Antihidrogén előállítása Paul-csapdában

Barna Dani
Asacusa kísérlet
CERN
AD = Antiproton Decelerator

- Approved: 7 February 1997
- Operational: July 2000
- $1.5 \times 10^{13}$ protons @ 26 GeV/c from the PS on to a beryllium target
- Antiprotons selected @ 3.57 GeV/c
- Decelerated to 100 MeV/c ($E_{\text{kin}} = \sim 5$ MeV) (stochastic and electron cooling)
- Ejected to the experiments
3 experiments @ AD

- **ATRAP**
  Trapping antiprotons and positrons in a very strong magnetic field (Penning-trap)

- **ALPHA**
  Production of antihydrogen
  Trapping antihydrogen, laser spectroscopy (?
  => matter-antimatter?

- **ASACUSA** (diverse programme - next page)
3 experiments @ AD

- **ATRAP**
  Trapping antiprotons and positrons in a very strong magnetic field (Penning-trap)

- **ALPHA**
  Production of antihydrogen
  Trapping antihydrogen, laser spectroscopy (?)
  => matter-antimatter?

- **ASACUSA** (diverse programme - next page)
3 experiments @ AD

- **ATRAP**
  - Trapping antiprotons and positrons in a very strong magnetic field (Penning-trap)

- **ALPHA**
  - Production of antihydrogen
  - Trapping antihydrogen, laser spectroscopy (?)
  - => matter-antimatter?

- **ASACUSA** (diverse programme - next page)

Nested potential well needed for opposite charges ($\bar{p}$ and $e^+$)
Antiprotonic helium spectroscopy + heavy 3-body QED theory ⇒ antiproton mass.

\[
\frac{|m_p - m_\bar{p}|}{m_p}
\]

A test of CPT invariance. Note that the comparison of the \( \bar{p} \) and \( p \) charge-to-mass ratio, given in the next data block, is much better determined.

<table>
<thead>
<tr>
<th>VALUE</th>
<th>CL%</th>
<th>DOCUMENT ID</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>(&lt;2 \times 10^{-9})</td>
<td>90</td>
<td>1 HORI 06</td>
<td>SPEC ( \bar{p}e^-) He atom</td>
</tr>
<tr>
<td>(&lt;1.0 \times 10^{-8})</td>
<td>90</td>
<td>1 HORI 03</td>
<td>SPEC ( \bar{p}e^-) ( ^4)He, ( \bar{p}e^-) ( ^3)He</td>
</tr>
<tr>
<td>(&lt;6 \times 10^{-8})</td>
<td>90</td>
<td>1 HORI 01</td>
<td>SPEC ( \bar{p}e^-) He atom</td>
</tr>
<tr>
<td>(&lt;5 \times 10^{-7})</td>
<td>90</td>
<td>2 TORII 99</td>
<td>SPEC ( \bar{p}e^-) He atom</td>
</tr>
</tbody>
</table>

1 HORI 01, HORI 03, and HORI 06 use the more-precisely-known constraint on the \( \bar{p} \) charge-to-mass ratio of GABRIELSE 99 (see below) to get their results. Their results are not independent of the HORI 01, HORI 03, and HORI 06 values for \( |q_p + q_\bar{p}|/e \), below.

2 TORII 99 uses the more-precisely-known constraint on the \( \bar{p} \) charge-to-mass ratio of GABRIELSE 95 (see below) to get this result. This is not independent of the TORII 99 value for \( |q_p + q_\bar{p}|/e \), below.
- Antiproton ionization x-section @ extreme low energies
- Antiproton annihilation x-section @ extreme low energies
- Antihydrogen production in a cusp magnetic trap
- Antihydrogen production in a Paul-trap (antihydrogen atomic beam, ground-state hyperfine splitting measurement)
Ground-state HFS of $\overline{\text{H}}$

Splitting due to and depending on the $\overline{\text{p}}$ and $\text{e}^+$ magnetic moments

First measurement would improve $\mu_{\overline{\text{p}}}$ (current precision 0.3% from antiprotonic atom spectra)

More precise measurements: $\overline{\text{p}}$ magnetic form factor

Measure at $B=0$!
Ground-state HFS of $\bar{H}$

- Sextupole
- High-field seekers defocused
- 1.4-GHz spin-flip cavity
  (high-field seeker $\Leftrightarrow$ low-field seeker @ resonance)
- anti-H detector

Diagram:
- Microwave frequency
- anti-H count
2 Paul-traps for Hbar production

1st stage: Linear Paul-trap - capture and cool antiprotons

5.3 MeV antiprotons from the AD, decelerated to ~100 keV by an RFQD
2 Paul-traps for Hbar production

2\textsuperscript{rd} stage: 3D Paul-trap simultaneous trapping of antiprotons and positrons, antihydrogen synthesis

transfer antiprotons to 3D Paul-trap

positrons

antihydrogen atomic beam
What is a Paul-trap?

