Tetraquark and molecule charmonium states on the lattice

O.E. Solovjeva in collaboration with Dr. E.V. Luschevskaya , Prof. O.V. Teryaev

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Introduction

Some problems:

- What is the structure X,Y,Z states?
- How can we construct correlation functions for various interpretations of these states?

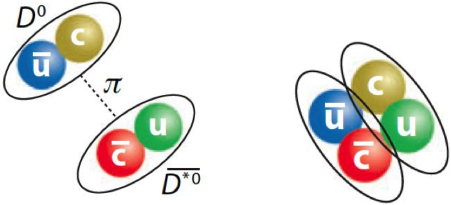
Charmonium spectroscopy (XYZ mesons)

Several exotic states:

1. $X(3872)$ near DD^* threshold, $J^{PC} = 1^{++}$
   $X(3872) \to J/\psi\rho,\ J/\psi\omega,\ D\bar{D}^*$ etc.;
2. $X(3900)$, $J^{PC} = 1^{+-}$. It was discovered in $J/\psi\pi^{\pm}$ inv. mass by BESII and confirmed by Belle and CLEOc, possible quark structure is $\bar{c}c\bar{d}u$;
3. $X(4140)$, $J^{PC} = 1^{++}$ was found in J/ϕ inv. mass by CDF and by CMS and D0.
4. and many more XYZ mesons

1. $D^{(*)}\bar{D}$ molecules, composed of a charmed meson $D^{(*)}$ and an antimeson $\bar{D}$,
2. tetraquark states consisting of diquark-antidiquark pairs, bound by QCD forces,
3. $\bar{c}cg$ hybrid states consisting of charm-anticharm quark pair and additional gluons, and
4. a compact $\bar{c}c$ core, bound inside a light meson, hadro-charmonium.

We consider 2 popular interpretations forX(3872) or X(...) with $J^{PC} = 1^{++}$:
tetraquark and $D^{(*)}\bar{D}$ molecules



D^0–$\overline{D^{*0}}$ "molecule"   Diquark–diantiquark

X(3872)

The correlation function corresponding to the tetraquark state

$$\langle \bar{c}(x)\gamma_\mu c(x)\bar{q}(x)\gamma_\mu q(x)\bar{c}(y)\gamma_\mu c(y)\bar{q}(y)\gamma_\mu q(y))\rangle_A \simeq$$

$$Tr\left(\frac{1}{D+m_c}(x,y)\gamma_\mu \frac{1}{D+m_c}(x,y)\gamma_\mu\right)\cdot Tr\left(\frac{1}{D+m_q}(x,y)\gamma_\mu \frac{1}{D+m_q}(x,y)\gamma_\mu\right).$$

The correlation function corresponding to the molecule state

$$\langle \bar{c}(x)\gamma_\mu q(x)\bar{c}(x)\gamma_\mu q(x)\bar{c}(y)\gamma_5 q(y)\bar{c}(y)\gamma_5 q(y))\rangle_A \simeq$$

$$Tr\left(\frac{1}{D+m_c}(x,y)\gamma_\mu \frac{1}{D+m_q}(x,y)\gamma_\mu\right)\cdot Tr\left(\frac{1}{D+m_c}(x,y)\gamma_5 \frac{1}{D+m_q}(x,y)\gamma_5\right)$$

Details of the configurations

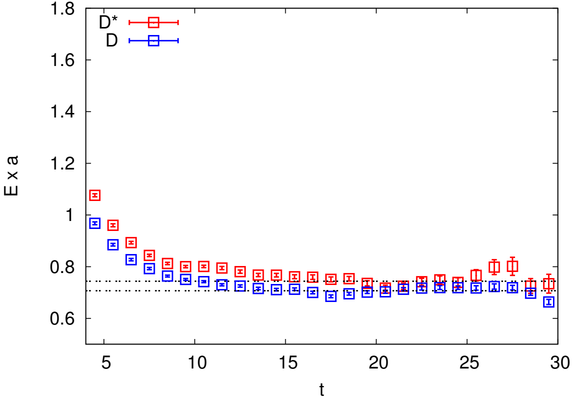
Configurations of the QCDSF collaboration

