The Antiproton Project at GSI

- Introduction
- Status of Physics with Antiprotons
- The Antiproton Facility at GSI (HESR)
- Physics
    - Charmonium Spectroscopy
    - Search for charmed Hybrids and Glueballs
    - Experiments with open charm particles
    - Antiproton-Nucleus interactions
    - Further possibilities
- Conclusions

Introduction

HESR = High Energy Storage Ring $(E_{\bar{p}} \leq 15 GeV)$

Fixed Target Machine $\rightarrow E_{CM} \lesssim 5.5\ GeV$

$\bar{p}$ – Momenta : $1.5 - 15.0\ GeV/c$

Luminosity : $2x10^{32} cm^{-2} s^{-1}$

$\frac{\Delta p}{p}$: $\geq 10^{-4}$ $(\geq 10^{-5}$ for electron cooling, $E_{\bar{p}} \leq 8\ GeV/c)$

Measuring Program

Non perturbative QCD-effects (Emphasis on Charm sector)

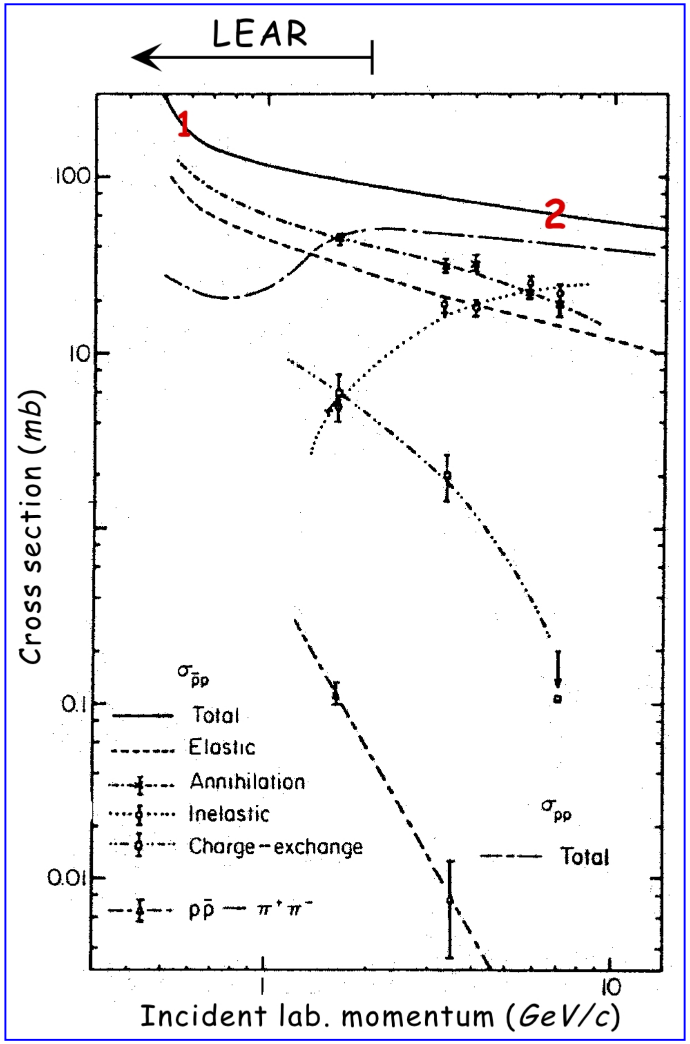
— Effective hadron masses in matter

— Quark Confinement ($Q\bar{Q}$-potential, ...)

— Gluonic Hadrons (Hybrids, Glueballs)

— CP-violation

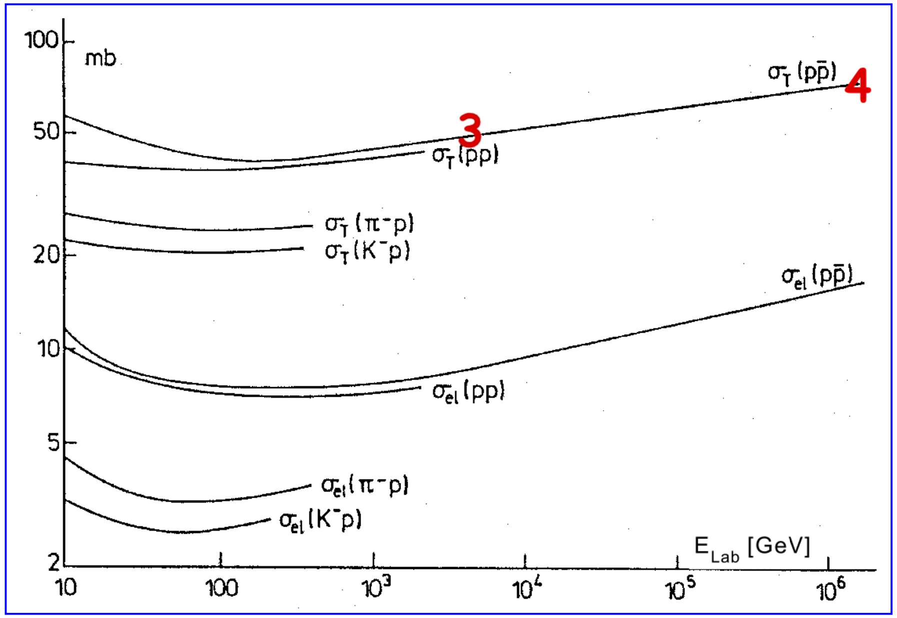
Physics with Antiprotons (1)



Low and medium energy antiprotons

① $\bar{p}p$-atoms as initial state
Final states: Only Annihilation (2π, 3π, $\rho\pi$, $f_2\pi$, ...)

② Precision measurements in the $c\bar{c}$-system
Rare process (*nb*)



High energy antiprotons (SPSC, Tevatron)

③ Discovery of $W^{\pm}$, Z^0
Rare Process (*nb*): Drell-Yan-Production

④ Discovery of *t*-quark
Rare process (*pb*): Pair ($t\bar{t}$)-Production

Physics with Antiprotons (2)

Recent Discoveries using $\overline{p}$ -beams

- Top Quark (Fermi Lab)
- $W^{\pm}, Z^{0}$ (CERN)
- High precision charmonium spectroscopy (Fermi Lab)
  - Masses and (partial) widths of χ, η_c - states
  - $\alpha_s(m_c)$
  - Multipole Structure of χ_1, χ_2 - states
- LEAR-Results (CERN)
  - Trapped Antiprotons ($m_{\overline{p}} / m_p$, Antihydrogen (AD))
  - T/CP/CPT-Tests
  - Meson/Exotics-Spectroscopy (Light Quark Sector)
    - Candidate for Glueball ground state ($f_0(1500)$)
    - Two resonances with exotic quantum numbers $J^{PC} = 1^{-+}$

Physics with Antiprotons (3)

e^+e^-- collisions:

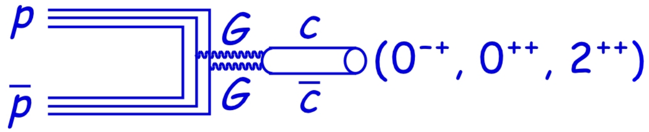
Only 1^{--}-states are directly formed
(Well measured, e^-e^+ energy scans)

