Recent results of baryon spectroscopy at BESIII

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For BESIII collaboration
Hadron 2013, Nara, Japan
Spectrum of Nucleon Resonances

N Spectrum  10  5  7  3
Δ Spectrum  7  3  7  5

→ Particle Data Group
(Phys. Rev. D86, 010001 (2012))
→ little known
(many open questions left)
Where are the “missing” baryons

Quark models predict many more baryons than have been observed

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Where are the “missing” baryons

Are the states missing in the predicted spectrum because our models do not capture the correct degrees of freedom?

Or have the resonances simply escaped detection?

Nearly all existing data result from $\pi N$ experiments
Excited state baryon spectroscopy from lattice QCD

R. Edwards et al., PR D84 074508 (2011)

Missing states?

Exhibits broad features expected of $SU(6) \otimes O(3)$ symmetry

Counting of levels consistent with non-rel. quark model, no parity doubling
Charmonium decays can give novel insights into baryons and give complementary information to other experiments.

\[ J/\psi (\psi') \rightarrow \bar{B}B \rightarrow N^*, \Lambda^*, \Sigma^*, \Xi^* \]

- Pure isospin 1/2 filter: \( \psi \rightarrow N \bar{N} \pi, \psi \rightarrow N \bar{N} \pi \pi \)
- Missing \( N^* \) with small couplings to \( \pi N \) & \( \gamma N \), but large coupling to \( gggN \): \( \psi \rightarrow N \bar{N} \pi / \eta / \eta' / \omega / \phi, \bar{p} \Sigma \pi, \bar{p} \Lambda K \) ...
- Interference between \( N^* \) and \( N^* \) bar bands in \( \psi \rightarrow N \bar{N} \pi \) Dalitz plots may help to distinguish some ambiguities in PWA of \( \pi N \)
- Not only \( N^* \), but also \( \Lambda^*, \Sigma^*, \Xi^* \)
- High statistics of charmonium @ BES III

<table>
<thead>
<tr>
<th>Previous Data</th>
<th>BESIII now</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>( J/\psi )</td>
<td>BESII 58 M</td>
<td>1.2 B (20x BESII)</td>
</tr>
<tr>
<td>( \psi ) (3686)</td>
<td>CLEO: 28M</td>
<td>0.5 B (20x CLEO)</td>
</tr>
<tr>
<td>( \psi ) (3770)</td>
<td>CLEO: 0.8/fb</td>
<td>2.9/fb (3.5x CLEO)</td>
</tr>
<tr>
<td>Above open charm threshold</td>
<td>CLEO: 0.6/fb@4160</td>
<td>0.4/fb @4040, 2/fb@4260, 0.5/fb @4360, Data for lineshape</td>
</tr>
<tr>
<td>R scan &amp; ( \tau )</td>
<td>BESII</td>
<td>( R ) @2.23, 2.4, 2.8, 3.4, 25/pb tau</td>
</tr>
</tbody>
</table>
$J/\psi \rightarrow \eta \bar{p} p @BES1$

$J/\psi \rightarrow \pi^+\bar{p} n @BES2$

$J/\psi \rightarrow \pi^0\bar{p} p @BES2$
Recent results @ BES3

- Observation of the isospin violating decay $J/\psi \rightarrow \Lambda \bar{\Sigma}^0 + c. c.$
- Measurements of $\chi_{cJ} \rightarrow p \bar{n} \pi^- \text{ and } p \bar{n} \pi^- \pi^0$
- Measurements of $\psi' \rightarrow \bar{p} K \Sigma^0 \text{ and } \chi_{cJ} \rightarrow \bar{p} K \Lambda$
- PWA of $\psi' \rightarrow \pi^0 p \bar{p}$
- PWA of $\psi' \rightarrow \eta p \bar{p}$

Using 2009 data sets
Observation of the isospin violating decay
\[ J/\psi \rightarrow \Lambda \bar{\Sigma}^0 + c. c. \]
\[
\chi_{cJ} \rightarrow p\bar{n}\pi^- \text{ and } p\bar{n}\pi^-\pi^0
\]

Substructures of \(\chi_{c0} \rightarrow p\bar{n}\pi^-\)

<table>
<thead>
<tr>
<th>(\chi_{c0})</th>
<th>(\chi_{c1})</th>
<th>(\chi_{c2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B(\chi_{cJ} \rightarrow p\bar{n}\pi^-)) (10^{-3})</td>
<td>1.30 ± 0.03 ± 0.12</td>
<td>0.40 ± 0.02 ± 0.05</td>
</tr>
<tr>
<td>(B(\chi_{cJ} \rightarrow \bar{p}n\pi^+)) (10^{-3})</td>
<td>1.38 ± 0.03 ± 0.12</td>
<td>0.41 ± 0.02 ± 0.04</td>
</tr>
<tr>
<td>(B(\chi_{cJ} \rightarrow p\bar{n}\pi^-\pi^0)) (10^{-3})</td>
<td>2.36 ± 0.08 ± 0.20</td>
<td>1.08 ± 0.05 ± 0.12</td>
</tr>
<tr>
<td>(B(\chi_{cJ} \rightarrow \bar{p}n\pi^+\pi^0)) (10^{-3})</td>
<td>2.23 ± 0.08 ± 0.18</td>
<td>1.06 ± 0.05 ± 0.11</td>
</tr>
<tr>
<td>(B(\chi_{cJ} \rightarrow p\bar{n}\pi^-)) (10^{-3}) (PDG [1])</td>
<td>1.14 ± 0.31</td>
<td>(\cdots)</td>
</tr>
</tbody>
</table>

