• The Antiproton Physics Program
  Charmonium spectroscopy
  Hybrids and glueballs
  Medium modification of hadrons
  Hypernuclei
  Hadron structure functions
  Proton e.m. form factors
• The PANDA Detector concept
GSI Future Facility

**Primary Beams**
- $^{238}\text{U}^{28+}$ 1.5 GeV/u; $10^{12}$/s ions/pulse
- 30 GeV protons; $2.5\times10^{13}$/s
- $^{238}\text{U}^{73+}$ up to 25 (- 35) GeV/u; $10^{10}$/s

**Secondary Beams**
- Broad range of radioactive beams up to 1.5 - 2 GeV/u
- Antiprotons 3 (0) - 30 GeV

**Storage and Cooler Rings**
- Radioactive beams
- $e - A$ collider
- $10^{11}$ stored and cooled $\bar{p}$ 0.8 - 14.5 GeV

**Key Technical Features**
- Cooled beams
- Rapidly cycling superconducting magnets
HESR - High Energy Storage Ring

- Production rate $2 \times 10^7$/sec
- $P_{\text{beam}} = 1 - 15 \text{ GeV/c}$
- $N_{\text{stored}} = 5 \times 10^{10}$

- Internal Target

High luminosity mode

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

High resolution mode

- $\delta p/p \sim 10^{-5}$ (electron cooling)
- Lumin. = $10^{31} \text{ cm}^{-2} \text{ s}^{-1}$
Charmonium (c̅c ) spectroscopy: precision measurements of mass, width, decay branches of all charmonium states, especially for extracting information on q̅q models of mesons.
Charmonium ($c\bar{c}$) spectroscopy: precision measurements of mass, width, decay branches of all charmonium states, especially for extracting information on $q\bar{q}$ models of mesons.

Search for gluonic excitations (charmed hybrids, glueballs) in the charmonium mass range ($3 - 5$ GeV/$c^2$).
Antiproton Physics Program

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Search for modifications of meson properties in the nuclear medium and their possible relationship to the partial restoration of chiral symmetry for light quarks.

Diagram:
- Pionic atoms
  - $\pi^-$, $\pi^0$, $\pi^+$
  - $25$ MeV
  - $100$ MeV
  - $50$ MeV

- Kaons
  - $K^+$, $K^-$
  - $100$ MeV

- Hyperons
  - $D^-$, $D^+$
  - $50$ MeV

Vacuum vs. nuclear medium: $\rho = \rho_0$
Charmonium (cc) spectroscopy: precision measurements of mass, width, decay branches of all charmonium states, especially for extracting information on quark models of mesons.

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D−50 MeV D+ vacuum vacuum nuclear medium

π 25 MeV K 100 MeV K+ K− π− π+

Precision γ-ray spectroscopy of single and double hypernuclei for extracting information on their structure and on the hyperon-nucleon and hyperon-hyperon interaction.

Trigger

3 GeV/c

secondary target

Ξ−(dss) p(uud) → Λ(uds) Λ(uds)
Antiproton Physics Program

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Inverted DVCS to extract parton distributions proton form-factors at large $Q^2$ up to 25 GeV$^2/c^4$. D-meson decay spectroscopy BR and decay dalitz plots, CP-Violation in the D/\Lambda sector.
Charmonium spectroscopy

Charmonium spectrum is becoming more clear...

- 5 new measurements of $\eta_c$ mass
Charmonium spectroscopy

Even on the ground state on the simplest parameters there are consistency problems...

Five new measurements published 2002-2003, four by $e^+e^-$ experiments
Charmonium spectroscopy

Charmonium spectrum is becoming more clear...

- 5 new measurements of $\eta_c$ mass
- $\eta_c'$ unambiguously seen
Charmonium spectroscopy

\[ \eta_c' \]

3637.7±4.4 MeV

New measurements of mass are consistent!

\[ \tau_{tot} = (19 \pm 10) \text{ MeV} \]
Charmonium spectroscopy

Charmonium spectrum is becoming more clear...

- 5 new measurements of $\eta_c$ mass
- $\eta_c'$ unambiguously seen

Open problems...
- $h_{1c}$ not confirmed
- States above $D\bar{D}$ thr. are not well established
### Charmonium spectroscopy

