Testing Fundamental Physics with Trapped Antihydrogen: Recent Results and Future Plans of the ALPHA Experiment at CERN

Leaders
Aug 28th 2021 edition

In praise of physics

Fundamental physics is humanity’s most extraordinary achievement

It sees worlds in grains of sand and infinities in hours

The Economist

Scott Menary

ALPHA

YORK
Testing the **Foundations** of Physics with Trapped Antihydrogen

- Foundations of Physics
- CPT Invariance - The Standard Model
- Making Trapped Antihydrogen
- Spectroscopy - ALPHA 2
- Foundations of Physics
  - Equivalence Principle - General Relativity
- Dropping Antihydrogen - ALPHA-g
- The Future
Es handelt sich um Variationsprobleme, die eine kontinuierliche Gruppe (im Lieschen Sinne) gestatten; die daraus ergebenden Folgerungen für die zugehörigen Differentialgleichungen finden ihren allgemeinsten Ausdruck in den in § 1 formulierten, in den folgenden Paragraphen bewiesenen Sätzen. Über diese aus Variationsproblemen entspringenden Differentialgleichungen lassen sich viel präzisere Aussagen machen als über beliebige, eine Gruppe gestattende Differentialgleichungen, die den Gegenstand der Lieschen Untersuchungen bilden. Das folgende beruht also auf einer Verbindung der Methoden der formalen Variationsrechnung mit denen der Lieschen Gruppentheorie. Für spezielle Gruppen und Variationsprobleme ist diese Verbindung der Methoden nicht neu; ich erwähne Hamel und Herglotz für spezielle endliche, Lorentz und seine Schüler (z. B. Fokker), Weyl und Klein für spezielle unendliche Gruppen. Insbesondere sind die zweite Kleinische Note und die vorliegenden Ausführungen gegenseitig durch einander beeinflusst.

1) Die endgültige Fassung des Manuskriptes wurde erst Ende September eingeübt.

In einer eben erschienenen Arbeit von Kneser (Math. Zeitschrift Bd. 2) handelt es sich um Aufstellung von Invarianten nach ähnlicher Methode.
Invariance/Symmetry ➔ Conservation Laws

- Time Zero ➔ Energy
- Position of origin ➔ Linear Momentum
- Angle of axes ➔ Angular Momentum
Discrete Symmetries $\leftrightarrow$ Conserved Quantum Numbers

\[ \vec{F} = \frac{1}{4\pi\varepsilon_0} \frac{qQ}{|\hat{r}|^2} \hat{r} \]

\( \vec{F} \) is force on \( q \) due to \( Q \)

- **Charge conjugation** (particle to antiparticle)
  \[ qQ \implies (-q)(-Q) = qQ \]

- **Parity Inversion**
  \( \vec{r} \implies -\vec{r} \)
  \[ | -\vec{r} |^2 = |\vec{r}|^2 \]

- **Time Reversal**
  \[ \hat{r} \implies -\hat{r} \]

\( \sigma(AB \to CD) = \sigma(CD \to AB) \)
CPT Invariance and The Standard Model

Every theory with

- an Hermitian Hamiltonian $\mathcal{H} = \mathcal{H}^\dagger$
- local operators $\mathcal{O} = \mathcal{O}(x, t)$, constructed from spin zero, one-half and one fields
- usual connection between spin and statics is valid, i.e., fermion fields anticommute $\{\psi_i, \psi_j\} = \delta_{ij}$
- products are normally ordered, i.e., $\psi_1^\dagger \psi_2^\dagger \psi_1 \psi_2$

is invariant under the combined action of $\mathbf{C}$, $\mathbf{P}$, and $\mathbf{T}$ (G. Lüders, Annals Phys. 2, 1957). The Standard Model is such a theory.

CPT Invariance requires particles and their antiparticles have the same mass and magnetic moment as well as equal and opposite electric charge. Also atoms and anti-atoms have the exact same energy levels.
The most precisely measured system in physics is the hydrogen atom.

In particular, the 1S-2S transition frequency is measured to be:

\[ f = 2,466,061,413,187,035 \text{ (10) Hz} \]

Measuring the same quantity for antihydrogen would then constitute a very powerful test of CPT Invariance of the Standard Model.

