BLED WORKSHOPS
IN PHYSICS
VOL. 16, NO. 1
p. 87

Proceedings of the Mini-Workshop
Exploring Hadron Resonances
Bled, Slovenia, July 5 - 11, 2015

Vector and scalar charmonium resonances with lattice QCD*

Luka Leskovec[a], C.B. Lang[b], Daniel Mohler[c], Saša Prelovsek[a,d]

[a]Jozef Stefan Institute, Ljubljana, Slovenia
[b]Institute of Physics, University of Graz, Graz, Austria
[c]Fermi National Accelerator Laboratory, Batavia, Illinois, USA
[d]University of Ljubljana, Ljubljana, Slovenia

Abstract. We study $\bar{D}D$ scattering with lattice QCD in order to determine the masses and decay widths of vector and scalar charmonium resonances above the open charm threshold. In the vector channel, the resulting elastic phase shift yields the familiar vector resonance $\psi(3770)$. At $m_\pi = 156$ MeV the simulated resonance mass and decay width agree with experimental data within the large statistical uncertainty. In the scalar channel we study the first excitation of the $\chi_{c0}(1P)$, as there is presently no commonly accepted candidate for it. We simulate $\bar{D}D$ scattering in s-wave with lattice QCD and investigate several different scenarios. The simulated data suggests an unobserved narrow resonance with the mass slightly below 4 GeV. Further studies are needed to shed light on the puzzle of the excited scalar charmonia.

Charmonium states below the open-charm threshold $\bar{D}D$ are well understood theoretically and experimentally, as their masses, decay widths and selected transition matrix elements are experimentally among the most precisely known quantities of the Standard Model. Theoretically these states are described either by models motivated by QCD or by lattice QCD. Recent lattice QCD studies have calculated the charmonium mass splittings taking into account both the continuum limit and extrapolating the results down to the physical point [1, 2], while radiative transition rates between low-lying charmonia have been determined for example in Refs. [3, 4].

In this work we use lattice QCD to study the charmonium and charmonium-like states near or above the open-charm thresholds. Our focus lies in the effects of strong decay of near threshold charmonium or charmonium-like states to a pair of charmed mesons $\bar{D}D$. Our assumptions of elastic $\bar{D}D$ scattering seem well justified from a phenomenological point of view as any possible open-charm threshold effects would arise from coupling of the resonances to the $\bar{D}D$ decay channel.

In our calculations we use two ensembles of gauge configurations with the parameters listed in [5]. Ensemble (1) has $N_f = 2$ and $m_\pi = 266$ MeV, while ensemble (2) has $N_f = 2 + 1$ and $m_\pi = 156$ MeV. Further details on the gauge ensembles and our implementation of charm quarks may be found in [6–8] for

* Talk delivered by Luka Leskovec

ensemble (1) and in [9, 10] for ensemble (2). We treat the charm quark with the Fermilab method [11, 12] to minimize the heavy-quark discretization effects. In our implementation, the heavy mesons obey the dispersion relation:

$$E_M(p) = M_1 + \frac{\mathbf{p}^2}{2M_2} - \frac{(\mathbf{p}^2)^2}{8M_4^3} + \dots , \quad (1)$$

where $\mathbf{p} = \frac{2\pi}{L}\mathbf{q}$, $\mathbf{q} \in N^3$ and M_1, M_2 and M_4 are the parameters of the dispersion relation.

To investigate the charmonium resonance in elastic $\bar{D}D$ scattering we require also the dispersion relation for D mesons, $E_D(p)$. As D mesons include the charm quark their dispersion relation is also given by Eq. (1) with parameters M_1, M_2 and M_4 for D mesons listed in [5].

We study two specific channels, the vector charmonium channel with $J^{PC} = 1^{--}$, where the J/ψ, $\psi(2S)$, $\psi(3770)$ and other resonances are present, and the scalar charmonium channel with $J^{PC} = 0^{++}$, where the $\chi_{c0}(1P)$ is present.