Similar threshold enhancements: a \(p\bar{p}\) threshold enhancement in \(B\) meson decays, \(\psi'\) decays, and in the shape of the timelike electromagnetic form factor of the proton measured at BABAR.
\[ \psi' \rightarrow \bar{p}K\Sigma^0, \Sigma^0 \rightarrow \gamma\Lambda \]

\[ \chi_{cJ} \rightarrow \gamma \chi_{cJ}, \chi_{cJ} \rightarrow \bar{p}K\Lambda \]

<table>
<thead>
<tr>
<th>Channel</th>
<th>[ \psi' \rightarrow \bar{p}K^+\Sigma^0 \text{ + c.c.} ]</th>
<th>[ \chi_{c0} \rightarrow \bar{p}K^+\Lambda \text{ + c.c.} ]</th>
<th>[ \chi_{c1} \rightarrow \bar{p}K^+\Lambda \text{ + c.c.} ]</th>
<th>[ \chi_{c2} \rightarrow \bar{p}K^+\Lambda \text{ + c.c.} ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ \mathcal{B} \text{(BESIII)} ]</td>
<td>[ (1.67 \pm 0.13 \pm 0.12) \times 10^{-5} ]</td>
<td>[ (13.2 \pm 0.3 \pm 1.0) \times 10^{-4} ]</td>
<td>[ (4.5 \pm 0.2 \pm 0.4) \times 10^{-4} ]</td>
<td>[ (8.4 \pm 0.3 \pm 0.6) \times 10^{-4} ]</td>
</tr>
<tr>
<td>PDG</td>
<td>[ (10.2 \pm 1.9) \times 10^{-4} ]</td>
<td>[ (3.2 \pm 1.0) \times 10^{-4} ]</td>
<td>[ (9.1 \pm 1.8) \times 10^{-4} ]</td>
<td></td>
</tr>
</tbody>
</table>

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PR D 87, 012007 (2013)
Partial wave analysis

Tasks:
- **Map out the resonances**
- **Systematic determination of resonance properties:**
  - spin-parity,
  - resonance parameters,
  - production properties,
  - decay properties, ... 
  - resonances tend to be broad and plentiful, leading to intricate interference patterns, or buried under a background in the same and in other waves.

Event-wise ML fit to all observables simultaneously

$$\omega(\xi) \equiv \frac{d\sigma}{d\Phi} = \left| \sum_i c_i R_i B(p,q) Z(L) \right|^2$$

Event-wise efficiency correction

$$P(\xi) = \frac{\omega(\xi) \epsilon(\xi)}{\int \omega(\xi) \epsilon(\xi)}$$

Tools: PWA
- **Decompose to partial wave amplitudes**
- **Make full use of data**
- **Handle the interference**
- **Extract resonance properties with high sensitivity and accuracy**
Feynman Diagram Calculation toolkit: automatic generate partial wave amplitudes

The amplitude constructed using the effective Lagrangian approach with the Rarita-Schwinger formalism can be written out by Feynman rules for tree diagrams (the spin wave functions for particles, the propagators, and the effective vertex couplings).

Feynman diagrams in $\psi' \rightarrow \pi^0 p\bar{p}$

Eg. For Spin = $3/2$

$$A_{\frac{3}{2}^+} = \bar{u}(\kappa_2, s_2) \kappa_{2\mu} P^{\mu\nu}_{\frac{3}{2}} (c_1 g_{\nu\lambda} + c_2 \kappa_{1\nu} \gamma_{\lambda} + c_3 \kappa_{1\nu} \kappa_{1\lambda}) \gamma_5 v(\kappa_1, s_1) \psi^\lambda$$

$$P^{\mu\nu}_{\frac{3}{2}^+} = \frac{\gamma \cdot p + M_{N^*}}{M_{N^*}^2 - p^2 + iM_{N^*} \Gamma_{N^*}} [g^{\mu\nu} - \frac{1}{3} \gamma^{\mu} \gamma^{\nu} - \frac{2 p^{\mu} p^{\nu}}{3M_{N^*}^2} + \frac{p^{\mu} \gamma^{\nu} - p^{\nu} \gamma^{\mu}}{3M_{N^*}}]$$

FDC Project by J.X Wang,

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\[ \psi' \rightarrow \pi^0 p\bar{p}, \eta p\bar{p} \]

Scatter plots of \( p\bar{p} \) invariant mass versus \( \gamma\gamma \) invariant mass

Two vertical bands: \( \psi' \rightarrow \pi^0 p\bar{p}, \eta p\bar{p} \)
Horizontal band: \( \psi' \rightarrow X + J/\psi, J/\psi \rightarrow p\bar{p} \)
\[ \psi' \rightarrow \pi^0 p\bar{p} \]

