The $X(3872)$ Files

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with Masaoki Kurunoki

- What is the $X(3872)$?
- How is it produced?
- How does it decay?
Discovery of the $X(3872)$

by the Belle collaboration

November 2003

announcement of a “narrow charmonium-like state”

$B^+ \rightarrow XK^+$

$X \rightarrow J/\psi \pi^+\pi^-$

with mass near 3872 MeV
Discovery of the $X(3872)$ (cont.)

Belle collaboration

![Graphs showing $M(\pi^+\pi^1\Gamma) - M(\Gamma^1\Gamma)$ (GeV) for data (a) and MC (b).]
What is the \textit{X}(3872)?

- charmonium?
  Barnes, Godfrey, Eichten, Lane, Quigg

- \textit{DD}\textsuperscript{*} molecule?
  Tornqvist, Voloshin, Wong, Braaten, Kusunoki, Swanson, Nussinov

- threshold enhancement (cusp) in \textit{DD}\textsuperscript{*} scattering?
  Bugg
  \textsuperscript{a1}\text{threshold} from large negative \textit{DD}\textsuperscript{*} scattering length
What is the $X(3872)$? (cont.)

- tetraquark ($c q ar{c} q$)  
  Vijande, Fernandez, Valcarce

- Kaluza-Klein excitation of $J/\psi \rho$  
  Arkhipov

- charmonium hybrid ($c \bar{c} g$)?  
  Li

- glueball mixing with charmonium?  
  Seth

- diquark-antidiquark bound state ($c q + \bar{c} q$)?  
  Maiani, Piccinini, Polosa, Riquer
Is the $X(3872)$ a charmonium?

Missing charmonium multiplets near 3872 MeV

$\begin{align*}
2^1P_1 & : 1^{+-} \\
2^3P_0 & : 0^{++} \\
2^3P_1 & : 1^{++} \\
2^3P_2 & : 2^{++} \\
1^1D_2 & : 2^{--} \\
1^3D_1 & : 1^{--} \quad \psi(3770) \\
1^3D_2 & : 2^{--} \\
1^3D_3 & : 3^{--}
\end{align*}$

Isospin: $I=0$

(in the absence of large mixing with $D(\ast)\bar{D}(\ast)$ states)
Missing Charmonium Multiplets

\[ X(3870) \]

\[
\begin{align*}
2^1P_1 & \quad 2^3P_0 & \quad 2^3P_1 & \quad 2^3P_2 & \quad 1^3D_2 & \quad 1^3D_1 & \quad 1^3D_2 & \quad 1^3D_3 \\
1^+ & \quad 0^+ & \quad 1^+ & \quad 2^+ & \quad 2^+ & \quad 1^- & \quad 2^- & \quad 3^-
\end{align*}
\]
Is the $X(3872)$ a $DD^*$ molecule?

$$M_{D^0} + M_{D^{*0}} - M_X = -0.5 \pm 0.9 \text{ MeV}$$
$$M_{D^+} + M_{D^{*-}} - M_X = -8.1 \pm 1.4 \text{ MeV}$$

Molecule composed of $D^0\bar{D}^{*0}$ and $D^{*0}\bar{D}^0$?

- tiny binding energy: $M_{D^0} + M_{D^{*0}} - M_X < 1 \text{ MeV}$
- charge conjugation $C = \pm: \frac{(D^0\bar{D}^{*0} \pm D^{*0}\bar{D}^0)}{\sqrt{2}}$
- indefinite isospin: $\frac{(|I = 0\rangle + |I = 1\rangle)}{\sqrt{2}}$
Is the $X(3872)$ a $DD^*$ molecule?

Charm molecules?
Bander, Shaw, Thomas, Meshkov, Voloshin, Okun, de Rujula, Georgi, Glashow, Nussinov, Sidhu (1976-78)

Binding mechanisms

pion exchange
- $S$-wave $1^{++}$ or $P$-wave $0^{++}$

pion exchange + quark exchange
- $S$-wave $1^{++}$

charmonium ($x_{c1}(2P)$ or $h_c(2P)$) near $\bar{D}D^*$ threshold
- $S$-wave $1^{++}$ or $S$-wave $1^{+-}$

Tornqvist 1991
Swanson
Braaten, Kusunoki
Production of $X(3872)$

Exclusive production

discovery mode: $B^+ \rightarrow X(3872) K^+$

$\text{Br}[B^+ \rightarrow X K^+] \text{ Br}[X \rightarrow J/\psi \pi^+ \pi^-] = (1.3 \pm 0.3) \times 10^{-5}$

Belle, Babar

Inclusive production

$p\bar{p} \rightarrow X(3872) + \text{anything}$
mostly prompt (not from $b$ hadron decay)

CDF, D0
Decays of $X(3872)$

- $X$ is very narrow
  
  $\Gamma_X < 2.3 \text{ MeV}$ at 90% C.L.

