Experiments at the Antiproton Decelerator Facility of CERN

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RIKEN
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antihydrogen trap

antiproton/proton balance
In the AD we are «listening» to the sound of extremely simple, well understandable Antimatter systems to detect exotic physics, which appears as changes in pitch / frequency beating.
Six collaborations, pioneering work by Gabrielse, Oelert, Hayano, Hangst, Charlton et al.

BASE, Fundamental properties of the antiproton and test of clock WEP.

ALPHA, Spectroscopy of 1S-2S in antihydrogen

ASACUSA, ALPHA
Spectroscopy of GS-HFS in antihydrogen

ASACUSA
Antiprotonic helium spectroscopy

ALPHA, AEgIS, GBAR
Test free fall weak equivalence principle with antihydrogen

PUMA
Antiproton/nuclei scattering to study neutron skins

Updated PBC Mandate

- The physics objectives also include projects aimed **at addressing fundamental particle physics questions using the experimental techniques of nuclear, atomic and astroparticle-physics, as well as emerging technologies such as quantum sensors.**

<table>
<thead>
<tr>
<th>Portal</th>
<th>Coupling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dark Photon, $A_\mu$</td>
<td>$\frac{e}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$</td>
</tr>
<tr>
<td>Dark Higgs, $S$</td>
<td>$(\mu S + \lambda S^2) H^\dagger H$</td>
</tr>
<tr>
<td>Axion, $a$</td>
<td>$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu} \tilde{G}_i^{\mu\nu}$, $\frac{g_5 a}{f_a} \overline{\psi} \gamma^\mu \gamma^5 \psi$</td>
</tr>
<tr>
<td>Sterile Neutrino, $N$</td>
<td>$y_N LHN$</td>
</tr>
</tbody>
</table>

- This talk: Present experiments which apply atomic physics and quantum metrology methods to study fundamental physics questions using simple antimatter systems at lowest energy and with highest resolution
Methods and Achievements

- This community is performing measurements using quantum technologies at world leading precision...

Innovation and Technology

- Antihydrogen traps
- Advanced Multi Penning trap systems
- Ultra-stable ultra-high power lasers
- Transportable antimatter traps and reservoir traps
- Advanced magnetic shielding systems
- Quantum Logic Spectroscopy

...and is a vital part of the low energy precision physics community...
Historical Milestones

- First capture of antiprotons
- Proton moment from hydrogen (1971)
- Hydrogen MASER
- Positron Moment
- Single Penning traps
- Accelerators
- Multi Penning traps
- Start of AD program ATRAP, ASACUSA, ATHENA
- Trapped antihydrogen
- Hot antihydrogen
- Cold antihydrogen
- Frequency meas.

Plus:
- 30 fold improved antiproton lifetime limits by BASE
- First gravity study with HBAR by ALPHA

- HBAR GSHFS
- PBAR/He
Matter / Antimatter Asymmetry

Combining the \( \Lambda \)-CDM model and the SM our predictions of the baryon to photon ratio are **inconsistent by about 9 orders of magnitude**

<table>
<thead>
<tr>
<th>Naive Expectation</th>
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<tbody>
<tr>
<td>Baryon/Photon Ratio</td>
<td>(10^{-18})</td>
</tr>
<tr>
<td>Baryon/Antibaryon Ratio</td>
<td>1</td>
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</table>

<table>
<thead>
<tr>
<th>Observation</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Baryon/Photon Ratio</td>
<td>(0.6 \times 10^{-9})</td>
</tr>
<tr>
<td>Baryon/Antibaryon Ratio</td>
<td>10 000</td>
</tr>
</tbody>
</table>

**Sakharov conditions**

1.) B-violation (plausible)
2.) CP-violation (observed / too small)
3.) Arrow of time (less motivated)

**Alternative Source: CPT violation** – adjusts matter/antimatter asymmetry by natural inversion given the effective chemical potential.

