Hadron Physics

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Overview

The Panda Physics Program

Charmonium spectroscopy
Charmed hybrids and glueballs
Interaction of charmed particles with nuclei
(Double) Hypernuclei
Many further options

Detector Concepts for Panda

Conclusions
QCD running coupling constant

Transition from the quark-gluon to the hadronic degrees of freedom

\[ \lambda = \frac{\hbar}{\sqrt{Q^2}} \]

perturbative strong

QCD

transition from perturbative to non-perturbative regime

perturbative QCD

constituent quark

mesons and baryons

0 0.1 0.3 1

Rn

r [fm]

10 1 0.1 0.05 Q^2 [GeV^2]

K. Peters - Hadron Physics @ Panda
Objects of Interest

SU(3)_c Symmetry tells us that

\[ q^{3i+n}q^{3j+n}g^k \]

is color neutral

<table>
<thead>
<tr>
<th>Expression</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( i=1 \quad j,n,k=0 )</td>
<td>baryon (B=i-j)</td>
</tr>
<tr>
<td>( i,j,k=0 \quad n=1 )</td>
<td>meson</td>
</tr>
<tr>
<td>( i,j,n=0 \quad k&gt;1 )</td>
<td>glueball</td>
</tr>
<tr>
<td>( i,j=0 \quad n=1 \quad k&gt;0 )</td>
<td>meson hybrid</td>
</tr>
<tr>
<td>( i=1 \quad j,n=0 \quad k&gt;0 )</td>
<td>baryon hybrid</td>
</tr>
<tr>
<td>( i,n=1 \quad j,k=0 )</td>
<td>penta quark</td>
</tr>
<tr>
<td>( i,j,k=0 \quad n=2 )</td>
<td>four quark</td>
</tr>
<tr>
<td>( i,j,k=0 \quad n=3 / i,j=3 \quad k,n=0 )</td>
<td>baryonium (hexa quark)</td>
</tr>
</tbody>
</table>
Objects of Interest

- Quark
- AntiQuark

**Mesons/Baryons**

**Molecules/Multiquarks**

**Hybrids**

**Glueballs**

+ Effects due to the complicated QCD vacuum
Light Meson Spectrum

Each box corresponds to 4 nonets (2 for $L=0$)

- Radial excitations
- Exotic nonets
- Glueballs
- Hybrids

Lattice
- $1^{-+}$ 1.9 GeV
- $0^{++}$ 1.6 GeV

$q_\bar{q}$ Mesons

$L = 0, 1, 2, 3, 4$

($L = q\bar{q}$ angular momentum)
Level Mixing

Mixing (Light Quark)
- broad states
- high level density

Better:
- narrow states and/or
- lower level density
- charmed systems!

Experimental approach:
- Charm physics: Transition
  - chiral to heavy quark limits
- Proton-Antiproton:
  - rich hadronic source
Charmonium Physics

Open questions ...

\( \eta_c \) – inconsistencies
\( \eta_{c'} \) - \( \psi(2S) \) splitting
\( \chi_{1c} \) (\( ^1P_1 \)) unconfirmed
Peculiar decays of \( \psi(4040) \)
Terra incognita for any 2P and D-States

... Exclusive Channels

Helicity violation
G-Parity violation
Higher Fock state contributions
Charmonium Physics

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

**e^+e^- interactions:**
Only 1^-- states are formed
Other states only by secondary decays
(moderate mass resolution)

**p\bar{p} reactions:**
All states directly formed
(very good mass resolution)
small and well controlled beam momentum spread $\Delta p/p$ is extremely important
Charmonium Physics with $p\bar{p}$

Expect 1-2 fb$^{-1}$ (like CLEO-C)

\begin{align*}
& p\bar{p} (>5.5 \text{ GeV/c}) \rightarrow J/\psi & 10^7/d \\
& p\bar{p} (>5.5 \text{ GeV/c}) \rightarrow \chi_{c2} (\rightarrow J/\psi \gamma) & 10^5/d \\
& p\bar{p} (>5.5 \text{ GeV/c}) \rightarrow \eta_{c'} (\rightarrow \phi\phi) & 10^4/d \mid_{\text{rec.}?}
\end{align*}

Comparison of PANDA@HESR to E835

- Maximum energy 15 GeV/c instead of 9 GeV/c
- Luminosity 10x higher
- Detector with magnetic field – charged final states
- $\Delta p/p$ 10x better
- Dedicated machine with stable conditions
Charmed Hybrids

Gluonic excitations of the quark-antiquark-potential may lead to bound states.

**LQCD:**
- **Ω-potential** of excited gluon flux in addition to **Σ-potential** for one-gluon exchange
- $m_{Hc} \sim 4.2-4.5 \text{ GeV/c}^2$

Light charmed hybrids could be narrow if open charm decays are inaccessible or suppressed.