- DC quadrupole field
- "Deconfinement" along this axis
- Confinement along this axis
What is a Paul-trap?

RF quadrupole field

Ponderomotive force = time-averaged force

points to minimum field (=center)

INDEPENDENT FROM THE SIGN OF THE CHARGE!
What is a Paul-trap?

Equation of motion: \[ x'' + \left( \frac{e}{mr_0^2} \right) \left( U - V \cos \omega t \right) x = 0 \]

Newton's  \( F = m \cdot a \)

where  \( F = \text{quadrupole} \times \sin(t) \)

DC term, normally not used in traps, only in the mass filter
What is a Paul-trap?

Equation of motion: \[ x'' + \left( \frac{e}{mr_0^2} \right) (U - V \cos \omega t) x = 0 \]

Introducing \[ a = \frac{4eU}{m \omega^2 r_0^2} \quad q = \frac{2eV}{m \omega^2 r_0^2} \quad \xi = \frac{\omega t}{2} \]

Equivalent to the Mathieu equation: \[ \frac{d^2 u}{d \xi^2} + (a - 2q \cos 2 \xi) u = 0 \]

Mass filter Stability for both x/y within this region:

A trap operates on this line (no DC component) stability if \( q < \sim 0.9 \)

(Nobel Prize 1989, Wolfgang Paul: Paul-trap and quadrupole mass filter)
What is a Paul-trap?

Equation of motion: \[ x'' + \left( \frac{e}{mr_0^2} \right) (U - V \cos \omega t) x = 0 \]

Introducing \[ a = \frac{4eU}{m\omega^2 r_0^2} \quad q = \frac{2eV}{m\omega^2 r_0^2} \quad \xi = \frac{\omega t}{2} \]

Equivalent to the Mathieu equation: \[ \frac{d^2 u}{d\xi^2} + \left( a - 2q \cos 2\xi \right) u = 0 \]

Mass filter
Stability for both x/y within this region:

Secular motion: slow, large (as if in a harmonic 'pseudopotential')
Cooling = damping this motions

Micromotion (~driving frequency + harmonics)

(Nobel Prize 1989, Wolfgang Paul: Paul-trap and quadrupole mass filter)
Why a Paul-trap?

- Superconducting magnets of Penning traps are massive, difficult to access with lasers (assist radiative recombination), etc.

- Harmonic pseudopotential: cooling $\rightarrow$ compression
  Hope: point-like source of antihydrogen

- Output: ground-state atoms (excited states ionized by high RF field at the edges, constituents recaptured)

- The principle is charge-independent, can trap 2 opposite charges!
THE LINEAR PAUL-TRAP
Linear Paul-trap: capture

0 kV DC

shutter electrode @ -5 kV DC

Degrader foil

Antiproton bunch
Linear Paul-trap: capture

Trapping:
Longitudinally: DC potential
Transversally: RF Quadrupole electric field between 4 rods (=Paul-trap)
Simulation: $\bar{p}$-energy after degrader foil

Shutter electrodes at $>-5$ kV

>5 kV deep transverse pseudopotential well
Parameters of our Paul-trap

TRAP SIZE: (← beam size)
- longitudinal: 15 cm
- transverse: 30 mm Ø
Parameters of our Paul-trap

- Nonlinear resonances
- q-parameter of Mathieu eq. for a trap of this size

TRAP SIZE: (← beam size)
- longitudinal: 15 cm
- transverse: 30 mm Ø

Voltage between neighbouring electrodes [kV]
Frequency [MHz]
Parameters of our Paul-trap

TRAP SIZE: (beam size)
- longitudinal: 15cm
- transverse: 30 mm Ø

isolines of transv. pseudopotential well depth [keV]
Parameters of our Paul-trap

Parameter space increases (but also the RF losses)

TRAP SIZE: (→ beam size)
- longitudinal: 15 cm
- transverse: 30 mm Ø

isolines of transv. pseudopotential well depth [keV]
Parameters of our Paul-trap

**Chosen parameters:**
- $f_{drive} = 35 \text{ MHz}$
- $V = 50 \text{ kV}$
- $q = 0.88$
- $f_{sec} = 14.7 \text{ MHz}$

**TRAP SIZE:** (← beam size)
- longitudinal: 15 cm
- transverse: 30 mm Ø

Need a SRF resonator!
The same double-coil for other 2 electrodes

Winding in counter-directions

Lumped elements to keep size at 35 MHz 'reasonable'
Resonator eigenmodes: quadrupole (trapping) mode

