$\Lambda(1405)$ and Negative-Parity Baryons in Lattice QCD

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The $\Lambda(1405)$ is still a mysterious particle due to its small mass. It is the lightest negative-parity baryon although it contains a strange valence quark. The conventional quark model, in which the $\Lambda(1405)$ is assigned as the flavor-singlet state in the 70 dimensional representation under the spin-flavor SU(6) symmetry, cannot explain this small mass. Since the mass is just below the $\bar{K}N$ threshold, there is another interpretation based on a five-quark picture, a $\bar{K}N$ bound state or a $\pi\Sigma$ resonance. It is likely that the actual $\Lambda(1405)$ will be a mixed state of these two pictures. However, to clarify the dominant picture is quite important for hyper-nuclear physics and astro-nuclear physics, because the proton in the K^-p bound state suffers from the Pauli blocking effect in nuclear matter. It may influence on the existence of the kaonic nuclei and kaon condensation in neutron stars.

Quenched lattice QCD is a useful tool to distinguish between the three- and the five-quark pictures of the $\Lambda(1405)$, because it is more valence-like than full QCD due to the absence of sea quarks. Recently, we have calculated the $\Lambda(1405)$ and other low-lying negative-parity baryon spectra in anisotropic quenched lattice QCD [1, 2, 3].

We employ the standard Wilson gauge action and the $O(a)$ tadpole-improved Wilson quark action. We adopt the anisotropic lattice since fine resolution in the temporal direction makes us easy to follow the change of heavy-baryon correlations and to determine hadron masses. We take the renormalized anisotropy as $\xi = a_\sigma/a_\tau = 4$, where a_σ and a_τ are the spatial and temporal lattice spacings, respectively. The simulation is carried out on the three lattices: $12^3 \times 96$ at $\beta = 5.75$, i.e., $a_\sigma^{-1} = 1.034(6)$GeV, $16^3 \times 128$ at $\beta = 5.95$, i.e., $a_\sigma^{-1} = 1.499(9)$GeV, and $20^3 \times 160$ at $\beta = 6.10$, i.e., $a_\sigma^{-1} = 1.871(14)$GeV. The scale a_σ^{-1} is determined from the K^* meson mass.

As for the quark mass, we adopt four different values which roughly cover around strange quark mass and correspond to the pion mass being about $0.6-0.9$GeV. We use the standard baryon operators which survive in the nonrelativistic limit: the $(\bar{q}^T C\gamma_5)q$ form for the octet and the $(\bar{q}^T C\gamma_\mu)q$ form for the decuplet. Here, C is the charge conjugation matrix. For the $\Lambda(1405)$, we use the flavor-singlet operator following the assignment of the quark model as $(u^T C\gamma_5 d)s + (d^T C\gamma_5 u)s + (s^T C\gamma_5 u)d$. Both the positive- and negative-parity baryon spectra can be obtained from these operators using the parity projection. In the source operator, each quark is spatially smeared with the Gaussian function with the width ~ 0.4 fm for better overlap with the low-lying states.

The numerical results of the baryon spectrum for the finest $\beta = 6.10$ lattice are shown in Fig.1. The physical u, d and s quark masses are determined with the π and K meson masses. For each baryon, two of quark masses are taken to be the same value, m_1, and the other quark mass m_2 is taken to be an independent value. The baryon masses are then expressed by the function of m_1 and m_2, but the numerical results seem to be well described with the linear form, $m_B(m_1, m_2) = m_B(0,0) + B_B \cdot (2m_1 + m_2)$. Therefore, we fit the baryon spectrum to the linear form in the sum of corresponding pseudoscalar meson mass squared, $\langle m_{\rm PS}^2(m_i)\rangle = 1/N_q \sum_{i=1}^{N_q} m_{\rm PS}^2(m_i, m_i) = 2B \sum_{i=1}^{N_q} m_i$ with $N_q = 3$ for baryons. (See Fig.1.)

From Fig.1, the chiral extrapolated results of the negative-parity baryon spectrum are heavier than those of the corresponding positive-parity sectors for octet and decuplet, as expected. The flavor-singlet negative-parity baryon is, however, lighter than the positive-parity one. This is consistent with the conventional quark model, in which the flavor-singlet positive-parity baryon is assigned as a state with the principal quantum number $N = 2$, while the negative-parity sector has $N = 1$.

Various baryon masses at the $\beta = 6.10$ lattice together with the experimental values are shown in Fig.2. As for the negative-parity baryons, most of the lattice results comparatively well reproduce the experiment. The flavor-singlet baryon is, however, exceptional: its calculated mass of about 1.7GeV is much heavier than the $\Lambda(1405)$ with a difference of more than 300 MeV. The difference between them is actually the largest in all the hadrons in consideration. We also note that the flavor-singlet baryon has one strange valence quark and therefore the systematic error from the chiral extrapolation should be less than that of the nucleon and the delta. Even if one takes the systematic error coming from the quenching effect of 10% level into account, this discrepancy of more than 300 MeV cannot be accepted. Therefore, it is natural to consider that the flavor-singlet baryon is physically different from the $\Lambda(1405)$. The flavor-octet negative-parity Λ baryon mass is almost the same as the flavor-singlet one and thus it also is not likely to be a candidate of the $\Lambda(1405)$.

We have focused on the $\Lambda(1405)$ spectrum in quenched lattice QCD. In our calculation with the anisotropic lattice, the flavor-singlet baryon mass measured with the three-quark operator is found to be about 1.7GeV, which is much heavier than the $\Lambda(1405)$.

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References

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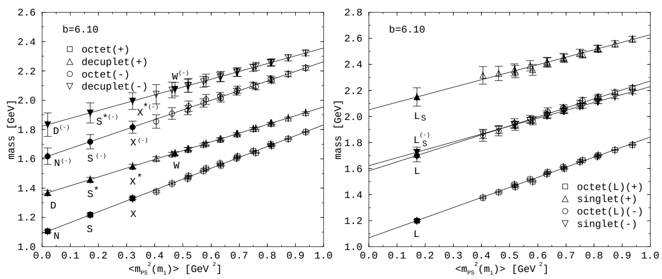

Figure 1: The positive- and negative-parity baryon spectra for the $\beta = 6.10(a_\sigma^{-1} \simeq 1.9\text{GeV})$ lattice. The octet and the decuplet baryons are shown in the left figure and the octet(Λ) and the singlet baryons in the right. The open symbols denote the lattice data and the filled symbols the fitted results from the linear chiral extrapolation.

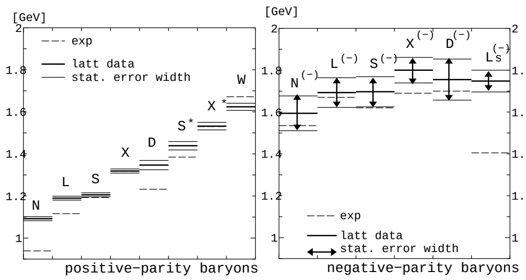

Figure 2: The baryon masses from lattice QCD at $\beta = 6.10$ and experimental values, $N(1535), \Lambda(1670), \Sigma(1620), \Xi(1690), \Delta(1700)$ and $\Lambda(1405)$ for the negative-parity baryons.