ANTIMATTER IN THE LAB

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LECTURE # 1 (This lecture)
- What is antimatter?
- Some historical reminders
- Discrete symmetries
- Primordial antimatter search

LECTURE # 2 (This lecture)
- Antiprotons at low energies: cooling and trapping
- Experiments at the AD: exotic atoms made of antimatter
- Antihydrogen: a tool to study matter-antimatter asymmetry
- Everyday’s application of antimatter
Production of antimatter

The case of antiprotons

\[ p + p \rightarrow \bar{p} + p + p + p \]

\[ \sqrt{s} = \sqrt{2m_p^2 + 2E_p m_p} \]

Pair production: Threshold energy at 5.6 GeV

Bevatron was right at threshold when producing the first antiprotons!

Need higher proton energies to produce more antiprotons
Antiproton Cooling

Production at 26 GeV/c

Maximum production at 3.7 GeV/c (~ collection momentum)
Sharp fall-off around the peak

FIG. 1. Normalized antiproton yield (antiprotons per proton) at 26 GeV/c proton-beam momentum. The normalization is chosen so that the yield is one at the maximum.
Antiprotons at lower energies
Antiprotons at lower energies
Antiproton Cooling

Cooling: reduce phase space and increase phase-space density

\[ D = \frac{N}{\sqrt{E_h E_v L \frac{\Delta p}{p}}} \]

- \( E_h, E_v \): horizontal, vertical emittances
- \( L \): longitudinal spread
- \( N \): number of particles
- \( \Delta p / p \): momentum spread

Cooling methods:

- Stochastic cooling
- Electron cooling
Electron cooling

Le/C: fraction of circ. covered by electrons
R: classical radii, F ~ 0.3

\[ \tau_e = \frac{C}{L_e} \frac{F_1 \gamma_0^2}{r_e r_i n_e c \ln \Lambda} \left[ \left( \frac{k_B T_{be}}{m_e c^2} \right)^{3/2} + \left( \frac{k_B T_{bi}}{m_i c^2} \right)^{3/2} \right] . \]

before cooling —
after cooling —

\[ \Delta p/p < 10^{-4} \quad \epsilon < 1 \pi \text{ mm mrad} \]
Electron cooling

Le/C: fraction of circ. covered by electrons
R: classical radii, F ~ 0.3

Δp/p < 10^{-4}
ε < 1 π mm mrad
Stochastic cooling

Measure beam center by pick-ups
Correction signal to opposite kicker

Pioneered at CERN for discovery W,Z bosons

Nobel Prize S. van der Meer

Cooling power decreases with decreasing energy

Cooling time ~ number of particles

$$\frac{\Delta p}{p} \sim 0.07\%$$
$$\epsilon = 3 - 4 \pi \text{mm.mrad}$$
Electron cooler

Stochastic cooling lines
The Antiproton Decelerator

- Injection and Stochastic Cooling
- Stochastic Cooling
- Electron Cooling
- Electron Cooling & Extraction

Momentum [GeV/c] vs Time [s]
All-in-one machine:

Antiproton capture
deceleration & cooling
100 MeV/c (5.3 MeV)
Pulsed extraction

2-4 x 10^7 antiprotons per pulse of 100 ns length
1 pulse / 85–120 seconds
Decelerator after the AD : 5.3 MeV -> 100 keV

In commissioning. 
Delivery of $\bar{p}$ to all AD experiments planned for 2021
Can be seen at the AD!
Long trapping times require good vacuum!
Penning traps

Long trapping times require good vacuum!

