New Opportunities in the Physics Landscape at CERN

Antiproton Decelerator (AD)

Summary and Prospects

Klaus Jungmann, KVI, University of Groningen, NL

• Physics Motivation
• Unique Possibilities
• Tests of Fundamental Theories
• Precision Measurements
• Novel Techniques and Instrumentation
• Applications
• High Visibility
Physics Motivation
How do we work in Physics?

Sir Isaac Newton (1642 - 1727)

Basic Principles on which Scientists work in Physics

First Theory on Gravity
A Theory is only as good as it is experimentally verified.

A Theory without experimental verification has no standing.
• Excellent Description of ALL Observations

• However, many Open Questions

  Why 3 generations?
  Why some 30 parameters?
  Why one electric charge?
  What about CP violation?
  Why matter-antimatter asymmetry?

• Gravity not included

  No Combind Theory of Gravity and Quantum Mechanics.

• Contents of the Cosmos

  What’s the other 96% beyond matter?
Physics within the Standard Model:
complex systems, spectra, lifetimes...

Speculative Models:
Supersymmetry, Cold dark matter, Tachyons, Radiative muon generation, Technicolor, Leptoquarks, Extra gauge bosons, Extra dimensions, LeftRight Symmetry, Compositeness, Lepton flavour violation, ....

⇒ No Status in Physics, yet: “Not Even Wrong”
Experiments at the Frontiers of Standard Theory

**Direct Search Frontier**

- CERN
- Jura mountains
- Geneve Airport
- LHC tunnel (27km)

**Precision Frontier**

- complementary approaches

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Test of Fundamental Symmetries
Precision Measurements
First Capture of Antiprotons in a Penning Trap: A Kiloelectronvolt Source

G. Gabrielse, X. Fei, K. Helmerson, S. L. Rolston, R. Tjoelker, and T. A. Trainor
Department of Physics, University of Washington, Seattle, Washington 98195

H. Kalinowsky and J. Haas
Institute für Physik, University of Maine, West Germany

and

W. Kells
Fermi National Accelerator Laboratory
(Received 8 August 1986)

Since then CERN has a HIGHLY PUBLICLY VISIBLE program on Low Energy Precision Tests of most fundamental theories.
Precision requires Time

- pbar - p \( q/m \) 45 years
- electron \( g-2 \) 60 years
- muon \( g-2 \) 45 years
- muonium 1s-2s 15 years

Highly precise

Proton and Antiproton \( q/m \) compares to 0.1 ppb

Clock Comparisons

Proton and Antiproton gravitational acceleration equal to 1 ppm
Verifications of **CPT Symmetry**

Tests of particle/antiparticle symmetry (PDG)

- Inconsistent definition of figure of merit: comparison difficult
- Pattern of CPT violation unknown (P: weak interaction, CP: mesons)

→ **Arbitrary number juggling to get**

“accuracy” better than experiments !!!
generic CPT and Lorentz violating DIRAC equation

\[(i\gamma_{\mu} D_{\mu} - m - a \gamma_{\mu} - b \gamma_{5} \gamma_{\mu} - \frac{1}{2} H_{\mu\nu} \sigma_{\mu\nu} + ic \gamma_{\mu} D_{\nu} + id \gamma_{5} \gamma_{\mu} D_{\nu}) \psi = 0\]

\[iD_{\mu} \equiv i\partial_{\mu} - qA_{\mu}\]

\(a_{\mu}, b_{\mu}, c_{\mu}, d_{\mu}, H_{\mu\nu}\) break Lorentz Invariance

Kostelecky et al.:

- Interaction with a finite strength
- Figure of merit energy based

→ Completely different systems appear much more interesting!
Verifications of CPT symmetry

Using the Kostelecky et al. Standard Model Extension scheme

\[ \begin{align*}
| (g_- - g_+) / g_{av} | \\
| (q_- - q_+) / q_{av} | \\
| (m_- - m_+) / m_{av} | \\
\left| \left( \frac{q}{m_+} - \frac{q}{m_-} \right) / \frac{q}{m_{av}} \right| \\
| (m_- - m_+) / m_{av} | \\
| (\nu_+ - \nu_-) / \nu_{av} | \\
\end{align*} \]
First Laser-Controlled Antihydrogen Production

C.H. Storry, 1 A. Speck, 1 D. Le Sage, 1 N. Guise, 1 G. Gabrielse, 1 D. Grzonka, 2 W. Oelert, 2 G. Schepers, 2 T. Sefzik, 2 H. Pittner, 3 M. Herrmann, 3 J. Walz, 3 T.W. Hänsch, 3, 4 D. Comeau, 5 and E.A. Hessel 5

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(2) IKF, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany
(3) Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, 85748 Garching, Germany
(4) Ludwig-Maximilians-Universität München, Schellingstrasse 4/III, 80799 München, Germany
(5) York University, Department of Physics and Astronomy, Toronto, ON, Canada

(Dated: Submitted to PRL; 17 April 2006)

Lasers are used for the first time to control the first stage of a cycle in which resonant charge exchange collisions are involved. One of the other methods used so far – producing antiprotons, ionizing them, and then capturing them in a Penning trap. Two attractive features of this method are its simplicity and energy, and that the production of antihydrogen is done very close to what is needed for confinement.

