Exotics at PANDA

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Outline

- Introduction
  - exotic states

- Present experimental status and its interpretation
  - light meson spectrum
  - hidden and open charm spectrum

- Advantages of $\bar{p}$ annihilation for the search of exotics

- PANDA
  - physics program
  - detector

- Physics performance studies for PANDA

- Partial Wave Analysis
  - investigations of the $\bar{p}p$ annihilation mechanism
Introduction

- Exotics fall in the category of hadrons

- Hadrons
  - bound states in the non perturbative QCD regime
  - description very challenging
    - lattice QCD
    - phenomenological models

Knowledge of the complete hadron spectrum and accurate measurements of its properties are needed.
Introduction

- Quark model
  - mesons = $q\bar{q}$ pairs are the constituents
  - quantum numbers are characterized by $J^{PC}$

- Gluons carry color charge
  - constituents of QCD bound states (exotics)
  - also states with exotic quantum numbers possible

3 categories of exotics

- Hybrids
  - states with excited gluonic degrees of freedom

- Glueballs
  - hadrons with no valence quark content

- Multiquark states
  - molecule: loosely bound pair of mesons close to threshold
  - tetraquarks: tightly bound $(q\bar{q})(q\bar{q})$ states
Charmed Hybrids

- $c\bar{c}$ states with gluonic degrees of freedom
- 8 charmed hybrids with masses < 5 GeV/c$^2$ expected
- Lightest charmonium hybrid predicted by flux tube model and LQCD
  - $\tilde{\eta}_{c1} : M \sim 4.3$ GeV/c$^2$ with exotic quantum number $J^{PC}=1^{-+}$

\begin{table}[h]
\centering
\begin{tabular}{c|c|c}
\hline
 & $^{1}S_0$ ($\uparrow\downarrow$) & $^{3}S_1$ ($\uparrow\uparrow$) \\
\hline
 & combined with a gluon & \\
\hline
$(q\bar{q})_8$ & $1^-$ (TM) & $1^+$ (TE) \\
\hline
$^{1}S_0$, 0-- & 1++ & 1-- \\
\hline
$^{3}S_1$, 1-- & 0++ $\leftarrow$ exotic & 0-- \\
 & 1++ & 1-- $\leftarrow$ exotic \\
 & 2+- $\leftarrow$ exotic & 2-- \\
\hline
\end{tabular}
\end{table}
Glueballs

- Glueballs with exotic quantum numbers cannot mix with normal mesons
  - should be rather narrow
  - easier to identify

- LQCD: heavy glueballs with exotic quantum numbers
  - $M(J^{PC}=0^{+-}) \sim 4140 \text{ MeV}/c^2$
  - $M(J^{PC}=2^{+-}) \sim 4740 \text{ MeV}/c^2$

- Flavor blind decay
  - decay modes in charmed final states

Morningstar, Peardon, PRD60 (1999) 34509
Morningstar, Peardon, PRD56 (1997) 4043
Exotics in the Light Meson Region

More than 10 states have been classified as possible exotics. Almost all of these candidates have been seen in $\bar{p}p$ reactions.

- Exotics in the light meson spectrum difficult to identify
  - lots of and broad conventional states
  - overlap with conventional states

| $f_0(980)$ | 4q state - molecule |
| $f_0(1500)$ | 0$^+$ glueball candidate |
| $f_0(1370)$ | 0$^+$ glueball candidate |
| $f_0(1710)$ | 0$^+$ glueball candidate |
| $\eta(1410); \eta(1460)$ | 0$^-$ glueball candidate |
| $f_1(1420)$ | hybrid, 4q state |
| $\pi_1(1400)$ | hybrid candidate 1$^{-+}$ |
| $\pi_1(1600)$ | hybrid candidate 1$^{-+}$ |
| $\pi(1800)$ | hybrid candidate 0$^+$ |
| $\pi_2(1900)$ | hybrid candidate 2$^{++}$ |
| $\pi_3(2000)$ | hybrid candidate 1$^{-+}$ |
| $a_2'(2100)$ | hybrid candidate 1$^{++}$ |
**Exotics in the Light Meson Region**

*Example: $f_0(1500)$*

- found in $\bar{p}p \rightarrow 3\pi^0, 2\pi^0\eta, \pi^0 K_L K_L$, ...
- $0^{++}$ glueball candidate
- mixture with $q\bar{q}$ scalar nonet?

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**Crystal Barrel @ LEAR**
Exotics in the Charm Region

- In the $c\bar{c}$ spectrum width and number of states are lower
  - less overlap
  - exotics easier to identify

- Lots of new $X$, $Y$, $Z$ states observed in the past years
  - mainly from $B$-factories and other $e^+e^-$ machines
  - most of them $1^{--}$ states (can be produced directly)
  - many of them not understood

Examples

Belle:
- $X(3872)$

BaBar:
- $Y(4260)$
Exotics in the Charm Region

Many open questions give hints for the existence of exotics

- Very narrow state $X(3872)$
  - multiquark / molecule close to $D\bar{D}^*$ threshold?
  - precise measurements of masses and line shapes needed
- Mass difference in the decays $X(3872) \rightarrow \psi \pi \pi$ and $X(3872) \rightarrow D\bar{D} \pi$
- Too many $1^{-}-$ states
  - $Y(4260)$ lowest lying $1^{-}-$ hybrid state?
- . . .

