Antiproton Physics
(Overview of the PANDA Physics Program)

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International School of Nuclear Physics,
From Quarks and Gluons to Hadrons and Nuclei
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• The strong interaction and QCD
• ÆPANDA at FAIR
  – Experimental Setup
  – The ÆPANDA Physics Program
  – Physics Performance
• Summary and Outlook
The modern theory of the strong interactions is Quantum Chromodynamics (QCD), the quantum field theory of quarks and gluons based on the non abelian gauge group SU(3). It is part of the Standard Model.

At high energies, where the strong coupling constant $\alpha_s$ becomes small and perturbation theory applies, QCD is well tested.

In the low-energy regime, however, QCD becomes a strongly coupled theory, many aspects of which are not understood.

Confinement

Asymptotic freedom
Theoretical Approaches to non-perturbative QCD

- **Potential models.** Bound systems of heavy quarks can be treated in the framework of non-relativistic potential models, with forms which reproduce the asymptotic behaviour of QCD. Masses and widths are obtained by solving Schrödinger’s equation.

- **Lattice QCD (LQCD)**
  - The QCD equations of motions are discretized on a 4-dimensional space-time lattice and solved by large-scale computer simulations.
  - Enormous progress in recent years (e.g. gradual transition from quenched to unquenched calculations).
  - Ever increasing precision, thanks also to synergies with EFT.

- **Effective Field Theories (EFT)**
  They exploit the symmetries of QCD and the existence of hierarchies of scales to provide effective lagrangians that are equivalent to QCD for the problem at hand.
  - With quark and gluon degrees of freedom (e.g. Non Relativistic QCD or NRQCD)
  - With hadronic degrees of freedom (e.g. Chiral Perturbation Theory).
Examples of Theory Calculations

LQCD Glueball Spectrum

Morningstar und Peardon, PRD60 (1999) 034509

LQCD + NRQCD Charmonium Spectrum

Maiani et al., PRD71(2005)014028

Four quark for the X(3872)
Experimental Measurements

• **Spectroscopy of QCD bound states.** Precision measurement of particle spectra to be compared with theory calculations. Identification of the relevant degrees of freedom.
  – light quarks, $c\overline{c}$, $b\overline{b}$
  – $D$ meson
  – baryon

• **Search for new forms of hadronic matter:** hybrids, glueballs, multiquark states ...

• **Hadrons in nuclear matter.** Origin of mass.

• **Hypernuclei.**

• **Study of nucleon structure.**
  – Form Factors
  – GDAs

• **Spin physics.**
Experimental Techniques

**e^+e^- collisions**
- direct formation
- two-photon production
- initial state radiation (ISR)
- B meson decay
  (BaBar, Belle, BES, CLEO(-c), LEP ...)

+ low hadronic background
+ high discovery potential
- direct formation limited to vector states
- limited mass and width resolution for non vector states

**p̅p annihilation**
- (LEAR, Fermilab E760/E835, PANDA)
- high hadronic background
+ high discovery potential
+ direct formation for all (non-exotic) states
+ excellent mass and width resolution for all states

**Hadroproduction**
- (CDF, D0, LHC)

**Electroproduction**
- (HERA)
Experimental Technique
Highlights from Fermilab
In $\bar{p}p$ collisions the coherent annihilation of the 3 quarks in the $p$ with the 3 antiquarks in the $\bar{p}$ makes it possible to form directly states with all non-exotic quantum numbers.

The measurement of masses and widths is very accurate because it depends only on the beam parameters, not on the experimental detector resolution, which determines only the sensitivity to a given final state.
The cross section for the process:
\[ \overline{pp} \rightarrow R \rightarrow \text{final state} \]
is given by the Breit-Wigner formula:
\[
\sigma_{BW} = \frac{2J + 1}{4} \frac{\pi}{k^2} \frac{B_{in} B_{out} \Gamma_R^2}{(E - M_R)^2 + \Gamma_R^2 / 4}
\]