CLEO-c: PRD 82 092002 (2010)

Interference is NOT considered
PWA of $\psi' \rightarrow \pi^0 p\bar{p}$


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PWA of $\psi' \rightarrow \pi^0 p\bar{p}$


2 New N* are found (1/2+, 5/2-)

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PWA of $\psi' \rightarrow \eta p \bar{p}$

PR D 88, 032010 (2013)
PWA of $\psi' \rightarrow \eta p\bar{p}$

PR D 88, 032010 (2013)

- N(1535) and PHSP(1/2-) are dominant
- No evidence for a ppbar resonance

Mass and width of N(1535)
- $M = 1524 \pm 5^{+10}_{-4}$ MeV/$c^2$
- $\Gamma = 130^{+27+57}_{-24-10}$ MeV/$c^2$

PDG value:
- $M = 1525$ to 1545 MeV/$c^2$
- $\Gamma = 125$ to 175 MeV/$c^2$

Branching fraction:
- $B(\psi' \rightarrow N(1535)\bar{p}) \times B(N(1535) \rightarrow \eta p) + c.c. = (5.2 \pm 0.3^{+3.2}_{-1.2} \times 10^{-5})$

* For N(1535)
Summary and outlook

- PWA is a key tool in hadron spectroscopy
- Charmonium decays: a nice lab for $N^*, \Sigma^*, \Delta^*, \Lambda^*, \Xi^*$
- $0.5 \times 10^8 \, \psi'$ and $1.2 \times 10^9 \, J/\psi$ (and a lot of $\chi_c, \eta_c$) @ BES3
- Many discoveries are expected.

Thanks for your attention
**backups**

**check of extra $N^*$**

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
<th>$J^P$</th>
<th>C.L.</th>
</tr>
</thead>
<tbody>
<tr>
<td>N(1675)</td>
<td>1675</td>
<td>145</td>
<td>$5/2^-$</td>
<td>2.3$\sigma$</td>
</tr>
<tr>
<td>N(1680)</td>
<td>1680</td>
<td>130</td>
<td>$5/2^+$</td>
<td>3.1$\sigma$</td>
</tr>
<tr>
<td>N(1700)</td>
<td>1700</td>
<td>100</td>
<td>$3/2^-$</td>
<td>1.0$\sigma$</td>
</tr>
<tr>
<td>N(1710)</td>
<td>1710</td>
<td>100</td>
<td>$1/2^+$</td>
<td>3.6$\sigma$</td>
</tr>
<tr>
<td>N(1885)</td>
<td>1885</td>
<td>160</td>
<td>$3/2^-$</td>
<td>1.0$\sigma$</td>
</tr>
<tr>
<td>N(1900)</td>
<td>1900</td>
<td>498</td>
<td>$3/2^+$</td>
<td>0.1$\sigma$</td>
</tr>
<tr>
<td>N(2000)</td>
<td>2000</td>
<td>300</td>
<td>$5/2^+$</td>
<td>2.4$\sigma$</td>
</tr>
<tr>
<td>N(2065)</td>
<td>2065</td>
<td>150</td>
<td>$3/2^+$</td>
<td>3.2$\sigma$</td>
</tr>
<tr>
<td>N(2080)</td>
<td>2080</td>
<td>270</td>
<td>$3/2^-$</td>
<td>0.9$\sigma$</td>
</tr>
<tr>
<td>N(2090)</td>
<td>2090</td>
<td>300</td>
<td>$1/2^-$</td>
<td>1.3$\sigma$</td>
</tr>
<tr>
<td>PHSP</td>
<td>10</td>
<td>10</td>
<td>$1/2^+$</td>
<td>0.1$\sigma$</td>
</tr>
</tbody>
</table>

**check of extra $1^- p\bar{p}$ resonance**
<table>
<thead>
<tr>
<th>Resonance</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>N(1535) S11</td>
<td>&gt;&gt;5σ</td>
</tr>
<tr>
<td>PHSP S11</td>
<td>&gt;&gt;5σ</td>
</tr>
<tr>
<td>N(1440) P11</td>
<td>0.8σ</td>
</tr>
<tr>
<td>N(1520) D13</td>
<td>3.7σ</td>
</tr>
<tr>
<td>N(1650) S11</td>
<td>&lt;0.1σ</td>
</tr>
<tr>
<td>N(1700) D13</td>
<td>1.7σ</td>
</tr>
<tr>
<td>N(1710) P11</td>
<td>2.0σ</td>
</tr>
<tr>
<td>N(1720) P13</td>
<td>2.5σ</td>
</tr>
<tr>
<td>N(1900) P13</td>
<td>3.1σ</td>
</tr>
<tr>
<td>N(2080) D13</td>
<td>0.6σ</td>
</tr>
</tbody>
</table>
backups

The structure in B decays is much wider and is not really at threshold. It can be explained by fragmentation mechanism.

Threshold enhancement in J/ψ decays is obviously much more narrow and just at threshold, and it cannot be explained by fragmentation mechanism.