1S-2S Spectroscopy of Antihydrogen in ALPHA

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Prediction of Antimatter

Paul A. M. Dirac

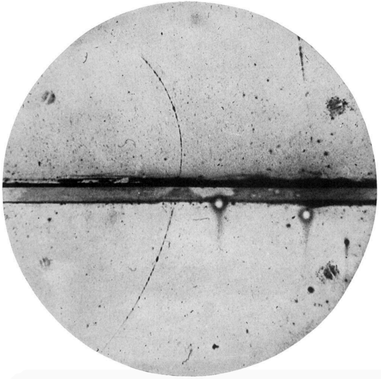
1928 Publishes his equation of motion for the electron

1931 Predicts the existence of the positron

Discovery of the Positron

Carl D. Anderson, 1932

- Studying cosmic particles with a bubble chamber
- Particles would lose energy in lead barrier, allowing the charge to be determined
- Found a light, positively charged particle



Antimatter as Rocket Fuel

In the year 2151?

No!

Highest production of $\bar{p}$: 10^{11} per hour (1.67×10^{-13} g/h)

Would take 5 years to boil 1L of water.

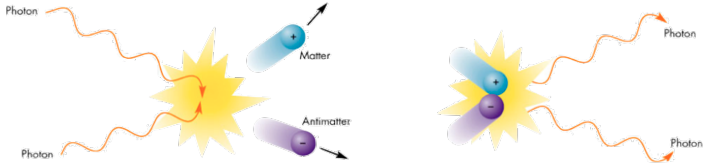
Reasons for Studying Antimatter

Antimatter allows for direct tests of fundamental symmetries and may hold clues to some of the biggest unanswered questions in physics:

- Why is there no antimatter in the Universe (Baryon asymmetry)
- Is CPT symmetry conserved?
- Does the weak equivalence principle hold for antimatter?

Baryon Asymmetry

- Observations show no evidence for large scale antimatter in the Universe
- No satisfactory explanation, consistent with experiment, has been given
- One of the main unanswered questions in physics and a shortcoming of the Standard Model



CPT Symmetry

- Combination of the Charge conjugation, Parity inversion, and Time reversal symmetries
- C, P, and CP are each broken in the standard model
- No process has been observed to break CPT symmetry
- CPT symmetry is proven to hold in any quantum field theory which:
  - Is Lorentz invariant
  - Is local
  - Has a Hermitian Hamiltonian

Antimatter gravity: The Weak Equivalence Principle

In Einstein's general relativity, *any body must experience the same acceleration in the gravitational field, regardless of its composition*

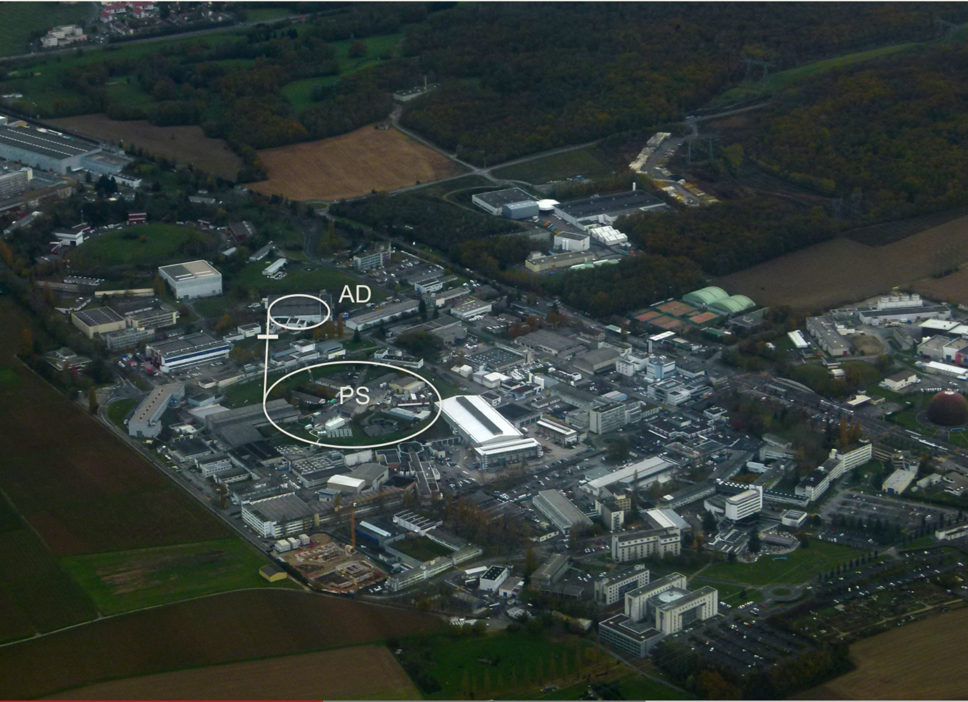
This is expected to hold true for antimatter, but a direct, model-independent test has not been made

