Charmonium Spectroscopy with the PANDA experiment at FAIR

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*on behalf of the PANDA Collaboration*

*Workshop on Physics at Future High Intensity e⁺e⁻ Collider, Hefei, China, January 13th – 17th 2015*

**Outline**

- **Introduction**
  - Motivation, physics programme
  - Advantage of anti-protons
  - Resonance scan method

- **Hadron spectroscopy**
  - Exotic hadrons
  - Open charm
  - Charmonium-like exotics

- **Summary & outlook**
Recent Hot Topics

Hadron Spectroscopy

BESIII, arXiv:1303.5949

$Z_c(3900)$

unexpected, manifestly exotic!

Nucleon Structure

M. Stolarski, DIS 2014

proton spin $\frac{1}{2}$ not yet understood
Hadron Physics and QCD

• Why are there no free quarks?

• Are there other colour neutral objects?

• What is the structure of the nucleon?

• What are the spin degrees of freedom?
Anti-Proton ANnihilation in DArmstadt

- Meson spectroscopy
  - Light mesons
  - Charmonium
  - Exotic states: glue-balls, hybrids, molecules / multi-quarks
- (Anti-) Baryon production
- Nucleon structure
- Charm in nuclei
- Strangeness physics
  - hypernuclei,
  - S = -2 nuclear system

\[ \text{mass [GeV/c}^2\text{]} \]
\[ \text{p \ momentun [GeV/c]} \]
Anti-Proton ANnihilation in DArmstadt

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\[
\begin{array}{cccccccc}
0 & 2 & 4 & 6 & 8 & 10 & 12 & 15 \\
\Lambda\Lambda & \Omega\Omega & D\bar{D} & D_s\bar{D}_s & \Lambda_c\bar{\Lambda}_c & \Omega_c\bar{\Omega}_c \\
qq\bar{q} & cc\bar{q}q & n\bar{g},s\bar{g} & cc\bar{g} & n\bar{g},s\bar{g} & cc\bar{g} & ggg,gg & ggg \\
\text{light } qq & c\bar{c} & J/\psi, \eta_c, \chi_{cJ} \\
n\bar{g}, s\bar{g} & \pi, \rho, \omega, f_2, K, K' & \end{array}
\]
Advantages of Anti-Protons

- Gluon rich process

- Gain ~ 2 GeV in annihilation
  
  \textit{(low momentum transfer)}

- $B = 0$ system

- Access to all fermion-antifermion quantum numbers \textit{(not in e+e-)}

- Access to states of high spin $J$

- Precise mass resolution in formation reactions

Formation:

\[ J^{PC} = 1^- \]

\rightarrow \text{Only } J^{PC} = 1^- \text{ allowed in } e^+e^-

\[ J = 0, 2, \ldots \]
\[ C = + \]

\[ J = 1 \]
\[ C = - \]

\rightarrow \text{All } J^{PC} \text{ allowed for } (q\bar{q}) \text{ accessible in } p\bar{p}
Anti-Protons – Resonance Scan Method

- Cooled $\bar{p}$ beam: Excellent energy resolution!
- Production rate: Convolution of resonance and beam profile
- Principle has been proven to work ...

Resonance Cross Section

Beam profile

Measured Rate

$E_{CM}$
Resonance Scan Method -- an example: $\chi_{c1,2}$

Production:

\[ e^+e^- \rightarrow \psi' \rightarrow \chi_{1,2} \rightarrow \gamma(\gamma J/\psi) \rightarrow \gamma e^+e^- \]

- Invariant mass reconstruction depends on the detector resolution $\approx 10$ MeV

Formation:

\[ \bar{p}p \rightarrow \chi_{1,2} \rightarrow \gamma J/\psi \rightarrow \gamma e^+e^- \]

- Resonance scan:
  - mass resolution depends on the beam resolution

\[ e^+e^- \rightarrow \psi(2S) \rightarrow \gamma \chi_c \rightarrow \gamma \gamma J/\psi \rightarrow \gamma e^+e^- \]
Resonance Scan Method -- an example: $\chi_{c1,2}$

