Searching for Physics Beyond the Standard Model Using Antiprotons at BASE

E. Wursten[1,2], M. Bohman[1,3], M. Borchert[1,4], J.A. Devlin[1,2], S. Erlewein[1,2,3], M. Fleck[1,5], J. A. Harrington[1,3], A. Mooser[1,2], M. Sato[1,5], C. Smorra[1], M. Wiesinger[1,3], K. Blaum[3], Y. Matsuda[5], C. Ospelkaus[4], W. Quint[6], J. Walz[7,8], Y. Yamazaki[1] and S. Ulmer[1]

[1]RIKEN, Fundamental Symmetries Laboratory, Japan; [2]CERN, Switzerland; [3]Max-Planck-Institut für Kernphysik, Germany; [4]Leibniz University Hannover, Germany; [5]University of Tokyo, Japan; [6]GSI - Helmholtzzentrum für Schwerionenforschung GmbH, Germany; [7]Johannes Gutenberg-Universität Mainz, Germany; [8]Helmholtz-Institut Mainz, Germany

Baryon Antibaryon Symmetry Experiment

Motivation

Baryon asymmetry of the Universe: where has all the **antimatter** gone?

Sakharov conditions [1]:
- Baryon number violation
- C and CP violation
- Interactions out of thermal equilibrium or **CPT violation**

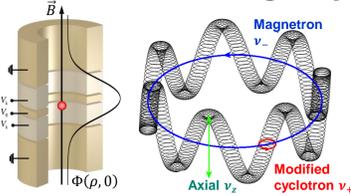Other more exotic models assume a difference in the interaction of antimatter with
- **Gravity**
- **Dark matter**

BASE compares fundamental properties of the antiproton and the proton:
- Mass m
- Charge q
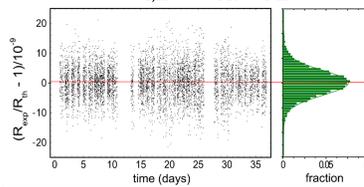- Magnetic moment μ
- Lifetime τ
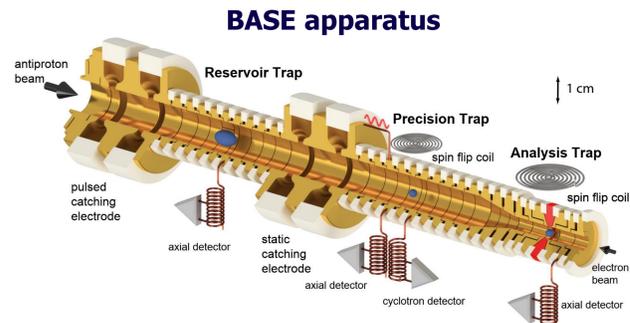
BASE Experiment

Motion in a Penning Trap

Cyclotron frequency is given by

$$\nu_c = \sqrt{\nu_+^2 + \nu_-^2 + \nu_z^2} = \frac{1}{2\pi}\frac{q}{m}B$$

BASE apparatus

Magnetic moment

$$\frac{\mu_{\bar{p}}}{\mu_N} = \frac{g_{\bar{p}}}{2}\frac{q_{\bar{p}}/m_{\bar{p}}}{q_p/m_p} = \frac{\nu_L}{\nu_c}$$

Larmor frequency is determined using the continuous Stern-Gerlach effect and single spin-flip spectroscopy

Charge-to-mass ratio

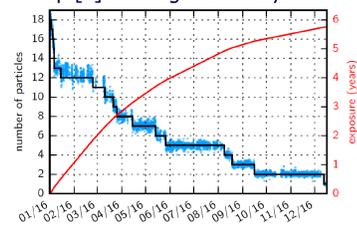$$R_{\exp} = \frac{\nu_{c,\bar{p}}}{\nu_{c,H^-}} = \frac{(q/m)_{\bar{p}}}{(q/m)_{H^-}}$$

$$\frac{(q/m)_{\bar{p}}}{(q/m)_p} + 1 = 1(69)\times 10^{-12} \quad \textbf{69ppt} \text{ [2]}$$

Lifetime

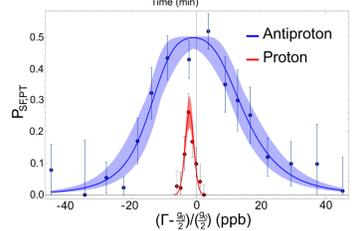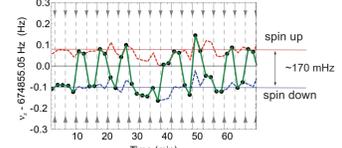Antiprotons stored in the reservoir trap [3] for longer than a year

$$\tau_{\bar{p}} > 10.2a \text{ [4]}$$

$$\frac{g_p}{2} = +2.792\,847\,344\,62(82) \quad \textbf{0.3ppb} \text{ [5]}$$
$$\frac{g_{\bar{p}}}{2} = -2.792\,847\,344\,1(42) \quad \textbf{1.5ppb} \text{ [6]}$$

Standard Model Extension

CPT theorem
Any quantum theory, formulated on flat spacetime is symmetric under the combined action of CPT transformations, provided the theory respects:
- Locality
- Unitarity (conservation of probability)
- Lorentz invariance

Standard Model Extension [7]:
- Spontaneous breaking of Lorentz symmetry
- Effective field theory at low energy
- Add all terms to SM Lagrangian that preserve U(1) gauge invariance, e.g.:
  $$\mathcal{L}^{(3)} = -a^\mu\bar{\psi}\gamma_\mu\psi - b^\mu\bar{\psi}\gamma_5\gamma_\mu\psi - \tfrac{1}{2}H^{\mu\nu}\bar{\psi}\sigma_{\mu\nu}\psi$$
- The terms modify the particle's energy levels in the Penning trap (ν_c and ν_L)
- The coefficients are constant in an inertial frame
- BASE lab frame is not an inertial frame...
  => **modulations at sidereal frequency and its harmonics**!
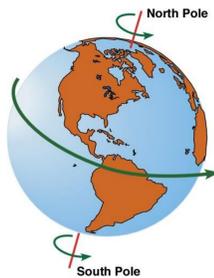
$$\frac{(q/m)_{\bar{p}}}{(q/m)_p} < 0.72\text{ppb/day}$$
Analysis for improved limits ongoing!