1S-2S Spectroscopy

The 1S-2S transition frequency in hydrogen is one of the most precisely measured numbers in physics:

$f_{1S-2S} = 2\ 466\ 061\ 413\ 187\ 035\ (10)$ Hz

Comparing this value with its equivalent in antihydrogen is one of the most appealing and conceptually simple matter / antimatter comparisons, and is one of the main motivations for doing cold antimatter physics.


AD
PS

The AD Experiments

- 6 experiments share the beam from the Antiproton Decelerator
- All are built to compare matter to antimatter at low energy and with high precision
- This is the only place in the world that low energy antimatter can be studied

The ALPHA Experiment

Antihydrogen **L**aser **PH**ysics **A**pparatus

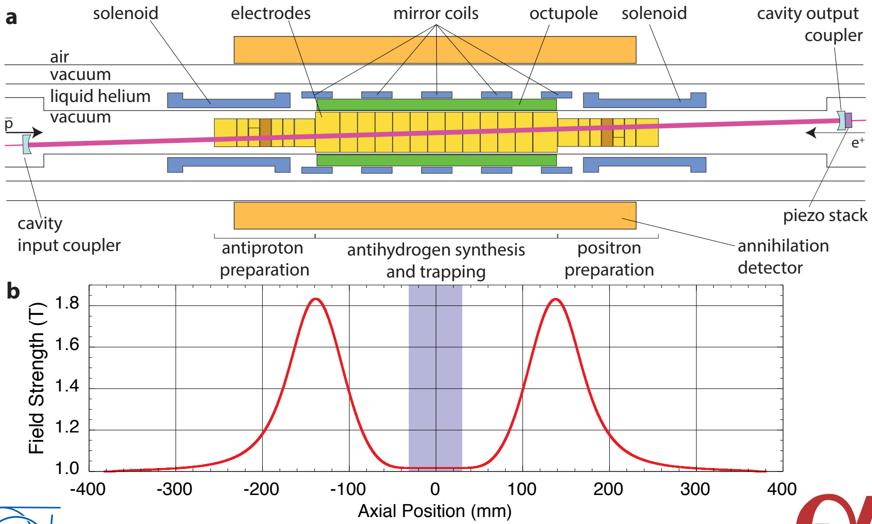
- 2002 (ATHENA) Production of $\bar{\mathrm{H}}$
- 2010 First trapping of $\bar{\mathrm{H}}$
- 2011 First resonant transitions
- 2016 First laser-driven transition

Typical Mixing Numbers

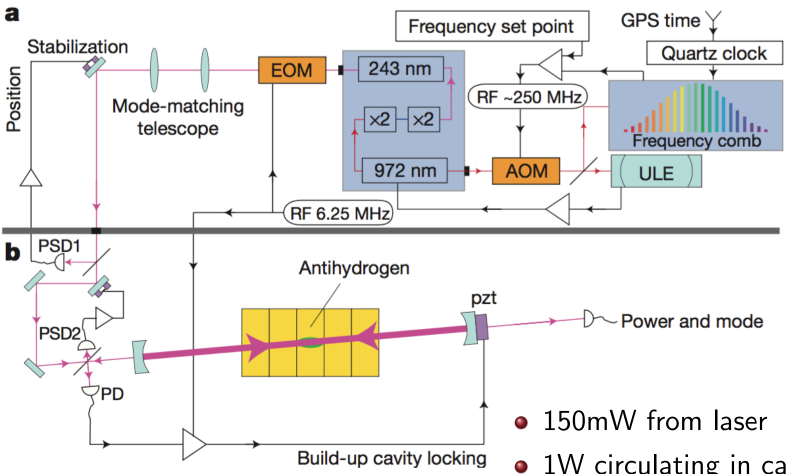
- 90,000 antiprotons
- 3 million positrons
- 50,000 antihydrogen atoms produced
- $\sim$ 20 trapped

