Exotic $c\bar{c}$ Mesons

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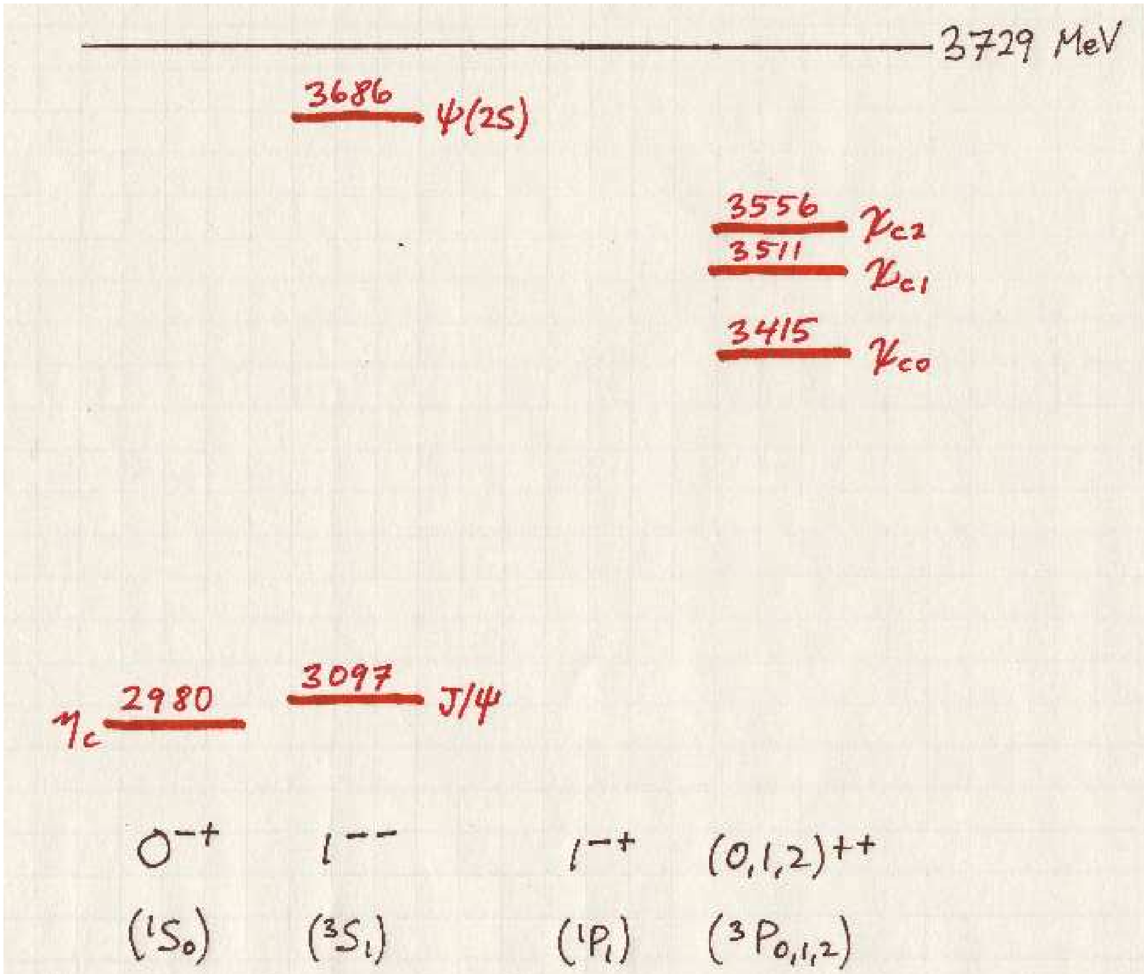
support:

