Physics with Antiprotons: From Antihydrogen to the Top-Quark

- General survey on $\bar{p}p$ - reactions / History

- From $TeV$ to $meV$
  - Discovery of the Top-Quark
  - Discovery of $W^\pm, Z^0$
  - High precision measurements in the $(c\bar{c})$ - system
  - Physics at LEAR
    - Low and medium energy $\bar{p}N$ - interactions
    - Antiprotonic X-ray measurements
    - $\bar{p}$ - nucleus interactions
    - T/CP/CPT - tests
    - Meson/Exotics - Spectroscopy
    - Physics with trapped antiprotons
    - Antihydrogen

- Conclusions
Survey on $\bar{p}p$-reactions

Low and medium energy antiprotons

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

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
### Historical Survey on experiments with Antiprotons

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1955</td>
<td>Discovery of the antiproton @ Bevatron/Berkeley</td>
</tr>
<tr>
<td>1960-1990</td>
<td>Experiments with conventional, secondary beams @ CERN, BNL, KEK, Serpukhov, ...</td>
</tr>
<tr>
<td></td>
<td>Bubble chamber experiments: Very precise, but low statistics</td>
</tr>
<tr>
<td></td>
<td>Several meson-resonances firstly seen in</td>
</tr>
<tr>
<td></td>
<td>$\bar{p}p$-annihilation reactions, others confirmed</td>
</tr>
<tr>
<td></td>
<td>Electronic detectors: More data on rare channels, Discovery of $\bar{p}$-atoms</td>
</tr>
<tr>
<td></td>
<td>Search for resonant and deeply bound $\bar{NN}$-states (Baryonium)</td>
</tr>
<tr>
<td>1972-1986</td>
<td>Invention of stochastic cooling, ICE-Test facility, SPSC-Project/CERN</td>
</tr>
<tr>
<td>1983-1984</td>
<td>Formation of $c\bar{c}$-states at ISR</td>
</tr>
<tr>
<td>1983</td>
<td>Discovery of $W^{\pm}, Z^{0}$ @ SPSC (UA1, UA2 - Detectors)</td>
</tr>
<tr>
<td>1984-1996</td>
<td>LEAR: $\bar{NN}$ interaction, Meson/Exotics-spectroscopy,</td>
</tr>
<tr>
<td></td>
<td>$\bar{p}$-Nucleus interactions, Exotic atoms ($\bar{p}p$, $\bar{p}He$),</td>
</tr>
<tr>
<td></td>
<td>T/CP-violation in $K^0$, $\bar{K}^0$-decay, Trapped Antiprotons</td>
</tr>
<tr>
<td>1985-</td>
<td>Tevatron at FNAL</td>
</tr>
<tr>
<td>1996-2000</td>
<td>$c\bar{c}$-Spectroscopy at Fermilab</td>
</tr>
<tr>
<td>1996-1997</td>
<td>First $H$ signal at LEAR and Fermilab</td>
</tr>
<tr>
<td>1995</td>
<td>Discovery of the top-quark at Fermilab</td>
</tr>
<tr>
<td>2000</td>
<td>Physics with AD</td>
</tr>
<tr>
<td></td>
<td>? HESR</td>
</tr>
</tbody>
</table>
Discovery of the Top-Quark (FNAL, 1995)

Tevatron: $\sqrt{s} = 1.8$ TeV
Detectors: CDF, DØ

Production

- $\sigma \approx 4$ pb (High $p_\perp$)
- $\sigma_T \approx 60$ mb (10 o.m. bigger) ($<p_\perp> \approx 0.5$ GeV)

Trigger on high $p_\perp$ and secondary (b) vertex

$\Rightarrow m_t = (174.3 \pm 5.1)$ GeV/$c^2$
Discovery of the Intermediate Vector Bosons $W^\pm, Z^0$ (CERN, 1983)

SPSC: $\sqrt{s} = 630$ GeV
Detectors: UA1, UA2

Production/Decay (Drell-Yan)

