Heavy flavour hadronic molecules

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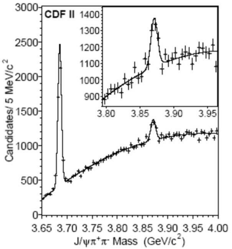
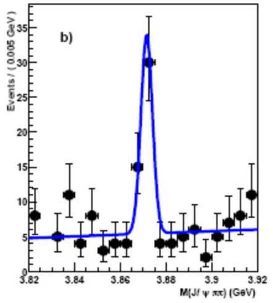
Outline

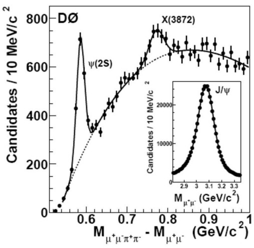
Experimental situation of $X(3872)$

Narrow state seen in B decays and $p\bar{p}$ collision decaying to $\pi\pi J/\psi$, $\pi\pi\pi J/\psi$, $\gamma J/\psi$ and $D^0\bar{D}^0\pi^0$.





Belle



BaBar

Measured Properties of $X(3872)$

- Quantum Numbers compatible with $J^{PC}=1^{++}$ (strongly preferred by the data) and $J^{PC}=2^{-+}$.
- Width : $\Gamma = 3.0\left\{\begin{array}{c} +2.1 \\ -1.7 \end{array}\right. MeV$
- Mass : $M_X = 3871.55 \pm 0.20\, MeV/c^2$ $\rightarrow$ below $D^0\bar{D}^{*0}$ mass threshold of $3871.80 \pm 0.35\, MeV/c^2$
- $R_1 = \frac{\mathcal{B}(X\rightarrow J/\psi\pi^+\pi^-\pi^0)}{\mathcal{B}(X\rightarrow J/\psi\pi^+\pi^-)} = \left\{\begin{array}{l} 1.0 \pm 0.4 \pm 0.3 \text{ (Belle)} \\ 0.8 \pm 0.3 \text{ (BaBar)} \end{array}\right.$,
- $R_2 = \frac{\mathcal{B}(X\rightarrow J/\psi\gamma)}{\mathcal{B}(X\rightarrow J/\psi\pi^+\pi^-)} = \left\{\begin{array}{l} 0.33 \pm 0.12 \text{ (BaBar)} \\ 0.14 \pm 0.05 \text{ (Belle)} \end{array}\right.$,
- $R_3 = \frac{\mathcal{B}(X\rightarrow \psi(2S)\gamma)}{\mathcal{B}(X\rightarrow J/\psi\pi^+\pi^-)} = 1.1 \pm 0.4$ (BaBar).

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Experimental data suggest a weakly-bound D^0D^{*0} molecule coupled to $2P$ $c\bar{c}$ states.

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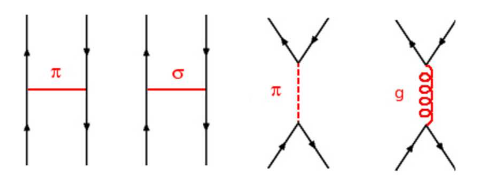
Ingredients of constituent quark model

- Model includes:
  - Chiral symmetry breaking $\longrightarrow$ Pseudo-Goldstone Bosons.



  - QCD perturbative effects $\longrightarrow$ One Gluon Exchange.
  - Confinement $\longrightarrow$ Non necessary for Meson-Antimeson interaction.
- Interactions:

$$V_{q_i q_j} = \begin{cases} q_i q_j = nn \Rightarrow V_{CON} + V_{OGE} + V_\pi + V_\sigma \\ q_i q_j = nQ \Rightarrow V_{CON} + V_{OGE} \\ q_i q_j = QQ \Rightarrow V_{CON} + V_{OGE} \end{cases}$$

Model Results for 1^{--} sector.