**Experimental signatures sensitive to CPT violation can be derived from** precise comparisons of the fundamental properties of simple matter / antimatter conjugate systems
Fundamentality of CPT Invariance

- A relativistic theory which conserves CPT requires only five basic ingredients (Axioms):

  - Lorentz and translation invariance
  - Energy Positivity
  - Micro Causality (Locality)
  - A stable vacuum ground state without momentum nor angular momentum
  - Unitary Field Operators Interpretation

**READ:** R. Lehnert, CPT Symmetry and its violation, *Symmetry* 8 (2016) 11, 114

Parameterized in the Standard Model Extension

<table>
<thead>
<tr>
<th></th>
<th>$\psi\psi$</th>
<th>$i\psi^\gamma_5\psi$</th>
<th>$\psi\gamma^\mu\psi$</th>
<th>$\psi\gamma^\mu\gamma^\nu\psi$</th>
<th>$\psi\gamma^\mu\gamma^\nu\gamma^\rho\psi$</th>
<th>$\delta_{\mu\nu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>+1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
</tr>
<tr>
<td>P</td>
<td>+1</td>
<td>-1</td>
<td>$(-1)^p$</td>
<td>$(-1)^p$</td>
<td>$(-1)^p(-1)^p$</td>
<td>$(-1)^p$</td>
</tr>
<tr>
<td>T</td>
<td>+1</td>
<td>-1</td>
<td>$(-1)^p$</td>
<td>$(-1)^p$</td>
<td>$(-1)^p(-1)^p$</td>
<td>$(-1)^p$</td>
</tr>
<tr>
<td>CPT</td>
<td>+1</td>
<td>+1</td>
<td>-1</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
</tr>
</tbody>
</table>
The Standard Model Extension

Motivation

- KK and String theories
- Loop-Quantum Gravity
- Non-commutative FT
- Brane scenarios
- Random dynamics models

- SME contains the Standard Model and General Relativity, but adds CPT violation
  
  \[ \mathcal{L}' \supset \frac{\lambda}{M^k} \langle T \rangle \cdot \overline{\psi} \Gamma (i \partial)^k \psi + \text{h.c.} \]

  Expectation value / Mass Scale / Coupling strength

  Lorentz bilinear

- E.g. \( k=2 \) produces attractive baryogenesis scenario

- Which type of measurable signatures of these «BSM» theories would be imprinted onto the structure of the vacuum-box of relativistic quantum field theories.

  \[ \mathcal{L} = ? \]

- Construct effective field theory which features:
  - microcausality
  - positivity of energy
  - energy and momentum conservation
  - standard quantization methods

Limits on Exotic Physics – ONE example

- Test the Standard Model (CPT invariance) by comparing the fundamental properties of protons and antiprotons with high precision

\[
(i \gamma^\mu D_\mu - m) - a_\mu \gamma^\mu - b_\mu \gamma^5 \gamma^\mu)\psi = 0
\]

Dirac equation  CPT-odd modifications

\[
b_\mu \gamma^5 \gamma^\mu \rightarrow b_x \begin{pmatrix} -\sigma_x & 0 \\ 0 & \sigma_x \end{pmatrix} + b_y \begin{pmatrix} -\sigma_y & 0 \\ 0 & \sigma_y \end{pmatrix} + b_z \begin{pmatrix} -\sigma_z & 0 \\ 0 & \sigma_z \end{pmatrix}
\]

Pseudo-magnetic field, with different coupling to matter and antimatter, respectively

\[
\Delta V_{int} = b_{z,D} \begin{pmatrix} 0 & 0 \\ 0 & \pm \sigma_z \end{pmatrix}
\]


Would correspond to the discovery of a boson field which exclusively couples to antimatter.

\[
H \psi = (H_0 + V_{exotic}) \psi
\]

\[
\Delta E_{exotic} = \langle \psi | V_{exotic} | \psi \rangle
\]

Sensitive: comparisons of particle/antiparticle magnetic moments in traps
A Typical AD Detector...

• ...is in essential aspects very different to a particle physics detector...

• destructive measurements at high lumiosity

• Non-destructive frequency measurements at highest frequency resolution
Example: the BASE trap

- We have
  - A vacuum of 5e-19 mbars
  - best characterized vacuum on earth,
  - comparable to pressures in the interstellar medium
- Antiproton storage times of several 10 years.
- Not more than 5000 residual atoms in a vacuum volume of 1.2l
- Order 100 to 1000 trapped antiprotons
- A local inversion of the baryon asymmetry

<table>
<thead>
<tr>
<th>BASE ANTIMATTER INVERSION</th>
<th></th>
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<tbody>
<tr>
<td>local volume</td>
<td>0.0001³ m³</td>
</tr>
<tr>
<td>Baryons in local trap volume</td>
<td>1.65*10⁻⁷</td>
</tr>
<tr>
<td>Antibaryon in local trap volume</td>
<td>100</td>
</tr>
<tr>
<td>Antibaryon/Baryon Ratio</td>
<td>5.9*10⁸</td>
</tr>
<tr>
<td>Ratio Inversion</td>
<td>3.8*10¹²</td>
</tr>
</tbody>
</table>

- Pbar consumption (excl. steering and trap loading):
  - Since 2014: 68 particles lost
  - Since 2014: 34 particles lost due to exp. mistakes
- Average loss rate is at 1 particle in 2.5 months.
- **Direct lifetime limits**: t > 26.5a (80-fold impr.)

