Radiative X(3872) decays in a charmonium-molecule hybrid model

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X(3872) is the very interesting few body system !

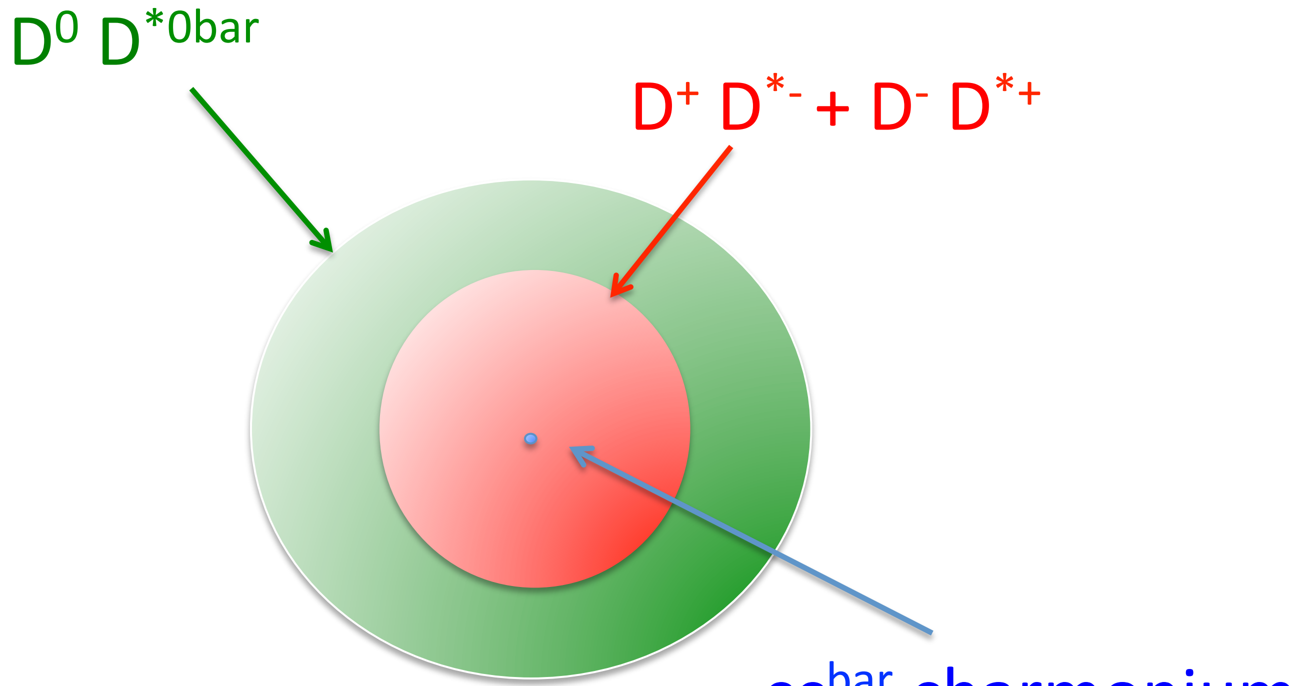
The 22nd European Conference on Few Body Problems in Physics,
Cracow, Poland, Sept. 10, 2013

Contents

- Charmonium-molecule Hybrid model
- Why X(3872) is so special?
- Radiative decays of X(3872)
- Radiative decay rates in our model
- Summary