- $X$ decays into $J/\psi \pi^+\pi^-$
  
  \[
  \text{Br}[B^+ \rightarrow XK^+] \text{Br}[X \rightarrow J/\psi \pi^+\pi^-] = (1.3 \pm 0.3) \times 10^{-5}
  \]
  dominated by $J/\psi \rho^*$

- $X$ decays into $J/\psi \pi^+\pi^-\pi^0$
  
  \[
  \frac{\text{Br}[X \rightarrow J/\psi \pi^+\pi^-\pi^0]}{\text{Br}[X \rightarrow J/\psi \pi^+\pi^-]} = 1.1 \pm 0.5
  \]
  dominated by $J/\psi \omega^*$
Decays of $X(3872)$

- limits on other branching fractions:

$$R[H] \equiv \frac{\text{Br}[X \to H]}{\text{Br}[X \to J/\psi \pi^+ \pi^-]}$$

<table>
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<tr>
<th>Decay</th>
<th>Limit $R$</th>
<th>Experiment</th>
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<tr>
<td>$X_{c1} \gamma$</td>
<td>$&lt; 0.89$</td>
<td>Belle</td>
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<tr>
<td>$X_{c2} \gamma$</td>
<td>$&lt; 1.1$</td>
<td></td>
</tr>
<tr>
<td>$J/\psi \gamma$</td>
<td>$&lt; 0.4$</td>
<td></td>
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<tr>
<td>$D^0 D^0$</td>
<td>$&lt; 4$</td>
<td></td>
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<tr>
<td>$D^+ D^-$</td>
<td>$&lt; 3$</td>
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<tr>
<td>$D^0 D^0 \pi^0$</td>
<td>$&lt; 5$</td>
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</tr>
<tr>
<td>$J/\psi \eta$</td>
<td>$&lt; 6$</td>
<td>Babar</td>
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</tbody>
</table>
Universality of Few-Body Systems with Large Scattering Length

If S-wave scattering length $a$ is large compared to natural length scale $\ell$ for low energy scattering,

then few-body systems with low energies compared to natural energy scale $1/(\mu \ell^2)$

have universal properties that depend only on $a$

Review: Braaten and Hammer, arXiv:cond-mat/0410417
Universality (cont.)

universal properties for $a > 0$

- binding energy of molecule
  \[ E_b = \frac{1}{2\mu a^2} \]

- wavefunction of molecule
  \[ \psi(r) = \frac{e^{-r/a}}{\sqrt{2\pi a r}} \]
Universality (cont.)

The $DD^*$ System

natural momentum scale: $m_\pi = 1.4$ fm
natural length scale: $1/m_\pi = 140$ MeV
natural energy scale: $m_\pi^2/(2\mu) = 10$ MeV

Universal binding energy: $E_b = 1/(2\mu a^2)$

$E_b < 1$ MeV $\implies a > 5$ fm

Large scattering length in $D^0 \bar{D}^{*0} + D^{*0} \bar{D}^0$ channel
Universality (cont.)

Effective Field Theory for large scattering length

\[ \mathcal{L} = \psi_a^\dagger \left( i \frac{\partial}{\partial t} + \frac{1}{2m_a} \nabla^2 \right) \psi_a + \psi_b^\dagger \left( i \frac{\partial}{\partial t} + \frac{1}{2m_b} \nabla^2 \right) \psi_b \]

\[ -g(\Lambda)(\psi_a^\dagger \psi_a)(\psi_b^\dagger \psi_b) \]

renormalizable: \[ g(\Lambda) = \frac{16\pi a}{[1 - (2/\pi)a\Lambda]} \]

2 \rightarrow 2 T-matrix: \[ T(p) = \frac{16\pi}{[-1/a - ip]} \]

bound state (if \( a > 0 \)): \[ E_b = \frac{1}{(2\mu a^2)} \]
Decays of Constituents of $X(3872)$

decay of constituent: $D^{*0} \rightarrow D^0\pi^0$, $D^0\gamma$

$\Gamma[D^{*0}] \approx 50$ keV

interference between $D^0\bar{D}^0$, $D^0\bar{D}^{*0}$

$C = +: \implies$ constructive for $D^0\bar{D}^0\pi^0$
destructive for $D^0\bar{D}^0\gamma$