BASE: $P < 2 \times 10^{-18} \text{ mbar}$

$\tau(\bar{p}) > 10.2 \text{ years (68\% confidence level)}$

Stefan Sellner et al.
“Improved limit on the directly measured antiproton lifetime”
New Journal of Physics, 19, (2017)
AD EXPERIMENTS
AD EXPERIMENTS

ASACUSA

BASE
ASACUSA
ATRAP

ALPHA
ATRAP
ASACUSA
AEGIS
GBAR
ANTIHYDROGEN EXPERIMENTS
How to make antihydrogen

\[ \text{AD} \rightarrow \bar{p} \]

[Diagram]

\[ \text{Na}_{22} \]

\[ \bar{e}^+ \]
How to make antihydrogen

\[ \bar{p} + e^+ \rightarrow \bar{H} + \gamma \]

\[ \bar{p} + e^+ + e^+ \rightarrow \bar{H} + e^+ \]

\[ e^+ \text{ from Na22} \]
How to make antihydrogen

\[ \bar{p} + e^+ \rightarrow \bar{H} + \gamma \]

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How to make antihydrogen

\[ \bar{p} + e^+ \rightarrow \bar{H} + \gamma \]

\[ \bar{p} + e^+ + e^+ \rightarrow \bar{H} + e^+ \]

\[ \bar{p} + Ps^* \rightarrow \bar{H}^* + e^- \]
How to make antihydrogen

\[ \bar{p} + e^+ \rightarrow \bar{H} + \gamma \]

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How to make antihydrogen

\[ \bar{p} + e^+ \rightarrow \bar{H} + \gamma \]

\[ \bar{p} + e^+ + e^+ \rightarrow \bar{H} + e^+ \]

\[ \bar{p} + Ps^* \rightarrow \bar{H}^* + e^- \]

\[ \bar{p} + Ps \rightarrow \bar{H} + e^- \]

\[ \bar{H} + Ps \rightarrow \bar{H}^+ + e^- \]

**Equations:**
- \[ \bar{p} + e^+ \rightarrow \bar{H} + \gamma \]
- \[ \bar{p} + e^+ + e^+ \rightarrow \bar{H} + e^+ \]
- \[ \bar{p} + Ps^* \rightarrow \bar{H}^* + e^- \]
- \[ \bar{p} + Ps \rightarrow \bar{H} + e^- \]
- \[ \bar{H} + Ps \rightarrow \bar{H}^+ + e^- \]
3-body recombination

\[ \bar{p} + e^+ + e^+ \rightarrow \bar{H} + e^+ \]
3-body recombination

\[ \bar{p} + e^+ + e^+ \rightarrow \bar{H} + e^+ \]

Vs.

Charge-exchange

\[ \bar{p} + Ps^* \rightarrow \bar{H}^* + e^- \]
EXPERIMENTAL CONCEPTS

3-body recombination

\[ \bar{p} + e^+ + e^+ \rightarrow \bar{H} + e^+ \]

Vs.

Charge-exchange

\[ \bar{p} + Ps^* \rightarrow \bar{H}^* + e^- \]

\[ \bar{p} + Ps \rightarrow \bar{H} + e^- \] (1)

\[ \bar{H} + Ps \rightarrow \bar{H}^+ + e^- \] (2)

Antihydrogen ion

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Antiprotons at lower energies
Antiprotons at lower energies
Antiprotons at lower energies

Production and detection of cold antihydrogen atoms

ATHENA Nature 419 (2002) 456
Spectroscopy of $\bar{H}$

**HYDROGEN**

- $^1S_{1/2}$
- $^2P_{1/2}$
- $^2P_{3/2}$

**Bohr**

**Dirac**

**Lamb**

**HFS**

\[ \nu_F = \frac{16}{3} \left( \frac{M_p}{M_p + m_e} \right)^3 m_e \mu_p \mu_N \alpha^2 cR_y \]

\[ \Delta \nu (\text{Zemach}) = \nu_F \frac{2Z \alpha m_e}{\pi^2} \int \frac{d^3 p}{p^4} \left[ \frac{G_E (p^2) G_M (p^2)}{1 + \kappa} - 1 \right] \]
Hyperfine splitting

21cm line

Image credit: NASA
Hyperfine splitting

21cm line

Image credit: NASA

Pioneer plaque

Image credit: NASA

CERN SUMMER STUDENT LECTURE - 2018 -
EXPERIMENTAL CONCEPTS

ASACUSA apparatus

not to scale

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**EXPERIMENTAL CONCEPTS**

ALPHA-2 apparatus

TRAP

\[ kT = \mu(B - B_0) \]
\[ \frac{\mu B}{k} = 0.6 \text{ K.T}^{-1} \]

