X(3872) and Other Exotic Mesons

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IPM-METU Joined Conference
Study of hadronic spectrum has always brought many surprises.
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Discovery of the charmonium

Introduction

- Study of hadronic spectrum has always brought many surprises.
- Discovery of the charmonium
- Most recently, the discovery of possible pentaquark states by LHCb.
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- Discovery of the charmonium
- Most recently, the discovery of possible pentaquark states by LHCb.
The hadrons are made up of quarks and gluons
The interactions of quarks and gluons are described by an SU(3) gauge theory called QCD
QCD is a non-perturbative theory-difficult to extract predictions
Two properties that interactions of quarks and gluons should have:
- Asymptotic freedom-QCD is asymptotically free
- Confinement-it is believed that QCD is confining
Conventional Hadrons, Confinement and QCD

- Quarks carry color charge (can have three different colors: rgb)
- Gluons carry a color and an anti-color charge
- Confinement: Physically observable states are colorless
- Simplest colorless combination: color + anti-color
  \[ (3 \otimes \bar{3} = 1 \oplus 8): \]
  
  **Mesons:**

  - The second simplest: 3 colors
    \[ (3 \otimes 3 \otimes 3 = 1 \oplus 8 \oplus 8 \oplus 10) \]
    
    **Baryons:**
In non-relativistic systems, the interaction between a quark and anti-quark can be described by a potential model.

If the separation between quarks is small, one gluon exchange is enough to describe their interaction (asymptotic freedom): \( \lim_{r \to 0} V(r) \propto \frac{\alpha_s(r)}{r} \).

If the separation between quarks is large, the potential raises linearly (confinement): \( \lim_{r \to \infty} V(r) \propto r \).

Cornell potential:

\[
V(r) = -\frac{4}{3} \frac{\alpha_s(r)}{r} + kr
\]

Add S-L coupling, S-S interaction, relativistic corrections,
Challenge: hadronic states above open-charm thresholds

A. Nefediev, XHadrons Conference, 2015

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Potential quark model is very successful below thresholds

Close to and above thresholds, potential quark model is less successful.

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\[ |\mathcal{M}\rangle = (\bar{q}^a q^a) + (\bar{q}^a g^{ab} q^b) + (\bar{q}^a q^a (\bar{q}^b q^b)) + (qq^a (\bar{q} \bar{q})^a) + \cdots \]

They are conventional mesons, but potential quark models are not good enough.

Molecules: Meson-Meson, Baryon-Baryon, or Meson-Baryon: Bound states of colorless objects

Genuine tetraquarks, pentaquarks, etc.

Hibrids: Valence gluons

More exotic states
\[ |\mathcal{M}\rangle = (\bar{q}^a q^a) + (\bar{q}^a g^{ab} q^b) + ((\bar{q}^a q^a)(\bar{q}^b q^b)) + (qq)^a (\bar{q}\bar{q})^a + \cdots \]

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- **Molecules:** Meson-Meson, Baryon-Baryon, or Meson-Baryon: Bound states of colorless objects
- **Genuine tetraquarks, pentaquarks, etc.**
- **Hibrids:** Valence gluons
- **More exotic states**
What is a well known example of a hexa quark state?
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All nuclei are baryon molecules!
Diquarks

\[ \epsilon_{abc} q^b q^c \sim \bar{q}_a \]

Colorwise, 2 quarks can behave like an anti-quark:
\[ 3 \otimes 3 = \bar{3} \oplus 6 \]

\[ \bar{\epsilon}^{abc} \bar{q}_b \bar{q}_c \sim q^a \]

Color-wise, 2 anti-quarks can behave like a quark:
\[ \bar{3} \otimes \bar{3} = 3 \oplus \bar{6} \]

In a colorless state, if a quark (anti-quark) is replaced by an anti-diquark (diquark) it remains colorless.
**Meson**
Replace anti-quark in a meson by a diquark:

**Baryon**
Replace anti-quark in a meson by a diquark:

**Pentaquark**
Replace both quarks in a baryon by anti-diquarks:

**Tetraquark**
Replace quark in a baryon by an anti-diquark:
Consequences of Diquark Picture

- Many excited states, hence many exotics
- Diquark can split into a diquark and a meson

\[ T \rightarrow TM \]
Many excited states, hence many exotics
Diquark can split into a diquark and a meson

\[ \text{H} \rightarrow \text{H} \quad (T \rightarrow B\bar{B}) \]
X(3872) first observed in 2003 by BELLE in $B \rightarrow J/\psi \pi\pi K$
Quantum numbers determined to be $J^{PC} = 1^{++}$ by LHCb in 2013
$m_X = 3871.69 \pm 0.17 \text{ MeV}, \Gamma < 1.2 \text{ MeV}$
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$m_{D^0} + m_{D^*0} - m_X < 1 \text{ MeV}$.

A Meson molecule is a weakly bound state of two mesons due to contact interactions, exchange of other light mesons, etc.

