Trapped Antihydrogen

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Contents

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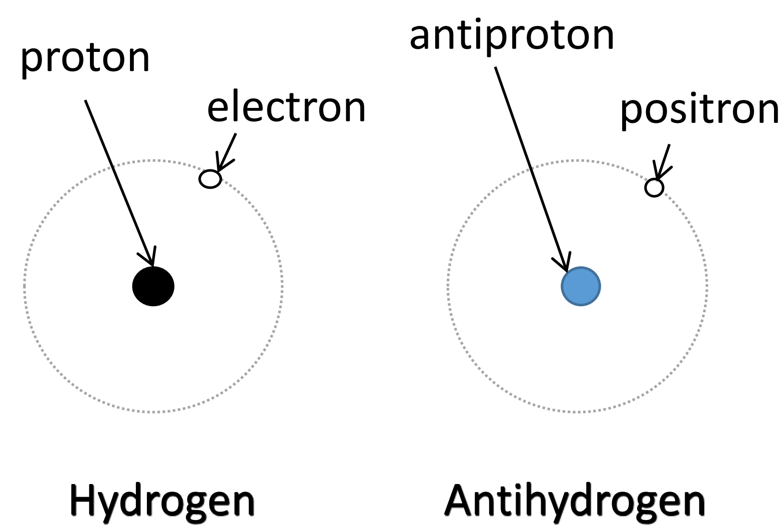
1. Introduction

- Antihydrogen is the bound state of an antiproton and a positron.

  It is an anti-atom.

  Antihydrogens are electrically neutral.

- It has been produced at low energies at CERN since 2002.
- It is used for a precision test of nature's fundamental symmetries.
- In this paper, a new technical development is reported; <u>trapping of antihydrogens.</u>



Mass of antiproton is 938 MeV/c^2
Mass of positron is 0.511 MeV/c^2
Binding energy of antihydrogen is 13.6 eV

2. Procedure of the experiment

1) Trap antiprotons

2) Trap positrons

3) Form Antihydrogens

4) Trap Antihydrogens with a magnetic field

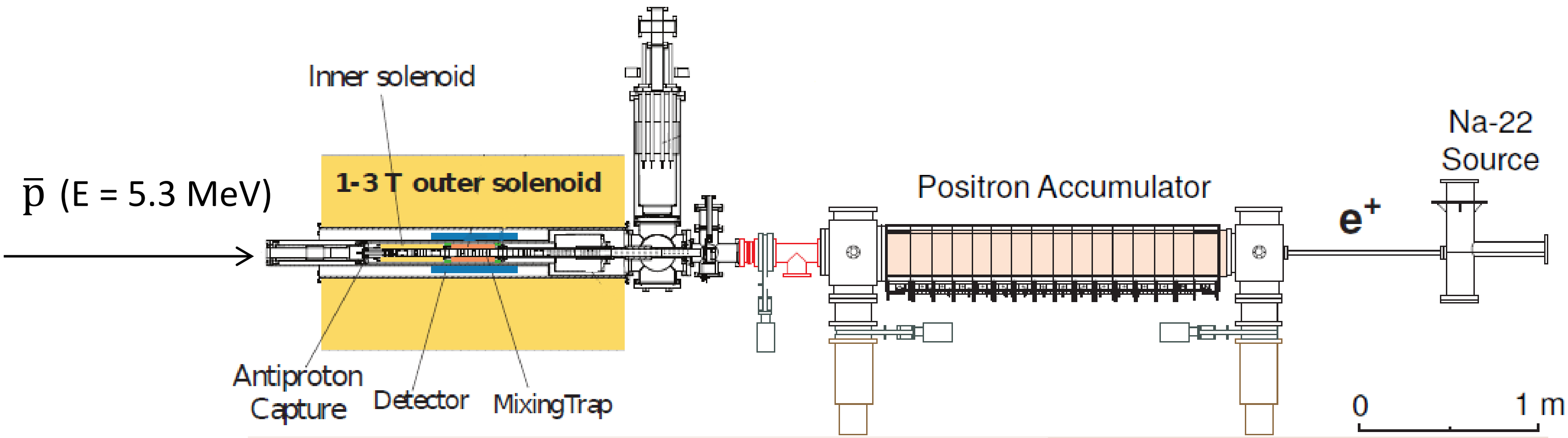
5) Switch off the magnetic field and release Antihydrogens

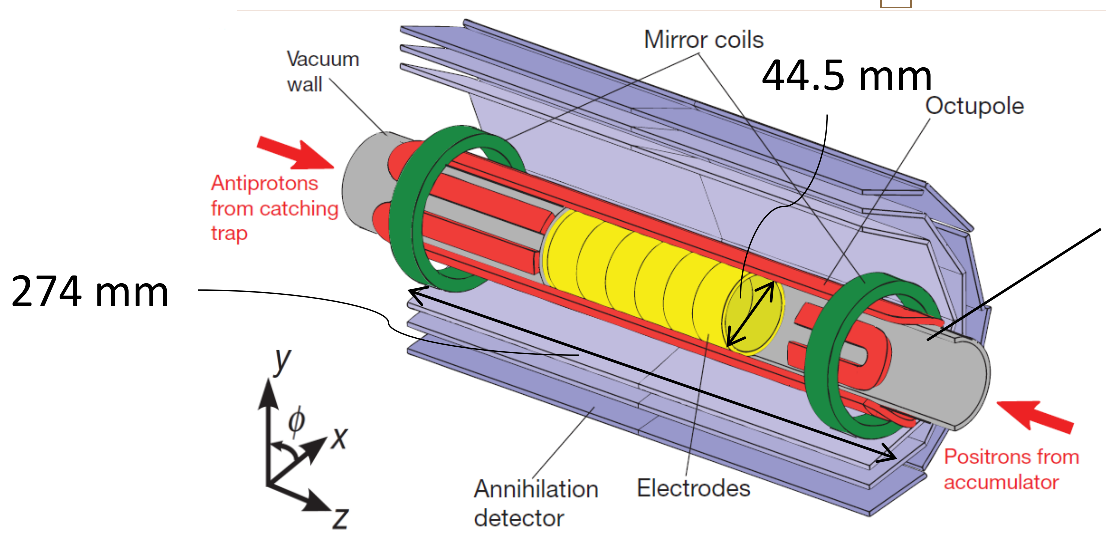
6) Detect pions from Antiproton Annihilation