With this instrument: Investigate properties of antimatter very precisely
Main Tool: Penning Trap

radial confinement: \( \vec{B} = B_0 \hat{z} \)

axial confinement:
\[
\Phi(\rho, z) = V_0 c_2 \left( z^2 - \frac{\rho^2}{2} \right)
\]

\( v_z = \frac{1}{2\pi} \sqrt{\frac{2C_2 q V_0}{m}} \)

\( v_+ = \frac{1}{2} \left( \nu_c + \sqrt{\nu_c^2 - 2v_z^2} \right) \)

\( v_- = \frac{1}{2} \left( \nu_c - \sqrt{\nu_c^2 - 2v_z^2} \right) \)

Invariance Theorem

\[
\nu_c = \sqrt{v_+^2 + v_-^2 + v_z^2}
\]

Axial \( v_z = 680 \text{ kHz} \)
Magnetron \( v_- = 8 \text{ kHz} \)
Modified Cyclotron \( v_+ = 28.9 \text{ MHz} \)

Gives undisturbed access to cyclotron frequencies

\[
\nu_c = \frac{1}{2\pi} \frac{q_{\text{ion}}}{m_{\text{ion}}} B
\]
Measurements in Precision Penning traps

Cyclotron Motion

\[ \omega_c = \frac{e}{m_p} B \]

Larmor Precession

\[ \omega_L = g \frac{e}{2m_p} B \]

Determinations of the q/m ratio and g-factor reduce to measurements of frequency ratios -> in principle very simple experiments -> full control, (almost) no theoretical corrections required.

S. Ulmer, A. Mooser et al. PRL 107, 103002 (2011)

High Precision Mass Spectrometry

High Precision Magnetic Moment Measurements
Frequency Measurements in Penning Traps

- Concept of image current detection

\[ I_{p,x} \sim \frac{q}{D_{eff}} (2\pi v_x) x \]
\[ I_{p,x} \sim 0.1 \text{ fA} / (\text{MHz} \mu\text{m}) \]

- Resonant Detection

\[ R_p = Q(2\pi v_x L) \]
\[ R_p = 100 \text{ M}\Omega \text{ to } 500 \text{ M}\Omega \]

- Voltage drops of order

\[ U_{p,x} \sim 10 \text{ nV} / (\text{MHz} \mu\text{m}) \]

Charge-to-Mass Ratio Measurement

- In BASE one frequency ratio measurement takes 240 s, 50 times faster than in 1999 measurement


- Sideband Method
  
  \[ \nu_+ = \nu_{rf} + \nu_l + \nu_r - \nu_z \]

  2.5 Hz linewidth
  Limited by fit scatter
  Thermal equilibrium measurement

- Peak Method

  25 mHz linewidth
  Limited by magnetic field scatter
  Excited measurement
  Considerable systematic shifts

Result of 6500 proton/antiproton Q/M comparisons:

\[ \frac{(q/m)_p}{(q/m)_{\bar{p}}} + 1 = 1(69) \times 10^{-12} \]

Stringent test of CPT invariance with Baryons.
Consistent with CPT invariance

New measurement:

- Acquired 35000 frequency ratio measurements over 1.5 years, distributed over the sidereal year.
- Used two measurement methods, tunable axial detector to suppress systematics, and a rebuilt apparatus

\[ R_{\text{exp,c,1}} = 1.001 \, 089 \, 218 \, 763 \, (23) \]
\[ R_{\text{exp,c,2}} = 1.001 \, 089 \, 218 \, 7XX \, (2X) \]

Final data analysis is work in progress

**BASE Measurements – Proton to Antiproton Q/M**

- **Constrain of the gravitational anomaly for antiprotons:**

\[
\frac{\omega_{c,p} - \omega_{c,\bar{p}}}{\omega_{c,p}} = -3(\alpha_g - 1) \frac{U}{c^2}
\]

Our recent result sets an upper limit of

\[|\alpha_g - 1| < 1.9 \times 10^{-7}\]

- **Planned Longer Term Measurements**

  - Set differential constraints on the weak equivalence principle by measuring charge-to-mass ratio as a function of gravitational potential at surface of earth.
  - Final data analysis is work in progress.