In the vector channel we focus on the near open-charm threshold states $\psi(3770)$ and $\psi(2S)$ and the effect of the $\bar{D}D$ threshold on them. The $\psi(3770)$ with $M = 3773.15 \pm 0.33$ MeV and $\Gamma = 27.2 \pm 1.0$ MeV is located only $\simeq 45$ MeV above $\bar{D}D$ threshold [13, 14]. The $\psi(3770)$ dominant decay mode is $\psi(3770) \to \bar{D}D$ in p-wave with a branching fraction of 0.93^{+8}_{-9} [13]. It is a well-established experimental resonance and is generally accepted to be predominantly the conventional $^{2s+1}nL_J = ^3 1D_1$ $\bar{c}c$ state [15].

In the scalar channel the only established scalar charmonium state is the $\chi_{c0}(1P)$, interpreted as the $^3 1P_0$ $\bar{c}c$ and it is located well below the open charm threshold. A further known resonance, the $X(3915)$ with a decay width of 20 ± 5 MeV is seen only in the $J/\psi\,\omega$ and $\gamma\gamma$ decay channels [13]. While BaBar has determined its J^P quantum numbers to be 0^+ [16], their determination assumes that a $J^P = 2^+$ resonance would be produced in the helicity 2 state, which does not necessarily hold for exotic mesons[1] [18]. Consequently the PDG recently assigned the $X(3915)$ to the $\chi_{c0}(2P)$ [13], however certain convincing reasons given by Guo & Meissner [19] and Olsen [20] raise doubts about this assignment:

- The dominant decay mode is expected to be a "fall-apart" mode into $\bar{D}D$, which would to a broad resonance. $m_{D\bar{D}}$ invariant mass spectra of various experiments show no evidence for $X(3915) \to D\bar{D}$.
- The partial decay width for the OZI suppressed $X(3915) \to \omega J/\psi$ seems large as detailed in Ref. [19], which in turn results in contradicting limits for this decay in Ref. [20].

To study the vector and scalar charmonium resonance we performed a lattice QCD calculation of elastic $\bar{D}D$ scattering in p-wave and s-wave. Several $\bar{c}c$ and $D\bar{D}$ interpolating fields were used in both channels, where the (stochastic) distillation method [21, 22] was used to evaluate the Wick contractions.

In the vector channel, the well known $\psi(3770)$ resonance is present just above $\bar{D}D$ threshold. We performed two scattering analyses [23]: in the first case (a) taking into account the $\psi(3770)$ and $\bar{D}D$ and in the second case (b) also the $\psi(2S)$ to

[1] See Ref. [17] on why the $X(3915)$ could be a $J = 2$ resonance.

investigate its effects on the $\bar{D}D$ threshold on the $\psi(2S)$ [24]. The results for both cases are presented in Table 1. Our determination of the $\psi(3770)$ decay width

	Ensemble (1)		Ensemble (2)		exp
	case (a)	case (b)	case (a)	case (b)	$D^+D^-/D^0\bar{D}^0$
$\psi(3770)$					
m_R [GeV]	3.784(7)(10)	3.774(6)(10)	3.786(56)(10)	3.789(68)(10)	3.77315(33)
g (no unit)	13.2(1.2)	19.7(1.4)	24(19)	28(21)	18.7(1.4)
$\psi(2S)$					
m_B [GeV]		3.676(6)(9)		3.682(13)(9)	3.686109^{+12}_{-14}

Table 1. Parameters of the various Breit-Wigner fits for the vector resonance $\psi(3770)$ and bound state $\psi(2S)$. The $\psi(3770) \to D\bar{D}$ width $\Gamma = g^2p^3/(6\pi s)$ is parametrized in terms of the coupling g and compared the value of the coupling derived from experiment [13]. The first errors are statistical and the second errors (where present) are from the scale setting uncertainty. The experimental data and errors are based on PDG values.

might be affected by the $\Psi(4040)$ on Ensemble (1), however Ensemble (2) does not suffer from this issue and the determination of the resonance parameters is more reliable on Ensemble (2).

In the scalar channel the scattering analysis was performed only on Ensemble (1), as the resulting scattering data on Ensemble (2) (with $m_\pi = 156$ MeV) is too noisy. The calculation on Ensemble (1) (with $m_\pi = 266$ MeV) renders the scattering phase shift only at a few values of the $\bar{D}D$ invariant mass, which does not allow for a clear answer to the puzzles in the scalar channel. We investigated several different models for the scattering phase shift and have found that our data supports the existence of single narrow resonance slightly below 4 GeV with a decay width $\Gamma[\chi'_{c0} \to D\bar{D}] \leq 100$ MeV if the $\chi_{c0}(1P)$ is treated as a $\bar{D}D$ bound state. The other scenarios with only one narrow resonance state, a broad resonance or two nearby resonances are not supported by our data, however we cannot exclude these possibilities with statistical certainty.

