Searching for Physics beyond the Standard Model using Antiprotons at BASE

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Baryon Antibaryon Symmetry Experiment

Motivation

The **Standard Model of Particle Physics** is very successful, but there are still some open issues concerning:

- the matter/antimatter asymmetry,
- dark matter, dark energy,
- gravity, …

The BASE experiment studies protons and antiprotons, can we use it to investigate these the issues?

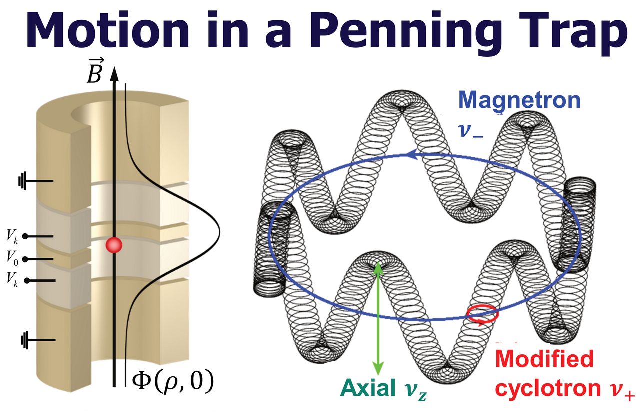
The baryon asymmetry of the Universe: where has all the **antimatter** gone? According to Sakharov we need [1]:

- Baryon number violation
- C and CP violation
- Interactions out of thermal equilibrium or **CPT violation**

Can we find traces of an anomalous interaction of antimatter with **dark matter** or **gravity?**