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Formation:

$p\bar{p} \rightarrow \chi_{1,2} \rightarrow \gamma J/\psi \rightarrow \gamma e^+e^-$

- Resonance scan:
  $\rightarrow$ mass resolution depends on the beam resolution

CrystalBall (SLAC): $3512.3 \pm 4$ MeV/$c^2$
E835 (Fermilab): $3510.641 \pm 0.074$ MeV/$c^2$
Resonance Scan Method -- an example: $\chi_{c1,2}$

**Production:**

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**Formation:**

$$\bar{p}p \rightarrow \chi_{1,2} \rightarrow \gamma J / \psi \rightarrow \gamma e^+e^-$$

- Resonance scan:
  -> mass resolution depends on the beam resolution

**NB:** Interpretation of many states depends on width of states!

- **E760/835@Fermilab** $\approx 240 \text{ keV}$
- **PANDA@FAIR** $\approx 50 \text{ keV}$

*CrystalBall (SLAC)*: 3512.3 $\pm$ 4 MeV/c$^2$
*E835 (Fermilab)*: 3510.641 $\pm$ 0.074 MeV/c$^2$
Cross section expectations for:

- Glueballs, light hybrids
  - rates comparable to light hadrons
- Charmed hybrids/molecules
  - rates comparable to charmed hadrons
- Key issue
  - High luminosity + good trigger
Spectroscopy – Exotic Hadrons
Mesons and (Spin) Exotic States

Constituent quark model
- color neutral $q\bar{q}$ systems
- quantum numbers $I^G J^{PC}$
- $P = (-1)^{L+1}$, $C = (-1)^{L+S}$, $G = (-1)^{I+L+1}$
- $J^{PC}$ multiplets: $0^{++}, 0^{--}, 1^{--}, 1^{+-}, 1^{--}, 2^{++}, ...$
- Forbidden: $0^{--}, 0^{+-}, 1^{+-}, 2^{-+}, 3^{--}, ...$

Three categories of exotics:
- Glueballs $\rightarrow$ $gg, ggg$
- Hybrids $\rightarrow (q\bar{q})g$
- Molecules / multiquarks
  $\rightarrow (qqq)(q\bar{q}), (q\bar{q})(q\bar{q})$ or: $qqq\bar{q}, qqqq\bar{q}$

$\rightarrow$ The observation of exotic hadrons would be a confirmation of QCD
Lattice Predictions

- Lattice QCD $\rightarrow$ Predictions for masses/properties
- Current predictions for mesons, glueballs, hybrids

Prediction: Spin exotic hybrids

Prediction: Spin exotic glueballs

Charmonium Hybrid Candidate $\tilde{\eta}_{c1}$

- From LQCD calculations:
  Spin-exotic hybrid candidate $\tilde{\eta}_{c1}$ with $m \approx 4.3\text{GeV}/c^2$, $J^{PC} = 1^{-+}$
- Exclusive reconstruction in two favoured channels:

$$\bar{p}p \rightarrow \tilde{\eta}_{c1} \eta \rightarrow \chi_{c1} \pi^0 \pi^0 \eta$$

$$\bar{p}p \rightarrow \tilde{\eta}_{c1} \eta \rightarrow D^0 \bar{D}^{0*} \eta$$

- Production X-section assumed similar to $\bar{p}p \rightarrow \psi(2S) \eta$ (33pb)
  $\rightarrow$ Need good calorimetry + good particle identification
\[ \bar{p} p \rightarrow \tilde{\eta}_{c1} \eta \rightarrow \chi_{c1} \pi^0 \pi^0 \eta \]

- Simulation @ 15 GeV/c
  - 80k signals + 80k each background, e.g.
    \[ \bar{p} p \rightarrow J/\psi \pi^0 \pi^0 \pi^0 \eta, \bar{p} p \rightarrow \chi_{c1} \pi^0 \eta \eta \]
  - 9C kinematic fit (mass constraints, 4C energy momentum)