We can now accumulate trapped antihydrogen from many mixing cycles

The ALPHA Experiment

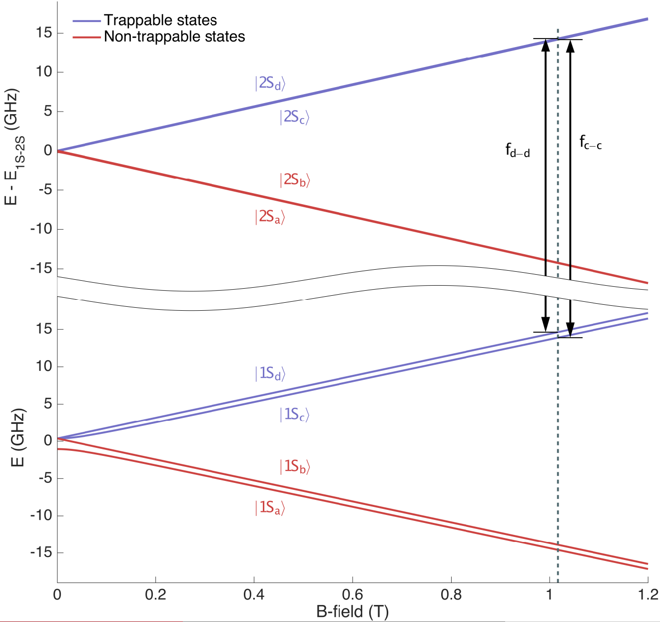


Laser System



- 150mW from laser
- 1W circulating in cavity

Hydrogen 1S and 2S Hyperfine Structure



Experimental Procedure

- Trap antihydrogen from two mixing cycles (about 20 atoms)
- Clear out any remaining charged particles
- 300s hold time at d-d frequency
- 300s hold time at c-c frequency
- Ramp down magnets to detect remaining atoms

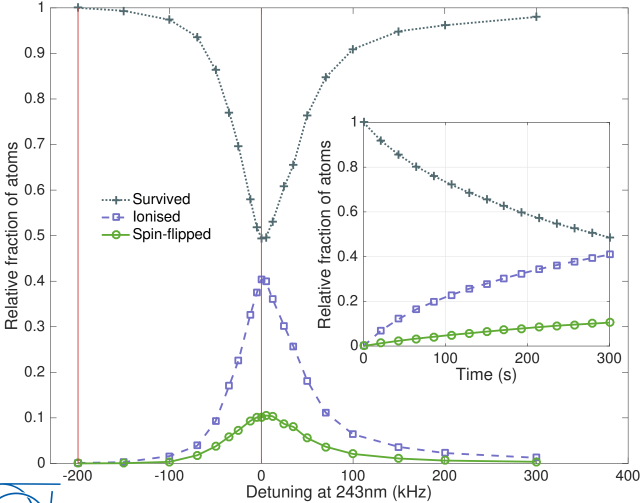
3 types of trials:

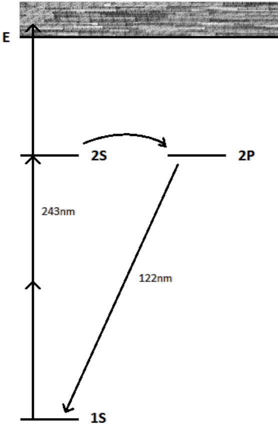
- On resonance
- Off resonance
- No laser

11 repetitions of each type were conducted

Simulation

Simulate the response of ordinary hydrogen in the ALPHA trap





Data: Disappearance mode

Count the atoms left in the trap after the laser exposure.
On- and off- resonance differ by 92 ± 15 counts

Type	Detected events	Background	Uncertainty
Off-resonance	159	0.7	13
On-resonance	67	0.7	8.2
No laser	142	0.7	12

Detector efficiency here is 0.688

Data: Appearance mode

Look for annihilations during the 300s hold times

Type	Detected events	Background	Uncertainty
d-d off resonance	15	14.2	3.9
d-d on resonance	39	14.2	6.2
No laser	22	14.2	4.7
c-c off resonance	12	14.2	3.5
c-c on resonance	40	14.2	6.3
No laser	8	14.2	2.8
total off resonance	27	28.4	5.2
total on resonance	79	28.4	8.9
total No laser	30	28.4	5.5