- **Direct experiments planned by Aegis, GBAR, ALPHA**

- **Our recent result sets an upper limit of**

  \[|\alpha_g - 1| < 1.9 \times 10^{-7}\]

Antihydrogen Production and Trapping

Nested Penning Trap with
• Antiprotons and
• Positrons

trapped close to each other.

Different antiproton/positron injection methods

Initialy: less than one atom per attempt

ALPHA collaboration: Nature 468, 673 (2010)
Antihydrogen Trapping History

Improved mixing methods

even antihydrogen accumulation was demonstrated by ALPHA

> 1000 atoms were accumulated

planned: improve antihydrogen production yield by sympathetic cooling of positrons, before the mixing

??? How to do spectroscopy with such a small amount of atoms ???

ALPHA Collaboration, Nature Communs. 8, 681 (2018)
Antihydrogen Spectroscopy

- **1S/2S Spectroscopy** – dipole-forbidden very narrow transition.

Trapped antihydrogen is by definition in low field seeking state (positron moment in «down» state)

Resonant laser-field produces loss-mechanisms by resonant ionization and by inducing parasitic positron spin transitions

- Measure annihilation signal as a function of laser frequency (appearance and disappearance mode accessible)

The Result


Future perspective: Laser cooling of antihydrogen just demonstrated

ALPHA collaboration, Nature 592, 35 (2021)
Antiprotonic Helium (ASACUSA)

- Helium atom with one of the electrons replaced by an antiproton

- For exotic spin-1 bosons: general approach assuming rotational invariance -> 16 spin dependent interactions (Moody-Wilczek-Dobrescu-Mocioiu formalism)

- Elegant and technically challenging experiments on circular states lead to measurements of the antiproton-to-electron mass ratio (0.6 p.p.b.)

- First limits on exotic antimatter/axion coupling derived

\[ V_2 = \frac{f_2^p \hbar c}{\pi} (s_p \cdot s_a) e^{-r/\lambda} \]
\[ V_3 = \frac{f_3^p \hbar^2}{4m_e^2c^2} s_p \cdot s_e \left[ \frac{1}{r^3} + \frac{4\pi}{3} \delta^3(r) \right] - (s_p \cdot r) (s_e \cdot r) \left( \frac{1}{r^3} + \frac{3\pi}{2} + \frac{3}{r^2} \right) e^{-r/\lambda}, \]
\[ V_{4-5} = \frac{f_4^p \hbar^2}{4m_e^2c^2} s_p \cdot s_e \left[ \frac{m_p}{m_p + m_e} \nabla_p - \frac{m_p}{m_p + m_e} \nabla_e \right] \times r \left( \frac{1}{r^3} + \frac{1}{r^2} \right) e^{-r/\lambda} + \]
\[ V_{6+5} = \frac{f_6^p \hbar^2}{4m_e^2c^2} s_p \cdot s_e \left[ \frac{m_p}{m_p + m_e} \nabla_p - \frac{m_p}{m_p + m_e} \nabla_e \right] \times r \left( \frac{1}{r^3} + \frac{1}{r^2} \right) e^{-r/\lambda} + \]
\[ V_8 = -\frac{f_8^p \hbar^3}{4\pi m_e^2c^2} s_p \cdot \left( \frac{m_p}{m_p + m_e} \nabla_p - \frac{m_p}{m_p + m_e} \nabla_e \right) \left[ s_p \cdot \left( \frac{m_p}{m_p + m_e} \nabla_p - \frac{m_p}{m_p + m_e} \nabla_e \right), e^{-r/\lambda} \right] \]
Gravity Experiments – GBAR/AEgIS/ALPHA-g

• Motivation: Test the weak equivalence principle by studying antihydrogen in the gravitational field of the earth.

• Ingredients
  • Production of $\bar{\text{H}}^+$
  • Sympathetic cooling of this charged system by coupling it to laser-cooled Be ions
  • Resonant stripping
  • Drop and annihilate

Goal: Measurement of $g$ to 0.1% level

Production of $\bar{\text{H}}^+$ opens bright perspective for future precision experiments
GSHFS of Antihydrogen: ALPHA/ASACUSA CUSP

1. Measure the ground state hyperfine splitting using a Rabi beam experiment.

   Hydrogen: \( \nu_{HF} = 1,420,405,748.4(3.4) \)

   Antihydrogen: 1.420 4(5)GHz

2. Demonstrated with hydrogen with 2.7 p.p.b. precision
   ASACUSA collaboration, Nature Comms. 8, 15749 (2017)

3. Successful production of first beam of antihydrogen atoms
   ASACUSA collaboration, Nature Comms. 5, 3089 (2014)
Continuous Stern-Gerlach Effect

\[ \frac{\mu_{\tilde{p}}}{\mu_N} = \frac{g_p e_{\tilde{p}}/m_{\tilde{p}}}{2 e_p/m_p} = \frac{v_L}{v_c} \]

Image Current Measurements

\[ \vec{B} \]


S. Ulmer et al., PRL 107, 103002 (2011)
Larmor Frequency – extremely hard

Measurement based on continuous Stern Gerlach effect.

