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Z_c States in a Chiral Quark Model

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Since the discovery of the $X(3872)$ in 2003 several states that do not accommodate on the naive quark model have been discovered by several Collaborations. Among them, the Z_c charged states are natural candidates for tetraquarks or meson-meson molecules, since their charge force a minimal quark content $c\bar{c}n\bar{n}$ with n a light quark. Additionally, their strong coupling to two-meson channels such as J/ψ and the closeness of their mass to $D^{(*)}\bar{D}^{(*)}$-channels stimulates different theoretical interpretations, from molecules to tetraquarks or simple kinematic effects.
In this work we perform, in the framework of the constituent quark model, a coupled-channels calculation of the isospin-1 $J^{PC} = 1^{+-}$ sector including $D^{(*)}\bar{D}^{(*)} + h.c.$, $\pi J/\psi$ and $\rho\eta_c(1S)$ channels. The meson-meson interaction is described in terms of quark-quark interaction using the Resonating Group Method (RGM). For the quark-quark interaction a nonrelativistic quark model is employed, which satisfactorily describes a wide range of properties of (non)conventional hadrons containing heavy quarks, thus we present a parameter-free calculation.
The results support that both $Z_c(3900)^{\pm}$ and $Z_c(4020)^{\pm}$ arise as virtual states below the $D\bar{D}^* + h.c.$ and $D^*\bar{D}^*$ thresholds, respectively, which causes an enhancement over such thresholds, describing the available data. This conclusion coincides with that of the other calculations made with effective Lagrangians.

KEYWORDS: Potential models, Charmed mesons, Exotic mesons

1. Introduction

Since the so called November revolution in 1974, up to the discovery of the $X(3872)$ by the Belle Collaboration [1] in 2003, all discovered heavy mesons were well accommodated in the naive quark model. However the $X(3872)$ was measured on the $\pi^+\pi^- J/\psi$ final state, with the pions coming from the decay of a ρ meson, being this an isospin-1 channel. This was a clear indication that the state could not be a simple $c\bar{c}$ naive quark model state. The closeness of its mass to the $D\bar{D}^*$ threshold pushed the molecular interpretation, and calculations beyond the naive quark model were developed. In this framework the state is understood as a mixture between molecular and naive quark model components [2, 3].

Very soon after, the $D_{s0}(2317)$ and the $D_{s1}(2460)$ were discovered by the BaBar [4] and CLEO [5] Collaborations respectively. The states are well below naive quark model predictions and they are also seen as good candidates for molecular or mixed states [6, 7].

However, the unavoidable evidences of states beyond the naive quark model arrived in 2011 with the discovery of the charged $Z_b(10610)$ and $Z_b(10650)$ states [8]. Later on, the analogs on the charmonium sector, $Z_c(3900)$ and $Z_c(4020)$ were found.

The charged $Z_c(3900)$ was discovered by BESIII in the $e^+e^- \to \pi^+\pi^- J/\psi$ reaction [9] at the energy of the $Y(4260)$, and so seen as a decay product of the $Y(4260)$. Then the neutral partner was found in an analysis of CLEO-c data [10], confirming also the charged states but at a different energy. BESIII found a state in $e^+e^- \to \pi^\pm(D\bar{D}^*)^\mp$ [11] with $J^P = 1^+$ quantum numbers but with a slightly lower mass. However with the determination of the quantum numbers of the $Z_c(3900)$ as $J^P = 1^+$ by BESIII [12] the two states were seen as the same.

The charged $Z_c(4020)$ was discovered by BESIII in the $e^+e^- \to \pi^+\pi^- h_c$ [13] and $e^+e^- \to (D^*\bar{D}^*)^\pm\pi^\mp$ [14] reactions. The neutral partner was also measured in the reaction $e^+e^- \to \pi^0\pi^0 h_c$ [15].

The charged and neutral states formed an isospin 1 triplet and so this implies the need of a quark-antiquark light pair. It is also important to notice that the states are close but above the $D\bar{D}^*$ and $D^*\bar{D}^*$ thresholds respectively. So there has been different interpretations, from two meson states [16–18] to compact tetraquarks [19–24] or threshold effects [25].

In this work we will analyze if this states can be understood in the framework of the Chiral Quark Model.

2. Theoretical framework

The present work will use the Chiral Quark Model [26]. The basic assumptions of the model are the following. Chiral symmetry is spontaneously broken so quarks acquire a dynamical (constituent) mass and interact through the exchange of pseudo-Goldstone bosons, in this case by pions. The quarks are confined within hadrons by a phenomenological screened-confining potential. However the lowest order perturbative QCD contribution, given by a one-gluon exchange interaction is also included.

Within this model we study two-meson dynamics using the Resonating Group Method. The method uses the internal wave functions of the interacting mesons which are obtained solving the two body problem. Using them, together with the interaction between quarks, the two-meson potential is derived and the T-matrix is obtained from the solution of the Lippmann-Schwinger equation.