3. The ALPHA apparatus

- The ALPHA apparatus uses several traps.
- The ALPHA apparatus has a novel superconducting magnet in order to trap neutral antihydrogens through interaction with their magnetic moments.

CERN Antiproton Decelerator





Central mixing part

4. Experiment
Step 1&2. Trap antiprotons and positrons

- Antiprotons

  Number : 3×10^4

  Radius : 0.8 mm

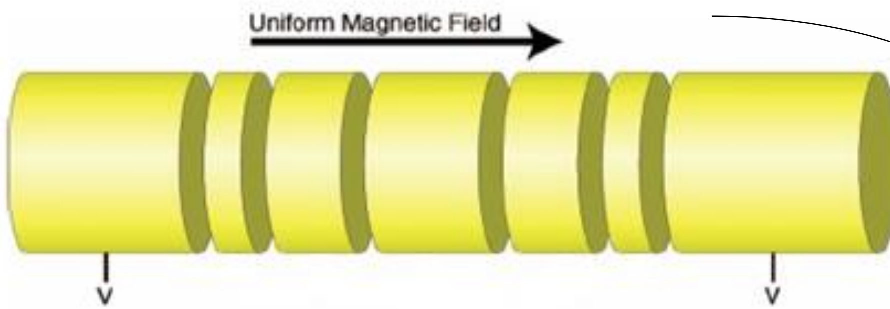
  Temperature : 200 K

- Positrons

  Number : 2×10^6

  Radius : 0.9 mm

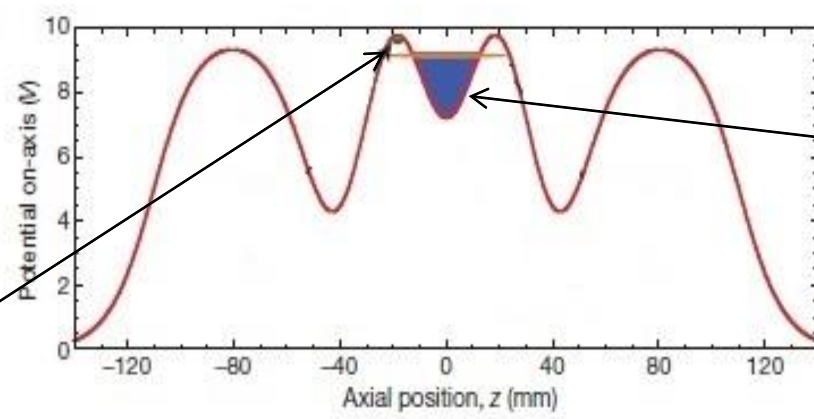
  Temperature : 40 K



Penning trap uses
a static electric field and
a static magnetic field.
(B = 1 T)

Antiprotons and positrons are trapped in their respective potential wells.

Schematic view of potential

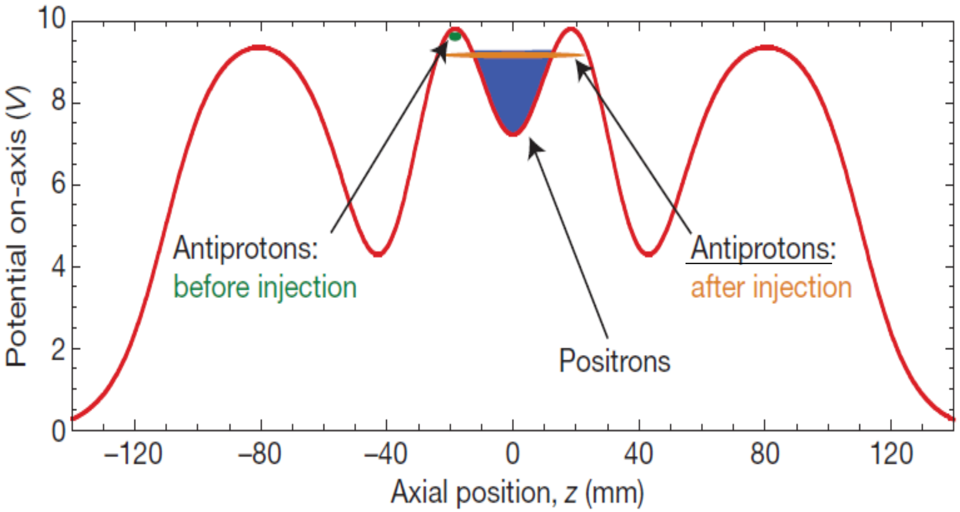


a well for trapping positrons

a well for trapping antiprotons

Step 3. Form antihydrogens

- The antiprotons are excited into the positron well using an oscillating electric field.
- Antiprotons and positrons interact for 1 second in the potential.
- After the 1 second mixing period, the remaining charged particles (antiprotons and positrons) are ejected from the experiment.