Energy of magnetic dipole in magnetic field
\[ \Phi_M = - (\mu_p \cdot \vec{B}) \]

Leading order magnetic field correction
\[ B_z = B_0 + B_2 \left( z^2 - \frac{\rho^2}{2} \right) \]

This term adds a spin dependent quadratic axial potential

-> Axial frequency becomes a function of the spin state
\[ \Delta \nu_z \sim \frac{\mu_p B_2}{m_p \nu_z} = \alpha_p \frac{B_2}{\nu_z} \]

- Very difficult for the proton/antiproton system.
\[ B_2 \sim 300000 \, T/m^2 \]

- Most extreme magnetic conditions ever applied to single particle.
\[ \Delta \nu_z \sim 170 \, mHz \]

Single Penning trap method is limited to the p.p.m. level

Frequency Measurement
Spin is detected and analyzed via an axial frequency measurement

S. Ulmer, A. Mooser et al. PRL 106, 253001 (2011)
The Mainz Double Penning-Trap Method

Invented by H. Haeffner, in group of G. Werth also highly relevant in electron mass measurements and tests of BS QED (Blaum / Sturm et al.)

Initialize the spin state

1.) measure cyclotron $\nu_c$
2.) drive spin transition at $\nu_{rf}$

particle transport

analyze the spin state

no spin-flip in PT

spin flipped in PT

measures spin flip probability as a function of the drive frequency in the homogeneous magnetic field of the precision trap
The «holy-grail»: single antiproton spin flips

- First non-destructive observation of single-antiproton spin-quantum transitions.
- Double trap method ultimately requires single spin-flip resolution with high fidelity.
Invented: BASE Two-Particle Method

Idea: divide measurement to two particles

«hot» cyclotron particle which probes the magnetic field in the precision trap

«cold» cyclotron particle to flip and analyze the spin-eigenstate

pay: measure with two particles at different mode energies

win: 60% of time usually used for sub-thermal cooling useable for measurements

challenges:

- transport without heating
- more challenging systematics
The Magnetic Moment of the Antiproton

first measurement more precise for antimatter than for matter...

\[ \frac{g_p}{2} = 2.792\,847\,350\,9 \]

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

A. Mooser et al., Nature 509, 596 (2014)


G. Schneider et al., Science 358, 1081 (2017)
| Year | Proton $g_p/2$ | Antiproton $g_{\bar{p}}/2$ | CPT $|g_p/g_{\bar{p}}| - 1$ | Collaboration |
|------|----------------|------------------------|----------------------------|---------------|
| 2011 | 2.792 847 353 (28) | 2.786 2 (83) | 0.002 4 (29) | Pask (JASACUSA) |
| 2013 | 2.792 846 (7) | 2.792 845 (12) | 0.000 000 4 (49) | diSciacc (ATRAP) |
| 2014 | **2.792 847 349 8 (93)** | 2.792 845 (12) | 0.000 000 8 (43) | Mooser/BASE/diSciacc (ATRAP) |
| 2016 | **2.792 847 349 8 (93)** | 2.792 846 5 (23) | 0.000 000 30 (82) | Mooser/Nagahama (BASE) |
| 2017/1 | **2.792 847 349 8 (93)** | 2.792 847 341 1 (42) | 0.000 000 002 0 (36) | Mooser/Smorra (BASE) |
| 2017/2 | **2.792 847 344 62 (82)** | 2.792 847 344 1 (42) | -0.000 000 000 2 (15) | Schneider/Smorra (BASE) |

