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A coupled-channel analysis of the $X(3872)$

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I. Introduction to the $X(3872)$

Experimental status:

• The PDG (2008) reference of the $X(3872)$ collects several consistent reports of this particle, which mass and width is averaged as:

$$m = 3872.3 \pm 0.8 \text{ MeV}/c^2,\ \Gamma = 3.0^{+1.9}_{-1.4} \pm 0.9 \text{ MeV}/c^2$$

• This state was reported as a new charmonium state, with a very narrow width, in Belle, in 2003, by Choi et al., observed in the $\pi^+\pi^- J/\psi$ decay channel from the process $B^\pm \to K^\pm \pi^+\pi^- J/\psi$.

• The confirmation of the $X(3872)$ was reported in CDF2, in 2004, by Acosta et al., and in D0, in 2004, by Abazov et al., having been observed, as well, in channel $\pi^+\pi^- J/\psi$, in the collision $p\bar{p} \to X\pi^+\pi^- J/\psi$.

• BABAR also observed the state, in 2008, by Aubert et al., in the same decay as Belle 03.

• Also, the PDG reports two observations of the $X(3872)$ in the channel $D^0\bar{D}^{*0}$, from the decay $B \to D^0\bar{D}^{*0}K$ (BABAR 08 and Belle 06).

• The J^{PC} possible assignments for the $X(3872)$ are $J^{PC} = 1^{++}$ or $J^{PC} = 2^{-+}$.

Theoretical interpretations:

The $X(3872)$ is a non predicted charmonium state, because of the mass and the quantum numbers of it. It is a state with mass near $D^0(1865)D^{*0}(2007)$ threshold. Recently it has been a very subject of interest.

- Törnqvist (2004). Interprets this state as a $D\bar{D}^*$ deuteron like meson-meson state, calling it deuson. He expected large isospin breaking, and so, the decay to $J/\psi\rho$. Bounding is made by pion exchange.

- Bugg (2008). Examines a mechanism for resonance capture at thresholds. It involves a threshold cusp, positive interference with resonance via confinement and attractive t and u-channel exchanges. The $X(3872)$ requires a virtual state or resonance. He uses the formula of Flatté.

- Oset and Gamermann (2009). Treat isospin breaking in dynamical generation of the $X(3872)$. Simultaneous decay into $J/\psi\pi\pi$ and D^0D^{*0} shows a preference for slightly unbound virtual state of $D\bar{D}^* + cc$.

- ▶ Faessler et al. (2009). Treat the $X(3872)$ as a molecular DD^* bound state in a potential model. Exchange of pseudoscalar, scalar and vector mesons generates the potential, from the heavy hadron chiral perturbation theory.

- ▶ Kalashnikova and Nefediev (2009). They analyze data from BABAR, concluding that it favors dynamically generated virtual state in $D\bar{D}^*$ system, and from Belle, concluding it favors the $c\bar{c}$ 2^3P_1 component.

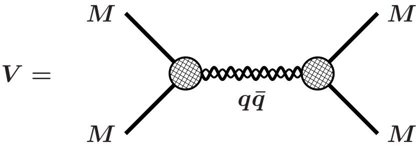
- ▶ Simonov and Danilkin (2009). Channel coupling via decay products. Weinberg eigenvalue method. Pair creation vertex derived nonperturbatively have $^3P_0$ form. They calculate shifts and widths of energy levels as well as mixing between them. They find two peaks, at 3.872 GeV and 3.94 GeV with width $\Gamma \sim 30$ MeV.

- ▶ Bugg (2010). Propose resonances as linear combinations of $q\bar{q}$ and meson-meson MM in an analogy with covalent bond. Mixing originates lowering of one eigenstate and upping of the other. Cusps arise at thresholds.

II. The Resonance Spectrum Expansion coupled-channel model

The model describes elastic-scattering processes of the form $AB \to CD$. The A, B, C and D are mesons. In our studies, non-exotic mesons.

A scheme from this process can be:



We have two phases, a meson-meson (MM) phase and a confinement ($q\bar{q}$) phase.

As it is a coupled-channel model, the MM represents several correlated possibilities of meson pairs.

The confinement phase represents a whole spectrum of $q\bar{q}$ states.

The mechanism for the transition is the annihilation of a quark pair at the first vertex and the creation of another quark pair at the second vertex, according to the OZI rule.