$\sigma \approx (1-5) \text{ nb} \quad \text{(High } p_{\perp})$

$\sigma_T \approx 50 \text{ mb} \quad \text{(7 o.m. bigger) } \langle p_{\perp} \rangle \approx 0.4 \text{ GeV}$

$m_{W^\pm}$ = \begin{cases} (80.2 \pm 0.6 \pm 0.5 \pm 1.3) \text{ GeV/c}^2 \text{ (UA1)} \\ (82.7 \pm 1.0 \pm 2.7) \text{ GeV/c}^2 \text{ (UA2)} \end{cases}

$m_{Z^0}$ = \begin{cases} (93.1 \pm 1.0 \pm 3.1) \text{ GeV/c}^2 \text{ (UA1)} \\ (91.4 \pm 1.2 \pm 1.7) \text{ GeV/c}^2 \text{ (UA2)} \end{cases}

$\Gamma_W \leq 5.4 \text{ GeV/c}^2$ ; $J^P(W) = 1^-$

$\Gamma_{Z^0} = \begin{cases} (2.7^{+1.2}_{-1.0} \pm 1.3) \text{ GeV/c}^2 \text{ (UA1)} \\ (2.7 \pm 2.0 \pm 1.0) \text{ GeV/c}^2 \text{ (UA2)} \end{cases}$

FNAL- and LEP- data not considered
$c\bar{c}$-Spectroscopy (1)

$c\bar{c}$-system (QCD) corresponds to $e^+e^-$-system (QED)

$e^+e^-$- collisions

Drawback:
Only $J^{PC} = 1^{--}$ states are directly produced in $e^+e^-$
Other states are only visible in $\gamma$-transitions,
  e.g. $\chi_1, \chi_2, \chi_0, \eta_c, \eta_c',...$
  Data with moderate mass resolution

$\bar{p}p$ - collisions

All ($c\bar{c}$) - states can be directly formed

Production

Decay

(\text{CC})_{g.s.} \rightarrow e^+e^-, \mu^+\mu^-, \gamma\gamma, \phi\phi
\text{(CC)}_{\text{exc.}} \rightarrow (\text{CC})_{g.s.} + \gamma
$c\bar{c}$-Spectroscopy (2)

**Experimental method**
Scan with $\bar{p}$-beam with adjustable momenta (3.4 - 6.3 GeV/c)

\[ \sigma(\bar{p}p \to (c\bar{c}) \to e^+e^-,..) \approx nb \to pb \]

Background:
\[ \sigma_{\text{tot}} = 50 mb \to \text{Trigger on } e^+e^-, \mu^+\mu^-, \gamma\gamma,.. \]

Resonance parameters from excitation curve

Critical:
- Excellent knowledge of beam energy
- Very good $\bar{p}$-beam energy resolution ($O \sim 10^{-4}$)

Experiments:
- CERN/ISR: R 704 (Demonstration of method)
- Fermilab/$\bar{p}$-Cooler-Ring ($\leq 8$ GeV/c): E 760, E 835

Many beautiful results

But: Much is to be done
- Search for missing states
- Specific decay modes
Low and medium energy $\bar{p}p(n)$ - Reactions (1)

Total = Elastic + CEX + Annihilation cross section

$\sigma_{\text{Elast.}} < 0.5 \sigma_{\text{Tot.}} \rightarrow$ No diffractive scattering

(dominate for $p_{\bar{p}} \geq 3.5 \text{ GeV/c}$)

No structures near threshold $\rightarrow$ No narrow

Baryonium states

Elastic + CEX - scattering

$\frac{d\sigma}{d\Omega}(\theta)$, Analyzing Power ($\theta$), measured from 180(70) - 1940 MeV/c

Forward peak like in diffractive scattering

Strong $p$-wave already at threshold

(Strong $s$-wave absorption, $\neq pp$)
Interpretation of data (Elastic + CEX)
Often in terms of a potential-model

Real part (Long range): No problem, Meson-exchange picture
(G-parity transformation from $V_{NN}$)