The production rate \( \nu \) is a convolution of the BW cross section and the beam energy distribution function \( f(E, \Delta E) \):
\[
\nu = L_0 \left\{ \varepsilon \int dE f(E, \Delta E) \sigma_{BW}(E) + \sigma_b \right\}
\]
The resonance mass \( M_R \), total width \( \Gamma_R \) and product of branching ratios into the initial and final state \( B_{in} B_{out} \) can be extracted by measuring the formation rate for that resonance as a function of the cm energy \( E \).
Example: $\chi_{c1}$ and $\chi_{c2}$ scans in Fermilab E835
PANDA at FAIR

Experimental Setup

The PANDA Physics Program

Physics Performance
FAIR at a glance
Facility for Antiproton and Ion Research
The FAIR Complex

From existing GSI UNILAC & SIS18 & new proton linac

100 Tm Synchrotron
SIS100

300 Tm Stretcher Ring
SIS300

Antiproton production

Rare isotope Production & separator

Collector & Cooler Ring

Accumulator Ring
Deceleration

HESR & PANDA

Compressed Barionic Matter experiment

+ Experiments:
E-I collider
Nuclear Physics
Atomic Physics
Plasma Physics
Applied Physics

NESR

High Energy Storage Ring

New Experimental Storage Ring

PANDA at FAIR
High-Energy Storage Ring

• Production rate $2 \times 10^7$/sec

• $P_{\text{beam}} = 1 - 15$ GeV/c

• $N_{\text{stored}} = 5 \times 10^{10}$ $p^-$

• Internal Target

  High resolution mode

  • $\delta p/p \sim 10^{-5}$ (electron cooling)
  • Lumin. = $10^{31}$ cm$^{-2}$ s$^{-1}$

  High luminosity mode

  • Lumin. = $2 \times 10^{32}$ cm$^{-2}$ s$^{-1}$
  • $\delta p/p \sim 10^{-4}$ (stochastic cooling)
PANDA Detector

- Micro Vertex Detector
- Central Tracker
- GEM Detectors
- Mini Drift Chambers
- Shashlyk Calorimeter
- Muon Range System
- TOF Wall
- Dipole
- RICH
- Disc DIRC
- EM Calorimeter
- Barrel DIRC
- Solenoid
- Barrel TOF
- Beampipe
- Targets system
- Target Spectrometer

- $p$ of momentum from 1.5 up to 15 GeV/c
- 2 Tesla solenoid
- Proton pellet target or gas jet target
- Micro Vertex Detector
- Inner Time of Flight detector
- Tracking detector: Straw Tubes
- DIRC
- Electromagnetic Calorimeter
- Muon counters
- Multiwire Drift Chambers
Multiwire Drift Chambers/ Straw tubes
- deflecting dipole: 2 Tesla·meter
- Forward DIRC and RICH
- Forward Electromagnetic Calorimeters
- Time of Flight counters
- Hadron Calorimeter
PANDA Collaboration

> 430 Scientists
56 Institutions
16 Countries

U Basel
IHEP Beijing
U Bochum
U Bonn
U & INFN Brescia
IFIN Budapest
U & INFN Catania
U Cracow
GSI Darmstadt
TU Dresden
JINR Dubna
(LIT,LPP,VBLHE)
U Edinburgh
U Erlangen
NWU Evanston
U & INFN Ferrara
U Frankfurt
LNF-INFN Frascati
U & INFN Genoa
U Glasgow
U Gießen
KVI Groningen
IKP Jülich I + II
U Katowice
IMP Lanzhou
U Mainz
U & INFN Milano
Politecnico di Milano
U Minsk
TU München
U Münster
BINP Novosibirsk
LAL Orsay
U & INFN Pavia
IHEP Protvino
PNPI Gatchina
U of Silesia, Katowice
U Stockholm
KTH Stockholm
U & INFN Torino
Politecnico di Torino
U Oriente, Torino
U & INFN Trieste
U Tübingen
U & TSL Uppsala
U Valencia
SMI Vienna
SINS Warsaw
U Warsaw
PANDA Physics Program