Detector efficiency here is 0.376

Data: Appearance mode

Look for annihilations during the 300s hold times

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d-d off resonance	15	14.2	3.9
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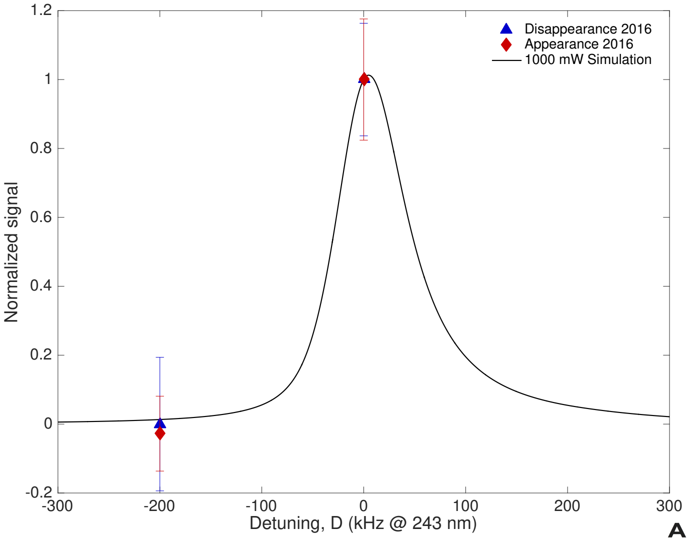
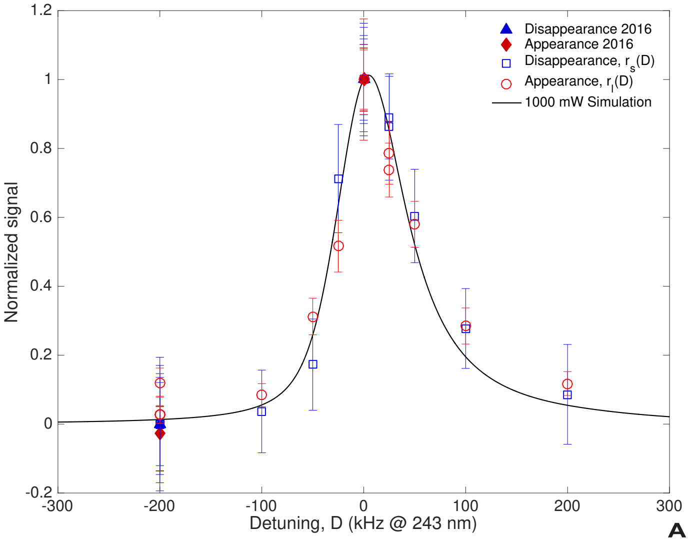
Observation of the 1S–2S transition in trapped antihydrogen

M. Ahmadi[1], B. X. R. Alves[2], C. J. Baker[3], W. Bertsche[4,5], E. Butler[6], A. Capra[7], C. Carruth[8], C. L. Cesar[9], M. Charlton[3], S. Cohen[10], R. Collister[7], S. Eriksson[3], A. Evans[11], N. Evetts[12], J. Fajans[8], T. Friesen[2], M. C. Fujiwara[7], D. R. Gill[7], A. Gutierrez[13], J. S. Hangst[2], W. N. Hardy[12], M. E. Hayden[14], C. A. Isaac[3], A. Ishida[15], M. A. Johnson[4,5], S. A. Jones[3], S. Jonsell[16], L. Kurchaninov[7], N. Madsen[3], M. Mathers[17], D. Maxwell[3], J. T. K. McKenna[7], S. Menary[17], J. M. Michan[7,18], T. Momose[12], J. J. Munich[14], P. Nolan[1], K. Olchanski[7],

2016 Result


Disappearance 2016
Appearance 2016
1000 mW Simulation
Normalized signal
Detuning, D (kHz @ 243 nm)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-300
-200
-100
0
100
200
300

2017 Result


Disappearance 2016
Appearance 2016
Disappearance, $r_s(D)$
Appearance, $r_l(D)$
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1.2
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-300
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0
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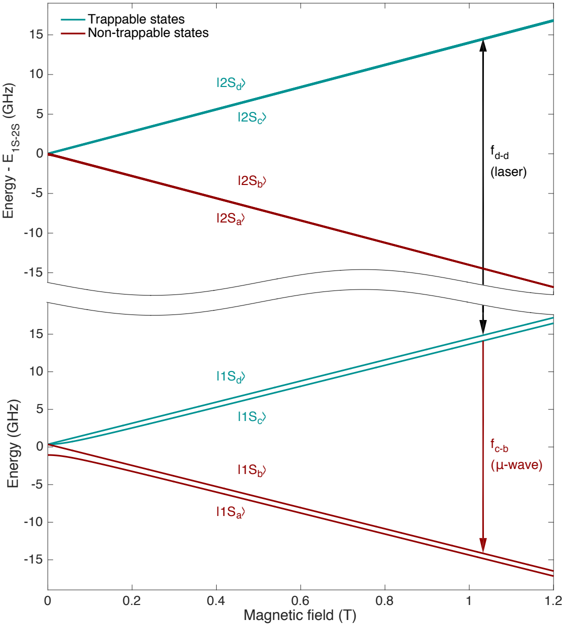
300

