Antihidrogén előállítása Paul-csapdában

Darna =ani
Asacusa vísérlet
:7Fy
A= 1 Antiproton =cercelator

- Appro9edO J 2ebruar0 .55J
- xperationalO 3ul0 @666
- .GV / .6† protons m @S Me(Ec kro~ the P) on to a ber0lliu~ target
- Antiprotons selected m fGVJ Me(Ec
- =cercelated to .66 je(Ec }7vin 1 NV je(w }stochastic and electron coolingw
- 7+ected to the e/per~ents
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

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Antiprotonic helium spectroscopy + heavy 3-body QED theory ⇒ antiproton mass.

\[ \left| m_p - m_{\bar{p}} \right| / m_p \]

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.

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<th>DOCUMENT ID</th>
<th>TECN</th>
<th>COMMENT</th>
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<td>&lt;2 × 10^{-9}</td>
<td>90</td>
<td>1 HORI</td>
<td>06</td>
<td>SPEC $\bar{p}e^-He$ atom</td>
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<tr>
<td>&lt;1.0 × 10^{-8}</td>
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<td>03</td>
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<td>2 TORII</td>
<td>99</td>
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</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)
Mround-state \( \ell 2 \) ok!

Splitting due to and depending on the \( p^- \) and \( e^B \)-magnetic-\( \sim \)-ents

First measurement would improve \( \mu_p \) current precision 6Gf4 kro-

More precise measurements on \( p^- \)-magnetic-\( \sim \)-actor

Measurement at D16z
Mround-state 12) ok!

anti-!

anti-! detector

Gq-M!W spin-klip ca9it0
}high-kield seeever¶ lo%-kield seeever m resonance

anti-! count

jicro%a9e kre?uenc0
1st stage: Linear Paul-trap - capture and cool antiprotons

5.3 MeV antiprotons from the AD, decelerated to ~ 100 keV by an RFQD
@ Paul-traps kor !bar production

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

transfer antiprotons to 3D Paul-trap

positrons

antihydrogen atomic beam
'hat is a Paul-trap*

DC quadrupole field

“Deconfinement” along this axis

Confinement along this axis
'hat is a Paul-trap*

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

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

where \( U \) and \( V \) are quadrupole and sinusoidal potentials, respectively.

This equation is used in traps and not used in the mass filter.
'hat is a Paul-trap*

7?uation ok ~otionO  \[ x'' + \left( \frac{e}{mr_0^2} \right) (U - V \cos \omega t) x = 0 \]

8ntroducing \[ a = \frac{4eU}{m \omega^2 r_0^2} \quad q = \frac{2eV}{m \omega^2 r_0^2} \quad \xi = \omega t / 2 \]

7?ui9alent to the Mathieu equationO \[ \frac{d^2 u}{d \xi^2} + (a - 2q \cos 2\xi) u = 0 \]

jass kilter  
)tabilit0 kor both /E0  %ithin this regionO

A trap operates on this line  
}no =: co~ponentw

stabilit0 ik ? → N6G5

)yobel Pri\We .5<5I 'olkgang PaulO  Paul-trap  and  ?uadrupole ~ass kilter w
'hat is a Paul-trap*

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3ecular ~otion slo%l large }as ik in a har~onic CpseudopotentialCw ooling 1 da~ping this ~otions

jass kilter /tabilit0 kor both /E0 %ithin this regionO

jicro~otion }Ndri9ing kre?uenc0 B har~onicsw

}yobel Pri\We .5<5l 'olkgang PaulO  Paul-trap and ?uadrupole ~ass kilter w
'h0 a Paul-trap*

- Superconducting magnets ok Penning traps are assisted difficult to access with lasers assist radiative recombination etc

- Arionic pseudopotential cooling R compression open point-live source ok antihydrogen

- Output ground-state atoms cited states ionized b0 high F2 kield at the edges constituents recaptured

- The principle is charge-independent can trap @ opposite charges
T!7 L8y7AF PAUL-TFAP
Linear Paul-trap capture

- Antiproton bunch
- Shutter electrode @ -5 kV DC
- 0 kV DC
- =egrader coil
Linear Paul-trap capture

-5 kV DC

shutter electrode @ -5 kV DC

Trapping
Longitudinal potential
Transversal F2 Quadrupole electric field between q rods

1Paul-trap
Simulation of $\bar{p}$-energy after degrader coil

Longitudinal energy (keV)

Transverse energy (keV)

Hutter electrodes at $> -V$

$> V$ deep transverse pseudopotential cell
Parameters ok our Paul-trap

TFAP $^{87}$O $\rightarrow$ bea$\sim$ siWew

- longitudinal $O \cdot Vc$
- transverse $O \cdot 6$ $\sim$ $\emptyset$
Parameters ok our Paul-trap

- longitudinal
- transversal

Nonlinear resonances

Voltage between neighbouring electrodes [kV]

Frequency [MHz]
Parameters ok our Paul-trap

- longitudinal
- transverse

Isolines ok trans9G pseudopotential %ell depth [ve()]

Voltage between neighbouring electrodes [kV]

