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Lattice searches for tetraquarks: X,Y,Z states and light scalars

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Abstract. Searches for tetraquarks and mesonic molecules in lattice QCD are briefly reviewed. In the light quark sector the most serious candidates are the lightest scalar resonances σ, κ, a_0 and f_0. In the hidden-charm sector I discuss lattice simulations of $X(3872)$, $Y(4140)$ and $Z^+(4430)$. The most serious challenge in all these lattice studies is the presence of scattering states in addition to possible tetraquark/molecular states. The topics covered in this talk are presented in [1], so only a brief outline is given below.

1 Introduction

Some of the observed resonances, i.e. light scalars and some hidden-charm resonances, are strong candidates for tetraquarks $[qq][\bar{q}\bar{q}]$ or mesonic molecules $(\bar{q}q)(\bar{q}q)$. Current lattice methods do not distinguish between both types, so a common name "tetraquarks" will be often used to denote both types of $\bar{q}\bar{q}qq$ Fock components below.

In order to extract the information about tetraquark states, lattice QCD simulations evaluate correlation functions on $L^3 \times T$ lattice with tetraquark interpolators $\mathcal{O} \sim \bar{q}\bar{q}qq$ at the source and the sink $C_{ij}(t) = \langle 0|\mathcal{O}_i(t)\mathcal{O}_j^\dagger(0)|0\rangle_{\mathbf{p}=0} = \sum_n Z_i^n Z_j^{n*}\, e^{-E_n\, t}$. If the correlation matrix is calculated for a number of interpolators $\mathcal{O}_{i=1,..,N}$ with given quantum numbers, the energies of the few lowest physical states E_n and the corresponding couplings $Z_i^n \equiv \langle 0|\mathcal{O}_i|n\rangle$ can be extracted from the eigenvalues $\lambda^n(t) = e^{-E_n(t-t_0)}$ and eigenvectors $\mathbf{u}^n(t)$ of the generalized eigenvalue problem $C(t)\mathbf{u}^n(t) = \lambda^n(t,t_0)C(t_0)\mathbf{u}^n(t)$.

In addition to possible tetraquarks, also the two-meson scattering states M_1M_2 unavoidably contribute to the correlation function and this presents the main obstacle in extracting the information about tetraquarks. The scattering states $M_1(k)M_2(-k)$ at total momentum $\mathbf{p} = \mathbf{0}$ have discrete energy levels $E_{M_1M_2} \simeq E_{M_1}(k) + E_{M_2}(-k)$ with $E_M(k) = \sqrt{m_M^2 + \mathbf{k}^2}$ and $\mathbf{k} = \frac{2\pi}{L}\mathbf{n}$ in the non-interacting approximation when periodic boundary conditions in space are employed.

The resonance manifests itself on the lattice as a state in addition to the discrete tower of scattering states and it is often above the lowest scattering state (at $E \simeq M_1 + M_2$ for S-wave decay). So the extraction of a few states in addition to the ground state may be crucial. Once the physical states are obtained, one needs to determine whether a certain state corresponds to a one-particle (tetraquark) or a two-particle (scattering) state. The available methods to distinguish both are reviewed in [1] and all exploit the approximations employed on the lattice: the finite spatial or the finite temporal extent of the lattice.

2 Some results

The question whether the light scalar mesons σ and κ have a sizable tetraquark component has been addressed in simulation [2]. The energy spectrum has been determined using a number of $\bar{q}\bar{q}qq$ interpolators in a dynamical as well as quenched simulation. In $I = 0$ channel, an additional light state has been found on top of the expected scattering states $\pi(0)\pi(0)$ and $\pi(\frac{2\pi}{L})\pi(-\frac{2\pi}{L})$. This additional state may be related to the observed σ with the sizable tetraquark component. Similarly, an additional light state on top of $K(0)\pi(0)$ and $K(\frac{2\pi}{L})\pi(-\frac{2\pi}{L})$ scattering states has been found in the $I = 1/2$ channel; this state may be related to the observed κ with the sizable tetraquark component. Other lattice simulations aimed at the similar question are reviewed in [1].

The simulations [3–5] aimed at determining the nature of hidden-charm resonances $X(3872)$, $Y(4140)$ and $Z^+(4430)$, extract only the ground state in the given J^{PC} channel using an exponential fit $C(t) \propto e^{-E_1 t}$. Then they try to determine whether the extracted state is a scattering state or a tetraquark/molecular state using the available criteria.

The $\bar{c}\bar{u}cu$ and $\bar{c}\bar{s}cs$ ground states with $J^{PC} = 1^{++}$ in the quenched simulation [3] seem to behave as one-particle states. They have been found at 3890 ± 30 MeV ($\bar{c}\bar{u}cu$) and at 4100 ± 50 MeV ($\bar{c}\bar{s}cs$), which is indeed close to the observed resonances $X(3872)$ and $Y(4140)$. Note however, that the lowest scattering states DD^* and $J/\psi\phi$ are extremely close and that they should be found in addition to the one-particle states before the indication for the tetraquarks/molecules can be fully trusted.

The dynamical simulation [4] studies the DD^* scattering, which is related to the resonance $X(3872)$. The attractive interaction between D and D^* has been found, with a possible indication for a bound-state formation at small m_π.

The quenched simulation [5] searched for $Z^+(4430)$ in $J^P = 0^-,\ 1^-,\ 2^-$ channels using the molecular D_1D^* interpolators. The most reliable results are obtained for $J^P = 0^-$, where the attractive interaction between D_1 and D^* has been observed.

The only dynamical simulation that determined several energy levels using $\bar{c}\bar{q}cq$ and $\bar{c}c$ interpolators in the same variational basis was a pioneering simulation [6]. So far it found some candidates for $D\bar{D}$ scattering states and for charmonia, but no candidates for tetraquarks yet.

3 Conclusions

Proving a sizable tetraquark or molecular Fock component in a hadronic resonance using lattice QCD simulation is not an easy task. A resonance appears as a state in addition to the discrete tower of scattering states. So the extraction of few states in addition to the ground state is expected to be crucial. Given the resulting physical eigenstates, one needs to determine whether a certain state corresponds to a one-particle (tetraquark/molecular) or a two-particle (scattering) state.

There are some indications for an additional state in $I = 0,\ 1/2$ light scalar channels, which might correspond to observed σ and κ with strong tetraquark components [2]. There have been surprisingly few lattice simulations of very interesting experimentally observed exotic XYZ resonances, and much more work on the lattice is needed to pin down their structure.

References

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