Production of pentaquarks in $pA$-collisions

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Pentaquark fact sheet

**LHCb discovery, > 9σ significance**

- PRL 115 (2015), 072001

![Graph showing LHCb discovery](image)

**Possibility of pentaquarks**

- M. Gell-Mann, Phys. Lett. 8 (1964) 214

**Possibility of \( \bar{c}c \) pentaquarks**

- S. J. Brodsky *et al*, PLB 93 (1980), 451, PRL 64 (1990) 1011, PLB 411, 152 (1997)

- Intrinsic charm of proton
- Attractive force between \( \bar{c}c \) and light baryons
- More exotic exotics: \( \bar{c}c – He^3 \) bound states
- Many new exotic states in \( \bar{c}c \) sector

**\( \bar{c}c \) in other exotics: tetraquarks**

- \( Z_c(3900) \)
- \( Z_c(3900)^+? \)
- \( X(3872) \)
- \( X(4140)? \)
- \( X(4274)? \)
- \( Z(4430) \)
- \( Z_c(4025)^+? \)

**Indirect evidence from**

\( \Lambda_b^0 \rightarrow J/\psi \pi^- p \ (\sim 3\sigma) \)

[arXiv:1606.06999]
What is a pentaquark?

Molecule \((D_c, \bar{D}_c, \ldots) + \Sigma_c, \bar{\Sigma}_c\)

- M. Karliner et. al, PRL 115 (2015), 122001
- H. X. Chen et. al., PRL 115 (2015), 172001
- G. J. Wang et. al., PRD 93, 034031.
- J. He, arXiv:PLB 753, 547.

[many developments in this direction ...]

Non-molecular structure

- A. Mironov et. al, JETP Lett. 102 (2015), 271
- S. Takeuchi et. al, arXiv:1608.05475

Common points of all models

- Should have other decay channels
- Should have siblings from multiplets

Molecule \(\left( J/\psi, \psi(2S), \chi_c \right) + p \)

- D. E. Kahana et. al, arXiv:1512.01902
- M. I. Eides, et. al, PRD 93, 054039
- U. G. Meißner et. al, PLB 751, 59 (2015)

Threshold singularity

- F. K. Guo et. al, PRD 92 (2015), 071502
- Anisovich et. al, MPL. A 30, 1550212
- X-H. Liu et al, arXiv:1507.05359
Can we rule out a triangle singularity?

**Cusp vs LHCb peak**

- F. K. Guo, U.-G. Meißner, W. Wang and Z. Yang, PRD 92 (2015), 071502
- $M_{Pc} - M_{\chi c_1} - M_P = 0.9 \pm 3.1$ MeV

**Argand plots [$\chi_c p$ vs. LHCb]**
How can we rule out a threshold cusp?

Check for existence of a peak in other decay channels

- Observation in $\Lambda_0 \rightarrow J/\psi \pi^- p$: $\sim 3\sigma$
  
  [arXiv:1606.06999]

- Study other production mechanisms
What are the production mechanisms of $P_c^+$?

$\Lambda_b$ decays [LHCb]

$\Lambda_b^0 \rightarrow \Lambda_b^{'S} \rightarrow P_c^+ \rightarrow J/\psi p$

$\pi N \rightarrow P_c \rightarrow J/\psi N$ [proposed]
- Q. F. Lu et al, arXiv:1510.06271.
- J-PARC: $\pi$-beams up to 20 GeV.
- Can check existence of $P_c^0$.

$\gamma p \rightarrow P_c^+ \rightarrow J/\psi p$ [proposed]
- Q. Wang et al, PRD 92 (2015) 034022
- V. Kubarovsky et al, PRD 92 (2015), 031502
- M. Karliner et. al, PLB 752 (2016), 329.

Cross-section sizeable for JLAB 12 GeV.
Our suggestion: pentaquark production in \( pA \)

**Two-stage process**
- Production of \( \bar{c}c \) pair
- Fusion \( \bar{c}c + p \rightarrow Pc^+ + X \).

**Coherence and formation time**

\[ Eg \sim 10 \text{GeV}: \text{[PLB206 (1988) 685-690]} \]

\[ t_{\text{form}} \sim 0.2 \text{fm}, \quad t_{\text{coh}} \sim 10 \text{fm} \]

\( \Rightarrow \) Bare \( \bar{c}c \) pair passes through the nucleus

**Kinematic constraint**
- \( \bar{c}c \) should be slow in nucleus rest frame

**Main advantage**

No electroweak intermediaries, expect higher cross-sections
Distributions of $\bar{c}c$ dipoles

**Dipole size distribution**

- Mild dependence on $\sqrt{s}$, $(\bar{c}c)$
- Exponential decrease with size
  - For reference: $\sigma_{tot}^{(J/\psi)} \gtrsim 10^4 \text{nb}$

⇒ Expect significantly smaller cross-sections than for charmonium.