**important $\langle r^2 \rangle$ and $r_{Breakup}$**
Simplest Hybrids

S-Wave+Gluon \((q\bar{q})_8g\) with \((\_)_8=coloured\)

\[\begin{array}{c}
^{1}S_{0} \uparrow\downarrow \\
^{3}S_{1} \uparrow\uparrow
\end{array}\]
combined with a 1\(^{+}\) or 1\(^{-}\) gluon

<table>
<thead>
<tr>
<th>Gluon</th>
<th>1(^{-}) (TM)</th>
<th>1(^{+}) (TE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{1}S_{0}), 0(^{-})</td>
<td>1(^{++})</td>
<td>1(^{--})</td>
</tr>
<tr>
<td>(^{3}S_{1}), 1(^{-})</td>
<td>0(^{+-})</td>
<td>0(^{--})</td>
</tr>
</tbody>
</table>

Exotic J\(^{PC}\) cannot be formed by \(q\bar{q}\)
Charmed Hybrid Level Scheme

\[ 1^{-} (0,1,2)^{-} < 1^{++} (0,1,2)^{-} \]

JKM00, NPB83Suppl83(2000)304 and
Manke, PRD57(1998)3829

L-Splitting

\[ \Delta m \sim 100-250 \text{ MeV}/c^2 \]

for \( 1^{--} \) to \( 0^{+-} \)

S-Splittings

Page thesis, 1995 and
PRD35(1987)1668

4.14 \((0^{-+})\) to 4.52 GeV/c\(^2\) \((2^{-+})\)

consistent w/LQCD

JKM, NPB86suppl(2000)397,
PLB478(2000) 151
Charmed Hybrid Level Scheme

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consistent w/LQCD
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 formation yield 8:1 due to colour octet in hybrids
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\( c\bar{c} \) requires the quarks to annihilate (no rearrangement)
yield comparable to charmonium production
formation yield 8:1 due to colour octet in hybrids
Momentum range for a survey \( p\bar{p} \rightarrow \sim 15 \text{ GeV} \)
Exotics in Proton-Antiproton

Exotics are heavily produced in $p\bar{p}$ reactions

High production yields for exotic mesons (or with a large fraction of it)

$f_0(1500)\pi \rightarrow \sim 25 \%$ in $3\pi^0$
$f_0(1500)\pi \rightarrow \sim 25 \%$ in $2\eta\pi^0$
$\pi_1(1400)\pi \rightarrow >10 \%$ in $\pi^\pm\pi^0\eta$

Interference with other well known (conventional) states is mandatory for the phase analysis
Open charm discoveries

The $D_s^{\pm}$ Spectrum $|c_s\rangle + c.c.$ was not expected to reveal any surprises, but chiral and heavy quark aspects meet

- Potential model
- Old measurements
- New observations

Potential model
Old measurements
New observations

Events in peak

$D_{sJ}^*(2317)$ $D_{sJ}^*(2458)$ $D^0K$ $D^*K$ $D_s$ $D_s^*$ $D_{s1}$ $D_{s2}$

$D_{sJ}^*(2317)$ Combinatorial $D_s^{*+\gamma}$ $D_s^{*(2112)}$
Heavy Glueballs

Light gg/ggg-systems are complicated to identify (mixing!)

Exotic heavy glueballs

\[ m(0^{+-}) = 4140(50)(200) \text{ MeV} \]
\[ m(2^{+-}) = 4740(70)(230) \text{ MeV} \]

Width unknown, but!

nature invests more likely in mass than in momentum

newest proof: double \( c \bar{c} \) yield in \( e^+e^- \)

Flavour-blindness

predicts decays into charmed final states too

Same run period as hybrids

In addition: scan \( m > 2 \text{ GeV}/c^2 \)

Morningstar und Peardon, PRD60 (1999) 034509
Morningstar und Peardon, PRD56 (1997) 4043
Accessible $c \bar{c}$-Hadrons at PANDA @ HESR @ GSI

Two-body Thresholds
Molecules
Gluonic Excitation
$q \bar{q}$ Mesons

Other exotics with identical decay channels → same region
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

D-Mesons are the QCD analogue of the H-atom.
  chiral symmetry to be studied on a single light quark
The expected signal:
strong enhancement of the D-meson cross section,
relative \( D^+ \ D^- \) yields, in the near/sub-threshold region.

\[
\frac{\sigma_{pA}}{A\sigma_{pN}} (A) = ?
\]

Complementary to heavy ion collisions
Lowering of the $D^+D^-$ mass allow charmonium states to decay into this channel, thus resulting in a dramatic increase of width

- $\psi(1D)$: $\Gamma = 20 \rightarrow 40$ MeV
- $\psi(2S)$: $\Gamma = 0.32 \rightarrow 2.7$ MeV

Experiment:

**Dilepton-Channels and/or highly constrained hadronic channels**

Idea

Study relative changes of yield and width of the charmonium states.
$J/\psi$ Absorption in Nuclei

Important for the understanding of heavy ion collisions

Related to QGP
**J/ψ Absorption in Nuclei**

Important for the understanding of heavy ion collisions

Related to QGP

**Reaction**

\[ p + A \rightarrow J/\psi + (A-1) \]

