CHALLENGES AND APPROACHES OF UNVEILING THE NATURE OF ANTIMATTER AT CERN
(WITH A PARTICULAR FOCUS ON THE AEGIS EXPERIMENT)

Lillian Smestad, Postdoctoral researcher, The Research Council of Norway/CERN on behalf of the AEgIS collaboration

6th International Conference on New Frontiers in Physics (ICNFP2017)
17th - 29th of August 2017, Kolymbari, Crete, Greece
Sometime in the early universe…

Why are we here?
1) Test of fundamental CPT symmetry
Matter and antimatter should have equal properties (masses, lifetimes, |charge|, g-factors, …)
➤ Compare spectral lines of hydrogen and antihydrogen
➤ Study antiprotons and antiprotonic helium

2) Test of the Weak Equivalence Principle with antimatter
Inertial mass and gravitational mass are identical
➤ Compare the free fall of hydrogen and antihydrogen

Any observed difference would hint at new physics
**Approach**

Perform $\bar{H}$ measurements either with:

- **Trapped antihydrogen**
  - Require strong magnetic field gradient (broadened level lines)
  - Only the coldest anti-atoms can be trapped

or with:

- **A beam of cold antihydrogen**
  - Stark acceleration of Rydberg atoms (very sensitive to inhomogeneous electric field)
  - In-flight spectroscopy; anti-atoms of higher energy are also useful

*General problem: Low number of particles! Need particles as cold as possible for precision*
THE ANTIPROTON DECELERATOR

1. Antiproton production

2. Injection at 3.5 GeV/c

3. Deceleration and cooling (3.5 - 0.1 GeV/c)

4. Extraction ($\approx 2 \times 10^7$ in 200 ns)

**Roughly $3 \times 10^7$ antiprotons of 5.3 MeV are extracted every $\sim 120$ seconds and sent to a particular experiment.**
THE ANTIMATTER FACTORY

Currently five experiments in the Antimatter Factory

➤ AEGIS ➤ ALPHA ➤ ASACUSA ➤ ATRAP ➤ BASE ➤ GBAR (future)
ANTIHYDROGEN PRODUCTION

1) Three-body recombination ("mixing")
   ➤ Populations mixed in a trap
   ➤ High expected rate, $\sigma = 10^{-7}$ cm$^2$ @1K, $n >> 10$
   ➤ Long-duration process

2) Charge exchange
   ➤ Positronium introduced to trapped $\bar{p}$ cloud
   ➤ $\sigma = a_0 n_{Ps}^4, \sigma = 10^{-9}$ cm$^2$ @1K, $n$ given by $n_{Ps}$, temperature given by the antiproton
   ➤ Small solid angle $\Rightarrow$ low rate
   ➤ More narrow and well-defined quantum state distribution
   ➤ Demonstrated by ATRAP with Cesium (PRL 93 (2004) 263401)

Advantages:
Pulsed production (time of flight)
Potentially colder than via mixing
A TYPICAL ANTIHYDROGEN EXPERIMENT

Needed for antihydrogen:

- **Antiprotons:**
  - Production: GeV
  - Deceleration: MeV
  - Capture: keV
  - Cooling: meV

- **Positrons:**
  - Production: MeV
  - Deceleration/accumulation: eV

Needed for manipulations:

- Ultra High Vacuum (UHV)
- Cryogenic: T~10K
- Magnetic field: 1-5T
- Electrical field: ~10kV

Motivation

Approach

Antimatter physics

AEgIS

Future
PENNING TRAP

– the workhorse of experiments in the AD facility
FIRST COLD ANTIHYDROGEN

@AD in 2002

by

ATHENA (Nature 419(2002)456)

ATRAP (PRL 89 (2002) 213401)

Important step: must be cold for precision
TRAPPING OF ANTIHYDROGEN

@AD in 2010

First detection of trapped antihydrogen by ALPHA
(Nature 468 (2010) 673)

- Magnetic field gradient for confinement
- Depth typically 50µeV (can trap 0.5K H)

![Diagram of ALPHA apparatus]

Trapped antihydrogen
MICROWAVE SPECTROSCOPY

@AD in 2012 by ALPHA (Nature 483 (2012) 439)

- Injecting microwaves to induce positron spin-flips
- Look for annihilations during the injection ("appearance mode") as well as reduction in signal when trap is opened ("disappearance mode")
**BEAM FOR IN-FLIGHT HFS**

@AD in 2014 by ASACUSA (Nature Com. 5 (2014) 3089)

Defocusing of high-field seeking states

Spin-polarized beam 2.7 m downstream

➤ Rate of a few atoms/hour
➤ Most still in Rydberg states (n>29)
LASER SPECTROSCOPY