- \( \eta \rightarrow \gamma \gamma \)
- \( \chi_{c1} \rightarrow J/\psi \gamma \)
- \( \tilde{\eta}_{c1} \rightarrow \chi_{c1} \pi^0 \pi^0 \)

\[ \epsilon \approx 7\% \]

- Signal to noise: \[ \frac{S}{N} > 250 \cdot \frac{\sigma_S}{\sigma_B} \] => well feasible for \( \sigma_B \approx 10 \sigma_S \! \)
\( \bar{p}p \rightarrow \tilde{\eta}_c \eta \rightarrow D^0 \bar{D}^{0*} \eta \)

- Simulation @ 15 GeV/c
  - 200k signals + background, e.g. \( \bar{p}p \rightarrow D^0 \bar{D}^{0*} \pi^0 \)
  - 11C kinematic fit (mass constraints, 4C energy momentum)

\[
D^0 \rightarrow K^- \pi^+ \pi^0
\]
\[
D^{0*} \rightarrow D^0 \pi^0
\]
\[
\tilde{\eta}_c \rightarrow D^0 \bar{D}^{0*}
\]

\( \varepsilon \approx 5\% \)

- Signal to noise: 
  \[
  \frac{S}{N} > 2900 \cdot B(\tilde{\eta}_c \rightarrow D^0 \bar{D}^{0*}) \quad \Rightarrow \quad \text{feasible for non-vanishing BR}
  \]

[arXiv:0903.3905, hep-ex]
Open charm: The $D_s$ spectrum

- Qualitative agreement theory vs. experiment on $D$ states – details however still open
- Many new $D_J$ mesons ($LHCb$)
- Narrow states (2003): $D_s^*(2317)$ and $D_s^*(2416)$ still under discussion (and other broad states recently)
- Masses: Significantly lower than expected (quark potential model), and just below $DK$ and $D^*K$ threshold
- Widths: Only upper limits
- Interpretation unclear: $DK$ / $D^*K$ molecules, tetraquarks, chiral doublers, ...? Sensitive to width
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### Interpretation $\leftrightarrow$ Width of $D_{s0}^*(2317)$

<table>
<thead>
<tr>
<th>Different theoretical approaches, different interpretations</th>
<th>$\Gamma(D_{s0}^*(2317)^+ \rightarrow D_s\pi^0) \text{ (keV)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>P. Colangelo and F. De Fazio, Phys. Lett. B 570, 180 (2003)</td>
<td>$7 \pm 1$</td>
</tr>
<tr>
<td>A. Faessler, T. Gutsche, V.E. Lyubovitskij, Y.L. Ma, Phys. Rev. D 76 (2007) 133</td>
<td>$79.3 \pm 32.6$</td>
</tr>
<tr>
<td>M. Cleven, H. W. Giesshammer, F. K. Guo, C. Hanhart, Ulf-G. Meißner hep-ph: arXiv 1405.2242 (2014)</td>
<td><strong>NEW!</strong> Strong and radiative decays of $D_{s0}^*(2317)$ and $D_{s1}(2460)$</td>
</tr>
</tbody>
</table>

**Pure $c\bar{s}$ state**

**Tetraquark state**

**DK had. molecule**

**Dynamically gen. resonance**

**DK had. molecule**
Width of $D_{s0}^*(2317)$

- Theoretical interpretations very sensitive for $\Gamma(D_{s0}^*(2317))$
- Formation reaction not possible: $\bar{p}p \not\to D_{s0}^*(2317)$
  \[ \Rightarrow \text{Energy-scan with recoil @ threshold: } \bar{p}p \to D^+_s D_{s0}^*(2317)^- \]

\[
\frac{\sigma(s)}{|M|^2} = \frac{\Gamma}{4\pi \sqrt{s}} \int_{-\infty}^{\sqrt{s} - m_{D_s}} dm \sqrt{(s - (m + m_{D_s})^2)(s - (m - m_{D_s})^2)} \frac{(m - m_{D(2317)})^2 + (\Gamma/2)^2}{(m - m_{D(2317)})^2 + (\Gamma/2)^2}
\]

