The $X(1835)$ and $X(p\bar{p})$ puzzle at BESIII

MENU2019, Pittsburgh

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Outline

1. What do we want to probe?
2. The BESIII experiment at IHEP
3. The $X(1835)$ and $X(p\bar{p})$
4. Summary
Ordinary vs. exotic matter

• Charmonium decays are well suited for light hadron spectroscopy.
• Especially radiative $J/\psi$ decays, which are OZI suppressed and therefore gluon rich.
• $J/\psi$ production cross section is large and production rates for exotic hadrons is expected to be larger or similar to the ones for conventional hadrons.
Hunting glueballs at BESIII

- Lattice QCD predictions for glueballs:
  - $0^{++}$ ground state: $1.0 \sim 1.7 \text{ GeV}/c^2$
  - $2^{++}$ ground state: $2.3 \sim 2.4 \text{ GeV}/c^2$
  - $0^{-+}$ ground state: $2.3 \sim 2.6 \text{ GeV}/c^2$

Those glueballs could also mix with ordinary $q\bar{q}$ states!

- Gluon rich environment of $J/\psi$ decays ideal place to search for glueballs
- Systematic experimental studies needed, like $J/\psi \rightarrow \gamma/\omega/\phi + X$

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The BESIII experiment at IHEP located in Beijing

- Symmetric $e^+e^-$ double ring collider
- $\sqrt{s} = 2.0 - 4.6$ GeV
- Design luminosity: $L_{\psi(3770)} = 10^{33}$ cm$^{-2}$ s$^{-1}$
- States with $J^{PC} = 1^{--}$ are produced directly
- Other $J^{PC}$ via radiative or hadronic transitions

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The BESIII experiment at IHEP located in Beijing

- **$J/\psi$**: $1 \cdot 10^{10}$ events
- **$\psi'$**: $0.5 \cdot 10^9$ events
- **$\psi(3770)$**: 2.9 fb$^{-1}$
- **$\psi(4160)$**: 3.1 fb$^{-1}$
- **$4230 + 4260$**: 1.9 fb$^{-1}$
- **$\psi(4415)$**: 1 fb$^{-1}$
- **4600**: 0.5 fb$^{-1}$
- **4360**: 0.5 fb$^{-1}$
- **4040**: 0.5 fb$^{-1}$

World largest $J/\psi$, $\psi(3686)$, $\psi(3770)$, ... data samples
The $e^+ e^- \rightarrow \text{hadrons}$ cross section as motivation

- Diplike structure in $e^+ e^- \rightarrow \text{hadrons}$ at $\sqrt{s} \approx 2m_p c^2$
- Attributed to a narrow, subthreshold state
- Possibility of bound $N\bar{N}$ states with mass near $2m_p$ - baryonium – is considered

\[ \sigma_{ee \rightarrow \text{hadrons}} / \sigma_{ee \rightarrow J/\psi} \approx \text{Im} \Pi_{\text{em}}(M) \]

arXiv:1602.04120
The $e^+ e^- \rightarrow \text{hadrons}$ cross section as motivation

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- $p$ timelike magnetic form factor $|G|$ exhibits very steep falloff above $p\bar{p}$ threshold
- Investigation of low-mass $p\bar{p}$ systems with different quantum numbers needed
- BESIII: $p\bar{p}$ systems with even $C$ parity!
The $e^+ e^- \rightarrow \text{hadrons}$ cross section as motivation
The $e^+ e^- \rightarrow \text{hadrons}$ cross section as motivation
Observation of $X(p\bar{p})$ in radiative $J/\psi \rightarrow \gamma pp\bar{p}$ decays

- Narrow enhancement near $2m_p$ in invariant mass spectrum of $pp\bar{p}$ pairs from radiative $J/\psi \rightarrow \gamma pp\bar{p}$ decays
- Fit with S-wave Breit-Wigner + $J/\psi \rightarrow \pi^0 pp\bar{p}$-background:

$$M = 1859^{+3}_{-10} \text{(stat)}^{+5}_{-25} \text{(syst)} \text{ MeV/c}^2$$
$$\Gamma < 30 \text{ MeV/c}^2 \text{ at 90% C.L.}$$