Step 4. Trap Antihydrogens with a magnetic field

1) Magnetic moment of antihydrogen

- Antihydrogen is electrically neutral and is not trapped by Penning trap. Therefore, interaction of magnetic moment and magnetic field is used to trap antihydrogens.
- An antiproton and a positron have magnetic moments;

$$\mu_{e^+} = g_{e^+}\mu_B s,\ \ g_{e^+} \approx 2.0,\ \ \mu_B = \frac{e\hbar}{2m_{e^+}},\ \ s = \pm\frac{1}{2}$$

$$\mu_{\overline{p}} = -g_{\overline{p}}\,\mu_N s,\ \ g_{\overline{p}} \approx 3.4,\ \ \mu_N = \frac{e\hbar}{2m_{\overline{p}}},\ \ s = \pm\frac{1}{2}$$

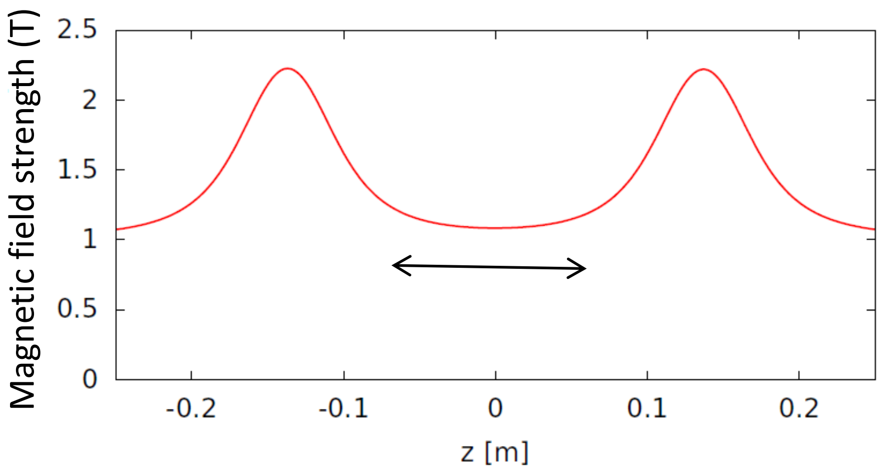
(μ_B : Bohr magneton, μ_N : Nuclear magneton)

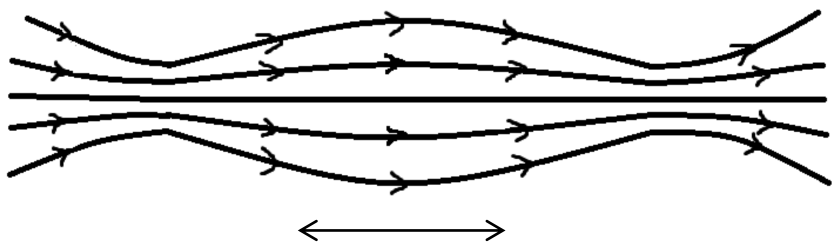
- The magnetic moment of antihydrogen is dominated by that of positron because of the large mass ratio, $m_{\overline{p}}/m_{e+} \sim 1800$.

Step 4. Trap Antihydrogens with a magnetic field
2) Trapping of neutral antihydrogen

- The magnetic potential energy between the external magnetic field and the atom's magnetic moment is given as

$$U_{mag} = -\mu_{\overline{H}} \cdot B = \mp \mu_B B \qquad \text{for } S = \pm 1/2$$





- Antihydrogens with magnetic moment parallel to the magnetic field B are trapped in the central region where the magnetic field is low.
- Antihydrogens with magnetic moment anti-parallel to the magnetic field B are not trapped. They escape from the experiment.

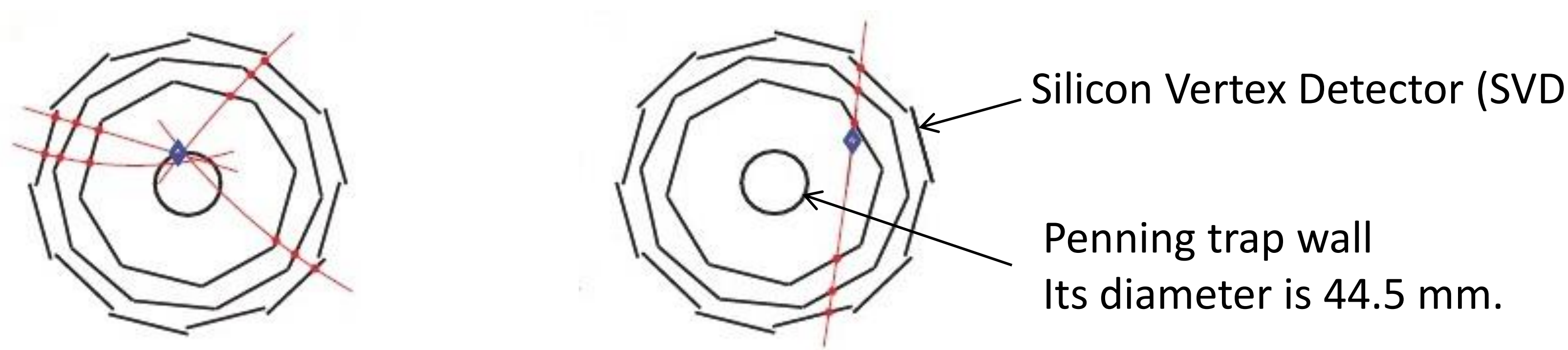
Step 6. Detect pions from Antiproton annihilation

- Antihydrogen trapping is confirmed by releasing trapped antihydrogens and detecting their annihilations in material.

$$p + \bar{p} \rightarrow \pi^{+} + \pi^{+} + \pi^{-} + \pi^{-} \cdots$$

- The antiproton annihilation vertex at the Penning trap wall (black circle) is identified with the track reconstruction.
- Antiproton annihilation can be distinguished from a cosmic ray by considering their track topologies.