DOE, Division of High Energy Physics

DOE, Division of Basic Energy Sciences

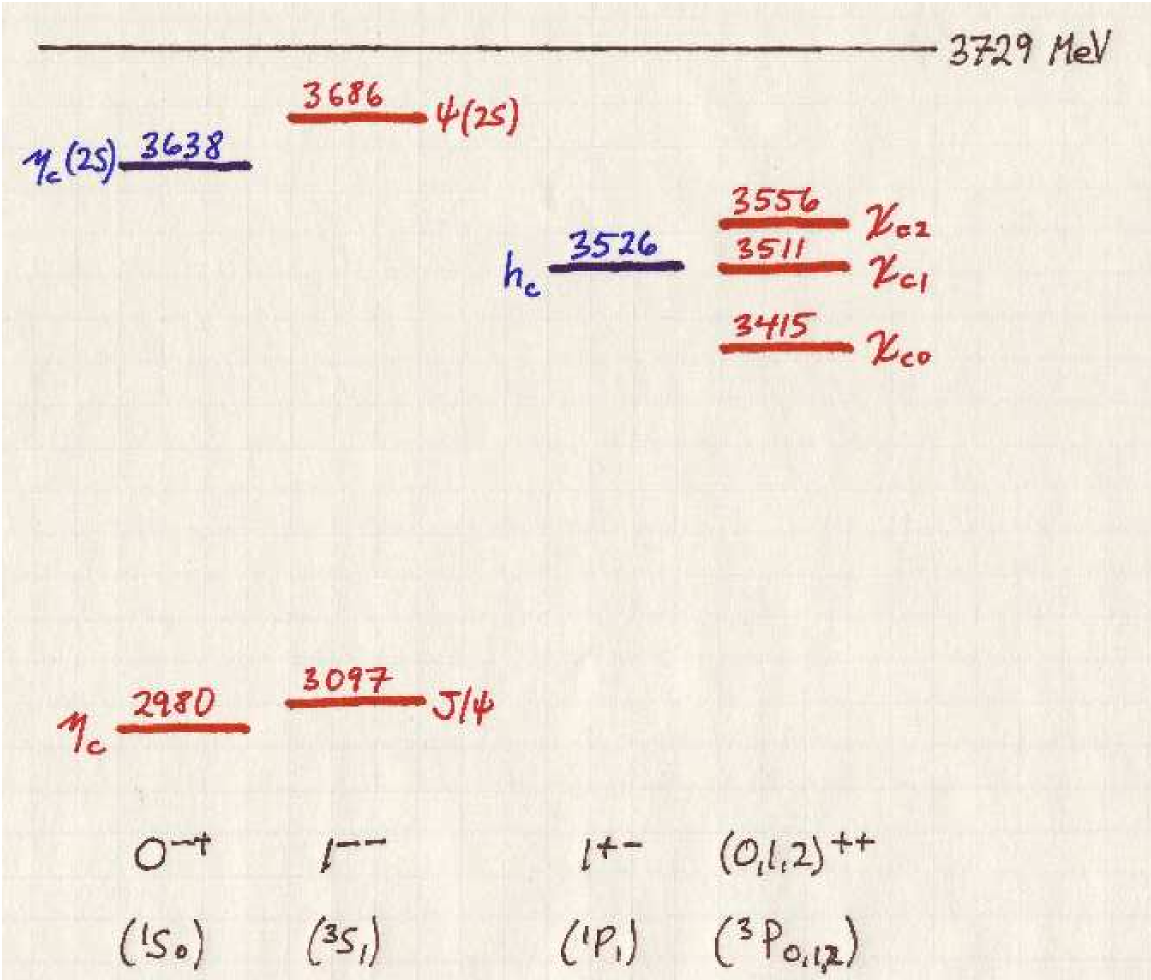
$c\bar{c}$ mesons below $D\bar{D}$ threshold

