Quarkonia, Resonances and Spectroscopy

Gagan Mohanty

Mumbai

20th Particles & Nuclei International Conference

25-29 August 2014
Hamburg, Germany
Enter the quark model

Examples...

Meson

Baryon
Basics of the quarkonia

- Usually refer to charmonium \((c \bar{c})\) and bottomonium \((b \bar{b})\) states

charm and bottom quarks are heavy: \(m_c \sim 1.5 \text{ GeV} \sim 1.6 m_p\)
\(m_b \sim 4.5 \text{ GeV} \sim 4.8 m_p\)

velocities are small: \(v/c \sim 0.25\) for \(c \bar{c}\) \((\sim 0.1\) for \(b \bar{b}\))
Nonrelativistic Quantum Mechanics is valid

\[
- \frac{\hbar^2}{2m_r} \nabla^2 \Psi + V(r)\Psi = E\Psi
\]

What about \(V(r)\)?
Cornell potential

Two parameters: slope and intercept

Same $V(r)$ works both for charmonium ($c\bar{c}$) and bottomonium ($b\bar{b}$)
Side-by-side comparison

Charmonium \((c\bar{c})\)  
Positronium \((e^+ e^-)\)

\[ \begin{align*}
\psi' \quad & \quad 2^1S_0 (\eta_c) \quad \quad 2^3S_1 (\psi') \\
& \quad 2^1P_1 \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad 2^3P_0 (x_0) \\
J/\psi \quad & \quad 1^3S_1 (\psi) \\
& \quad 1^1S_0 (\eta_c)
\end{align*} \]

\[ \begin{align*}
\text{Dissociation energy} \\
& \quad 2^3S_1 \\
& \quad 2^3P_2 (x_2) \\
& \quad 2^3P_1 (x_1) \\
& \quad 2^1P_1 \\
& \quad 2^3P_0 (x_0)
\end{align*} \]

\[ \begin{align*}
\text{Relative energy (MeV)} \\
\text{Relative energy (eV)}
\end{align*} \]
All states below the “open charm” threshold are identified.

$2M_D = 3.73 \text{ GeV}$
Bottomonium spectra circa 2014

\[ 2M_B = 10.56 \text{ GeV} \]

Most of the states below “open bottom” threshold have been identified.
What about other varieties?

No *a priori* reason for mesons to exist only in $q\bar{q}$ configurations, or baryons to occur with only $qqq$ structures.

**Pentaquark:**
- e.g. an $S=+1$ baryon

**Glueball:**
- bundling gluons into a color singlet state

**Tetraquark state:**
- $q\bar{q}$-gluon hybrid meson:

"u" "c" "d" "g" "s"
Production of $\psi(2S) \rightarrow J/\psi\pi^+\pi^-$ in pp collisions

For the prompt $\psi(2S)$ production, NLO NRQCD predictions describe the data satisfactorily while the colour evaporation model is not that good at highest $p_T$ regions and NNLO* colour-singlet fails throughout fine-tuning required.

In the non-prompt case, NLO GM-VFNS and FONLL calculations do pretty good job although a peculiar tendency is observed for the theory to predict a slightly harder $p_T$ spectrum than that in data.

arXiv:1407.5532
Productions of $\chi_{c1}$ and $\chi_{c2}$ in pp collisions

NRQCD describes prompt $\chi_{c1}$ data rather well and the $k_T$ factorisation (CSM) significantly overestimates (underestimates) the data.

Non-prompt $\chi_c$ productions generally agree with predictions based upon the FONLL approach.
Double-differential cross sections of prompt $J/\psi$ and $\psi(2S)$

- Constitute a significant improvement over the previous results both in terms of accuracy and $p_T$ reach ($\geq 100$ GeV)
- Will contribute towards an improved understanding of quarkonium production in the scope of NRQCD or other theoretical approaches
Prompt $J/\psi$ pair production in pp collisions

The cross section of prompt $J/\psi$ pair production is measured to be $[1.49 \pm 0.07\text{(stat.)} \pm 0.13\text{(syst.)}]$ nb.

Probes $J/\psi$ pair production at higher $J/\psi$ $p_T$ and more central rapidity than the LHCb measurement.

No evidence for the $\eta_b$ state in the $J/\psi$ pair invariant-mass distribution.