- QCD BOUND STATES
  - CHARMONIUM
  - GLUONIC EXCITATIONS
  - HEAVY-LIGHT SYSTEMS
  - STRANGE AND CHARMED BARYONS
- NON PERTURBATIVE QCD DYNAMICS
- HADRONs IN THE NUCLEAR MEDIUM
- NUCLEON STRUCTURE
  - GENERALIZED DISTRIBUTION AMPLITUDES (GDA)
  - DRELL-YAN
  - ELECTROMAGNETIC FORM FACTORS
- ELECTROWEAK PHYSICS

ArXiV:0903.3905
The study of QCD bound states is of fundamental importance for a better, quantitative understanding of QCD. Particle spectra can be computed within the framework of non-relativistic potential models, effective field theories and Lattice QCD. Precision measurements are needed to distinguish between the different approaches and identify the relevant degrees of freedom.

- Charmonium Spectroscopy
- Gluonic Excitations
- Heavy-Light Systems
- Strange and Charmed Baryons
Main issues

- All 8 states below threshold observed, some (precision) measurements still missing:
  - $h_c$ (e.g. width)
  - $\eta_c(1S)$
  - $\eta_c(2S)$ (small splitting from $\psi(2S)$)
- The region above open charm threshold must be explored in great detail:
  - find missing $D$ states
  - explain newly discovered states ($c\bar{c}$ or other)
  - confirm vector states seen in $R$
Charmonium at PANDA

- At $2 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$ accumulate 8 pb$^{-1}$/day (assuming 50% overall efficiency) $\Rightarrow 10^4 \div 10^7$ (c c) states/day.
- Total integrated luminosity 1.5 fb$^{-1}$/year (at $2 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$, assuming 6 months/year data taking).
- Improvements with respect to Fermilab E760/E835:
  - Up to ten times higher instantaneous luminosity.
  - Better beam momentum resolution $\Delta p/p = 10^{-5}$ (GSI) vs $2 \times 10^{-4}$ (FNAL).
  - Better detector (higher angular coverage, magnetic field, ability to detect hadronic decay modes).
- Fine scans to measure masses to $\approx 100$ KeV, widths to $\approx 10\%$.
- Explore entire region below and above open charm threshold.
- Decay channels
  - $J/\psi + X$, $J/\psi \rightarrow e^+e^-$, $J/\psi \rightarrow \mu^+\mu^-$
  - $\gamma\gamma$
  - hadrons
  - $D \bar{D}$
- Precision measurement of known states
- Find missing states (e.g. D states)
- Understand newly discovered states

Get a complete picture of the dynamics of the cc system.
Hybrids and Glueballs

The QCD spectrum is much richer than that of the quark model as the gluons can also act as hadron components.

**Glueballs** states of pure glue

**Hybrids** $q \bar{q} g$

- Spin-exotic quantum numbers $J^{PC}$ are powerful signature of gluonic hadrons.
- In the light meson spectrum exotic states overlap with conventional states.
- In the $c \bar{c}$ meson spectrum the density of states is lower and the exotics can be resolved unambiguously.
- $\pi_1(1400)$ and $\pi_1(1600)$ with $J^{PC}=1^{-+}$.
- $\pi_1(2000)$ and $h_2(1950)$
- Narrow state at 1500 MeV/c$^2$ seen by Crystal Barrel best candidate for glueball ground state ($J^{PC}=0^{++}$).
Gluon rich process creates gluonic excitation in a direct way

- $c \bar{c}$ requires the quarks to annihilate (no rearrangement)
- yield comparable to charmonium production
- even at low momenta large exotic content has been proven
- Exotic quantum numbers can only be achieved in production mode
Open Charm Physics

- New narrow states $D_{sJ}$ recently discovered at B factories do not fit theoretical calculations.
- At full luminosity at $\overline{p}$ momenta larger than 6.4 GeV/c PANDA will produce large numbers of $D\overline{D}$ pairs.
- Despite small signal/background ratio ($5 \times 10^{-6}$) background situation favourable because of limited phase space for additional hadrons in the same process.
An understanding of the baryon spectrum is one of the primary goals of non-perturbative QCD. In the nucleon sector, where most of the experimental information is available, the agreement with quark model predictions is astonishingly small, and the situation is even worse in the strange baryon sector.