<table>
<thead>
<tr>
<th>Decay channels studied</th>
<th>Total BR seen (%)</th>
<th>Decay Channels With error &lt;30%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta_c$</td>
<td>20</td>
<td>26.1</td>
</tr>
<tr>
<td>$\eta'_c$</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>$J/\psi$</td>
<td>134</td>
<td>41.5</td>
</tr>
<tr>
<td>$\psi'$</td>
<td>51</td>
<td>48.0</td>
</tr>
<tr>
<td>$\chi_{c0}$</td>
<td>17</td>
<td>10.1</td>
</tr>
<tr>
<td>$\chi_{c1}$</td>
<td>12</td>
<td>4.0</td>
</tr>
<tr>
<td>$\chi_{c2}$</td>
<td>18</td>
<td>6.5</td>
</tr>
<tr>
<td>$h_c$</td>
<td>2</td>
<td>?</td>
</tr>
<tr>
<td>$\psi (3770)$</td>
<td>2</td>
<td>$\sim 0$</td>
</tr>
<tr>
<td>$\psi (4040)$</td>
<td>6</td>
<td>$\sim 0$</td>
</tr>
<tr>
<td>$\psi (4160)$</td>
<td>1</td>
<td>$\sim 0$</td>
</tr>
<tr>
<td>$\psi (4415)$</td>
<td>2</td>
<td>$\sim 0$</td>
</tr>
</tbody>
</table>
Charmonium Physics

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

- \( e^+e^- \) 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)

\[ \text{Br}(p\bar{p} \rightarrow \eta_c) = 1.2 \times 10^{-3} \]

\[ \text{Br}(e^+e^- \rightarrow \psi) \cdot \text{Br}(\psi \rightarrow \gamma \eta_c) = 2.5 \times 10^{-5} \]
Exotic hadrons

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

The “exotic hadrons” fall in 3 general categories:

- Multiquarks \((q\bar{q})(q\bar{q})\)
- Hybrids \((q\bar{q}) g\)
- Glueballs \(gg\)

In the light meson spectrum exotic states overlap with conventional states
Exotic hadrons

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The “exotic hadrons” fall in 3 general categories:

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- **Hybrids** \((q\bar{q})\ g\)
- **Glueballs** \(gg\)

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 therefore the overlap...
In the light meson region, about 10 states have been classified as “Exotics”. Almost all of them have been seen in $p\bar{p}$...

**TABLE 1. Main non-$q\bar{q}$ candidates**

<table>
<thead>
<tr>
<th>Particle</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_0(980)$</td>
<td>$4\bar{q}$ state</td>
</tr>
<tr>
<td>$f_0(1500)$</td>
<td>$0^+$ glueball candidate</td>
</tr>
<tr>
<td>$f_0(1720)$</td>
<td>$0^+$ glueball candidate</td>
</tr>
<tr>
<td>$\eta(1410)$, $\eta(1460)$</td>
<td>$0^-$ glueball candidate</td>
</tr>
<tr>
<td>$f_1(1410)$</td>
<td>hybrid, $4\bar{q}$ state</td>
</tr>
<tr>
<td>$\pi_1(1400)$</td>
<td>hybrid candidate</td>
</tr>
<tr>
<td>$\pi_1(1600)$</td>
<td>hybrid candidate</td>
</tr>
<tr>
<td>$\pi_1(1800)$</td>
<td>hybrid candidate</td>
</tr>
<tr>
<td>$\pi_1(2000)$</td>
<td>hybrid candidate</td>
</tr>
</tbody>
</table>
Exotic states are produced with rates similar to $q\bar{q}$ conventional systems

Even exotic quantum numbers can be reached $\sigma \sim 100 \text{ pb}$

All ordinary quantum numbers can be reached $\sigma \sim 1 \text{ \mu b}$
Glueballs

- Light gg/ggg-systems are complicated to be identified

- Oddballs: exotic heavy glueballs
  - $m(0^{+-}) = 4740(50)(200)$ MeV
  - $m(2^{+-}) = 4340(70)(230)$ MeV

- Width unknown, but!
  - nature invests more likely in mass than in momentum good prob. to see in charm channels

  - Same run period as hybrids

Morningstar und Peardon, PRD60 (1999) 034509
Morningstar und Peardon, PRD56 (1997) 4043
Recently, different experiments have reported evidences of an exotic baryon with $K^+n$ quantum numbers: $\Theta^+(1540)$; $\Gamma \sim 18$ MeV

\begin{align*}
\gamma n \rightarrow K^- (K^+n) & \quad \text{T.Nakano et al., Phys. Rev. Lett. 91, 012002 (2003).} \\
K^+Xe \rightarrow (K^0p)Xe' & \quad \text{V.V. Barmin et al., hep-ex/0304040.} \\
\gamma d \rightarrow (K^-p)(K^+n) & \quad \text{S. Stepanyan et al., hep-ex/0307018.}
\end{align*}

The $\Theta^+(1540)$ state cannot be a 3-quarks state. Its minimal quark content is $(uudds\bar{s})$

Theorists [R.Jaffe & F.Wilezek (hep-ph/0307341), M.Karliner & Lipkin (hep-ph/0307343)] predict charm and bottom analogues of the $\Theta^+(1540)$:

$\Theta_c^+$ with mass $2985 \pm 50$ MeV

$\bar{p}$ could be a good tool to search for multiquark states
Hadrons in nuclear matter

One of the fundamental questions of QCD is the generation of

MASS

The light hadron masses are larger than the sum of the constituent quark masses!