@AD in 2016 by ALPHA (Nature 541 (2017) 506)

First observation of the 1S-2S transition in antihydrogen

- Laser excitation of ground-state antihydrogen via two photons (243 nm)

Comparing frequencies of this transition for hydrogen and antihydrogen:

Consistent with CPT invariance to $\sim 2 \times 10^{-10}$
THE AEGIS EXPERIMENT

Antimatter Experiment: Gravity, Interferometry, Spectroscopy

Motivation  Approach  Antimatter physics  AEGIS  Future
THE AEGIS EXPERIMENT

Antimatter Experiment: Gravity, Interferometry, Spectroscopy

Probing universality of free fall (the Weak Equivalence Principle)

First precise direct test of gravitational interaction between matter and antimatter
THE AEGIS EXPERIMENT

- Antihydrogen produced via charge exchange with Ps
- Cold pulsed beam of antihydrogen by Stark acceleration
- Beam deflection measured with a moiré deflectometer

Different from other experiments in the AD hall

Motivation  Approach  Antimatter physics  AEGIS  Future

AEgIS, NIMB (2008) 266 (3) 351-356
AEgIS, Nature Communications 5 (2014) 4538
Positron trap

Positron accumulator

Chamber for Ps experiments

1T trap

5T trap

Target for Ps production and \( \bar{H} \) formation

Gravity module not in place yet

Positron source

Positron transfer line

Antiproton line

**Motivation**  
**Approach**  
**Antimatter physics**  
**AEgIS**  
**Future**
Gravity module [future]

Positron system

Laser hut

5T

1T

H production region
Achievements towards the gravity measurement:

➤ Catching and cooling of large number of antiprotons
➤ Transfer of the antiproton plasma in the production region
➤ Production, transfer and storage of an high number of positrons
➤ Studies of Ps formation and laser excitation to Rydberg levels
➤ Positronium production in the 1T

Under development:

➤ Rydberg excitation of Ps in the 1T
➤ Antihydrogen formation
➤ Synthesis of a forward anti-hydrogen beam
➤ Detectors for gravity measurement
➤ Transmission targets for improved antihydrogen production
➤ Techniques for cooling antiprotons
Two main challenges: colder / more antiprotons
From 2017: new low energy $\bar{p}$ decelerator **ELENA**.
ELENA

- Dramatically slows down the antiprotons from the AD
- Increases the trapping efficiency x 100
- Allows 4 experiments to run in parallel
- Allows new experiments to come in
Antihydrogen research at CERN covers a wide range

- Atomic physics
- Gravity
- Nuclear physics
- Plasma physics
- Cosmology
- Material science

- Requires modest resources but much patience & time
- Relies on many technologies from many fields of science
- Requires breakthroughs in numerous areas, most of which come from atomic and laser physics (cooling, manipulations, ...)

Lillian Smestad (RCN/CERN)  
ICNFP, Kolymbari, Crete. 29th of August 2017
Antimatter lends itself to studying fundamental structures of nature

The CERN Antimatter Factory, uniquely designed for the purpose, is currently hosting five experiments

Many advances within antimatter research have been made the last years, many developments are underway

The main challenges of the field are: acquiring sufficient amount of antimatter and having it cold enough to obtain precision in measurements

The AEgIS experiment aims to carry out the first precise direct measurement of gravity on antimatter by the use of a cold antihydrogen beam and a Moiré deflectometer

The 2017 AEgIS goal is antihydrogen production – we are entering data-taking mode: very exciting

The Extra Low ENergy Antiproton ring is currently being commissioned: the field of antimatter research will get a big boost after the Long Shutdown 2 of the LHC (2019-2020) – the future is bright!

Thank you for your attention!
BACK-UP
Rydberg atoms are very sensitive to inhomogeneous electric fields

Stark deceleration of hydrogen demonstrated

Beam deflection measured with a moiré deflectometer

Has been successfully used for a gravity measurement with ordinary matter, $\Delta(g)/g = 2 \times 10^{-4}$

$\Delta(g)/g = 1\%$ expected with $10^5$ H at 100mK

$$h = \frac{g}{a} \left( \frac{L}{v_h} \right)^2$$
MOIRÉ DEFLECTOMETER

A proof-of-principle measurement

AEGIS, Nature Communications 5 (2014) 4538

Mini-moiré deflectometer:
L=25mm, slit=12µm, pitch=40µm, 100µm thick gratings

➢ Tested 2012 in the AEGIS antiproton beam line, \( E_P \sim 100\text{keV} \)
➢ Measured with emulsion detector (next slide)

EM deflection of antiprotons: \( \Delta y = 9.8 \pm 0.9 \text{ (stat.)} \pm 6.4 \text{ (syst.) } \mu m \)
DETECTOR TEST CHAMBER

A new test-chamber installed on the secondary $\bar{p}$ extraction line in the AEgIS experimental area

➤ Moderating AD shot of 5.3 MeV to 0-16 keV with foils and electrostatic setup
➤ Use of clean, low energy antiprotons for detector and material studies
➤ Has been used for measuring silicon pixel detector
➤ Will be used for optimizing gravity detector design
ON-AXIS PS PRODUCTION

Change from reflection mode production to on-axis transmission mode production.