$N_{\text{sig}} = 446 \pm 23$

arXiv:1406.0484

PLB 707 (2012) 52
Observation of exclusive charmonium pairs

- First observation of the central exclusive production of pairs of charmonia
- Measurements of individual cross section of $J/\psi J/\psi$ and $J/\psi\psi(2S)$ and their ratio are in agreement with preliminary theory predictions
- No signal for the production of pairs of $P$-wave charmonia

$\sigma^{J/\psi J/\psi} = 58 \pm 10{\text{(stat)}} \pm 6{\text{(syst)}} \text{ pb}$,
$\sigma^{J/\psi J/\psi(2S)} = 63^{+27}_{-18}{\text{(stat)}} \pm 10{\text{(syst)}} \text{ pb}$,
$\sigma^{\psi(2S)\psi(2S)} < 237 \text{ pb}$,
$\sigma^{\chi_{c0}\chi_{c0}} < 69 \text{ nb}$,
$\sigma^{\chi_{c1}\chi_{c1}} < 45 \text{ pb}$,
$\sigma^{\chi_{c2}\chi_{c2}} < 141 \text{ pb}$,
Resonant substructures in $B_s^0 \rightarrow \bar{D}^0 K^- \pi^+$

- Precise measurement of $D_{s2}^*(2573)^-$ mass and width
- An excess of events near 2.86 GeV is found in $m(\bar{D}^0K^-)$ spectrum
- To describe the data well, we need an admixture of spin-1 and spin-3 states
- The previously seen $D_{sj}^*(2860)^-$ state is composed of at least two particles

[Graphs and data plots demonstrating the measurements and distributions]
X(3872): Belle observed in $B \to (J/\psi \pi^+ \pi^-)K$

Confirmed by many other experiments:
- in exclusive $B$ decays by BABAR and LHCb
- in high-energy $p\bar{p}$ (CDF and D0) and $pp$ collisions (CMS, LHCb)

Steve with a big fish!

\(M = 3872 \pm 1 \text{ MeV}\)
\(\Gamma < 2.3 \text{ MeV}\)

PRL 91 (2003) 262001
Is it the conventional $\psi_{c2}$?

Charmonium model prediction:

$$\frac{BF(\frac{c_2 \rightarrow c_1}{\rho})}{BF(\frac{c_2 \rightarrow J/\psi}{+ J/\psi})} > 5$$
Does the $X(3872)$ decay to $\gamma \chi_{c1}$?

B → K$\chi_{c1}$?

(The peak near 3823 MeV/c$^2$ is the conventional triplet D-wave charmonium state, $\psi_2$)

No $X(3872)$ signal

\[
\frac{BF(c_2 \rightarrow c_1)}{BF(c_2 \rightarrow ^+ J/\psi)} < 0.25
\]

PRL 111 (2013) 032001
Data favour the $1^{++}$ over the $2^{-+}$ hypothesis for the $X(3872)$ at $>8\sigma$ significance.

- Multidimensional angular analysis involving $\cos \theta_X$, $\cos \theta_{\pi\pi}$, $\Delta \phi_{X,\pi\pi}$, $\cos \theta_{J/\psi}$ and $\Delta \phi_{X,J/\psi}$

- Closes the door for conventional $c\bar{c}$ meson assignment
X(3872) looks like a $D^*0\overline{D}^0$ molecule

Caveat: It is still possible that “either/or” is not the correct hypothesis. The X(3872) could be a linear combination of a molecule and a charmonium state, in which the molecular component is dominant.

Predicted by N.A. Törnqvist: Z Phys C 61, 525 (1994)
Observation of $Z^+(4430)$ in $B \to K\psi'\pi$ decays

$M = 4433 \pm 4{\text{(stat)}} \pm 2{\text{(syst)}}$ MeV

$\Gamma = 45 \ ^{+18}_{-13}{\text{(stat)}} ^{+30}_{-13}{\text{(syst)}}$ MeV

with a product branching fraction

$[4.1 \pm 1.0{\text{(stat)}} \pm 1.4{\text{(syst)}}] \times 10^{-5}$

➢ The first candidate for an exotic, charged charmonium-like state

Veto $K^*$ and $K^{**}$ resonances in the study

➢ Important technical objection: Could higher $K^{**}$ resonances & interference effects produce such structure?

