Low-energy antiprotons at CERN and at FAIR

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Stefan Meyer Institute for Subatomic Physics, Vienna
Current source: AD @ CERN

Antiproton production
CERN PS
p 26 GeV
$5 \times 10^7 \bar{p} / \text{shot}$
• **All-in-one machine:**
  • Antiproton capture
  • deceleration & cooling
  • 100 MeV/c (5.3 MeV)

• **Pulsed extraction**
  • $2-4 \times 10^7$ antiprotons per pulse of 100 ns length
  • 1 pulse / 85–120 seconds
New development: ELENA @ CERN-AD

- Decelerator after AD 5 MeV → 100 keV

<table>
<thead>
<tr>
<th>Energy range, MeV</th>
<th>5.3 - 0.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intensity of ejected beam</td>
<td>1.8</td>
</tr>
<tr>
<td>$\varepsilon_{x,y}$</td>
<td>4 / 4</td>
</tr>
<tr>
<td>$\Delta p/p$ of extracted beam, [95%], standard</td>
<td>8·10</td>
</tr>
</tbody>
</table>

Operation from 2017 for > 10 years

100 keV
1 pulse every ~100 s:
average $10^5 \overline{p}/s$
AD & ELENA area and experiments
Antihydrogen: CPT and gravity

- **CPT symmetry tests**
  - precision spectroscopy of $\bar{H}$
  - 1S-2S, GS-HFS
    - ATRAP, ALPHA, ASACUSA, AEgIS
  - Laser spectroscopy of $\bar{p}$He$^+$
    - ASACUSA
  - $\bar{p}$ g-factor
    - ATRAP, BASE

- **Antimatter gravity**
  - never directly measured
  - AEgIS, GBAR, ALPHA

AD experiments
HYDROGEN AND ANTIHYDROGEN

HYDROGEN

1s-2s  
2 photon  
λ=243 nm  
Δf/f=10^{-14}

Ground state hyperfine splitting  
f = 1.4 GHz  
Δf/f=10^{-12}
ASACUSA Scientific project

(1) Spectroscopy of $\bar{p}$He

(2) $\bar{p}$ annihilation cross-section

(3) $\bar{h}$ production and spectroscopy

The $\bar{h}$ team

University of Tokyo, Komaba: K. Fujii, N. Kuroda, Y. Matsuda, M. Ohtsuka, S. Takaki, K. Tanaka, H.A. Torii

RIKEN: Y. Kanai, A. Mohri, D. Murtagh, Y. Nagata, B. Radics, S. Ulmer, S. Van Gorp, Y. Yamazaki

Tokyo University of Science: K. Michishio, Y. Nagashima

Hiroshima University: H. Higaki, S. Sakurai


HFS MEASUREMENT IN AN ATOMIC BEAM

- formation in nested Penning trap
- atoms evaporate
- cusp trap provides polarized beam
- spin-flip by microwave
- spin analysis by sextupole magnet
- low-background high-efficiency detection of antihydrogen

achievable resolution
- better $10^{-6}$ for $T \leq 100$ K
- $> 100 \overline{H}$/s in 1S state into $4\pi$ needed
- event rate 1 / minute: background from cosmics, annihilations upstrees

E.W. et al. ASACUSA proposal addendum CERN-SPSC 2005-002
**Recent Results**

- **$\bar{\text{H}}$ Beam Observed**
  - $n \leq 43$: 6 events / 15 min
  - $n \leq 29$: 4 events / 15 min

- **H Beam HFS Measurement**

![Diagram](image)

**Table 1 | Summary of antihydrogen events detected by the antihydrogen spectrometer**

<table>
<thead>
<tr>
<th>$n$</th>
<th>Double coincidence events</th>
<th>Corrected counts/150 s</th>
<th>Normalised counts/150 s</th>
</tr>
</thead>
<tbody>
<tr>
<td>27</td>
<td>8</td>
<td>59.1</td>
<td>0.101</td>
</tr>
<tr>
<td>28</td>
<td>10</td>
<td>85.7</td>
<td>0.147</td>
</tr>
<tr>
<td>29</td>
<td>14</td>
<td>122.1</td>
<td>0.245</td>
</tr>
<tr>
<td>30</td>
<td>19</td>
<td>159.5</td>
<td>0.319</td>
</tr>
</tbody>
</table>

**Figure a**

- Normalised counts/150 s vs. $E$ (MeV)

**Figure b**

- Normalised counts/150 s vs. $f_{\text{excite}} - 1420400$ (kHz)

$\Delta f/f < 10$ ppb
We performed exposures with stopping antiprotons in June and December, 2012. The emulsion detector consisted of sandwiches each made of 5 films on five double sided plastic substrates (68 x 68 x 0.3 mm$^3$). We irradiated emulsion films with antiprotons passing through a small hole in a gate valve. The vacuum flange by a crossed bar frame. Lower right: Emulsion detector attached to the vacuum flange. Right: Holder of the miniature moiré deflectometer. The simulation below shows as an example the expected interference pattern at the emulsion layer, generated by a pair of minimum ionizing tracks (MIP). The fog density varies with the glycerine concentration.

Emulsion properties after glycerine treatment (A) and with treatment (B). The detection efficiency per AgBr crystal with 6 GeV/c charged pions on a 10 mm$^3$ target is shown in figure 4. For 3.5 days in the high vacuum chamber without glycerine (A) and in a highly sensitive one (B). The detection efficiency per AgBr crystal with 6 GeV/c charged pions on a 10 mm$^3$ target is shown in figure 4. For 3.5 days in the high vacuum chamber without glycerine (A) and in a highly sensitive one (B). The fog density varies with the glycerine concentration.