Frequency [MHz]
Parameters ok our Paul-trap

Parameter space increases (but also the RF losses)

- longitudinal $O_{\text{Vc}}$
- transverse $O_{\text{6}}$ ~ $\bar{O}$

Isolines ok trans9G pseudopotential %ell depth $[ve()]$
Parameters ok our Paul-trap:

- longitudinal $V_c$
- transverse $\phi$

Voltage between neighbouring electrodes [kV]
Frequency [MHz]

TFAP $\phi$ bea~siWew

hosen para~eters

$\kappa_{\text{dis}} 1 \ fV \ j!W$

$\kappa_{\text{sec}} 1 \ .qGJ \ j!W$

yeed a $\text{F}2$

resonator z
The same double-coil Kor other electrodes

Lumped elements to veep similar fV j!W CreasonableC

'inding in counter-directions

The same double-coil Kor other @ electrodes
Fesonator eigen-odes
?uadrupole }trappingw ~ode

- Counter-running currents in the @ coils
- D-kield ~ostl0 bet%een the @ coils
- 7kecti9e L is Cs~allCl resonant kre?uenc0 is ClargeC
Fesonator eigen-odes?uadrupole trappingw ~ode

- Counter-running currents in the @ coils
- D-kield ~ostl0 bet%een the @ coils
- 7kfecti9e L is Cs~allCI resonant kre?uenc0 is ClargeC

Virtual shortcircuit (same RF potential and phase)

Can add anything without disturbing the quadrupole mode
Fesonator eigen-odes

dipole – resistive cooling

- Parallel currents in the @ coils
- Live a double-solenoid D-kield in a larger solenoid
- 7klecti9e L is ClargeCl resonant frequency is Cs~aliC

Used kor coolingEdetectionO e/cited b0 secular ~otion

:oupling an e/ternal resonant resisti9e circuit to this ~ode
Fesonator eigen-odesO
dipole – resistive cooling

- Parallel currents in the @ coils
- Live a double-solenoid D-field in a larger solenoe
- Electric L is large CI resonant frequency is small CI
- Just match secular frequency

One possibility to tune cooling mode freq. to secular frequency

UNWANTED! for efficient cooling maximize
Resonant Rshunt x Δf ~ 1/C

Used for cooling detection Edetection
Cited b0 secular motion:
- Coupling an external resonant resistive circuit to this mode
To tune the cooling mode frequencies to have the quadrupole and dipole mode eigenfrequencies apart enough to keep the shunt loss \( \Delta k \) within the largest possible without additional tuning capacitance.
D-kield patterns ok the t%o ~odes

oolingEdiagnostic ~ode

Trap ~ode
D-kield patterns ok the two modes

Antenna for cooling Edetection should couple to cooling mode only for ini~u~ coupling to trap mode to avoid saturation ok diagnostics.
Construction design

“7ndcap” segments
- same F2 potential sapphire capacitance
- @ v( =: to confine p-s to the Cperkect C-quadrapole transverse field

}asv about detailsGGGw

- @ v( != cables inside the coils
Construction design

- Upside down 9ie%w

- Axial double-coils
  - Provide superfluid liquid supply to the electrodes
  - Shielded path for the endcap segments bias cable

Superfluid reservoir
Construction I design

- SupportO
  - yiohi~ rings
  - Sapphirie isolator rods

This F2 structure can be kloated to ke% .66 (to e+ect antiprotons z)
Design

yiobiu~ shield to confine surface currents to superconducting surfaces
Construction design

- Sputtered copper: good heat-conductivity, easier to cool
- To provide U!
Construction design

Dea~port klangesO

- to hold thin coil %indo% on entrance side }
- to hold shutter electrodes }-V v(w
The high-Q endcap capacitance

0.2mm sapphire disk
!elius-distributor B ca9it0 9essel

Large grain SiWe
yb disv

Toov 0ear to yb-sputter
Test casit0 kor the linear trap

jodeling the quadrupole model “halk” ok the real resonator double-coil pairw

(essell i~ersed in superkluid heliu~

- jicrophonics **
- F2I cr0ogenic propertiesI etc
Test cavity for the linear trap

- Capacitor plate against top plate of glass vessel representing the electrodes and capacitance to virtual ground
- Sapphire rod support
- @With capacity and diagnostic probes
- Double-coil ~ inner-diameter pipe killed with superfluid helium

Conclusions
- Microphonics XY could locv to oscillating eigenfrequency
- Cooling is sufficient
- Q-factor not too good but enough for f/.6
7-bearing welding test version nB. with realistic electrode...
Quadrupole mode in the final trap
Quadrupole mode in the final trap

Virtual ground plane

Representing virtual ground

Representing shutters

ELECTRODE
Test cavity 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 ANTI PROTONS 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:
  \( \bar{p} \Rightarrow 1 \text{ MHz, } 40 \text{ V} \)
  \( e^+ \Rightarrow 350 \text{ MHz, } 5 \text{ kV} \)

  2 frequencies at the secular motions (cooling)
Piège de Paul 3D

antiprotons

positrons
Cryostat
Helium distributor (superfluid He)

Linear Paul-trap

3D Paul-trap