Different methods available to produce Antihydrogen

(a) two-fiber detection
(average background rate is 2.2 / 40 ms)
ionized \( \overline{\text{H}} \) signal

(b) detection well depth
antiproton calibration
(calibrated signal channel)

(time (ms))
Scientists Create 'Star Trek' Antihydrogen in Quantity

By Alex Dominguez

posted: 02:59 pm ET 18 September 2002

ATHENA

Production and detection of cold antihydrogen atoms


ANTHENT

Physical Review Letters 89, 213401 online (2002)

ATRAP

Background-Free Observation of Cold Antihydrogen with Field-Ionization Analysis of Its States


(ATRAP Collaboration)
(Anti-)Hydrogen CPT Tests

Laser spectroscopy 1s-2s  -------- Microwave spectroscopy
1s Hyperfine Structure

\[ \Delta \nu_{1s2s} = \frac{3}{4} R_\infty + \epsilon_{\text{QED}} + \epsilon_{\text{nucl}} + \epsilon_{\text{weak}} + \epsilon_{\text{CPT}} \]

\[ \Delta \nu_{\text{HFS}} = \text{cons.} \times \alpha^2 R_\infty + \epsilon_{\text{QED}} + \epsilon_{\text{nucl}} + \epsilon_{\text{weak}} + \epsilon_{\text{CPT}} \]

“Long distance” Interaction  “Contact” interaction

\[ R_\infty = m_e c^2 \times \alpha^2 / 2 \hbar \]
(Anti-)Hydrogen Spectroscopy

Hydrogen 1s-2s Saturation Intensity \( I_s = 0.9 \text{ W/cm}^2 \)

Excitation Rate \( R_e = 4\pi \times 84 \times (\text{I/W/\text{s/cm}^2}) \times \text{Hz} \)

Photo Ionization Rate \( R_p = 9 \times \text{I/W/\text{s/cm}^2} \)

Zeeman shift \( \delta \nu_Z = 0.3 \times \text{I/W/\text{s/cm}^2} \)

ac Stark shift \( \delta \nu_{ac} = 1.7 \times \text{I Hz/W/cm}^2 \)

Velocity at 1mK \( V_{1K} = 4 \text{ m/s} \)

Time-of-flight broadening \( \Delta \nu_{TOF} = 3 \text{ kHz} \)

Lyman a detection efficiency \( \Omega \times \text{eff}_{MCP} (= 10^{-4} \times 10^{-2}) \)

\( 10^{11} \text{ H-atoms} \)

\( \frac{\delta \nu}{\nu_{1s2s}} = 10^{-13} \) (1s integration time)

Just one Problem: Lyman-\( \alpha \) detection via field quenching \( \Rightarrow \) atoms can be used once only

(all 1s, \( m_F \) states get equally populated)

Line center accuracy in absence of systematic errors:

\[
\delta \nu = \frac{\Delta \nu_{\text{exp.}}}{(\text{Sign./Noise})} \approx \frac{\Delta \nu_{\text{exp.}}}{\sqrt{N_{\text{particles}}}}
\]

Antihydrogen experiments benefit from more particles

* numbers verified with L. Willmann
$\bar{\text{pH}}$ Ground-state Hyperfine Structure

$\bar{p}$ and $e^+$ trap recombination

antihydrogen detector

sextupole 1 microwave cavity sextupole 2

SIMULATION

Need less particles (2 $\bar{\text{pH}}$ / s) because of narrow natural linewidth

from B. Juhasz
pHe+ Atom – a naturally occurring trap for antiprotons

- Serendipitously discovered by Tokyo group at KEK
- 3-body system, Metastable
- ~ 3% of stopped antiprotons survive with average lifetime of ~ 3 μs
- Precision laser spectroscopy by ASACUSA:
  - best test of 3-body QED theories
  - proton-antiproton mass & charge comparison (PDG)
- Enters CODATA constant adjustment significantly

Hayano, Yamazaki et al.
Progress in atomcule spectroscopy

- First antiprotonic helium measurement using LEAR
- Higher statistics, better lasers and wavelength calibration
- Femtosecond optical comb generator Continuous-wave pulse amplified laser
- Development of RFQD
- Sub-Doppler two-photon spectroscopy
- Known mass of proton (proton-to-electron ratio)

Year:
- 1992
- 1994
- 1996
- 1998
- 2000
- 2002
- 2004
- 2006
- 2008
- 2010
At the CERN AD a number of unique, important CPT tests were already conducted and improved ones are on their way:

- **ASACUSA** $\bar{p}He$, $\bar{p}He^+$, $\bar{p}H$, $\bar{p}$
- **ATRAP** $\bar{p}$, $\bar{p}H$
- **ALPHA** $\bar{p}H$

