nonperturbative regime. This is one of the motivations for the experimental effort currently under way at Jefferson Lab which is accumulating data of unprecedented quality and quantity on $N \to N^*$ transitions.

One of the long-standing puzzles in baryon spectroscopy has been the low mass of the first positive parity excitation of the nucleon (the $N^*(1440)$ Roper resonance) compared with the lightest odd parity state. Without fine tuning of parameters, valence quark models tend to leave the mass of the Roper too high. Another challenge is presented by the odd parity $\Lambda^*(1405)$, whose anomalously small mass has been interpreted as an indication of strong coupled channel effects, and a weak overlap with a three-valence quark state. While model studies have provided some understanding of the level orderings and mass splittings in the baryons spectrum, it is hoped that lattice QCD [1,2,3,4] will provide a definitive resolution of some of the outstanding issues.

Recently a new approach to nonperturbative $\mathcal{O}(a)$ fermion action improvement has been developed based on the Fat-Link Irrelevant Clover (FLIC) fermion action [5]. First results for the spin-1/2 excited nucleon and hyperon, and spin-3/2 N^* and Δ^*, spectra were presented in Refs. [6] and [7], respectively. Here we update the earlier analyses [6] by including more configurations, and using correlation matrix techniques to better resolve individual excited states of the nucleon and Λ.

2. INTERPOLATING FIELDS

Following standard procedure, we calculate two-point correlation functions from baryon interpolating fields constructed to maximize overlap with states with specific quantum numbers. In this analysis two interpolating fields are considered. For the positive parity proton these are given by,

$$\chi_1^{p+}(x) = \epsilon_{abc} \left(u_a^T(x)\ C\gamma_5\ d_b(x) \right) u_c(x) \ , \quad (1)$$

$$\chi_2^{p+}(x) = \epsilon_{abc} \left(u_a^T(x)\ C\ d_b(x) \right) \gamma_5\ u_c(x) \ , \quad (2)$$

where the fields u, d are evaluated at Euclidean space-time point x, and a, b and c are color labels.

As explained in Refs. [1,6], because of the Dirac structure of the "diquark" in the parentheses in Eqs. (1) and (2), one expects correlation functions constructed from χ_2^{p+} to be dominated by larger mass states than those arising from χ_1^{p+}. More-

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over, the χ_2^{p+} interpolating field is known to have little overlap with the nucleon ground state [1,8].

For the Λ states, we consider several interpolating fields with different SU(3) properties. To test the extent to which SU(3) flavor symmetry is valid in the baryon spectrum, we construct an interpolating field ("Λ^c") composed of terms common to both the singlet and octet Λ interpolating fields [9],

$$\begin{aligned}\chi_1^{\Lambda^c}(x) &= \frac{1}{\sqrt{2}}\epsilon_{abc}\left\{\left(u_a^T(x)\ C\gamma_5\ s_b(x)\right)d_c(x)\right.\\ &\quad \left.-\ \left(d_a^T(x)\ C\gamma_5\ s_b(x)\right)u_c(x)\right\}, \quad (3)\end{aligned}$$

and similarly for $\chi_2^{\Lambda^c}$. Such interpolating fields allow for mixing between singlet and octet states induced by SU(3) flavor symmetry breaking, and may be useful in determining the nature of the $\Lambda^*(1405)$ resonance.

3. RESULTS & DISCUSSION

The simulations are performed on a $16^3 \times 32$ lattice at $\beta = 4.60$, with a lattice spacing of $a = 0.122(2)$ fm, based on a sample of 392 configurations. For the gauge fields, a mean-field improved plaquette plus rectangle action is used, while for the quark fields, the FLIC action [5] is implemented with $n = 4$ sweeps of APE smearing at $\alpha = 0.7$. Further details of the simulations are given in Ref. [5].

In Fig. 1 we show the N and $N^*(\frac{1}{2}^-)$ masses as a function of m_π^2 for the new simulations with the FLIC action. For comparison, we also show results from earlier simulations with Wilson [6] and domain wall fermions (DWF) [4], and a nonperturbatively improved clover action [3] with different source smearing and volumes.

There is excellent agreement between the different improved actions for the nucleon mass. The Wilson results lie systematically low in comparison to these due to large $\mathcal{O}(a)$ errors in this action [5]. A similar pattern is repeated for the $N^*(\frac{1}{2}^-)$ masses. A mass splitting of around 400 MeV is clearly visible between the N and N^* for all actions, including the Wilson. The trend of the $N^*(\frac{1}{2}^-)$ data with decreasing m_π is also consistent with the mass of the lowest physical negative parity N^* state.

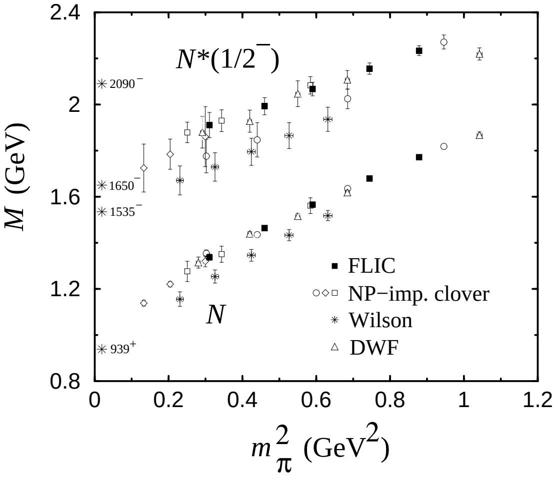

Figure 1. Masses of the nucleon (N) and the lowest $J^P = \frac{1}{2}^-$ excitation ("N^*"), obtained from the χ_1 interpolating field. The FLIC and Wilson results are from the present analysis.