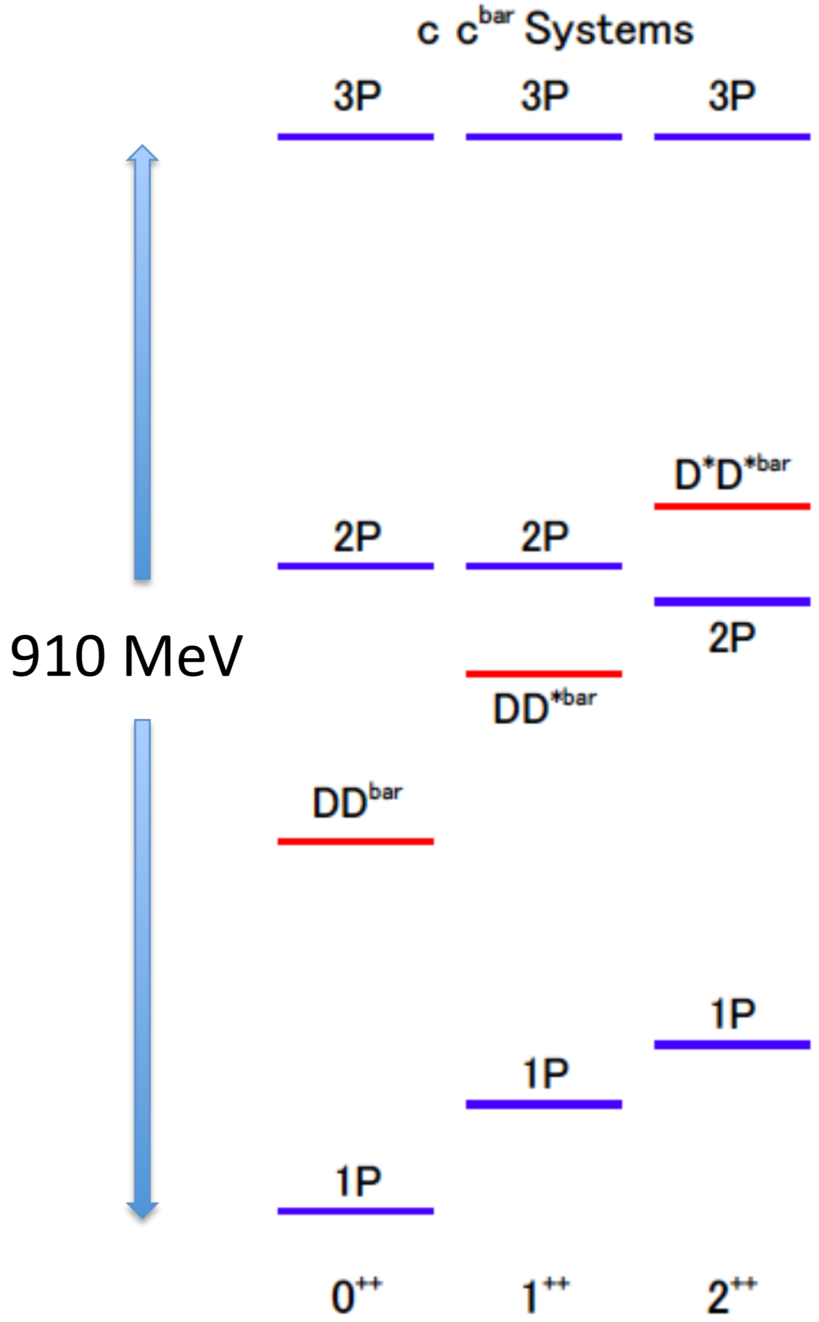
Charmonium-molecule hybrid structure of X(3872)