The other states only visible through secondary reactions,

e.g.: $e^+e^- \to \psi' \to \chi + \gamma$ (moderate mass resolution)

$p\bar{p}$ - collisions:

All states can be directly formed (Very good mass resolution, scans with $\bar{p}$)



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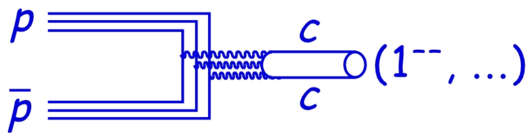
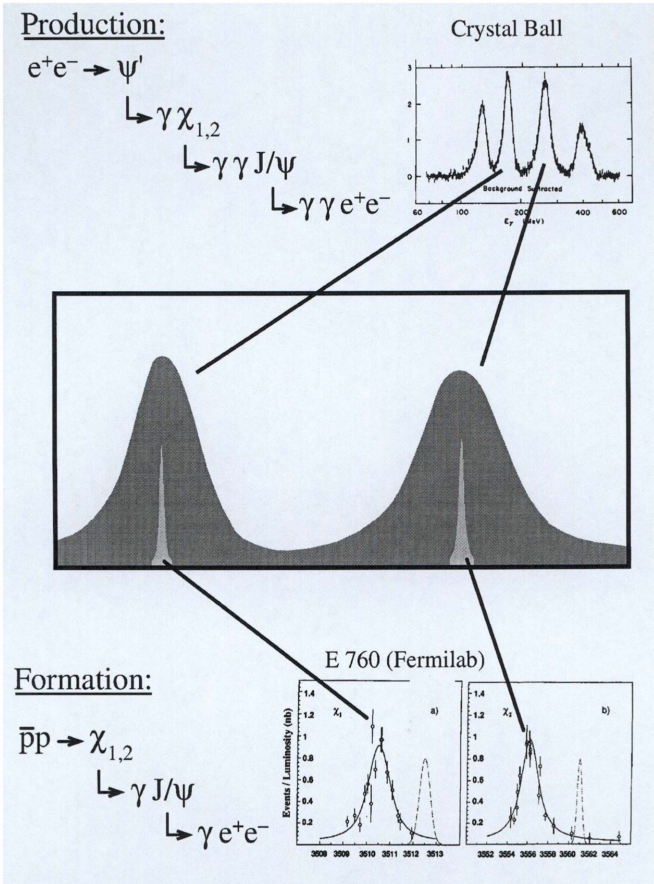
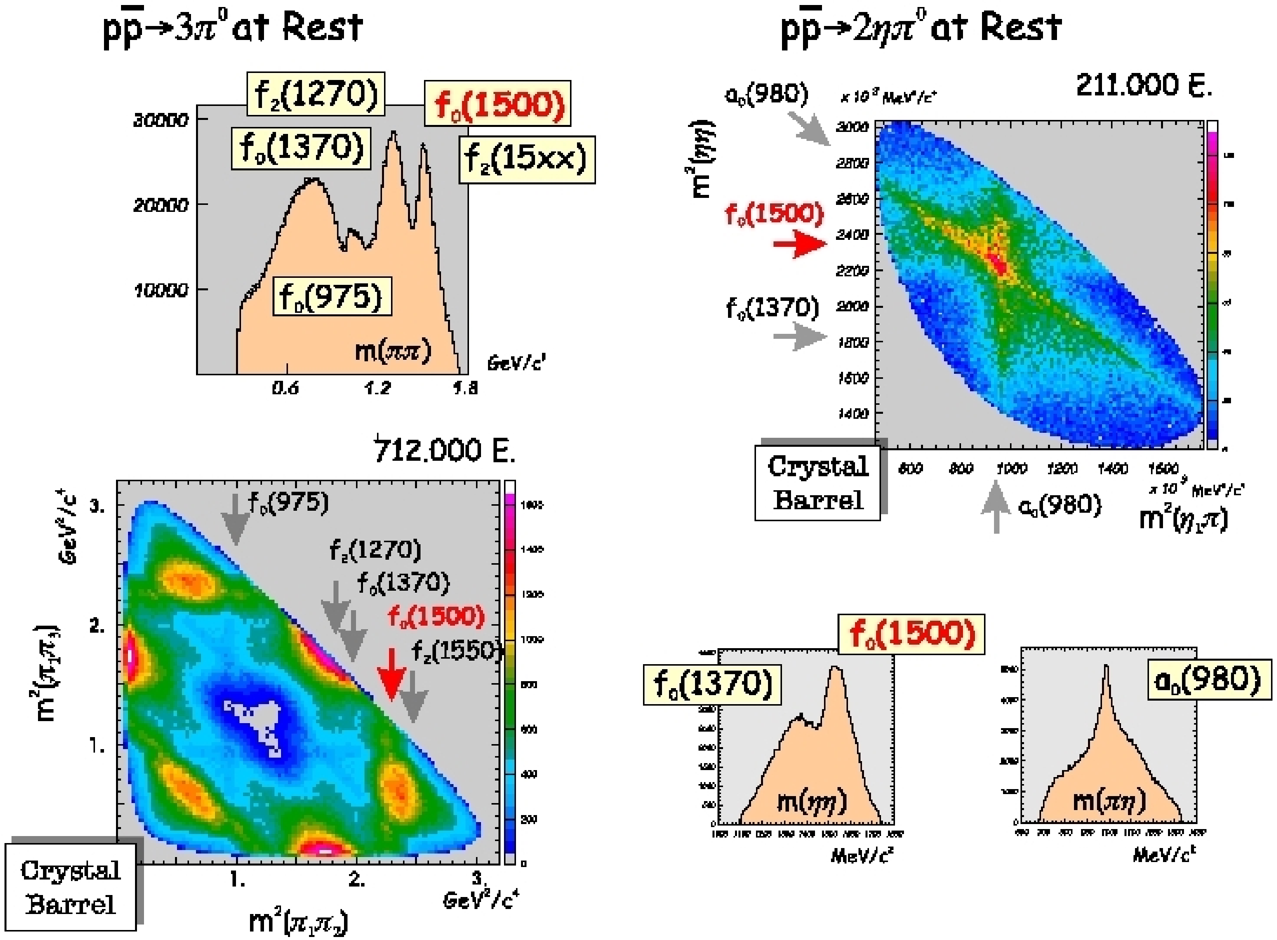




Physics with Antiprotons (4)

LEAR: Candidate for Glueball Groundstate



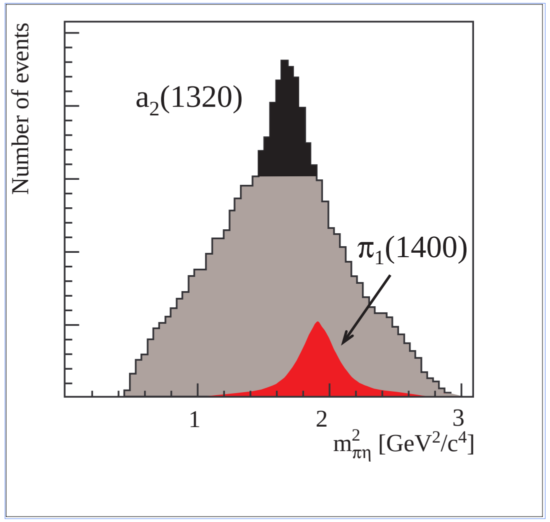
Physics with Antiprotons (5)