Drive only the d-d transition

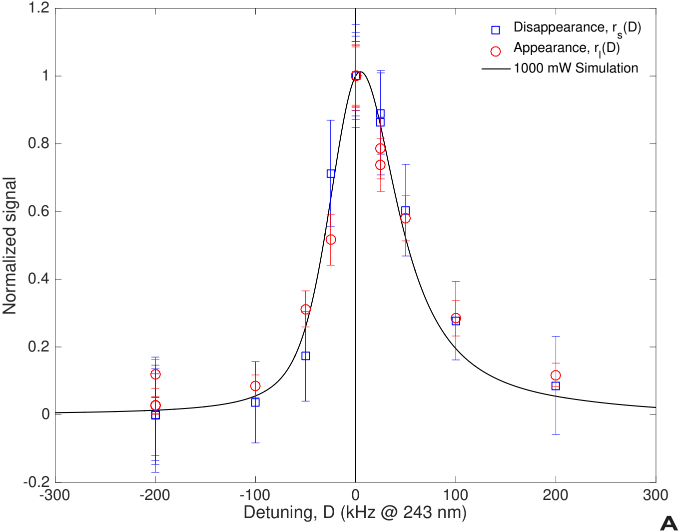


Experimental Procedure

- Trap antihydrogen from three mixing cycles (about 40 atoms)
- Clear out any remaining charged particles
- 300s laser exposure at fixed frequency near d-d transition
- 32s microwave sweep to eject c-state atoms
- Ramp down magnets to detect remaining atoms

- Interspersed trials of 4 different laser frequencies in a frequency 'set'
- 4 sets of 4 frequencies completed over 10 weeks
- 0 kHz and -200 kHz detuning included in every set
- +25 kHz repeated as another check of reproducibility
- 9 unique laser frequencies used on $\sim$ 15 000 atoms

2017 Result



Normalized signal
Detuning, D (kHz @ 243 nm)
Disappearance, $r_s(D)$
Appearance, $r_l(D)$
1000 mW Simulation
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-300
-200
-100
0
100
200
300

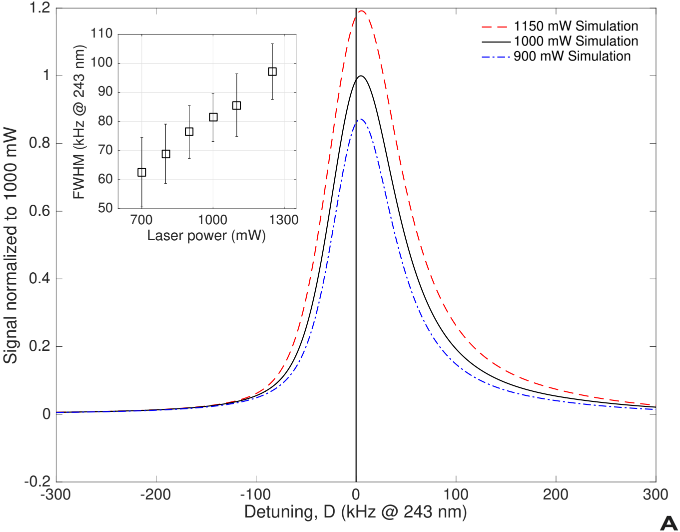
Analysis Strategy

- Fit the data with an appropriate function, derived from simulations.
- Compare to the simulation of ordinary hydrogen

BUT!

- The absolute laser power in the experiment is difficult to measure.
- The laser powers in different sets are unlikely to be identical

Effect of Laser Power



Analysis Strategy

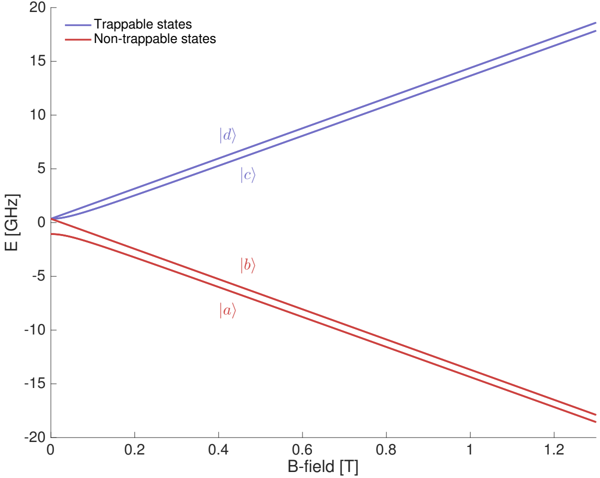
- Parameterize the fitting function in terms of laser power and make this the fit parameter
- Perform the fit with one laser power per set and a single frequency offset from the hydrogen simulation

