Strong Interaction Physics with PANDA

A personal selection

June 15, 2010 | Albrecht Gillitzer

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Outline

- Introduction
- The PANDA experiment: physics & detector
- Spectroscopy
  - Hidden and open charm mesons
  - Baryons
- Hadrons in the nuclear medium
- Summary
strong arguments…

- confinement of quarks and gluons
- spontaneous chiral symmetry breaking, hadron masses
- existence of non-\(qq\)/qqq configurations
- interplay of hadron and quark-gluon degrees of freedom
Why antiprotons?

- difficult to make
- BUT:
  - gluon rich process
  - gain ~2 GeV in annihilation, reduced momentum transfer
  - $B = 0$ system
  - all fermion-antifermion quantum numbers accessible
  - very high resolution in formation reactions
  - high angular momentum accessible
Physics Program

\( \bar{p}p, \bar{p}d \) collisions:
- meson spectroscopy
  - charmonium
  - glueballs, hybrids, tetraquarks, molecules
  - \( D \) mesons
- baryon spectroscopy
- reaction dynamics
- proton structure
- \( CP \) violation

\( \bar{p}A \) collisions:
- \( \Lambda \Lambda \) hypernuclei
- hadrons in the nuclear medium

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Physics & Feasibility

- 1st physics performance report for PANDA finished in 2009
- comprehensive physics program discussed
- simulations of at least one benchmark channel for each topic
- available on arXiv

arXiv:0903.3905v1
### HESR antiproton beam

| Effective target thickness (pellets): $4 \times 10^{15}$ cm$^{-2}$ |
| Beam radius at target (rms): 0.3 mm |

<table>
<thead>
<tr>
<th></th>
<th>High Resolution Mode</th>
<th>High Luminosity Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Momentum range</strong></td>
<td>1.5 – 8.9 GeV/c</td>
<td>1.5 – 15 GeV/c</td>
</tr>
<tr>
<td><strong># antiprotons</strong></td>
<td>$10^{10}$</td>
<td>$10^{11}$</td>
</tr>
<tr>
<td><strong>Peak luminosity</strong></td>
<td>$2 \times 10^{31}$ cm$^{-2}$s$^{-1}$</td>
<td>$2 \times 10^{32}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td><strong>Momentum spread (rms)</strong></td>
<td>$\Delta p/p \sim 3 \times 10^{-5}$</td>
<td>$\Delta p/p \sim 1 \times 10^{-4}$</td>
</tr>
<tr>
<td><strong>Beam cooler</strong></td>
<td>Electron $\leq 8.9$ GeV/c</td>
<td>Stochastic $\geq 3.8$ GeV/c</td>
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</tbody>
</table>
Versatile Detector

Detector requirements:

• nearly $4\pi$ solid angle (partial wave analysis)
• high rate capability ($2 \cdot 10^7$ reactions /s)
• good PID ($\gamma$, e, $\mu$, $\pi$, K, p)
• momentum resolution ($\sim$1%)
• vertex detection for D, $K_s$, $\Lambda$ ($ct = 317$ $\mu$m for $D^{\pm}$)
• intelligent trigger (charm, strangeness, leptons)
• flexible modular design (hypernuclear physics)
Pellet or cluster jet target

2 T superconducting solenoid

2 Tm dipole
Central Tracker

Micro-Vertex-Detector

Forward Trackers
Panda

PANDA detector

Hadron Calorimeter

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Particle production in \(\bar{p}p\) collisions

Formation:

- All \(J^{PC}\) allowed for \((q\bar{q})\) accessible in \(\bar{p}p\)
- Only \(J^{PC} = 1^{--}\) allowed in \(e^+e^-\)

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

\[J = 1\]
\[C = -\]
Example: $X_{c1,2}$

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

Formation:

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

Resonance scan: Resolution depends on the beam resolution

E760@Fermilab $\approx 240$ keV

PANDA $\approx 30$ keV
Charmonium spectroscopy

- open questions below $D\bar{D}$ threshold: widths, branching
- new „XYZ“ states (Belle, BaBar, CLEO, CDF, D0, …)
- new degrees of freedom: molecules, tetraquarks, gluonic excitations?
- conventional states above $D\bar{D}$
- high $L$ states: access in $\bar{p}p$ but not in $e^+e^-$
How can PANDA contribute?

- simulation studies for several channels and vs:
  \[ J/\psi\pi^+\pi^- , J/\psi\pi^0\pi^0, \chi_{cJ} \rightarrow J/\psi\gamma, J/\psi\gamma, J/\psi\eta, \eta_{cJ} \]
- direct formation in \( \bar{p}p \): line shapes!
- d target: \( \bar{p}n \) with p spectator tagging, e.g. \( Z'-(4430) \)

\[ \bar{p}p \rightarrow Y(4260) \rightarrow J/\psi\pi^+\pi^- \approx 100 \text{ events/day} \]
\[ \rightarrow J/\psi\pi^0\pi^0 \approx 40 \text{ events/day} \]
\[ S/N = 25 \]

C. Hanhart et al.,
PRD 76 (2007) 034007

E. Braaten, M. Lu,
PRD 77 (2008) 014029
Beyond standard quark configurations

QCD allows much more than what we have observed:

**Baryons**

**Mesons**

**Exotics:**

- **Hybrids**
- **Glueballs**
- **Tetraquarks**

May have $J^{PC}$ not allowed for $\bar{q}q$
Exotics production in $\bar{p}p$ collisions

