TESTING THE PREDICTED DYNAMICALLY GENERATED HIDDEN CHARM SCALAR X STATE THROUGH THE RADIATIVE DECAY OF THE $\psi(3770)$ AND THE $D\bar{D}$ INVARIANT MASS SPECTRUM*

Daniel Gamermann, Eulogio Oset

Hadronic and Nuclear Theory Group-IFIC, CSIC-Universidad de Valencia
Valencia, Spain

Bing Song Zou

IHEP and Theoretical Physics Center for Science Facilities, CAS
Beijing 100049, China

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In this talk we present our model to generate resonances dynamically from the interaction of two mesons in coupled channels. Our phenomenological model describes many of the experimentally known scalar and axial charmed resonances and it also predicts a hidden charm scalar state with mass close to the $D\bar{D}$ threshold. We investigate the possibility to observe this resonance through the radiative decay of the $\psi(3770)$ and we also perform a calculation of the mass spectrum of $D\bar{D}$ in the reaction $e^+e^- \to J/\psi D\bar{D}$, assuming that the $D\bar{D}$ pair originates from this scalar resonance.

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1. Introduction

Many of the scalar and axial charmed resonances already discovered have been described as dynamically generated states in coupled channels. For instance chiral Lagrangians and heavy quark symmetry can fairly reproduce the spectrum of scalar [1,2] and axial [3,4] charmed resonances.

Instead of using heavy quark symmetry, our group has developed a phenomenological model that has as starting point a SU(4) flavor symmetric Lagrangian. This symmetry is then broken down to SU(3) by considering the exchange of heavy and light vector mesons as the underlying interaction of the contact terms in the Lagrangians. Our works reproduce most of the results from heavy quark symmetry for scalar [5] and axial [6] resonances

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with minor differences, but it also has a richer spectrum for axial resonances since it considers also the interaction of heavy pseudoscalars with light vector mesons, which could not be studied from the heavy quark symmetry Lagrangians. This phenomenological model also makes new predictions in the hidden charm sector: one scalar resonance with mass close to the $D\bar{D}$ threshold and a negative C-parity axial state almost degenerated in mass with the $X(3872)$.

In this talk we concentrate in the predicted scalar state. In the next section we explain the phenomenological model and how to generate resonances. Later we compute the radiative decay of the $\psi(3770)$ into this new state and next we calculate the $D\bar{D}$ mass spectrum in the reaction $e^+e^- \to J/\psi D\bar{D}$, assuming the scalar X as an intermediate state.

2. Phenomenological model

The starting point of our model are fields containing the pseudoscalar and vector mesons from the 15-plet of SU(4):

$$\Phi = \begin{pmatrix} \frac{\eta}{\sqrt{3}} + \frac{\pi^0}{\sqrt{2}} + \frac{\eta'}{\sqrt{6}} & \pi^+ & K^+ & \overline{D}^0 \\ \pi^- & \frac{\eta}{\sqrt{3}} - \frac{\pi^0}{\sqrt{2}} + \frac{\eta'}{\sqrt{6}} & K^0 & D^- \\ K^- & \overline{K}^0 & \sqrt{\frac{2}{3}}\eta' - \frac{\eta}{\sqrt{3}} & {D_s}^- \\ D^0 & D^+ & {D_s}^+ & \eta_c \end{pmatrix} . \quad (1)$$

The vector field, $\mathcal{V}_\mu$, is analogous to the pseudoscalar one. These fields differ from those used in [5, 6] because of the inclusion of η–η' and ω–ϕ mixing. This mixing is implemented by summing to the SU(4) 15-plet a singlet and writing the fields in physical basis.