J/psi rho and J/psi omega components are neglected for simplicity

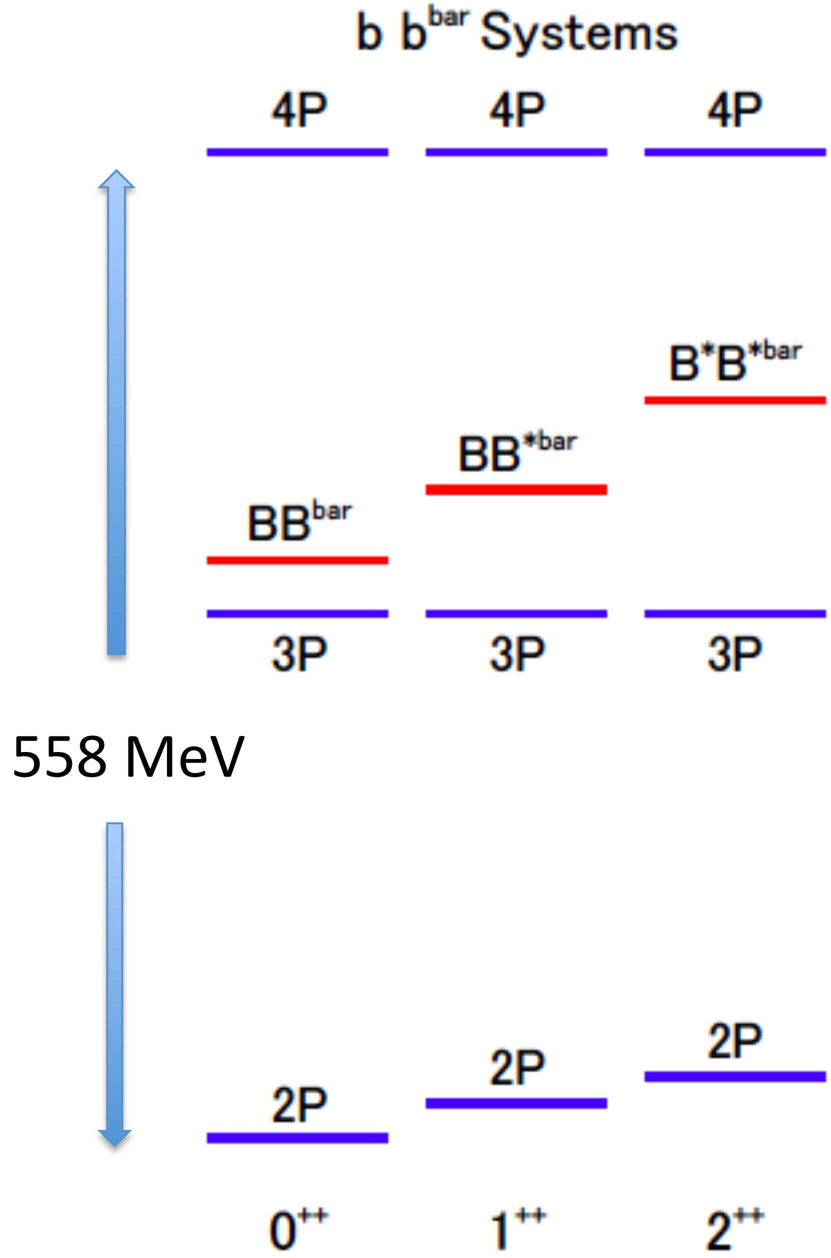


Ref. : Prog. Theor. Exp. Phys. 2013, 0903D01,

Why X(3872) is so special?



How about bb^{bar} systems?



Radiative decays of X(3872)

- Experimental resuls
- Babar $$R = \frac{B(X(3872) \to \psi' \gamma)}{B(X(3872) \to J/\psi \gamma)} = 3.4 \pm 1.4$$

Phys. Rev. Lett. 102, 132001 (2009)

- Belle $$R = \frac{B(X(3872) \to \psi' \gamma)}{B(X(3872) \to J/\psi \gamma)} < 2.1$$

Phys. Rev. Lett. 107, 091803 (2011)

- Radiative decays are sensitive to the structure of X(3872)
- If X(3872) is DD* molecule, the transition probabilities of X(3872) -> J/ψ γ, ψ' γ are very small
- If X(3872) includes $J^{PC} = 1^{++}$ charmonium component, E1 transition is possible.
- $J^{PC} = 1^{++}$ charmonium is $2\ ^3P_1$ state: $\chi_{c1}(2P)$

- Matrix elements of E1 transitions are propotional to

$$\langle J/\psi | r | X(3872):\chi_{c1}(2P)\rangle$$

$$\langle \psi' | r | X(3872):\chi_{c1}(2P)\rangle$$

J/ψ is 1S and ψ'is 2S, so ψ' matrix element is larger -> support Babar's result

- If X(3872) has χ_{c1}(1P) component, situation will change, R becomes smaller

Coupling between C C-bar core, D^0 D^{*0}-bar and D^+ D^{*-}

- cc-bar core states: $|c\bar{c}:1P\rangle$ $|c\bar{c}:2P\rangle$
- D^0 D^{*0}-bar state : $\left|D^0\overline{D^{*0}}\right\rangle = \int d^3\vec{q}\,\varphi_0(\vec{q})\left|D^0\overline{D^{*0}}(\vec{q})\right\rangle$
- D^+ D^{*-} state : $\left|D^+D^{*-}\right\rangle = \int d^3\vec{q}\,\varphi_+(\vec{q})\left|D^+D^{*-}(\vec{q})\right\rangle$
  in the center of mass frame
  q is the conjugate momentum of the relative coordinate

$$\left\langle D^0\overline{D^{*0}}(\vec{q}\,')\middle|D^0\overline{D^{*0}}(\vec{q})\right\rangle = \delta^3(\vec{q}\,'-\vec{q})$$