$\text{BABAR}$ was able to describe the structure purely in terms of reflections of higher $K^*$ states although did not contradict the above observation
DP analysis with interference and $K^*$ resonances

- Recent Dalitz plot analysis from Belle still finds a signal of $5\sigma$ significance
- A spin parity assignment of $1^+$ is found to be preferred over $0^-$ at $2.9\sigma$ level while all other are ruled out with greater than $4.3\sigma$ significance

Any news from LHCb or other?
Observation of the resonant nature of $Z(4430)$

4D fit to the decay amplitude reveals that the data cannot be described with the $(K\pi)$ resonances alone.

The same is corroborated by a model-independent approach.

A highly significant signal for the $Z^+(4430)$ resonance is obtained with an unambiguous determination $J^P$ as $1^+$. 

PRL 112 (2014) 222002
Amplitude analysis of $B \rightarrow J/\psi K\pi$

- Look for possible exotic, charmonium-like resonances in the $J/\psi\pi$ system
- 4D amplitude analysis comprising $(M_{K\pi}^2, M_{J/\psi\pi}^2, \cos \theta, \phi)$, where $\theta$ is the $J/\psi$ helicity angle and $\phi$ is the angle between the two planes containing $J/\psi(\ell^+\ell^-)$ and $K\pi$ systems in the $B$ rest frame
- Resonances: 10 $K^*$ resonances and the $Z_c(4430)^+$ state for the $J/\psi\pi$ system; additional $Z_c^+$ states are used for a cross-check
- Tried out five spin-parity hypotheses: $0^-, 1^+, 1^-, 2^+, 2^-$ for the $Z_c^+$ ($J^P = 0^+$ is forbidden due to parity conservation)

![Graphs showing resonance analysis](image)

- Blue solid lines are projections of the $J/\psi\pi$ invariant mass including a new $Z_c^+$ state along with the $Z_c(4430)$
- Red dashed lines with the $Z_c(4430)$ only

711 fb$^{-1}$
Observation of a new state in $B \rightarrow J/\psi K\pi$

<table>
<thead>
<tr>
<th>$J^P$</th>
<th>$0^-$</th>
<th>$1^-$</th>
<th>$1^+$</th>
<th>$2^-$</th>
<th>$2^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass, MeV/$c^2$</td>
<td>4220 ± 14</td>
<td>4315 ± 40</td>
<td>4196 ± 27</td>
<td>4209 ± 14</td>
<td>4203 ± 24</td>
</tr>
<tr>
<td>Width, MeV</td>
<td>71 ± 20</td>
<td>220 ± 80</td>
<td>370 ± 61</td>
<td>64 ± 18</td>
<td>121 ± 53</td>
</tr>
<tr>
<td>Significance</td>
<td>3.3σ</td>
<td>2.3σ</td>
<td>8.2σ</td>
<td>3.9σ</td>
<td>1.9σ</td>
</tr>
</tbody>
</table>

- A new $Z_c^+$ state [$Z_c(4200)^+$] with $J^P = 1^+$ is found with 7.2σ significance
  \[
  M = 4196^{+31+17}_{-29-6} \text{ MeV}/c^2, \quad \Gamma = 370^{+70+70}_{-70-85} \text{ MeV}
  \]
- Other $J^P$ hypotheses are excluded: $0^- (6.7\sigma), 1^- (7.7\sigma), 2^- (5.2\sigma), 2^+ (7.6\sigma)$
- Evidence for the $Z_c(4430)^+$ at the 4.0σ significance level

\[
\mathcal{B}(\bar{B}^0 \rightarrow J/\psi K^- \pi^+) = (1.15 \pm 0.01 \pm 0.05) \times 10^{-3}
\]
\[
\mathcal{B}(\bar{B}^0 \rightarrow J/\psi K^*(892)) = (1.19 \pm 0.01 \pm 0.08) \times 10^{-3}
\]
\[
\mathcal{B}(\bar{B}^0 \rightarrow Z_c(4430)^+ K^-) \times \mathcal{B}(Z_c(4430)^+ \rightarrow J/\psi \pi^+) = (5.4^{+4.0+1.1}_{-1.0-0.9}) \times 10^{-6}
\]
\[
\mathcal{B}(\bar{B}^0 \rightarrow Z_c(4200)^+ K^-) \times \mathcal{B}(Z_c(4200)^+ \rightarrow J/\psi \pi^+) = (2.2^{+0.7+1.1}_{-0.5-0.6}) \times 10^{-5}
\]
\[
\frac{\mathcal{B}(Z_c(4430)^+ \rightarrow \psi(2S)\pi^+)}{\mathcal{B}(Z_c(4430)^+ \rightarrow J/\psi \pi^+)} \sim 10
\]
Resonant structure of $\Upsilon(5S) \to (b\bar{b})\pi^+\pi^-$