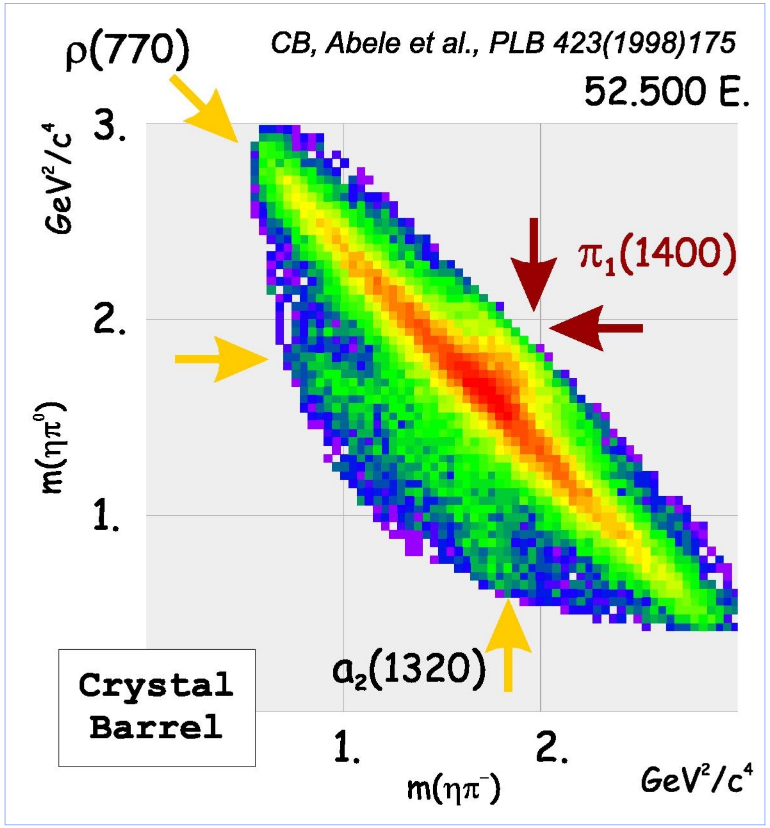
LEAR: Spin Exotics

$\bar{p}_{Stop}\, d \rightarrow X(1^{-+}) + \pi + p,\ X(1400) \rightarrow \eta\pi^0, \eta\pi^-;\ X(1600) \rightarrow \pi\eta'$ (Firstly seen by VES, GAMS, BNL)

General observations

- High Statistics data needed
- Exotics couple to $\bar{p}p$ with a strength similar to $q\bar{q}$-states





Physics with Antiprotons (6)

Merits of Antiprotons

— High cross sections

↳Facilitates search for rare particles

— Most particles can be directly created in formation processes regardless of their J^{PC} quantum numbers

— $\bar{p}$ -induced reactions ($\lesssim$ 15 *GeV*) have low particle multiplities

↳Reconstruction of full events, Reliable PWA

— Exotic states are produced with rates similar to $\bar{q}q$, qqq-systems

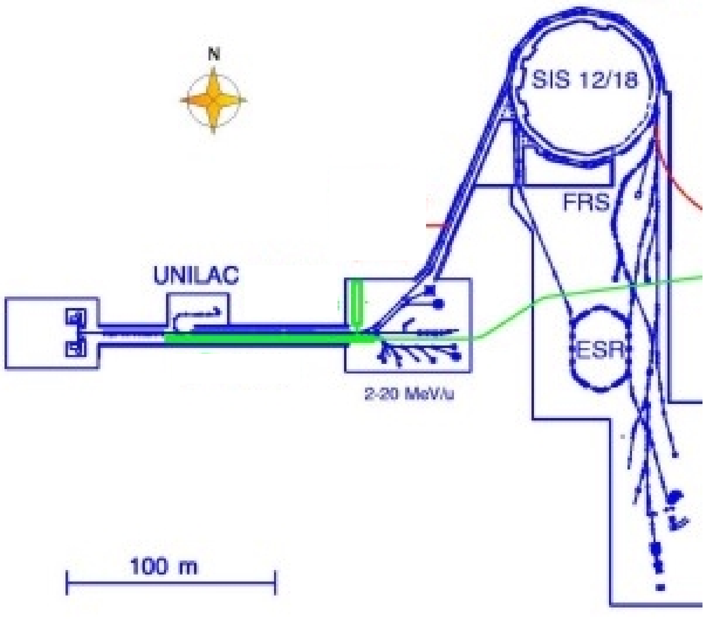
— (Cooled) beams have small $\Delta p/p$ and small emittances

↳Clean experimental conditions

GSI (Present Status)

GSI = Gesellschaft für Schwerionenforschung/Darmstadt/Germany

Today



Since 1969:

- Superheavy Elements
- Exotic nuclei, far from stability line
- Hot and dense nuclear matter
- QED tests
- Hadronic masses in nuclear matter
  - Deeply bound pionic atoms
  - Effective K^+, K^-- masses in nuclear matter

GSI (Future Plans)

