ASACUSA status report
2017 and plans for 2018

128th Meeting of the SPSC
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Co-spokesperson, ASACUSA
ASACUSA collaboration

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I. Antiprotonic helium

II. CUSP experiment for $\bar{\text{H}}$ spectroscopy

III. Fragmentation studies in antiproton-nucleus annihilation

IV. Experiments with a polarized hydrogen beam

V. ASACUSA hardware contribution to ELENA
I Antiprotonic helium
Antiproton-to-electron mass ratio

Needs 3-body theory

\[ \frac{\overline{p}}{\nu} = \frac{m_{\overline{p}}}{m_e} \left( \frac{1}{n^2} - \frac{1}{n'^2} \right) + \text{QED} \]
Previous results and methods

- $m_{\bar{p}}/m_e$ 2016

  Antiproton-to-electron mass ratio 1836.1526734 (15)

- Sub-Doppler two-photon laser spectroscopy

  $2-3\sigma$ away from CODATA 2010
Setup for 2-photon spectroscopy
2017 results (under analysis)

- Goal: $m_p/m_e < 0.5$ ppb
Beam usage 2017 and plans for 2018

- 2017: RFQD troubles
  - Lost 7 weeks

May, June, early July (7 weeks): RFQD problems, almost total loss of beam except for tuning. Realignment of upstream magnetic elements.

RFQD recovers and data-taking starts July 18th.
Weeks 29, 30, 31, 34 (4 weeks): pbar-4He+ (36,34)→(34,32)
Week 35 (1 week): pbar-3He+ (35,33)→(33,31)

Accumulated 29 days of publishable data (half of expected data)

- Plans for 2018

Continuation of pbar-4He two-photon
  - pbar-4He (n,l)=(36,34)→(34,32) Finished!
  - (31,30)→(30,29)
  - pbar-3He (35,33)→(33,31) Now measuring
  - (30,29)→(29,28)

Goal: antiproton-to-electron mass ratio <5×10–10
In improvements towards ELENA: lasers

- Metastable-to-metastable state transitions

Fully DPSS Nd:YAG laser pumped Ti:Sapphire laser with long-pulse alexandrite oscillator

Potential improvement: factor 100
Induction deceleration cavity for $\bar{p}$

• Goal: minimize stopping volume of $\bar{p}$ in low-density gas for efficient laser spectroscopy
• Transformer with ferromagnetic cores
  • Primary winding = pulsed excitation
  • Secondary winding = beam
• Deceleration 100 keV to <50 keV
• R&D ongoing, operation after LS2
• Collaboration with KEK/J-PARC and CLIC
II. CUSP experiment for $\overline{\text{H}}$ spectroscopy
In-beam HFS spectroscopy

- Goals
  - In-beam measurement of ground-state hyperfine structure of antihydrogen to ppm-level and below
  - Produce polarized slow (<100 K) Hbar beam

- Resolution: line width $\Delta \nu \sim 1/T$
  - 1000 m/s, 10 cm:
  - $7 \times 10^{-6}$ for $T = 50$ K *cf part IV*
  - > 100 $\overline{H}$/s in 1S state into $4\pi$ needed
  - event rate 1 / minute: background from cosmics, annihilations upstreams
Ground-State Hyperfine Splitting of H/$\bar{\text{H}}$

- spin-spin interaction positron - antiproton
- Leading: Fermi contact term

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

Transition frequency (Hz)

- \( \nu_{\text{HFS}} \)
- \( \Delta_{\text{CPT}} (\mu_p) \)
- \( \Delta_{\text{CPT}} (\mu_e) \)

Experimental values for hydrogen

Current precision

Theoretical uncertainty

(2) experimental errors
Ground-State Hyperfine Splitting of H/\(\bar{\text{H}}\)

- spin-spin interaction positron - antiproton
- Leading: Fermi contact term

Hydrogen HFS and QED: finite size effects

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>H: deviation from Fermi contact term</td>
<td>(-32.77(1)) ppm</td>
</tr>
<tr>
<td>finite electric &amp; magnetic radius (Zemach corrections):</td>
<td>(-41.43(44)) ppm</td>
</tr>
<tr>
<td>polarizability of p/(\bar{\text{p}})</td>
<td>+1.88(64) ppm</td>
</tr>
<tr>
<td>remaining deviation theory-experiment:</td>
<td>+0.86(78) ppm</td>
</tr>
</tbody>
</table>

C. E. Carlson et al., *PRA* 78, 022517 (2008)

Finite size effect of proton/antiproton important below ~ 10 ppm

\[ \nu_F = \frac{16}{3} \left( \frac{M_p}{M_p + m_e} \right)^3 \frac{m_e \mu_p}{M_p \mu_N} \alpha^2 c \ \text{Ry} \]
Comparison of CPT tests

- Mass & frequency

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Atomic fountain

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Mass [GeV/c^2]

- e-e^+
- n-\bar{n}
- p-\bar{p}
- K^0-\bar{K}^0

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Energy/\hbar [GHz]

- \nu_{1s-2s}
- \nu_{nS-2P}
- H-\bar{H}
- H\nu_{HFS}

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ALPHA coll.