Projected end views (x-y plane)



Antiproton annihilation

cosmic ray event

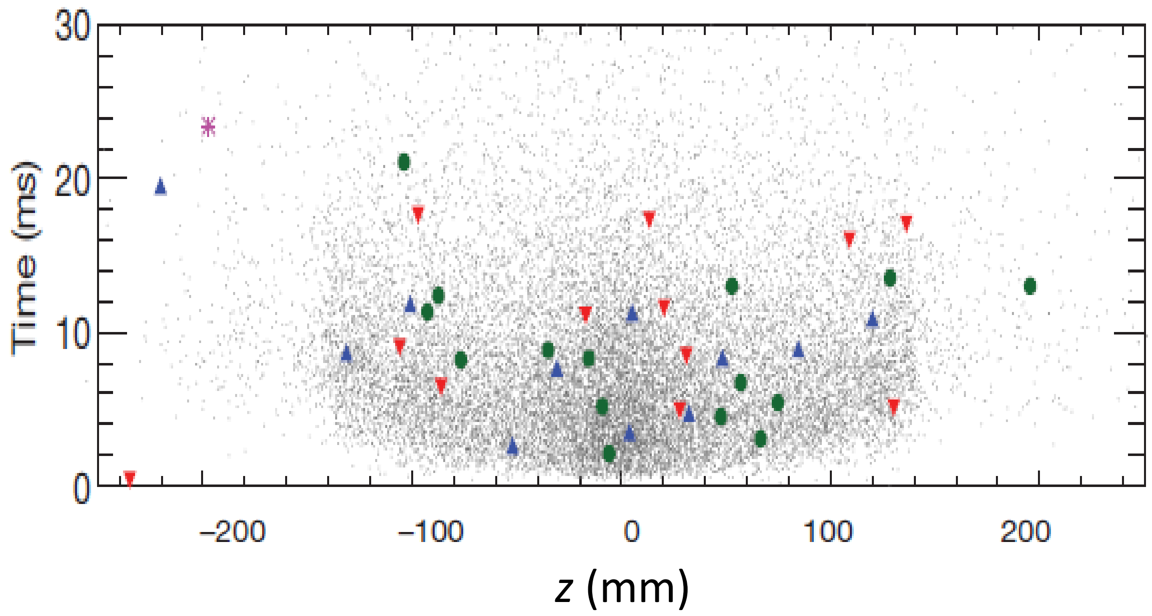
Step 6. Detect pions from Antiproton annihilation

- The magnetic field is then switched off and antihydrogens are released.

  Antiproton annihilations in 30 ms after the magnet switch off are looked for.

- The whole process is repeated 335 times and 38 annihilation events are detected.

- The measured background is 1.4 ± 1.4 events (scaled to 335 attempts).



Green, blue, and red points are from three different data sets.

- The figure shows *time*–*z* distribution for annihilation.
- The small gray dots in the figure are from a numerical simulation of antihydrogen atoms and their annihilations.

Measured distributions are consistent with the predicted behaviour of neutral antihydrogen.

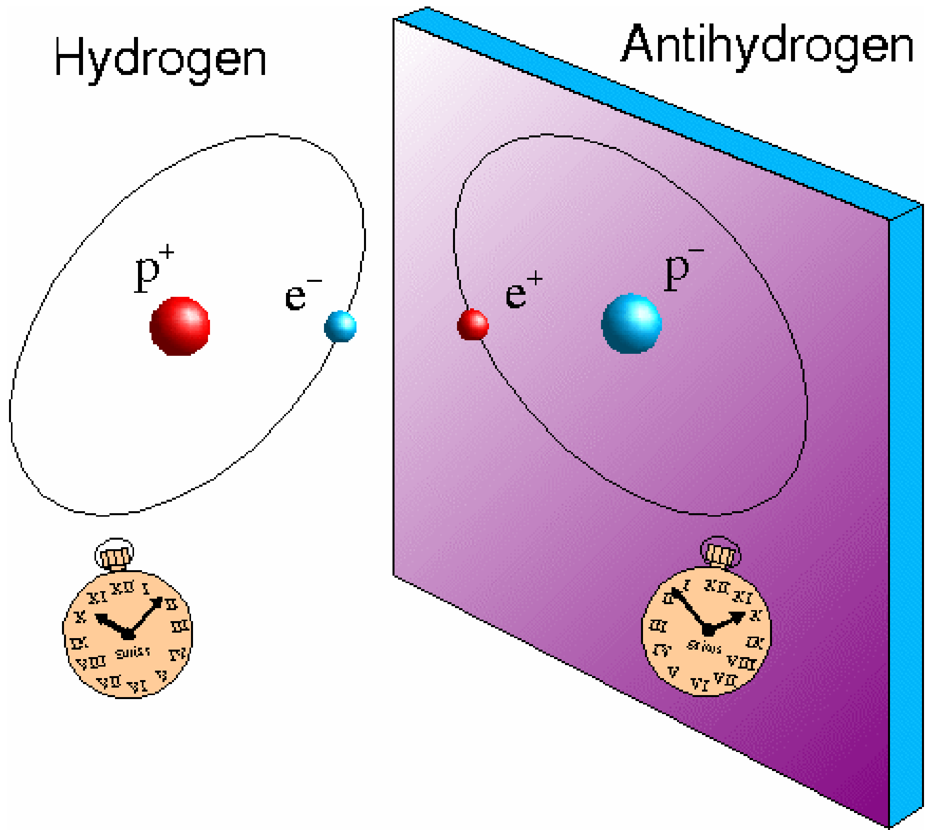
5. Summary

- An antihydrogen is the bound state of an antiproton and a positron.
  It is an anti-atom.
  Antihydrogens are electrically neutral.
- Antihydrogens are formed from antiprotons and positrons.
- The antiprotons are provided by CERN Antiproton Decelerator.
- The positrons are produced in the decay of ^{22}Na radioactive source.
- The ALPHA apparatus has a novel superconducting magnet in order to trap neutral antihydrogens with the magnetic field.
- Antihydrogen trapping is confirmed by detecting their annihilations.
- In total, 38 annihilation events were observed.
- The measured background was 1.4 ± 1.4 events compared to the 38 annihilation events.
- This way, the technique to trap neutral antihydrogens with a magnetic field was established.

