New mesons with open and hidden charm

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Outline

New states recently discovered in the open and hidden charm sector:

1. Open charm
   - $D^*_{sJ}(2317)$
   - $D_{sJ}(2460)$
   - $D_{sJ}(2632)$
   - $D_{sJ}(2860)$
   - $D^*_0(2308)$
   - $D'_1(2440)$
2. Hidden charm
   - h_c
   - η'_c
   - $X(3872)$
   - $X(3940)$
   - $Y(3940)$
   - $Z(3930)$
   - $Y(4260)$
   - ...

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1. Open charm
   - $D_{sJ}^*(2317)$
   - $D_{sJ}(2460)$
   - $D_{sJ}(2632)$
   - $D_{sJ}(2860)$ $\longrightarrow$ Possible J^P assignment
   - $D_0^*(2308)$
   - $D_1'(2440)$
2. Hidden charm
   - h_c
   - η_c'
   - $X(3872)$ $\longrightarrow$ Possible interpretation
   - $X(3940)$
   - $Y(3940)$
   - $Z(3930)$
   - $Y(4260)$
   - ...

$D_{sJ}(2860)$

A new D_{sJ} state has been observed in the DK system inclusively produced in the system $e^+e^- \to DK$.

- Reconstructed in D^0K^+, with D^0 both decaying to $K^-\pi^+$ and $K^-\pi^+\pi^0$, and in $D^+K^0_S$
- $M = 2856.6 \pm 1.5 \pm 5.0$ MeV
- $\Gamma(D_{sJ}(2860) \to DK) = 48 \pm 7 \pm 10$ MeV
- Not (yet) observed neither in D^*K nor in $D_s\eta$ (no experimental bound)

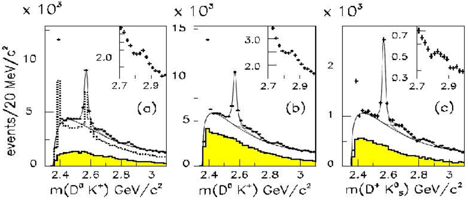

Figure: Invariant mass distribution of DK for (a) $D^0_{K^-\pi^+}K^+$, (b) $D^0_{K^-\pi^+\pi^0}K^+$ and (c) $D^+_{K^-\pi^+\pi^+}K^0_s$ (BaBar Collaboration, hep-ex/0607082, July 2006).

Possible quantum number assignments?

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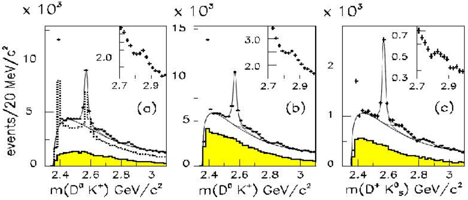

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Heavy-Light $c\bar{s}$ mesons spectroscopy

Framework

Defined:

- s_Q heavy quark spin
- $s_{\bar{q}}$ light antiquark spin
- ℓ orbital angular momentum of the light degrees of freedom (light quarks and gluons)
- $s_\ell = s_{\bar{q}} + \ell$

s_ℓ^P doublets (with $P =$ parity) of $Q\bar{q}$ mesons, each one made of two particles with quantum numbers $J^P = s_\ell^P \pm 1/2$.

Heavy-Light $c\bar{s}$ mesons spectroscopy

Table: States with $c\bar{s}$ as reported on PDG 2006

s_ℓ^P	$\frac{1}{2}^-$	$\frac{1}{2}^+$	$\frac{3}{2}^+$
$J^P = s_\ell^P - \frac{1}{2}$	$D_s(1965)\ (0^-)$	$D_{sJ}^*(2317)\ (0^+)$	$D_{s1}(2536)\ (1^+)$
$J^P = s_\ell^P + \frac{1}{2}$	$D_s^*(2112)\ (1^-)$	$D_{sJ}(2460)\ (1^+)$	$D_{s2}(2573)\ (2^+)$

Table: Doublets still to be filled

s_ℓ^P	$\frac{3}{2}^-$	$\frac{5}{2}^-$
$J^P = s_\ell^P - \frac{1}{2}$	$(P_{s1}^{*\prime})\ (1^-)$	$(P_{s2}^{*\prime})\ (2^-)$
$J^P = s_\ell^P + \frac{1}{2}$	$(P_{s2}^{*})\ (2^-)$	$(P_{s3})\ (3^-)$

