Measurements of the exotic tetraquark candidate X(3872) in pp and pPb

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for the LHCb Collaboration
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A schematic model of baryons and mesons

M. Gell-Mann
California Institute of Technology, Pasadena, California

Received 4 January 1964

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $F = -\frac{1}{2}$, and baryon number $\frac{1}{2}$. We then refer to the members $u_3$, $d_3$, and $s_3$ of the triplet as "quarks". q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq), (qqq), etc., while mesons are made out of (q$\bar{q}$), (qq$\bar{q}$), etc. It is assuming that the lowest baryon configuration (qqq) gives just the representations 1, 8, and 10 that have been observed, while the lowest meson configuration (q$\bar{q}$) similarly gives just 1 and 8.

In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $\overline{AAA}$, $\overline{AAAA}$, etc., where $\overline{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\overline{AA}$, $\overline{AAAA}$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $\overline{AA}$ and AAA, that is, "deuces and treys".
A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon $b$ if we assign to the triplet $t$ the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{2}$, and baryon number $\frac{1}{2}$. We then refer to the members $u^\dagger$, $d^\dagger$, and $s^\dagger$ of the triplet as "quarks" $q$ and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q q q)$, $(q q q q)$, etc., while mesons are made out of $(q \bar{q})$, $(q q \bar{q})$, etc. It is assuming that the lowest baryon configuration $(q q q)$ gives just the representations $1$, $8$, and $10$ that have been observed, while the lowest meson configuration $(q \bar{q})$ similarly gives just $1$ and $8$.

States with $>3$ quarks have been expected since the beginning of the quark model.
Conventional $c\bar{c}$ States

Nonrelativistic potential model: solve Schrodinger equation with the potential

$$V^{(c\bar{c})}(r) = -\frac{4}{3} \frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2} \delta(r) S_c \cdot \bar{S}_{\bar{c}}$$

Barnes, Godfrey, Swanson, Phys. Rev. D 72, 054026 (2005)

Calculated States
Measured States

Rev. Mod. Phys. 90, 015003 (2018)
Conventional $c \bar{c}$ States

New charmonium states still being found: LHCb observed state consistent with $\psi_3 (1^3 D_3)$ found in $D\bar{D}$ and $D^+D^-$ mass spectra in 2019

Crucial to account for conventional states when searching for exotics

Rev. Mod. Phys. 90, 015003 (2018)
Exotic $c\bar{c}$ States

20+ states containing $c\bar{c}$ have been discovered since 2003 that do not fit in the picture of typical charmonium:
Collectively known as “XYZ” particles

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Multiple explanations explored in literature:

- Compact tetraquark/pentaquark
- Diquark-diquark
  - $u\bar{c}$ \(\rightarrow\) $u\bar{c}$
- Hadrocharmonium/adjoint charmonium
  - $u\bar{c}$ \(\rightarrow\) $u\bar{c}$

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    - PLB 666 344 (2008)
    - PLB 671 82 (2009)

- **Hadronic Molecules**
  - PRD 77 014029 (2008)
  - PRD 100 0115029(R) (2019)
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- **Mixtures of exotic + conventional states**
  \[ X = a \left| c\bar{c} \right\rangle + b \left| c\bar{c}q\bar{q} \right\rangle \]

Rev. Mod. Phys. 90, 015003 (2018)
X(3872) - a puzzle

• The first exotic hadron – discovered in $J/\psi\pi^+\pi^-$ mass spectrum from B decays by Belle in 2003

• LHCb measured quantum numbers (PRL 110 222001 2013)
  - Incompatible with expected charmonium states

Recently renamed $\chi_{c1}(3872)$ by PDG
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$D^0\bar{D}^*$ Molecule

- Very small binding energy
- Very large radius, ~7 fm

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$D^0\bar{D}^*$ Molecule

$D^0$

$\bar{D}^*$

Very small binding energy

Very large radius, ~7 fm

Tightly bound via color exchange between diquarks

Small radius, ~1 fm

Recently renamed $\chi_c(3872)$ by PDG
Effects of Binding Energy

- Suppression of weakly-bound quarkonia states has been studied for decades in pA collisions
  - Ratios of $\psi^{(2S)}/J/\psi$ and $Y(2S,3S)/Y(1S)$