The graph shows the measurements of $g_p/g_{\bar{p}} - 1$ (p.p.b.) over the years, with data points from various collaborations. The measurements indicate a significant discrepancy between proton and antiproton $g$-factors, supporting the CPT symmetry violation hypothesis. The latest data from 2017/2 is highlighted, showing a deviation of $-0.000 000 000 2 (15)$, which is consistent with previous measurements. The deviations over the years are noted, with significant improvements in precision as indicated by the decreasing uncertainties.
\[
\frac{g_p}{2} = 2.792\,847\,344\,3 (46)
\]

\[
\frac{g_p}{2} = 2.792\,847\,344\,62 (83)
\]

\[
\left| \frac{g_p}{2} - \frac{g_p}{2} \right| = 0.3 (8.3) \, 10^{-9} \, \text{GeV}
\]

3000-fold improved limits on CPT-odd interactions in the baryon sector
Spontaneous breaking of any continuous symmetry leads to the existence of (almost) massless NG-bosons

\[ \phi(\vec{r}, t) \approx \frac{\sqrt{2} \rho_{DM}}{m_\phi} \sin(m_\phi t) \]

\[ \rho_{DM} = 0.4 \text{ GeV/cm}^3 \]

\[ Q = 6 \cdot 10^6 \]

\[ v_\phi = \frac{m_\phi c^2}{\hbar} \]

**Possible Signatures**

\[ \alpha(t) = \alpha_0(1 + g_\gamma \phi(\vec{r}, t)) \]

\[ m_e(t) = m_{e,0}(1 + \frac{g_e}{m_{e,0}} \phi(\vec{r}, t)) \]

\[ m_p(t) = m_{p,0}(1 + \frac{g_p}{m_{p,0}} \phi(\vec{r}, t)) \]

**Axion-like particles**

\[ \delta(\nu_{\text{atom}} - \nu_{\text{Laser}}) = \left( 2 g_\gamma + \frac{g_e}{m_{e,0}} \right) \left( \frac{\sqrt{2} \rho_{DM}}{m_\phi} \right) \text{ for } \nu < \nu_{c,r} \]

\[ \delta(\nu_{\text{atom}} - \nu_{\text{Laser}}) = \left( 2 g_\gamma + \frac{g_e}{m_{e,0}} \right) \left( \frac{\sqrt{2} \rho_{DM}}{m_\phi} \right) h_{\text{atom}}(t) \text{ for } \nu > \nu_{c,r} \]

These type of studies are possible within ALPHA and ASACUSA

Antypas et al., arXiv:2012.01519
Axion Wind Model

• Frist of all: a quick comment on axion fermion coupling


this “derivative interaction” would induce a pseudo magnetic field and a modulation of the antiproton spin transition frequency

Improves previous antiproton/axion limits by 5 orders of magnitude

By 4 o.o.m. less stringent than current best matter limits

QLS with Antiproton Spins

- Apply the very same method to read-out the antiproton spin state

- Initial conditions of experiment
  \[ |\psi\rangle_0 = |\uparrow_p\rangle |0\rangle_{m,p} |\uparrow_L\rangle |0\rangle_{m,L} \]
  \[ |\psi\rangle_0 = |\downarrow_p\rangle |0\rangle_{m,p} |\uparrow_L\rangle |0\rangle_{m,L} \]

- Magnetic SWAP gate in sideband trap
  \[ |\psi\rangle_1 = |\uparrow_p\rangle |0\rangle_{m,p} |\uparrow_L\rangle |0\rangle_{m,L} \]
  \[ |\psi\rangle_1 = |\uparrow_p\rangle |1\rangle_{m,p} |\uparrow_L\rangle |0\rangle_{m,L} \]

- Phonon SWAP gate in wafer trap
  \[ |\psi\rangle_2 = |\uparrow_p\rangle |0\rangle_{m,p} |\uparrow_L\rangle |0\rangle_{m,L} \]
  \[ |\psi\rangle_2 = |\uparrow_p\rangle |0\rangle_{m,p} |\uparrow_L\rangle |1\rangle_{m,L} \]

- Phonon/Spin coupling in Be trap
  \[ |\psi\rangle_3 = |\uparrow_p\rangle |0\rangle_{m,p} |\uparrow_L\rangle |0\rangle_{m,L} \]
  \[ |\psi\rangle_3 = |\uparrow_p\rangle |0\rangle_{m,p} |\downarrow_L\rangle |0\rangle_{m,L} \]
  \[ |\psi\rangle_4 = |\uparrow_p\rangle |0\rangle_{m,p} |\uparrow_L\rangle |0\rangle_{m,L} \]
  \[ |\psi\rangle_4 = |\uparrow_p\rangle |0\rangle_{m,p} |\downarrow_L\rangle |0\rangle_{m,L} \]