BASE Experiment

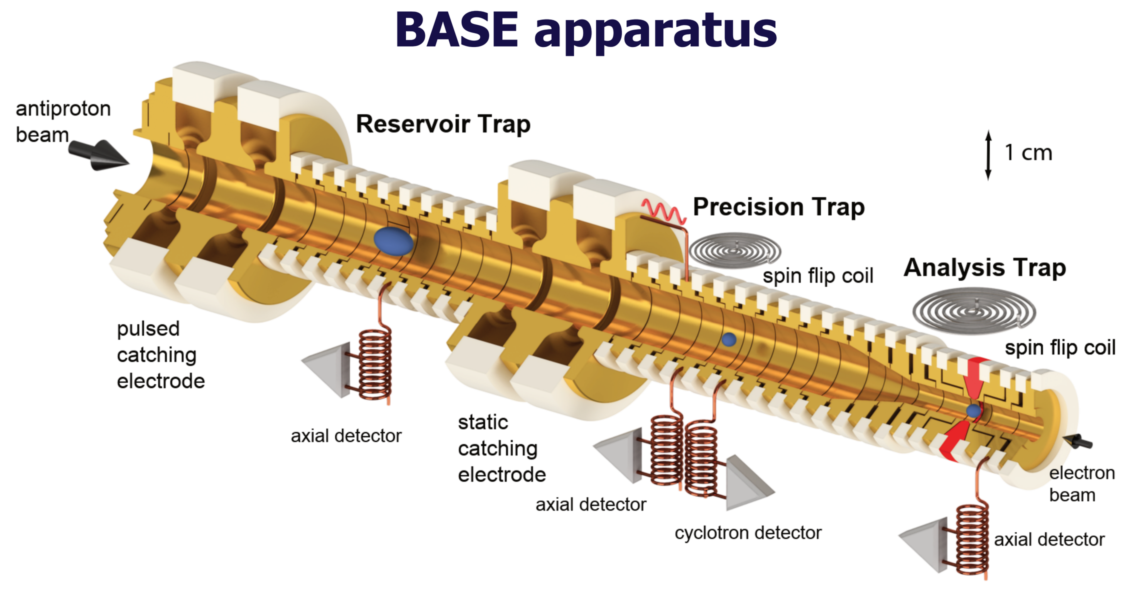
Motion in a Penning Trap



Cyclotron frequency is given by

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

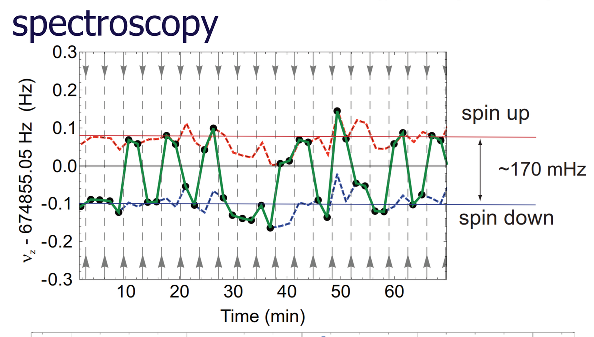
BASE apparatus

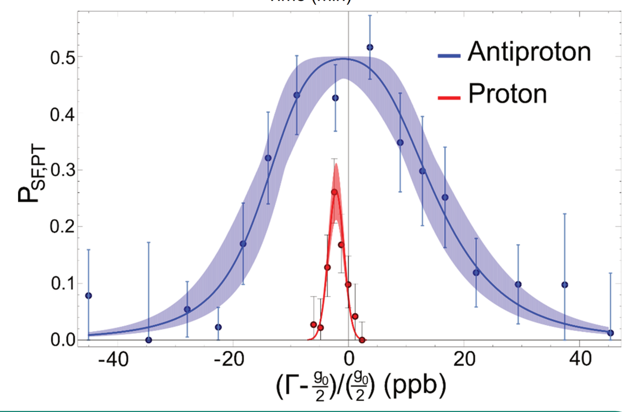


Magnetic moment

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

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



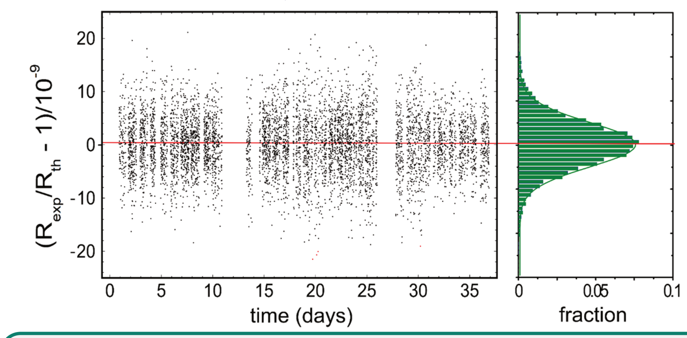


$$\frac{g_p}{2} = +2.792\,847\,344\,62(82)\ \textbf{0.3ppb}\ [5]$$

$$\frac{g_{\bar{p}}}{2} = -2.792\,847\,344\,1(42)\ \textbf{1.5ppb}\ [6]$$

Charge-to-mass ratio

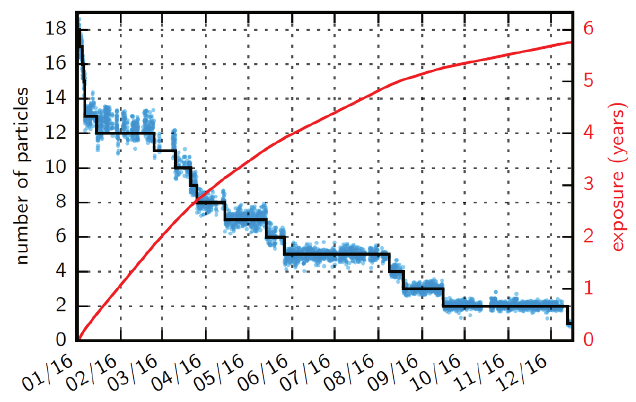
$$R_{\text{exp}} = \frac{\nu_{c,\bar{p}}}{\nu_{c,H^-}} = \frac{(q/m)_{\bar{p}}}{(q/m)_{H^-}}$$



$$\frac{(q/m)_{\bar{p}}}{(q/m)_p} + 1 = -3(16) \times 10^{-12}\ \textbf{16ppt}\ [2]$$

Lifetime

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



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

Scalar Dark Matter & Antimatter

Model

Scalar bosons are a candidate for **dark matter**:

- They would form a **coherently oscillating classical field**, oscillating at the Compton frequency:

$$\phi(t) \approx \phi_0 \cos(m_\phi t)$$

- We are enveloped by a cloud of dark matter as we move throughout the Milky Way. Its density is

$$\langle \rho_\phi \rangle \approx \frac{m_\phi^2 \phi_0^2}{2}$$

- Assume a **Higgs-like interaction** between the scalars ϕ and the fermions ψ:

$$\mathcal{L}_{\text{int}} = -\sum_\psi \frac{\phi m_\psi \bar{\psi}\psi}{\Lambda_\psi}$$