Back up

CPT theorem

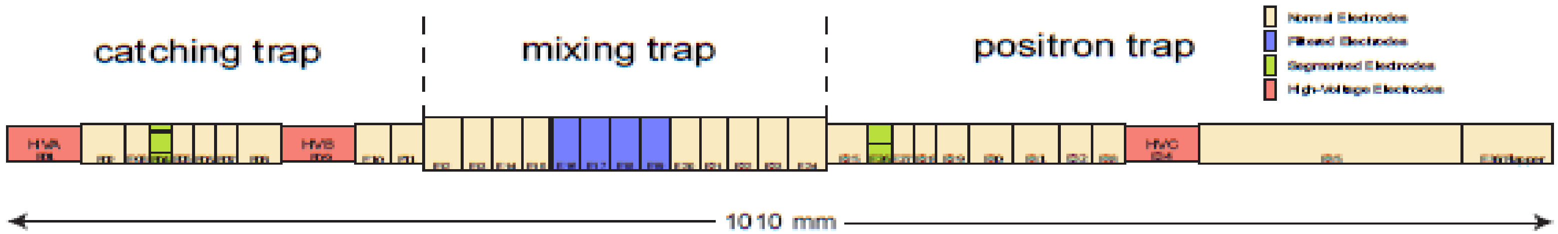
- The CPT theorem says that every relativistic quantum field theory has a symmetry that simultaneously reverses charge (C), reverses the orientation of space (or ‘parity,’ P), and reverses the direction of time (T).



Penning Trap

- Penning traps are widely-used class of charged particle traps.
- The prototypical Penning trap consist of a solenoidal magnetic field and a quadratic electric potential.

$$B = B_Z \hat{Z}, \quad \phi = \frac{V_0}{2d}\left(z^2 - \frac{r^2}{2}\right)$$



- This figure shows the ALPHA Penning-Malmberg trap electrodes.
- The trap is positioned in a 1 T solenoidal magnetic field directed along the trap axis.
- The ends of the cylinders are open, which allows access for particles to be introduced or for diagnostic devices.

Magnetic trap

- Forming a magnetic field minimum in the axial direction (parallel to the Penning trap axis) is easily achieved by the mirror coils.
- To create a minimum of magnetic field perpendicular to the axis, a transverse multipole field is used.
- For an ideal multipole magnet of order ℓ, the magnet adds a transverse component of magnetic field

$$B_\perp \propto B^\ell$$

- An octupole ($\ell = 3$) field is generated using eight current bars with the current flowing in alternating directions.
- The depth of the magnetic trap is the difference in the magnetic field magnitude on the axis (which is just the solenoidal field, Bz) and that at the wall radius.

$$\Delta|\mathbf{B}| = \sqrt{B_z^2 + B_w^2} - B_z.$$

Superconducting magnet

- The magnetic dipole moment for antihydrogen is very small, and to make traps strong enough, we need very high currents.
- Therefore, we use superconducting wire in our magnets.
  A superconductor can carry very high currents without dissipating any heat.
- However, superconductors only operate at very low temperatures.
  Our magnets are placed in a bath of liquid helium, which has a temperature of 4.2 K.
- Superconducting magnets can very quickly extract the current and shut off the magnetic field.–This happens in less than 0.01 s.
- This means that the antihydrogen atoms will escape over a very short period of time and we will know exactly when to look for them, so that we won't mistake cosmic rays for antihydrogen atoms.

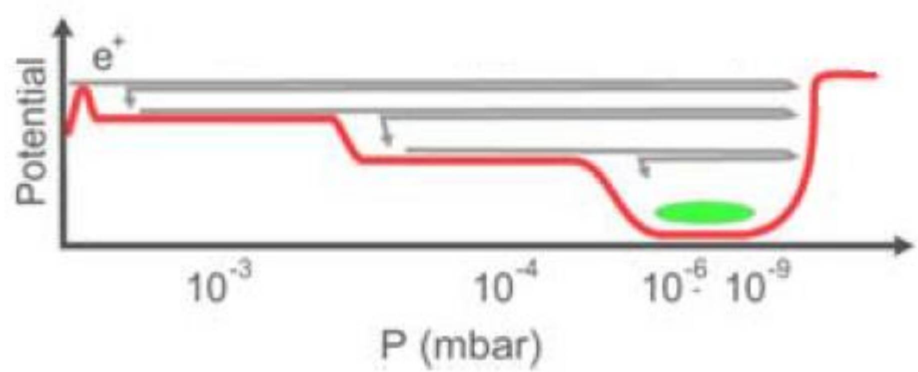
Particle sources
1) Positrons

- Positrons from beta decay can have several hundred keV of energy, and are too energetic to be trapped.

$$^{22}_{11}\mathrm{Na} \rightarrow {}^{22}_{10}\mathrm{Ne} + {}^{0}_{1}e^{+} + \nu_e$$

