Holographic heavy-quark symmetry[†]

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Hadrons containing heavy quarks, i.e., charm and bottom quarks, have attracted much interest in hadron and nuclear physics. Accelerator experiments have found rich spectra of heavy hadrons for conventional states, three-quark baryons and quark-antiquark mesons, and exotic hadrons having complex structures such as multiquark states and hadronic composite states[1)]. Various structures of heavy hadrons are generated by the nature of internal quark potentials and/or hadron-hadron interactions which result from fundamental phenomena of quantum chromodynamics (QCD).

In heavy quark sectors, a new symmetry that has not been appeared in the light-quark sector is expected to be important. It is called heavy-quark spin symmetry[2)], and it emerges because of the suppression of the spin-dependent interaction between quarks, which is inversely proportional to quark masses. This symmetry leads to a specific feature: mass degeneracy of heavy hadrons having different spins. In the case of mesons, we find small mass splittings between spin-0 pseudo-scalar mesons and spin-1 vector mesons in experimental results, e.g., the mass splitting of BB^* ($\sim$45 MeV) in the bottom-quark sector is much smaller than that of KK^* ($\sim$ 400 MeV) in the strange-quark sector. The symmetry also affects decays and productions of heavy hadrons with different spins. Hence, the heavy-quark spin symmetry plays a significant role in heavy-hadron spectroscopy.

The spectra of heavy hadrons have been studied using various theoretical approaches, such as the quark model and lattice QCD. In addition, we found that the gauge/gravity correspondence[3)] is a promising approach because it provides powerful methods to deal with strongly coupled theories.

The gauge/gravity correspondence has been applied to investigate hadron spectra by introducing dynamical quarks described by excitations on probe D-branes. For example, $\mathcal{N}=2$ hypermultiplet flavors (= quark multiplets) added to $\mathcal{N}=4$ SU(N_c) super Yang-Mills theory are realized by introducing N_f probe D7-branes on the $\mathrm{AdS}_5\times\mathrm{S}^5$ background (generated by N_c D3-branes) on the gravity side[4)]. In this model, the quarks are given as fundamental strings stretched between D3- and D7-branes. The masses of pseudo-scalar and vector mesons are obtained as fluctuations of the scalar and vector fields on the flavor D-branes[4)].

In the gauge theory holding supersymmetry, however, both pseudo-scalar and vector mesons are members of the same multiplet, and the masses are completely degenerate regardless of the value of the quark mass. Even when the supersymmetry is broken by finite temperature, Shark-Schwartz compactification, etc, the supersymmetry is recovered in the heavy-quark limit (i.e., in the UV limit) in most of the top-down models. Hence, the presence of the heavy-quark spin symmetry has not been obvious in the gauge/gravity duality. In order to determine whether the heavy-quark spin symmetry exists, we need to investigate meson mass degeneracies in theories that are non-supersymmetric even in the UV region.

In this study, we propose a semi-bottom-up, deformed D3-D7 model. The background geometry is deformed from the conventional $\mathrm{AdS}_5\times\mathrm{S}^5$ and obtained as

$$ds^2_{str}=r^{2\alpha}\eta_{\mu\nu}dx^\mu dx^\nu+R^2r^{-2\beta}\left(\frac{dr^2}{r^2}+r^{2\delta}d\Omega_5^2\right), \tag{1}$$

$$e^\phi=g_0r^{-4\gamma}, \tag{2}$$

in the string frame, where R corresponds to the radius of AdS_5, $d\Omega_5^2$ represents the metric of S^5, and ϕ is the dilaton. Here r is the non-dimensional coordinate. The background geometry is given in the UV leading form and generally holds no supersymmetry or conformal symmetry. We introduce 4 deformation parameters $(\alpha,\beta,\delta,\gamma)$ for the background, but they are constrained by several conditions so that the theory would have physically reasonable properties. The standard D3 background corresponds to $(\alpha,\beta,\delta,\gamma)=(1,0,0,0)$. We investigate the spectra of the pseudo-scalar and vector quarkonia at the limit $m_Q\to\infty$, computed as the fluctuations of the fields on the flavor D7-brane placed on this background.

We observed a slight mass difference between pseudo-scalar and vector quarkonia, which is at most $\simeq 1.5\%$, even in the non-supersymmetric analysis. The mass degeneracy is found in not only ground states but also excited states.

References
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