$C = -: \quad$ opposite

Universal wavefunction: $\psi(r) = e^{-r/\alpha}/(\sqrt{2\pi}\alpha r)$
Decays of Constituents of $X(3872)$ (cont.)

$$C = \pm: \quad \Gamma[X \to D^0 \bar{D}^0 \pi^0] = 2(A \pm B) \Gamma[D^{*0}]$$

$C = +$: constructive interference by factor of 2 as $E_b \to 0$
Probabilities of other Channels of $X(3872)$

As $E_b$ is tuned to 0, the probability for molecular channel approaches 1:
\[ \frac{\bar{D}^0 D^{*0} + D^0 \bar{D}^{*0}}{\sqrt{2}} \]

Probabilities for other channels approach 0 as $E_b^{1/2}$:
- $D^{\pm} D^{*\mp}$
- charmonium
- $J/\psi \rho$, ...

Probabilities of other channels of $X(3872)$ (cont.)

Hadronic coupled-channel model

\[ \bar{D}^0 D^{*0} + D^0 \bar{D}^{*0}, \]
\[ D^+ D^{*-} + D^- D^{*-}, \]
\[ J/\psi \omega, J/\psi \rho^0 \]
Production of $X(3872)$ in $\gamma(4S)$ Decay by Coalescence of Charm Mesons

Braaten, Kusunoki

$\gamma(4S) \rightarrow X\pi^+\pi^-$:
decay of $B$ mesons into $D\pi$ and $D^{*}\pi$
followed by coalescence of $D$ and $D^{*}$

$\gamma(4S) \rightarrow B^+B^- \rightarrow D^{0}\pi + D^{*0}\pi^- \rightarrow X\pi^+\pi^-$

universal coalescence amplitude:

$A[D^{0}D^{*0} \rightarrow X] = (16\pi m_{X}^2/\mu a)^{1/2}$
Production of $X(3872)$ in $\Upsilon(4S)$ Decay (cont.)

Production of $X(3872)$ in $\Upsilon(4S)$ Decay (cont.)

Decay rate ...
... depends only on masses and $\Gamma_B$
... scales like $E_b^{1/2} \log E_b$ as $E_b \to 0$
... suppressed by $(\Gamma_B/M_B)^2$

$$\text{Br}[\Upsilon(4S) \to X\pi^+\pi^-] \approx 10^{-30}$$
$B \rightarrow X(3872) + K$

separate decay into ...

... short distances: $|p| > \Lambda \sim m_\pi$

... long distances: $|p| < \Lambda$ ($|p| \sim 1/|a|$)

At short distances, $B$ decays into $D^0 \bar{D}^{*0} + K$ (or $D^{*0} \bar{D}^0 + K$)

At long distances, $D^0 \bar{D}^{*0}$ bind to form $X$
$B \rightarrow X(3872) + K$ (cont.)

**Short-distance factors**

Decay rates for $B$ into $D^0 \bar{D}^{*0} + K$, $D^{*0} \bar{D}^0 + K$

Analysis of Babar data on $B \rightarrow D^{(*)} \bar{D}^{(*)} + K$

(22 branching fractions)

Reduce to 4 independent form factors using ...

... heavy quark symmetry

... isospin symmetry

... factorization of $H_{\text{weak}}$ into current-current interactions

Approximate 4 form factors by 4 complex constants
$B \rightarrow X(3872) + K$ (cont.)

**Long-distance factors**

Wavefunction at the origin for $X$:

$$\psi(r = 0) = \int \frac{d^3p}{(2\pi)^3} \frac{\sqrt{8\pi a}}{p^2 + 1/a^2} \approx \left( \frac{2}{\pi^3 a} \right)^{1/2}$$

$|\psi(r = 0)|^2$ scales as $a^{-1} \sim E_b^{1/2}$

for order-of-magnitude estimate, set $\Lambda = m_{\pi}$
$B \rightarrow X(3872) + K$ (cont.)

Approximate 4 form factors by 4 complex constants
Fit to 22 branching fractions \textit{from Babar}

Result of analysis:

$$\text{Br}[B^+ \rightarrow X K^+] \approx (3 \times 10^{-5}) \frac{\Lambda^2}{m^2_\pi} \left(\frac{E_b}{0.4 \text{ MeV}}\right)^{1/2}$$

Consistent with Belle data

$$\text{Br}[B^+ \rightarrow X K^+] \text{Br}[X \rightarrow J/\psi \pi^+ \pi^-] = (1.3 \pm 0.3) \times 10^{-5}$$

provided $J/\psi \pi^+ \pi^-$ is a major decay mode of $X$
$\text{Br}(X \to J/\psi \pi \pi)$

X(3872) production much lower than other allowed Charmonium states:
- against Charmonium assignment
- allows to set lower limit on Br

$\text{Br}(X \to J/\psi \pi \pi) > 4\%$ @ 90\% C.L
$B \rightarrow X(3872) + K$ (cont.)