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arXiv:hep-ex/0305048
Observation of $X(p\bar{p})$ in radiative $J/\psi \to \gamma p\bar{p}$ decays

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$$\Gamma < 30 \text{ MeV}/c^2 \text{ at 90% C.L.}$$

- Further evidence that peak mass is below $2m_p$:
  - Sharp and monotonic increase at threshold after weighting each event by $q_0/q$ to remove kinematic threshold behaviour ($q =$ proton momentum in $p\bar{p}$ rest frame, $q_0$ is the value for $M_{p\bar{p}} = 2 \text{ GeV}/c^2$)

- 58M $J/\psi$ events in 2003

→ Search for $X(p\bar{p})/X(1835)$ in possible decay channels to understand and clarify their nature!
\( X(p\bar{p}) \) in \( J/\psi \to \gamma p\bar{p} \) – Spin-Parity Analysis

225M \( J/\psi \) events in 2011

Fit components:
- \( X(p\bar{p}) \)
- \( 0^{++} \) phase space
- \( f_2(1910) \)
- \( f_0(2100) \)

Breit-Wigner propagators, parameters of \( f_2, f_0 \) fixed to PDG

\( \rightarrow J^{PC} = 0^{-+} \)

\[ M = 1832^{+19}_{-5} \text{(stat)}^{+18}_{-17} \text{(syst)} \text{MeV}/c^2 \]

\( \Gamma < 76 \text{ MeV}/c^2 \) at 90\% C.L.
$X(p\bar{p})$ in $\psi' \to \gamma p\bar{p}$ – Spin-Parity Analysis

106M $\psi'$ events in 2011

Fit components:
- $X(p\bar{p})$ (fixed to $J/\psi$ analysis)
- $0^{++}$ phase space
- $f_2(1910)$
- $f_0(2100)$

Breit-Wigner propagators, parameters of $f_2, f_0$ fixed to PDG

$$\rightarrow R = \frac{B(\psi' \to \gamma X(p\bar{p}))}{B(J/\psi \to \gamma X(p\bar{p}))} = (5.08^{+0.71}_{-0.45})\%$$


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**X(1835) in radiative J/ψ → γπ⁺π⁻η' decays**

- Baryonium interpretation would be supported by observation of the resonance in decay modes which are expected for a p̅p bound state.
- Fit: Breit-Wigner function convolved with Gaussian mass resolution function (σ = 13 MeV/c²) + polynomial bkg
  
  \[
  M = 1833.7 \pm 6.1\text{ (stat)} \pm 2.7\text{ (syst)} \text{ MeV/c}^2 \\
  \Gamma = 67.7 \pm 20.3\text{ (stat)} \pm 7.7\text{ (syst)} \text{ MeV/c}^2
  \]

- Good agreement with mass and width of X(p̅p)
  
  \[X(p̅p) \rightarrow X(1835)\] is prime candidate for the source of the p̅p mass threshold enhancement

- \[BR(X \rightarrow p̅p)/BR(X \rightarrow π^+π^-η') \approx 1/3\]
  
  \[\rightarrow\] Unusually strong coupling to p̅p as expected for p̅p quasi-bound state
**X(1835) in radiative $J/\psi \rightarrow \gamma \pi^+ \pi^- \eta'$ decays**

\[ M = 1833.7 \pm 6.1\text{ (stat)} \pm 2.7\text{ (syst)} \text{ MeV/c}^2 \]
\[ \Gamma = 67.7 \pm 20.3\text{ (stat)} \pm 7.7\text{ (syst)} \text{ MeV/c}^2 \]

- 225M $J/\psi$ events in 2011
- 1.1B $J/\psi$ events in 2016
Radiative $J/\psi \rightarrow \gamma \pi^+ \pi^- \eta'$ decays – Model 1

• Typically two circumstances where an abrupt distortion of a resonance’s line shape shows up:

1) Threshold effect caused by the opening of an additional decay mode.

2) Interference between two resonances.