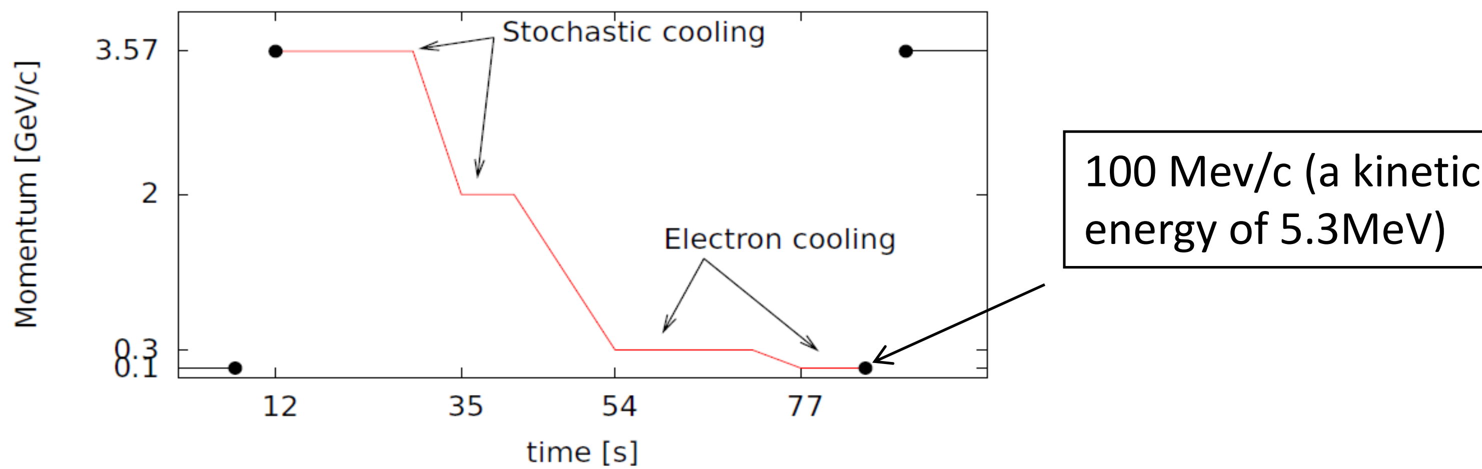
- In a Surko-type accumulator, a fraction of the positrons emitted from the radioisotope become implanted in a thin layer of material, moderator, usually a layer of frozen neon or argon.

- Inside the moderator, a small fraction of the positrons lose energy through interactions with the material and are emitted from the surface of the moderator with a few electronvolts of energy.



2) Antiprotons

- Antiprotons are produced at AD, through the collision of protons at 26 GeV with an iridium target and captured into a storage ring with an momentum of 3.5 GeV/c.
- Two techniques are used to perform cooling of the beam: stochastic cooling, electron cooling.

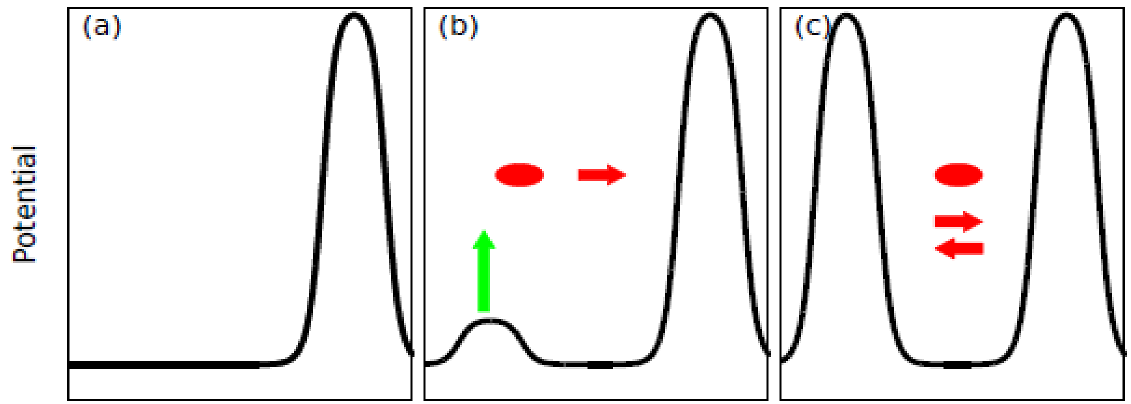


- Stochastic cooling acts by detecting deviations of particle momenta from the nominal value as they pass a sensor.
- Electron cooling combines the antiproton beam with a cold electron beam over a short length. The antiprotons transfer energy to the electrons through Coulomb interactions.

Antiproton cooling (collisional cooling)

- After extraction from the AD, the antiprotons must be confined in a Penning trap.
- It is exceedingly difficult to produce wells that can trap particles of such high energies, so the first energy reduction is performed by passing the antiprotons through a 218 μm thick Alminium foil ('degrader').
- As the antiprotons pass through the degrader, they lose energy through interactions with the foil material.
- In this model, around half of the antiprotons stop in the degrader and annihilate.
- The antiprotons that escape the degrader have a broad energy distribution ranging from zero to $\sim$ 5 MeV.

- Before the arrival of the antiproton beam from the AD, a $\sim$ 4 keV blocking potential is erected using a high voltage electrode 225 mm after the degrading foil.