[C. Hanhart]

⇒ Lineshape at threshold depends on $\Gamma(D_{s0}(2317)^*)$
Reconstruction of $p\bar{p}\to D_s^+D_{s0}^*(2317)^-\pi^0$

- Simulation @ 8.8 GeV/c
  - 40k signals, 40k each background, e.g. $\bar{p}p \to D_s^+D_s^-\pi^0$
  - 10M generic background events
  - Inclusive reconstruction of $D_s^\pm$, missing mass technique

$m_{\text{miss}}$, $m_{\text{miss}}$ vs. $m_{D_s}$, $m_{\text{miss}} + m_{D_s}$ make use of strong correlation between masses

$\approx 20$ MeV

Efficiency $\varepsilon \approx 20\% - 36\%$

[arXiv:0903.3905, hep-ex]

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Charmonium Spectroscopy with PANDA at FAIR
14/01/2015
Energy scan simulation around threshold

\[ \bar{p}p \rightarrow D_s^\pm D_{s0}^{*}(2317)^\mp \]

\[ M_{\text{sum}} = M_{\text{miss}}(D_s) + M(D_s) \]

\[ \Gamma = 100 \text{ keV} \]

15 measured points within 4 MeV window

[M.Mertens, PhD thesis]
Energy scan simulation around threshold

Extracted excitation function

Sensitivity of width Measurement

Relative accuracy $\sigma_\Gamma/\Gamma < 1/3$ for $\Gamma > 100$

[M.Mertens, PhD thesis]
Meson Spectroscopy – Charmonium-like (exotics)
Charmonium Spectroscopy with PANDA at FAIR

- **X(3872)**

- **X(3940)**
  - PRL 98,082001 (2007)

- **Y(3940)**
  - PRL 94,182002 (2005)

- **X(3915)**
  - PRL 104,092001 (2010)

- **Y(4260)**
  - PRL 95,142001 (2005)

- **Y(4350)**
  - PRL 98,212001 (2007)

- **Y(4008)**

- **Y(4660)**

- **Z(4430)⁻**
  - PRL 100,142001 (2008)

- **Z₁⁻ & Z₂⁻**
  - PRD 78,072004 (2008)

- **Y(4140)**
  - PRL 102,242002 (2009)

- **X(4350)**
  - PRL 104,112004 (2010)
• Since 2003 charmonium-like spectrum found richer as expected

• Observation of states that do not fit theoretical models/predictions

• The case of the X(3872):
  ➢ isospin violating, very narrow
  ➢ quantum numbers known (1^{++}, LHCb)
  ➢ width unclear
  ➢ nature not yet clear.. needed: measurement of width

• X,Y,Z states:
  ➢ some need still confirmation
  ➢ masses poorly known
  ➢ statistics poor, nature unclear:
    Molecules, tetraquarks, hybrids, ..?
  Z_c(3900): First order exotic?
How PANDA can contribute:
Study lineshapes

- Panda: Neutral & charged, e.g. J/ψπ⁻π⁺, J/ψπ⁰π⁰, χcγ→J/ψγγ, J/ψγ, J/ψη, ηcγ, ...
- Direct formation in ¯p p → lineshapes
- Example: X(3872)

![Graphs showing lineshapes](image)

Compare lineshapes in different final states

- D⁰D⁺π⁰
- D⁰D⁺⁰
  - C. Hanhart *et al.*, PRD 76 (2007) 034007
• Upper limit on branching ratio by LHCb:
  \[ BR(X \to \bar{p}p) < 0.002 \times BR(X \to J/\psi \pi^+ \pi^-) \Rightarrow \Gamma < 1.2\ \text{MeV} \]
  EPJ C73 (2013) 2462
• And \( BR(X \to J/\psi \pi^+ \pi^-) > 0.026 \) (PDG 12) \( \Rightarrow \sigma(\bar{p}p \to X(3872)) < 67\ \text{nb} \)