- Readout

\[ Be^+ \] level scheme

- Be trap
- sideband trap
- reservoir trap
- precision trap
- wafer trap
AXION SEARCH

calibrated with a trapped antiproton

https://journals.aps.org/prl/accepted/15071Y2dJe514a63281b1498fe4274156d3788acc
Conversion of Axion-like particles into photons in the detector

Axions can couple to photons via the interaction term \( \mathcal{L}_{\text{int}} = -\frac{g_{a\gamma}}{4} F_{\mu\nu} \tilde{F}^{\mu\nu} \)

This modifies Maxwell’s equations

\[
\begin{align*}
\nabla \cdot \vec{E} &= \rho - g_{a\gamma} \vec{B} \cdot \nabla a \\
\nabla \times \vec{B} - \partial_t \vec{E} &= \vec{j} + g_{a\gamma} (\vec{B} \partial_t a - \vec{E} \times \nabla a) \\
\n\nabla \cdot \vec{B} &= 0 \\
\n\nabla \times \vec{E} + \partial_t \vec{B} &= 0
\end{align*}
\]

Inside the resonator housing, \( d \ll \lambda_a \), and where there is a strong field \( B_e \), the axions source a magnetic field

\[
|\vec{B}_a| = \frac{1}{2} r g_{a\gamma} |\vec{B}_0| \sqrt{\rho_a \hbar c}
\]

Future Projection

• With a purpose-built experiment we should be able to improve sensitivity considerably

\[
\frac{V_a}{V_n} \propto \frac{\pi}{2} g \gamma \sqrt{\nu_a \rho_a \hbar c_0} \sqrt{\frac{f(Q)}{4k_B g(T_z)}} \sqrt{(r_2 - r_1)(r_2 + r_1)^{3/2} B_e}
\]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Current</th>
<th>New</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>5.5 K</td>
<td>0.05K – 0.1K</td>
<td>&gt; 3</td>
</tr>
<tr>
<td>Q</td>
<td>40 k</td>
<td>160 k</td>
<td>&gt; 1.4</td>
</tr>
<tr>
<td>e_n</td>
<td>1 nV/√Hz</td>
<td>0.1 nV/√Hz</td>
<td>&gt; 3</td>
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<tr>
<td>B_0</td>
<td>1.8 T</td>
<td>7.0 T</td>
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<td>Geometry</td>
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<td>16</td>
</tr>
<tr>
<td>Peak Sens.</td>
<td>1</td>
<td></td>
<td>&gt; 260</td>
</tr>
</tbody>
</table>

Bandwidth-gain currently under development (F. Voelksen)
Recent lab result: 600 kHz tunability achieved (x 3000)

Devlin et al, PRL126, 041301 (2021)

Technologies available to build such an experiment / discussion with IAXO started
BASE-CDM – Under Development

Under development, Jack Devlin, Barbara Latacz, Stefan Ulmer

Some discussion with RADES group on HTS/REBCO/YBCO coating

- **Upstream resonator**
  - Bandwidth: 10MHz – 100MHz
  - Bandwidth tuner

- **Central resonator**
  - Bandwidth: 10MHz – 100MHz

- **Downstream resonator**
  - Bandwidth: 100kHz – 500kHz

- **Bandwidth tuners**
  - Central resonator
  - Downstream resonator

- **RF amplifiers**
  - Upstream
  - Downstream

- **Cryogenic magnetometer array**

- **Tuning bank**
Summary

• The physics community at the antiproton decelerator of CERN uses methods of low energy / high precision atomic physics and quantum spectroscopy to study simple antimatter systems with ultra high resolution, sensitive to signals imposed by exotic physics.

• A lot of creative potential and (quantum) expertise is available in this community at CERN.

• Tremendous progress produced in recent years.

• Bright future perspective for considerably improved precision measurements, thanks to the very strong support of CERN.
Thanks very much for your attention

60 Research Institutes/Universities – 339 Researchers – 6 Collaborations
Quantum Logic Spectroscopy

Initial state of coulomb coupled particles in a Paul-trap which share a phonon mode

\[ |\psi\rangle_0 = |\downarrow\rangle_S |\downarrow\rangle_L |0\rangle_m \]

**Laser pulse** which excites the spectroscopy particle

\[ |\psi\rangle_1 = (\alpha |\downarrow\rangle_S + \beta |\uparrow\rangle_S) |\downarrow\rangle_L |0\rangle_m \]
\[ |\psi\rangle_1 = (\alpha |\downarrow\rangle_S |0\rangle_m + \beta |\uparrow\rangle_S |0\rangle_m) |\downarrow\rangle_L \]