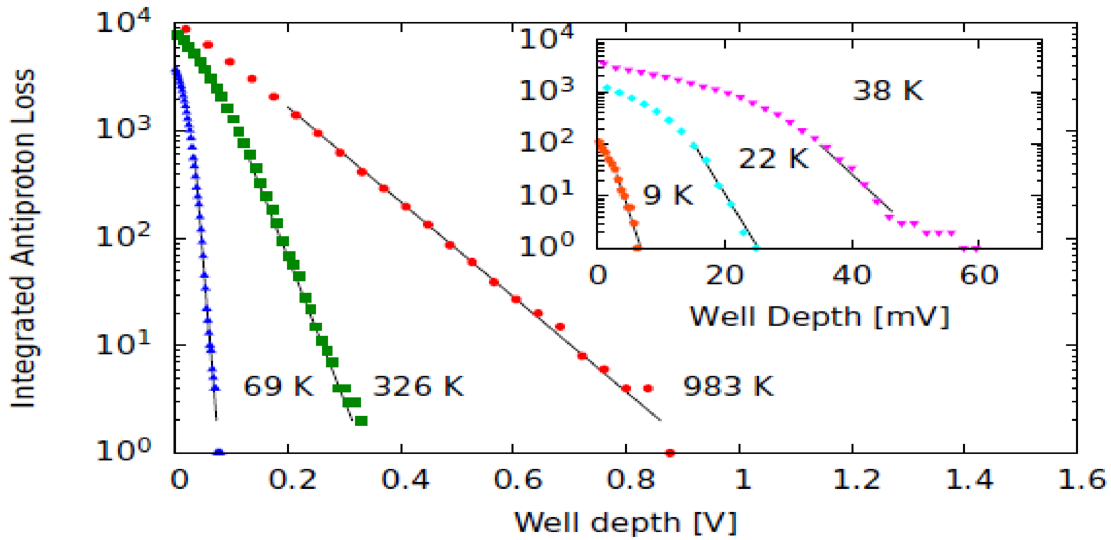


- ➢ Before the antiproton beam arrives, a reflecting potential is erected (a).
- ➢ As the antiprotons enter the apparatus, the gate electrode is triggered and begins to rise (b).
- ➢ The antiprotons are then trapped between the two electrodes(c).

- At the end of this procedure, we are left with a cloud of antiprotons with energies around 4 keV.

Antiproton cooling (evaporative cooling)

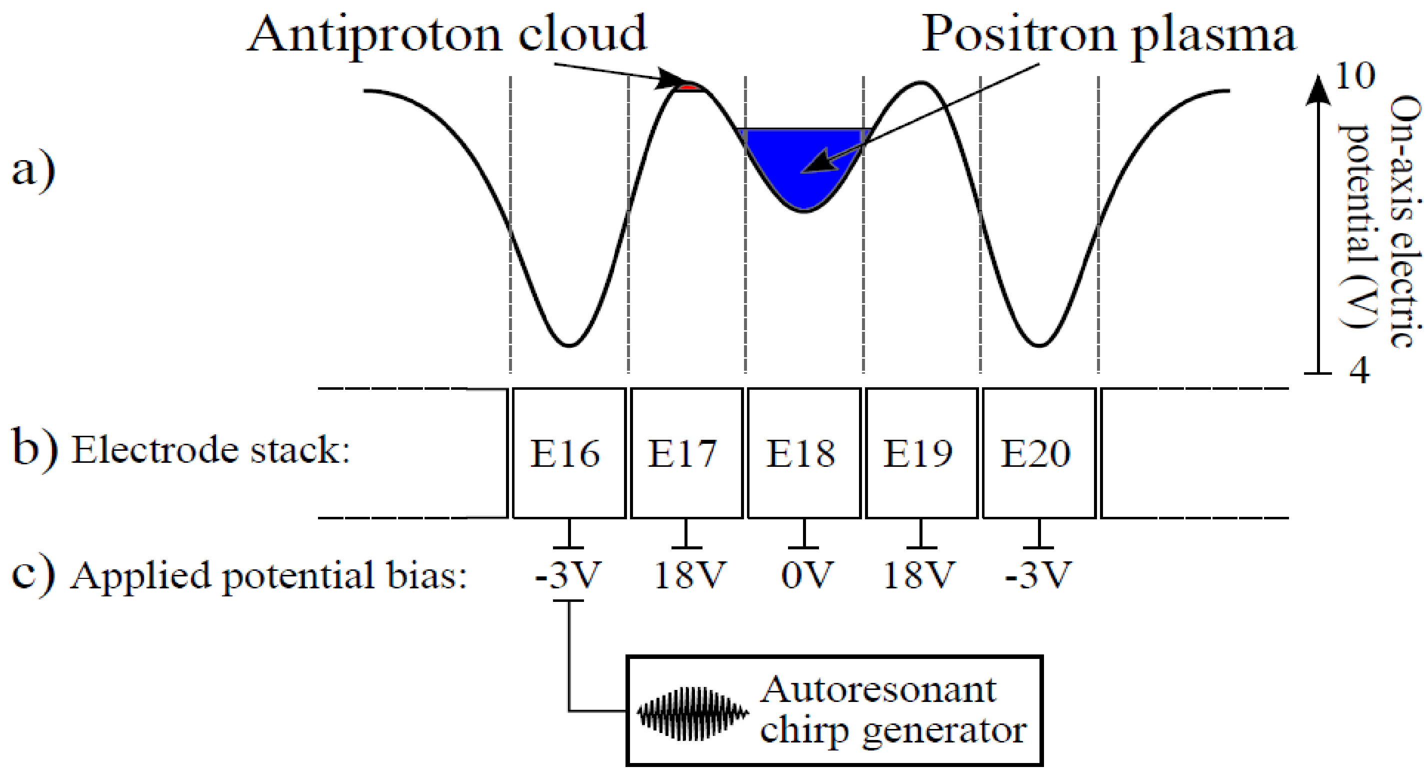
- Before carrying out evaporative cooling, a cloud of antiprotons was placed into a 1.5 V deep potential well.
- The depth of the well was then slowly reduced, ramping the voltage applied to one of the electrodes linearly in time, allowing the highest-energy antiprotons to escape.



example of number and temperature of the antiprotons remaining in the well

- This technique cools keV-range antiprotons to energies of the order meV, a six order-of-magnitude reduction.