For these fields, hadronic currents are defined:

$$J_\mu = (\partial_\mu \Phi)\Phi - \Phi\partial_\mu\Phi \,, \quad (2)$$
$$\mathcal{J}_\mu = (\partial_\mu \mathcal{V}_\nu)\mathcal{V}^\nu - \mathcal{V}_\nu\partial_\mu\mathcal{V}^\nu \,. \quad (3)$$

The Lagrangians are constructed by coupling these currents:

$$\mathcal{L}_{\rm PPPP} = \frac{1}{12f^2}\,{\rm Tr}(J_\mu J^\mu + \Phi^4 M)\,, \quad (4)$$

$$\mathcal{L}_{\rm PPVV} = -\frac{1}{4f^2}\,{\rm Tr}\left(J_\mu \mathcal{J}^\mu\right) \,. \quad (5)$$

The matrix M in (4) is diagonal and given by: $M = \text{diagonal}\,(m_\pi^2, m_\pi^2, 2m_K^2 - m_\pi^2, 2m_D^2 - m_\pi^2)$.

In the way they are constructed the interaction of the currents from the Lagrangians in Eqs. (4) and (5) are SU(4) symmetric. Since SU(4) is badly broken in nature, we break this symmetry in the Lagrangians by assuming vector meson dominance. This means that the underlying interaction behind the coupling of the hadronic currents is the exchange of vector mesons. Hence, in a given process, if the hadronic current has charm quantum number, the vector exchanged should be carrying charm and, therefore, be a heavy meson. In such a process we suppress the term in the Lagrangian by a factor $\gamma = m_{\rm L}^2/m_{\rm H}^2$ where $m_{\rm L}$ is the typical value of a light vector-meson mass (800 MeV) and $m_{\rm H}$ the typical value of the heavy vector-meson mass (2050 MeV). We also suppress the exchange of the J/ψ meson by a similar factor in currents carrying hidden charm. A last source of SU(4) symmetry breaking is the use of different meson decay constants. For light mesons we use $f = f_\pi = 93$ MeV but for heavy ones $f = f_D = 165\,$MeV.

From the Lagrangians we get tree level amplitudes for any two meson initial and final state that expand a coupled channel space. The amplitudes are projected in s-wave and collected in a matrix V that is plugged as kernel to solve the scattering equation:

$$T \;=\; V + VGT\,. \tag{6}$$

In this equation G is a diagonal matrix with each one of its elements given by the loop function for each channel in the coupled channel space. For channel i with mesons of masses m_1 and m_2 G_{ii} is given by:

$$\begin{aligned} G_{ii} \;=\; & \frac{1}{16\pi^2}\Bigg(\alpha_i + {\rm Log}\frac{m_1^2}{\mu^2} + \frac{m_2^2 - m_1^2 + s}{2s}{\rm Log}\frac{m_2^2}{m_1^2} + \frac{p}{\sqrt{s}} \\ & \times \left({\rm Log}\frac{s - m_2^2 + m_1^2 + 2p\sqrt{s}}{-s + m_2^2 - m_1^2 + 2p\sqrt{s}} + {\rm Log}\frac{s + m_2^2 - m_1^2 + 2p\sqrt{s}}{-s - m_2^2 + m_1^2 + 2p\sqrt{s}}\right)\Bigg)\,, \end{aligned} \tag{7}$$

where p is the three momentum of the two mesons in the center of mass frame. The two parameters μ and α are not independent, we fix $\mu = 1500\,$MeV and change α to fit our results within reasonable values in the natural range [7].

The imaginary part of the loop function ensures that the T-matrix is unitary, and since this imaginary part is known, it is possible to do an analytic continuation for going from the first Riemann sheet to the second one. Possible physical states (resonances) are identified as poles in the T-matrix calculated in the second Riemann sheet for the channels which have the threshold below the resonance mass. The residues of the poles in each channel give information about the coupling of the resonance to its building blocks.

This model generates dynamically poles that can be associated to most of the known scalar and axial charmed resonances. In the scalar sector [5] it reproduces the $D_{s0}(2317)$ and the $D_0(2400)$. It also generates the three components of a charmed sextet, but these are too broad in our model to be of any experimental relevance, and we also get a hidden charm singlet around 3.7 GeV. In the axial sector a richer spectrum is found [6]. We reproduce in this sector the $D_{s1}(2460)$, $D_1(2430)$, $D_{s1}(2536)$ and $D_1(2420)$. Two sextets are generated, but with some very broad states and two hidden charm singlets, one identified as the $X(3872)$ and the other, with negative C-parity, is another prediction of the model.