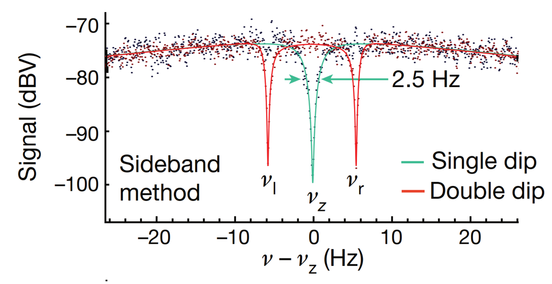
- If we **assume CPT symmetry is broken** and the scalar field couples more strongly to the antiproton than the proton ($\Lambda_{\bar{p}} \ll \Lambda_p$), this will result in an **oscillating mass ratio**:

$$\frac{m_{\bar{p}}}{m_p} \approx 1 - \frac{\phi_0 \cos(m_\phi t)}{\Lambda_{\bar{p}}}$$

Measurement

We have a cyclotron frequency ratio dataset spanning 1.5 years with more than **30000 antiproton-proton frequency comparisons**. Two method were used:

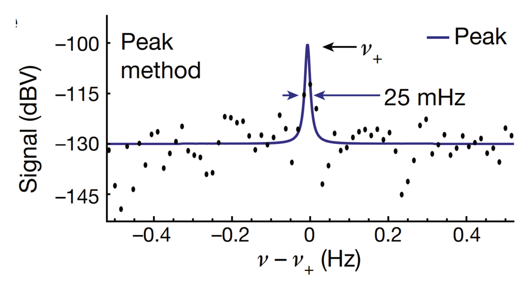
Sideband method



Particle is in equilibrium with the axial detection system, the radial modes are measured by inducing Rabi oscillations:

- **1.6ppb** scatter per shot
- Relatively minor systematic effects

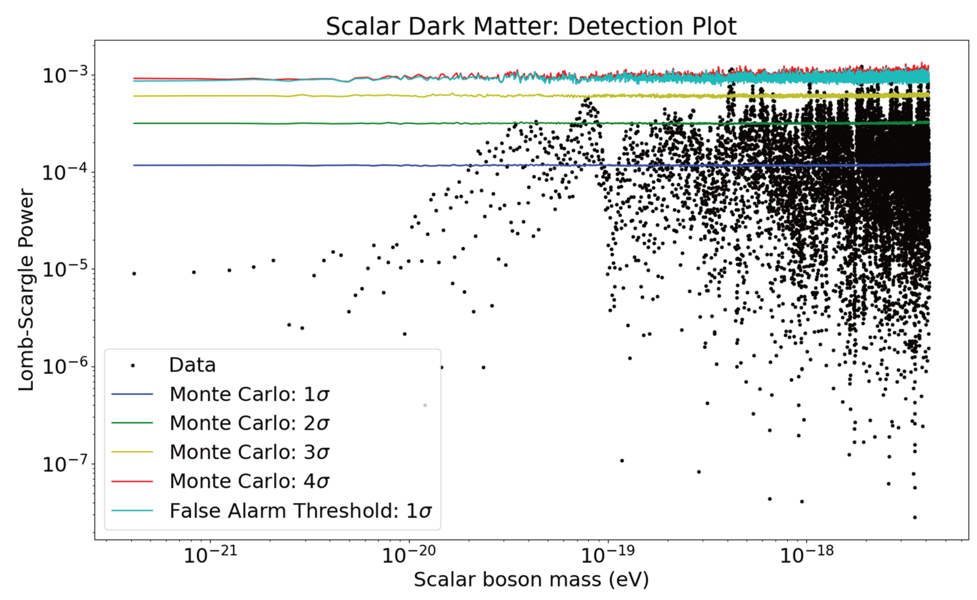
Peak method



Radial mode is determined by exciting the particle and measuring the frequency directly with a dedicated detection system:

- **0.8ppb** scatter per shot
- Larger systematics due to high radial energy

Preliminary results



The dataset allows us to study

- **Scalar boson masses** between 10^{-21}eV and 10^{-17}eV
- Simulations are underway to take the "**Look-elsewhere effect**" into account by calculating the "False-alarm probability" for peak detection
- The 95% CL exclusion region for the interaction strength is being calculated