(nL)	States	QM	Exp.
(1S)	J/ψ	3096	3096.916 ± 0.011
(2S)	$\psi(2S)$	3703	3686.09 ± 0.04
(1D)	$\psi(3770)$	3796	3772 ± 1.1
(3S)	$\psi(4040)$	4097	4039 ± 1
(2D)	$\psi(4160)$	4153	4153 ± 3
(4S)	$\psi(4360)$	4389	4361 ± 9
(3D)	$\psi(4415)$	4426	4421 ± 4
$\begin{bmatrix}(5S)\\(4D)\end{bmatrix}$	$\psi(4660)$	$\begin{bmatrix}4614\\4641\end{bmatrix}$	4664 ± 11

Table: Masses in *MeV* of $J^{PC} = 1^{--}$ $c\bar{c}$ mesons (nL) refers to the dominant partial wave and QM denotes the results of the model.

Reference : *Phys. Rev. D* **78**, 114033 (2008).

XYZ Mesons

Meson	Mass (Exp)	Candidate?	J^{PC}	Mass (Th)
$Y(4360)$	4361 ± 9	$\psi(4360)$	1^{--}	4389
$Y(4660)$	4664 ± 11	$\begin{bmatrix}(5S)\\(4D)\end{bmatrix}, \psi(4660)$	1^{--}	$\begin{bmatrix}4614\\4641\end{bmatrix}$
$X(4160)$	4156 ± 15	η_{c2}	2^{-+}	4166
$Z(3930)$	3929 ± 5	χ_{c2}	2^{++}	3968

Table: Candidates for some XYZ mesons in our CQM $c\bar{c}$ spectrum.

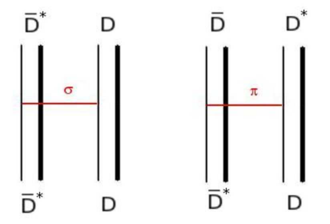
No $c\bar{c}$ candidates for $X(4260), Y(4008), X(3940), Y(3940), X(3872)$

Resonating Group Method and Gaussian Expansion Method

- Quark interactions → Cluster interaction.
- Direct RGM Potential:

$$
\begin{aligned}
{}^{RGM}V_D(\vec{P}', \vec{P}_i) \;=\; & \sum_{i\in A, j\in B} \int d\vec{p}_{\xi'_A} d\vec{p}_{\xi'_B} d\vec{p}_{\xi_A} d\vec{p}_{\xi_B} \\
& \phi_A^*(\vec{p}_{\xi'_A})\phi_B^*(\vec{p}_{\xi'_B}) V_{ij}(\vec{P}', \vec{P}_i)\phi_A(\vec{p}_{\xi_A})\phi_B(\vec{p}_{\xi_B})
\end{aligned}
$$

- $\phi_C(\vec{p}_C)$ is the wave function for cluster C solution of Schrödinger's equation using Gaussian Expansion Method.



$^3P_0$ Interaction

- Pair creation Hamiltonian:

$$\mathcal{H} = g \int d^3x \bar{\psi}(x)\psi(x)$$

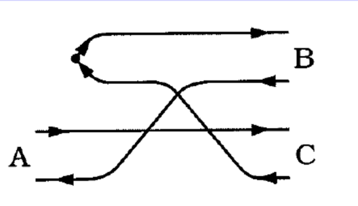
- Non relativistic reduction:

$$T = -3\sqrt{2}\gamma' \sum_\mu \int d^3p d^3p' \, \delta^{(3)}(p+p') \left[\mathcal{Y}_1 \left(\frac{p-p'}{2} \right) b^\dagger_\mu(p) d^\dagger_\nu(p') \right]^{C=1, I=0, S=1, J=}$$

with $\gamma' = 2^{5/2}\pi^{1/2}\gamma$ and $\gamma = \frac{g}{2m}$

- Transition potential:

$$\langle \phi_{M_1}\phi_{M_2}\beta | \, T \, |\psi_\alpha\rangle = P h_{\beta\alpha}\delta^{(3)}(\vec{P}_{cm})$$