Real part (Short range): Problem! Annihilation region
Several (phenomenological) ansaetze:
- $q\bar{q}$ - interactions
- Cut-off parameters

Imaginary part: Short range strong absorption (annihilation)

Resumee:
Good description of data, but not from first principles
No unambiguous statements on quark-distributions inside nucleon
Low and medium energy $\bar{p}p(n) - $ Reactions (3)

**Annihilation Reactions**

Global picture:

$\sigma_{\text{ann}}(E)$, Multiplicities,

Dominant at threshold $((\bar{p}p)_\text{Atom})$

**Interpretation of Data**

1. **Isospin statistical model (Pais)**
   
   $\sigma(\bar{p}p \rightarrow n \pi) \propto n_{\pi^+} n_{\pi^-} n_{\pi^0}$ ($n = n_{\pi^+} + n_{\pi^-} + n_{\pi^0}$)

   Threshold Dominance model (Vandermeulen), Valid up to 3.5 GeV/c

   $\text{BR (non strange meson pair)} = p \cdot C_{\text{ab}} \exp \left[ -A \left( E_{\text{cm}}^2 - (m_a + m_b)^2 \right)^{1/2} \right]$ 

   **Production Rate the higher the higher the mass of a, b**

   Annihilation prefers to produce mass, not energy
Specific annihilation channels

Many data at rest $\rightarrow$ BR's
- Dynamical selection rules
- Strong OZI - violations

Few data in flight:
$\bar{p}p \rightarrow \pi^+\pi^-, \pi^0\pi^0$ (up to 20 $\bar{p}$ - momenta)
Angular distributions change rapidly with $\bar{p}$ - momentum

\[ \downarrow \]
Dominating partial waves
(Resonances in Formation processes)

Recent results:
$\bar{p}p \rightarrow \omega\pi^0, \omega\eta, \omega\omega, \pi^0\eta\eta$ (9 $\bar{p}$ - momenta)

Unambiguous analysis
Low and medium energy $\bar{p}p(n)$ - Reactions (5)

Particularly well investigated: $\bar{p}p \rightarrow \Lambda\bar{\Lambda}, \Sigma^0\Lambda, \Sigma^-\Sigma^-, \Sigma^+\Sigma^+$

Measured quantities:
- $\sigma(p_\bar{p})$, $\frac{d\sigma}{d\Omega}$, Polarisations (Self analyzing decay),
- Spin - Correlations, Spin Transfer

Observations:
- Strong $p$ - wave contribution near threshold
- $\Lambda$ and $\bar{\Lambda}$ spins are aligned to $S = 1$
  (Reflection of $s\bar{s}$ in the nucleon?)
- $\frac{d\sigma}{d\Omega}$ strongly forward peaked

Total cross sections for the $\bar{p}p \rightarrow \Lambda\bar{\Lambda}, \Sigma^0\Lambda$ and $\Sigma^-\Sigma^-$ reactions
Low and medium energy $\bar{p}p(n)$ - Reactions (6)

Interpretation of data
Only possible (yet) in terms of models (Highly non perturbative QCD-sector)

Meson/Baryon - exchange picture
Exchange of $\pi$, K, Baryons (Single or multiple)

Quark/Gluon - picture
Quark Line Rule
$SU(3)$ - Symmetry
Quark Rearrangement/Quark Annihilation ($^3P_0$, $^3S_1$-Vertices)
Polarized intrinsic Strangeness

Resumee: Data can be well described by models.
Observables sensitive on nucleon structure ($s\bar{s}$-content, Diquarks,...).
Differentiation between models needs more and better data.
Antiprotonic X-rays (1) - \( \bar{p}p(d) \) - System

Shifts and widths due to strong interaction:

\[
\begin{align*}
\varepsilon_{1s} &= (-730 \pm 20) eV \\
\Gamma_s &= (1122 \pm 57) eV \\
\Gamma_{2p} &= (34.0 \pm 2.9) eV
\end{align*}
\]

2\( \rightarrow \)1 transition (\( \approx 10 \) keV): pn-CCD

3\( \rightarrow \)2 transition (\( \approx 2 \) keV): Crystal Spectrom.