→ 1): Assume that state around 1.85 GeV/$c^2$ couples to $p\bar{p}$
   → Line shape above $p\bar{p}$ threshold affected

Flatté formula:

$$ T = \frac{\sqrt{\rho_{out}}}{\mathcal{M}^2 - s - i \sum_k g_k^2 \rho_k} \approx \frac{\sqrt{\rho_{out}}}{\mathcal{M}^2 - s - i g_0^2 \left( \rho_0 + \frac{g_{ppp} \rho_{pp}}{g_0^2} \right)} $$

• $X(1920)$ needed for fit
Radiative $J/\psi \to \gamma \pi^+ \pi^- \eta'$ decays – Model 1

- Fit results:
  \[ \log L = 630503.3 \to 630549.5 \to \text{improved by 46} \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M$ (MeV/c²)</td>
<td>1638.0 ± 121.9$^{+27.8}_{-254.3}$</td>
</tr>
<tr>
<td>$g_0^2$ [(GeV/c²)²]</td>
<td>93.7 ± 35.4$^{+47.6}_{-43.9}$</td>
</tr>
<tr>
<td>$g_{pp}^2/g_0^2$</td>
<td>2.31 ± 0.37$^{+0.83}_{-0.60}$</td>
</tr>
<tr>
<td>$M_{\text{pole}}$ (MeV/c²)</td>
<td>1909.5 ± 15.9$^{+9.4}_{-27.5}$</td>
</tr>
<tr>
<td>$\Gamma_{\text{pole}}$ (MeV/c²)</td>
<td>273.5 ± 21.4$^{+6.1}_{-64.0}$</td>
</tr>
<tr>
<td>Branching ratio</td>
<td>$(3.93 \pm 0.38^{+0.31}_{-0.84}) \times 10^{-4}$</td>
</tr>
</tbody>
</table>

- Value of $g_{pp}^2/g_0^2$ implies large coupling with $p\bar{p}$ final state
- Fit suggests broad state above $p\bar{p}$ threshold with strong couplings to $p\bar{p}$
  \[ \to p\bar{p} \text{ moleculelike state ?!} \]
Radiative $J/\psi \to \gamma \pi^+ \pi^- \eta'$ decays – Model 2

2): Assume existence of a narrow resonance near $p\bar{p}$ threshold
\implies Interference between this resonance and $X(1835)$ produces line shape distortion

Line shape = $T^2$:

$$T = \frac{\sqrt{\rho_{out}}}{M_1^2 - s - iM_1\Gamma_1} + \frac{\beta e^{i\theta} \sqrt{\rho_{out}}}{M_2^2 - s - iM_2\Gamma_2}$$
Radiative $J/\psi \to \gamma \pi^+ \pi^- \eta'$ decays – Model 2

Log $\mathcal{L} = 630503.3 \to 630540.5 \rightarrow$ improved by 37

$X(1835)$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (MeV/$c^2$)</td>
<td>$1825.3 \pm 2.4^{+17.3}_{-2.4}$</td>
</tr>
<tr>
<td>Width (MeV/$c^2$)</td>
<td>$245.2 \pm 13.1^{+4.6}_{-9.6}$</td>
</tr>
<tr>
<td>B.R. (constructive interference)</td>
<td>$(3.01 \pm 0.17^{+0.26}_{-0.28}) \times 10^{-4}$</td>
</tr>
<tr>
<td>B.R. (destructive interference)</td>
<td>$(3.72 \pm 0.21^{+0.18}_{-0.35}) \times 10^{-4}$</td>
</tr>
</tbody>
</table>

$X(1870)$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (MeV/$c^2$)</td>
<td>$1870.2 \pm 2.2^{+2.3}_{-0.7}$</td>
</tr>
<tr>
<td>Width (MeV/$c^2$)</td>
<td>$13.0 \pm 6.1^{+2.1}_{-3.8}$</td>
</tr>
<tr>
<td>B.R. (constructive interference)</td>
<td>$(2.03 \pm 0.12^{+0.43}_{-0.70}) \times 10^{-7}$</td>
</tr>
<tr>
<td>B.R. (destructive interference)</td>
<td>$(1.57 \pm 0.09^{+0.49}_{-0.86}) \times 10^{-5}$</td>
</tr>
</tbody>
</table>