**Fermi-smeared c\(\bar{c}\)-Production**

J/ψ, ψ’ or interference region selected by \(p\)-Momentum

Longitudinal und transverse Fermi-distribution is measurable
Hypernuclear physics
  3rd dimension of nuclear chart
  Focus: Double Hypernuclei

Inverted DVCS - WACS
  Measure dynamics of quarks and gluons in a hadron
  Handbag diagram – electromagnetic final states

Proton Formfactors at large $Q^2$
  $s$ up to $25 \text{ GeV}^2/c^4$

$D_{(S)}$-Physics
  Spectroscopy: Threshold production
  BR and decay dalitz plots with high statistics

CP-Violation in the D-Sector
The Antiproton Facility
Antiproton production similar to CERN,

**HESR = High Energy Storage Ring**

- Production rate $10^7$/sec
- $P_{\text{beam}} = 1.5 - 15$ GeV/c
- $N_{\text{stored}} = 5 \times 10^{10}$ p

**Gas-Jet/Pellet/Wire Target**

**High luminosity mode**
- Luminosity $= 2 \times 10^{32}$ cm$^{-2}$s$^{-1}$
- $\Delta p/p \sim 10^{-4}$ (stochastic cooling)

**High resolution mode**
- $\Delta p/p \sim 10^{-5}$ (electron cooling)
- Luminosity $= 10^{31}$ cm$^{-2}$s$^{-1}$
Proposed Detector (Overview)

High Rates
  Total $\sigma \sim 55$ mb
Vertexing
  ($\sigma_p, K_S, \Lambda, \ldots$)
Charged particle ID
  ($e^\pm, \mu^\pm, \pi^\pm, p, \ldots$)
Magnetic tracking
Elm. Calorimetry
  ($\gamma, \pi^0, \eta$)
Forward capabilities
  (leading particles)
Sophisticated Trigger(s)
Participating Institutes
(with Representative in the Coordination Board)

42 Institutes (35 Locations) from 9 Countries:

U Oriente, Alessandria  KVI Groningen
U Bochum  IKP Jülich I + II
U Bonn  U Katowice
U & INFN Brescia  U Mainz
U Catania  TU München
U Cracow  U Münster
GSI Darmstadt  BINP Novosibirsk
TU Dresden  U Pavia
JINR Dubna I + II  U of Silesia
U Edinburgh  U Stockholm
U Erlangen  U Torino
NWU Evanston  Politecnico di Torino
U & INFN Ferrara  U & INFN Trieste
U Frankfurt  U Tübingen
LNF-INFN Frascati  U & TSL Uppsala
U & INFN Genova  IMEP Vienna
U Glasgow  SINS Warsaw
U Gießen

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<table>
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<th>Topic</th>
<th>Competitor</th>
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<tr>
<td><strong>Confinement Charmonium</strong></td>
<td>all $c\bar{c}$ states with high resolution</td>
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<tr>
<td></td>
<td><em>CLEO-C</em> only $1^{--}$ states</td>
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<td><strong>Gluonic Excitations</strong></td>
<td>charmed hybrids</td>
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<tr>
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<td>heavy glueballs</td>
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<td><em>CLEO-C</em> light glueballs</td>
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<td></td>
<td><em>Hall-D</em> light hybrids</td>
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<tr>
<td><strong>Nuclear Interactions</strong></td>
<td>D-mass shift</td>
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<td></td>
<td>$J/\psi$ absorption ($T\sim 0$)</td>
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<tr>
<td></td>
<td><em>DaΦne</em> K-mass shift</td>
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<tr>
<td><strong>Hypernuclei</strong></td>
<td>$\gamma$-spectroscopy of $\Lambda$- and $\Lambda\Lambda$-hypernuclei</td>
</tr>
<tr>
<td></td>
<td><em>BNL</em> indirect evidence only</td>
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<td></td>
<td><em>JHF</em> single HN</td>
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<td><strong>Open Charm Physics</strong></td>
<td>Rare D-Decays</td>
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<td>CP-physics in Hadrons</td>
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<td><em>CLEO-C</em> rare D-Decays</td>
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<td>CP-physics in D-Mesons</td>
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<td><strong>ν,K-beams</strong></td>
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<td><em>JHF</em> rare K-Decays (?)</td>
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<td>neutrino physics</td>
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</table>
Why Antiprotons?

**high resolution** spectroscopy with \( p \)-beams in formation experiments:
\[
\Delta E \approx \Delta E_{\text{beam}}
\]

**high yields** of gluonic excitations in \( pp \)
  glueballs, charmed hybrids

**event tagging by** pair wise associated production,
  (particle, anti-particle) e.g. \( pp \rightarrow D \bar{D} \)

**large \( \sqrt{s} \) at low momentum transfer**
  important for in-medium "implantation" of hadrons:
  study of in-medium effects of charmed states
Summary & Outlook

Investigation of charmed hadrons and their interaction with matter is a mandatory task for the next decade.

The antiproton facility HESR @ GSI addresses many important questions.

A high performance storage ring and detector are envisaged to utilize a luminosity of $L=2 \cdot 10^{32} \text{ cm}^{-2}\text{s}^{-1}$. 