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  - Ratios of $\psi(2S)/\psi$ and $\Upsilon(2S,3S)/\Upsilon(1S)$
- In general, final state effects are required to explain difference in suppression between states
- Prevalent in regions with high particle multiplicity

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Talk by Shanzen Chen

Poster by Jana Crkovska


LHCb Preliminary
pPb $\sqrt{s_{NN}} = 8.16$ TeV
converted photons
$1.5 < y < 4.0$

- $\chi_c1$
- $\chi_c2$

cf. PLB 749 98 (2015)
Effects of Binding Energy

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  - Ratios of $\psi(2S)/J/\psi$ and $\Upsilon(2S,3S)/\Upsilon(1S)$
- In general, final state effects are required to explain difference in suppression between states
- Prevalent in regions with high particle multiplicity
- Weakly bound hadronic molecules may show similar effects.

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Talk by Shanzen Chen
Probing X(3872) structure via interactions with the underlying event

Prompt production:
- X(3872) produced at collision vertex can be subject to further interactions with co-moving particles (medium?) produced in the event
- Potentially subject to breakup effects

Event display of $B_s^0 \rightarrow \mu^+ \mu^-$ candidate, PRL 118 191801 (2017)
Probing $X(3872)$ structure via interactions with the underlying event

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Production in $b$-decays:
- Hadrons containing $b$ travel down the beampipe and decay away from the primary vertex and decay in vacuum
- $X(3872)$ from decays not subject to further interactions
- Control sample

Event display of $B_s^0 \rightarrow \mu^+ \mu^-$ candidate, PRL 118 191801 (2017)
The LHCb Detector

\[ X(3872) \to J/\psi \pi^+ \pi^- \]

Vertex detector (VELO):
- Separation of prompt and \( b \)-decay production
- Number of VELO tracks gives measure of event activity

Two RICH detectors:
- Pion identification

Muon System:
- Layers of absorber/tracking
- Muon hardware trigger

Rapidity coverage: \[ 2 < \eta < 5 \]
X(3872) selection

Reconstruct the $\mu^+\mu^-\pi^+\pi^-$ final state from the decays:

\[ X(3872) \rightarrow J/\psi (\rightarrow \mu^+\mu^-)\rho (\rightarrow \pi^+\pi^-) \]

\[ \psi(2S) \rightarrow J/\psi (\rightarrow \mu^+\mu^-)\pi^+\pi^- \]

Select $J/\psi$ from dimuons, combine with two identified pions. Perform kinematic refit, constraining $J/\psi$ mass to known value and all four tracks to identical vertex.

Direct comparison between conventional charmonium $\psi(2S)$ and exotic $X(3872)$ via ratio of cross sections:

\[ \frac{\sigma_{Xe1}(3872)}{\sigma_{\psi(2S)}} \times \frac{B[\chi_{e1}(3872) \rightarrow J/\psi \pi^+\pi^-]}{B[\psi(2S) \rightarrow J/\psi \pi^+\pi^-]} \]
Simultaneous fit to invariant mass and pseudo proper time spectrum:

\[ t_z = \frac{z_{\text{decay}} - z_{\text{PV}}}{p_z} M \]

Fit to mass constrains S/B while fit to \( t_z \) constrains prompt fraction.
Prompt fraction

\[ f_{\text{prompt}} = \frac{N_{\text{prompt}}}{N_{\text{prompt}} + N_{b-\text{decay}}} \]

- Significant decrease in prompt fraction of both \( X(3872) \) and \( \psi(2S) \) as event activity increases:
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  - Events with \( b\bar{b} \) production naturally have higher multiplicity, due to fragmentation and decays
    - OPAL, PLB 550 33 (2002)
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- Formation of prompt \( X(3872) \) and \( \psi(2S) \) may be disrupted at the vertex, which cannot affect production via \( b \) decays in vacuum.
Ratio of cross sections

\[
\frac{\sigma_{\chi_{c1}(3872)}}{\sigma_{\psi(2S)}} \times \frac{B[\chi_{c1}(3872) \rightarrow J/\psi \pi^+ \pi^-]}{B[\psi(2S) \rightarrow J/\psi \pi^+ \pi^-]} = \frac{N_{\chi_{c1}(3872)} f_{\chi_{c1}(3872)}^{\text{prompt}}}{N_{\psi(2S)} f_{\psi(2S)}^{\text{prompt}}} \times \frac{\varepsilon_{\psi(2S)}}{\varepsilon_{\chi_{c1}(3872)}}
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LHCb Preliminary

pp \( \sqrt{s} = 8 \) TeV

Prompt Component:
Increasing suppression of \( X(3872) \) production relative to \( \psi(2S) \) as event activity increases
**Ratio of cross sections**

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Prompt Component:
Increasing suppression of \(X(3872)\) production relative to \(\psi(2S)\) as event activity increases.