$D_{sJ}(2860)$

- State in an unfilled doublet
- Radial excitation of a state belonging to a filled doublet

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Heavy quark limit

Fields:

- $s_\ell^P = \frac{1}{2}^- \to H_a = \frac{1+\gamma^\mu v_\mu}{2}[P^*_{a\mu}\gamma^\mu - P_a\gamma_5]$
- $s_\ell^P = \frac{1}{2}^+ \to S_a = \frac{1+\gamma^\mu v_\mu}{2}\left[P'^{\mu}_{1a}\gamma_\mu\gamma_5 - P^*_{0a}\right]$
- $s_\ell^P = \frac{3}{2}^+ \to T_a^\mu = \frac{1+\gamma^\mu v_\mu}{2}\left\{P^{\mu\nu}_{2a}\gamma_\nu - P_{1a\nu}\sqrt{\frac{3}{2}}\gamma_5\left[g^{\mu\nu} - \frac{1}{3}\gamma^\nu(\gamma^\mu - v^\mu)\right]\right\}$
- $s_\ell^P = \frac{3}{2}^- \to X_a^\mu = \frac{1+\gamma^\mu v_\mu}{2}\left\{P^{*\mu\nu}_{2a}\gamma_5\gamma_\nu - P^{*\prime}_{1a\nu}\sqrt{\frac{3}{2}}\left[g^{\mu\nu} - \frac{1}{3}\gamma^\nu(\gamma^\mu - v^\mu)\right]\right\}$
- $s_\ell^P = \frac{5}{2}^- \to$
  $X_a'^{\mu\nu} = \frac{1+\gamma^\mu v_\mu}{2}\left\{P^{\mu\nu\sigma}_{3a}\gamma_\sigma - P^{*\prime\alpha\beta}_{2a}\sqrt{\frac{5}{3}}\gamma_5\left[g^\mu_\alpha g^\nu_\beta - \frac{1}{5}\gamma_\alpha g^\nu_\beta(\gamma^\mu - v^\mu) - \frac{1}{5}\gamma_\beta g^\mu_\alpha(\gamma^\nu - v^\nu)\right]\right\}$

Interaction Lagrangians:

- $\mathcal{L}_H = g\, Tr[\bar{H}_a H_b \gamma_\mu\gamma_5\mathcal{A}^\mu_{ba}]$
- $\mathcal{L}_S = h\, Tr[\bar{H}_a S_b \gamma_\mu\gamma_5\mathcal{A}^\mu_{ba}] + h.c.$
- $\mathcal{L}_T = \frac{h'}{\Lambda_\chi} Tr[\bar{H}_a T^\mu_b\gamma^\nu(iD_\mu\mathcal{A}_\nu + iD_\nu\mathcal{A}_\mu)_{ba}\gamma_5] + h.c.$
- $\mathcal{L}_X = \frac{k'}{\Lambda_\chi} Tr[\bar{H}_a X^\mu_b\gamma^\nu(iD_\mu\mathcal{A}_\nu + iD_\nu\mathcal{A}_\mu)_{ba}\gamma_5] + h.c.$
- $\mathcal{L}_{X'} = \frac{1}{\Lambda_\chi{}^2} Tr[\bar{H}_a X'^{\mu\nu}_b[k_1\{D_\mu, D_\nu\}\mathcal{A}_\lambda + k_2(D_\mu D_\nu\mathcal{A}_\lambda + D_\nu D_\lambda\mathcal{A}_\mu)]_{ba}\gamma^\lambda\gamma_5] + h.c.$

Operators:

- $D_{\mu ba} = -\delta_{ba}\partial_\mu + \mathcal{V}_{\mu ba} = -\delta_{ba}\partial_\mu + \xi^\dagger\partial_\mu\xi + \xi\partial_\mu\xi^\dagger)_{ba}/2$
- $\mathcal{A}_{\mu ba} = i(\xi^\dagger\partial_\mu\xi - \xi\partial_\mu\xi^\dagger)_{ba}/2$

Theoretical predictions in the heavy quark limit

Table: Predictions for the ratio $R = \dfrac{\Gamma(D_{sJ} \to D^* K)}{\Gamma(D_{sJ} \to DK)}$ for every possible quantum number assignment for $D_{sJ}(2860)$ (n is the radial quantum number).