\[
\Rightarrow a_s(\bar{p}p) = (-0.88 \pm 0.03) + i(0.67 \pm 0.04) \text{ fm}
\]

Separation of \( 2^3 P_0 \):

\[
\begin{align*}
\varepsilon(2^3 P_0) &= (140 \pm 30) meV \\
\Gamma(2^3 P_0) &= (80 \pm 60) meV
\end{align*}
\]

Sensitive on specific \( \bar{NN} \) interaction
Antiprotonic X-rays (2) - \( pHe \) System

Metastable states \((\tau \approx \mu s)\), deexcited by Laser-injection

⇒ Measurements on \( \Delta E \) with extreme precision

\[ \frac{m_p - m_p}{m_p} \leq 5 \times 10^{-7} \]

\[ \frac{q_p - e}{e} \leq 5 \times 10^{-7} \]

Future (AD): Increase of precision, \( \mu_p \)

Pulsed excimer-pumped tunable Dye-Laser Resonant enhancement of annihilation, \( \Delta \lambda / \lambda_0 = 0.5 \text{ ppm} \)
Antiprotonic X-rays (3) - $\bar{p}$ - nucleus - System

X-rays of transitions between various energy levels measured in many nuclei

Levels, not affected by strong interaction $\Rightarrow m_\bar{p}$, $\mu_\bar{p}$

\[
\mu_\bar{p} = (2.8005 \pm 0.0090) \mu_{nm} \text{(Best value)}
\]

Levels, affected by strong interaction $\Rightarrow (\epsilon, \Gamma)_{S,I}$ (last accessible level)

Interpretation:

\[
\epsilon + i \frac{\Gamma}{2} \propto \int (a_{pp} \cdot \rho_p + a_{pn} \rho_n) |\psi|^2 \, dt
\]

Only nuclear surface contributes $\Rightarrow$ Neutron halo established, e.g. $t_n - t_p = 0.6 \text{fm (}^{172}\text{Yb)}$
**$p$-induced nuclear reactions**

$p_{\text{stop}}$:

- Interaction only with nuclear periphery
- Discrimination between $\bar{p}n$ and $\bar{p}p$ annihilations in single nucleon interactions (quite rare)
- Identification of residual nuclei from $\gamma$-ray spectra $\rightarrow N(\bar{p}n)/N(\bar{p}p)$

Neutron Halo factor:

$$\text{Neutron Halo factor} = \frac{N(\bar{p}n)}{N(\bar{p}p)} \frac{Z \ 	ext{Im}(a_p)}{N \ 	ext{Im}(a_n)}$$

Large for nuclei with low $B_n$

$\downarrow$ Neutron Halo

$\bar{p}$ @ higher energies:

- Bulk annihilation, Heating of nuclei to $\geq 800$ MeV, Soft heating $\Rightarrow$ No dramatic density increase, No violent collective effects (High-Spins, Deformation), Formation of five pions in average ($\Delta$-matter ?)
- Experimental results:
  1 GeV: Particle spectra in good agreement with INC-calculations, Fission important, No Multi-Fragmentation
  8 GeV (ideal energy): INC-model works, Higher particle multiplicities than in $\pi$-induced reactions, Multi-Fragmentation observed
CP/T/CPT - Tests (1)

CP-Lear: Investigation of CP-/T-/CPT-symmetries in the neutral Kaon system

- Measurement of time dependent decay asymmetries for the main $K^0$, $\bar{K}^0$-decay modes

- Tagging of Strangeness of $K^0$, $\bar{K}^0$ at production time ($\bar{p}p \rightarrow K^+\pi^-K^0$)