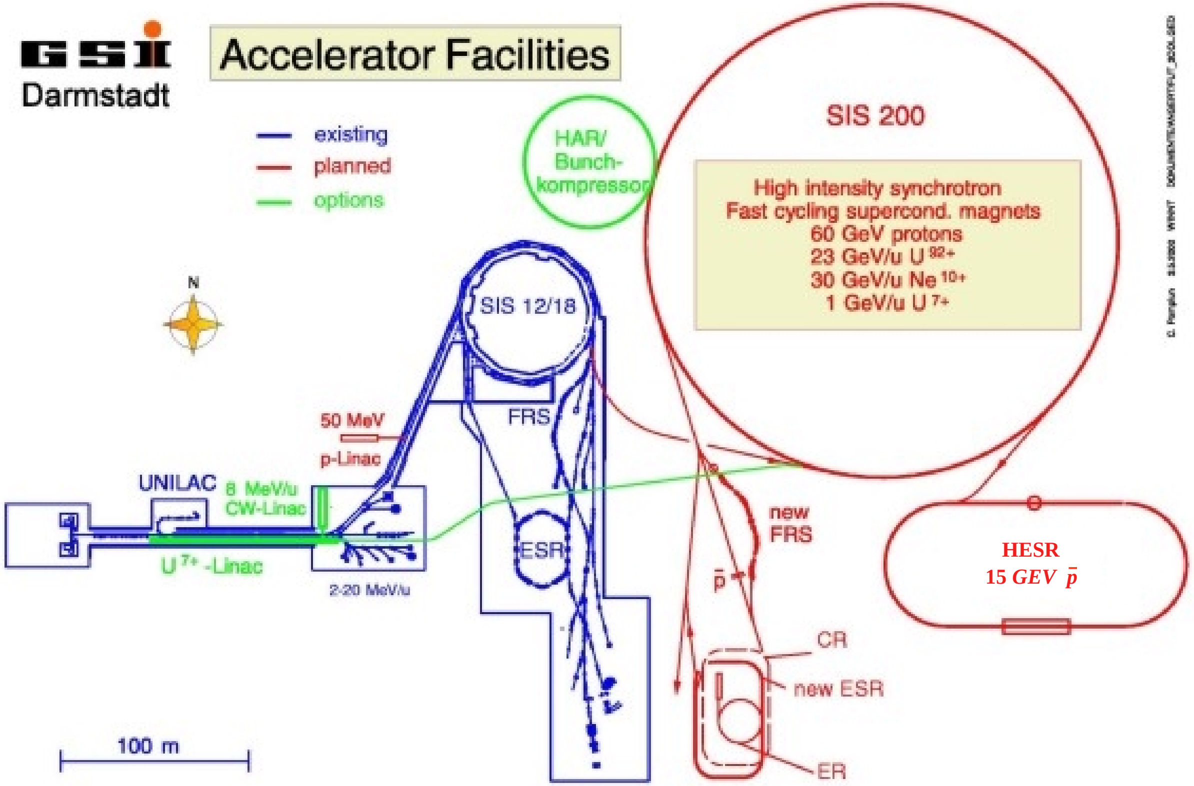
Future

— Rare isotope physics

— Plasma physics

— Hadronic matter at highest baryon densities

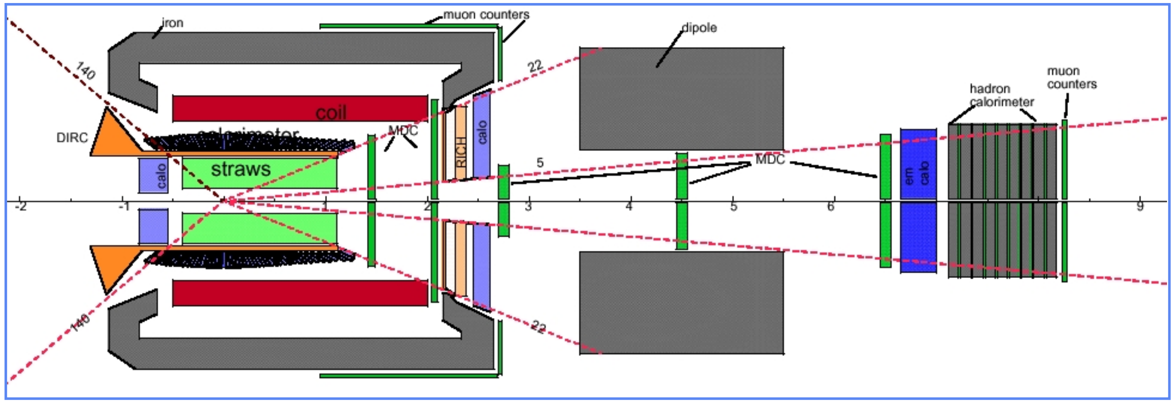
— Cooled antiproton beams ($E \leq 15\ GeV$)



The Antiproton Facility at GSI

Detector requests

- Nearly full solid angle for charged particles and Gammas
- High rate capability
- Good particle identification (e, μ, π, K, p)
- Efficient trigger on e, μ, K, D

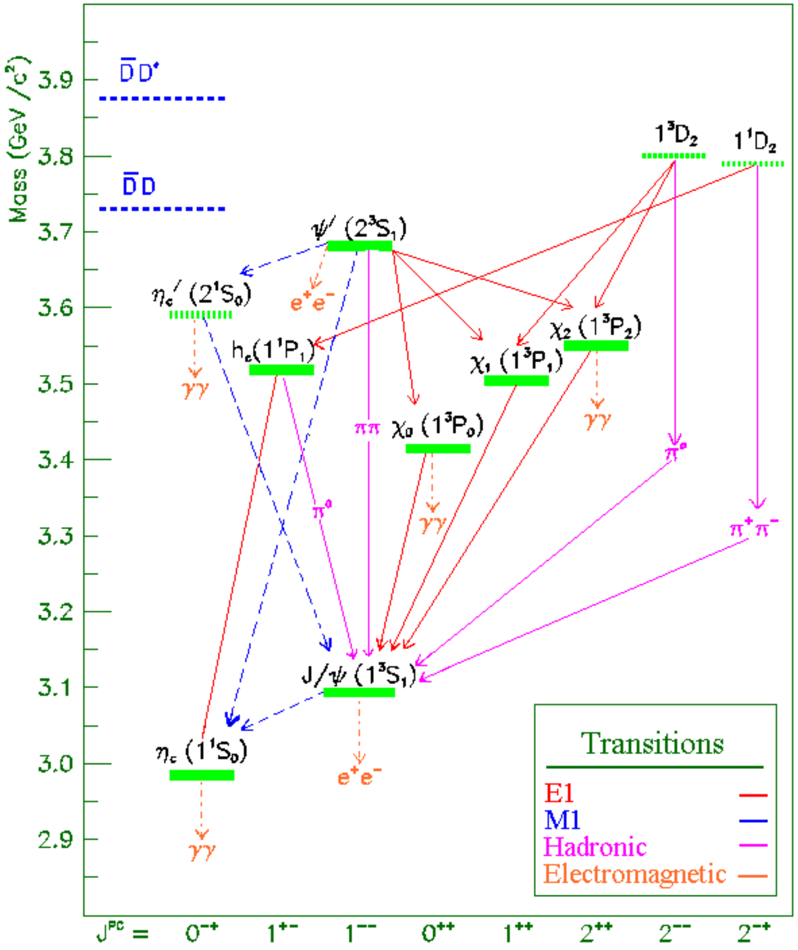


General purpose detector

- Target: Jet/Pellet/Wire
- Tracking: Pixels (MVD) / Straws / Mini-Drift-Chambers (MDC)
- E.M. Calorimeter: $PbWO_4$, APD-Readout
- Muons: Plastic Scint. Strips
- PID: Aerogel Cerenkov (ACC) / DIRC
- Trigger: High $p_\perp$ electrons/muons / Multiplicity jump (K^0_S, Λ, ...) / Secondary vertex (D's,...)
  Invariant masses / Global kinematical conditions

Charmonium Spectroscopy (1)

$c\bar{c}$ - system (QCD) $\hat{=}$ e^+e^--system (QED)



Energies/Energy splittings/Widths of states

↳Details of $Q\bar{Q}$ -interactions

Exclusive Decays

↳Mixing of perturbative/non-pert. effects

Charmonium Spectroscopy (2)

Experimental situation

R704 (CERN/ISR) / E 760/835 (Fermilab)

↳ Discovery of h_c ($^1P_1$) - state

Very precise values for masses and widths of χ_c, η_c-states

Measurement of previously unknown decay channels

But: Severe limitations (Non magnetic detector, beamtime, beam momentum reproducibility,…)

Many questions left open:

- η_c' not yet established (Spin-Spin-Interaction)
- Properties of $^1P_1$ still poorly known
- D-wave states (some of them very narrow) and radially excited P-states above $D\bar{D}$ -threshold not found yet
- Angular distributions of radiative decays of χ-states not fully understood (Structure of states)
- Rates of exclusive ($c\bar{c}$)- decays not understood,
  e.g. $J/\psi \to \rho\pi, \pi^+\pi^-, \omega\pi^0, \rho\eta$ / $\psi' \to \gamma + \pi, \eta$ / $\chi_J \to \rho\rho, \phi\phi, \rho\eta$
  (Mixing of pert./non-pert. effects)

Charmonium Spectroscopy (3)

Measuring program at HESR

Expected rates:

$$\bar{p}(\geq 5.5 GeV/c)p \rightarrow J/\psi(\rightarrow e^+e^-,\ \mu^+\mu^-)\ (0.6\mu b) \approx 10^7\ /\text{day} \approx 10^6\ /\text{day} \quad \text{reconstr.}$$

$$\bar{p}(\geq 5.5 GeV/c)p \rightarrow \chi_2(\rightarrow J/\psi + \gamma)\ (3.7 nb) \approx 10^5\ /\text{day} \approx 10^4\ /\text{day} \quad \text{reconstr.}$$

Scans in the energy regions of interest in steps of 10-1 MeV

Parallel search for decays in $e^+e^-, \mu^+\mu^-, \gamma\gamma, \phi\phi, \ldots$

Search for Charmed Hybrids (1)

Charmed Hybrids: $(c\bar{c}g)$

Predictions:

Masses (LQCD, Bag-Model, Flux-Tube-Model,...)

