FIP Sensitivity of the Experiments at the Antiproton Decelerator of CERN

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RIKEN
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antihydrogen trap

antiproton/proton balance
The AD/ELENA-Facility

BASE, Fundamental properties of the antiproton

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/equivalence principle with antihydrogen

PUMA Antiproton/nuclei scattering to study neutron skins

Six collaborations, pioneering work by Gabrielse, Oelert, Hayano, Hangst, Charlton et al.


60 Research Institutes/Universities – 350 Scientists – 6 Active Collaborations
Tests of CPT Invariance, inspired by matter/antimatter asymmetry

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

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

**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

\[
\mathcal{L}' \supset \frac{\lambda}{M_k^k} \langle T \rangle \cdot \overline{\psi} \Gamma (i \partial^k) \psi + \text{h.c.}
\]

Lorentz bilinear

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

\[\mathcal{L} = ?\]

Used Techniques: Classical AMO Methods

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

**matter sector 2016**

<table>
<thead>
<tr>
<th></th>
<th>proton lifetime (direct)</th>
<th>proton m</th>
<th>proton magn. moment</th>
<th>hydrogen 1S/2S</th>
<th>hydrogen GSHFS</th>
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<tbody>
<tr>
<td>proton lifetime</td>
<td>$&gt;1.67 \times 10^{34}$ y</td>
<td>90 p.p.t.</td>
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<td>antiproton lifetime</td>
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<td>120 p.p.t.</td>
<td>4.4 p.p.m.</td>
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**matter sector 2021**

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<td>$&gt;1.67 \times 10^{34}$ y</td>
<td>30 p.p.t.</td>
<td>0.3 p.p.b.</td>
<td>0.004 p.p.t.</td>
<td>0.7 p.p.t.</td>
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<td>antiproton lifetime</td>
<td>$&gt;30$ y</td>
<td>30 p.p.t.</td>
<td>1.5 p.p.b.</td>
<td>2 p.p.t.</td>
<td>400 p.p.m.</td>
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Experiments with Ultra-High Precision

Tests of Fundamental Symmetries by comparing the fundamental DC-properties of protons and antiprotons / hydrogen and antihydrogen

Tests of Fundamental Symmetries by search for oscillatory structures in the recorded data-sets

Ultra Sensitive Measurement Instruments, that can be used for other purposes, e.g. ADMX-style haloscopes, mCP detection, etc.

AD-Program Fundamental Constants 2020

<table>
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<th>Physical Quantity</th>
<th>Fractional Precision</th>
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<tr>
<td>$m_p/m_e$</td>
<td>$10^{-15}$</td>
</tr>
<tr>
<td>$v_{1S\rightarrow 2S}$</td>
<td>$10^{-12}$</td>
</tr>
<tr>
<td>$v_{GS-HFS}$</td>
<td>$10^{-9}$</td>
</tr>
<tr>
<td>$v_{Lp}/v_{c,p}$</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>$v_{c,p}/v_{c,p}$</td>
<td>$10^{-3}$</td>
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Clock Resolution

Spontaneous breaking of any continuous symmetry leads to the existence of (almost) massless NG-bosons

$\Phi(x,t) = \frac{\gamma_0}{\sqrt{2}} \sin(m_p t)$

$\rho_{NG} = 0.4 \text{ GeV/cm}^2$

$\theta = 6 \times 10^9$

$\upsilon = m_p c^2/\hbar$

Possible Signatures

$\alpha(t) = \alpha_0 (1 + \phi_0 \Phi(x,t))$

$m_n(t) = m_{n,0} (1 + \frac{\theta}{m_p,0} \Phi(x,t))$

$m_p(t) = m_{p,0} (1 + \frac{\theta}{m_n,0} \Phi(x,t))$

(Anti-)Atomic Transition Frequencies

$\Delta \nu_{HFS} = \left[ 2 \gamma_1 + \gamma_2 \right] \frac{\Delta \nu_{HFS}}{\gamma_2}$ for $\gamma_2 < \gamma_1$

$\Delta \nu_{HFS} = \left[ 2 \gamma_1 + \gamma_2 \right] \frac{\Delta \nu_{HFS}}{\gamma_2} \cos(\gamma_1)$ for $\gamma_2 > \gamma_1$

These types of studies are possible within ALPHA and ASACUSA

Antypas et al., arXiv:2012.01519
Example for Oscillation Study: Axion Wind Model

- First 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 at the “Compton frequency” of CDM

\[
\delta \omega^P(t) \approx \frac{C_{1} m_{a} a_{0} |\psi|}{f_{a}} [A \cos(\Omega_{\text{sid}} t + \alpha) + B] \sin(\omega_{a} t)
\]

Improves previous antiproton/axion limits by 5 orders of magnitude

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

The coupling of axions to EM waves modifies Maxwell’s equations:

$$\nabla \times \mathbf{H} - \dot{\mathbf{D}} = g_{ay} (\mathbf{D} \times \nabla a - \mathbf{H} \dot{a}) + j_{el}$$

If we apply a strong external magnetic field, have no free charge density $j_{el}$ and consider that the earth is moving through the dark matter halo this equation becomes:

$$\nabla \times \mathbf{B} - \dot{\mathbf{D}} = g_{ay} \mathbf{B} \dot{a}$$

A B field along the theta direction will be excited

$$\mathbf{B}_a = -\frac{1}{2} g_{ay} \mathbf{B}_0 \sqrt{\frac{\rho_a}{\hbar c}} \phi$$

Lots of experiments are using this basic idea to look for low frequency axions and axion-like particles (DM radio, ADMX-SLIC, ABRACADABRA, SHAFT...)

Sikivie et al. PRL 112, 131301 (2014)  
The situation in the experiment

The axion signal:

\[ V_a = \frac{\pi}{2} Q \sqrt{f(\nu, Q, q) k_\nu a l N_T (r_2^2 - r_1^2)} g a_\gamma \|B_e\| \sqrt{\rho_a \hbar c}. \]

The resonator background:

\[ V_n = \sqrt{\epsilon_n^2 \Delta \nu + \kappa^2 4 k_\nu T_z \Delta \nu R_p f(\nu, Q, q)} \]

We detect \( \sqrt{V_n^2 + V_a^2} \)

[Figure showing Fourier transform of \( \sqrt{V_n^2 + V_a^2} \)]

$\frac{V_a}{V_n} \propto \frac{\pi}{2} g_a \sqrt{\nu_a \rho a \hbar c_0} \sqrt{\frac{f(Q)}{4k_B g(T_z)}} \sqrt{(r_2 - r_1)(r_2 + r_1)^{3/2} B_e}$

Under development, Jack Devlin, Barbara Latacz, Stefan Ulmer

Cryogenic magnetometer array

Tuning bank

rf amplifiers downstream

bandwidth tuner downstream resonator

downstream resonator

500kHz – 1MHz

Central resonator

10MHz – 100MHz

upstream resonator

100kHz – 500kHz

rf amplifiers upstream

bandwidth tuner central resonator
Thanks very much for your attention

60 Research Institutes/Universities – 339 Researchers – 6 Collaborations