- In $\bar{p}p$ collisions a large fraction of the inelastic cross section is associated to channels with a baryon-antibaryon pair in the final state.
- This opens up the opportunity for a comprehensive baryon spectroscopy program at PANDA.
- Example: $\bar{p}p \rightarrow \Xi\Xi$ cross section up to 2 $\mu$b, expect sizeable population of excited $\Xi$ states. In PANDA these excited states can be studied by analyzing their various decay modes e.g. $\Xi\pi$, $\Xi\pi\pi$, $\Lambda\bar{K}$, $\Sigma\bar{K}$, $\Xi\eta$ ...
- $\Omega$ baryons can also be studied, but cross sections lower by approximately two orders of magnitude.
In the quark picture hyperon pair production either involves the creation of a quark-antiquark pair or the knock out of such pairs out of the nucleon sea. Hence, the creation mechanism of quark-antiquark pairs and their arrangement to hadrons can be studied by measuring the reactions of the type $\bar{p}p \rightarrow \bar{Y}Y$, where Y denotes a hyperon. By comparing several reactions involving different quark flavours the OZI rule, and its possible violation, can be tested for different levels of disconnected quark-line diagrams separately. Furthermore the parity violating weak decay of most ground state hyperons introduces an asymmetry of the decay particles and gives access to spin degrees of freedom for these processes. A systematic investigation of these reactions will bring new information on single and multiple strangeness production and its dependence on spin observables.
Hadrons in Nuclear Matter

• Partial restoration of chiral symmetry in nuclear matter
  – Light quarks are sensitive to quark condensate
• Evidence for mass changes of pions and kaons has been deduced previously:
  – deeply bound pionic atoms
  – (anti)kaon yield and phase space distribution
• \( (c\bar{c}) \) states are sensitive to gluon condensate
  – small (5-10 MeV/c\(^2 \)) in medium modifications for low-lying \( (c\bar{c}) \) \( (J/\psi, \eta_c) \)
  – significant mass shifts for excited states:
    40, 100, 140 MeV/c\(^2 \) for \( \chi_{cJ}, \psi', \psi(3770) \) resp.
• D mesons are the QCD analog of the H-atom.
  – chiral symmetry to be studied on a single light quark
  – theoretical calculations disagree in size and sign of mass shift (50 MeV/c\(^2 \) attractive – 160 MeV/c\(^2 \) repulsive)

Hayaski, PLB 487 (2000) 96
Charmonium in Nuclei

- Measure $J/\psi$ and D production cross section in $p$ annihilation on a series of nuclear targets.
- $J/\psi$ nucleus dissociation cross section
- Lowering of the $D^+D^-$ mass would allow charmonium states to decay into this channel, thus resulting in a dramatic increase of width
  
  $\psi(1D) \ 20 \text{ MeV} \rightarrow 40 \text{ MeV}$
  $\psi(2S) \ 0.28 \text{ MeV} \rightarrow 2.7 \text{ MeV}$

$\Rightarrow$ Study relative changes of yield and width of the charmonium states.

- In medium mass reconstructed from dilepton ($c \bar{c}$) or hadronic decays (D)
Hypernuclear Physics

Hypernuclei, systems where one (or more) nucleon is replaced by one (or more) hyperon(s) \((Y)\), allow access to a whole set of nuclear states containing an extra degree of freedom: strangeness.

- Probe of nuclear structure and its possible modifications due to the hyperon.
- Test and define shell model parameters.
- Description in term of quantum field theories and EFT.
- Study of the \(YN\) and \(YY\) forces (single and double hypernuclei).
- Weak decays \(\Lambda \rightarrow \pi N\) suppressed, but \(\Lambda N \rightarrow NN\) and \(\Lambda \Lambda \rightarrow NN\) allowed \(\Rightarrow\) four-baryon weak interaction
- Hyperatoms
- Experimentally: in 50 years of study 35 single, 6 double hypernuclei established
Production of Double Hypernuclei

1. Hyperon-antihyperon production at threshold

2. Slowing down and capture of $E^-$ in secondary target nucleus

3. $\gamma$-spectroscopy with Ge-detectors
Nucleon Structure Using Electromagnetic Processes