before the B factories



$c\bar{c}$ mesons below $D\bar{D}$ threshold

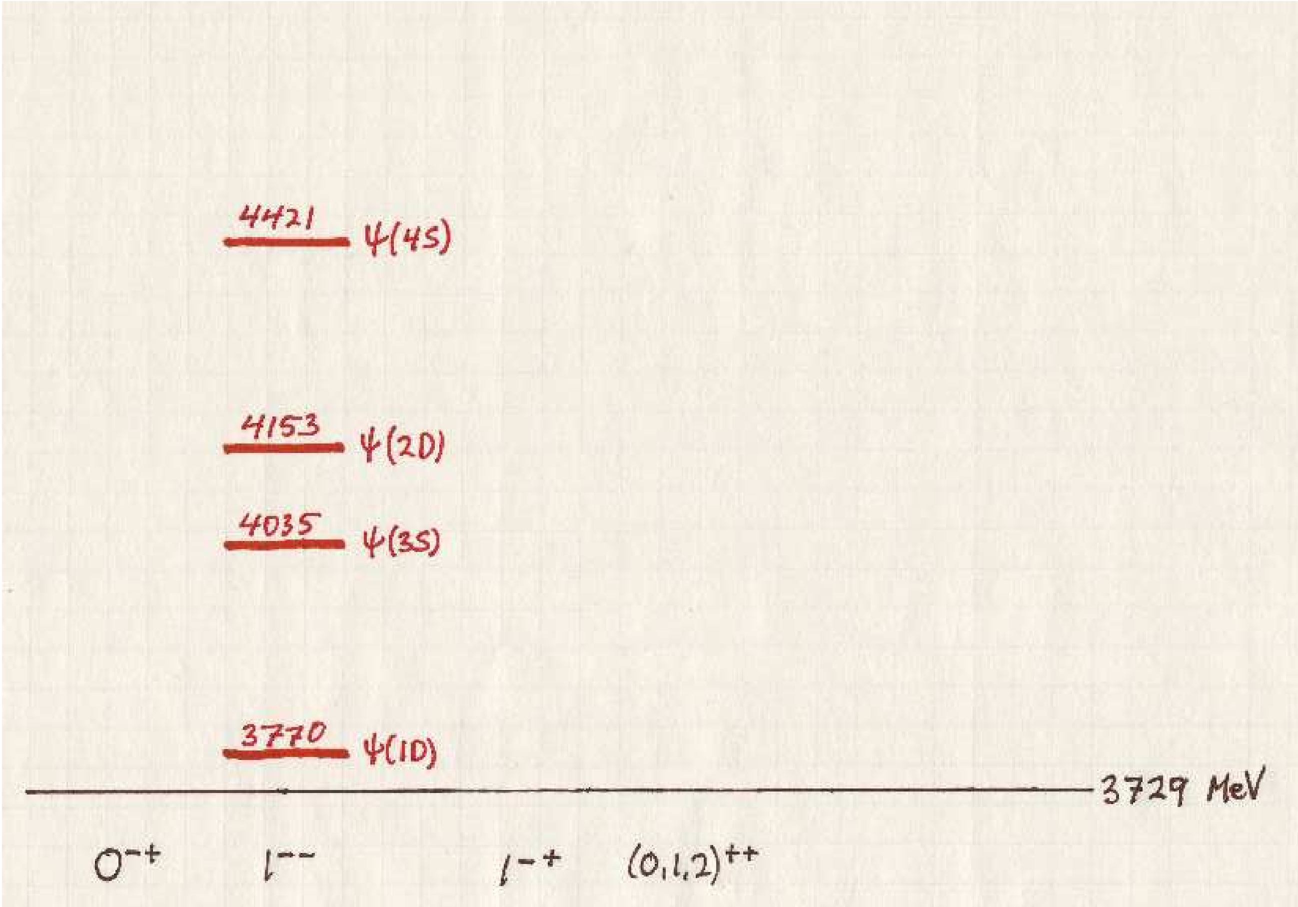
after the B factories



• 3 complete multiplets: $1S$, $1P$, $2S$

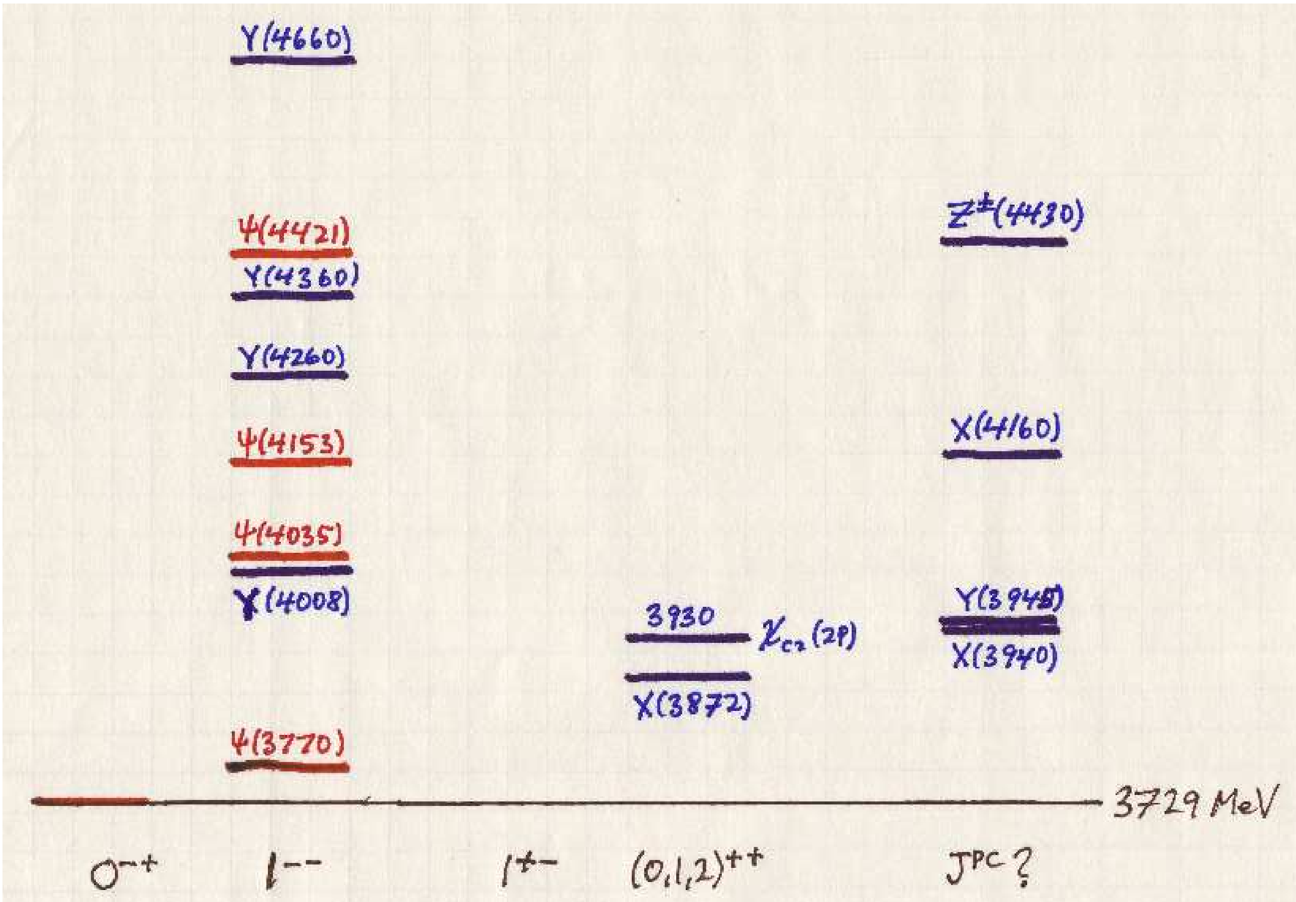
$c\bar{c}$ mesons above $D\bar{D}$ threshold

before the B factories



$c\bar{c}$ mesons above $D\bar{D}$ threshold

after the B factories



- four new 1^{--} states
- exotic $c\bar{c}$ mesons: $X(3872)$, $Z^{\pm}(4430)$

Recent reviews on new $c\bar{c}$ mesons

The New Heavy Mesons: A Status Report

Swanson, hep-ph/0601110

Quarkonia and their Transitions

Eichten, Godfrey, Mahlke, and Rosner, hep-ph/0701208

Charmonium — Voloshin, arXiv:0711.4556

The Exotic XYZ Charmonium-like Mesons

Godfrey and Olsen, arXiv:0801.3867

$X(3872)$

discovered by Belle collaboration November 2003

$$B^+ \longrightarrow K^+ + X, \qquad X \longrightarrow J/\psi\, \pi^+\pi^-$$

confirmed by CDF, BaBar, D0

Mass: 3871.4 $\pm$ 0.6 MeV

Width: $<$ 2.3 MeV (90% C.L.)

J^{PC}: 1^{++}