Sensitivity to $\Lambda$ and $E_b$ comes from wavefunction at the origin

Sensitivity cancels in ratio:

$$0 < \frac{\Gamma[B^0 \rightarrow XK^0]}{\Gamma[B^+ \rightarrow XK^+]} < 7 \times 10^{-2}$$

$\implies$ Suppression of $B^0 \rightarrow XK^0$

Note: $b \rightarrow c\bar{c}s$ weak decays respect isospin symmetry, so charmonium with $I = 0$ would imply no suppression
Search for $B^0 \to X(3872)K_s$

Preliminary

$B^0 \to X(3872)K_s$

$N = 8.4 \pm 4.5 \quad 2.7 \sigma$
$m_X = (3868.6 \pm 1.2) \text{MeV}$

$B^+ \to X(3872)K^+$

$N = 51 \pm 14 \quad 6.9 \sigma$
$m_X = (3871.3 \pm 0.6) \text{MeV}$

$\Delta M = (2.7 \pm 1.3 \pm 0.2) \text{MeV}$
Decay $B \rightarrow D^0 \bar{D}^{*0} + K$ near Threshold

Short-distance factor cancels in ratio with $\Gamma[B \rightarrow X(3872) + K]$

$$\frac{d\Gamma}{dM_{D\bar{D}^{*}}}[B^+ \rightarrow \bar{D}^0 D^{*0} K^+] = \Gamma[B^+ \rightarrow X K^+] \frac{\mu a^3 k_D}{\pi(1 + a^2 k_D^2)}$$

$k_D = \bar{D}^0$ momentum in $D^0 D^{*0}$ rest frame
Decay $B \rightarrow D^0 \bar{D}^{*0} + K$ (cont.)

Invariant mass distribution of $D^0 \bar{D}^{*0}$ relative to threshold
Line Shape of $X(3872)$ in $B \rightarrow J/\psi \pi^+\pi^- + K$

distribution of invariant mass $M$ of $J/\psi \pi^+\pi^-$

$$\frac{d\Gamma}{dM} \propto \frac{1}{\left| -\frac{1}{a} + \sqrt{-2\mu E} \right|^2}$$

energy of $J/\psi \pi^+\pi^-$ relative to $D^0 \bar{D}^{*0}$ threshold

$$E = \frac{\lambda(M, m_{D^0}, m_{D^{*0}})}{8\mu(m_{D^0} + m_{D^{*0}})^2}$$
Line Shape of $X(3872)$ (cont.)

inelastic scattering: $D^0 \bar{D}^{*0} \rightarrow J/\psi \pi^+ \pi^-$

scattering length $a$ has imaginary part

$$\frac{1}{a} = \gamma_{re} + i \gamma_{im}$$

invariant mass distribution

$$\frac{d\Gamma}{dM} \propto \frac{1}{(|2\mu E|^{1/2} - \gamma_{re})^2 + \gamma_{im}^2}$$

$$\propto \frac{1}{((2\mu E)^{1/2} + \gamma_{im})^2 + \gamma_{re}^2}$$

$E < 0$

$E > 0$
Line Shape of $X(3872)$ (cont.)

Invariant mass distribution for $J/\psi \pi^+\pi^-$ relative to $D^0 \bar{D}^{*0}$ threshold

$\gamma_{re} > 0$: "resonance"

$\gamma_{re} < 0$: "cusp"

($\gamma_m = 12$ MeV fixed)
Conclusions

The $X(3872)$ is a weakly-bound molecule of charm mesons with quantum numbers $J^{PC} = 1^{++}$:

$$|X\rangle \approx \frac{1}{\sqrt{2}} \left(|D^0 \bar{D}^{*0}\rangle + |D^{*0} \bar{D}^0\rangle\right)$$

Because it is so weakly bound ($E_b < 1$ MeV), it has universal properties that are determined by the large scattering length ($a > 5$ fm) of $D^0 \bar{D}^{*0}$ and $D^{*0} \bar{D}^0$ in the $C = +$ channel.

Effective field theory can be useful for elucidating those universal properties.
The Truth is Out There