We define an effective potential, which is given in momentum space, by:

$$V_{ij}(p_i, p_j'; E) = \lambda^2 j^i_{L_i}(p_i a) j^j_{L_j}(p_j' a) \sum_{n=0}^{\infty} \frac{g_i(n) g_j(n)}{E - E_n}$$

The spherical Bessel function comes from the Fourier transform of the spherical Dirac delta function, which we took as the transition potential.

We have two free parameters with physical meaning:

a - interaction distance for the transition

λ - global coupling

The coupled-channel Lippmann-Schwinger (LS) equation for the transition matrix is:

$$T_{ij}(p_i, p'_j; E) = V_{ij}(p_i, p'_j; E) + \sum_m \int dk k^2 V_{im}(p_i, p'_m; E) G_0^{(m)}(k; E) T_{mj}(k, p'_j; E)$$

The separability of the effective potential allows us to evaluate the LS equation in closed form.

The loop function for each meson-meson channel m is evaluated as:

$$\Omega^{(m)} = -i2a j_{L_m}(p_m a) h_{L_m}^{(1)}(p_m a) p_m \mu_m$$

In the effective potential formula we have the term:

$$R_{ij}(E) = \lambda^2 \sum_{n=0}^{\infty} \frac{g_i(n) g_j(n)}{E - E_n}$$

This is the Resonance Spectrum Expansion which gives the name of the model.

The many coupling constants $g_i(n)$ in this equation correspond to the couplings of all states of a certain spectrum to all the decay channels.

We take the harmonic oscillator spectrum, for simplicity, but also because it works in phenomenological applications. It reads:

$$E_n = m_q + m_{\bar{q}} + \omega(2n + 3/2 + L)$$

Also, an important property of the model is the manifest unitarity of the scattering matrix, whose relation to the transition matrix is given by:

$$S = \mathbb{1} + 2iT$$

III. The $X(3872)$ interpreted as an axial vector state

In this study we assign to the $c\bar{c}$ state X(3872) the quantum numbers ${}^3P_1$, i.e., the first 1^{++} state.

Table: Included meson-meson channels, in MeV

Channel	relative L	Threshold
$D^0 D^{*0}$	0	3872
$D^{\pm} D^{*\pm}$	0	3880
$D_s^{\pm} D_s^{*\pm}$	0	4080
$D^0 D^{*0}$	2	
$D^{\pm} D^{*\pm}$	2	
$D_s^{\pm} D_s^{*\pm}$	2	
$D^* D^*$	2	4018

IV. Behavior of poles near thresholds

We are enabled to search for poles of the T-matrix, in the complex-plane, numerically, since we can solve the T-matrix analytically. This poles are desirable to be representations of the mass (on the real part) and width (on the imaginary part) of physical states.

Setting up of the two free parameters (interacting distance $\mathbf{a}$ and global coupling $\boldsymbol{\lambda}$):

We set $\mathbf{a = 2.0}$ GeV^{-1} (0.4 fm).

To set the $\boldsymbol{\lambda}$ value we take as a reference the $\chi_{c1}(1P)$, an axial-vector state with mass 3511 MeV.

The evaluated T-matrix shall give us all the confinement poles inputed in the effective potential, which shall appear deviated because of the coupling. But also, it was seen in published work, that this model is able to produce dynamically generated poles.

The confinement poles shall be, in the decoupling case, i.e., when $\lambda \to 0$, the Harmonic-Oscillator (HO) states:

Table: HO eigenvalues, in MeV, with $\omega = 0.19$ and $L = 1$

n	$c\bar{c}$
0	3599
1	3979

In the present work, we could find only poles from the confinement.

Table: Pole positions with λ variation

$\boldsymbol{\lambda}$ [$\mathrm{GeV}^{-3/2}$]	Pole 1 [MeV]	Pole 2 [MeV]
3.2	3551	3871
3.0	3555	$3873 - i1$
2.2	3572	$3884 - i6$
1.2	3590	$3928 - i16$

In this study we are interested in explore the region near the $X(3872)$ threshold.

