Anisotropic lattice QCD studies of penta-quarks and tetra-quarks

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We study the penta-quark(5Q) $\Theta^+(1540)$ and the tetra-quark(4Q) $D_{s0}^+(2317)$ by using quenched lattice QCD. We adopt $12^3 \times 96$ anisotropic lattice QCD for high precision measurements, where the temporal lattice spacing is 4 times finer than the spatial ones as $a_s/a_t = 4$. We employ standard gauge action at $\beta = 5.75$ leading to the lattice spacing $a_s \simeq 0.18$ fm, and $O(a)$ improved Wilson (clover) action with $\kappa = 0.1410(0.010)0.1440$, which roughly covers the quark mass region of $m_s \le m_q \le 2m_s$. We use the hybrid boundary condition(HBC) [1] to discriminate a compact resonance state from two-hadron scattering states. HBC is a flavor-dependent spatial BC, which raises the NK and the NK* thresholds by 200−300 MeV in the spatial lattice of the size $L \sim 2$ fm, while a compact 5Q resonance ($uudd\bar{s}$) remains unaffected.

We first consider $J^P = 1/2^\pm$ iso-scalar 5Q state with a non-NK type interpolating field as $\psi \equiv \epsilon_{abc}\epsilon_{ade}\epsilon_{bfg}$ $(u_d^T C\gamma_5 d_e)(u_f^T C d_g) C\bar{s}_c^T$, where $C = \gamma_4\gamma_2$ denotes the charge conjugation matrix, and $a - g$ the color indices. After chiral extrapolation, we obtain $m_{5Q} = 2.25(12)$ GeV for $J^P = 1/2^+$, which is too massive to be identified as $\Theta^+(1540)$. For $J^P = 1/2^-$, we obtain $m_{5Q} = 1.75(4)$ GeV, which is located above the s-wave NK threshold(on the lattice) by about 100 MeV. Although it might be a candidate of $\Theta^+(1540)$ in this sense, HBC analysis indicates that it is an NK scattering state [1].

We next consider $J^P = 3/2^\pm$ iso-scalar 5Q states with three Rarita-Schwinger interpolating fields as $\psi_\mu \equiv \epsilon_{abc}\{(u_a^T C\gamma_5 d_b)u_c \cdot (\bar{s}_d\gamma_\mu d_d) - (u_a^T C\gamma_5 d_b)d_c \cdot (\bar{s}_d\gamma_\mu u_d)\}$, $\psi_\mu \equiv \epsilon_{abc}\{(u_a^T C\gamma_5 d_b)u_d \cdot (\bar{s}_d\gamma_\mu d_c) - (u_a^T C\gamma_5 d_b)d_d \cdot (\bar{s}_d\gamma_\mu u_c)\}$, and $\psi_\mu \equiv \epsilon_{abc}\epsilon_{def}\epsilon_{cfg}\ (u_a^T C\gamma_5 d_b)(u_d^T C\gamma_5\gamma_\mu d_e) C\gamma_5 \bar{s}_g$. Note that $J^P = 3/2^-$ assignment can explain the narrow decay width of $\Theta^+(1540)$ as pointed out by Ref. [2], and that $J^P = 3/2^+$ assignment can be supported by the diquark picture as the LS-partner of $J^P = 1/2^+$ 5Q state [3]. However, after the chiral extrapolations, we obtain only massive 5Q states as $m_{5Q} \simeq 2.1 - 2.2$ GeV for $J^P = 3/2^-$, and $m_{5Q} \simeq 2.4 - 2.6$ GeV for $J^P = 3/2^+$. These 5Q states are too massive to be identified as $\Theta^+(1540)$ [4].

$D_{s0}^+(2317)$ is a tetra-quark(4Q) candidate. It is so far believed to be iso-scalar due to its narrow decay width to $D_s^+\pi^0$. Recently, Terasaki pointed out the iso-vector possibility [5] in order to resolve the experimental constraint in the radiative decay [6] as $\Gamma(D_{s0}^+(2317) \to D_s^{*+}\gamma)/\Gamma(D_{s0}^+(2317) \to D_s^+\pi^0) < 0.052$. If it is iso-vector, it has a manifestly exotic iso-spin partner $D_{s0}^{++}(cu\bar{s}\bar{d})$, which we will consider here mainly in the idealized $\mathrm{SU}(4)_f$ limit. We employ a *diquark-antidiquark-type* interpolating fields as $\phi \equiv \epsilon_{abc}\epsilon_{dec}(u_a^T C\gamma_5 c_b)(\bar{d}_d^T C\gamma_5 \bar{s}_e)$. We use a spatial BC similar to HBC [7, 8]. We will refer to it as "*HBC*" as well. So far, we obtain a positive signal only in the light-quark sector. We find that, with HBC, 4Q states appear below the raised threshold by about 100 MeV, and that its chiral behavior is different from that of the two-PS-meson threshold [7, 8]. This indicates the existence of compact 4Q resonance state at $m_{4Q} \simeq 1.1$ GeV in the idealized $\mathrm{SU}(4)_f$ chiral limit. Note that, as long as the contribution from the disconnected diagram is negligible, $D_{s0}^{++}(cu\bar{s}\bar{d})$ is identical with $f_0(ud\bar{u}\bar{d})$. Then, this 4Q state may be identified as one of the scalar-nonet $f_0(980)$. For comparison, we also calculate the scalar $q\bar{q}$ masses. After chiral extrapolation, we obtain $m_{q\bar{q}} \simeq 1.35$ GeV, which may correspond to $f_0(1370)$ or $a_0(1450)$ consistent with the quark-model assignment. In this way, we see that the 4Q states can be lighter than the conventional $q\bar{q}$ in the light quark-mass region.

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