Result

- The line shape is in good agreement with the hydrogen calculation
- The center frequency is determined to a fractional precision of about 2×10^{-12} and is in agreement with the hydrogen calculation
- This is currently the best "antimatter clock"

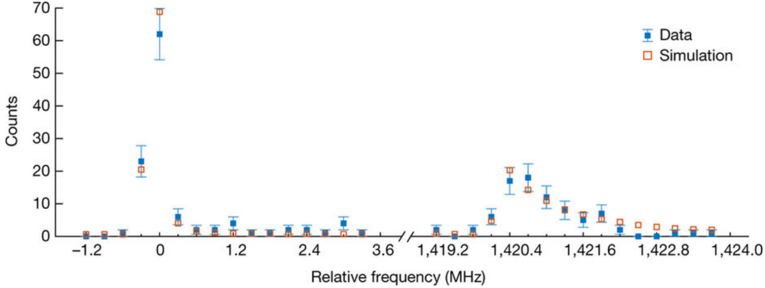
Ground State Hyperfine Spectroscopy

Flip the spin of the positron to expel atoms from the trap



Microwave Spectroscopy in Antihydrogen

Two transitions with constant separation, independent of magnetic field



$$\text{GSHF splitting} = 1,420.4 \pm 0.5\,\text{MHz}$$

Microwave Spectroscopy in Antihydrogen

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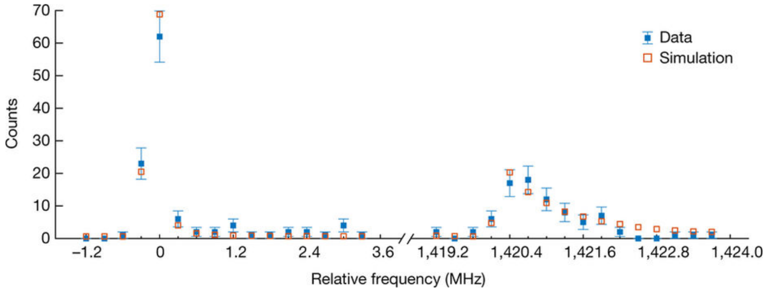
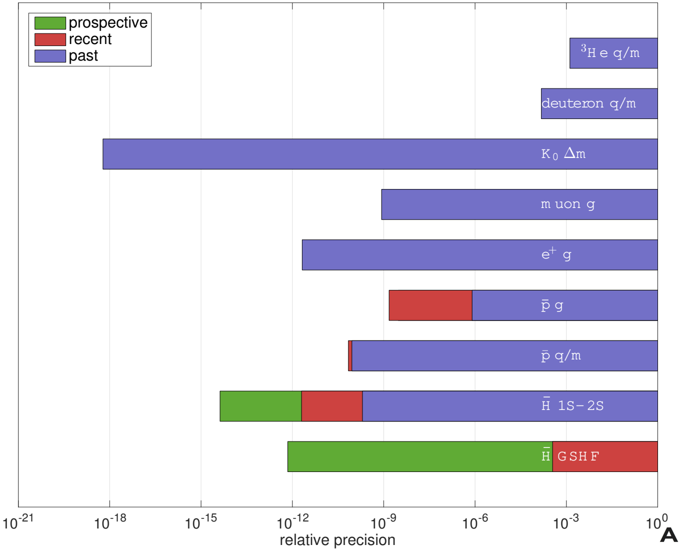


GSHF splitting $= 1,420.4 \pm 0.5\,\mathrm{MHz}$

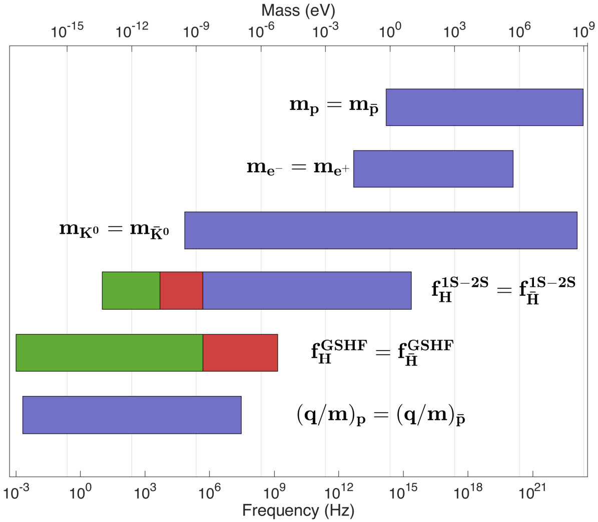
Improvements to come!