The production mechanism is not determined and a phenomenological point-like πAB production vertex is assumed, where $A + B = \{\pi J/\psi,\ \rho\eta_c,\ D\bar{D}^*,\ D^*\bar{D}^*\}$. The mass distribution is then given by

$$d\Gamma = \frac{1}{(2\pi)^3}\frac{k_{AB}k_{\pi Z_c}}{4\,s}|M^\beta(m_{AB})|^2 dm_{AB} \tag{1}$$

with

$$M^\beta(m_{AB}) = \left(A^\beta - \sum_{\beta'} A^{\beta'} \int d^3p \frac{T^{\beta'\beta}(p, k^\beta, E)}{p^2/2\mu - E - i0}\right)$$

where A^β is the production amplitude in the β channels, and $T^{\beta'\beta}$ is the T-matrix obtained from the Chiral Quark Model. In order to compare the invariant mass distributions with experiments a normalization factor $\mathcal{N}$ to translate into number of events is introduced.

3. Results

We perform a calculation of the $I^G(J^{PC}) = 1^+(1^{+-})$ channel including $\pi J/\psi$, $\rho\eta_c$, $D\bar{D}^*$ + h.c. and $D^*\bar{D}^*$ states.

The normalization factors and production amplitudes are obtained by a fit to the experimental data of the reactions $e^+e^- \to \pi^+\pi^- J/\psi$, $e^+e^- \to \pi^\pm(D\bar{D}^*)^\mp$ and $e^+e^- \to \pi^\pm(D^*\bar{D}^*)^\mp$

$$\chi^2(\{A, \mathcal{N}\}) = \sum_i \left(\frac{N^{\rm the}(x_i) - N^{\rm exp}(x_i)}{\sigma_i^{\rm exp}}\right)^2$$

and the values obtained are given in Table I.

The total χ^2/d.o.f is 1.89 which gives a reasonable description of the data. In Fig. 1 we show as an example the line-shape obtained for the $e^+e^- \to \pi^+\pi^- J/\psi$ reaction.

Table I. Normalization factors and production amplitudes obtained from a χ^2 fit to the experimental data.

Channel	$\mathcal{N}_{AB}(\times 10^7)$	$\mathcal{A}_{AB}$
$\pi J/\psi$	3.76 ± 0.09	0.34 ± 0.01
$D\bar{D}^*$	0.80 ± 0.04	0.76 ± 0.01
$D^*\bar{D}^*$	19.33 ± 0.7	0.66 ± 0.01
$\rho\eta_c(1S)$		-1.00 ± 0.04
$\chi^2_{\rm min}/$d.o.f.	1.89	

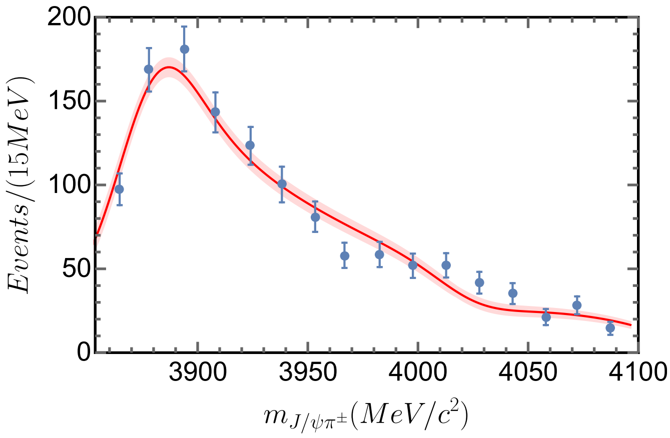

Fig. 1. Line shape for the reaction $e^+e^- \to \pi^+\pi^- J/\psi$. Experimental data are from [12].

Table II. Poles corresponding to the $Z_c(3900)$ and $Z_c(4020)$ states including different two-meson channels.

Calculation	$Z_c(3900)$ pole	RS	$Z_c(4020)$ pole	RS
$D\bar{D}^*$	$3871.37 - 2.17\,i$	(S)	-	-
$D\bar{D}^* + D^*\bar{D}^*$	$3872.27 - 1.85\,i$	(S,F)	$4014.16 - 0.10\,i$	(S,S)
$\rho\eta_c + D\bar{D}^*$	$3871.32 - 0.00\,i$	(S,S)	-	-
$\rho\eta_c + D\bar{D}^* + D^*\bar{D}^*$	$3872.07 - 0.00\,i$	(S,S,F)	$4013.10 - 0.00\,i$	(S,S,S)
$\pi J/\psi + \rho\eta_c + D\bar{D}^* + D^*\bar{D}^*$	$3871.74 - 0.00\,i$	(S,S,S,F)	$4013.21 - 0.00\,i$	(S,S,S,S)

Now the two meson states are found looking for poles of the two-meson T-matrix. The results are given on Tab. II. The $Z_c(3900)$ is obtained once the $D\bar{D}^*$ channel is included, while for obtaining the $Z_c(4020)$ it is necessary to include the $D^*\bar{D}^*$ channel. The two poles obtained within our model corresponds to virtual states very close to threshold.

Different scenarios find these states as bound, resonances or virtual states. For a comparison we give in Tab. III the results from other authors. For further details the reader is kindly refered to Ref. [32].