**Flux energy dependence (nucleus rest frame)**

- Suppression for onshell $\bar{c}c$ near endpoint
- Extra interactions/emissions of $\bar{c}c$

Higher $E_{\bar{c}c}$ permitted (smaller cross-section).
$P_c^+$ production mechanisms in LO pQCD

$\bar{c}c = 1_c$, $P$-wave $[P_c^+ = \chi_c p]$ 

$\bar{c}c = 1_c$, $S$-wave $[\psi(2S)p]$ 

$\bar{c}c = 8_c \left[ P_c^+ = \bar{D}^* + \Sigma_c \right]$ 

= sum over all diagrams with different gluon connections 

Dipole model: gluons $\Rightarrow$ dipole cross-sections
Kinematics and choice of framework

\[ \bar{c}c = 1_c, P\text{-wave} \]

Kinematic window
- \( g(x_1) \) suppressed at \( x_1 \sim 1 \)
- WF \( \Psi_{P^+_c}(x_1, \ldots) \) suppressed at \( x_1 \sim 0 \)
[\( \bar{c}c \) “slow” in the nucleus rest frame]
- \( \langle x_1 \rangle \sim 0.2 - 0.3 \langle x_2 \rangle \sim m_c^2/s \ll 1 \)

Relation of \( x_1 \) to a rapidity of \( P^+_c \)

\[
y_{P_c} = \frac{1}{2} \ln \left( \frac{P^+_c}{P^-_c} \right) = \ln \left( \frac{(1 + x_1) \sqrt{s}}{\sqrt{M^2_{P_c} + P^2_\perp}} \right),
\]

\( \Rightarrow \) Rapidity distribution of \( P^+_c \)⇔ access to l.c. fraction of \( \bar{c}c \) in \( P^+_c \)
What should we take into account in evaluations?

\[ \bar{c}c = 1_c, P\text{-wave} \]

2N correlator

- Studied at SRC at SLAC, JLAB, ...
- Shape is similar to deuteron WF
- Normalization \( \sim AZ; \Phi_{2N} \equiv \rho_{2N}^{1/2} \)

Gaussian param. for nucleon WF

\[ |\psi_p(\{\alpha_i, \vec{r}_i\})|^2 = |f_3(\alpha_1, \alpha_2, \alpha_3)|^2 \frac{1}{\pi^2 R_p^4} \exp \left( -\frac{1}{4 R_p^2} (r_1^2 + r_2^2 + r_3^2) \right) \bigg|_{\Sigma_i \vec{r}_i = 0}, \]

\[ f_n(\alpha_1, ..., \alpha_n) = \frac{N_n}{\left( M_B^2 - \sum_{i=1}^{n} \frac{m_i^2}{\alpha_i} \right)} \bigg|_{\sum \alpha_i = 1} \]

from S. J. Brodsky et.al. PLB 93 (1980), 451
What do we know about pentaquark WF?

Tightly bound state

- Superposition: \( |P_c^+\rangle = [\bar{c}c][uud] + [\bar{c}u][udc] + [\bar{d}d][uuc] + \ldots \)
- \( \langle r_{cc} \rangle \approx 1 - 2 \text{ fm} \). Should evaluate a wave function in some model

Charmonium molecule

- \( \bar{c}c \) in color singlet
- Small size, \( \langle r_{cc} \rangle \approx 0.4 - 0.7 \text{ fm} \)
- Far from center, \( \langle R_{cc} \rangle \gtrsim 1 \text{ fm} \)

\( \bar{D}(*)\Sigma_c \) molecule

- Colors of \( \bar{c}c \) uncorrelated
- \( \langle r_{cc} \rangle \approx 2 - 3 \text{ fm (far)} \)
- \( \langle R_{cc} \rangle \lesssim 0.5 \text{ fm} \)
What do we know about pentaquark WF?

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\[ \psi(\vec{r}_i, \vec{R}_{cc}, \vec{r}_{cc}) = \psi_{\text{baryon}}(\vec{r}_i) \times \psi_{\text{relative}}(\vec{R}_{cc}) \times \psi_{\text{meson}}(\vec{r}_{cc}) \]

\( \bar{D}(\ast) \Sigma_c \) molecule

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How much are results sensitive to $\langle R_{cc} \rangle$, $\langle r_{cc} \rangle$?