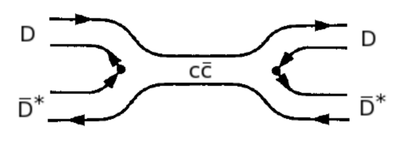


Modeling the 1^{++} sector

- Hadronic state: $|\Psi\rangle = \sum_\alpha c_\alpha |\psi\rangle + \sum_\beta \chi_\beta(P) |\phi_{M1}\phi_{M2}\beta\rangle$
- Solving the coupling with $c\bar{c}$ states $\rightarrow$ Schrödinger type equation:

$$\sum_\beta \int \left(H^{M_1 M_2}_{\beta'\beta}(P',P) + V^{eff}_{\beta'\beta}(P',P) \right) \chi_\beta(P) P^2 dP = E \chi_{\beta'}(P')$$

with $V^{eff}_{\beta'\beta}(P',P)$:



- The $c\bar{c}$ amplitudes are given by,

$$c_\alpha = \frac{1}{E - M_\alpha} \sum_\beta \int h_{\alpha\beta}(P) \chi_\beta(P) P^2 dP$$

Modeling the 1^{++} sector

- Inclusion of $J/\psi\rho$ and $J/\psi\omega$ channels necessary for strong decay description $\rightarrowtail$ Rearrangement diagrams
- Small contribution to the mass

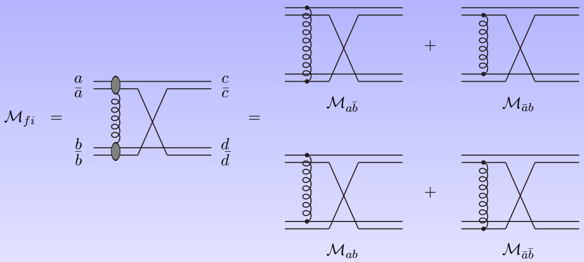


Figure: Diagrams included in the quark rearrangement process $DD^* \to \rho(\omega)J/\psi$.

Results for $X(3872)$ in a coupled channel approach

γ	E_{bind}	$c\bar{c}(2^3P_1)$	D^0D^{*0}	$D^{\pm}D^{*\mp}$	$J/\psi\rho$	$J/\psi\omega$
0.231	−0.60	12.40	79.24	7.46	0.49	0.40
0.226	−0.25	8.00	86.61	4.58	0.53	0.29

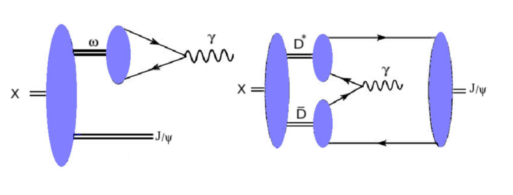
Table: Binding energy (in MeV) and channel probabilities (in %) for the $X(3872)$ state for two values of the $^3P_0$ model γ parameter.

Radiative decay description

- Decay through molecular component:

$$\Gamma_{ANN} = \frac{4}{27}\alpha\frac{qE_\Psi}{M_X}e^{-\frac{q^2}{2\beta_D^2}}\left(\eta_{00} - \frac{1}{2}\eta_{+-}\right)^2$$

$$\Gamma_{VMD} = \frac{4}{27}\alpha\frac{qE_\Psi}{M_X}\left(3|\phi_\rho(r=0)|\chi_{\rho J/\Psi}(q) + |\phi_\omega(r=0)|\chi_{\omega J/\Psi}(q)\right)^2$$



- Decay through $c\bar{c}$ component:

$$\Gamma_{E1}\left(n^{2S+1}L_J \to n'^{2S'+1}L'_{J'}\right) = \frac{4\alpha e_c^2 q^3}{3}(2J'+1)S_{fi}^E\,\delta_{SS'}\,|\mathcal{E}_{fi}|^2\frac{E_f}{M_i}$$

Strong decay description

$$\Gamma_{\pi^+\pi^- J/\psi} = \sum_{J,L} \int_0^{k_{max}} dk \frac{\Gamma_\rho}{(M_X - E_\rho - E_{J/\psi})^2 + \frac{\Gamma_\rho^2}{4}} \left|\mathcal{M}_{\rho J/\psi}(k)\right|^2.$$

where

$$\mathcal{M}_{\rho J/\psi} = \int d^3P \chi_{D\bar{D}^*}(P) h_{D\bar{D}^* \to \rho J/\psi}(P, P').$$

