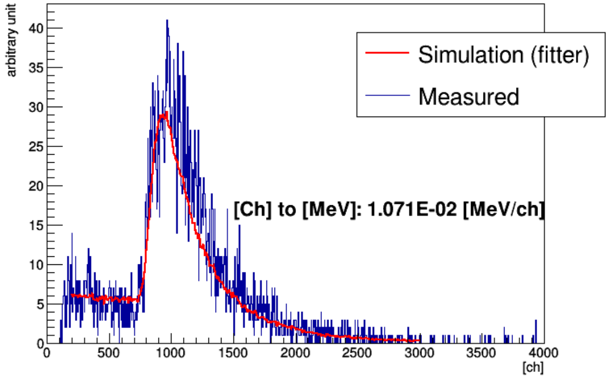
FADC noise

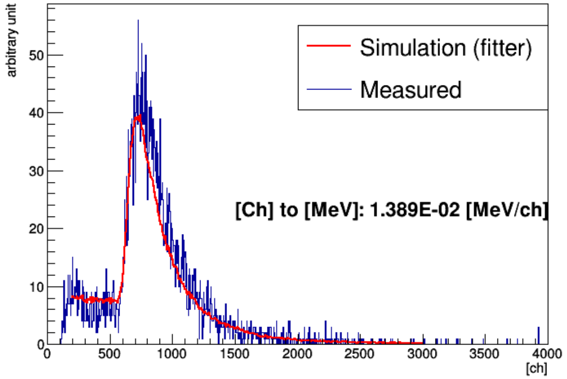
Data taking minimum threshold ≈ 3ch

th=1, 2[ch] : noise detected

The conversion factor

1 [ch] ≈ 1.2×10^{-2} [MeV]





The light efficiency

100 photoelectrons / MeV

$$\therefore\ 3[ch] \sim 3.6 \times 10^{-2}[MeV] \sim 3.6\ photoelectrons$$

Review on
Observation of the 1S-2S transition in trapped antihydrogen

Ahmadi, M. et al., Nature(2016)

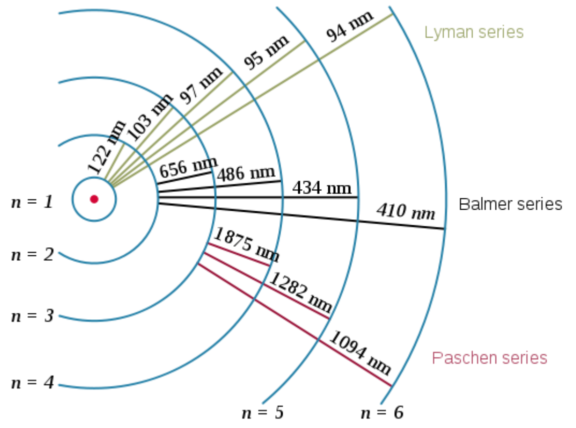
Ahram lee

1. Motivation
2. ALPHA experiment
3. Results
4. Conclusion

1. Motivation

The spectrum of the hydrogen(H) atom

has played a central part in fundamental physics.



Fraunhofer, Absorption lines in the solar spectrum
Balmer, Lyman et al., Transition lines
Rydberg, The empirical description of allowed wavelengths
Bohr, The quantum model

CPT Theorem

charge conjugation – parity reversal – time reversal symmetry
a cornerstone of the Standard Model
predict that H and anti-hydrogen($\bar{H}$) have the same spectrum

A comparison H and $\bar{H}$ frequencies
can be an extremely sensitive test of CPT symmetry

2. ALPHA experiment

Since low energy $\overline{H}$ synthesized by ATHENA(2002),
ATRAP – ALPHA – ASACUSA collaborations repeated this feat.

In 2010, ALPHA team showed that $\overline{H}$ could be held for up to 1000s.