Spontaneous chiral symmetry breaking seems to play a decisive role in the mass generation of light hadrons.

How can we check this?
Hadrons in nuclear matter

Since density increase in nuclear matter is possible a partial restoration of chiral symmetry

- Light quarks are sensitive to quark condensate

Evidence for mass changes of pions and kaons has been observed

- Deeply bound pionic atoms
- Kaon-production environments

\[ f^*_\pi = 0.78 f_\pi \]
**Hadrons in nuclear matter**

With \( \bar{p} \) beam up to 15GeV/c these studies will be extended

Subthreshold enhancement for D and \( \bar{D} \) meson production

expected signal:

- strong enhancement of the D-meson cross section, relative \( D^+ D^- \) yields, in the near/sub-threshold region.

Mass modifications of mesons

- **pionic atoms**
  - \( \pi^- \)\( \pi^+ \) 25 MeV

- **KAOS/FOPI**
  - \( K^+ \) 100 MeV
  - \( K^- \) 100 MeV

- **HESR**
  - \( D^- \) 50 MeV
  - \( D^+ \) 50 MeV

Hadrons in nuclear matter

\[
\sigma_{pp \rightarrow D^+ D^-}(\text{nb})
\]

in-medium

free masses

\( T \) (GeV)
Hadrons in nuclear matter

- The lowering of the D$\bar{D}$ thresh.
  - allow $\Psi, \chi_{c2}$ charmonium states to decay into this channel
  - states above D$\bar{D}$ thresh. would have larger width

- Idea
  - Study relative changes of yield and width of the charmonium state $\Psi(3770)$.
  - BR into $l^+l^-$ ($10^{-5}$ in free space)

**J/ψ Absorption in Nuclei**

- Important for the understanding of heavy ion collisions
  - Related to QGP
- Reaction
  - \( \bar{p} + A \rightarrow J/\psi + (A-1) \rightarrow e^+e^- \)
- A complete set of measurements could be done
  - \( J/\psi, \psi', \chi_J \) on different nuclear target
  - Longitudinal and transverse Fermi-distribution is measurable
Hypernuclear Physics

- Use $p\bar{p}$ interaction to produce a hyperon “beam” ($t\sim10^{-10}$ s) which is tagged by the antihyperon or its decay products.

-quark-gluon string model

(Kaidalov & Volkovitsky)
1. Hyperon-antihyperon production at threshold

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

3. $\gamma$-spectroscopy with Ge-detectors

Production of Double Hypernuclei

$\Xi^-(dss) p(uud) \rightarrow \Lambda(uds) \Lambda(uds)$

+28 MeV

$\bar{p}$ 3 GeV/c
Expected Counting Rate

- Ingredients (golden events)
  - luminosity $2 \cdot 10^{32} \text{ cm}^{-2}\text{s}^{-1}$
  - $\Xi^+\Xi^-$ cross section $2 \mu\text{b}$ for $p\bar{p}$
  - $p (100-500 \text{ MeV/c})$
  - $\Xi^+$ reconstruction probability $0.5$
  - stopping and capture probability
  - total captured $\Xi^-$
  - $\Xi^-$ to $\Lambda\Lambda$-nucleus conversion probability $p_{\Lambda\Lambda} \approx 0.05$
  - total $\Lambda\Lambda$ hypernucleus production $4500 / \text{month}$
  - gamma emission/event, $p_\gamma \approx 0.5$
  - $\gamma$-ray peak efficiency $p_{\text{GE}} \approx 0.1$

- $\sim 7 / \text{day} \ "\text{golden" \ } \gamma$-ray events ($\Xi^+$ trigger)
- $\sim 700 / \text{day} \ with \ KK \ trigger$

high resolution $\gamma$-spectroscopy of double hypernuclei will be feasible
Other physics topics...

- Reversed Deeply Virtual Compton Scattering

- CP-violation (D/Λ – sector)
  - D⁰D̄⁰ mixing
    SM prediction < 10⁻⁸
  - compare angular decay
    asymmetries for ΛΛ
    SM prediction ~ 2·10⁻⁵

- Rare D-decays:
  D⁺→μ⁺ν (BR 10⁻⁴)

Cross section σ ≈ 2.5pb @ s ≈ 10 GeV²
L = 2•10³² cm⁻² s⁻¹ → 10³ events per month
Other physics topics...

- Transverse quark distributions and Drell-Yan processes

  The idea is to study the reaction

  \[ \bar{p} \ N \rightarrow \mu^+ \ \mu^- \]

  to probe transverse spin of quarks. The goal is to measure the asymmetry in the transverse plane of the emission of the di-lepton pair.