Ensemble	β	V	$a,\ fm$	κ_0	$M_\pi L$	$L,\ fm$
E_I	5.65	$32^3 \times 64$	0.068	0.122005	4.67	2.19

m_c is fixed by tuning the spin-averaged kinetic mass $\frac{1}{4}(m_{\eta_c} + 3m_{J/\psi})$ to its physical value (D. Mohler, S. Prelovsek and R. Woloshyn, Phys.Rev. **D87**, 034501 (2013), [arXiv:1208.4059].) (We are in progress...)

Preliminary! D and D^* mesons

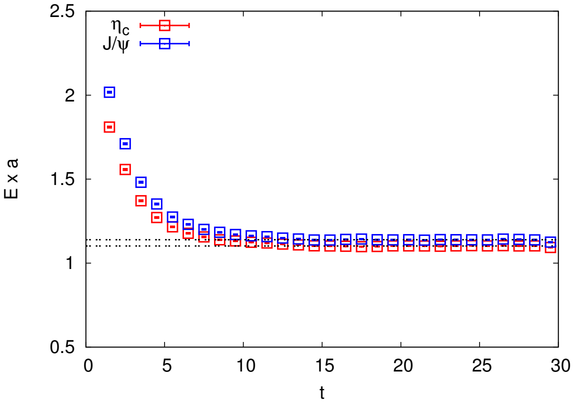
$$a = 0.068\ fm = 0.345\ \frac{1}{GeV}$$



$$E_D + E_{D^*} = (4192 \pm 24)\ MeV$$

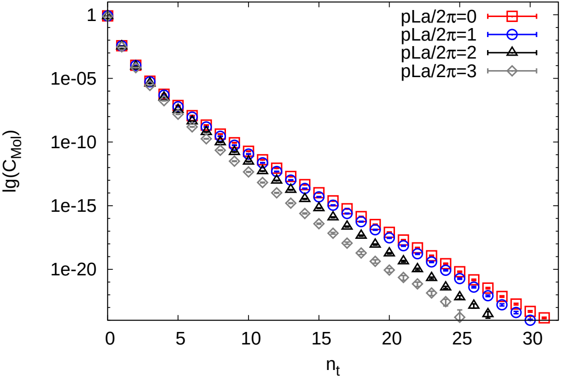
Preliminary! η_c and J/ψ

$$a = 0.068\ fm = 0.345\ 1/GeV$$



spin-averaged kinetic mass $\frac{1}{4}(m_{\eta_c} + 3m_{J/\psi}) = (3274 \pm 2)\ MeV$

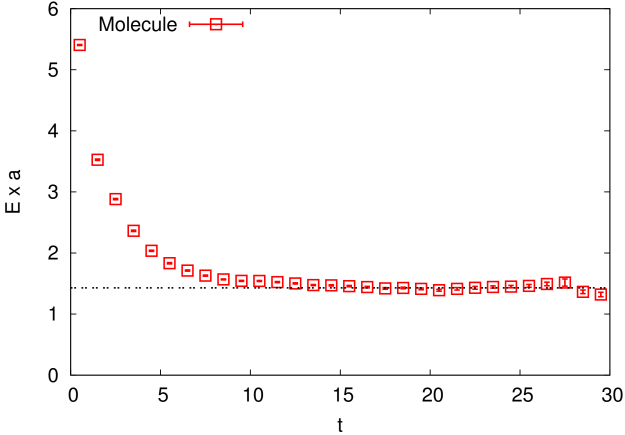
Correlation function of the molecule



Lattice $V = 32^3 \times 64$, $a = 0.068$ fm, $N_f = 2 + 1$ dynamical quarks, 256 lattice configurations