- Counter-running currents in the 2 coils
- B-field mostly between the 2 coils
- Effective L is 'small', resonant frequency is 'large'
Resonator eigenmodes: quadrupole (trapping) mode

- Counter-running currents in the 2 coils
- B-field mostly between the 2 coils
- Effective L is 'small', resonant frequency is 'large'

Virtual shortcircuit (same RF potential and phase)

Can add anything without disturbing the quadrupole mode
Resonator eigenmodes: dipole – resistive cooling

- Parallel currents in the 2 coils
- Like a double-solenoid, B-field in a larger volume
- Effective L is 'large', resonant frequency is 'small'

Used for cooling/detection: excited by secular motion

Coupling an external resonant resistive circuit to this mode
Resonator eigenmodes: dipole – resistive cooling

- Parallel currents in the 2 coils
- Like a double-solenoid, B-field in a larger volume
- Effective L is 'large', resonant frequency is 'small' (must match secular frequency)

One possibility to tune cooling mode freq. to secular frequency

UNWANTED! for efficient cooling maximize $R_{shunt} \times \Delta f \sim 1/C$

Used for cooling/detection: excited by secular motion

Coupling an external resonant resistive circuit to this mode
Why coupled coils?

To tune the cooling mode frequency (move the quadrupole and dipole mode eigenfrequencies apart-enough from each other), keeping $R_{\text{shunt}} \times \Delta f \sim 1/C$ the largest possible (i.e. without additional tuning capacitance)
B-field patterns of the two modes

Cooling/diagnostic mode

Trap mode
B-field patterns of the two modes

Cooling/diagnostic mode

Trap mode

Antenna for cooling/detection: selectively couple to cooling mode only, minimum coupling to trap mode to avoid saturation of diagnostics
Construction, design

“Endcap” segments
- same RF potential (sapphire capacitance)
- -2 kV DC to confine $\bar{p}$s to the 'perfect' quadrupole transverse field

(ask about details...)

-2 kV HV cables, inside the coils
Construction, design

(Upside down view)

Coaxial double-coils

- provide superfluid liquid-He supply to the electrodes
- shielded path for the endcap segments' bias cable (-2 kV)

Superfluid He reservoir
Construction, design

Support:
- Niobium rings
- Sapphire isolator rods

This RF structure can be floated to few 100 V to eject antiprotons!
Construction, design

Niobium shield to confine surface currents to superconducting surfaces
Construction, design

Vacuum vessel:

- Nb-sputtered copper (good heat-conductivity, easier to cool)
- To provide UHV
Construction, design

Beamport flanges:

- to hold thin foil window on entrance side ($\bar{p}$ slow-down, vacuum isolation)
- to hold shutter electrodes (-5 kV)
The high-Q endcap capacitance

$C = 400 \text{ pF}$

0.2mm sapphire disk
Helium-distributor + cavity vessel

Large grain size Nb disk

Took 1 year to Nb-sputter

346 mm
Test cavity for the linear trap

Modeling the quadrupole mode, “half” of the real resonator (1 double-coil pair)

- Microphonics ??
- RF, cryogenic properties, etc

Vessel, immersed in superfluid helium
Test cavity for the linear trap

Capacitor plate (against top plate of vessel), representing the electrodes' capacitance to virtual ground

Sapphire rod (support)

(2) capacitive excitation/diagnostic probes

Double-coil (8mm inner-diameter pipe, filled with superfluid helium)

Conclusions:
• Microphonics OK (could lock to oscillating eigenfrequency)
• Cooling is sufficient
• Q-factor not too good (but enough): $3 \times 10^6$
Quadrupole mode in the final trap
Quadrupole mode in the final trap

Virtual ground plane

Representing virtual ground

Representing shutters
Testcavity fully mounted in cryolab

- Teflon now, will be sapphire
- Temperature sensors in the endcaps
- Wires of the temperature sensors through the coil
- Final trap: HV endcap bias cables
- (RF leakage through these wires???)
Temperature sensor in the endcap
THE 3D PAUL-TRAP
FOR SIMULTANEOUS TRAPPING
OF ANTIPROTONS AND
POSITRONS
3D Paul-trap

- Full containment by RF field only

- The resonator needs 4 eigenfrequencies:

  2 for the simultaneous trapping of very different masses:
  \( \overline{p} \Rightarrow 1 \text{ MHz}, 40 \text{ V} \)
  \( e^+ \Rightarrow 350 \text{ MHz}, 5 \text{ kV} \)

  2 frequencies at the secular motions (cooling)
3D Paul-trap

antiprotons

positrons
Cryostat

Stand made by KFKI RMKI (OTKA K72172)