Figure: Trajectory of the Pole 2, from a Resonance to a Bound State

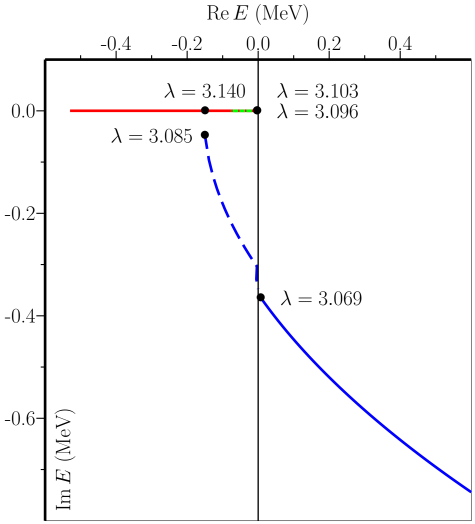


Figure: $T^2 \times$momentum, $0 \Rightarrow 3872$ MeV

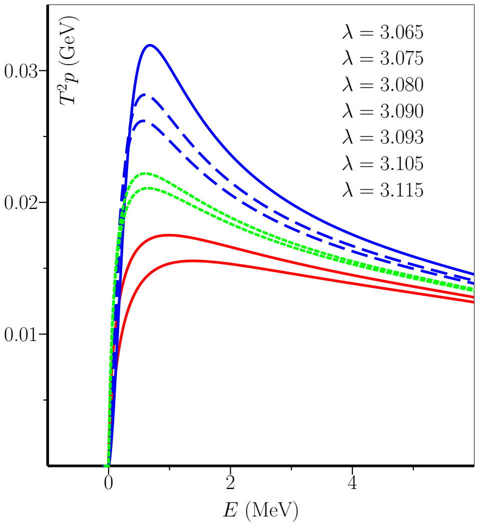


Figure: Fits to Belle data for $X(3872) \to \bar{D}D^*$, D.Bugg J.Phys.G:Nucl.Part.Phys.35(2008)

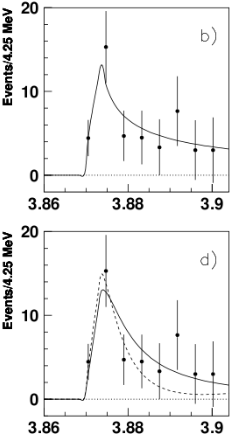


Figure: $T^2 \times$momentum, 0 $\Rightarrow$ 3872 MeV

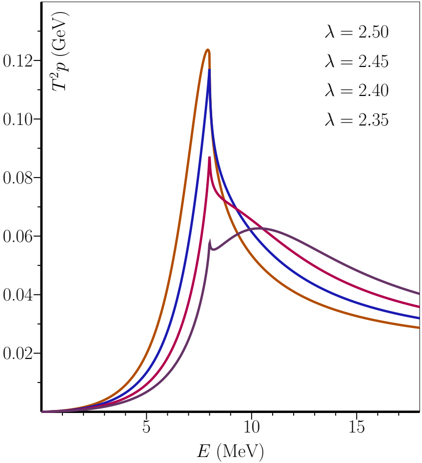
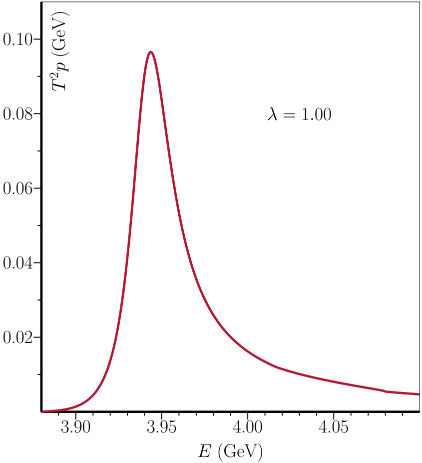


Figure: T^2×momentum



Observation:

We have not included in this work the $\rho J/\psi$ channel because it is OZI-forbidden. Although we expect a weaker coupling to this channel, the phase space of it is larger than in the case of $D^0 D^{*0}$ channel. The addition of this channel can be enough to generate the dynamical resonance we were not able to observe at this stage.

V. Conclusions and improvements

$\diamond$ The coupling of the OZI-allowed channels only cannot produce a dynamical resonance with the present simplicity of the model.

$\diamond$ The model can reproduce the form of the curve given by the experimental data in channel $D^0 D^{*0}$.

$\diamond$ The Resonance Spectrum Expansion model can reproduce different behaviors of poles, in particular, threshold behaviors, as well as the *cusp* structure.

$\triangleright$ The OZI-forbidden channel $\rho J/\psi$ should be coupled as well.

$\triangleright$ We can study also the possibility that $X(3872)$ is a 2^{-+} state.