- Fit suggests narrow state below $p\bar{p}$ threshold
- Unconventional meson, most likely a $p\bar{p}$ bound state?!
$X(1840)$ in radiative $J/\psi \to \gamma 3(\pi^+\pi^-)$ decays

- In the search for the $X(1835)$ in $J/\psi$ hadronic decays the $X(1870)$ in $J/\psi \to \omega\pi^+\pi^-\eta$ (PRL 107, 182001) and the $X(1810)$ in $J/\psi \to \gamma\omega\phi$ (PRD 87, 032008) were observed.
- $X(1835)$ was confirmed to be a pseudoscalar particle.
  - It may have properties in common with the $\eta_c$
  - Six charged pions is a known decay mode of the $\eta_c$
- Fit: Breit-Wigner + $J/\psi \to \pi^03(\pi^+\pi^-) + \text{pol3}$
  - $M = 1842.2 \pm 4.2^{+7.1}_{-2.6}$ MeV/$c^2$
  - $\Gamma = 83 \pm 14 \pm 11$ MeV
- No $\eta'$ signal in $\eta' \to 3(\pi^+\pi^-)$ observed
  - $BR(\eta' \to 3(\pi^+\pi^-)) < 3.1\times10^{-5}$
**$X(1835)$** in radiative $J/\psi \rightarrow \gamma K_S^0 K_S^0 \eta$ decays

- **Similarity:** $J/\psi \rightarrow \gamma \pi^+ \pi^- \eta' \iff J/\psi \rightarrow \gamma K \bar{K} \eta$
- In contrast to $J/\psi \rightarrow \gamma K^+ K^- \eta$, there is no background contamination for $J/\psi \rightarrow \gamma K_S^0 K_S^0 \eta$ from $J/\psi \rightarrow \pi^0 K_S^0 K_S^0 \eta$ and $J/\psi \rightarrow K_S^0 K_S^0 \eta$, which are forbidden by exchange symmetry and $CP$ conservation.

- Distinct $\eta_C$ signal
- Clear structure around 1.85 GeV/$c^2$
- Strong enhancement near $K_S^0 K_S^0$ threshold = $f_0(980)$

- Require $M_{K_S^0 K_S^0} < 1.1$ GeV/$c^2$ (and $M_{K_S^0 K_S^0 \eta} < 2.8$ GeV/$c^2$)
- More prominent structure around 1.85 GeV/$c^2$
- Excess of events around 1.6 GeV/$c^2$
**$X(1835)$ in radiative $J/\psi \to \gamma K_S^0 K_S^0 \eta$ decays**

- **PWA:**
  
  \[
  \begin{align*}
  X(1835) & \to f_0(980)\eta \\
  X(1560) & \to f_0(980)\eta
  \end{align*}
  \]
  
  \[j^{PC} = 0^{-+}\]  
  
  non-resonant $f_0(1500)\eta$ component

- **Fit results:**

  \[
  \begin{align*}
  X(1835): & \quad M = 1844 \pm 9\text{(stat)}^{+16}_{-25}\text{(syst)} \text{ MeV}/c^2 \\
  & \quad \Gamma = 192^{+20}_{-17}\text{(stat)}^{+62}_{-43}\text{(syst)} \text{ MeV} \\
  X(1560): & \quad M = 1565 \pm 8\text{(stat)}^{+0}_{-63}\text{(syst)} \text{ MeV}/c^2 \\
  & \quad \Gamma = 45^{+14}_{-13}\text{(stat)}^{+21}_{-28}\text{(syst)} \text{ MeV}
  \end{align*}
  \]

- **Is the $X(1560)$ the same state as the $\eta(1405)/\eta(1475)$ or new?**

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*Phys. Rev. Lett. 115, 091803*
Radiative decays like $J/\psi \to \gamma X, X \to \gamma V$ with $V = \rho, \phi$ do not change flavour structure of intermediate states.