- Tagging of Strangeness of $K^0$, $\bar{K}^0$ at decay time

\[ 0 \leq t \leq 20\tau_S \quad (K^0 \rightarrow \pi^-e^+\nu_e, \bar{K}^0 \rightarrow \pi^+e^-\bar{\nu}_e, \Delta S=\Delta Q) \]
(For semileptonic decays only)

\[ K^0(t) = a^-_L \left| K_S \right\rangle e^{-i\gamma_{S,L}t} + a^-_S \left| K_L \right\rangle e^{-i\gamma_{L}t} \]

\[ \bar{K}^0(t) = a^+_L \left| K_S \right\rangle e^{-i\gamma_{S,L}t} - a^+_S \left| K_L \right\rangle e^{-i\gamma_{L}t} \]

\[ \gamma_{S,L} = m_{S,L} - \frac{i}{2} \Gamma_{S,L} \]

\[ a_{S,L}^\pm = \frac{1}{\sqrt{2}} (1 \pm \varepsilon_{S,L}) \]

\[ \varepsilon_{S,L} = \varepsilon \pm \delta \]

$\varepsilon \neq 0$: T and CP violation

$\delta \neq 0$: T and CPT violation

Measurement of asymmetries

\[ A(t) = \frac{R(\bar{K}^0 \rightarrow f) - R(K^0 \rightarrow f)}{R(\bar{K}^0 \rightarrow f) + R(K^0 \rightarrow f)} \]

$f = \pi^+\pi^-, \pi^0\pi^0, \pi^+\pi^-\pi^0, \pi^0\pi^0\pi^0$

$\Rightarrow$ Parameters of CP-violation: $|\eta_{\pm}|$, $\phi_{\pm}$ (Best Value !), $|\eta_{00}|$, $\phi_{00}$, ...
**CP/T/CPT - Tests (2)**

**Semileptonic decays: \( f = \pi e^\nu_e \)**

- **Direct Test of T-violation \((\varepsilon \neq 0 ?)\)**

\[
A_T(t) = \frac{R(K^0 \rightarrow K^0(\pi^- e^+ \nu_e)) - R(K^0 \rightarrow K^0(\pi^+ e^- \bar{\nu}_e))}{R(K^0 \rightarrow K^0(\pi^- e^+ \nu_e)) + R(K^0 \rightarrow K^0(\pi^+ e^- \bar{\nu}_e))}
\]

\[= 4 \text{Re}(\varepsilon) \quad \text{(for} \ t \gg \tau_S)\]

Measurement: \(4 \text{Re}(\varepsilon) = (6.2 \pm 1.4 \pm 1.0) \times 10^{-3} \neq 0 !!\)

i.e.: \(R(K^0 \rightarrow K^0) > R(K^0 \rightarrow \bar{K}^0)\)

- **Direct Test of CPT-violation \((\delta \neq 0 ?)\)**

\[
A_\delta(t) = \frac{R(K^0 \rightarrow K^0(\pi^+ e^- \bar{\nu}_e)) - R(K^0 \rightarrow K^0(\pi^- e^+ \nu_e))}{R(K^0 \rightarrow K^0(\pi^+ e^- \bar{\nu}_e)) + R(K^0 \rightarrow K^0(\pi^- e^+ \nu_e))}
\]

\[= 8 \text{Re}(\delta) \quad \text{(for} \ t \gg \tau_S)\]

Measurement: \(\text{Re}(\delta) = (24 \pm 28) \times 10^{-5} !!\)

\((Jm \delta = (2.4 \pm 5.0) \times 10^{-5}, \text{Unit. Relat.)})\)

CPT-Invariance proven

\(\angle \angle \angle \angle \) CP-Invariance in K-decays due to T-violation !!

(Furthermore: No violation of \(\Delta S = \Delta Q\) in semilept. decays)
Meson/Exotics-Spectroscopy (1)

Mesons/Mesonic resonances: $q\bar{q}$

Exotics: Glueballs ($gg$, $ggg$), Hybrids ($\bar{q}qq$)

Multi quark-states ($\bar{q}qqq$, ...)

(Exotic $q$.-$n$. combinations, like $J^{PC} = 1^{-+}$, ...)