Production: all $J^{PC}$ accessible

Hybrids

<table>
<thead>
<tr>
<th>$J^{PC}$</th>
<th>$1^{--}$</th>
<th>$1^{+-}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^1S_0$</td>
<td>1++</td>
<td>1--</td>
</tr>
<tr>
<td>$^3S_1$, 1--</td>
<td>0++</td>
<td>0--</td>
</tr>
</tbody>
</table>

Exotic $J^{PC}$ would be clear signal

G. Bali, EPJA 1 (2004) 1 (PS)
Open charm: The $D_s$ spectrum

- New narrow states $D_s^*(2317)$ and $D_s^*(2460)$ seen by BaBar, Belle, CLEO
- Masses significantly lower than quark model expectation
- States are just below $D^0K$ and $D^*K$ threshold
- Interpretation unclear: $D^0K / D^*K$ molecules, tetraquarks, quiral doublers, ...?

B. Aubert et al. (BaBar Collab.), Phys. Rev. D 74 (2006) 032007
### $D_{s0}^*(2317)$ theoretical predictions

<table>
<thead>
<tr>
<th>Approach</th>
<th>$\Gamma(D_{s0}^*(2317) \rightarrow D_s\pi^0)$ (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P. Colangelo and F. De Fazio, Phys. Lett. B 570, 180 (2003)</td>
<td>7 ± 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 ± 32.6</td>
</tr>
</tbody>
</table>
Method: threshold scan

- reaction: \( \bar{p}p \rightarrow D_s^\pm D_{s0}^*(2317)^\mp \)

\[
\frac{\sigma(s)}{|M^2|} = \frac{\Gamma}{4\pi \sqrt{s}} \int_{-\infty}^{\sqrt{s}-m_{D_s}} dm \sqrt{s - (m + m_{D_s})^2} \sqrt{s - (m - m_{D_s})^2} \frac{1}{(m - m_{D(2317)})^2 + (\Gamma/2)^2}
\]

- excitation function only depends on \( m \) and \( \Gamma \) of \( D_s(2317) \)

- experimental accuracy determined by beam quality (\( \Delta p, \sigma_p/p \)), not by detector resolution
Simulation results: energy scan

$\Gamma = 100 \text{ keV}$

$M_{\text{sum}} = M_{\text{miss}}(D_s) + M(D_s)$
Simulation results: energy scan

Γ = 100 keV

Γ = 500 keV

σ vs √s

χ² vs Γ

ΔM vs Γ
Baryon spectroscopy

- similar cross section for annihilation to mesons and for final states with baryon-antibaryon
- baryons formed largely via excited states
- particularly large discovery potential in multi-strange baryons: very little known in Ξ and Ω spectrum
- charmed baryons, exotic baryons with hidden charm
Baryon spectroscopy

- characteristic event topology of $\Xi^-$ and $\Xi^*$ events
- $\sim\mu$b cross section for $\Xi$ $\Rightarrow$ $\sim10^7 \Xi$ /day produced with full luminosity

$\Xi^* \rightarrow \Xi^0 + \text{c.c.}$
Simulation: $\bar{p}p \rightarrow \Xi^+\Xi^-\pi^0$

- benchmark channel for the study of $\Xi$ resonances
- no empty regions or discontinuities in Dalitz plot
- $\Xi^-\pi^0$ mass resolution $\sim 4$ MeV

![Graph showing $m^2(\Xi^-\pi^0)$ vs. $m^2(\Xi^+\pi^0)$]
Hadrons in the nuclear medium

- original idea: mass shift of charmed hadrons in nuclear matter
- D mesons: attractive potential and/or bound states predicted
- problem: large momentum transfer → multistep processes required

C. Garcia-Recio et al., arXiv:1004.2634
Hadrons in the medium: $J/\psi$ absorption

- related to QGP signal in HI collisions

$$\bar{p} + A \rightarrow J/\psi + X \rightarrow e^+e^- + X$$
$$\bar{p} + A \rightarrow J/\psi + X \rightarrow \mu^+\mu^- + X$$

$P = e^- \sigma pdl$

measure cross section as function of $A$ and $p_{\bar{p}}$

deduce $J/\psi N$ dissociation cross section at lower, well-defined $J/\psi$ momentum

\[\text{note: } \sigma_{\bar{p}A \rightarrow J/\psi X} \ll \sigma_{pp \rightarrow J/\psi}\]

need to detect $S/B = 10^{-10}$!
Hadrons in the medium: $J/\psi$ absorption

- first detailed simulations of $4.05$ GeV/c $p + ^{40}\text{Ca} \rightarrow J/\psi + X \rightarrow e^+e^- + X$
- reconstruction efficiency $\epsilon_{\text{signal}} = 0.73$
- $\sigma_{\text{peak}} \sim 0.3$ nb $\rightarrow \#J/\psi \sim 200$ /day at maximum luminosity
- background seems to be controllable

$\sigma_{J/\psi N}$ extracted from A-dependence

- input: $\sigma_{J/\psi N} = 4.2$ mb
- fit: $\sigma_{J/\psi N} = 4.34$ mb
Summary

- Using $\bar{p}p$ and $\bar{p}A$ collisions, PANDA is complementary to other experiments.
- PANDA is well-suited to answer key questions regarding:
  - normal and exotic hidden charm mesons
  - multi-strange (and charmed) baryons
  - properties of hadrons in the nuclear medium
- much wider physics program
- high degree of flexibility: capability to respond to new topics arising in the future
International collaboration:

- > 400 scientists
- > 40 institutions
- 16 countries