3. The radiative decay of the $\psi(3770)$

Here we study the following radiative decay:

$$\psi(P,\epsilon(P)) \rightarrow X(Q) + \gamma(K,\epsilon(K))\,, \tag{8}$$

where ψ is the $\psi(3770)$ and X is the dynamically generated hidden charm scalar state.

The diagrams needed for the evaluation of this decay can be found in [8] along with the evaluation of their respective expressions.

The results of the numerical evaluation of this decay are in Table I.

TABLE I

Results for the radiative decay width of the $\psi(3770)$ calculated for different values of $\alpha_{\rm H}$.

$\alpha_{\rm H}$	Γ [KeV]
-1.40	1.97
-1.35	1.09
-1.30	0.79
-1.25	0.55

In [8] we made a statistical study of the uncertainties and found as final result for the radiative decay width $\Gamma_{\psi\rightarrow X\gamma} = (1.05 \pm 0.41)$ KeV. This width corresponds to a branching fraction of the same order of magnitude as other observed radiative decays like $\phi \rightarrow a_0(980)\gamma$ or $\phi \rightarrow f_0(980)\gamma$ which are observed reactions and proceed through similar loops but involving kaons instead of D mesons.

The BEPC-II facility is expected to produce 3.8×10^7 $\psi(3770)$ events in one year of run, this would correspond to about 1000 events into $X(3700)\gamma$ for $\Gamma_{\psi\rightarrow X\gamma} \sim 1$ KeV, which should be enough statistic in order to observe a clear peak, disregarding any technical problems that are beyond our reach.

4. The $D\bar{D}$ invariant mass spectrum

Belle has measured the $D\bar{D}$ invariant mass spectrum from the reaction $e^+e^- \to J/\psi D\bar{D}$ [9]. We assume this reaction as going through the scalar X resonance:

$$e^+e^- \to J/\psi X \to J/\psi D\bar{D}\,. \tag{9}$$

Measuring the $D\bar{D}$ invariant mass close to threshold, the only part of the amplitude $\mathcal{T}$ for the process of Eq. (9) which is strongly energy dependent is the X propagator. In this case the differential cross-section would be given by [10]:

$$\frac{d\sigma}{dM_{\rm inv}(D\bar{D})} = \frac{1}{(2\pi)^3}\,\frac{m_e^2}{s\sqrt{s}}\,|\vec{k}||\vec{p}||\mathcal{T}|^2\,, \tag{10}$$

where s is the square of the center of mass energy of the electron positron pair, $|\vec{p}|$ is the J/ψ three momentum in the center of mass frame of the J/ψ with the $D\bar{D}$ system and $|\vec{k}|$ is the D meson three momentum in the center of mass frame of the $D\bar{D}$ system.

In Eq. (10) $\mathcal{T}$ will be proportional to the X propagator. If the X is a genuine resonance its propagator would be of the Breit–Wigner type, but in our approach X is a dynamically generated resonance, so the information of its propagator is contained in the scattering T-matrix calculated from Eq. (6) and we use for $\mathcal{T}$ of Eq. (10) the $D\bar{D}$ channel of this T-matrix.

In Table II we show the results of performing a standard χ^2 test comparing our theoretical calculations [10] with the experimental data from [9].

TABLE II

Results of M_X and χ^2 for different values of $\alpha_{\rm H}$.

$\alpha_{\rm H}$	M_X(MeV)	$\frac{\chi^2}{\rm d.o.f}$
-1.4	3702	0.96
-1.3	3719	0.85
-1.2	3728	0.92
-1.1	Cusp	1.11

The values of χ^2 obtained are close to unity, showing a good agreement with data and, therefore, giving some support to the existence of this scalar X resonance.

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