$\bar{p}p$ - annihilation:
- Production mode ($E_{\bar{p}}$ fixed)
  e.g. $\bar{p}p \rightarrow (\pi^+\pi^-)\rho\pi^0$
  $\rightarrow (\eta\eta)f_0(1500)\pi^0$
  $\rightarrow \left((\pi^+\pi^-)\rho(\pi^+\pi^-)\rho\right)f_0(1500)\pi^0$

  [Unique feature: $\bar{p}_{stop} \rightarrow (\bar{pp})_{atom}$ as initial state]

- Formation mode ($E_{\bar{p}}$ varied)
  e.g. $\bar{p}p \rightarrow \xi(2220) \rightarrow \phi\phi \rightarrow K^+K^-K^+K^-$

Mass/Width determination: Invariant masses
  (Dalitz Plot)

$J^{PC}$ determination: Partial wave analysis
  (Angular distribution)

$p_{max}$ (LEAR) = 1.94 GeV/c $\Rightarrow$ Masses < 2.3 GeV/c$^2$
Meson/Exotics-Spectroscopy (2)

Experiments → High statistics and clean data, mostly on $\bar{p}_{\text{stop}}$

Results:

$\bar{p}_{\text{stop}}$:
- Most of the already known light mesons very clearly seen
- Discovery of new states, particularly with $J^{PC} = 0^{++}$
- Confirmation of two states with exotic quantum numbers ($1^{++}$)
- at 1400 and 1600 MeV/c$^2$.

Clarification of the $0^{+-}$-sector (1400-1500 MeV/c$^2$) ($E/i$)

$\bar{p}$ Higher momenta:

Fixed momentum: - Confirmation of results obtained with $\bar{p}_{\text{stop}}$
- Interesting structures at Fermilab (8 GeV/c)

$\bar{p}$ – scan: - High sensitivity scans in the $\bar{p}p$-threshold region
  (→ No narrow Baryonium states above or below threshold)
- Coarse scans at a few higher momenta (Not finished)

Interpretation of results:
- Evidence for exotic (gluonic) states
- For further clarification more and accurate data @ higher energies needed.
Trapped Antiprotons

Low energy Antiprotons (5.4 MeV) are cooled down (meV) and trapped in magn./electr. field

\[ \begin{align*}
\text{Cyclotron/Magnetron rotations} & \quad \text{Frequences} \\
\text{Axial oscillations} & \quad \text{coupled}
\end{align*} \]

Cyclotron Frequency:

\[ \hbar \omega_c = \frac{\hbar}{c} B \frac{e}{m_{\bar{p}}} \quad (\omega_c \approx 90 \text{ MHz}) \]

Resonance (\( \omega_{HF} = \omega_c \)) detected from change in axial oscillation (20 MHz)

Comparison between \( \bar{p} \) and \( H^- \)-ions:

\[ \left( \frac{e/m}{\bar{p}} \right) / \left( \frac{e/m}{p} \right) = 0.999 \ 999 \ 999 \ 1 \pm 0.000 \ 000 \ 000 \ 09 \]

Formation and Investigation of \( \bar{H} \) at AD: Similar technique
Formation of Antihydrogen ($\bar{H}$) in Flight

Idea: Munger, Brodsky, Schmitt

**PS 210 (LEAR)**

Production of $\bar{H}$ in Coulomb field of Xe-(cluster) target (1.94 GeV/c antiprotons)

Stripping in Si-counter → $e^+$ (stopped→$\gamma\gamma$ (511 keV)) + $\bar{p}$ (Spectrometer)

11 events identified
   (Background estimate: 2 ± 1)

**E 862 (Fermilab)**

Production of $\bar{H}$ in $H_2$-cluster target by 5.2-6.2 GeV/c antiprotons

67 events identified

Continuation @ AD: $\bar{H}$ - Formation at low energies
Conclusions

$\bar{p}p$ reactions very useful for investigations in many areas of particle and nuclear physics

Annihilation process has no restrictions in quantum numbers and is gluon rich, so that conventional and exotic quark/gluon states are easily produced

Experiments with antiprotons are easily performed, as antiprotons can be cooled down (tiny primary vertex, detectable secondary vertices)

The physics with antiprotons has just started. Look ahead to HESR!