Lattice QCD study of pentaquark baryons

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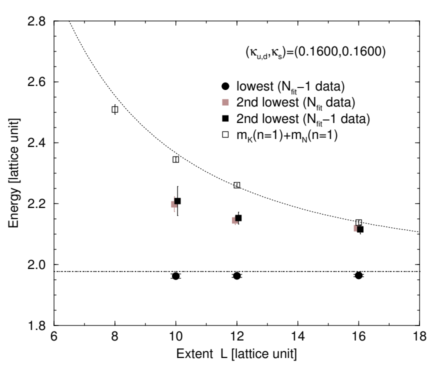
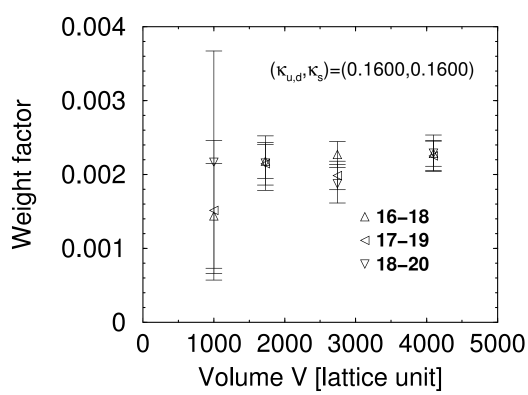
After the discovery [1] of $\Theta^+(1540)$, identifying the properties of the particle is one of the central problems in hadron physics. While the isospin of Θ^+ is likely to be zero, the spin and the parity and the origin of its tiny width still remain open questions [2]. In spite of many theoretical studies on Θ^+, the nature of this exotic particle, including the question about the existence of the particle, is still controversial.

The lattice QCD calculation is considered to be one of the reliable *ab initio* methods directly based on QCD. We then study $(I, J) = (0, \frac{1}{2})$ channel in quenched lattice QCD to search for the possible resonance state [3]. We adopt two independent operators with $I = 0$ and $J = \frac{1}{2}$ and diagonalize the 2×2 correlation matrices by the variational method for all the combinations of lattice sizes and quark masses to extract the first excited state slightly above the NK threshold in this channel. After the careful separation of the states, we investigate the volume dependence of the energy as well as the spectral weight of each state so that we can distinguish the resonance state from NK scattering states. We carry out simulations on four different sizes of lattices, $8^3 \times 24$, $10^3 \times 24$, $12^3 \times 24$ and $16^3 \times 24$ with 2900, 2900, 1950 and 950 gauge configurations using the standard plaquette (Wilson) gauge action at $\beta = 5.7$ and the Wilson quark action. On these conditions, we can detect the possible resonance state lying a few hundreds MeV above the NK threshold avoiding the contaminations of NK scattering states. The hopping parameters for the quarks are $(\kappa_{u,d}, \kappa_s)$=$(0.1600, 0.1650)$, $(0.1625, 0.1650)$, $(0.1650, 0.1650)$, $(0.1600, 0.1600)$ and $(0.1650, 0.1600)$, which correspond to the current quark masses $(m_{u,d}, m_s) \sim (240, 100)$, $(170, 100)$, $(100, 100)$, $(240, 240)$ and $(100, 240)$, respectively in the unit of MeV.

In the left panel, we show the lattice QCD data in $(I, J^P) = (0, 1/2^-)$ channel obtained with the hopping parameters $(\kappa_{\rm u,d}, \kappa_{\rm s}) = (0.1600, 0.1600)$ against the lattice extent L. The filled circles denote the lowest states in this channel and the filled squares represent the 2nd-lowest states. The lower line shows the simple sum $M_N + M_K$ of the nucleon mass M_N and kaon mass M_K. The upper line is the theoretical curve of $\sqrt{M_N^2 + (2\pi/L)^2} + \sqrt{M_K^2 + (2\pi/L)^2}$ with the possible next-smallest lattice momentum $p = 2\pi/L$. The open squares are the lattice QCD data of the sum $M_N(p = 2\pi/L) + M_N(p = 2\pi/L)$ of the nucleon energy $M_N(p = 2\pi/L)$ and the kaon energy $M_K(p = 2\pi/L)$ with the momentum $p = 2\pi/L$. The lowest states show no volume dependence and coincide with $M_N + M_K$, and therefore are concluded to be the NK scattering states with the relative momentum $p = 0$. The small deviations from the lower line implies the smallness of the scattering length in this channel. The 2nd-lowest states clearly deviate from the upperline or the open squares, which makes it rather difficult to regard the 2nd-lowest states as NK scattering states. We then expect the existence of a resonance state slightly above the NK threshold.

For further confirmation, we investigate a spectral weight for the 2nd-lowest state, which behaves as $1/V$ if the state is a two-particle state and shows no volume dependence if the state is a resonance state. The right figure shows the spectral weights of the 2nd-lowest state in this channel in the various lattice volumes. One can see that they show almost no volume dependence, which is another evidence of the existence of a resonance state slightly above the NK threshold in $(I, J^P) = (0, 1/2^-)$ channel.





References

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[2] M. Oka, Prog. Theor. Phys. **112**, 1 (2004) and references therein [arXiv:hep-ph/0406211].
[3] T. T. Takahashi, T. Umeda, T. Onogi and T. Kunihiro, arXiv:hep-lat/0410025; arXiv:hep-lat/0503019.