Lowest energy states: 3.9-4.5 GeV/c^2

Quantum numbers

Lowest energy states: $J^{PC} = 2^{\pm\mp}, 1^{\pm\mp}, 1^{\pm\pm}, 0^{\pm\mp}$

(3 spin-exotic)

Ground state: $J^{PC} = 1^{-+}$ (spin-exotic)

Widths

Could be narrow in some cases (~MeV), e.g

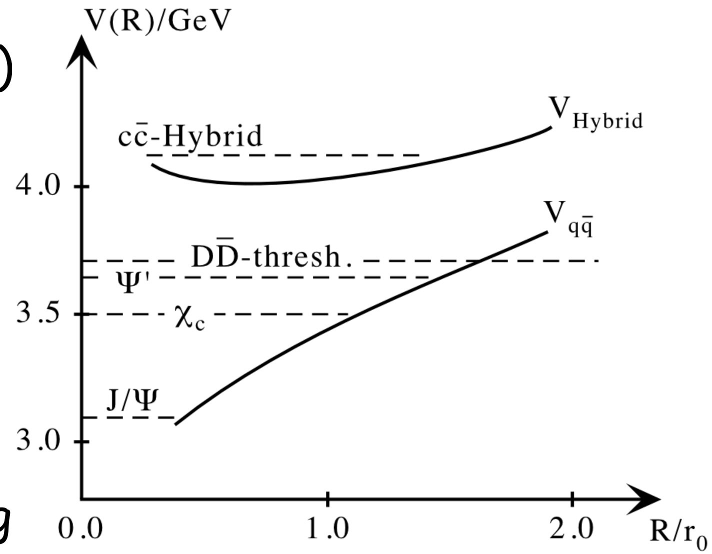
$0^{+-} \not\to \bar{D}D, \bar{D}^* D^*, \bar{D}_S D_S$ (CP– Inv.)

$(Q\bar{Q}g) \not\to (\bar{Q}q)_{L=0} + (Q\bar{q})_{L=0}$ (Dynam. Sel. Rule)

$(Q\bar{Q}g) \to (\bar{Q}q)_{L=0} + (Q\bar{q})_{L=1}$ (First allowed Decay; Th. $\approx 4.3\, GeV/c^2$)

Favorite decays, if $D\bar{D}$ forbidden:

$(c\bar{c}g) \to (c\bar{c}) + \cdots$, e.g. $1^{-+} \to J/\psi + \omega, \phi, \gamma$



Search for Charmed Hybrids (2)

Measuring program at HESR

States with non exotic *q.-n.*:

$\bar{p}$ -scan: $\bar{p}p \rightarrow (c\bar{c}g)$ (3.9 - 4.3 GeV/c^2 ; J/ψ-trigger)

$\bar{p}p \rightarrow (c\bar{c}g)$ (4.3 - 5.0 GeV/c^2 ; D-trigger),

$\approx 10^4 (c\bar{c}g) \rightarrow J/\psi + \eta$ per day (Decay channel selects *q.-n.*)

States with exotic *q.-n.*:

Production experiment: $\bar{p}p \rightarrow (c\bar{c}g) + \pi^0(\eta)$

$\hookrightarrow J/\psi + \omega, \phi, \gamma$

$\approx 10^2 (c\bar{c}g)$ per day, PWA of Dalitz-Plots (see LEAR)

In addition: Measuring program on light hybrids ≈ 2 GeV/c^2, Scan- and production mode

Favorite channels: $\bar{p}p \rightarrow (c\bar{c}g) \rightarrow f_1(1285)\pi, K_1\bar{K}, \ldots$

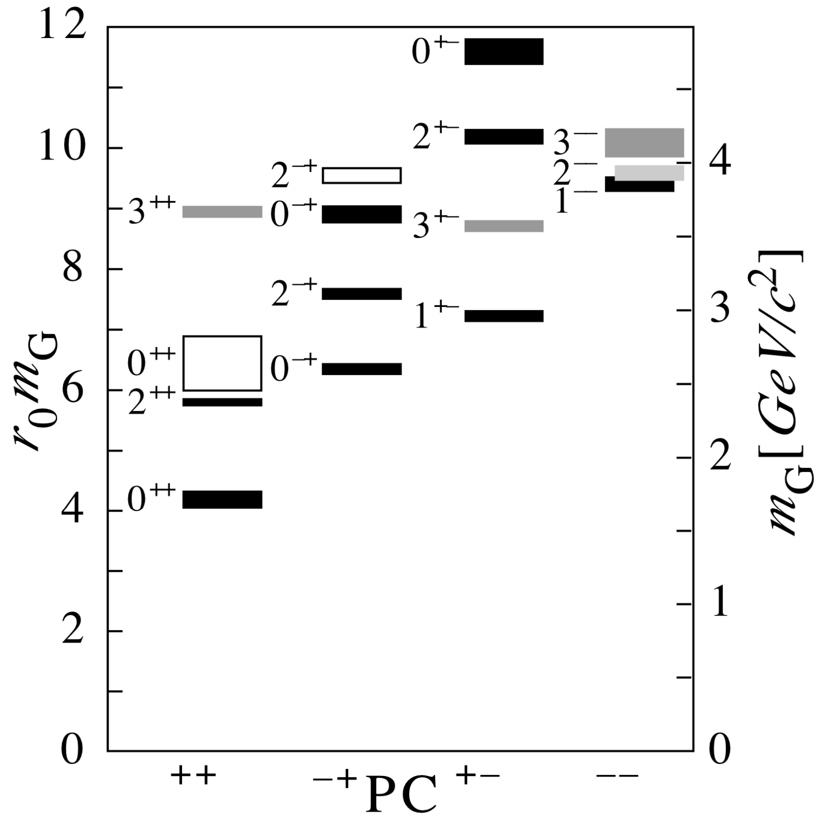
Large cross sections (μb)

Search for Glueballs (1)

Glueballs (*gg*)

Predictions:

- Masses:
  - 1.5-5.0 GeV/c^2 (Ground state found? ; Candidates for further states?)
- Quantum numbers:
  - Several spin exotics (oddballs), e.g. $J^{PC} = 2^{+-}$ (4.3 GeV/c^2)
- Widths: ≥ 100 MeV/c^2
  - — Decay into two lighter glueballs often forbidden because of q.-n.
  - — No mixing effects for oddballs