Comparison of CPT tests

- Mass & frequency

- Standard Model Extension SME

\[ (i \gamma^\mu D_\mu - m_e - a^e_\mu \gamma^\mu - b^e_\mu \gamma_5 \gamma^\mu - \frac{1}{2} H^e_{\mu\nu} \sigma^{\mu\nu} + ic^e_{\mu\nu} \gamma^\mu D^\nu + id^e_{\mu\nu} \gamma_5 \gamma^\mu D^\nu) \psi = 0. \]

D. Colladay and V.A. Kostelecky, PRD 55, 6760 (1997)

- Minimal SME: only HFS
- Non-minimal SME: also 1S-2S shows CPTV

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Comparison of CPT tests

• Mass & frequency

- Mass & frequency

- Standard Model Extension SME

\[ \text{From: NuPECC Long Range Plan 2017 (M. Doser) + EW Kostelecky & Bluhm arXiv:0801.0287} \]
Setup

Cavity & sextupole not used in 2017
Status before 2017

- **Mixing scheme**: direct injection MUSASHI → CUSP
- $\bar{\text{H}}$ beam observed 2.7m downstream, low rate\(^1\)
- $\bar{\text{H}}$ quantum state studied by external field ionizer FID & $\bar{\text{H}}$ detector
- Fast axial separation of $\bar{\text{p}}$ and $\text{e}^+$ observed: low $\bar{\text{H}}$ yield

\(^1\text{N. Kuroda et al, Nat. Commun. 5, 3089 (2014).}\)
New mixing schemes 2017

- Slow extraction scheme
- Cross merging scheme

AMT scintillators

Magnetic field distribution along the axis

Potential configuration for H synthesis

Potential on axis [V]

Distance from the center of the cusp [cm]
**H** detector analysis

- 2D BGO & track fitting

- Machine learning
  - Cosmics rejection 99.7%
  - False positive rate: 0.0039 s\(^{-1}\)
  - \(\bar{\nu}\) efficiency ~ 80%

n=14 significance 4.5 \(\sigma\)
\(\tau(n=14) \sim 50\,\mu s\)

C. Malbrunot et al., Phil. Trans. A 2018, in print
Antihydrogen detector fibre upgrade

Fibre bundle 2x2 of 1x1 mm² fibres
2 layers
7.7 mm geometrical resolution in z at r=0
Beam usage 2017 and plans for 2018

- **Weeks 38,39,40**
  - $\bar{p}$ transfer MUSASHI -> CUSP

- **Weeks 42,43,44**
  - Trials of new merging schemes

- **Weeks 46,47,48**
  - Slow extraction scheme & Cross merging scheme

- **Week 50**
  - Slow continuous extraction of $\bar{p}$ to Timepix3

- **Continued plans for 2018**
  - Continue optimizing new mixing schemes
  - Control of positron plasma parameters (temperature, density)
  - Implement 3D tracking for the antihydrogen detector
  - Determine $n$-distribution for new mixing schemes and $e^+$ conditions
  - $\bar{p}$ annihilation studies for different targets
    - 1-2 weeks at the end with 1-2 w break

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III Fragmentation studies in antiproton-nucleus annihilations
Existing studies

• Data from GRACE (AEgIS)
  • Emulsion
  • Low statistics
• No good agreement with Monte Carlo codes
  • GEANT4: Chips, Fritiof
  • FLUKA
• More data welcome

AEgIS collaboration, *Journal of Instrumentation* 12, P04021 (2017)
Slow extraction from MUSASHI

- Energy 150 eV
- 240 $\bar{p}/4$ cm$^2$ / 2 AD shots
- 100 extractions / shift
- Duration 20 s
First results

• 90,000 annihilation events in C taken during ~4 shifts, analysis ongoing
• Plans for 2018: measure several different target foils
IV Experiments with a polarized hydrogen beam
Goal

• Validate the spectroscopy technique for $\bar{H}$ using H-beam
  • Source of polarized 50 K H-beam
  • Parts of $\bar{H}$ apparatus used, setup located at CERN cryolab, now Bat. 275

• Perform measurements to determine SME coefficients
  • Permanent sextupoles
  • New optics for alternating measurements of $\sigma$ and $\pi$ transitions
σ-transition in H using $\bar{H}$ setup

Error 2.7 ppb: 18x improvement over Kush, Phys. Rev. 100, 1188 (1955)
Deviation from maser ($\Delta f/f \sim 10^{-12}$): 3.4 Hz < 1σ error
Extrapolation to $\bar{H}$: 8000 atoms needed to achieve 1 ppm