Standard Model Extension

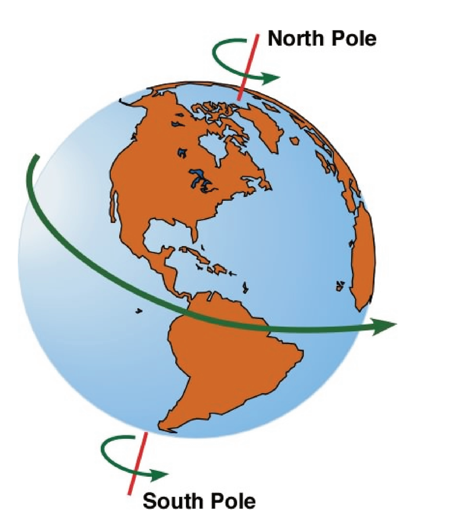
CPT theorem

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.: $\mathcal{L}^{(3)} = -a^\mu \bar{\psi}\gamma_\mu\psi - b^\mu \bar{\psi}\gamma_5\gamma_\mu\psi - \frac{1}{2}H^{\mu\nu}\bar{\psi}\sigma_{\mu\nu}\psi$
- 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**!



Oscillation amplitude limit:

$$\frac{(q/m)_{\bar{p}}}{(q/m)_p} < 0.2\text{ppb per sidereal day}$$

Weak Equivalence Principle for Clocks

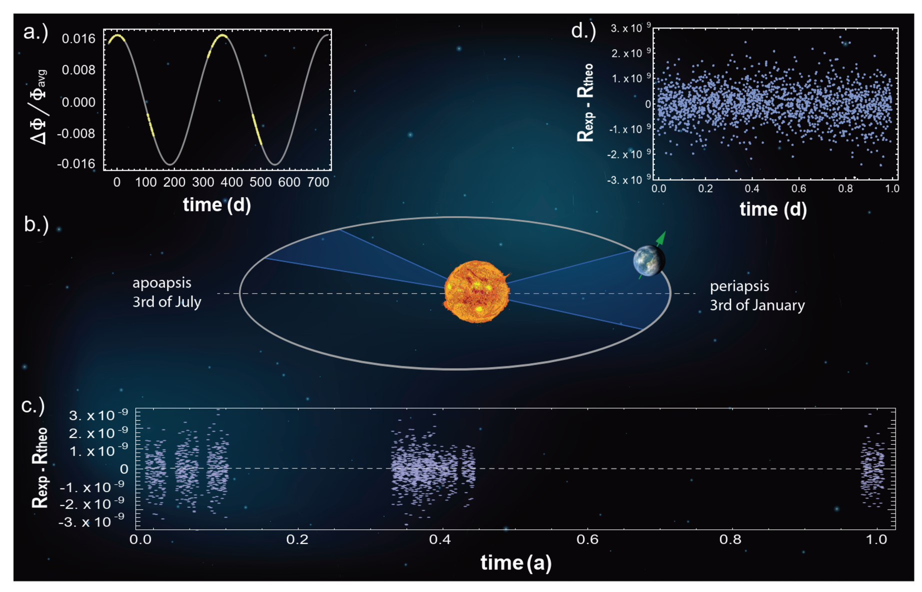
The cyclotron frequency acquires a **redshift** in the gravitational potential [8]:

$$U = \frac{GM}{r}$$

It could be that antimatter feels a different gravitational coupling and sees a slightly different potential αU. This would imply a **cyclotron frequency difference**:

$$\frac{\bar{\omega}_c - \omega_c}{\omega_c} = 3(\alpha_g - 1)\,U/c^2$$

What is the absolute gravitational potential U at the surface of the Earth? ($U/c^2 = 3 \times 10^{-5}$) is still critically debated in the scientific community



Differential measurement

The trajectory of the Earth around the Sun is elliptical, resulting in a change of the gravitational potential during orbit of

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

Analysing the cyclotron frequency difference for yearly variation gives $|\alpha_g - 1|$<0.03 (CL 68%) [2]

References

[1] A.D. Sakharov, JETP Lett **5**, 24 (1967)
[2] M. Borchert et al., Nature **601**, 53 (2022)
[3] C. Smorra et al., IJMS **389**, 10 (2015)
[4] S. Sellner et al., NJP **19**, 083023 (2017)
[5] G. Schneider et al., Science **358**, 1081 (2017)
[6] C. Smorra et al., Nature **239**, 47 (2017)
[7] Y. Ding et al., PRD **94**, 056008 (2016)
[8] R.J. Hughes et al., PRL **66**, 854 (1991)

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