CPT Tests and relative precision



CPT Tests on an Energy Scale

Comparing the sensitivity to absolute energy differences of various CPT tests



Understanding the Line Shape

Shifts and broadening effects calculated assuming 1W of circulating laser power and typical trap parameters

Effect	Approximate Size
1st order Doppler	cancels
2nd order Doppler	80 Hz
Transition time	160 kHz
AC Stark	5 kHz
DC Stark	150 Hz
Magnetic shift d-d (c-c)	96 Hz/G (1.9 kHz/G)
Ionisation width	4 kHz

Future Improvements

The main contributions to the line width are:

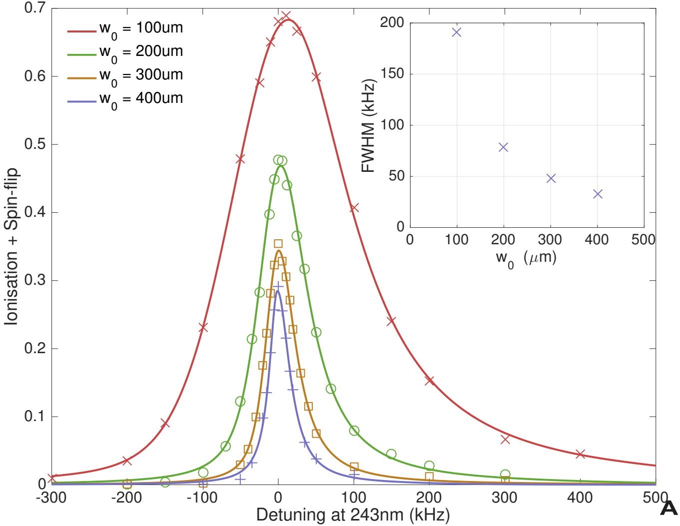
- Transit time broadening
- Depletion effects

Reduction of linewidth to be gained through:

- Increasing the laser beam size
- Cooling the $\overline{\mathrm{H}}$ (Laser cooling or adiabatic expansion)
- Operating at low depletion

Future Improvements

Expansion of laser beam size:



Future Improvements

New measurement strategies:

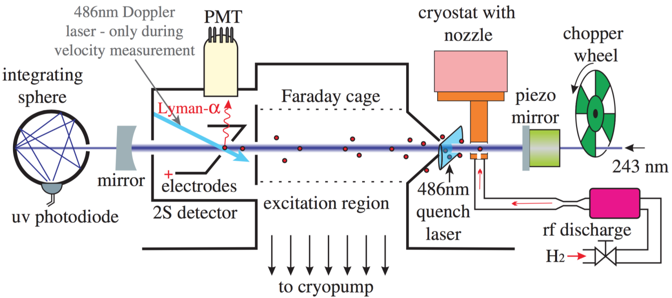
- Measure at low magnetic field
- Measure at several laser powers (extract AC stark shift)
- Measure at several temperatures (extract 2nd order Doppler)

None of these are unthinkable!

Thank you

1S-2S Transition in Hydrogen

- $f_{1S-2S} = 2\,466\,061\,413\,187\,035\,(10)$ Hz
- Measured with a cold hydrogen beam



Hänsch et al. 2011

Table of uncertainties

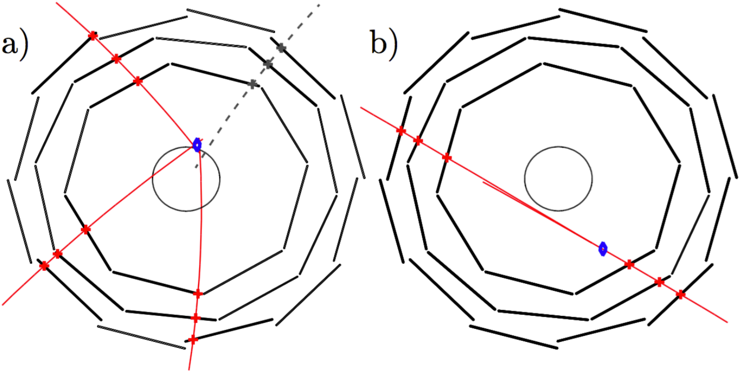
Type of uncertainty	Estimated size (kHz)	Comment
Statistical uncertainties	3.8	Poisson errors and curve fitting to measured data
Modelling uncertainties	3	Fitting of simulated data to piecewise-analytic function
Modelling uncertainties	1	Waist size of the laser, antihydrogen dynamics
Magnetic-field stability	0.03	From microwave removal of $1S_c$-state atoms (see text)
Absolute magnetic-field measurement	0.6	From electron cyclotron resonance
Laser-frequency stability	2	Limited by GPS clock
d.c. Stark shift	0.15	Not included in simulation
Second-order Doppler shift	0.08	Not included in simulation
Discrete frequency choice of measured points	0.36	Determined from fitting sets of pseudo-data
Total	5.4	