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$s_\ell^p = \frac{3}{2}^+$, $J^P = 2^+$, $n = 1$	d-wave	0.63
$s_\ell^p = \frac{3}{2}^-$, $J^P = 1^-$, $n = 0$	p-wave	0.06
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$D_{sj}(2860)$

Conclusions

The assignment $J^P = 3^-$ is favored, but only experiments will be able to confirm it

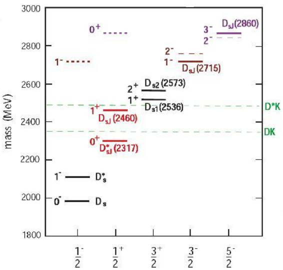

Figure: Proposed $c\bar{s}$ spectrum

Other interpretation

First radial excitation of $D^*_{sJ}(2317)$: 0^+ of the $s^P_\ell = 1/2^+$ doublet (F.E. Close, E. van Beveren)

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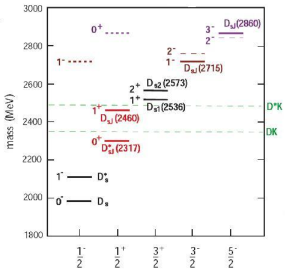

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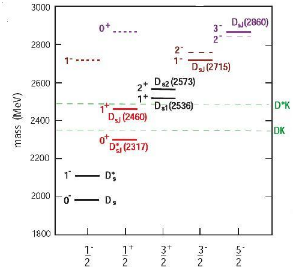

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Remark

After the publication of our paper Belle collaboration published some data which supports the $J^P = 3^-$ assignment

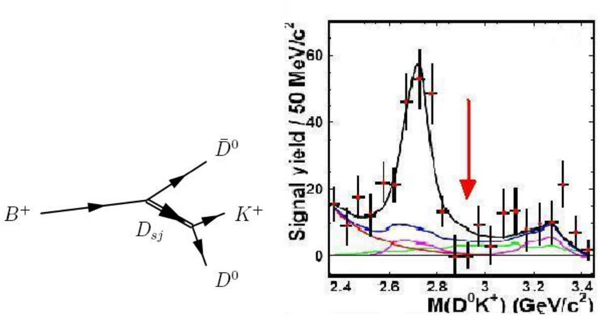

Figure: Invariant mass of the $D^0 K^+$ system in the process $B^+ \to D^0 \bar{D}^0 K^+$ (Belle Collaboration, hep-ex/0608031, August 2006)

$X(3872)$

- Found in the $J/\psi\pi^+\pi^-$ distribution, both in B decays ($B^{-(0)} \to K^{-(0)}X$), and in $p\bar{p}$ annihilation
- No evidence of resonances in the charged channel $J/\psi\pi^\pm\pi^0$ or $J/\psi\eta$
- For the X meson produced in B decays $\dfrac{B(B^0 \to K^0X)}{B(B^+ \to K^+X)} = 0.61 \pm 0.36 \pm 0.06$
- Not observed in e^+e^- annihilation
- $M = 3871.9 \pm 0.6$ MeV
- Only an upper bound for the width: $\Gamma < 2.3$ MeV (90% CL)
- Angular distribution of the final state compatible with $J^P = 1^+$
- $X \to J/\psi\gamma$ observed with $\dfrac{B(X \to J/\psi\gamma)}{B(X \to J/\psi\pi^+\pi^-}= 0.19 \pm 0.07 \to C = +1$
- $J/\psi\pi^+\pi^-\pi^0$ observed with $\dfrac{B(X \to J/\psi\pi^+\pi^-\pi^0)}{B(X \to J/\psi\pi^+\pi^-)} = 1.0 \pm 0.4 \pm 0.3 \to$ isospin violation
- If 2^3P_1 is identified with $Y(3940) \to$ overpopulation of $c\bar{c}$ 1^{++} states
- The mass of the resonance coincides with the mass of the $D^{*0}\overline{D}^0$ pair
- Near-threshold $D^0\bar{D}^0\pi^0$ enhancement in $B \to D^0\bar{D}^0\pi^0K$ decay with central value of the mass 4 MeV higher than PDG value