Table 1. Comparison between the reference conditions. Water loss in the gelatine layer, we investigated:
- Impact parameter resolution ($\Delta p$)
- Impact parameter ($p$)
- Track finding efficiency ($\varepsilon$)

Emulsion in high vacuum have not been developed at Nagoya University (Japan) with increased sensitivity. They were developed at Nagoya University (Japan) with increased sensitivity. They were developed at Nagoya University (Japan) with increased sensitivity. They were developed at Nagoya University (Japan) with increased sensitivity.
AEGIS - Antimatter Experiment: Gravity, Interferometry, Spectroscopy

• **Free Fall of \( \bar{p} \)**
  • \( \bar{H} \) production at 100 mK
  • resonant charge exchange with excited positronium
  • acceleration of Rydberg \( \bar{H} \) by Starck effect
  • pulsed production, measure TOF & position
**p DEFLECTOMETER RESULT**

- **Pattern observed**
  - Shift between p and light observed
  
  \[ \Delta y = 9.8 \pm 0.9\text{ (stat)} \pm 6.4\text{ (syst)} \mu m \]

- consistent with residual B, E fields
- sensitivity of \( \mu m \) reached
- \( \bar{H} \) beam case
  - velocity \( \times 10^{-4} \)
  - distance \( \times 40 \)
  - Force \( 10^{-10} \)

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_Aghion, S. et al. Nature Communications, 5, 4538 (2014)_{
• High brightness low energy beams
  • two storage rings with 300 keV (LSR) and 20 keV (USR)
  • electron cooling
    • $\varepsilon \sim 1 \pi$ mm mrad
    • $\Delta p/p \sim 10^{-4}$
• Storage rings with internal targets for collision studies
• Slow and fast extraction
• Ion traps
  • HITRAP facility for HCl & pbar
• Many new experiments possible
• same facilities can be used for HCl

Factor 100 more pbar trapped or stopped in gas targets than now

Operation after ~2020?
Antiprotons at FAIR

High Energy Storage Ring for Antiprotons (HESR): 0.8–15 GeV

SIS 100 / 300

pbar production
Capture and accumulation

New low-energy facility

pbar program in CDR
CRYRING@ESR: phase I of FLAIR

CRYRING has been delivered to GSI and is currently getting installed
Vision: antiprotons from CR/RESR?

- Current ESR experimental hall could be used for full FLAIR program
- without accumulation rates are similar to ELENA
Scenarios: $\bar{p}$ rates in MSV from HESR

- **Leftover from PANDA**
  - few $10^9$ per 60 min
  - decelerate & transfer to ESR
    - T. Katayama: 100s, 80% eff.
  - average $5 \times 10^5$/s
  - $5 \times 10^7$/s every 100 s
  - similar to AD-ELENA
  - fast or slow extracted

- **Low-energy $\bar{p}$ production: full use of HESR**
  - CR 13 Tm
  - ESR 10 Tm, but above transition energy
  - deceleration needed to avoid loss: HESR
  - T. Katayama:
    - start with $10^9$ $\bar{p}$ (stacking for 100s)
    - deceleration to 30 MeV in HESR&ESR: $8 \times 10^8$ $\bar{p}$/100 s
    - max. $10^{10}$ $\bar{p}$ (stacking for 1000s): similar average rate
Low Energy Antiproton Physics @ FLAIR

FLAIR TDR - E. Widmann CAMOP - Physica Scripta 72, C51-C56 (2005)
Low Energy Antiproton Physics @ FLAIR

- Spectroscopy for tests of CPT and QED
  - Antiprotonic atoms (pbar-He, pbar-p), antihydrogen

- Atomic collisions
  - Sub-femtosecond correlated dynamics: ionization, energy loss, antimatter-matter collisions

- Antiprotons as hadronic probes
  - X-rays of light antiprotonic atoms: low-energy QCD
  - X-rays of neutron-rich nuclei: nuclear structure (halo)
  - Antineutron interaction
  - Strangeness –2 production

- Medical applications: tumor therapy

FLAIR TDR - E.Widmann CAMOP - Physica Scripta 72, C51-C56 (2005)
FLAIR day-1 experiments
unique at FLAIR: slow $\bar{p}$ extraction → hadron physics

• $\bar{p}$ as probe of nuclear structure
  • halo structure of RI
  • nested Penning trap

determination of the halo factor ($f_{\text{halo}}$)

• hadron physics with stopped $\bar{p}$
  • search for (deeply) bound baryonic matter with strangeness $-1$ and $-2$
  • needs $4\pi$ detector

M. Wada, Y. Yamazaki
NIM B214 (2004) 196

Summary and Outlook

• Low energy antiprotons offer exciting possibilities for a variety of fields
  • Fundamental symmetries, nuclear & atomic physics
• CERN-AD and ELENA: Antihydrogen
  • essential for continuation of current program
  • getting crowded
• FLAIR: offers further opportunities
  • continuous $\bar{p}$ beams available from CRYRING
  • nuclear and particle physics type experiments (not possible at AD)
  • Availability of radioactive ion beams (RIB) offers new synergies
    • requires independent beam line from (S)FRS
  • Cooled antiprotons down to 20 keV (with USR)
  • higher rates (phase 2, with RESR)
• Major components of FLAIR are ready or will be soon
  • CRYRING can play a major role in future experiments with (continuous) beams of slow antiprotons