Charm spectroscopy at the PANDA experiment
Introduction

- **PANDA** (AntiProton Anihilation at Darmstadt)
  - **Hadron** physics experiment: Study of strong interactions

- Running coupling constant in transition region: Long distance features of QCD?

**Questions:**
- Hadronization: Mechanism of quark confinement?
- Inner structure of hadrons?
- Macroscopic properties of hadrons: Origin of mass and spin?
- Existence of other colour neutral objects?
Introduction

- PANDA (AntiProton Annihilations at Darmstadt)

- Broad physics program ...
  - Structural analysis of nucleons
  - Hypernuclei physics
  - In-medium effects of hadrons
  - Hadron spectroscopy

- Focus on the charm quark sector

- Search for exotic states

Conventional QCD states

Mesons

D mesons
Charmonium

Baryons

Glueballs?
Hybrids?
Multi-quark systems?

Thomas Würschig, Charm spectroscopy at PANDA, PANIC 2011
PANDA at FAIR

Future FAIR facility

Injectors

Synchrotrons

Storage rings

SIS 18
SIS 300
SIS 100

GSI

CBM
Super FRS
NuSTAR
FLAIR

Antiproton target: $10^7$/s production rate

Proton
Antiproton

UNILAC
SIS 18
SIS 100
SIS 300

HESR

NERP

FLAIR


Thomas Würschig, Charm spectroscopy at PANDA, PANIC 2011
**High Energy Storage Ring (HESR)**

- Up to $10^{11}$ stored antiprotons
  - Beam momentum: $(1.5 \ldots 15)$ GeV/c
- Fixed internal target
  - Frozen hydrogen or heavier nuclear targets

**Operation modes**

a) High luminosity: 
$$L = 2 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \iff \Delta p/p \approx 10^{-4}$$

b) High resolution: 
$$L = 10^{31} \text{ cm}^{-2} \text{ s}^{-1} \iff \Delta p/p \approx 4 \cdot 10^{-5}$$
PANDA at FAIR

- High Energy Storage Ring (HESR)

Beam-target interaction:
\[ \propto 20 \text{ million annihilations} / \text{s} \]
Quasi continuous time distribution of events

Operation modes

a) High luminosity:
\[ L = 2 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \iff \Delta p/p \approx 10^{-4} \]

b) High resolution:
\[ L = 10^{31} \text{ cm}^{-2} \text{ s}^{-1} \iff \Delta p/p \approx 4 \cdot 10^{-5} \]
High charm production rates, e.g.:

\[ \propto 10^7 \text{ } D \text{ pairs per year} \]

\[ \propto 10^9 \text{ } J/\psi \text{ per year} \]

High resolution mode off by factor of ten only...

Physics performance report:

arXiv:0903.3905v1 [hep-ex]
PANDA at FAIR

- Detector setup
  - 4π coverage
  - Detection of charged and neutral particles

- Key features:
  - Vertex resolution \( \propto 100 \ \mu m \)
  - Momentum resolution \( \propto 1\% \)

Fully exclusive measurements with a flexible trigger
• Detector setup
  ➢ 4π coverage
  ➢ Detection of charged and neutral particles

Fully exclusive measurements with a flexible trigger

➢ Key features:
  Vertex resolution $\propto 100 \ \mu m$
  Momentum resolution $\propto 1\%$

Photon detection 1 MeV … 10 GeV
Particle identification: $\gamma$, $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $p$

Energy resolution $\sigma(E)/E \propto 1.5%/\sqrt{E}$
Charm spectroscopy

Discovery

Confirmation

High-precision data

- Mass
- Width

Decay pattern

- Quantum numbers
- Partial widths
Charm spectroscopy

- High-precision data in formation experiments

- Fine-tuned energy scan in relevant mass region necessary

  ... On the market: BESIII only: $e^+e^-$ collider limited to $J^{PC} = 1^{--}$

  → PANDA will allow formation experiments for any $J^{PC}$
**Charm spectroscopy**

**Charmonium sector**

- **Experimental status**
  - Below threshold
  - All states established
  - No high-precision data for spin-singlets