Sensitivity of $\sigma_{Pc}$ [mb] on $\langle R_{cc} \rangle$, $\langle r_{cc} \rangle$

- Sensitivity is sizeable
- $\sigma_{Pc}$ peaks at $\langle R_{cc} \rangle \sim 3$ fm
- $\Rightarrow$ Please consider all the following results as a factor-of-two estimates

Fix $\langle R_{cc} \rangle$ from experiment?

- Mild sensitivity of $p_T$-slope (interplay with $k_F$, $B_{prot}$).

Rapidity distribution

- $y \to y_{min}$: suppression from $\Psi_{Pc}$
- $y \gg y_{min}$: suppression from $g(x_1)$
How large are the cross-sections?

Cross-sections for $pPb \rightarrow P_c^+$ [nb]

| $\sqrt{s_{NN}}$ | (a)  | (b)  | (c)  | (d)  |
|------------------|------|------|------|------|
| 200 GeV         | 0.6 $\mu$b | 16   | 6.5  | 2.9  |
| 7 TeV           | 1.9 $\mu$b | 120  | 137  | 19   |
| 13 TeV          | 2 $\mu$b | 163  | 208  | 21   |

- (a) = $1_c$, $1P$
- (b) = $1_c$, $2S$
- (c) = $8_c$, with $g$ emission
- (d) = $8_c$, with multiple interaction

Rough estimate of cross-sections

- $\frac{d\sigma_{pA \rightarrow P_c^+}}{dy_{Pc}} \sim |M_{fi}|^2 \frac{d\sigma_{pp \rightarrow M\bar{c}c}}{dy_{Pc}}$
- Charmonium cross-section $d\sigma_{pp \rightarrow M\bar{c}c}$ from experiment, $M_{fi}$-overlap integral
- Reasonable agreement if experimental cross-sections are used

ALICE @forward rapidities [PLB 704 (2011), 442]:

$$\left| \frac{d\sigma}{dy}_{pp \rightarrow J/\psi} \right| \approx 3 \mu b \Rightarrow \left| \frac{d\sigma}{dy}_{pA \rightarrow J/\psi} \right| \approx 600 \mu b$$
How do we compare with other mechanisms?

Cross-section “per nucleon” $[\text{nb}]$

| $\sqrt{s_{NN}}$ | (a) | (b) | (c) | (d) |
|-----------------|-----|-----|-----|-----|
| 200 GeV         | 2.9 | 0.08| 0.03| 0.01|
| 7 TeV           | 9   | 0.58| 0.66| 0.09|
| 13 TeV          | 9.6 | 0.78| 1   | 0.1 |

- (a)=$1_c$, 1P
- (b)=$1_c$, 2S
- (c)=$8_c$, with $g$ emission
- (d)=$8_c$, with multiple interaction

Cross-sections at least not smaller!

LHCb mechanism

- Suppression $\sim m_b^2 m_s^2 G_F^2$
- Full production rate very small:
  \[ \sigma_{\text{tot}} \sim \frac{10^3 \text{events}}{3 \text{fb}^{-1}} \sim 300 \text{fb} \sim 3 \times 10^{-4} \text{nb} \]

Electroproduction cross-sections

\[ \sigma_{ep \to e P_c^+ X} \sim \frac{d^2 n}{dE_\gamma dQ^2} \otimes \sigma_{\gamma p \to P_c^+ X} ; \quad \frac{d^2 n}{dE_\gamma dQ^2} \sim \frac{\alpha_{\text{em}}}{\pi} \]

- Q. Wang et al, PRD 92 (2015) 034022
- V. Kubarovsky et al, PRD 92 (2015), 031502
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Summary

$P^+_c$ can be produced in $pA$ collisions

- The cross-sections are sizeable, contain important information about $P^+_c$ internal structure
  - Rapidity distribution $\Leftrightarrow$ access to light-cone fraction of $\bar{c}c$ in $P^+_c$
  - Slope of $p_T$ distribution $\Rightarrow$ mild sensitivity to average distance between $\bar{c}c$ and center of mass

- Suggested $P^+_c$ production occurs in the following kinematics:
  - Collider kinematics (RHIC, LHC, ...): very forward rapidities
  - Fixed-target experiments (AFTER@LHC, PANDA, ...): central rapidities

Outlook

- If $\exists P^0_c = udd\bar{c}c$ (neutral “sibling” of $P^0_c$), this should be also produced via $\bar{c}c + n \rightarrow P^0_c$ subprocess in $pA$ collisions.
- If there are heavier pentaquark states, can also see them!
Thank You for your attention!