Axions & Dark Matter

Axion-like particles (ALP) are a candidate for **dark matter**
- They would form a coherently oscillating classical field
- We pass through a cloud of dark matter as we move through the Milky Way generating an "**axion wind**" [8]
- Assume an interaction between the ALPs a and the antiprotons ψ
  $$\mathcal{L}_{\text{int}} = \frac{C_{\bar{p}}}{2f_a}\partial_\mu a\bar{\psi}\gamma^\mu\gamma^5\psi$$
- Results in anomalous spin precession
  $$\mathcal{H}_{\text{int}} = \frac{C_{\bar{p}}a_0}{2f_a}\sin(m_a t)\,\boldsymbol{\sigma}_{\bar{p}}\cdot\boldsymbol{p}_a$$
  which implies an **oscillating g-factor** at the Compton frequency of the ALP and sidebands due to the Earth's rotation
- Coupling could be different for p and $\bar{p}$
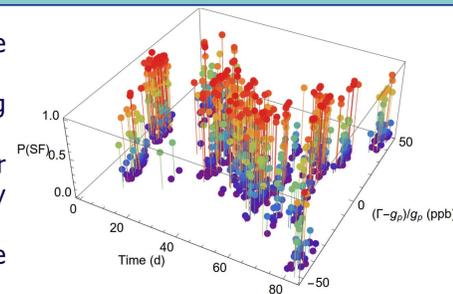
Dataset of 85 days would allow us to constrain:
- ALP masses between 10^{-22} and 10^{-17} eV/c^2
- We expect to improve dark matter-antimatter astrophysical limits by several orders of magnitude

This would be the first laboratory search for dark matter with antiparticles!
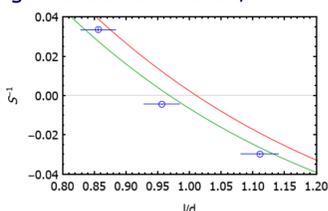
Adjustable Self-Shielding Coil System

Principle

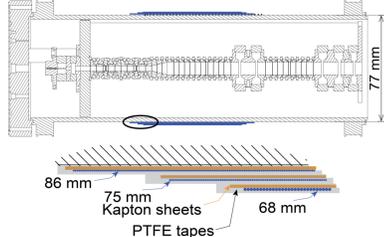Closed superconducting coil shields changes of **B** along its axis [9]
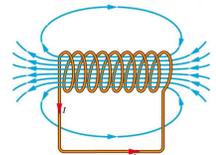
Shielding factor S:
$$S^{-1} = \frac{\Delta B_e + B_{\text{Coil}}}{\Delta B_e}$$

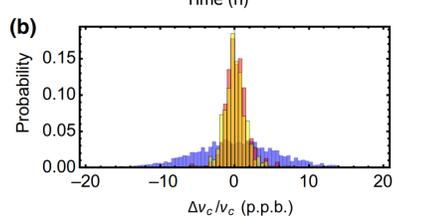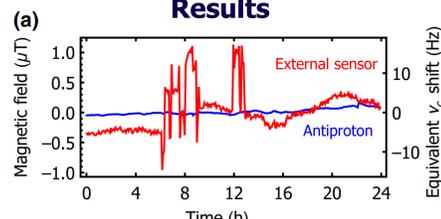Shielding factor depends on its length-to-diameter ratio l/d

Implementation

Adjustable three-coil system [10]

77 mm

86 mm
75 mm Kapton sheets
68 mm
PTFE tapes

Results

(a)
External sensor
Antiproton

(b)

2018-2019: AD on: 1.4(1) p.p.b. AD off: 1.5(1) p.p.b. 2014: 5.9(1) p.p.b.

Scatter improved by factor 4, not limited by magnetic field noise anymore!

Weak Equivalence Principle

The cyclotron frequency acquires a **redshift** in the gravitational potential [11]:
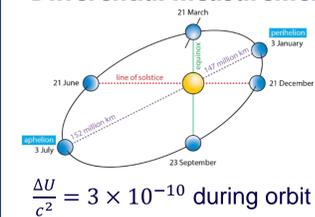$$U = \frac{GM}{r}$$

It could be that antimatter feels a different gravitational coupling and sees a slightly different potential αU. This would imply a **cyclotron frequency difference**:
$$\frac{\bar{\omega}_c - \omega_c}{\omega_c} = 3(\alpha_g - 1)U/c^2$$

Value for U at the Earth's surface ($U/c^2 = 3\times 10^{-5}$) still critically debated in the scientific community

Differential measurement

$$\frac{\Delta U}{c^2} = 3\times 10^{-10} \text{ during orbit}$$

Assuming we can constrain the yearly amplitude to the 69ppt-level, this would set a **limit of 6% on α_g**, which is comparable to goals of antihydrogen gravity experiments

References
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[3] C. Smorra et al., IJMS **389**, 10 (2015)
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[9] G. Gabrielse et al., JAP **63**, 5143 (1988)
[10] J.A. Devlin et al., PRAppl **12**, 044012 (2019)
[11] R.J. Hughes et al., PRL **66**, 854 (1991)