The ALPHA Collaboration ~ 55 physicists from 17 institutions
Antiprotons for ALPHA

<2021 - Antiproton Decelerator
- ~30 million antiprotons every ~2 minutes
- KE of 5.3 MeV
- 8 hours of beam per day

2021 - ELENA
- ~7.5 million antiprotons every ~2 minutes
- KE of 100 keV
- Beam delivered 24/7
Catching Trap

ALPHA 2

ALPHA-g

Positron Accumulator
antiproton catching trap

antihydrogen formation and trapping

Superconducting External Solenoid

ALPHA-g Atom Traps

Interconnect Magnet

Beamline Modules

Catching Trap

ALPHA-II Atom Trap
Penning Trap

- Varying electric field for axial confinement
- Solenoidal magnetic field for radial confinement

Atom Trap

- Octupole for magnetic gradient
- Potential energy of magnetic dipole in $\mathbf{B}$ field

$$U = -\mu \mathbf{H} \cdot \mathbf{B}$$

- Antihydrogen is confined to minimum $U$
$\mu \bar{H}$ for ground state $\bar{H}$ is dominated by positron
Hence $\mu \bar{H} \approx \mu_B \sim 6 \times 10^{-11}$ MeV/T

The magnetic field gradient in ALPHA is $\Delta B \approx 0.8$ T
The trap depth is therefore on the order of $\Delta U \sim \mu_B \Delta B \approx 50 \mu$eV (0.5 °K)

Only ultra cold antihydrogen can be trapped
Need to do lots of cooling at all stages of antihydrogen production.

- p from AD
- e⁺ from ²²Na

1s

- H synthesis in minimum-B trap

minutes to hours

- H hold

few seconds

- Trap Ramp Down
detection with tracker
The Double-Sided Silicon Vertex Detector

30,000 channel strips
~0.8 m² active area
Major background is cosmic rays

Two methods for cosmic ray rejection

- Cuts on reconstructed vertex position and “straightness” of combined track - Efficiency ~68% with false-positive rate of 47 MHz

- Machine Learning: Boosted Decision Trees - Efficiency ~40% with false positive rate of 4 MHz
Spectroscopy with Antihydrogen

- Trap antihydrogen (3 mixing cycles, ~40 atoms)
- Clear out any remaining charged particles
- 300s laser exposure at frequencies near the $|1S,d\rangle$ to $|2S,d\rangle$ transition
- 32s microwave sweep to eject $|1S,c\rangle$
- Ramp down magnets to detect remaining Hbars
**CPT Test**

- **Appearance** - 1991 antihydrogen detected during laser illumination
- **Disappearance** - 6137 antihydrogen detected during trap shutdown

\[ \geq 15000 \bar{\text{H}} \text{ trapped} \]

Our result for antihydrogen:

\[ f = 2,466,061,103,079.4 \ (5.4) \ \text{kHz} \]

The value for hydrogen at the same field:

\[ f = 2,466,061,103,080.3 \ (0.6) \ \text{kHz} \]

\[ \Delta f = 0.9 \pm 5.4 \ \text{kHz} \ < \sim 2 \times 10^{-20} \ \text{GeV} \]

They agree to a part in \(10^{12}\)
Laser Cooling of Antihydrogen
Laser Cooling of Antihydrogen Achieved!
Testing the Equivalence Principle using Antihydrogen
The Equivalence Principle

\[ F_I = m_I \alpha \quad F_G = G \frac{m_G M_E}{R_E^2} \]

\[ F_I = F_G \]

\[ m_I \alpha = G \frac{m_G M_E}{R_E^2} \]

\[ a = \left( \frac{m_G}{m_I} \right) g \]

so \( a = g \) if \( m_G = m_I \)

- Newton compared the period of a pendulum for a number of bob materials (gold, sand, wood, water, wheat!) and found it to be equal to a part in a thousand

\[ T = 2\pi \sqrt{\frac{m_I \ell}{m_G g}} \]

**Proposition VI. Theorem VI.**

That all bodies gravitate towards every planet; and that the weights of bodies towards any the same planet, at equal distances from the centre of the planet, are proportional to the quantities of matter which they severally contain.

It has been, now of a long time, observed by others, that all sorts of heavy bodies (allowance being made for the inequality of retardation which they suffer from a small power of resistance in the air) descend to the earth from equal heights in equal times; and that equality of times may distinguish to a great accuracy, by the help of pendulums. I tried the thing in gold, silver, lead, glass, sand, common salt, wood, water, and wheat. I provided two wooden boxes, round and equal: I filled the one with wood, and suspended an equal weight of gold (as exactly as I could) in the centre of oscillation of the other. The boxes hanging by equal threads of 11 feet made a couple of pendulums perfectly equal in weight and figure, and equally receiving the resistance of the air. And, placing the one by the other, I observed them to play together forward and backward, for a long time, with equal vibrations. And therefore the quantity of matter in the gold (by Cor. I and 6, Prop. XXIV, Book II) was to the quantity of matter in the wood as the action of the motive force (or vis motrix) upon all the gold to the action of the same upon all the wood; that is, as the weight of the one to the weight of the other: and the like happened in the other bodies. By these experiments, in bodies of the same weight, I could manifestly have discovered a difference of matter less than the thousandth part of the whole, had any such been. But, without all doubt, the nature of gravity towards the planets is the same as towards the earth. For, should we imagine our foolish...
The Equivalence Principle and General Relativity

I was sitting in a chair in the patent office at Bern when all of sudden a thought occurred to me: “If a person falls freely he will not feel his own weight.” I was startled. This simple thought made a deep impression on me. It impelled me toward a theory of gravitation.