Two peaks in all 5 modes

minimal quark content

$|b\bar{b}u\bar{d}\rangle$

flavor-exotic states

Dalitz plot analysis

no non-res. contribution

$M[h_b(1P)\pi^\pm]$
Fit results

Average over 5 channels

\[ M_1 = 10607.2 \pm 2.0 \text{ MeV} \]
\[ \Gamma_1 = 18.4 \pm 2.4 \text{ MeV} \]
\[ M_{Z_b} - (M_B + M_{B^*}) = + 2.6 \pm 2.1 \text{ MeV} \]

\[ M_2 = 10652.2 \pm 1.5 \text{ MeV} \]
\[ \Gamma_2 = 11.5 \pm 2.2 \text{ MeV} \]
\[ M_{Z_b'} - 2M_{B^*} = + 1.8 \pm 1.7 \text{ MeV} \]

Angular analysis \( \Rightarrow \) both states are \( J^P = 1^+ \)  
Decays \( \Rightarrow \) \( I^G = 1^+ \) (\( C = - \) for \( Z_b^0 \))

Proximity to thresholds favors molecule over tetraquark

\[ Z_b \sim |B B^*_B\rangle = |\begin{array}{c}
\uparrow \\
\downarrow \\
\end{array}\rangle + |\begin{array}{c}
\downarrow \\
\uparrow \\
\end{array}\rangle \]
\[ h_b(m_P)\pi \]
S-wave not suppressed

\[ Z_b' \sim |B^* B^*_B\rangle = |\begin{array}{c}
\uparrow \\
\uparrow \\
\end{array}\rangle - |\begin{array}{c}
\downarrow \\
\downarrow \\
\end{array}\rangle \]

Phase btw \( Z_b \) and \( Z_b' \) amplitudes is \( \sim 0^\circ \) for \( Y(nS)\pi\pi \) and \( \sim 180^\circ \) for \( h_b(m_P)\pi\pi \)

Bondar et al, PRD84,054010(2011)
Observation of $Z_b \rightarrow B\bar{B}^*$ and $Z_{b'} \rightarrow B^*\bar{B}^*$

<table>
<thead>
<tr>
<th>Channel</th>
<th>Fraction, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Upsilon(1S)\pi^+$</td>
<td>0.32 ± 0.09</td>
</tr>
<tr>
<td>$\Upsilon(2S)\pi^+$</td>
<td>4.38 ± 1.21</td>
</tr>
<tr>
<td>$\Upsilon(3S)\pi^+$</td>
<td>2.15 ± 0.56</td>
</tr>
<tr>
<td>$h_b(1P)\pi^+$</td>
<td>2.81 ± 1.10</td>
</tr>
<tr>
<td>$h_b(2P)\pi^+$</td>
<td>4.34 ± 2.07</td>
</tr>
<tr>
<td>$B^+\bar{B}^<em>0 + \bar{B}^0B^</em>$</td>
<td>86.0 ± 3.6</td>
</tr>
<tr>
<td>$B^{*+}\bar{B}^*0$</td>
<td>-</td>
</tr>
</tbody>
</table>

$BF[Z_{b'} \rightarrow B\bar{B}^*] = (25 \pm 10)\%$ insignificant

If included, other fractions of $Z_{b'}$ are reduced by 1.33.

$Z_{b'} \rightarrow B\bar{B}^*$ is suppressed w.r.t. $B^*\bar{B}^*$ despite much larger PHSP.

**Explanations:**

Molecule $\Rightarrow$ admixture of $B\bar{B}^*$ in $Z_{b'}$ is small, challenging for tetraquark?
Zb states seems to have neutral partner

\[ \Upsilon(5S) \rightarrow \Upsilon(nS) \pi^0 \pi^0 \] decay

In this fit mass and width are fixed from the charged Zb result.