- isospin violating decays: $X \longrightarrow J/\psi\, \rho^* \longrightarrow J/\psi\, \pi\pi$ $(I = 1)$
  $X \longrightarrow J/\psi\, \omega^* \longrightarrow J/\psi\, \pi\pi\pi$ $(I = 0)$

- mass higher in $D^0 \bar{D}^0 \pi^0$
  than in $J/\psi\, \pi^+\pi^-$ by 3.8 $\pm$ 1.1 MeV

New 1^{--} $c\bar{c}$ mesons

discovered by Belle and Babar collaborations
through initial state radiation

$$e^+e^- \longrightarrow \gamma + e^+e^- \longrightarrow \gamma + Y$$

- decay into $J/\psi\,\pi\pi$ OR $\psi(2S)\,\pi\pi$

$$\begin{aligned}
Y(4008) &\longrightarrow J/\psi\,\pi^+\pi^- \\
Y(4260) &\longrightarrow J/\psi\,\pi^+\pi^- \\
Y(4360) &\longrightarrow \psi(2S)\,\pi^+\pi^- \\
Y(4660) &\longrightarrow \psi(2S)\,\pi^+\pi^-
\end{aligned}$$

- no resonant peaks in $\sigma[e^+e^-]$

$$\sigma[e^+e^- \to D\bar{D}, D^*\bar{D}, D^*\bar{D}^*]$$

$Z^{\pm}(4430)$

discovered by Belle collaboration August 2007

$$B^+ \longrightarrow K^0 + Z^+, \quad Z^+ \longrightarrow \psi(2S)\,\pi^+$$

Mass: 4433 $\pm$ 5 MeV

Width: 45^{+35}_{-18} MeV

J^P: ??