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Table III. Pole position, in MeV/c^2, from other authors.

Calculation	$Z_c(3900)$	type
This work	3871.74	virtual
Refs. [27]	$3878 - 23\,i$	resonance
Ref. [28]	$3894 \pm 6 \pm 1 - 30 \pm 12 \pm 6\,i$	resonance
	$3886 \pm 4 \pm 1 - 22 \pm 6 \pm 4\,i$	resonance
	$3831 \pm 26^{+7}_{-28}$	virtual
	$3844 \pm 19^{+12}_{-21}$	virtual
Ref. [29]	$3709 \pm 94 - 183(46)\,i$	virtual
	$3748 \pm 76 - 157(32)\,i$	virtual
	$3686 \pm 56 - 44(27)\,i$	virtual
Ref. [30]	$3876 - 5\,i$	resonance
Calculation	$Z_c(4020)$	type
This work	4013.21	virtual
Ref. [31]	$(3990 - 4000) - 50\,i$	bound/virtual

References

[1] S.K. Choi *et al.*, Phys. Rev. Lett. **91**, 262001 (2003).
[2] P.G. Ortega, J. Segovia, D.R. Entem, and F. Fernández, Phys. Rev. D **81**, 054023 (2010).
[3] E. Cincioglu, J. Nieves, A. Ozpineci, and A.U. Yilmazer, Eur. Phys. J. C **76**, 576 (2016).
[4] B. Aubert *et al.* (BABAR Collaboration), Phys. Rev. Lett. **90**, 242001 (2003).
[5] D. Besson *et al.* (CLEO Collaboration), Phys. Rev. D **68**, 032002 (2003); **75**, 119908(E) (2007).
[6] P.G. Ortega, J. Segovia, D.R. Entem, and F. Fernández, Phys. Rev. D **94**, 074037 (2016).
[7] M. Albaladejo, D. Jido, J. Nieves, E. Oset, Eur. Phys. J. C **76**, 300 (2016).
[8] A. Bondar *et al.*, Phys. Rev. Lett. **108**, 122001 (2012).
[9] M. Ablikim *et al.* (BESIII Collaboration), Phys. Rev. Lett. **110**, 252001 (2013).
[10] T. Xiao, S. Dobbs, A. Tomaradze, Phys. Lett. B **727**, 366 (2013).
[11] M. Ablikim *et al.* (BESIII Collaboration), Phys. Rev. Lett. **112**, 022001 (2014).
[12] M. Ablikim *et al.* (BESIII Collaboration), Phys. Rev. Lett. **119**, 072001 (2017).
[13] M. Ablikim *et al.* (BESIII Collaboration), Phys. Rev. Lett. **111**, 242001 (2013).
[14] M. Ablikim *et al.* (BESIII Collaboration), Phys. Rev. Lett. **112**, 132001 (2014).
[15] M. Ablikim *et al.* (BESIII Collaboration), Phys. Rev. Lett. **113**, 212002 (2014).
[16] F.-K. Guo, C. Hidalgo-Duque, J. Nieves, and M.P. Valderrama, Phys. Rev. D **88**, 054007 (2013).
[17] J. He, X. Liu, Z.-F. Sun, and S.-L. Zhu, Eur. Phys. J. C **73**, 2635 (2013).
[18] X.-H. Liu, L. Ma, L.-P. Sun, X. Liu, and S.-L. Zhu, Phys. Rev. D **90**, 074020 (2014).
[19] A. Esposito *et al.*, Int. J. Mod. Phys. A **30**, 1530002 (2015).
[20] J.M. Dias, F.S. Navarra, M. Nielsen, and C.M. Zanetti, Phys. Rev. D **88**, 016004 (2013).
[21] S.S. Agaev, K. Azizi, and H. Sundu, Phys. Rev. D **96**, 034026 (2017).
[22] Z.-G. Wang, and T. Huang, Phys. Rev. D **89**, 054019 (2014).
[23] C.-F. Qiao, and L. Tang, Eur. Phys. J. C **74**, 3122 (2014).
[24] C. Deng, J. Ping, and F. Wang, Phys. Rev. D **90**, 054009 (2014).
[25] E.S. Swanson, Phys. Rev. D **91**, 034009 (2015).
[26] J. Vijande, F. Fernández, and A. Valcarce, J. Phys. G **31**, 481 (2005).
[27] F. Aceti *et al.*, and M. Nielsen, Phys. Rev. D **90**, 016003 (2014).
[28] M. Albaladejo, F.-K. Guo, C. Hidalgo-Duque, and J. Nieves, Phys. Lett. B **755**, 337 (2016).
[29] Y. Ikeda *et al.* (HAL QCD), Phys. Rev. Lett. **117**, 242001 (2016).
[30] J. He, Phys. Rev. D **92**, 034004 (2015).
[31] F. Aceti, M. Bayar, J. M. Dias, and E. Oset, Eur. Phys. J. A **50**, 103 (2014).
[32] P.G. Ortega, J. Segovia, D.R. Entem, and F. Fernández, arvix:1808.00914 [hep-ph].