Study of $\bar{p}p$ reactions might answer some of these open questions
\( \bar{p}p \) annihilation

- \( \bar{p}p \) annihilation is a gluon rich process
  - cross section for glueballs and light hybrids similar to light hadrons (\( \sim 1–100 \ \mu \text{b} \))
  - cross section for charmed hybrids and molecules similar to charmed hadrons (\( \sim 1-100 \ \text{nb} \))

**Formation: only non exotic quantum numbers**

**Production with recoil particle: all quantum numbers**
\( \bar{p}p \) vs. \( e^+e^- \)

- In \( \bar{p}p \) experiments all c\( \bar{c} \) states can be formed and not just 1\( ^-^- \) states as in \( e^+e^- \) experiments
- Measurements of masses and widths only given by the resolution of the beam energy and not depending on detector limitations

**Example:** \( \chi_{c1} \)

- \( e^+e^- \) at Crystal Ball
  - only via production mode accessible
  - \( e^+e^- \rightarrow \gamma \chi_{c1} \rightarrow \gamma \gamma J/\psi \rightarrow \gamma\gamma e^+e^- \)

- \( \bar{p}p \) at E835
  - via formation mode accessible
  - \( \bar{p}p \rightarrow \chi_{c1} \rightarrow \gamma J/\psi \rightarrow \gamma e^+e^- \)

CBall, Edwards et al. PRL 48 (1982) 70
PANDA Physics Program

- $\bar{p}p$- and $\bar{p}A$- annihilation
  - $\bar{p}$ momentum 1.5-15 GeV/c
  - $\bar{p}$ resolution: $\Delta p/p \sim 10^{-5}$
- Charmonium and open charm spectroscopy
- Search for exotics
- Baryon spectroscopy
- Baryon-antibaryon production
- Meson production in nuclear medium
- Hypernuclear physics
- Nucleon structure from EM processes

Multipurpose detector required!
PANDA Detector

- Tracking Devices: MVD, Central Tracker, GEMs, Straw Tubes
- Electromagnetic Calorimeter: PWO Crystals (TS), Shashlyk (FS)
- PID Devices: (DISC) DIRC, Muon Detector, RICH, TOF

- Standard HEP design for fixed target experiment: target+forward spectr.
- Target spectrometer: Solenoid with $B_z = 2$ T
- Forward spectrometer: Dipole with $B \cdot L = 2$ Tm
PANDA Physics Performance Report

• Published in 03/2009: arXiv:0903.3905v1 [hep:exp]

• Feasibility studies for the major channels of interest

• $1.3 \times 10^9$ Monte Carlo events produced

• More than 20 institutes contributed to these Monte Carlo studies
Benchmark Channel: Charmed Hybrid $\tilde{\eta}_{c1}$

Lightest charmonium hybrid ($m\sim4.3$ GeV/c$^2$) with exotic quantum numbers $1^{-+}$ → expected to be narrow with sizable branching fraction to $D\bar{D}^*$ and $\chi_{c1}\pi^0\pi^0$

2 decay channels studied @ 15 GeV/c

$\bar{p}p \rightarrow \tilde{\eta}_{c1}\eta \rightarrow \chi_{c1}\pi^0\pi^0\eta \rightarrow \ldots \rightarrow e^+e^-7\gamma$

$\bar{p}p \rightarrow \tilde{\eta}_{c1}\eta \rightarrow D^0\bar{D}^{0*}\eta \rightarrow \ldots \rightarrow K^+K^-\pi^+\pi^-8\gamma$

- Efficiency 7% and 5%, respectively
- Background under control
  - due to $7C$ and $11C$ kinematic fit
  - $\tilde{\eta}_{c1} \rightarrow D^0\bar{D}^{0*} : S/B \sim 2.9 \times 10^3 \times \mathcal{B}(\tilde{\eta}_{c1} \rightarrow D^0\bar{D}^{0*})$
  - $\tilde{\eta}_{c1} \rightarrow \chi_{c1}\pi^0\pi^0 : S/B > 250 \times \mathcal{B}(\tilde{\eta}_{c1} \rightarrow \chi_{c1}\pi^0\pi^0)$
Benchmark Channel: $\bar{p}p \rightarrow Y(4260) \rightarrow J/\psi \pi^+ \pi^- \rightarrow e^- e^+ \pi^+ \pi^-$

$Y(4260)$: $1^-$ resonance found at BaBar in $e^+e^- \rightarrow J/\psi \pi^+ \pi^-$ using ISR.

Charmed hybrid as possible interpretation.