Decay results

Strong decay results

- Experimental results:

$$R_1 = \frac{\mathcal{B}(X \to J/\psi \pi^+\pi^-\pi^0)}{\mathcal{B}(X \to J/\psi \pi^+\pi^-)} = \begin{cases} 1.0 \pm 0.4 \pm 0.3 \\ 0.8 \pm 0.3 \end{cases},$$

- Theoretical results:

E_{bind}(MeV)	$\Gamma_{\pi^+\pi^- J/\psi}(KeV)$	$\Gamma_{\pi^+\pi^-\pi^0 J/\psi}(KeV)$	R_1
-0.60	27.61	14.40	0.52
-0.25	24.18	10.64	0.44

Decay results

Radiative decay results

- Experimental results:

$$R_2 = \frac{\mathcal{B}(X\to J/\psi\gamma)}{\mathcal{B}(X\to J/\psi\pi^+\pi^-)} = \begin{cases} 0.33 \pm 0.12 \\ 0.14 \pm 0.05 \end{cases},$$

- Theoretical results:

E_{bind}(MeV)	$\Gamma^{VMD}_{J/\psi\gamma}$	$\Gamma^{ANN}_{J/\psi\gamma}$	R_2^M	$\Gamma^{c\bar{c}}_{J/\psi\gamma}$	$R_2^{c\bar{c}}$	R_2
-0.60	0.014	0.056	$2.5\,10^{-3}$	8.15	0.29	0.30
-0.25	0.011	0.045	$2.3\,10^{-3}$	5.25	0.22	0.22

Table: Decays in KeV.

Molecular component $\rightarrowtail$ Vector meson dominance (VMD) and Annihilation (ANN) mechanisms.

R_2^M is the ratio including only the contributions from the molecular part.

$R_2^{c\bar{c}}$ from the $c\bar{c}$ component and R_2 is the full result.

Decay results

Radiative decay results

- Experimental results:
  $R_3 = \frac{\mathcal{B}(X\to\psi(2S)\gamma)}{\mathcal{B}(X\to J/\psi\pi^+\pi^-)} = 1.1 \pm 0.4.$
- Theoretical results:

E_{bind}(MeV)	$\Gamma^{ANN}_{\Psi(2S)\gamma}$	R_3^M	$\Gamma^{c\bar{c}}_{\Psi(2S)\gamma}$	$R_3^{c\bar{c}}$	R_3
-0.60	0.134	$4.8\,10^{-3}$	9.80	0.35	0.34
-0.25	0.101	$4.2\,10^{-3}$	6.31	0.26	0.26

Table: Decays in KeV.

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R_3^M is the ratio including only the contributions from the molecular part.
$R_3^{c\bar{c}}$ from the $c\bar{c}$ component and R_3 is the full result.

$X(3872)$ as a $J^{PC} = 2^{-+}$ state

- Ref: `arxiv/hep-ex:1005.5190`
- DD^* P-wave molecule $\rightarrowtail$ Need to increase the strenght of g_{ch}.

$$g_{ch}^{\prime 2} \approx 21 g_{ch}^2 \tag{1}$$

- Coupling to $\eta_{c2}(3811\,MeV)$ and $\eta_{c2}(4166\,MeV)$? $\rightarrowtail$ $^3P_0$ potential smaller than in 1^{++} sector.
- Results for isospin ratio:

$$R_1 = \frac{\mathcal{B}(X \to J/\psi\pi^+\pi^-\pi^0)}{\mathcal{B}(X \to J/\psi\pi^+\pi^-)} = 0.0051,$$

- BUT... If we increase g_{ch} we find 4 DD^* states in 1^{++} !: 3871.8 MeV, 3852.1 MeV, 3731.6 MeV and 3721.7 MeV.