Coupling between C C-bar core, D^0 D^{*0}-bar and D^+ D^{*-}

- Charge conjugation + state is assumed
- Interaction: Isospin symmetric

$$\left\langle D^0 \overline{D^{*0}}(\vec{q}) \middle| V \middle| c\bar{c}:1P \right\rangle = \left\langle D^0 \overline{D^{*0}}(\vec{q}) \middle| V \middle| c\bar{c}:2P \right\rangle$$

$$= \frac{g\Lambda^2}{\vec{q}^2 + \Lambda^2} = \left\langle D^+ D^{*-}(\vec{q}) \middle| V \middle| c\bar{c}:1P \right\rangle = \left\langle D^+ D^{*-}(\vec{q}) \middle| V \middle| c\bar{c}:2P \right\rangle$$

Coupling between C C-bar core, D^0 D^{*0}-bar and D^+ D^{*-}

- Schroedinger Equation

$$\begin{pmatrix} m_{c\bar{c}(1P)} - E & 0 & V & V \\ 0 & m_{c\bar{c}(2P)} - E & V & V \\ V & V & m_{D^0} + m_{D^{*0}} + \frac{\hat{p}^2}{2\mu_0} + -E & 0 \\ V & V & 0 & m_{D^+} + m_{D^{*-}} + \frac{\hat{p}^2}{2\mu_+} - E \end{pmatrix} \begin{pmatrix} c_1 \left| c\bar{c}(1P) \right\rangle \\ c_2 \left| c\bar{c}(2P) \right\rangle \\ c_3 \left| D^0 \overline{D^{*0}} \right\rangle \\ c_4 \left| D^+ D^{*-} \right\rangle \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

$$\frac{1}{\mu_0} = \frac{1}{m_{D^0}} + \frac{1}{m_{D^{*0}}}, \quad \frac{1}{\mu_+} = \frac{1}{m_{D^+}} + \frac{1}{m_{D^{*-}}}$$

Numerical results: Mass

- Mass of the cc-bar core:
  1P: 3.51 GeV 2P: 3.95 GeV
  from S. Godfrey, N. Isgur, Phys. Rev. D 32 (1985) 189.

- Cutoff Lambda = 0.5 GeV,
  Calculated bound states energy are
  3.492 GeV and <u>3.87157 GeV</u>

- χ_{c1}(1P) mass shift by coupling to DD* is about 20MeV

Numerical results: Wavefunction

$$\left|X(3872)\right\rangle = 0.071\left|c\overline{c}(1P)\right\rangle - 0.326\left|c\overline{c}(2P)\right\rangle$$
$$+0.907\left|D^{0}\overline{D^{*0}}\right\rangle + 0.255\left|D^{+}D^{*-}\right\rangle$$

- cc^{bar} 1P component is small.

E1 transition

- We have used results of the non-relativistic quark potential model by
  T. Barnes, S. Godfrey, E.S. Swanson,
  Phys. Rev. D72, 054026 (2005)
- Color Coulomb + linear scalar confinement + Gaussian smeared contact hyperfine interaction

- E1 transition width

$$\Gamma(X(3872) \to J/\psi\,(\psi') + \gamma) = \left(\frac{2}{3}\right)^4 \alpha \left|\left\langle \psi_f \left| r \right| \psi_i \right\rangle\right|^2 E_\gamma^3 \frac{E_f^{c\bar{c}}}{M_i^{c\bar{c}}}$$

$$\left|\left\langle J/\psi \left| r \right| \chi_{c1}(1P) \right\rangle\right|^2 = 4.13 \times 10^{-6}$$

$$\left|\left\langle J/\psi \left| r \right| \chi_{c1}(2P) \right\rangle\right|^2 = 1.49 \times 10^{-7}$$

$$\left|\left\langle \psi' \left| r \right| \chi_{c1}(1P) \right\rangle\right|^2 = 7.85 \times 10^{-6}$$

$$\left|\left\langle \psi' \left| r \right| \chi_{c1}(2P) \right\rangle\right|^2 = 1.08 \times 10^{-5}$$

$$\Gamma(X(3872) \rightarrow J/\psi + \gamma) = 29.2\ keV$$

$$\Gamma(X(3872) \rightarrow \psi' + \gamma) = 13.4\ keV$$

$$R = \frac{\Gamma(X(3872) \rightarrow \psi' + \gamma)}{\Gamma(X(3872) \rightarrow J/\psi + \gamma)} = 0.458$$