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- $J/\psi\pi^+\pi^-\pi^0$ observed with $\frac{B(X \to J/\psi\pi^+\pi^-\pi^0)}{B(X \to J/\psi\pi^+\pi^-)} = 1.0 \pm 0.4 \pm 0.3 \to$ isospin violation
- If 2^3P_1 is identified with $Y(3940) \to$ overpopulation of $c\bar{c}$ 1^{++} states
- The mass of the resonance coincides with the mass of the $D^{*0}\overline{D}^0$ pair
- Near-threshold $D^0\bar{D}^0\pi^0$ enhancement in $B \to D^0\bar{D}^0\pi^0 K$ decay with central value of the mass 4 MeV higher than PDG value

$X(3872)$

- Found in the $J/\psi\pi^+\pi^-$ distribution, both in B decays ($B^{-(0)} \to K^{-(0)}X$), and in $p\bar{p}$ annihilation
- No evidence of resonances in the charged channel $J/\psi\pi^\pm\pi^0$ or $J/\psi\eta$
- For the X meson produced in B decays $\dfrac{B(B^0 \to K^0X)}{B(B^+ \to K^+X)} = 0.61 \pm 0.36 \pm 0.06$
- Not observed in e^+e^- annihilation
- $M = 3871.9 \pm 0.6$ MeV
- Only an upper bound for the width: $\Gamma < 2.3$ MeV (90% CL)
- Angular distribution of the final state compatible with $J^P = 1^+$
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$X(3872)$

What kind of particle is $X(3872)$?

- Charmonium?
- Molecule(bound state $D^0 - \bar{D}^{*0}$)?
- $qq\ \bar{q}\bar{q}$ diquark-anti-diquark?

$X(3872)$

What kind of particle is $X(3872)$?

- Molecule(bound state $D^0 - \bar{D}^{*0}$)?

$X(3872)$: molecule?

Definition

$$|X(3872)\rangle \;=\; a\,|D^{*0}\overline{D}^{0} + \overline{D^{*}}^{0} D^{0}\rangle \;+\; b\,|\psi\rangle$$

- $|D^{*0}\overline{D}^{0} + \overline{D^{*}}^{0} D^{0}\rangle \longrightarrow$ “molecular” part $\longrightarrow$ peripheral interactions
- $|\psi\rangle = |D^{*+}D^{-} + D^{*-}D^{+}\rangle + \ldots \longrightarrow$ “core” part $\longrightarrow$ all other interactions
- $a \gg b$ (molecule dominates)

Remarks

- The decay of the molecule is mainly due to the decay of its component
- $X \longrightarrow D^{+}D^{-}\gamma$ suppressed with respect to $X \longrightarrow D^{0}\bar{D}^{0}\gamma$
- Observation of such a suppression $\Rightarrow$ signature for the molecule

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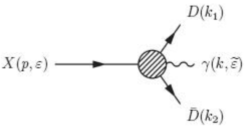
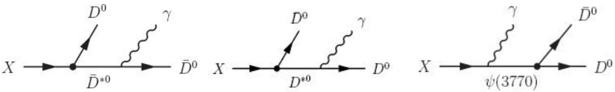
$X \to D\bar{D}\gamma$

Considering $X(3872)$ as a pure $Q\bar{Q}$ meson the radiative transition $X \to D\bar{D}\gamma$ could be considered as the sum of the three processes:





Two unknown parameter

- c governing the radiative $\langle X|\psi(3770)\gamma\rangle$ matrix element
- $\tilde{g}_1$ governing the couplings $XD\bar{D}^*$

Ratio $\frac{\Gamma(X \to D^+ D^- \gamma)}{\Gamma(X \to D^0 \bar{D}^0 \gamma)}$

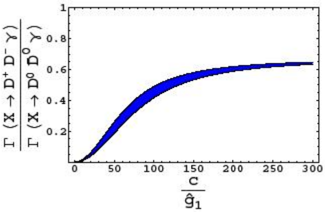


Figure: Ratio of charged $X \to D^+ D^- \gamma$ to neutral $X \to D^0 \bar{D}^0 \gamma$ widths versus the ratio of hadronic parameters $c/\widetilde{g}_1$

- In the region $c/\widetilde{g}_1 \to 0$ the process $X \to D^* \bar{D} \to DD\gamma$ dominates
- In the region $c/\widetilde{g}_1 \to \infty$ the process $X \to \psi(3770)\gamma \to DD\gamma$ dominates

