Coupled channel description for $X(3872)$ and other XYZ mesons

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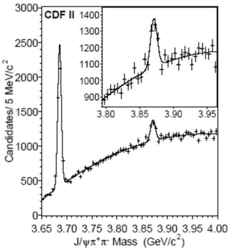
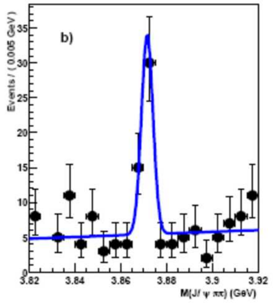
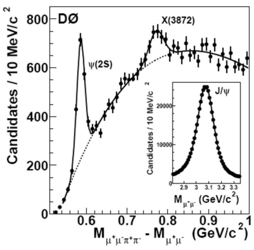
Experimental situation of $X(3872)$

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 : $\Gamma < 2.3 MeV$
- Mass : $M_X = 3871.61 \pm 0.16 \pm 0.19\ MeV/c^2$ $\rightarrow$ below $D^0 \bar{D}^{*0}$ mass threshold of $3871.80 \pm 0.35\ MeV/c^2$
- $\frac{\mathcal{B}(X \to J/\psi \pi^+ \pi^- \pi^0)}{\mathcal{B}(X \to J/\psi \pi^+ \pi^-)} = 1.0 \pm 0.5,$
- $\frac{\mathcal{B}(X \to J/\psi \gamma)}{\mathcal{B}(X \to J/\psi \pi^+ \pi^-)} = 0.33 \pm 0.12,$
- $\frac{\mathcal{B}(X \to \psi(2S) \gamma)}{\mathcal{B}(X \to J/\psi \pi^+ \pi^-)} = 1.1 \pm 0.4.$

Interpretation problems

- Charmonium - Too heavy for a 1D charmonium state and too light for a 2P one.
- Tetraquark - No more four-quark bound state configurations have been found in this mass region.
- And More... - Glueballs, diquark clusters, hybrids,... are other possible explanations.
- Molecule - Most popular explanation, but troubles to explain the radiative decay rates.

$$\frac{\mathcal{B}(X \to J/\psi\pi^+\pi^-\pi^0)}{\mathcal{B}(X \to J/\psi\pi^+\pi^-)} = 1.0 \pm 0.5,$$

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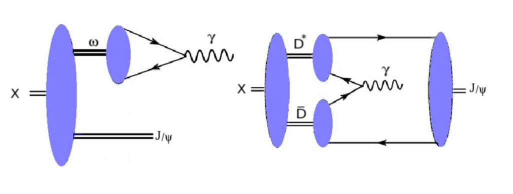

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Experimental data suggest a weakly-bound $D^0 D^{*0}$ molecule coupled to $2P$ $c\bar{c}$ states.

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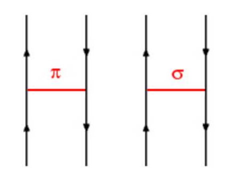
Ingredients of constituent quark model

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



σ and π interactions.

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

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

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.

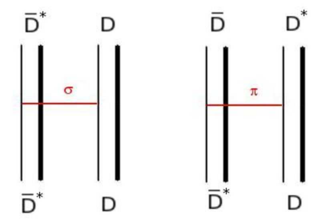
No $c\bar{c}$ candidates for $X(4260), Y(4008), X(3940), Y(3940), X(3872)$

Resonant Group Method

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

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

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



DD^* bound state from $\pi+\sigma$ interaction

- $C-$parity eigenstate convention:

$$C\left|P\bar{V}\pm\bar{P}V\right\rangle = \pm\left|P\bar{V}\pm\bar{P}V\right\rangle,$$

- In DD^* system:

$$|\phi_{M1}\phi_{M2}\rangle = \frac{1}{\sqrt{2}}\left(\left|D\bar{D}^*\right\rangle + \left|\bar{D}D^*\right\rangle\right)$$

- Solving the eigenvalue equation:

$$\sum_{\beta}\int H^{M_1M_2}_{\beta'\beta}(P',P)\chi_\beta(P)P^2dP = E\chi_{\beta'}(P')$$

No bound state is found from $\pi+\sigma$ exchange neither in $J^{PC}=1^{++}$ nor in $J^{PC}=2^{-+}$.

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To find a bound state in $J^{PC} = 1^{++}$ we need to increase our chiral constant: $g^{modified}_{ch}/g^{original}_{ch} = 106\%$ for $\pi + \sigma$ interaction.

$^3P_0$ Interaction

- Pair creation Hamiltonian:

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

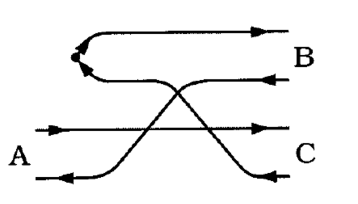
- Non relativistic reduction:

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

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

- Transition potential:

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



$^3P_0$ results for $c\bar{c}$ strong decays

γ parameter fitted to $\psi(3770) \to DD$.