Likely to result in an improvement of $\bar{H}$ production.

Depends on:
- Distance to antiproton cloud
- Emission pattern
- Thermalisation

Possible bonus (if antiprotons cold enough): Remove the need for Stark acceleration of antihydrogen?
graphene or carbon foil

silica layer (few nm)

silica columns (~60 nm, with a spacing of ~160nm)

~1000 nm

Add something for focusing here?

Characterization of a transmission positron/positronium converter for antihydrogen production

S. Aghion\textsuperscript{a,b}, C. Amsler\textsuperscript{c,d}, T. Ariga\textsuperscript{e}, G. Bonomi\textsuperscript{e,f}, R. S. Brusa\textsuperscript{g,h}, M. Caccia\textsuperscript{b,i}, R. Caravita\textsuperscript{j,k}, F. Castelli\textsuperscript{b,m}, G. Cerchiari\textsuperscript{n}, D. Comparat\textsuperscript{o}, G. Consolati\textsuperscript{a,b}, A. Dametrio\textsuperscript{p}, L. Di Noto\textsuperscript{j,k}, M. Doser\textsuperscript{l}, A. Freadtate\textsuperscript{c}, C.

\textit{AEgIS, NIMB (2017) 407, 55-66}

Targets developed in collaboration with Aarhus University

- 20 nm carbon foil, \textasciitilde{}750 nm silica layer
- Ultraporous meso-structured silica film (\textasciitilde{}0.4 g/cm$^3$)
Transmission target in **transmission mode**

- **e\(^+\)**
- Backscattered e\(^-\)
- Secondary e\(^-\)
- Ps emitted by C
- Carbon foil
- SiO\(_2\) columns

**MCP surface, \(V\text{_{sat}} = [-800V, 200V]\)**

**Phosphor screen**

\(V\text{_{sat}}+1400V\)

\(V\text{_{sat}}+4200V\)

Transmission target in **reflection mode**

- **e\(^+\)**
- Backscattered e\(^-\)
- Secondary e\(^-\)
- Ps emitted by SiO\(_2\)
- SiO\(_2\) columns
- Carbon foil

**MCP surface, \(V\text{_{sat}} = [-800V, 200V]\)**

**Phosphor screen**

\(V\text{_{sat}}+1400V\)

\(V\text{_{sat}}+4200V\)
1. SSPALS measurement (PbWO₄)

2. Imaging of the forward-emitted particles (MCP–phosphor screen coupled to a CCD camera)

3. Time of Flight measurement of forward-emitted particles (MCP–phosphor screen coupled to a fast PMT)

\[ f_d = \frac{\int_{35ns}^{350ns} V(t)dt}{\int_{-3ns}^{350ns} V(t)dt} \]

Only o-Ps can be present after this time

Around 10% Ps emitted in transmission (in agreement with previous work on similar target)

<table>
<thead>
<tr>
<th>Transmission mode</th>
<th>Reflection mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fraction of e⁺ stopped in C</td>
<td>0.02</td>
</tr>
<tr>
<td>Fraction of e⁺ stopped in SiO₂</td>
<td>0.65</td>
</tr>
<tr>
<td>( f_d ), distance 0.8 cm</td>
<td>0.03</td>
</tr>
<tr>
<td>( f_d ), distance 3 cm</td>
<td>0.07</td>
</tr>
</tbody>
</table>
PS TRANSMISSION TARGET

1. SSPALS measurement (PbWO4)
2. Imaging of the forward-emitted particles (MCP–phosphor screen coupled to a CCD camera)
3. Time of Flight measurement of forward-emitted particles (MCP–phosphor screen coupled to a fast PMT)

Based on intensity of image when implanting on the MCP; lower limit of ~10% of e⁺ crossing the target
PS TRANSMISSION TARGET

1. SSPALS measurement (PbWO4)
2. Imaging of the forward-emitted particles (MCP–phosphor screen coupled to a CCD camera)
3. Time of Flight measurement of forward-emitted particles (MCP–phosphor screen coupled to a fast PMT)

- fast e+ crossing the target with around 1 keV.
- secondary electrons emitted with few eV

Successful first tests, developments planned:
- target design
- change of positron test chamber to facilitate measurements

Must be deflected for the purpose of antihydrogen production: possible with a set of grids