BEAM

Cusp trap

Microwave Cavity

\( \bar{\text{H}} \) beam detector

Sextupole Magnet

**Vs.**

ASACUSA apparatus

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In a TRAP:
Precision of ~ 500 kHz

M. Ahmadi et al.
In a TRAP:
Precision of ~ 500 kHz

M. Ahmadi et al.

In a BEAM:
Precision of ~3Hz on HYDROGEN

M. Diermaier et al. Nature
Communications 8, 15749 (2017)
In a TRAP:
Relative precision obtained: $2 \times 10^{-12}$ (~ 5 kHz)

Comparison to H in the same apparatus

**Constraints for further precision**
- More \( \tilde{\text{H}} \)
- Control the QS (for beam)
- Colder \( \tilde{\text{H}} \):
  - Laser cooling (sympathetic cooling of particles/ions) \( \text{Be}^+, \text{La}^-, \text{C}_2^- \)
  - Lyman-alpha cooling of \( \tilde{\text{H}} \)
ON THE GRAVITY SIDE

\[ m_g = m_i \]

Credits: http://newscenter.lbl.gov/2013/04/30/antimatter-up-down/
**Antigravity:** $g_{\text{matter}} = -g_{\text{antimatter}}$

separation of matter and antimatter in Universe

**Quantum gravity**

Graviton ($S=2$) $\rightarrow$ add Gravivector ($S=1$), Graviscalar ($S=0$)

simplest case: static potential

$$V = -\frac{Gm_1m_2}{r}(1 \mp a e^{-r/v} + b e^{-r/s})$$

$\, \, a$: Gravivector, $\, \, b$: Graviscalar

$-$ attractive (matter-matter), $+$: repulsive: matter-antimatter

matter experiments: $|a-b|$

antimatter: $a+b$
STATUS OF THE FIELD

C. Amole et al. Nature Communications 4, 1785 (2013)

-65 < g/\bar{g} < 110

Green dots---simulated annihilations

Red circles---434 Observed annihilations

Vertical position of annihilation vertex during release of trapping field
AEGIS: DEFLECTOMETER

S. Aghion et al. Nature Communications 5 (2014) 4538

\[
h = \frac{g}{2} \left( \frac{L}{v_h} \right)^2
\]

\(~1-10\%~

FUTURE GOALS
FUTURE GOALS
FUTURE GOALS

ALPHA: VERTICAL TRAP

~10% - 1%

GBAR: DROPPING EXPERIMENT

First experiment connected to ELENA

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Inject antiprotons along magnetic field axis

Energy ~ few keV

Precisions measurement : only 1 \( \bar{p} \)

Detect image current in resonance circuit due to charge movement in the Penning trap

Detection by cryogenic resonance circuit (low noise)

\[
\nu_c^2 = \nu_r^2 + \nu_z^2 + \nu_r^2
\]

G. Gabrielse, W. Quint (LEAR)
\[ \nu_c = \frac{1}{2\pi} \frac{Q_{\bar{p}}}{M_{\bar{p}}} B \]

\[ \frac{\left(\frac{Q}{M}\right)_{\bar{p}}}{\left(\frac{Q}{M}\right)_{p}} - 1 = 1(69) \times 10^{-12} \]

\[
\frac{g_p,\bar{p}}{2} = \frac{\nu_L}{\nu_C} = \frac{\mu_p,\bar{p}}{\mu_N}
\]

\[
\frac{g_p}{2} = 2.792\,847\,344\,62\ (82)
\]

G. Schneider et al., Science 358, 1081 (2017)

\[
\frac{g_p}{2} = 2.792\,847\,344\,1\ (42)
\]


first measurement more precise for antimatter than for matter
ANTIPROTONIC HELIUM
ANTIPROTONIC HELIUM

Three-body system $\text{He}^{++}e^-\bar{p}$, $\bar{p}$ in highly excited, near circular states $(n,l) \sim (38,37)$

Comparison to 3-body QED calculations that use proton mass, magnetic moment

laser and microwave spectroscopy

CPT test

antiproton properties

mass, charge: $7 \times 10^{-10}$ 2011

magnetic moment: $2.9 \times 10^{-3}$ 2009
Your body produces antimatter:

The body of an 80 kg individual produces 180 positrons per hour! These come mostly from the disintegration of potassium-40, a natural isotope which is absorbed by drinking water, eating and breathing.