- Without cc^{bar}:1 $^3P_1$ component

$$\left|X(3872)\right\rangle = -0.293\left|c\overline{c}(2P)\right\rangle + 0.921\left|D^0\overline{D^{*0}}\right\rangle + 0.259\left|D^+D^{*-}\right\rangle$$

$$\Gamma(X(3872) \rightarrow J/\psi + \gamma) = 5.1\,keV$$

$$\Gamma(X(3872) \rightarrow \psi' + \gamma) = 7.7\,keV$$

$$R = \frac{\Gamma(X(3872) \rightarrow \psi' + \gamma)}{\Gamma(X(3872) \rightarrow J/\psi + \gamma)} = 1.50$$

Summary and outlook

- We have studied radiative decays of X(3872).
- The calculated size of the cc^{bar}:1 $^3P_1$ component in X(3872) is about 0.5%.
- Our result is consistent with experimental results.
- The ratio of the radiative decay widths is very sensitive to the size of the cc^{bar}:1 $^3P_1$ component in X(3872).
- Effects of the J/psi rho and J/psi omega components in X(3872) should be studied.

Back up

About X(3872)

- First observation: 2003, Belle, KEKB
  cited more than 700 times
- $B^- \rightarrow K^- \pi^+ \pi^- J/\psi$ decay
  Sharp peak of the invariant mass distribution of $\pi^+ \pi^- J/\psi$
- Mass: (3871.68 ± 0.17) MeV
  about 0.2 MeV below $D^0 D^{*0}$-bar thresold
- Width: less than 1.2 MeV
- Quantum Number: $J^{PC} = 1^{++}$
- Other decay mode:
  $X(3872) \rightarrow \gamma J/\psi$、$\gamma\psi(2S)$
  $X(3872) \rightarrow \pi^+ \pi^- \pi^0 J/\psi$
  $X(3872) \rightarrow D^0 \underline{D}^{*0}$

Charmonium-molecule hybrid model of X(3872)

- Our works:

  M. Takizawa and S. Takeuchi, Prog. Theor. Exp. Phys. 2013, 0903D01, Hadronic model approach

- Other groups works:

  R. D. Matheus, F. S. Navarra, M. Nielsen, and C. M. Zanetti, Phys. Rev. D, 80, 056002 (2009). QCD sum rule approach

  I. V. Danilkin and Y. A. Simonov, Phys. Rev. Lett., 105, 102002 (2010). Quark model approach with cc^{bar}-DD^{*bar} int.

  S. Coito, G. Rupp, and E. van Beveren, Eur. Phys. J. C, 71, 1762 (2011). Hadronic model approach with rho-J/psi, omega-J/psi

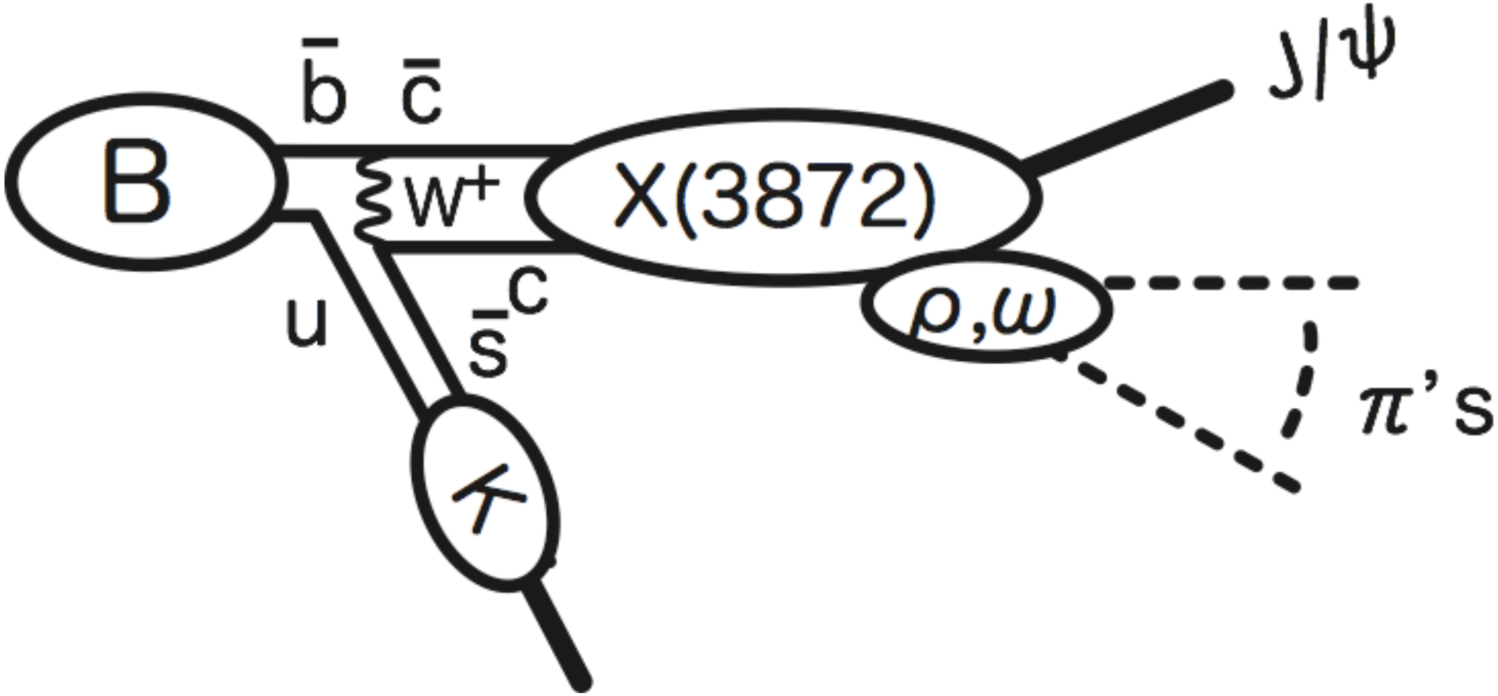
Charmonium-molecule hybrid structure has following properties