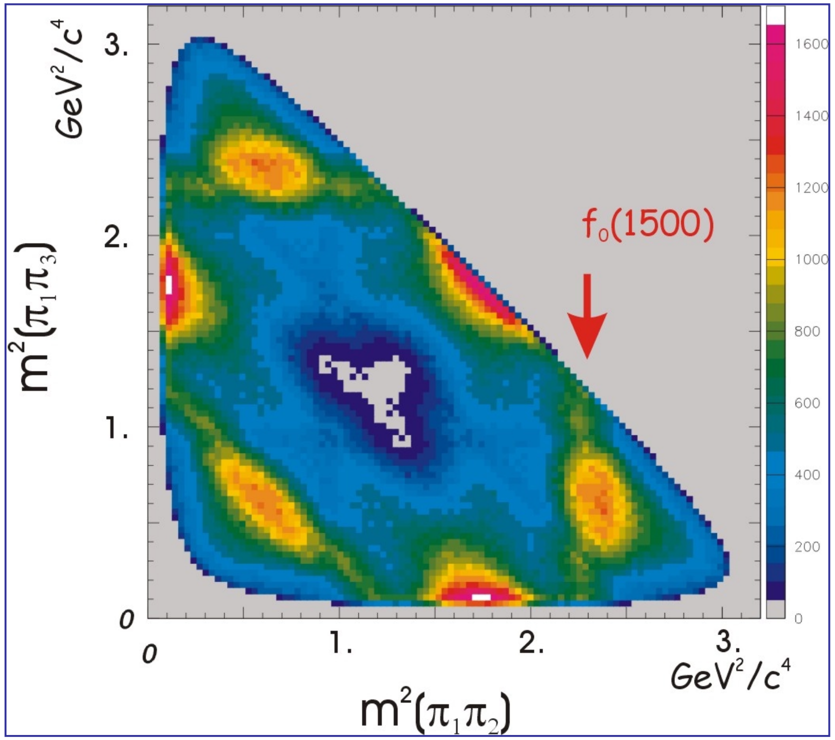


Search for Glueballs (2)

Production cross section:

Maybe high in $\bar{p}p$-annihilation (see $f_0(1500)$)

Comparable to $q\bar{q}$-systems (! μb)



Experimental program at HESR

$\bar{p}$ -scan for non-exotics: $\bar{p}p \to (gg) \to \phi\phi, \phi\eta$

(Most reasonable channels, easily distinguishable, low ℓ - waves (simple PWA))

Production exp. for exotics: $\bar{p}p \to (gg) + \pi$

Reasonable measuring times

Experiments with open Charm/Strangeness (1)

HESR

$\bar{p}(\geq 6.5\,GeV/c)p \rightarrow D\bar{D}(250nb) \approx 10^9$ /year $\approx 10^7$ /year reconstr. $\approx \tau/c$ – Factory

$\bar{p}(\geq 10.1\,GeV/c)p \rightarrow \Lambda_c\bar{\Lambda}_c(20nb) \approx 10^8$ /year $\approx 10^7$ /year reconstr.

$\bar{p}(\geq 14.1\,GeV/c)p \rightarrow \Omega_c\bar{\Omega}_c(0.1nb) \approx 10^6$ /year $\approx 10^5$ /year reconstr.

$\bar{p}(1.65\,GeV/c)p \rightarrow \Lambda\bar{\Lambda}(65\mu b) \approx 3x10^{11}$ /year $\approx 10^{10}$ /year reconstr. (CP– Violat.)

$\bar{p}(\geq 2.6\,GeV/c)p \rightarrow \Xi^-\Xi^+(2\mu b) \approx 10^{10}$ /year $\approx 10^7 - 10^9$ reconstr. Ξ^- /year $({}_{\Lambda\Lambda}A)$

Common feature:

- Particles come in pairs, charge symmetric conditions
- Moderate particle energies
- Trigger on one, investigate the other
- Low multiplicity events

Experiments with open Charm/Strangeness (2)

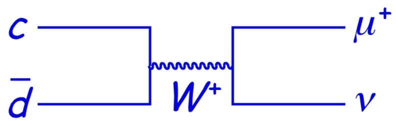
Experimental program

— Baryon Spectroscopy

New states, Quantum numbers and decay rates

— Rare D-decays

Example: $D^+ \to \mu^+ \nu (BR \sim 10^{-4})$



$\Gamma \sim f_0^2 \sim |\psi(0)|^2$

Sensitive Test of LQCD,····

— Direct CP-Violation in $\Lambda, \overline{\Lambda}$-decays

Compare angular decay asymmetries $(\alpha, \overline{\alpha})$ for $\Lambda \to p\pi^- / \overline{\Lambda} \to \overline{p}\pi^+$

$$A \approx \frac{\alpha + \overline{\alpha}}{\alpha - \overline{\alpha}}$$

Prediction (SM) ≈$2x10^{-5}$

HESR: 1 year of beamtime

Experiments with open Charm/Strangeness (3)

CP-Violation in charmed region

$D^0 / \overline{D}^0 -$ Mixing $(r) < 10^{-8} (SM)$ HESR: $\Delta r / r \sim 10^{-4}$

Direct CP-Violation (SCS)

Compare $D^+ \rightarrow K^+ \overline{K}^{0*} / D^- \rightarrow K^- K^{0*}$ Asymmetries $A \ (SM) \leq 10^{-3}$

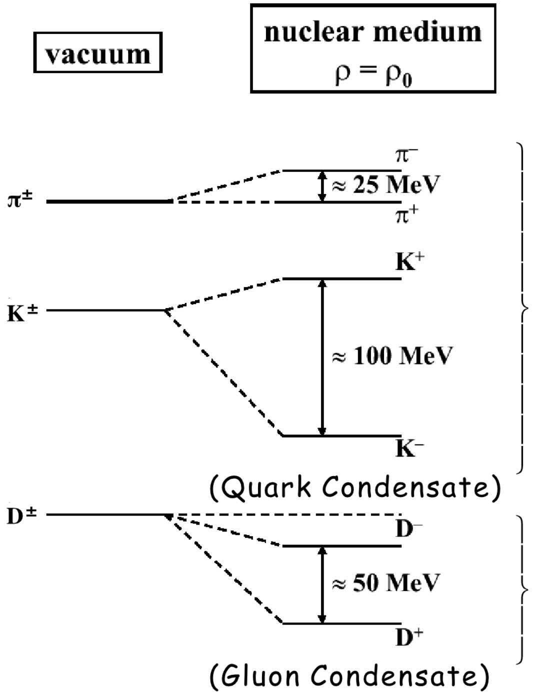
HESR $= \Delta A / A \approx 10^{-4} - 10^{-3}$

Antiproton-Nucleus-Interactions (1)