**The important quantum-logic pulse**

**Red sideband** which deexcites the spectroscopy particle and puts one motional quantum in the phonon mode.

\[ |\psi\rangle_2 = (\alpha |\downarrow\rangle_S |0\rangle_m + \beta |\downarrow\rangle_S |1\rangle_m) |\downarrow\rangle_L \]

**Translates the internal excited state to a coupled phonon state**

**Red sideband** pulse, which removes the phonon and excites the logic ion

\[ |\psi\rangle_{final} = |\downarrow\rangle_S (\alpha |\downarrow\rangle_L + \beta |\uparrow\rangle_L) |0\rangle_m \]

This algorithm translates the properties of the narrow transition of a spectroscopy ion onto the properties of the easily controllable logic ion.

Meanwhile routinely applied in NIST \(^1S_0 \rightarrow ^3P_0\) of 27Al\(^+\) clock, which reaches precision better \(10^{-18}\).
Sympathetic Cooling of Antiprotons

Two charged particles trapped in direct vicinity interact via coulomb interaction.

\[
U(x_a, x_b) = \frac{1}{4\pi\varepsilon_0 s_0} \frac{q_a q_b}{x_a + x_b} \approx \frac{1}{4\pi\varepsilon_0 s_0} \frac{q_a q_b}{s_0} \left( 1 + \frac{x_a - x_b}{s_0} + \frac{x_a^2}{s_0^2} + \frac{x_b^2}{s_0^2} + \frac{2x_a x_b}{s_0^3} \right)
\]

Resonant Coupling:

- Effective Energy Exchange


Quantum Spectroscopy at CERN

- First non-destructive observation of single-antiproton spin-quantum transitions.
- Double trap method ultimately requires single spin-flip resolution with high fidelity.
Future – Sympathetic Cooling of Antiprotons

- Current antiproton magnetic moment measurements are limited by particle preparation time and particle mode temperature
- Expect: With traditional methods another 50-fold improvement is possible, afterwards: limit of traditional methods will be reached!

**New Method**

- Couple protons/antiprotons sympathetically to laser cooled $^9$Be$^+$ ions and imprint Doppler temperatures to the antiproton
- Was demonstrated for $^9$Be$^+$ ions in Paul traps – implement same in Penning traps

**Effort at University of Mainz**

- 5 trap design implemented and simultaneous detection of $^9$Be$^+$ ion and proton in common endcap trap was demonstrated.

**Effort at University of Hannover and PTB**

- Recent dramatic progress: Detection of a single laser cooled $^9$Be$^+$ ion, in a Penning trap system which is fully compatible with the BASE trap system at CERN

The Vision

>100-fold improved antiproton cooling time seems to be in reach

Implement hyperfine clock for magnet stabilization
Quantum Technologies

Non-destructive spin transition spectroscopy

Quantum logic inspired sympathetic cooling of antiprotons, Hbar +, and positrons to laser-cooled Be+ ions

Improves
• spin detection fidelity
• Anihydrogen yield
• Resolution in test of WEP

Quantum logics inspired sympathetic cooling of antiprotons, Hbar +, and positrons to laser-cooled Be+ ions

Use Wineland Al-clock quantum-logic algorithm to measure antiproton spin

|ψ⟩₀ = |↑⟩₀|0⟩₀|0⟩₀|ħL₀|0⟩₀
|ψ⟩₁ = |↑⟩₀|0⟩₀|0⟩₀|ħL₁|0⟩₀
|ψ⟩₂ = |↑⟩₀|0⟩₀|0⟩₀|ħL₂|0⟩₀
|ψ⟩₃ = |↑⟩₀|0⟩₀|0⟩₀|ħL₃|0⟩₀
|ψ⟩₄ = |↑⟩₀|0⟩₀|0⟩₀|ħL₄|0⟩₀

Production of Hbar via Charge Exchange with Laser Excited PS

P⁺⁺ + p⁻⁻ → H⁻⁻ + e⁻⁻

More Quantum Methods

Deep UV two photon spectroscopy in antiprotonic helium

Atomic fountain microwave clocks

Laser Cooled Superconductors

coupled Penning traps with common SC-LC

Demonstrated reduction of SC-LC circuit temperature to sub-1K level

Axion detection / precision frequency measurements

Quantum Logic Spectroscopy

Quantum Logic Spectroscopy

Quantum Logic Spectroscopy

Quantum Logic Spectroscopy

Quantum Logic Spectroscopy