- Large isospin symmetry breaking
- No charged partner
- Reasonable production rate
- Consistent with Z_b

$B^+ \to K^+ + J/\psi + \pi\pi(\pi)$

- $B^+ \to$ <u>X(3872)</u> $+$ K^+

  $\to J/\psi +$ <u>vector meson</u> $\to \pi$'s



$$\frac{Br(X(3872)\to\pi^+\pi^-\pi^0 J/\psi)}{Br(X(3872)\to\pi^+\pi^- J/\psi)}=1.0\pm0.4\pm0.3$$

With kinematical suppression factor correction, Amplitude ratio is

$$\frac{A(X(3872)\to\rho J/\psi)}{A(X(3872)\to\omega J/\psi)}=0.27\pm0.02$$

M. Suzuki, Phys. Rev. D72: 114013, 2005

- Isovector component is smaller than isoscalar component : 25 - 30%
- Estimation of isospin component from this value is an issue of the discussion

D. Gamermann and E. Oset, Phys. Rev. D80:014003,2009.
M. Kerliner and H. J. Lipkin, arXiv:1008.0203.
K. Terasaki, Prog. Theor. Phys. 122:1205,2010.

Problems of X(3872) as C C-bar State

1. Estimated energy of 2 $^3P_1$ c c-bar state by the potential model is 3950 MeV, which is about 80 MeV higher than the observed mass of X(3872).

2. If X(3872) is c c-bar state, it is isoscalar.
   X(3872) $\rightarrow$ ρ^0 J/ψ $\rightarrow$ $\pi^+ \pi^-$ J/ψ : isovector
   This decay means large isospin breaking.

X(3872) as D^0 D^{*0}-bar Molecule

- $m_{D0} + m_{D^{*}0} = (3871.84 \pm 0.33)$ MeV
- $m_{X(3872)} = (3871.68 \pm 0.17)$ MeV

X(3872) is a very shallow bound state of D^0 D^{*0}-bar: D^0 D^{*0}-bar Molecule

Problem of X(3872) as $D^0\ D^{*0}$-bar Molecule

1. $D^0\ D^{*0}$-bar is 50% isovector and 50% isoscalar: Too big the isovector component

2. Why are there no charged X(3872)? $D^+\ D^{*0}$-bar, $D^0\ D^{*-}$ molecules

3. The production rate of such molecular-like state may be too small.

Why so large isospin symmetry breaking?

- $m_{D0} + m_{D^*0} = (3871.84 \pm 0.33)$ MeV

- $m_{D+} + m_{D^*-} = (3879.72 \pm 0.54)$ MeV

- $m_X = 3871.57$MeV

- Binding Energy
  Neutral D case: 0.27 MeV
  Charged D case: 8.15 MeV

Large difference

Coupling between C C-bar core and D^0 D^{*0}-bar, D^+ D^{*-}