$\nu_{HF} = 1 \ 420 \ 405 \ 748.4(3.4)(1.6) \ Hz$

In-beam measurement of the hydrogen hyperfine splitting and prospects for antihydrogen spectroscopy

M. Diermaier1, C.B. Jepsen2,1, B. Kolbinger1, C. Malbrunot2,1, O. Massicotte1, C. Sauercopf1, M.C. Simon1, J. Zmeskal1 & E. Widmann1

Received 4 Oct 2016 | Accepted 24 Apr 2017 | Published 12 Jun 2017 | DOI: 10.1038/nature23749 | OPEN
Non-minimal SME & H-beam

- Shift only for \( \pi \)-transition \( (\Delta m_F \neq 0) \)

\[
2\pi \delta \nu = - \frac{\Delta m_F}{2\sqrt{3}\pi} \sum_{q=0}^{2} (\alpha m_\pi)^{2q} (1 + 4\delta_{q2}) \\
\times \sum_{w} [g_{w(2q)10}^{NR(0B)} - H_{w(2q)10}^{NR(0B)} + 2g_{w(2q)10}^{NR(1B)} - 2H_{w(2q)10}^{NR(1B)}].
\]

- \( B \) direction dependence

\[
\Delta(2\pi \nu_\pi) = 2\pi \nu_\pi(B) - 2\pi \nu_\pi(-B) = -\frac{\cos \theta}{\sqrt{3}\pi} \sum_{q=0}^{2} (\alpha m_\pi)^{2q} (1 + 4\delta_{q2}) \sum_{w} [g_{w(2q)10}^{NR,Sun(0B)} - H_{w(2q)10}^{NR,Sun(0B)} + 2g_{w(2q)10}^{NR,Sun(1B)} - 2H_{w(2q)10}^{NR,Sun(1B)}].
\]

σ and π transitions in same setup condition

Trajectories

Field gradients

Beam direction

<table>
<thead>
<tr>
<th>Method</th>
<th>( \nu_0 \pm \delta \nu ) (Hz)</th>
<th>( \delta \nu/\nu ) (ppb)</th>
<th>( \nu_0 - \nu_{\text{fit}} ) (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma ) - extrapolation, eq. (5)</td>
<td>1 420 405 767 ± 15</td>
<td>10</td>
<td>+15</td>
</tr>
<tr>
<td>( \pi_1 ) - extrapolation, eq. (6)</td>
<td>1 420 405 760 ± 34</td>
<td>24</td>
<td>+8</td>
</tr>
<tr>
<td>weighted mean of above</td>
<td>1 420 405 766 ± 14</td>
<td>10</td>
<td>+14</td>
</tr>
<tr>
<td>( \sigma ) - ( \pi ) pairs, eq. (7)</td>
<td>1 420 405 753 ± 8</td>
<td>6</td>
<td>+1</td>
</tr>
</tbody>
</table>
**Ramsey method**

- Reduce line width by \(D/L\)
  - Strip-line cavity line shape not ideal
    - \(D = 10\) cm \(L = 1\) m

- Other microwave generation methods under study
  - \(TM_{110}\) cylindrical cavity
  - \(B_{osc}\) constant in \(z\)

- Current-driven plates
V. ASACUSA hardware contribution to ELENA
Beam profile monitors

- 42 beam profile monitors under construction
- 26 translator stages at CERN, 16 under repair
- 12 electrode sets at CERN, 30 more in production
- 3 operational and tested
- Readout system being developed
- 15% of cost not covered
Acknowledgements

• AD team for providing antiproton beam
• BE-RF group for RFQD troubleshooting
• Funding sources

ASACUSA collaboration
Spares
**Calculated two-photon transition frequency**

\[(n,l) = (36,34) \rightarrow (34,32)\]

<table>
<thead>
<tr>
<th>Term</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-relativistic energy</td>
<td>1 522 150 208.13 MHz</td>
</tr>
<tr>
<td>(m\alpha^4) order corrections</td>
<td>-50320.64</td>
</tr>
<tr>
<td>(m\alpha^5) order corrections</td>
<td>7070.28</td>
</tr>
<tr>
<td>(m\alpha^6) order corrections</td>
<td>113.11</td>
</tr>
<tr>
<td>(m\alpha^7) order corrections</td>
<td>-10.46(20)</td>
</tr>
<tr>
<td>(m\alpha^8) order corrections</td>
<td>-0.12(12)</td>
</tr>
<tr>
<td>Transition frequency</td>
<td>1 522 107 060.3(2)</td>
</tr>
<tr>
<td>Uncertainty from alpha charge radius</td>
<td>+/-0.007</td>
</tr>
<tr>
<td>Uncertainty from antiproton charge radius</td>
<td>&lt; 0.0007</td>
</tr>
</tbody>
</table>

Korobov, Hilico, Karr, PRA 89, 032511 (2014).