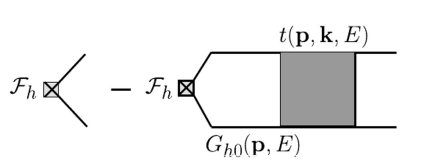
Unlikely Scenario $\rightarrowtail$ not a molecule

Lineshapes

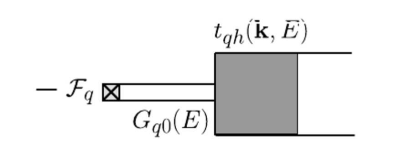
- Lippmann-Schwinger equation $\longrightarrow t^{\beta\beta'}(\vec{p},\vec{p}',E)$ matrix
- Lineshapes

$$\frac{dB_r((M_1M_2)^\beta)}{dE} = \text{const} \times k|\mathcal{M}^\beta(E)|^2\Theta(E)$$

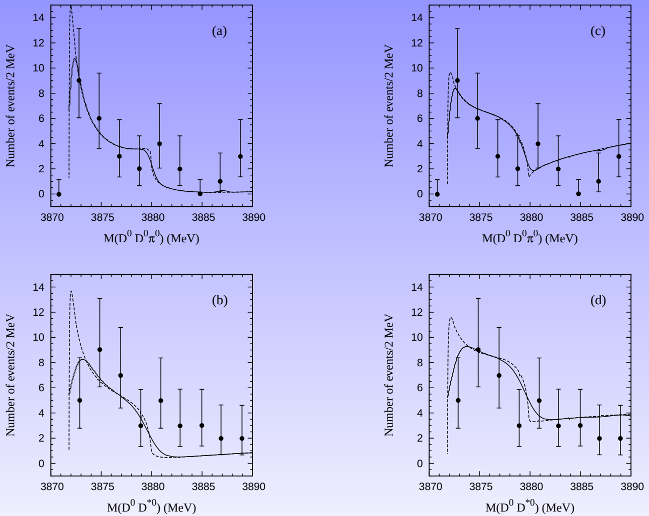
- Hadronic contribution $\mathcal{M}_h^\beta(E)$



- Mesonic contribution $\mathcal{M}_q^\beta(E)$



Lineshapes for $E_b = -0.25\ MeV$



Belle and BaBar data for the $B \to K D^0 \bar{D}^0 \pi^0$ (Belle) and $B \to K D^0 \bar{D}^{*0}$ (BaBar) reactions.

$Y(4008)$

- Mass and Width

$$J^{PC} = 1^{--},$$
$$M_Y = 4008 \pm 40^{+114}_{-28}\ MeV,$$
$$\Gamma_Y = 226 \pm 44 \pm 87\ MeV.$$

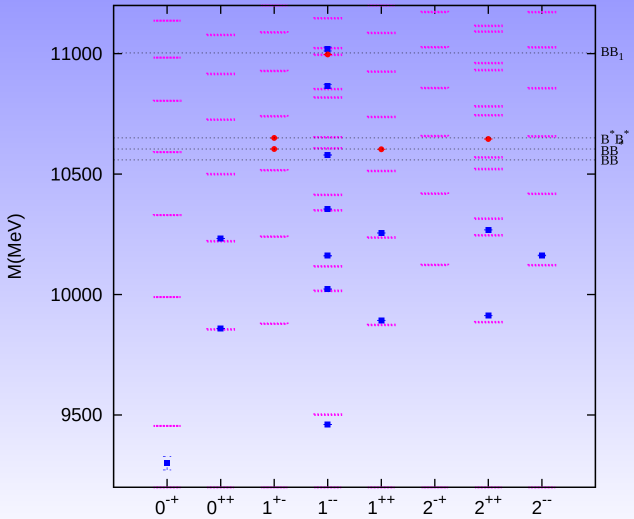
Mass (MeV)	$c\bar{c}(2^3S_1)$	$c\bar{c}(3^3D_1)$	$c\bar{c}(4^3S_1)$	D^*D^*
3650.973	92.45 %	0.22 %	0.01 %	7.30 %
3793.410	0.33 %	99.11 %	0.00 %	0.56 %
4016.423	0.59 %	0.03 %	34.53 %	64.53 %
4036.804	0.70 %	0.03 %	48.73 %	50.00 %

Table: Mass and probabilities with $^3P_0$ γ fitted to $\psi(3770) \to DD$ decay.