- Electromagnetic Form Factors of the proton in the timelike region at very high \( Q^2 \)

  From the measurements of the total and differential cross section of the process

  \[ \bar{p} \ p \rightarrow e^+ \ e^- \]

  \( G_E \) and \( G_M \) will be measured.
QCD systems to be studied at HESR/
## HESR (Expected Counting Rates)

One year of data taking ≈ 1-2(fb)$^{-1}$

<table>
<thead>
<tr>
<th>Final state</th>
<th>Cross section</th>
<th># rec. events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meson resonance + anything</td>
<td>100μb</td>
<td>$10^{10}$</td>
</tr>
<tr>
<td>$\Lambda\overline{\Lambda}$</td>
<td>50μb</td>
<td>$10^{10}$</td>
</tr>
<tr>
<td>$\Xi\Xi$</td>
<td>2μb</td>
<td>$10^{8}$</td>
</tr>
<tr>
<td>$\overline{D}D$</td>
<td>250nb</td>
<td>$10^{7}$</td>
</tr>
<tr>
<td>$J/\psi(\rightarrow e^+e^-, \mu^+\mu^-)$</td>
<td>630nb</td>
<td>$10^{9}$</td>
</tr>
<tr>
<td>$\chi_2(\rightarrow J/\psi\gamma)$</td>
<td>3.7nb</td>
<td>$10^{7}$</td>
</tr>
<tr>
<td>$\Lambda_c\overline{\Lambda}_c$</td>
<td>20nb</td>
<td>$10^{7}$</td>
</tr>
<tr>
<td>$\Omega_c\overline{\Omega}_c$</td>
<td>0.1nb</td>
<td>$10^{5}$</td>
</tr>
</tbody>
</table>
## Competition

**BES, BNL, CLEO-C, Daφne, Hall-D, JHF**

<table>
<thead>
<tr>
<th>Topic</th>
<th>Competitor</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Confinement Charmonium</strong></td>
<td><em>CLEO-C</em> only 1-- states formed</td>
</tr>
<tr>
<td>all c(\bar{c}) states</td>
<td></td>
</tr>
<tr>
<td>with high resolution</td>
<td></td>
</tr>
<tr>
<td><strong>Gluonic Excitations</strong></td>
<td><em>CLEO-C</em> light glueballs</td>
</tr>
<tr>
<td>charmed hybrids</td>
<td></td>
</tr>
<tr>
<td>heavy glueballs</td>
<td><em>Hall-D</em> light hybrids</td>
</tr>
<tr>
<td><strong>Nuclear Interactions</strong></td>
<td><em>BNL</em> indirect evidence only</td>
</tr>
<tr>
<td>D-mass shift</td>
<td></td>
</tr>
<tr>
<td>J/(\psi) absorption (T~0)</td>
<td></td>
</tr>
<tr>
<td><strong>Hypernuclei</strong></td>
<td><em>JHF</em> single HN</td>
</tr>
<tr>
<td>(\gamma)-spectroscopy of</td>
<td><em>Daφne</em></td>
</tr>
<tr>
<td>(\Lambda)- and (\Lambda\Lambda)-hyperfine</td>
<td></td>
</tr>
<tr>
<td><strong>Open Charm Physics</strong></td>
<td><em>CLEO-C</em> rare D-Decays</td>
</tr>
<tr>
<td>Rare D-Decays</td>
<td></td>
</tr>
<tr>
<td>CP-physics in Hadrons</td>
<td></td>
</tr>
<tr>
<td>CP-physics in D-Mesons</td>
<td></td>
</tr>
</tbody>
</table>
Detector requests:

- nearly $4\pi$ solid angle (partial wave analysis)
- high rate capability ($2 \times 10^7$ annihilations/s)
- good PID ($\gamma, e, \mu, \pi, K, p$)
- momentum resolution ($\sim 1\%$)
- vertex info for $D, K^0_s, \Lambda$ ($c_\tau = 317\; \mu m$ for $D^\pm$)
- efficient trigger ($e, \mu, K, D, \Lambda$)
- modular design (Hypernuclei experiments)
PANDA Detector
PANDA Collaboration

• At present a group of **150 physicists** from **40 institutions of 9 Countries.**


Spokesperson: Ulrich Wiedner – Uppsala
Deputy: Paola Gianotti - LNF

http://www.gsi.de/hesr/panda
Conclusions

Thanks to the new GSI HESR facility
$\bar{p}$ will be used to produce...

high resolution spectroscopy with $\bar{p}$-beam in formation experiments:
$\Delta E \approx \Delta E_{\text{beam}}$

high yields of gluonic excitations: glueballs, hybrids, multi-quark states
$\sigma \approx 100 \text{ pb}$

partial chiral symmetry restoration by implanting mesons inside the nuclear medium

hyperon-antihyperon taggable beams

Structure function studies

Proton f.f. at high $Q^2$