Preliminary! Energy of the molecule

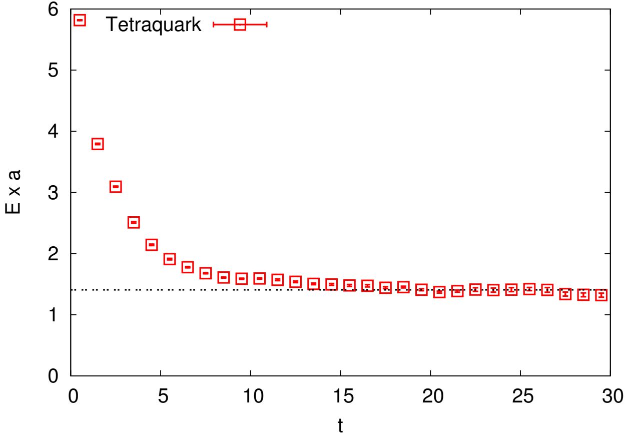
$$Tr\left(\frac{1}{D+m_c}(x,y)\gamma_\mu\frac{1}{D+m_q}(x,y)\gamma_\mu\right)\cdot Tr\left(\frac{1}{D+m_c}(x,y)\gamma_5\frac{1}{D+m_q}(x,y)\gamma_5\right)$$



$$E_{eff}^{t_0}=a^{-1}ln\frac{C(t,t_0)}{C(t+a,t_0)},\quad E_{Mol}=(4140\pm 19)\ MeV$$

Preliminary! Energy of the tetraquark

$$Tr\left(\frac{1}{D+m_c}(x,y)\gamma_\mu \frac{1}{D+m_c}(x,y)\gamma_\mu\right)\cdot Tr\left(\frac{1}{D+m_q}(x,y)\gamma_\mu \frac{1}{D+m_q}(x,y)\gamma_\mu\right).$$



$$E_{Tetr} = (4080 \pm 25)\ MeV, \quad E_{D\bar{D}} = (3878 \pm 48)\ MeV$$

Preliminary! Comparison lattice data and experimental value (PDG 2017) for X(3872)

$X(3872)$	$m_X - \frac{1}{4}(m_{\eta_c} + 3m_{J/\psi})$	$m_X - (m_{D^0} + m_{D^{0*}})$	$m_X - m_{J/\psi}$
latt. molecule	868 ± 17 MeV	-50 ± 5 MeV	778 ± 23 MeV
latt. tetraquark	806 ± 23 MeV	-112 ± 1 MeV	840 ± 17 MeV
experiment	803 ± 1 MeV	-0.14 ± 0.22 MeV	775 ± 4MeV

$X(3872)$ from DD^* scattering on the lattice

9 new interpolators have been added into consideration

$$m(X(3872)) - (m_D + m_{D^*}) = -8 \pm (15)\ MeV$$

The part of them corresponds to the tetraquark structure $[\bar{c}\bar{q}]_g[cq]_g$

$$m(X(3872)) - (m_D + m_{D^*}) = -9 \pm (8)\ MeV$$

arXiv:1503.03257 [hep-lat] , S.Prelovsek, L. Leskovec

$$m(X(3872)) - (m_D + m_{D^*}) = -13 \pm (6)\ MeV$$

simulations with $N_f = 2 + 1 + 1$ dynamical quarks
arXiv:1411.1389 [hep-lat] , S.Lee et al (Fermilab Lattice and MILC)

Conclusions

1. We have calculated the energies of the tetraquark and molecular states
2. We have obtained values of $m_X - \frac{1}{4}(m_{\eta_c} + 3m_{J/\psi}), m_X - m_{J/\psi}$ roughly close to the physical values .
3. Obtained states may be interpreted as the candidate for the X(3872) state (preliminary) (we should tune m_c).

Acknowledgments

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Thank you for your attention!