$V$ acts like a flavour filter

$$PDF_{BW} = \left( BW_0^2(s) + |A_1 \cdot BW_1(s) + A_2 \cdot BW_2(s) \cdot e^{i\varphi}|^2 \right) \otimes G(m_0, \sigma(s)) \cdot \varepsilon(s)$$

<table>
<thead>
<tr>
<th>Solution</th>
<th>Resonance</th>
<th>$m_R$ (MeV/c²)</th>
<th>$\Gamma$ (MeV)</th>
<th>$B$ (10^-6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta(1475)$</td>
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<td>$1477 \pm 7 \pm 13$</td>
<td>$118 \pm 22 \pm 17$</td>
<td>$7.03 \pm 0.92 \pm 0.91$</td>
</tr>
<tr>
<td>$X(1835)$</td>
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<td>$1839 \pm 26 \pm 26$</td>
<td>$175 \pm 57 \pm 25$</td>
<td>$1.77 \pm 0.35 \pm 0.25$</td>
</tr>
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<td>$1477 \pm 7 \pm 13$</td>
<td>$118 \pm 22 \pm 17$</td>
<td>$10.36 \pm 1.51 \pm 1.54$</td>
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<td>$X(1835)$</td>
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<td>$1839 \pm 26 \pm 26$</td>
<td>$175 \pm 57 \pm 25$</td>
<td>$8.09 \pm 1.99 \pm 1.36$</td>
</tr>
</tbody>
</table>

Polar angle distribution of radiative photon in $J/\psi$ rest frame favors $J^{PC} = 0^{-+}$ for $X(1835)$ assumption.

Observation of $X(1835) \to \gamma \phi$ indicates a sizable $s\bar{s}$ component.
X(1835) in J/ψ → ωη′π⁺π⁻ decays

- Comparison of production rates between J/ψ → ωX(1835) and J/ψ → γX(1835) to get information on q̅q or gluon component of X(1835).
  If it contains substantial q̅q components like η', it should be observed in J/ψ → ωX(1835)

- Two-dimensional fit to π⁺π⁻π⁰ and ηπ⁺π⁻ distributions to obtain number of J/ψ → ωη′π⁺π⁻ signal events.

$$BR(J/ψ → \omega\eta'\pi^+\pi^-) = (1.12 \pm 0.02(\text{stat}) \pm 0.13(\text{syst})) \times 10^{-3}$$
**X(1835) in J/ψ → ωη'π⁺π⁻ decays**

- Two-dimensional fit to π⁺π⁻π⁰ and ηπ⁺π⁻ distributions to obtain number of J/ψ → ωη'π⁺π⁻ signal events.

- Also performed in eight slices of η'π⁺π⁻ mass spectrum from 1.4 GeV/c² to 2.2 GeV/c² to extract background corrected distribution.

\[ BR(J/ψ → ωX(1835), X(1835) → η'π⁺π⁻) < 6.2 \times 10^{-5} \]

- \( X(1835) \) still only observed in radiative J/ψ decays, smaller Branching Ratio in hadronic decays could be an indication of large gluon component.
Summary I

\[ J/\psi \rightarrow \gamma p\bar{p} \quad \psi(2S) \rightarrow \gamma p\bar{p} \quad X(p\bar{p}) \text{ with } J^{PC} = 0^{-+} \text{ below } p\bar{p} \text{ threshold} \]

- **p\bar{p}** bound state (baryonium)?
  - Requires new resonance with mass around 1.85 GeV/c^2
  - Possible decay mode for p\bar{p} bound state is \( \pi^+\pi^-\eta' \)

\[ J/\psi \rightarrow \gamma \pi^+\pi^- \quad X(1835) \]

\[ J/\psi \rightarrow \gamma \gamma \phi \rightarrow X(1835) \]

\[ J/\psi \rightarrow \gamma K_S^0 K_S^0 \eta \rightarrow X(1835) \]

- **X(1835)** not observed in hadronic \( J/\psi \) decays, like \( J/\psi \rightarrow \omega \eta' \pi^+\pi^- \)
  - Large gluon component?

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Summary II

- BESIII offers a lot of high precision measurements around 1.85 GeV/c^2
- With the current statistics it is not possible to distinguish between all observed resonances
- More hadronic decay modes of the $J/\psi$ have to be analysed
- More data is needed to improve the performed analyses
Thanks for your attention!