• The electromagnetic form factors of the proton in the time-like region can be extracted from the cross section for the process:
  \( \bar{p}p \rightarrow e^+e^- \)
  – Moduli of form factors using angular distribution
  – Extend \( q^2 \) range
  – Improve accuracy of measurement

(talks by Yue Ma and Dmitry Khaneft on thursday)

• Hard Scattering Processes (\( \bar{p}p \rightarrow \gamma\gamma \))
  (test of factorization)

• Transverse parton distribution functions in Drell-Yan production.
Hard Scattering Processes and $\bar{p}p \rightarrow \gamma\gamma$

**Wide angle Compton scattering**

factorisation into hard amplitude
(calculable in perturbative QCD)
and soft amplitude
(information on parton distributions)

**Crossed Diagram**

$pp \rightarrow \gamma\gamma$

clear experimental signature
both baryons in ground state

$\sigma \approx 2.5 \text{pb} @ s \approx 10 \text{ GeV}^2$

$L = 2 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \rightarrow 10^3 \text{ events per month}$
Other Timelike Processes in PANDA

- $pp \rightarrow \gamma\gamma$
  - Handbag approach
  - Test of Factorisation

- $pp \rightarrow e^+e^-\gamma$
  - Determine TDA
    - (Transition Distribution Amplitude)
  - Measure FF in unphysical region
Physics Simulations
Sensitivity to $h_c$ Width Measurement

$$p\bar{p} \rightarrow h_c \rightarrow \eta_c + \gamma \rightarrow K^+K^-K^+K^-\gamma$$

$$\nu_i = [\varepsilon \times \int Ldt]_i \times [\sigma_{bkgd}(E) + \frac{\sigma_p \Gamma_R^2/4}{(2\pi)^{1/2}\sigma_i} \times \int \frac{e^{-(E-E')^2/2\sigma_i^2}}{(E' - M_R)^2 + \Gamma_R^2/4} dE']$$

Signal efficiency $\varepsilon = 0.24$

Each point corresponds to 5 days of data taking

Likelihood function:

$$\mathcal{L} = \prod_{j=1}^{N} \frac{\nu_j^{n_j} e^{-\nu_j}}{n_j!}.$$
Measurement of the $D_{s0}^{*}(2317)$ Width

inclusive $D_s(2317)$ reconstruction:

$$\bar{p}p \rightarrow D_s^\pm D_{s0}^{\mp\ast}(2317)$$

$$D_s^\pm \rightarrow \phi \pi^\pm, \phi \rightarrow K^+K^-$$

$$D_{s0}^{\ast}(2317) \rightarrow \text{anything:}$$

$\varepsilon_{\text{signal}}, \varepsilon_{\text{background}}, S/B$

The production cross section around threshold depends on the total width.

\[ \int Ldt = 126 \text{ pb}^{-1} \text{ (14 days)} \]

\[ S/B = 1/3 \]

\[ \Gamma = 1 \text{ MeV} \]

\[ m = 2317.30 \text{ MeV} / c^2 \]

\[ \Gamma = (1.16 \pm 0.30) \text{ MeV} \]

\[ m = (2317.41 \pm 0.53) \text{ MeV} / c^2 \]
Summary and Outlook

The HESR at the GSI FAIR facility will deliver $\bar{p}$ beams of unprecedented quality with momenta up to 15 GeV/c ($\sqrt{s} \approx 5.5$ GeV). This will allow PANDA to carry out the following measurements:

**SPECTROSCOPY**
- High-resolution charmonium spectroscopy in formation experiments
- Study of gluonic excitations (hybrids and glueballs) and other exotica (e.g. multiquark)
- Study of hadrons in nuclear matter
- Open charm physics
- Hypernuclear physics

**NUCLEON STRUCTURE**
- Proton Timelike Form Factors
- Crossed-Channel Compton Scattering
- Drell-Yan

The performance of the detector and the sensitivity to the various physics channels have been estimated reliably by means of detailed Monte Carlo simulations:
- Acceptance
- Resolution
- Signal/Background

The simulations show that the final states of interest can be detected with good efficiency and that the background situation is under control.