The mass of the $J^P = \frac{1}{2}^+$ state obtained from the $\chi_2^{p^+}$ interpolating field is shown in Fig. 2. In addition to the FLIC and Wilson results from the present analysis, also shown are the DWF results [4], and results from an earlier analysis with Wilson fermions together with the operator product expansion [1]. The most striking feature of the data is the relatively large excitation energy of the N', some 1 GeV above the nucleon. It has been speculated that the $\chi_2^{p^+}$ field may have overlap with the lowest $\frac{1}{2}^+$ excited state [4], however, there is little evidence that this state is the $N^*(1440)$. It is likely that the χ_2 interpolating field simply does not have good overlap with either the nucleon or the $N^*(1440)$, but rather a (combination of) excited $\frac{1}{2}^+$ state(s).

The spectrum of positive and negative parity Λ states is shown in Fig. 3. The positive (negative) parity states labeled Λ_1 (Λ_1^*) and Λ_2 (Λ_2^*) are constructed from the $\chi_1^{\Lambda^c}$ and $\chi_2^{\Lambda^c}$ interpolating fields, respectively. The pattern of mass splittings is similar to that observed for the N^*'s in Figs. 1 and 2. The importance of the correlator matrix analysis (filled symbols) is evident from a comparison with the naive results (open symbols), where the states have not been diag-

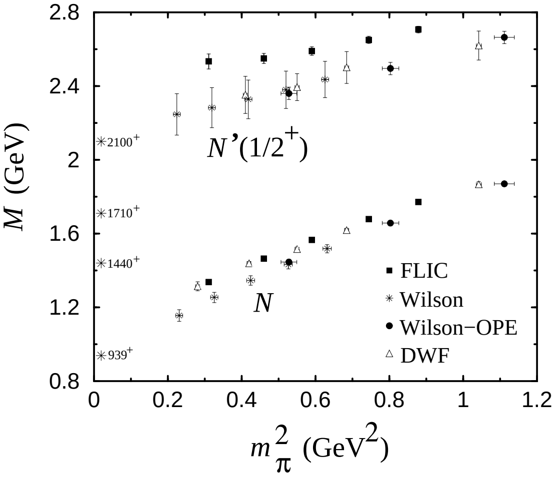

Figure 2. Masses of the nucleon, and the lowest $J^P = \frac{1}{2}^+$ excitation ("N'") obtained from the χ_2 interpolating field. The FLIC and Wilson results are from this analysis.

onalized. In particular, using the naive fitting scheme, it is difficult to obtain a mass splitting between Λ_1^* and Λ_2^*. Once the correlation matrix analysis is performed it is possible to resolve two separate mass states. There is little evidence that the Λ_2 has any significant overlap with the first positive parity excited state, $\Lambda^*(1600)$.

While it seems plausible that nonanalyticities in a chiral extrapolation [10] of N_1 and N_1^* results could eventually lead to agreement with experiment, the situation for the $\Lambda^*(1405)$ is not as compelling. Whereas a 150 MeV pion-induced self energy is required for the N_1, N_1^* and Λ_1 states, 400 MeV is required to approach the empirical mass of the $\Lambda^*(1405)$. This large discrepancy suggests that relevant physics may be absent from simulations in the quenched approximation. The study of more exotic interpolating fields may indicate the the $\Lambda^*(1405)$ does not couple strongly to χ_1^Λ or χ_2^Λ. Investigations at lighter quark masses involving quenched chiral perturbation theory will assist in resolving these issues.

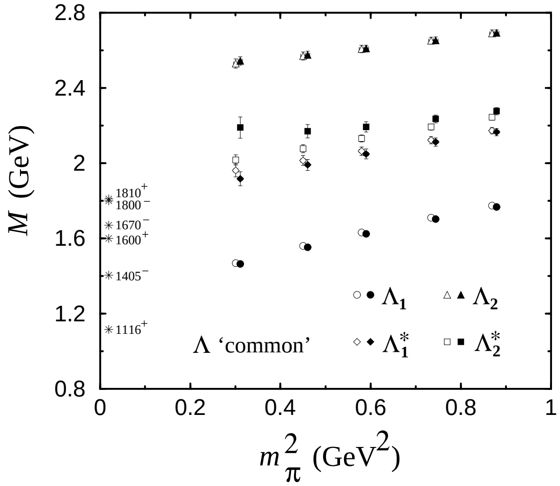

Figure 3. Masses of the $\Lambda(\frac{1}{2}^\pm)$ states, obtained from the $\chi_1^{\Lambda^c}$ and $\chi_2^{\Lambda^c}$ interpolating fields. The symbols are described in the text.

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