I^G: 1^+

decay products: $\psi(2S) = c\bar{c}$, $\pi^+ = u\bar{d}$

$\Longrightarrow Z^+$ has constituents $c\bar{c}u\bar{d}$

Manifestly exotic $c\bar{c}$ meson!!

What are the new $c\bar{c}$ mesons above $D\bar{D}$ threshold?

Ordinary $c\bar{c}$ mesons?

Charmonium: $c\bar{c}$

Exotic $c\bar{c}$ mesons?

Charmonium hybrids: $c\bar{c}g$

Tetraquark mesons: $c\bar{c}q\bar{q}$

compact tetraquark	$(c\bar{c}q\bar{q})_1$
diquark-antidiquark	$(cq)_{3^*} + (\bar{c}\bar{q})_3$
charm meson molecule	$(c\bar{q})_1 + (\bar{c}q)_1$
hadro-charmonium	$(c\bar{c})_1 + (q\bar{q})_1$
...	

Sexaquark mesons: $c\bar{c}qq\bar{q}\bar{q}$

Charmonium

Potential models

Barnes, Godfrey, and Swanson; Eichten, Lane, and Quigg

well-developed phenomenology

except for effects of coupling to charm meson pairs

Missing states:

$3S$ multiplet	
$\eta_c(3S)$	0^{-+}
$2P$ multiplet	
$h_c(2P)$	1^{+-}
$\chi_{c1}(2P)$	1^{++}
$\chi_{c0}(2P)$	0^{++}
$1D$ multiplet	
$\psi_3(1D)$	3^{--}
$\psi_2(1D)$	2^{--}
$\eta_{c2}(1D)$	2^{-+}

Missing multiplets: $4S$, $3P$, $2D$, ...

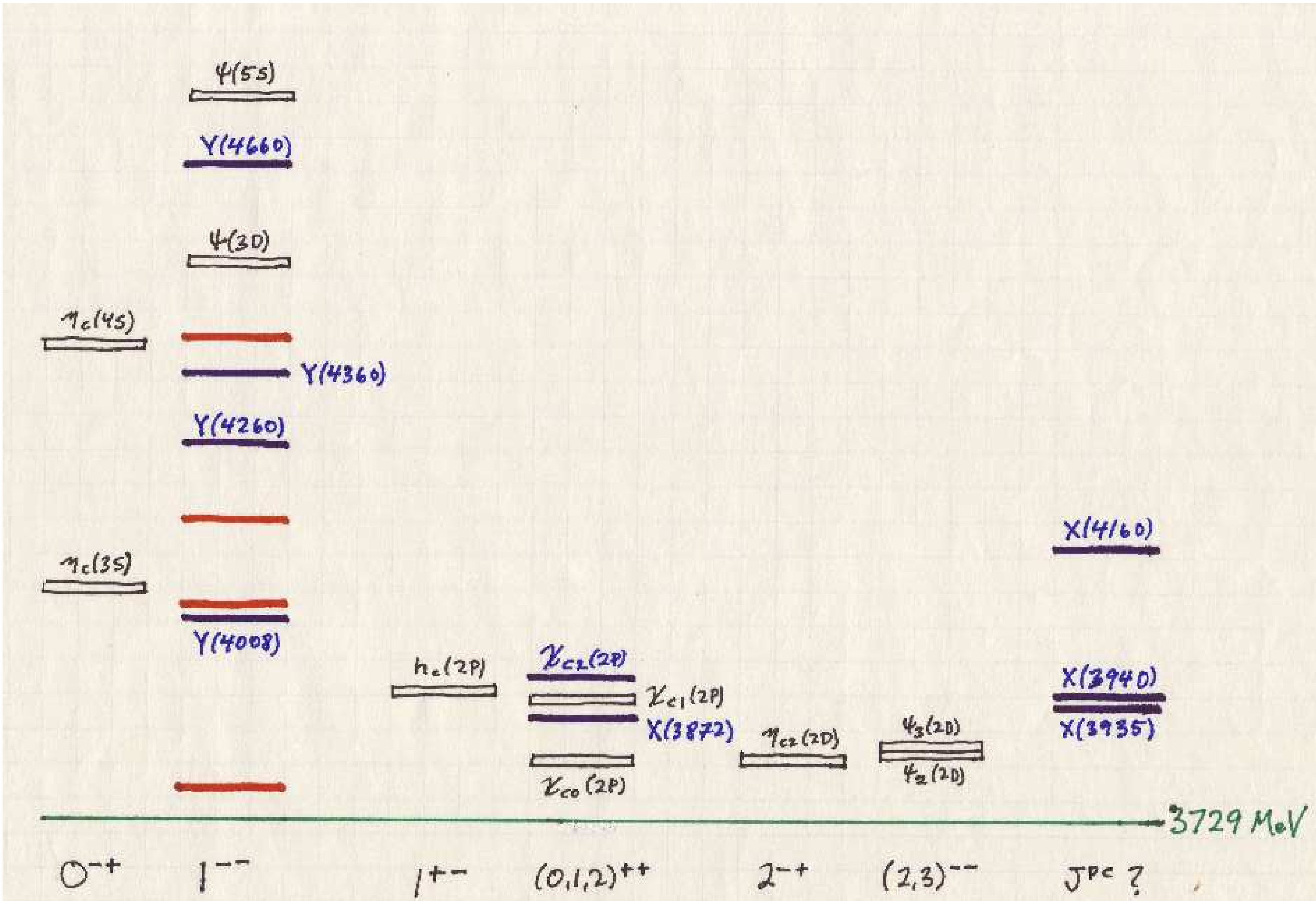
Charmonium (cont.)