• Here: Assume \( \sigma = 50\ \text{nb} \), Luminosity: \( 2 \times 10^{31}\ \text{cm}^{-2}\text{s}^{-1} \)
• Width resolution < 100 keV
Non-qq̅ mesons: Charged c̅c-like states

- Manifestly exotic: tetra-quark or molecular nature
- $Z_{c}(4430)^{±}$ seen by Belle, confirmed by LHCb
- $Z_{c}(3900)^{±}$ seen by BESIII, Belle
- $Z_{c}(4020)^{±}$, $Z_{c}(4040)^{±}$ seen by BESIII
- $Z_{c}(4050)^{±}$, $Z_{c}(4250)^{±}$ seen by Belle

Belle, PRL 100 (2008) 142001

BESIII, arXiv:1303.5949
Non-qq̅ mesons: Charged cc̅-like states

Studies planned with PANDA:

- **production** in $\bar{p}p$:
  
  $\bar{p}p \rightarrow Z(4430)^\pm \pi^\mp$

  $Z(4430)^\pm \rightarrow \psi(2S) \pi^\pm$

- **formation** in $\bar{p}n$:
  
  $\bar{p}d \rightarrow Z(4430)^- p_{\text{spectator}}$

  $\rightarrow \psi(2S) \pi^- p_{\text{spectator}}$

  spectator proton needed to reconstruct

  $\rightarrow$ **reduced mass resolution**
Facility for Antiproton and Ion Research
Facility for Antiproton and Ion Research

3000 physicists
50 countries

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Charmonium Spectroscopy with PANDA at FAIR
14/01/2015
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Scientific pillars of FAIR:
- **Atomic, Plasma Physics and Applications** – **APPA**
- **Compressed Baryonic Matter** – **CBM**
- **NUclear STructure, Astrophysics and Reactions** – **NUSTAR**
- **antiProtons ANnihilation at DArmstadt** – **PANDA**

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High resolution mode:
- $e^-$ cooling: $p \leq 8.9$ GeV/c
- $10^{10}$ anti-protons stored
- Luminosity up to $2 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$
- $\Delta p/p = 4 \times 10^{-5}$

High intensity mode:
- Stochastic cooling
- $10^{11}$ anti-protons stored
- Luminosity up to $2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$
- $\Delta p/p = 2 \times 10^{-4}$
Detector requirements:

- **4π coverage** (partial wave analysis)
- **High rates** (2 x 10^7 annihilations / s)
- **Good PID** (γ, e, μ, π, K, p)
- **Momentum res.** (~1%)
- **Vertexing** for D, K^0_s, Λ (cτ = 123 μm for D^0, p/m ≫ 2)
- **Efficient trigger** (e, μ, K, D, Λ)
- **No hardware trigger** (raw data rate ~TB/s)
AntiProton Annihilation at Darmstadt
AntiProton Annihilation at Darmstadt

13 m
Antiproton Annihilation at Darmstadt

Anti proton beam

Clusterjet- or Pellet-Target

Interaction point
AntiProton Annihilation at Darmstadt
AntiProton Annihilation at Darmstadt

Straw Tube Tracker

Luminosity Monitor

Micro Vertex Detector

GEM Detector

Forward Tracking System
AntiProton Annihilation at Darmstadt

Barrel DIRC
Barrel TOF
Endcap DIRC
Forward RICH
Forward TOF
Muon Detectors
Muon Range System
AntiProton Annihilation at Darmstadt

PWO Calorimeter

Forward Shashlyk EMC
Summary & conclusions

• Broad & fascinating physics programme at PANDA

• Anti-protons provide experimental key technique

• Accelerator and detector are on track

PANDA will be the facility to study QCD -- hadron structure and spectroscopy
Thank you for your attention!

The PANDA collaboration:
~ 520 Members, 69 Institutes, 18 Countries

Austria, Australia, Belarus, China, France, Germany, India, Italy, Poland, Romania, Russia, Spain, Sweden, Switzerland, Thailand, Netherlands, USA, UK