EPJ Web of Conferences **73**, 03010 (2014)
DOI: 10.1051/epjconf/20147303010

The *X*(3872) as a c$\bar{c}$ state plus extra components due to continuum effects

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Abstract. We present our unquenched quark model results of the charmonium spectrum with self energy corrections, that we use to discuss the nature of the $X(3872)$ resonance. In our picture, the $X(3872)$ is interpreted as a $c\bar{c}$ core plus higher Fock components due to the coupling to the meson-meson continuum.

1. Introduction

Continuum couling (or pair-creation) effects, neglected in the quark model (QM) [1–7] (see also Refs. [8–11]), give rise to virtual $q\bar{q} - q\bar{q}$ ($qqq - q\bar{q}$) components in meson (baryon) wave functions. They also determine a shift of the physical mass with respect to the bare mass, as already shown by several authors in the baryon [12] and meson [13–18] sectors. These effects are also relevant to the study of other observables, such as the contribution of the orbital angular momentum to the spin of the proton, the flavor asymmetry of the proton and the strangeness content of the nucleon. See Refs. [19]. Pair-creation effects are also important in the study of the $X(3872)$ [20], whose quark structure is still unknown. Indeed, at the moment, there are two possible interpretations for the meson: a weakly-bound $D\bar{D}^*$ molecule [21, 22] or a $c\bar{c}$ state [15, 17, 23, 24], both with $J^{PC} = 1^{++}$.

In this contribution, we show our results for the charmonium spectrum with self energy corrections [17], computed within the unquenched quark model (UQM) for mesons of Refs. [16–18]. Our results for the $c\bar{c}$ spectrum are used to discuss the nature of the $X(3872)$. According to our study of Ref. [17], this resonance is compatible with the meson $\chi_{c1}(2^3P_1)$, with $J^{PC} = 1^{++}$.

2. Self energies in the UQM

The Hamiltonian of the UQM [16–19] is given by

$$H = H_0 + V, \tag{1}$$

where H_0 acts only in the bare meson space and V couples a meson state $|A\rangle$ to the meson-meson continuum $|BC\rangle$. In the UQM approach [16–19], which is a generalization of the unitarized quark

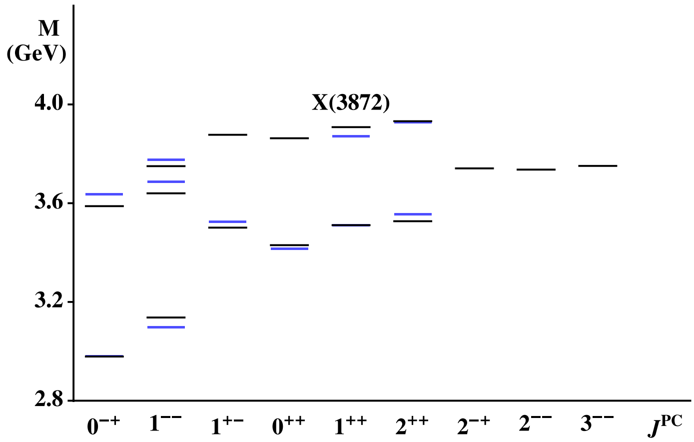

Figure 1. Comparison between the calculated masses (black lines) of $c\bar{c}$ states via Eq. (3) [17] and the experimental ones [25] (boxes). Figure from Ref. [17]. APS copyright.

model by Törnqvist and Zenczykowski [12], the effects of $q\bar{q}$ pairs are introduced explicitly into the QM through a ${}^3P_0$ pair-creation mechanism.

The dispersive equation for the self energy $\Sigma(E_a)$ is

$$\begin{aligned}\Sigma(E_a) &= \sum_{BC} \int_0^\infty q^2 dq \ \frac{\left|V_{a,bc}(q)\right|^2}{E_a - E_{bc}} \\ &= \sum_{BC,\ell,J} \int_0^\infty q^2 dq \ \frac{\left|\langle BC\vec{q}\ \ell J\ |T^\dagger|\ A\rangle\right|^2}{E_a - E_{bc}}\end{aligned} \tag{2}$$

and the bare energy E_a satisfies:

$$M_a = E_a + \Sigma(E_a), \tag{3}$$

where M_a is the physical mass of the meson A, B and C are the intermediate state mesons, with energies $E_b = \sqrt{M_b^2 + q^2}$ and $E_c = \sqrt{M_c^2 + q^2}$, $\vec{q}$ and ℓ the relative radial momentum and orbital angular momentum between B and C, and $\vec{J} = \vec{J}_b + \vec{J}_c + \vec{\ell}$ is the total angular momentum. The wave functions of the mesons A, B and C are written as harmonic oscillator wave functions, depending on a single oscillator parameter $\alpha = 0.5$ GeV [16–19]. The bare energies E_a's are computed within the relativized QM [3], with the values of the model parameters of Ref. [17], and the self energies $\Sigma(E_a)$'s within the UQM for mesons [16–18], summing over a complete set of accessible $SU_f(4)\otimes SU_{spin}(2)$ $1S$ intermediate states.

Finally, the results of our calculation are given in Fig. 1 [17].

3. Nature of the $X(3872)$ resonance

The quark structure of the $X(3872)$ resonance [20, 26] still remains an open puzzle. At the moment, there are two possible interpretations for the meson: a weakly bound meson-meson molecule [21, 22] or a $c\bar{c}$ state [15, 17, 23, 24], both with $J^{PC} = 1^{++}$, since the LHCb Collaboration [27] has ruled out the $J^{PC} = 2^{-+}$ hypothesis.

The first possibility is to interpret the $X(3872)$ as a $\chi_{c1}(2^3P_1)$ charmonium resonance [24]. Nevertheless, QM's predict this state to be at a higher energy with respect to $X(3872)$'s mass. For example, the relativized QM [3] predicts this state to be at 3.95 GeV, almost 80 MeV higher than $X(3872)$'s mass. Thus, our idea is to investigate if the introduction of loop corrections into the QM can help to improve this result for the $X(3872)$, whose unusual properties are due to its proximity to the $D\bar{D}^*$ decay threshold. In our calculation of Ref. [17], our UQM result for the mass of the $\chi_{c1}(2^3P_1)$ state is compatible with the meson $X(3872)$, the difference between our prediction and the experimental data being within the error of a QM calculation, of the order of $30 - 40$ MeV. The extra component, due to the coupling to the meson-meson continuum, is responsible for the downward energy shift.

The second possibility is to interpret the $X(3872)$ as a $D\bar{D}^*$ molecular state [21]. According to Refs. [28], the $D\bar{D}^*$ system with $J^{PC} = 1^{++}$ can be found by pion exchange and forms a meson-meson molecule. More recent molecular model calculations [29], that include quark exchange kernels for the transitions $D\bar{D}^* \to \rho J/\Psi$, $\omega J/\Psi$, to predict the $\omega J/\Psi$ decay mode of the $X(3872)$ [22], introduce large isospin mixing due to the mass difference between $D^0\bar{D}^{*0}$ and $D^+\bar{D}^{*-}$. Nevertheless, in Ref. [21] the authors state that the one-pion exchange binding mechanism should be taken with greater caution in the $D\bar{D}^*$ case than in the NN case. Moreover, in Refs. [30, 31] the authors observe also prompt production from the CDF collaboration and discuss whether a meson-meson molecule, with a dimension of a few fm and intrinsic fragility, can be promptly produced.

In Ref. [32], we computed the strong and radiative decays of the $X(3872)$ and compared our results to those of the molecular picture [22]. The two sets of results are incompatible. Moreover, only those corresponding to the $c\bar{c}$ interpretation for the $X(3872)$ seem in accordance with the present experimental data [25].

4. Discussion of the results

In this contribution, we showed the results of an unquenched quark model calculation of the $c\bar{c}$ spectrum with self energies corrections [17]. Even if these corrections are relatively small, approximately $2-6\%$ of the corresponding meson mass, these effects can become qualitatively important in the case of suspected non $q\bar{q}$ states, such as the $X(3872)$ [20]. In particular, in Ref. [17] it is shown that the continuum coupling effects of the $X(3872)$ give rise to $D\bar{D}^*$ and $D^*\bar{D}^*$ components in addition to the $c\bar{c}$ core.

In conclusion, our results of Ref. [17], that we analysed in this contribution, seem compatible with the $\chi_{c1}(2^3P_1)$ interpretation for the $X(3872)$.

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