---

**Diagram**

- Mass [GeV/c²]
- J/ψ
- h_c
- χ_{c0}
- χ_{c1}
- χ_{c2}
- η_c(1S)
- η_c(2S)
- ψ(2S)
- ψ(3770)
- X(3872)
- X(3940)
- Y(4260)
- Y(4320)
- Y(4660)
- Z(3930)
- D_s^*D_s^*
- D_s^*D_s
- D_sD_s
- D_sD^*
- D_s^*D^*_s
- D_sD^*_s
- Z^*(4430)
- D_sD
- D_sD^*

---

**Theory**
Charmonium sector

• Experimental status
  
  ➢ Above threshold: Incomplete picture, no high-precision data

  ✓ Only four states confirmed, all $J^{PC} = 1^{--}$

  ✓ Many predicted states not yet observed

  ✓ Discovery of new states
    → Discrepancies with conventional models
    → Established: $X(3872)$ and $Y(4260)$
    ... but not clearly assigned
Charm spectroscopy

- Experimental status:
  - Ground states: High-precision data
  - Excited states: Few experimental data, Incomplete picture
Physics simulation

• Radiative decay $h_c \rightarrow \eta_c \gamma$
  - Fully exclusive reconstruction
  - Expected event rate:
    - (High luminosity mode)
    - $20 / \text{day}$ to $92 / \text{day}$
  - Signal-to-background ratio:
    - $> 87$ to $8$
    - $8\%$ (Efficiency) to $25\%$

  - Resonance scan (10 data points $\leftrightarrow$ 5 days)
  - Achievable resolution well below 1 MeV (current upper limit)

$\Gamma = 0.5 \text{ MeV}$

\[ h_c \rightarrow \eta_c \gamma \rightarrow 3\gamma \quad h_c \rightarrow \eta_c \gamma \rightarrow \phi \phi \gamma \]

\begin{array}{|c|c|c|}
\hline
\Gamma_{R,MC} [\text{MeV}] & \Gamma_{R,\text{reco}} [\text{MeV}] & \Delta \Gamma_R [\text{MeV}] \\
\hline
1 & 0.92 & 0.24 \\
0.75 & 0.72 & 0.18 \\
0.5 & 0.52 & 0.14 \\
\hline
\end{array}

arXiv:0903.3905v1 [hep-ex]
Physics simulation

- \( \bar{p}p \rightarrow D^+ D^- \) production @ \( \psi(3770) \)
  
  ➢ Reconstruction: \( D^\pm \rightarrow K^\mp \pi^\pm \pi^\pm \)
  
  \[
  R = \frac{\sigma(\bar{p}p \rightarrow D^+ D^-)}{\sigma(\bar{p}p \rightarrow X)} = \frac{2.83 \text{nb} \cdot (0.092)^2}{60 \text{mb}} = 4.0 \cdot 10^{-10}
  \]
  
  Conservative estimate

- Signal Efficiency: 40%
- Mass resolution: \( \sim 10 \text{ MeV/c} \)
- \( S/N \sim 1.4 \)

- Projected difference of secondary vertices
- Vertex cut: \( S/N = 1 \)

- 6 orders of magnitude lower
Physics simulation

- Dalitz plot analysis
  - Center-of mass energy 900 MeV above threshold
  - Charged decay modes for $D$ mesons
  - Secondary vertex resolution $\sigma_i \leq 100 \, \mu m$

  $p\bar{p} \rightarrow D^*(2400)^0\overline{D}^0 \rightarrow D^+\overline{D}^0\pi^-$

  $D^0\overline{D}^+$

  $K^+\pi^- \rightarrow K^-\pi^+\pi^+$

- Full phase space coverage, isotropic reconstruction
- Good recovery of the $D^*$ resonance

A. Pitka, Diploma thesis
Physics simulation

- Inclusive study \( \bar{p}p \rightarrow D_s^\pm D_s^* (2317)^\mp \)
  