1) Effective masses of hadrons in the nuclear medium

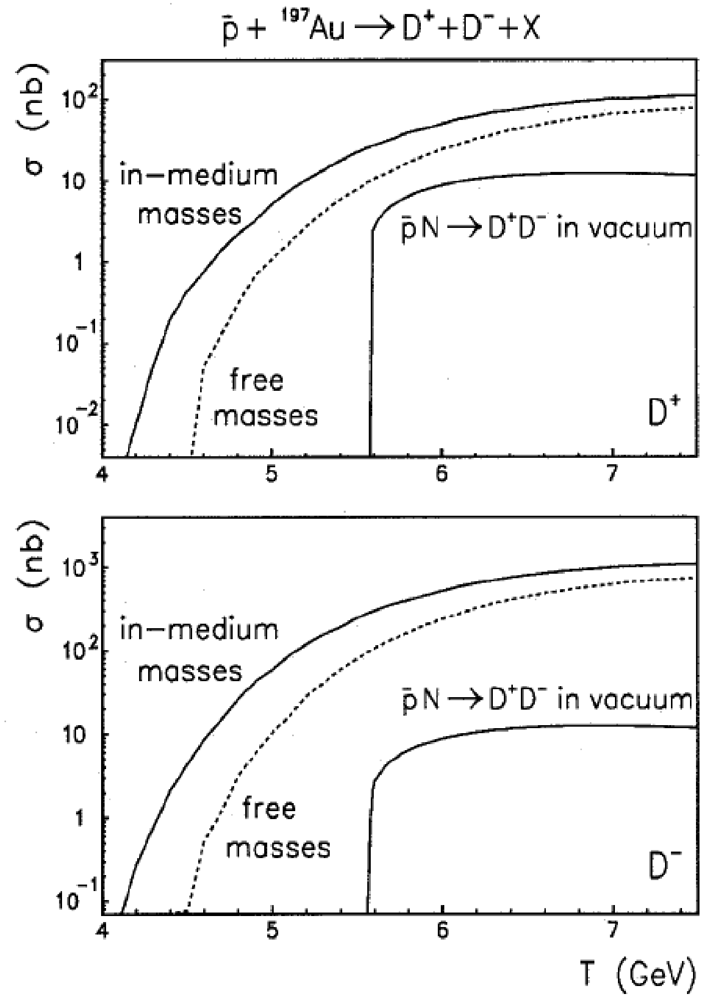
- $^{206}Pb(d, {}^{3}He)$, Q-Value $\rightarrow (m_{\pi^-})_{Eff.}$
- K^+, K^--Production in heavy ion collisions

  Excitation spectra $\rightarrow (m_K)_{Eff.}$



Recently measured at GSI

Theoretical prediction
(A. Hayashigaki, P.L. B487(2000)96;
Morath, Lee, Weise, Pr. Commmun.)



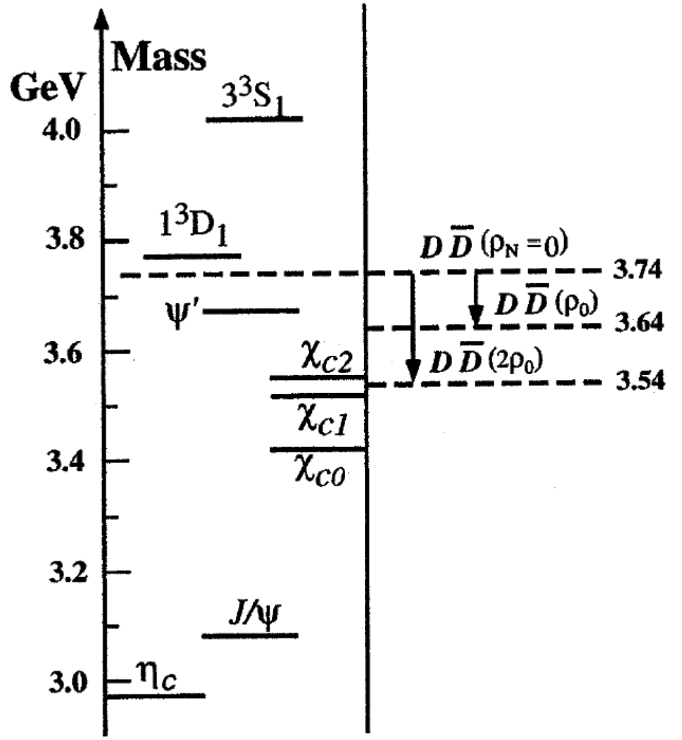
Antiproton-Nucleus-Interactions (2)

Effective *D*-masses in nuclear medium

— Dramatically increased $D\bar{D}$-decay rate of ψ' - and χ_2-states in nuclear medium

↳Substantial increase of widths (0.3 $MeV \rightarrow$?; 2.7 $MeV \rightarrow$?)

— Increased width of $\psi(3770)$ (31 $MeV \rightarrow$?)



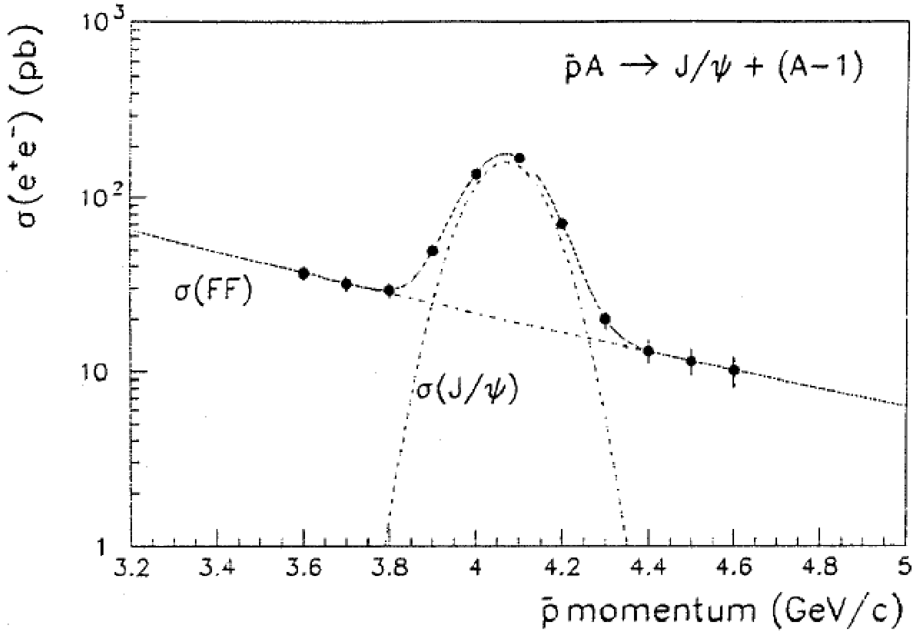
Antiproton-Nucleus-Interactions (3)

2) J/ψ - nucleon absorption cross section

Important for J/ψ - suppression in QGP

Proposed reaction:

$\bar{p}$ (3.4-4.6 GeV/c) + $A \rightarrow J/\psi$ + (A-1)



Furthermore:

— $c\bar{c}$ - dissociation to open charm in the presence of nucleons:

$\bar{p}d \rightarrow D^- + \Lambda_c^+$

— Elastic J/ψ - nucleon cross sections (Low momenta)

$\bar{p}d \rightarrow J/\psi + \gamma + n$

Antiproton-Nucleus-Interactions (4)

3) Strange Baryons in Nuclear Field

Hypernuclei = Third dimension of the nuclear chart || States with new symmetries, not available in ordinary nuclei || Non-mesonic weak decays || Basic properties of hyperons and strange exotic objects

— Double Λ-Hypernuclei (Three candidates exist yet)
  - Hyperon-Hyperon interaction (Meson-exchange vs. quark-exchange)
  - Breeder for *H*-dibaryon