Albert Einstein recalling the “happiest thought of my life,” 1922

\[ m_1 \frac{d^2 x^\lambda}{d\tau^2} = - m_0 \frac{dx^\mu}{d\tau} \Gamma_{\mu\nu}^\lambda \frac{dx^\nu}{d\tau} \]
Present Limit on Violation of the Equivalence Principle

Space test of the Equivalence Principle: first results of the MICROSCOPE mission

Pierre Touboul, Gilles Métris, Manuel Rodrigues, Yves André, Quentin Baghi, Joel Bergé, Damien Boulanger, Stefanie Bremer, Ratana Chhun, Bruno Christophe, Valerio Cipolla, Thibault Damour, Pascale Danto, Hansjoerg Dittus, Pierre Fayet, Bernard Foulon, Pierre-Yves Guidotti, Emilie Hardy, Phuong-Anh Huynh, Claus Lämmerzahl, Vincent Lebat, Françoise Liorzou, Meike List, Isabelle Panet, Sandrine Pires, Benjamin Pouilloux, Pascal Prieur, Serge Reynaud, Benny Rievers, Alain Robert, Hanns Selig, Laura Serron, Timothy Sumner, Pieter Visser

The Weak Equivalence Principle (WEP), stating that two bodies of different compositions and/or mass fall at the same rate in a gravitational field (universality of free fall), is at the very foundation of General Relativity. The MICROSCOPE mission aims to test its validity to a precision of $10^{-15}$, two orders of magnitude better than current on-ground tests, by using two masses of different compositions (titanium and platinum alloys) on a quasi-circular trajectory around the Earth. This is realised by measuring the accelerations inferred from the forces required to maintain the two masses exactly in the same orbit. Any significant difference between the measured accelerations, occurring at a defined frequency, would correspond to the detection of a violation of the WEP, or to the discovery of a tiny new type of force added to gravity. MICROSCOPE’s first results show no hint for such a difference, expressed in terms of Eötvös parameter $\delta(Ti, Pt) = [-1 \pm 9\text{(stat)} \pm 9\text{(syst)}] \times 10^{-15}$ (both $1\sigma$ uncertainties) for a titanium and platinum pair of materials. This result was obtained on a session with 120 orbital revolutions representing 7% of the current available data acquired during the whole mission. The quadratic combination of $1\sigma$ uncertainties leads to a current limit on $\delta$ of about $1.3 \times 10^{-14}$. 

$1.3 \times 10^{-14}$
The Equivalence Principle has never been tested with antimatter. Difficult to do with charged antiparticles (e.g., positrons) → antiatoms
ALPHA-g

Superconducting External Solenoid

ALPHA-g Atom Traps

Interconnect Magnet

Positron accumulator not shown

(Copy of) Production Region

Precise Measurement Region

Trigger/ECM

External Solenoid

External Solenoid

Free-Fall Measurement Region

~0.25 m

~2.3 m

~0.4 m
The radial Time Projection Chamber (rTPC)

- 2.3 m long, 20 cm inner diameter, 40 cm outer diameter
- 256 wires, 18,432 pads
- Resolutions:
  - $\sim 5 \text{ mm in } z$
  - $\sim 9 \text{ mm in } r$
  - $\sim 18^\circ$ in azimuth
It Worked!
More Cosmic Ray Rejection

Case 1: Cosmic ray

Case 2: $\bar{\Lambda}$ annihilation

$t_1 << t_2$

$t_1 \sim t_2 \sim t_3$
The Barrel Cosmic-ray Veto Detector

- 64 scintillator bars running the length of the rTPC
- Time resolution of <300 ps
- Will further reduce the cosmic rate to ~7 Hz
“Dropping” Antihydrogen

For an antihydrogen atom in the trap at vertical location $z$ the potential is:

$$U(z) = \mu_B B(z) - m_{\bar{H}}\bar{g} z$$

For $\Delta z = 40$ cm $\rightarrow \Delta U_G \approx 4 \times 10^{-8}$ eV

This corresponds to a magnetic field of

$$\frac{\Delta U_G}{\mu_B} \approx 0.7 \text{ mT}$$

For a 1% measurement must control the magnetic environment to $10^{-6}$ T
Some Future Plans (Dreams?)

- Antihydrogen Fountain - HAICU
- Antihydrogen Molecule
- Spectroscopy and Gravity test with Deuterium
Conclusions

• ALPHA has made huge gains in learning how to trap 100’s of antihydrogen atoms for many hours.

• We have tested CPT Invariance to a part in $10^{12}$ through measurements of the 1S-2S transition frequency.

• We have demonstrated laser cooling which will allow an improvement of several orders of magnitude on this measurement.

• We are installing ALPHA-g now with the intent to make an “up-down” measurement this year and a 1% test of WEP by 2024.

More information at www.york.ca/menary/experiments/research.html