Hidden bottom sector

Mesons	Threshold	J^{PC}	$^3P_0$	without $^3P_0$
BB	$10558.56\ MeV$	0^{++}	$g'^2_{ch} = 2.9 g^2_{ch}$	$-0.02\ MeV$
BB^*	$10604.38\ MeV$	1^{++}	$-1.31\ MeV$	$-8.96\ MeV$
		1^{+-}	$-0.01\ MeV$	$-0.05\ MeV$
B^*B^*	$10650.20\ MeV$	0^{++}	$g'^2_{ch} = 2.70 g^2_{ch}$	$g'^2_{ch} = 2.80 g^2_{ch}$
		1^{+-}	$-0.04\ MeV$	$-0.04\ MeV$
		2^{++}	$-4.02\ MeV$	$-9.26\ MeV$
$BB_1(^1P_1)$	$11002.5\ MeV$	1^{-+}	$-$	$g'^2_{ch} = 1.3 g^2_{ch}$
		1^{--}	$-5.2\ MeV$	$g'^2_{ch} = 1.13 g^2_{ch}$
$BB_1(^3P_1)$	$11002.5\ MeV$	1^{-+}	$-$	$g'^2_{ch} = 1.3 g^2_{ch}$
		1^{--}	$-4.61\ MeV$	$-0.002\ MeV$

Hidden bottom sector



Summary

- $X(3872)$ found as a weakly-bound $D^0 D^{*0}$ molecule coupled to 2^3P_1 $c\bar{c}$ state.
- Good description of the radiative and strong decays. Although $X(3872) \to \psi(2S)\gamma$ lower than expected.
- Lineshapes in good agreement with the data, specially for the mesonic production.
- $Y(4008)$ found as molecule in the same formalism, coupled to $c\bar{c}$ $\rightarrowtail$ Experimental confirmation needed.
- Rich spectroscopy in the hidden bottom sector.

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Summary

Thanks for your attention

$D_{s1}(2460)$

- Close thresholds

$$D^*K \longrightarrow M = 2504.16\,MeV,$$
$$DK^* \longrightarrow M = 2763.70\,MeV,$$
$$D^*K^* \longrightarrow M = 2904.84\,MeV.$$

- Close D_{s1} states

$$1^3P_1 \longrightarrow M = 2571.475\,MeV,$$
$$1^1P_1 \longrightarrow M = 2575.934\,MeV,$$

$M\,(MeV)$	$D_{s1}(1^3P_1)$	$D_{s1}(1^1P_1)$	D^*K	DK^*	D^*K^*
2501.628	72.03 %	0 %	23.5 %	4.47 %	0 %
2430.604	0 %	75.13 %	14.52 %	4.57 %	5.78 %
2494.290	52.62 %	9.32 %	33.92 %	3.40 %	0.73 %

Table: Mass and probabilities with $^3P_0\ \gamma$ fitted to $\psi(3770) \to DD$ decay.

Strong decay description

$$\Gamma_{\pi^+\pi^- J/\psi} = \sum_{J,L} \int_0^{k_{max}} dk \frac{\Gamma_\rho}{(M_X - E_\rho - E_{J/\psi})^2 + \frac{\Gamma_\rho^2}{4}} \left|\mathcal{M}_{\rho J/\psi}(k)\right|^2 .$$

where

$$\mathcal{M}_{\rho J/\psi} = \int d^3P \chi_{D\bar{D}^*}(P) h_{D\bar{D}^* \to \rho J/\psi}(P, P').$$

$$\Gamma_{\pi^+\pi^- J/\psi} = \sum_{J,L} \int_0^{k_{max}} dk \, \Gamma_\rho \left|\chi_{\rho J/\psi}(k)\right|^2 .$$

As the calculation is perturbative for the $\rho J/\psi$ component we have the relation

$$\chi_{\rho J/\psi} = \frac{\mathcal{M}_{\rho J/\psi}}{M_X - E_\rho - E_{J/\psi}}$$