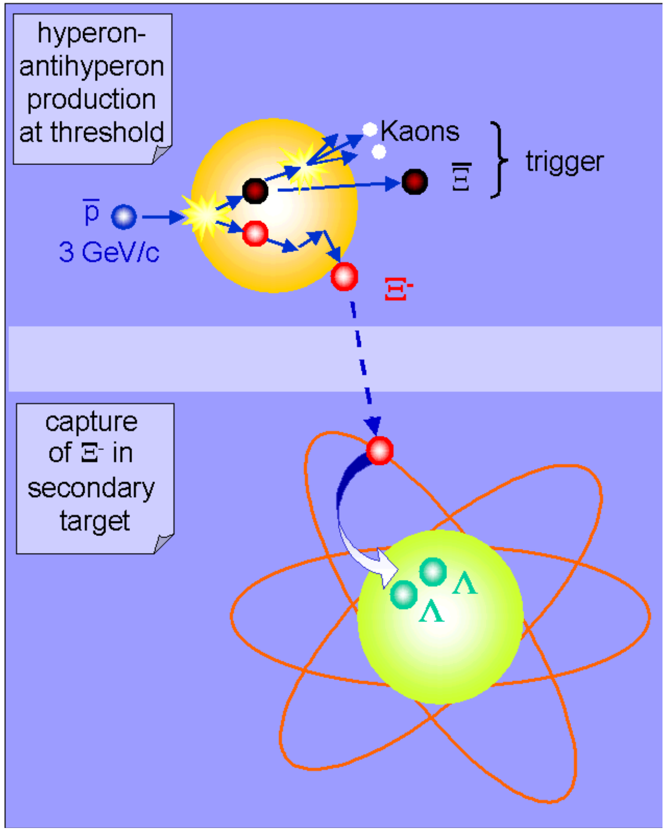
— High resolution spectroscopy of deeply bound hyperatoms

— Ω^--atoms ($\rightarrow$ Static quadrupol moment)

— Experimental Concept:

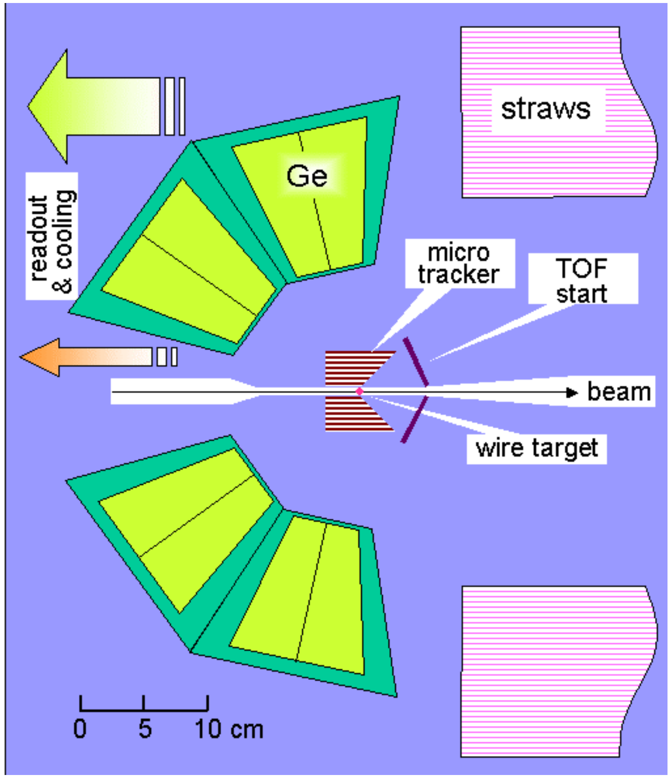
$$\bar{p}(2.6\,GeV/c) + A \rightarrow \Xi^-(\text{slow}) + \underbrace{\bar{\Xi}\,(KK\cdots)}_{\text{Trigger}}\;;\;\Xi^-(\text{slow}) + A' \rightarrow {}_{\Lambda\Lambda}A'$$

Active, secondary target



Antiproton-Nucleus-Interactions (5)

Experimental set up:



Secondary target: High resolution solid state micro-tracking detector (Diamond, *Si*)

High resolution spectroscopy:

Efficient, position sensitive *Ge*-γ-array

(see VEGA, AGATA at GSI, 100 *kHz*-rate)

HESR: 3×10^3 ($\bar{\Xi}$- Trigger) - 3×10^5 (Kaon-Trigger) stopped and reconstructed Ξ^- / day

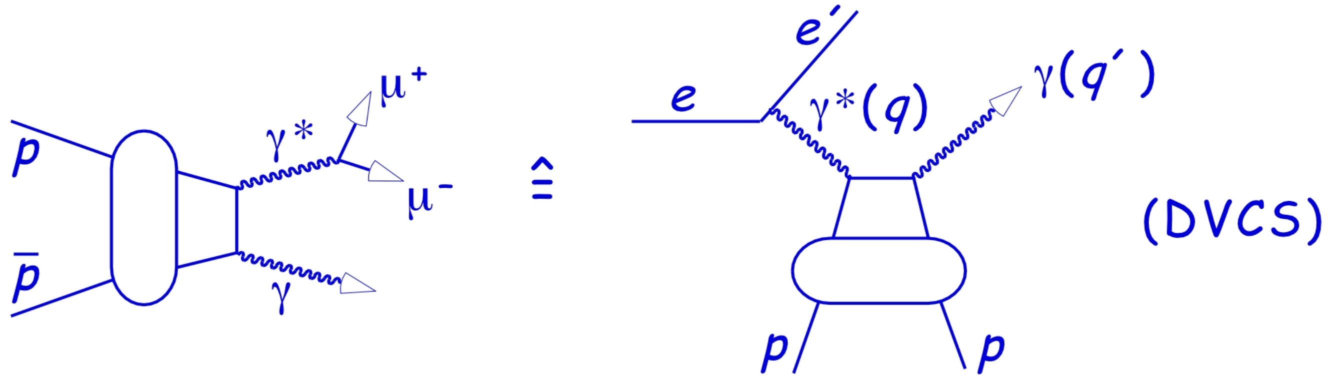
↳Hundreds of γ-transitions per day

Present experiments: 10^4 stopped Ξ in total

Further possibilities at HESR

Study of reversed Deeply Virtual Compton Scattering (DVCS)

$\bar{p} + p \to \gamma^* + \gamma \to \ell^+\ell^- + \gamma \to$ Nucleon structure functions



Low energy $\bar{p}$ -physics

- $\bar{p}p$-annihilation process
- Antiprotonic atoms
- Antihydrogen

Conclusions

— HESR will deliver cooled high quality antiproton beams with energies up to 15 *GeV*

— Antiproton induced reactions exhibit unique features

- — High statistics data
- — Low multiplicity events
- — Symmetric production of particles and antiparticles
- — High production rates for gluonic hadrons
- — Many states can be directly formed

— Rich and unique Physics Program with emphasis on charmed particles

- — J/ψ-Nucleon interactions
- — Effective masses of hadrons in nuclear matter
- — Precision charmonium spectroscopy
- — Search for charmed hybrids and heavier Glueballs
- — CP-violation in the charm sector
- — Low energy $\bar{p}$ - physics, including Antihydrogen experiments