Data Table

	Laser detuning, D (kHz)	Number of trials	Atoms lost during laser exposure, L	Atoms lost during microwave exposure, M	Surviving atoms, S	Initially trapped atoms, N_i
Set 1	−200	21	7 ± 7	383 ± 23	504 ± 25	894 ± 35
	−100	21	22 ± 9	415 ± 24	494 ± 24	931 ± 35
	0	21	264 ± 24	423 ± 24	217 ± 16	904 ± 38
	+100	21	75 ± 14	411 ± 23	424 ± 23	910 ± 35
Set 2	−200	21	26 ± 9	394 ± 23	466 ± 24	886 ± 34
	−25	21	113 ± 16	423 ± 24	326 ± 20	862 ± 35
	0	21	219 ± 22	390 ± 23	269 ± 18	878 ± 37
	+25	21	173 ± 20	438 ± 24	296 ± 19	907 ± 37
Set 3	−200	23	8 ± 7	354 ± 22	479 ± 24	841 ± 33
	0	23	303 ± 26	454 ± 25	248 ± 17	1,005 ± 40
	+50	23	176 ± 20	390 ± 23	339 ± 20	905 ± 37
	+200	23	36 ± 11	446 ± 24	459 ± 23	941 ± 35
Set 4	−200	21	7 ± 7	525 ± 26	541 ± 25	1,073 ± 37
	−50	21	86 ± 15	475 ± 25	495 ± 24	1,056 ± 38
	0	21	274 ± 25	480 ± 25	275 ± 18	1,029 ± 40
	+25	21	202 ± 21	516 ± 26	305 ± 19	1,023 ± 38
Total		344	1,991	6,917	6,137	15,045

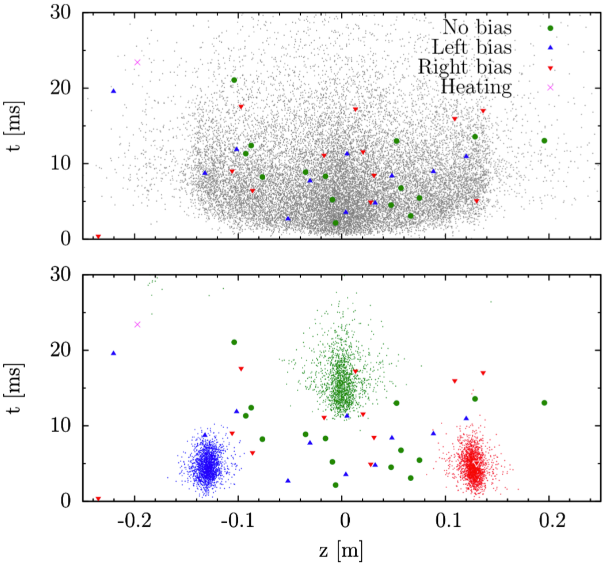
Cosmic Event Rejection

Cosmic discrimination based on event topology



Antiproton Discrimination

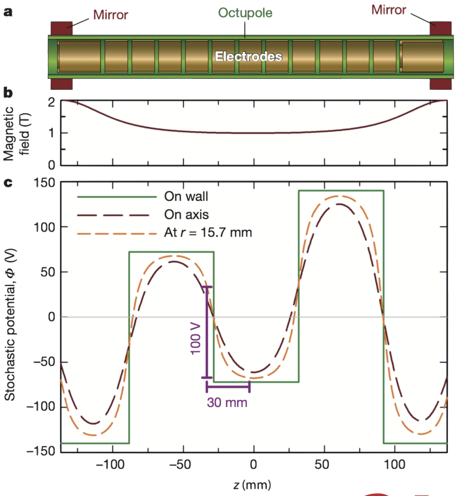
Annihilation distributions inconsistent with charged antiprotons



Charge Neutrality of Antihydrogen

1. Apply stochastically varying electric fields to the trapped antihydrogen
2. If antihydrogen is charged, it can be accelerated out of the magnetic trap by the stochastic fields
3. From the surviving atoms, deduce a limit on the charge of the antihydrogen atom

$$|Q| < 0.71 \times 10^{-9}\, e$$



Antimatter Gravity Technique 2013

Comparing data to simulations with different strengths of gravity using reverse, cumulative averages

We rule out $F > 110$ and $F < -60$, where

$$F \equiv \frac{M_g}{M}$$