10 e+/s !
“DAILY ”APPLICATIONS

Antiprotons in accelerators!
Antiprotons for nuclear studies (PUMA)

Medical imaging : PET

Material Science

Antiproton Therapy (under study)

- $\text{e}^+ \text{ emitting isotope (C-11, N-13, O-15)}$
  
- (Lifetimes $\sim$ few to 100 minutes)

- positron lifetime spectroscopy: positron wavefunction can be localized in the attractive potential of a defect
- Check material structure, defects etc

- 2-fluoro-2-deoxy-D-glucose “FDG”

\begin{itemize}
  \item Hydrogen
  \item Oxygen
  \item Carbon
  \item Fluorine - 18
\end{itemize}
A fuel?

Most powerful fuel you can imagine.

1g would be enough to drive a car around the earth for 1000 times or bring the space shuttle into orbit

BUT ....
1g of antimatter contains 90 TJ (~21kT of TNT)
1g of $\bar{p} \sim 6 \times 10^{23}$

CERN produces $3 \times 10^7 \bar{p}$/cycle $\sim 10^{15} \bar{p}$/yr
1g of antimatter contains 90 TJ (~21kT of TNT)
1g of $\bar{p} \sim 6 \times 10^{23}$

CERN produces $3 \times 10^7 \bar{p}/\text{cycle} \sim 10^{15} \bar{p}/\text{yr}$

Almost a billion years needed to produce 1g (not saying trapping them all!)
“DAILY ”APPLICATIONS

1g of antimatter contains 90 TJ (~21kT of TNT)
1g of \( \bar{p} \) \( \sim \) \( 6 \times 10^{23} \)

CERN produces \( 3 \times 10^7 \bar{p}/\text{cycle} \) \( \sim \) \( 10^{15} \bar{p}/\text{yr} \)

Almost a billion years needed to produce 1g (not saying trapping them all!)

Energy efficiency is about \( 10^{-9} \)
We need \( \sim 9 \times 10^{22} \text{ J} \)

Electricity discount price @ CERN 1kWh = \( 3.6 \times 10^6 \text{ J} = 0.1€ \)
1g of antimatter contains 90 TJ (~21kT of TNT)
1g of \(\bar{p}\) \(\sim 6 \times 10^{23}\)

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\[
2 \ 000 \ 000 \ 000 \ 000 \ 000 \ 000 \ €
\]
1g of antimatter contains 90 TJ (~21kT of TNT)
1g of \(\bar{p}\) ~ \(6 \times 10^{23}\)

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\[
2\,000\,000\,000\,000\,000\,000\,000\,€
\]

A year of \(\bar{p}\) trapped and annihilating would illuminate a light bulb for 5s
AD PHYSICS PROGRAMME: TESTING FUNDAMENTAL SYMMETRIES & CORNERSTONE OF SM

TEST BODIES: EXOTIC ANTIMATTER ATOMS & ANTIPROTONS

>20 YEARS OF UNIQUE RESEARCH WITH ANTIHYDROGEN

ENTERING PRECISION AREA WITH ANTIHYDROGEN

MANY OTHER IDEAS: CHARGE NEUTRALITY, PROTONIUM SPECTROSCOPY, PORTABLE PBAR TRAP …

ANTIMATTER AS MEDICAL AND SCIENTIFIC TOOLS

OTHER APPLICATIONS OF ANTIMATTER?
AD PHYSICS PROGRAMME:
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