Meson	Dominant Mode	Γ_{QM} (MeV)	Γ_{exp} (MeV)
$\psi(3770)$	DD	22.2	22.4 ± 2.5
$\psi(4040)$	D^*D^*	92.9	80 ± 10
$\psi(4160)$	D^*D^*	96.8	103 ± 8
$\psi(4360)$	DD_1	89.8	103 ± 11
$\psi(4415)$	DD_1	113.1	$119 \pm 16(^*)$
$\psi(4660)$	D^*D^*	107.9	42 ± 6

Table: Open flavor strong decays widths. The experimental values are from PDG except those denote with $*$ which are taken from Belle.

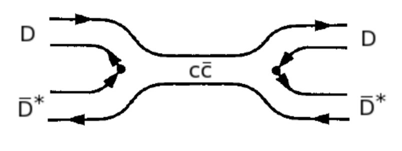
Modeling the 1^{++} sector

- 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 $\to$ 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

$$V^{eff}_{\beta'\beta}(P',P) = \sum_\alpha \frac{V_{\beta'\alpha}(P')V_{\alpha\beta}(P)}{E - M_\alpha}$$



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

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

First results

- $^3S_1$ and $^3D_1$ DD^* partial waves included.
- Coupling to 1^{++} ground and first excited $c\bar{c}$ states with bare masses within the model:

$$c\bar{c}(1^3P_1) \rightarrow \; M = 3503.9 \; MeV$$
$$c\bar{c}(2^3P_1) \rightarrow \; M = 3947.4 \; MeV.$$

First results:

$M\,(MeV)$	$c\bar{c}(1^3P_1)$	$c\bar{c}(2^3P_1)$	D^0D^{*0}	$D^{\pm}D^{*\mp}$	Assignment
3936	0 %	79 %	10.5 %	10.5 %	$\rightarrow X(3940)$
3865	1 %	32 %	33.5 %	33.5 %	$\rightarrow X(3872)$
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Parameter free calculation.

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Parameter free calculation.

Charge basis calculation. Isospin breaking.

Charge basis $\to$ Isospin breaking:

$$|D^{\pm}D^{*\mp}\rangle = \frac{1}{\sqrt{2}}\left(|DD^* I=0\rangle - |DD^* I=1\rangle\right)$$
$$|D^{0}D^{*0}\rangle = \frac{1}{\sqrt{2}}\left(|DD^* I=0\rangle + |DD^* I=1\rangle\right)$$

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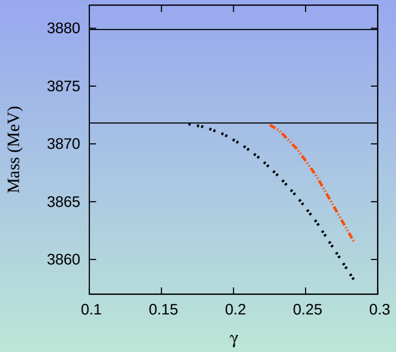
3937	0 %	79 %	7 %	14 %	$\to X(3940)$
3863	1 %	30 %	46 %	23 %	$\to X(3872)$
3467	95 %	0 %	2.5 %	2.5 %	$\to \chi_{c1}(3510)$

Isospin probabilities:

- $I=0 \to \mathcal{P} = 66\,\%$,
- $I=1 \to \mathcal{P} = 3\,\%$.

Variation with $^3P_0$ parameter γ.

$^3P_0$ too naive? $\longrightarrow$ Variation of γ.



$X(3872)$ Mass vs. γ

Legend

No $\pi + \sigma$ interaction included.

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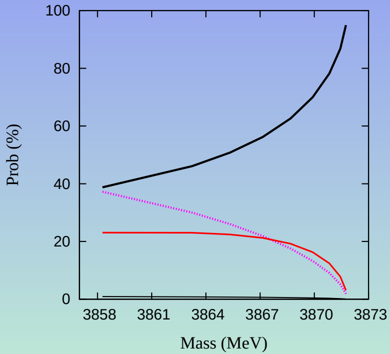

Legend

$D^0\bar{D}^{*0}$ component

D^+D^{*-} component

$c\bar{c}(2P)$ component

$c\bar{c}(1P)$ component

Probabilities for different channels vs. $X(3872)$ Mass

Final results

γ a 25% smaller $\to E_{bind} = -0.6\ MeV$.

$M\,(MeV)$	$c\bar{c}(1^3P_1)$	$c\bar{c}(2^3P_1)$	$D^0 D^{*0}$	$D^\pm D^{*\mp}$	Assignment
3942	0 %	88 %	4 %	8 %	$\to X(3940)$
3871	0 %	7 %	83 %	10 %	$\to X(3872)$
3484	97 %	0 %	1.5 %	1.5 %	$\to \chi_{c1}(3510)$

Isospin probabilities:

- $I = 0 \to \mathcal{P} = 70\,\%$,
- $I = 1 \to \mathcal{P} = 23\,\%$.

Summary

- $Y(4360)$ and $Y(4660)$ are 1^{--} $c\bar{c}$ states.
- $Z(3960)$ and $X(4160)$ can be identified as the $\chi_{c2}(2^{++})$ and the $\eta_{c2}(2^{-+})$ respectively.
- No bound state in $D\bar{D}^*$ if we only consider $\pi + \sigma$ exchange.
- When coupling to $c\bar{c}$ sector a bound state is found in $X(3872)$ mass range which may explain the experimental decays.
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