- Reconstruction efficiency: 33%
- Main background
  - $\bar{p}p \rightarrow \pi^+ \pi^- \pi^+ \pi^- \ \sigma = 50 \ \mu$b
  - misidentified as $J/\psi \pi^+ \pi^- \rightarrow e^+ e^- \pi^+ \pi^- < 10 \ \text{pb}$

- $\psi(2S)$ like $\pi\pi$ distribution

\[
\frac{d\Gamma}{dm_{\pi\pi}} \propto phsp \cdot (m^2_{\pi\pi} - \lambda m^2_{\pi\pi})^2
\]

- input: $\lambda = 4.0$
- result: $\lambda = 4.3 \pm 0.4$
Partial Wave Analysis is needed to identify resonances and to determine the quantum numbers $J^{PC}$.

Fit in the complete n-dimensional phasespace necessary.

**PWA Challenge**

Complexity of the production mechanism
- $J$ rises with beam momentum
- various initial states → many fit parameters

$ar{p}p$ production studied with Crystal Barrel @ LEAR data
- 9 different beam momenta between 600 and 1940 MeV/c studied

<table>
<thead>
<tr>
<th>$J$</th>
<th>Singulett $\lambda = 0$</th>
<th>Triplet $\lambda = \pm 1$</th>
<th>Triplet $\lambda = \pm 1, 0$</th>
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</thead>
<tbody>
<tr>
<td>0</td>
<td>$^{1}S_{0}$ 0++</td>
<td>$^{3}P_{0}$ 0++</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>$^{1}P_{1}$ 1++</td>
<td>$^{3}P_{1}$ 1++</td>
<td>$^{3}S_{1}, ^{3}D_{1}$ 1--</td>
</tr>
<tr>
<td>2</td>
<td>$^{1}D_{2}$ 2++</td>
<td>$^{3}D_{2}$ 2--</td>
<td>$^{3}P_{2}, ^{3}F_{2}$ 2++</td>
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<tr>
<td>3</td>
<td>$^{1}F_{3}$ 3++</td>
<td>$^{3}F_{3}$ 3++</td>
<td>$^{3}D_{3}, ^{3}G_{3}$ 3--</td>
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<td>$^{3}F_{4}, ^{3}H_{4}$ 4++</td>
</tr>
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<td>$^{3}G_{5}, ^{3}I_{5}$ 5--</td>
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<td>$^{3}I_{6}$ 6--</td>
<td>$^{3}H_{6}, ^{3}J_{6}$ 6++</td>
</tr>
</tbody>
</table>
PWA Strategy: $\bar{p}p \rightarrow \omega \pi^0 \rightarrow (\pi^0 \gamma) \pi^0$

- For PANDA it is important to know the $\bar{p}p$ production mechanism in detail and the contributing initial angular momentum states
  
  - $\bar{p}p \rightarrow \omega \pi^0 \rightarrow (\pi^0 \gamma) \pi^0$
    - no intermediate resonances expected
    - direct information of $\bar{p}p$ initial state

- Fit with largest contributing spin $J_{\text{max}}$

- Amplitudes calculated in helicity formalism by considering the complete reaction chain

- Utilizing event based likelihood method

- Criteria for the largest contributing spin
  - fit result (-logLh)
  - obtained weighted angular distribution for the $\omega$ production and $\omega$ decay
Result for $\bar{p}p \to \omega \pi^0$ @ 900 MeV/c

- Significant improvement from hypothesis with $J_{\text{max}} = 2$ to $J_{\text{max}} = 3$
- Minor changes for $J > 3$
- Largest contributing spin $J_{\text{max}} = 3$

Result for $J_{\text{max}} = 3$
Result for $\bar{p}p \rightarrow \omega \pi^0$

- Largest contributing spin $J_{\text{max}}$ depending on the beam momentum
  - $J_{\text{max}} = 3$ @ 600 and 900 MeV/c
  - $J_{\text{max}} = 4$ @ 1050, 1200 and 1350 MeV/c
  - $J_{\text{max}} = 5$ @ 1525, 1642, 1800 and 1940 MeV/c

- @ PANDA: $J_{\text{max}} \approx 13$ @ 15 GeV/c?
  - most of the interesting channels contain resonances with high masses
  - limited phasespace $\rightarrow$ lower $J_{\text{max}}$ expected

- Spin density matrix of the $\omega$ under investigation
  - contains more information about the $\bar{p}p$ production mechanism

\[ J_{\text{max}} = \frac{p_{\text{cms}}}{(171 \pm 24) \text{ MeV/c}} \]
Summary

- Many open question in the field of hadron physics
  - many puzzles in the charmonium and open charm mass region

  **PANDA**

- Broad physics program for open and hidden charm physics
- $\bar{p}$ annihilation gluon rich process
- Unambiguous identification of exotics can answer many of the puzzles
- Extensive and detailed benchmark studies
  - measurements of the channels of interest feasible
- Partial Wave Analysis
  - investigations of the $\bar{p}p$ annihilation mechanism started
  - extended studies for complicated decay channels foreseen
- Not mentioned: search for exotic baryons