Result

There is always a suppression of the charged channel with respect to the neutral one. The ratio is always smaller than 0.7

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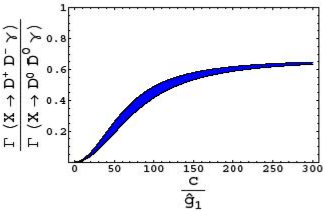

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Result

There is always a suppression of the charged channel with respect to the neutral one.
The ratio is always smaller than 0.7

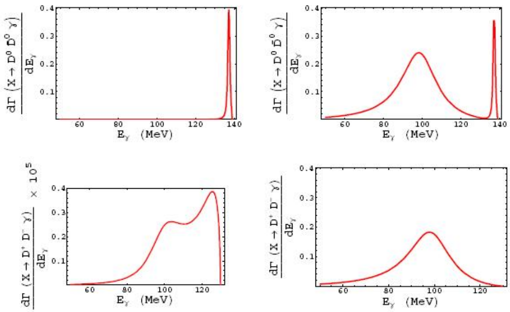
Photon spectrum

$c/\tilde{g}_1 = 1 \to D^*$ dominates

- Peak at $E_\gamma \simeq 139$ MeV$\to$ D^* decay

$c/\tilde{g}_1 = 300 \to \psi(3770)$ dominates

- Peak at $E_\gamma \simeq 100$ MeV
- Structure at $E_\gamma \simeq 139$ MeV



- Evident suppression
- Peak at $E_\gamma \simeq 125$ MeV

- Evident suppression
- No structure at $E_\gamma \simeq 139$ MeV

Summary, conclusions and remarks

Summary

Assuming for $X(3872)$ a pure $c\bar{c}$ structure:

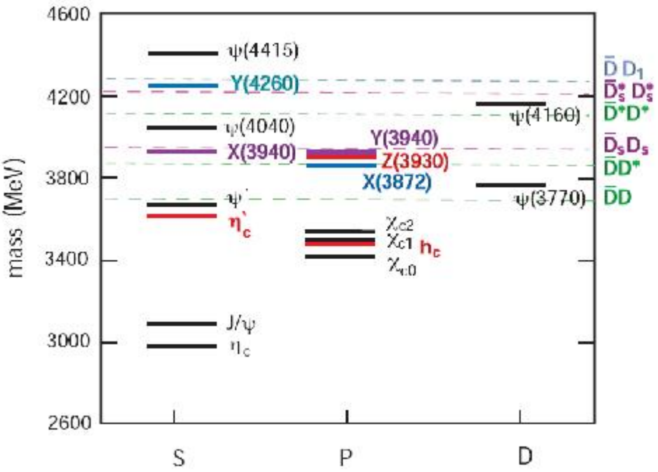
- The charged channel $X \to D^+D^-\gamma$ is suppressed with respect to $X \to D^0\bar{D}^0\gamma$ over all the range of the parameters governing the processes
- The photon spectrum of all the processes $X \to D\bar{D}\gamma$ is different with respect to the one resulting from assuming a molecular structure for $X(3872)$

Conclusions

- The suppression of the charged channel $X \to D^+D^-\gamma$ with respect to the neutral $X \to D^0\bar{D}^0\gamma$ one cannot be taken as a signature of the molecular structure of $X(3872)$
- Since at present the charmonium option for $X(3872)$ cannot be simply excluded, the analysis of the photon spectrum of radiative $X \to D\bar{D}\gamma$ decays can be useful in clarifying the situation

P. Colangelo, F. De Fazio, SN, hep-ph/0701052

Charmonium spectrum



Regge trajectories

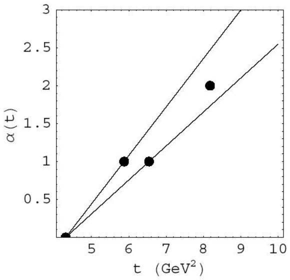


Figure: Chew-Frautschi plot for $c\bar{s}$ states. The $\alpha = 0$ point corresponds to the doublet $s_\ell^P = \frac{1}{2}^-$ ($t = \overline{M}_H^2$), the $\alpha = 1$ points to the states with $s_\ell^P = \frac{1}{2}^+, \frac{3}{2}^+$ ($t = \overline{M}_{S,T}^2$). The $\alpha = 2$ point represents the $D_{sJ}(2860)$ meson.