One can expect significant steering of Model Building and High Visibility next to a robust discovery potential.
(Anti-)Hydrogen Gravity Tests

\[ F = -m \cdot g \]

- Lyman –α laser required
- Lyman –α laser developed

• Lyman –α laser required
• Lyman –α laser developed
Gravity Tests @ CERN AD

At the CERN AD is the place to answer the most urgent question on antimatter gravity:

- **AEGIS** $\bar{p}H$
- **ATRAP** $\bar{p}H$
- **Free Fall** $\bar{p}H$

One can expect an answer to a most fundamental question, which only can be answered by experiment! High Visibility next to a robust discovery potential.
Standard Model Physics
Applications
Antiprotonic Radioactive Atoms

ASACUSA using RFQD & MUSAHI

Consistent with $A^{2/3}$
No surprise yet at 5 MeV

$\sigma_{ann}(pA) = cA^p$
$p = 0.61 \pm 0.09$
$c = 13.3 \pm 4.2$

$\gamma$, particles, daughter activity

n vs. p annihilation

2006-2008

Plab (MeV/c)
Antiproton Radio-Therapy

A significant win (factor ~4) in a sensitive window for tumor treatment and healthy tissue sparing
Physics within Standard Model and Applied Research @ CERN AD

At the CERN AD also SM physics and Applied Research is conducted:

• **ASACUSA**  \(\bar{p}\)-nucleus annihilation, atomic collisions

• **Double-Strangeness** \(\bar{p}\)-nucleus dedicated experiment

• **Production**

• **PAX**  \(\bar{p}\) polarization, \(\bar{p}^\uparrow – p\) interactions

• **ACE**  \(\bar{p}\) radiation-therapy

• ...

One can expect deeper insights and the development of novel techniques to the benefit of physics and society.
Antiproton Sources
Antiproton Decelerator (AD) @ CERN

- **Started operation** July 6, 2000
- Antiproton capture, deceleration, cooling
- Pulsed extraction
- Many Experiments
  - ASACUSA
  - ATRAP
  - ALPHA
  - AEGIS
  - Free Fall
  - PAX
  - ACE
  - ...
- Request for more and better antiproton beams
  - To speed up progress
  - To boost accuracy

⇒ ELENA
Consequent Future Development

**ELENA**@CERN

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**ELENA provides 10-100 times more particles**

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**Possible Option? TSR**@MPIK(Heidelberg) ⇒ ELENA ??

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**Table:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emittances at 100 keV, mm mrad</td>
<td>5.3 - 0.1</td>
</tr>
<tr>
<td>Intensity limitations due to space charge</td>
<td>16.7</td>
</tr>
<tr>
<td>Maximal incoherent tune shift</td>
<td>1.64 / 1.62</td>
</tr>
<tr>
<td>Bunch length at 100 keV, m/μs</td>
<td>5 / 5</td>
</tr>
<tr>
<td>Multiple scattering blow up rate for</td>
<td>1.7 × 10^7</td>
</tr>
<tr>
<td>3 × 10^{-12} Torr (N₂ equiv.), πmm mrad/s</td>
<td>0.10</td>
</tr>
<tr>
<td>IBS blow up times, s (Δp/p = 2 10^{-3})</td>
<td>1.3 / 300</td>
</tr>
<tr>
<td></td>
<td>3.2 / -30.6 / 3.9</td>
</tr>
</tbody>
</table>
New low-energy antiproton and ion facility

- **NESR**
  - min. 30 MeV

- **LSR**
  - 30 - 0.3 MeV

- **USR**
  - 300 - 20 keV

- **HITRAP**
  - 4 - 0 MeV
    - cooler trap

- Low-energy cave AP
  - Highly Charged Ions

- Supersonic gas jet
- Reaction microscope

- Extractions from HITRAP
- Traps

- Fast and slow extracted \( \bar{p} \) down to 300 keV
- Fast and slow extracted \( \bar{p} \) down to 20 keV or 5 keV

**Factor 100 more pbar trapped or stopped in gas targets than now**
New Facilities @ CERN AD or GSI/FAIR

New Facilities can provide up to 100 times more particles:

- **MUSASHI**  
  ASACUSA ‘s device to recycle p’s

- **ELENA**  
  Generic low cost CERN solution,  
  Start possible now

- **FLAIR**  
  GSI/FAIR solution not before 2015

One can expect faster progress and better results from more p’s

→ CERN and GSI should synchronize
Highly Motivated Urgent Antiproton Experiments with robust Discovery Potential and High Visibility
- CPT, Gravity, Determination of Fundamental Constants,
- SM Physics, Applications (Therapy)

Unique Facility worldwide until beyond 2015

Creative and Innovative Increasing Community
- Young people
- Novel Techniques and Novel Technology

Physics Program good on Time Path

Program needs more particles
→ ELENA well motivated

Productive and Prosperous Future Ahead
Thank YOU!