Missing charmonium states

old charmonium states

new $c\bar{c}$ mesons

missing charmonium states



Charm meson molecules

Bander, Shaw, Thomas, and Meshkov; Voloshin and Okun;

de Rujula, Georgi, and Glashow; Nussinov and Sidhu (1976-78)

Meson potential model

with one-pion-exchange and UV cutoff on $1/r^3$ potential

Tornqvist (1991, 1994)

predicted charm meson molecules near threshold

in several J^{PC} channels with $I = 0$

$D\bar{D}$: none

$D^*\bar{D}/D\bar{D}^*$: 1^{++}; 0^{-+}

(threshold = 3872 MeV)

$D^*\bar{D}^*$: 0^{++}, 1^{+-}, 2^{++}, 0^{-+}

(threshold = 4014 MeV)

Charm meson molecules (cont.)

Tornqvist essentially predicted $X(3872)$ in 1994

modulo effects of isospin splitting: D^+–D^0, D^{*+}–D^{*0}

Updated analysis — Swanson

use mass of $X(3872)$ to tune UV cutoff on $1/r^3$ potential

include quark exchange interactions

predictions for charm meson molecules

$D^*\bar{D}/D\bar{D}^*$: 1^{++} X(3872) (input)

$D^*\bar{D}^*$: 0^{++} X(4013) predicted

predictions for bottom meson molecules

$B^*\bar{B}/B\bar{B}^*$: 0^{-+}, 1^{++}

$B^*\bar{B}^*$: 0^{++}, 0^{-+}, 1^{+-}, 2^{++}

binding energies: 40 to 70 MeV

Diquark–antidiquark tetraquark mesons

Maiani, Piccinini, Polosa, and Riquer; Ishida, Ishida, and Maeda; Ebert, Faustov, and Galkin

constituent diquarks: $S \equiv (cq)_{3^*,S=0}$, $A \equiv (cq)_{3^*,S=1}$

S-wave tetraquarks

$$S\bar{S}: \quad 0^{++}$$
$$A\bar{S}, S\bar{A}: \quad 1^{++}, 1^{+-}$$
$$S\bar{S}: \quad 0^{++}, 1^{+-}, 2^{++}$$

flavor multiplets for each J^{PC}:

$$q = u, d, s: \quad 9 \text{ states}$$
$$q = u, d: \quad 4 \text{ states}: (X^-, X^0, X^+)\ X^{0'}$$

Diquark–antidiquark tetraquark mesons (cont.)

Problem: too many states

S-wave, $n = 1$, $(cq)_{3^*}$ diquarks $\Longrightarrow 9 \times 6 = 54$ states

also orbital excitations

radial excitations

$(cq)_6$ diquarks

4-body problem for constituent quarks

Vijande, Valcarce, et al.; Hiyama, Suganama, and Kamimura

no stable $Q\bar{Q}q\bar{q}$ states

with only 2-body color-dependent forces

QCD sum rules — Navarra, Nielsen, et al.

possibility of bound states in some channels: 1^{++} ?