\(b\)-decay component:
No significant change in relative production, as expected for decays in vacuum. Ratio is set by \(b\) decay branching fractions.

Consistent with ATLAS measurement:
\[
R = 0.0395 \pm 0.0032 \pm 0.0008 \quad (p_T>10\text{GeV}/c)
\]

**LHCb Preliminary**

\(pp\) \(\sqrt{s} = 8\text{ TeV}\)

- Prompt
- \(b\) decays

\(p_T > 5\text{ GeV}/c\)

**LHCb-CONF-2019-005**

\(JHEP 2017:117 (2017)\)
X(3872) in pPb collisions

LHCb Preliminary
PbPb $\sqrt{s_{NN}} = 8.16$ TeV
$-5.0 < y^* < -2.5$
$p_T > 5$ GeV/c

- Total fit
- Background
- $\chi_{c1}(3872)$

Entries/(4 MeV/c^2)

LHCb Preliminary
pPb $\sqrt{s_{NN}} = 8.16$ TeV
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- Total fit
- Background
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Theorists: predictions welcome

Matt Durham - LANL
Summary

• The study of exotic hadrons is an active area of discovery in QCD

• Data and techniques from heavy ion physics give us a new window into dynamics of exotic states in a dense QCD environment:
  • Prompt fraction of $X(3872)$ and $\psi(2S)$ decreases with multiplicity in pp
  • Relative production in $b$-decays shows no significant change with multiplicity
  • Indications that prompt $X(3872)$ may be suppressed more than prompt $\psi(2S)$ as multiplicity increases

• Consistent with the interpretation of $X(3872)$ as a large, weakly bound state such as a hadronic molecule.

This work is supported by the US Dept. of Energy/Office of Science/Nuclear Physics Division
Recent Hadronic Molecule Candidates

$P_c$ pentaquark states recently discovered by LHCb are very close to mass thresholds for hadronic molecules.
$\chi_c$ States in pPb

See Poster by Jana Crkovska
Observation of the $\Lambda_{b}^{0} \rightarrow \chi_{c1}(3872)pK^{-}$ decay

The LHCb collaboration

E-mail: Ivan.Belyaev@itep.ru

ABSTRACT: Using proton-proton collision data, collected with the LHCb detector and corresponding to 1.0, 2.0 and 1.9 fb$^{-1}$ of integrated luminosity at the centre-of-mass energies of 7, 8, and 13 TeV, respectively, the decay $\Lambda_{b}^{0} \rightarrow \chi_{c1}(3872)pK^{-}$ with $\chi_{c1}(3872) \rightarrow J/\psi \pi^{+}\pi^{-}$ is observed for the first time. The significance of the observed signal is in excess of seven standard deviations. It is found that (58 ± 15)% of the decays proceed via the two-body intermediate state $\chi_{c1}(3872)\Lambda(1520)$. The branching fraction with respect to that of the $\Lambda_{b}^{0} \rightarrow \psi(2S)pK^{-}$ decay mode, where the $\psi(2S)$ meson is reconstructed in the $J/\psi \pi^{+}\pi^{-}$ final state, is measured to be:

$$\frac{B(\Lambda_{b}^{0} \rightarrow \chi_{c1}(3872)pK^{-})}{B(\Lambda_{b}^{0} \rightarrow \psi(2S)pK^{-})} \times \frac{B(\chi_{c1}(3872) \rightarrow J/\psi \pi^{+}\pi^{-})}{B(\psi(2S) \rightarrow J/\psi \pi^{+}\pi^{-})} = (5.4 \pm 1.1 \pm 0.2) \times 10^{-2},$$

where the first uncertainty is statistical and the second is systematic.

KEYWORDS: B physics, Branching fraction, Exotics, Hadron-Hadron scattering (experiments)

ArXiv ePrint: 1907.00954