  ➢ Reconstruction: \( D_s^\pm \rightarrow \phi \pi^\pm, \quad \phi \rightarrow K^+ K^- \)
  \( \rightarrow D_s^* (2317)^\mp \) identification via missing mass
  \( \approx 40 \) events / day

  ➢ Excitation function around threshold

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

  ➔ Achievable resolution:
  - Particle width \( \propto 100 \text{ keV} \)
  - Mass shift \( \propto 0.1 \text{ MeV/c}^2 \)

  "Current PDG values"
  - \( \Gamma < 3.8 \text{ MeV} \)
  - \( \Delta M = 0.6 \text{ MeV/c}^2 \)
Physics simulation

- Resonance scan for the $X(3872)$
  - Exclusive reconstruction
    \[ X(3872) \rightarrow J/\psi \pi^+ \pi^- \rightarrow e^+ e^- \]
    \[ \approx 200 \text{ reconstructed events / day} \]

\[ \Gamma_{\text{in}} = 100 \text{ keV} \]
\[ \Gamma_{\text{reco}} = 110 \text{ keV} \]

\[ \rightarrow \text{Achievable resolution for particle width } \propto 100 \text{ keV} \]
  - Current upper limit: 2.3 MeV
  - Study of line shape accessible
Summary

• Charm spectroscopy
  - Interesting domain to study QCD at hadronic length scale
  - Many open questions within observed spectra
  - Current experimental status insufficient to solve these problems

• High-precision spectroscopy at PANDA
  - Complementary studies to existing charm experiments
  - Unique tool to access states of any quantum number

High luminosity
  ➢ High beam quality
  ➢ High resolution
  ➢ Optimized detector setup
  ➢ Highly efficient reconstruction

High statistics
More than 400 physicists from 53 institutions in 16 countries

U Basel
IHEP Beijing
U Bochum
IIT Bombay
U Bonn
IFIN-HH Bucharest
U & INFN Brescia
U & INFN Catania
JU Cracow
TU Cracow
IFJ PAN Cracow
GSI Darmstadt
TU Dresden
JINR Dubna
(U & INFN Ferrara
U Frankfurt
LNF-INFN Frascati
U & INFN Genova
U Glasgow
U Gießen
KVI Groningen
IKP Jülich I + II
U Katowice
IMP Lanzhou
U Lund
U Mainz
U Minsk
ITEP Moscow
MPEI Moscow
TU München
U Münster
BINP Novosibirsk
IPN Orsay
U & INFN Pavia
IHEP Protvino
PNPI Gatchina
U of Silesia
U Stockholm
KTH Stockholm
U & INFN Torino
Politecnico di Torino
U & INFN Trieste
U Tübingen
TSL Uppsala
U Uppsala
U Valencia
SMI Vienna
SINS Warsaw
TU Warsaw
Backup slides
Charm spectroscopy

Charmonium sector

D mesons

Open charm threshold

Established

New states

Theory
Charm spectroscopy

- High-precision data in formation ... with antiprotons!
Charmonium

Binding energy [eV]

Mass [GeV/c^2]

Dissociation threshold

\[ V = \frac{4}{3} \alpha_s \frac{1}{r} + kr \]

\[ V = \frac{4}{3} \alpha_s \frac{1}{r} \]

Positronium

Charmonium

Thomas Würschig, Charm spectroscopy at PANDA, PANIC 2011
**Introduction**

- **Detection concept**
  - Hermetic detector with modular sub-systems
  - Measurement of charged and neutral particles
  - Good particle identification and momentum resolution

**Tracking**
- Central trackers
- Forward trackers

**Particle identification**
- Muon system
- Electromagnetic calorimeter (EMC)
- Čerenkov detectors (DIRC, RICH)
- TOF systems

**Four-momentum reconstruction**
- Tracking system: Particle momentum
- Muon system+EMC: Particle energy

---

Thomas Würschig, Charm spectroscopy at PANDA, PANIC 2011