Lattice QCD?

dynamical quarks are essential

exotic quantum numbers are easiest

excited states are difficult

Charmonium hybrids

Lattice gauge theory (without dynamical light quarks)

- Born-Oppenheimer approximation

  Juge, Kuti, Morningstar

  lowest multiplet:

  0^{-+}, 0^{+-}, 1^{--}, 1^{++}, 1^{+-}, 1^{-+}, 2^{-+}, 2^{+-}

  masses $\approx$ 4200 MeV

- conventional lattice gauge theory

  Liao and Manke; Liu and Luo

  lowest states with exotic quantum numbers

  1^{-+} : 4400 MeV

  0^{+-} : 4700 MeV

  2^{+-} : 4900 MeV

Mass range compatible with new 1^{--} states:

$Y(4260)$, $Y(4360)$, $Y(4660)$

Charmonium hybrids (cont.)

Decays into two charm mesons

Isgur, Kokoski, and Paton; Close and Page; Kou and Pene

- S-wave + S-wave is suppressed: $D\bar{D}$, $D^*\bar{D}$, $D\bar{D}^*$, $D^*\bar{D}^*$
- P-wave + S-wave is favored: $D_1\bar{D}^{(*)}$, $D_2\bar{D}^{(*)}$

New 1^{--} $c\bar{c}$ mesons: $Y(4260)$, $Y(4360)$, $Y(4660)$

observed via $Y \to J/\psi\pi\pi$

OR $Y \to \psi(2S)\pi\pi$

not seen in $Y \to D\bar{D}, D^*\bar{D}, D^*\bar{D}^*$

charmonium hybrid mesons?

Hadro-charmonium

Voloshin, Dubynsky, Gorsky

light hadron h bound to charmonium ψ: $(\psi\ h) = (c\bar{c})_1 + (q\bar{q})_1$

multipole expansion for long-wavelength gluon fields:

$$\mathcal{H}_{\text{eff}} = -\tfrac{1}{2}\alpha_\psi \boldsymbol{E}^a \cdot \boldsymbol{E}^a$$

$\Longrightarrow$ attractive interaction
strong enough for bound state ??

new $c\bar{c}$ meson with J/ψ decay modes: $(J/\psi\ h)$?

$$Y(4008) \longrightarrow J/\psi\,\pi^+\pi^-$$
$$Y(4260) \longrightarrow J/\psi\,\pi^+\pi^-$$

new $c\bar{c}$ meson with $\psi(2S)$ decay modes: $(\psi(2S)\ h)$?

$$Y(4360) \longrightarrow \psi(2S)\,\pi^+\pi^-$$
$$Y(4660) \longrightarrow \psi(2S)\,\pi^+\pi^-$$
$$Z^\pm(4430) \longrightarrow \psi(2S)\,\pi^\pm$$

What is the $X(3872)$?

Two crucial experimental inputs

- mass is extremely close to $D^{*0}\bar{D}^0$ threshold

$$M_X - (M_{D^{*0}} + M_{D^0}) = -0.4 \pm 0.7 \text{ MeV}$$

- $J^{PC} = 1^{++}$

Conclusion

$X(3872)$ is a weakly-bound charm meson molecule

$$X = \frac{1}{\sqrt{2}}\left(D^{*0}\bar{D}^0 - D^0\bar{D}^{*0}\right)$$

What is the $X(3872)$? (cont.)

"Universality of Few-Body Systems with Large Scattering Length"

Braaten and Hammer, arXiv:cond-mat/0410417

S-wave resonances near threshold have universal properties
determined by a large scattering length
(or by small binding energy E_X and width)

apply to $X(3872)$

- $J^{PC} = 1^{++} \Longrightarrow$ S-wave coupling to $D^{*0}\bar{D}^0$
- mass within 1 MeV of $D^{*0}\bar{D}^0$ threshold $\Longrightarrow$ resonant coupling!

conclude $X(3872)$ is charm meson molecule (or virtual state)

$$X = \frac{1}{\sqrt{2}}\left(D^{*0}\bar{D}^0 - D^0\bar{D}^{*0}\right)$$

mean separation of constituents

$$\begin{aligned} \langle r \rangle_X &= \hbar/(8\mu E_X)^{1/2} \\ &= 3.5 \text{ fm} \qquad\qquad \text{if } E_X = 0.4 \text{ MeV} \end{aligned}$$

What is the $X(3872)$? (cont.)