In the molecular picture, $m_X = m_{D^0} + m_{D^*0} - B$ where $B > 0$ is the binding energy.

The mass is a coincidence in diquark picture.
\[ \frac{\Gamma(X \rightarrow \psi(2S)\gamma)}{\Gamma(X \rightarrow J/\psi(1S)\gamma)} = \begin{cases} < 2.1 & \text{BELLE 2011} \\ 3.4 \pm 1.4 & \text{BABAR 2009} \end{cases} \]

- In the quark model, \(X(3872)\) is a \(2P\) state: \(X \rightarrow \psi(2S)\gamma\) is the \(\Delta L = 1\) transition.

- Not so natural in the molecular picture.

- Even if \(X(3872)\) is a molecule, likely to have a significant charmonium component.
It decays into a final state with $I = 0$ and $I = 1$ with almost equal branching ratio:

$$\frac{B(X(3872) \to J/\psi \rho)}{B(X(3872) \to J/\psi \omega)} \sim 1 \Rightarrow \frac{A(X(3872) \to J/\psi \rho)}{A(X(3872) \to J/\psi \omega)} \approx 0.2$$

There is a large isospin symmetry breaking.

Isospin violation is naively expected to be of the order of

$$\delta = \frac{m_u - m_d}{\Lambda_{QCD}} \approx 2 - 3\%$$

Large isospin breaking naturally arises in the molecular picture due to the mass differences between the charged and neutral D mesons.
In the molecular picture of \( \Sigma(3872) \) can be written as

\[
\left| \Sigma(3872) \right\rangle = \left| \psi_1 \right\rangle \left| D^0 \bar{D}^*0 \right\rangle + \left| \psi_2 \right\rangle \left| D^+ D^*^- \right\rangle
\]

\[
= \frac{1}{\sqrt{2}} (\left| \psi_1 \right\rangle + \left| \psi_2 \right\rangle) |l = 0 \rangle + \frac{1}{\sqrt{2}} (\left| \psi_1 \right\rangle - \left| \psi_2 \right\rangle) |l = 1 \rangle
\]

\[
\equiv \cos \theta |l = 0 \rangle + \sin \theta |l = 1 \rangle
\]

\[
\langle \psi_1 | \psi_1 \rangle + \langle \psi_2 | \psi_2 \rangle = 1
\]

In terms of the wave functions \( \psi_1 \) and \( \psi_2 \), the mixing angle can be written as

\[
\tan^2 \theta = \frac{\int d^3r |\psi_1(\vec{r}) - \psi_2(\vec{r})|^2}{\int d^3r |\psi_1(\vec{r}) + \psi_2(\vec{r})|^2} \Rightarrow \theta \sim 39^\circ
\] (1)

Note that \( \theta_{\text{max}} = 45^\circ \).
Isospin Structure

In the molecular picture of $X(3872)$ can be written as

$$|X(3872)\rangle = |\psi_1\rangle|D^0\bar{D}^{*0}\rangle + |\psi_2\rangle|D^+\bar{D}^{*-}\rangle$$

$$= \frac{1}{\sqrt{2}} (|\psi_1\rangle + |\psi_2\rangle) |I = 0\rangle + \frac{1}{\sqrt{2}} (|\psi_1\rangle - |\psi_2\rangle) |I = 1\rangle$$

If $\theta \simeq \theta_{\text{max}}$, why $A(X(3872)\rightarrow J/\psi\rho) \sim 0.2$?

The $I = 1$ decay into $J/\psi\rho$ is suppressed by the wave function at the origin; $\psi_1(0) - \psi_2(0)$.

To create a $J/\psi$, $D$ and $\bar{D}^*$ should come to the same point.

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$|X(3872)\rangle = \frac{1}{\sqrt{2}} (|\psi_1\rangle + |\psi_2\rangle) |I = 0\rangle + \frac{1}{\sqrt{2}} (|\psi_1\rangle - |\psi_2\rangle)) |I = 1\rangle$

$\psi_i(r) \propto e^{-B_i r}$

- How to probe the $I = 1$ component of the $X(3872)$?
- The decay should be sensitive to the wave functions at large separation (since $\psi_2$ decays faster with distance)
- Solution: look for a process where the mesons making the molecule decay independently: $X \rightarrow D^0 \bar{D}^0 \pi^0$
$X \rightarrow D^0 \bar{D}^0 \pi^0$ receives contributions both from large separations and also small separations.
\[ \Gamma(X(3872) \rightarrow D^0 \bar{D}^0 \pi^0) \]

\[ L = 0.5 \text{ GeV} \]

Gray: Only tree level
Blue: Tree level + FSI
Red: \( D \bar{D} \) resonance is generated at the \( D^0 \bar{D}^0 \) threshold


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Hadronic spectrum is still a rich subject to study
The only discovered “new physics” upto now!
Even more than 10 years after its discovery, we are still waiting for new measurements about X(3872)!
There are lots of other exotic resonances already discovered, and waiting to be discovered