Combined significance for the two modes is 6.5\( \sigma \)
$Z_{b \pm}$ states cannot be bottomonium

$Z^+ = b \bar{d}$  \quad $Z^- = b \bar{u}$

Decays to $h_b(nP)$ or $\gamma(nS)$ \Rightarrow must contain a $b \bar{b}$ pair

Has electric charge \Rightarrow must contain $u$ and $d$ quarks
\[ B\bar{B}^* \text{ and } B^*\bar{B}^* \text{ molecules} \]

\[ Z_{b(106010)}^\pm \]

\[ \begin{align*}
    M_{Z_{b(106010)}} - (M_B + M_{B^*}) &= +3.9 \pm 2.1 \text{ MeV} \\
    M_{Z_{b(106050)}} - 2M_{B^*} &= +3.2 \pm 1.6 \text{ MeV}
\end{align*} \]

B-B* “molecule”

B*-B* “molecule”

Slightly unbound threshold resonances??
Back to charmonium: $Y(4260)$ in ISR

- No $X(3872)$
- Observed $Y(4260)$

From single-resonance fit:
- $N = 125 \pm 23$
- $M = 4259 \pm 8^{+2}_{-6} \text{ MeV/}c^2$
- $\Gamma = 88 \pm 23^{+6}_{-4} \text{ MeV}$
- $\Gamma(Y \rightarrow e^+e^-) \cdot B(Y \rightarrow J/\psi\pi^+\pi^-) = 5.5 \pm 1.0^{+0.8}_{-0.7} \text{ eV}$
- $J^{PC} = 1^{--}$ (ISR production)

Current statistics does not allow a significant discrimination between single- and multi-resonance hypothesis
Observation of $Z^+(3900)$ state in $\pi J/\psi$ spectra

**Charged ➔ Cannot be a conventional charmonium state, must contain 4 quarks**

$$M = 3899 \pm 3.6 \pm 4.9\text{MeV}$$
$$= 46 \pm 10 \pm 20\text{MeV}$$

Produced by running at the energy of $Y(4260)$

**Produced by running at the energy of $Y(4260)$**

$$M = 3894 \pm 6.6 \pm 4.5\text{MeV}$$
$$= 63 \pm 24 \pm 26\text{MeV}$$

Using $Y(4260)$ decays in ISR

**Using $Y(4260)$ decays in ISR**

PRL 110 (2013) 252001

PRL 110 (2013) 252002
New Particle scorecard:

\[
Z_b(106010)\pm \quad Z_b(106050)\pm \quad Z_c(3900)\pm
\]

**QUARK SOUP**
Researchers at colliders in China and Japan have succeeded in making exotic matter comprising four quarks, but are still debating whether the fleeting particles are meson pairs or true tetraquarks.

**ORDINARY MATTER**
- Baryon
- Meson

**EXOTIC MATTER**
- Meson ‘molecule’
- Tetraquark

**Diagram:**
- Ordinary matter: Baryon and Meson
- Exotic matter: Meson ‘molecule’ and Tetraquark
Hadron spectroscopy is one of most exciting and pursued areas by the $e^+e^-$ flavour factories and hadron collider experiments.

Some of the selected charmonium and bottomonium states are presented here that look very much exotic in nature.

These recent discoveries have created a renewed interest in the quarkonium sector and are pushing our friends over the corridor to the extreme(!).

Look for more such results from LHC, especially LHCb, the upcoming Belle-II and other experiments (PANDA…).

Thank you very much for your attention.
Summary and outlook

- Though close to five years have passed away since the last data taking, Belle continues to produce high-quality results.

- A small sample of those are presented here, based on the full data statistics:
  - First observation of $D^0$-$\bar{D}^0$ mixing using $D \rightarrow K\pi$ decays in $e^+e^-$ collisions.
  - $2.5\sigma$ indication for $D^0$-$\bar{D}^0$ mixing and no sign of CPV in $D \rightarrow K_S^0\pi^+\pi^-$.
  - An order-of-magnitude improvement over the previous result for $A_{CP}$ in the $D \rightarrow \pi^0\pi^0$ decay.
  - $1.8\sigma$ discrepancy with respect to the SM prediction for the lepton forward-backward asymmetry at low $q^2$ in inclusive $B \rightarrow X_s\ell^+\ell^-$ decays.
  - First observation of the $b \rightarrow s$ penguin decay $B \rightarrow \eta'K^*(892)^0$.
  - Observation of another charged charmonium-like state in $B \rightarrow J/\psi K\pi$.

- The unique explorations at the intensity frontier will continue with the start of Belle II.
  
  - Refer to yesterday’s talk by P. Urquijo.