Explanation of $X(3872)$ puzzles

- isospin violating decays

$$X \longrightarrow J/\psi\, \rho^* \longrightarrow J/\psi\, \pi^+\pi^- \qquad (I=1)$$
$$X \longrightarrow J/\psi\, \omega^* \longrightarrow J/\psi\, \pi^+\pi^-\pi^0 \qquad (I=0)$$

tuning the mass of any 1^{++} state

($D^*\bar{D}$ bound state, $\chi_{c1}(2P)$, ...)

to the $D^{*0}\bar{D}^0$ threshold (3871.8 MeV)

transforms it into a $D^{*0}\bar{D}^0$ molecule

$$X = \frac{1}{\sqrt{2}}\left(D^{*0}\bar{D}^0 - D^0\bar{D}^{*0}\right)$$

$\Longrightarrow$ equal superposition of $I=0$ and $I=1$

What is the $X(3872)$? (cont.)

Explanation of $X(3872)$ puzzles

- mass difference in $D^0\bar{D}^0\pi^0$ and $J/\psi\,\pi^+\pi^-$

$$M_X{}^{D^0\bar{D}^0\pi^0} - M_X{}^{J/\psi\,\pi^+\pi^-} = 3.8 \pm 1.1 \text{ MeV}$$

$B \longrightarrow K + D^0\bar{D}^0\pi^0$ proceeds via

1. resonance production: $B \longrightarrow K + X(3872)$
   followed by decay of constituent: $D^{*0} \longrightarrow D^0\pi^0$
   $\Longrightarrow$ resonant peak at $(M_{D^{*0}} + M_{D^0}) - E_X$
2. charm meson production: $B \longrightarrow K + D^{*0}\bar{D}^0$
   followed by decay $D^{*0} \longrightarrow D^0\pi^0$
   $\Longrightarrow$ threshold enhancement peaks at $(M_{D^{*0}} + M_{D^0}) + E_X$

$B \longrightarrow K + J/\psi\,\pi^+\pi^-$ proceeds only via

1. resonance production: $B \longrightarrow K + X(3872)$
   $\Longrightarrow$ resonant peak at $(M_{D^{*0}} + M_{D^0}) - E_X$

What is the $X(3872)$? (cont.)

Other predictions — Braaten and Lu

- Ratios of production rates*

$$\frac{\Gamma[B^0 \to K^0 + X]}{\Gamma[B^+ \to K^+ + X]} = \left| \frac{\gamma_1}{\gamma_1 - \kappa_1} \right|^2$$

$\kappa_1 = 125$ MeV

$\gamma_1 =$ inverse scattering length for $D^* \bar{D}$ in $I = 1$ channel

- Line shapes* of $X(3872)$

$B^+ \to K^+ + J/\psi\, \pi^+ \pi^-$:	zero 6 MeV above $D^{*0} \bar{D}^0$ threshold
$B^0 \to K^0 + J/\psi\, \pi^+ \pi^-$:	zero 2 MeV below $D^{*0} \bar{D}^0$ threshold
$B \to K + J/\psi\, \pi^+ \pi^- \pi^0$:	no zeroes near threshold
$B \to K + D^0 \bar{D}^0 \pi^0$:	no zeroes near threshold

* supercedes incorrect predictions by Braaten and Kusunoki and by Voloshin

Conclusions

- $Z^{\pm}(4430)$ is exotic tetraquark meson:

$$Z^{+} = c\bar{c}u\bar{d}$$

isospin multiplet: (Z^{-}, Z^{0}, Z^{+})
J^{P} quantum numbers?

- $X(3872)$ is weakly-bound charm meson molecule:

$$X = \frac{1}{\sqrt{2}}\left(D^{*0}\bar{D}^{0} - D^{0}\bar{D}^{*0}\right)$$

universal properties associated with large scattering length
insensitive to details of QCD
mechanism: binding of charm mesons?
$\chi_{c1}(2P)$ near threshold?
other?

Conclusions (cont.)

- New 1^{--} mesons may be charmonium hybrids

  $Y(4260)$? $Y(4360)$? $Y(4660)$?

  confirm by observation of decays into $D_1\bar{D}^{(*)}$, $D_2\bar{D}^{(*)}$

If exotic $c\bar{c}$ mesons exist,
then exotic $b\bar{b}$ mesons probably also exist

Theoretical challenge: predict their properties!

Experimental challenge: discover them!