The full results of this study presented at the Bled workshop and highlighted here can be found in Ref. [5]. The current situation at least in the scalar charmonium is not clear. To clarify the higher lying scalar states further experimental and lattice QCD efforts are required to map out the s-wave $D\bar{D}$ scattering in more detail. In the vector channel most issues seem clear, however small discrepancies appear due to different assumptions in the analyses. Future lattice studies of these states should be able to illuminate whether the assumptions are justified.

We are grateful to Anna Hasenfratz and the PACS-CS collaboration for providing the gauge configurations. The calculations were performed on computing clusters at Jozef Stefan Institute and the University of Graz.

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Vektorske in skalarne resonance čarmonija v kromodinamiki na mreži

Luka Leskovec[a], C. B. Lang[c], Daniel Mohler[d] in Saša Prelovšek[a,b]

[a] Institut Jožef Stefan, Ljubljana, Slovenija
[b] Univerza v Ljubljani, Ljubljana, Slovenija
[c] Institute of Physics, University of Graz, Graz, Austria
[d] Fermi National Accelerator Laboratory, Batavia, Illinois, USA

Proučujemo sipanje mezonov $\bar{D}$ na D s kromodinamiko na mreži, da bi določili mase in razpadne širine vektorskih in skalarnih resonanc čarmonija nad pragom za razpad v čarobne mezone. V vektorskem kanalu dobimo znano resonanco $\psi(3770)$. Simulacija pri vrednosti pionove mase $m_\pi = 156$ MeV da maso in razpadno širino resonance, ki se ujema z eksperimentalnimi podatki znotraj velike statistične negotovosti. V skalarnem kanalu proučujemo prvo vzbujeno stanje $\chi_{c0}(1P)$, za katero ni zaenkrat nobenega sprejetega kandidata. Za sipanje $\bar{D}$ na D v s-valu raziskujemo razne scenarije. Simulacija nakazuje še neopaženo ozko resonanco z maso malo pod 4 GeV. Potrebne so nadaljnje raziskave, da bi osvetlili uganke pri skalarnih vzbujenih stanjih čarmonija.

Resonance v modelu Nambuja in Jona-Lasinia

Mitja Rosina

Fakulteta za matematiko in fiziko, Univerza v Ljubljani, Jadranska 19, p.p.2964, 1001 Ljubljana, Slovenija in Institut J. Stefan, 1000 Ljubljana, Slovenija

Pred leti smo sestavili rešljivo verzijo modela Nambuja in Jona-Lasinia, ki še vedno ustrezno opiše spontani zlom kiralne simetrije in pojav mezonov pi. Njeni značilnosti sta regularizacija polja v škatli s periodičnimi robnimi pogoji ter poenostavljena kinetična energija in interakcija. Sedaj nas pa zanima opis resonanc, kadar so na voljo le diskretne laste vrednosti energije. Kot zgled navajamo mezon σ. Raziskava je lahko poučna za podobne probleme pri kromodinamiki na mreži.

Roperjeva resonanca — ignoramus ignorabimus?

S. Širca

Fakulteta za matematiko in fiziko, Univerza v Ljubljani, Jadranska 19, p.p.2964, 1001 Ljubljana, Slovenija in Institut J. Stefan, 1000 Ljubljana, Slovenija

V tem prispevku ponudimo kratek pregled nekaterih zadnjih dosežkov na področju raziskav Roperjeve resonance. Naštejemo nekaj najbolj razburljivih eksperimentalnih rezultatov iz centrov MAMI in Jefferson Lab ter drugih laboratorijev; osvetlimo nekaj poskusov, da bi razložili naravo te zagonetne strukture v okviru modelov s kvarkovskimi in mezonskimi ali barionskimi in mezonskimi prostostnimi stopnjami; in odpremo vpogled v znaten napredek, ki so ga v zadnjih letih naredili kromodinamski računi na mreži.