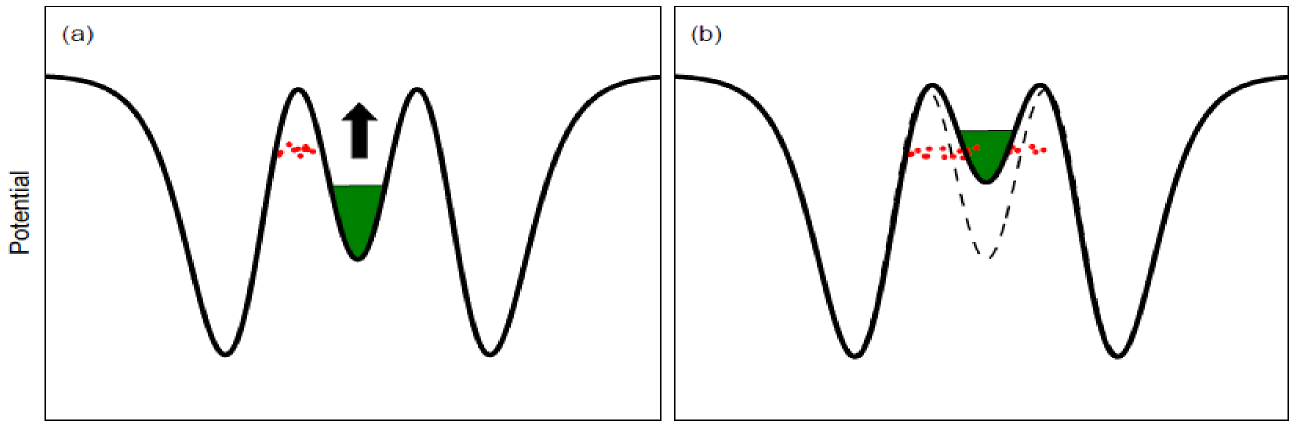
Nested well potential



- In a), the on–axis electric potential is shown, with the positrons confined in the central well, and the antiprotons in a side–well.
- b) shows a schematic of the electrode stack, with c) showing the applied voltages and the chirp signal generator.

Mixing scheme

- It is intended to introduce the antiprotons to the positron plasma with low kinetic energy.



➢ In (a), The antiprotons (the red dots) are prepared at a well-defined energy in one of the side wells.

➢ As the positron well is moved in (b), the antiprotons enter the positron plasma with a minimum of longitudinal energy.

- The antiprotons are released with small longitudinal kinetic energy inside the positron plasma, and should form antihydrogen with correspondingly low kinetic energy.

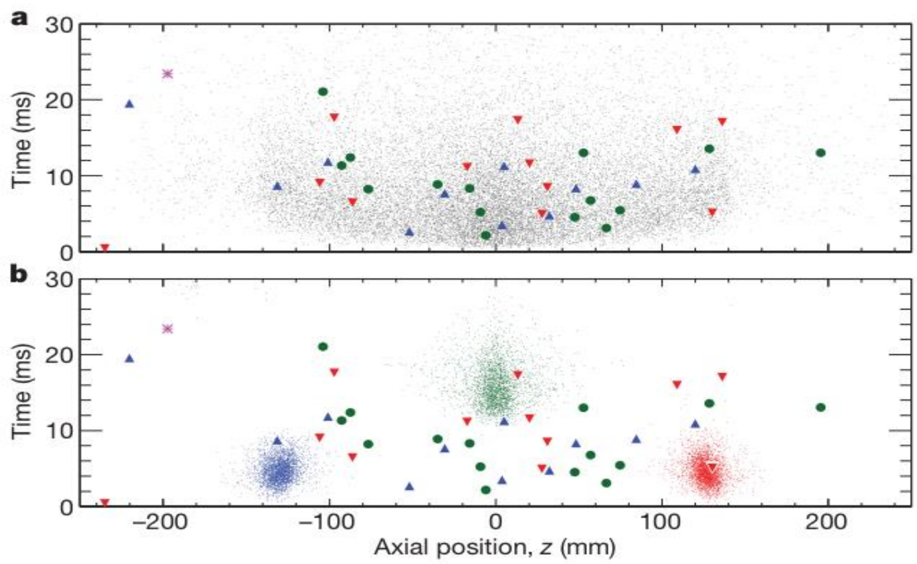
Detailed data analysis

- We look for antiproton annihilations from released antihydrogen in 30 ms after the start of the magnet shutdown.
- We conducted the above described search experiments 335 times, in three variations-no bias, left bias and right bias.
- It is demonstrated by using bias field to deflect any remaining antiprotons to the left (or right) of the apparatus as they are released.
- The variations allows us to distinguish between the release of trapped neutral antihydrogen and that of remaining antiprotons.
- We repeated the above experiments using heated positrons to ensure that any detected events are in fact antihydrogen.

Type of attempt	Number of attempts	Antiproton annihilation events
No bias	137	15
Left bias	101	11
Right bias	97	12
No bias, heated positrons	132	1
Left bias, heated positrons	60	0
Right bias, heated positrons	54	0

38 events!

Detailed data analysis



- Measured t-z distribution for annihilation with no bias (green circles), left bias (blue triangles), right bias (red triangles) and heated positrons (violet star).
- The gray dots of Fig.a are from a numerical simulation of antihydrogen atoms.
- The dots of Fig.b are from a numerical simulation of remaining antiprotons released from the trap.

It is shown from Fig.b that the measured annihilation distributions are not consistent with the simulation distribution for remaining antiprotons.

All measured distributions are consistent with the predicted behaviour of neutral antihydrogen.