Tests of
CPT symmetry

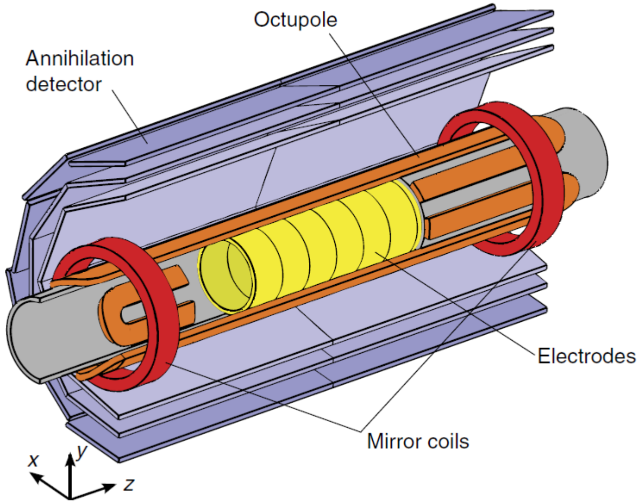
Gravitational
stuides

2. ALPHA experiment

How ALPHA works

$\bar{p}$ from AD

~90,000 particles



e^+ from Surko accumulator

~1.6 million particles

$\bar{H}$ synthesized about 25,000 atoms per mixing attempt
trapped about 14 atoms per trial

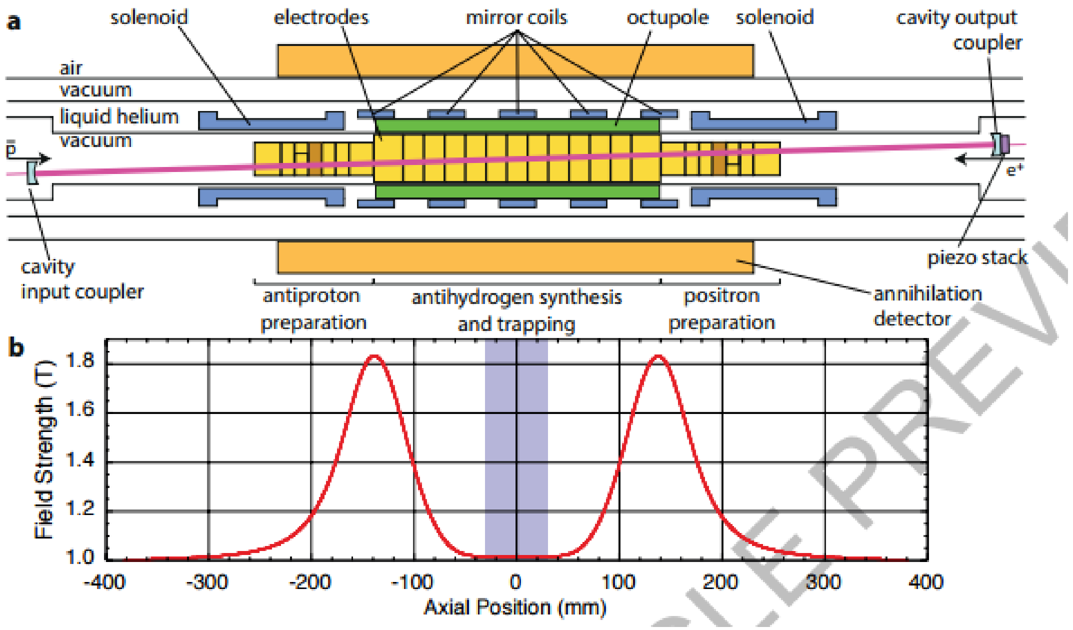
the Penning trap	the minimum-B trap (atom trap)	the silicon vertex detector(SVD)
: positron(e^+) & antiproton($\bar{p}$)	: antihydrogen ($\bar{H}$)	: annihilation detector

Ramping down the current
over 1.5s

2. ALPHA experiment

ALPHA-2 apparatus

the multipolar, superconducting trap as a second-generation device for $\bar{H}$



Mirror coils (on/off)

Axial confinement well

Octupole magnet (on/off)

Transverse confinement

External solenoid (on)

Elimination of charged particles

can trap atoms which have a kinetic energy less than about 0.5K,
within a cylindrical volume of 44mm diameter and 280mm length.

2. ALPHA experiment

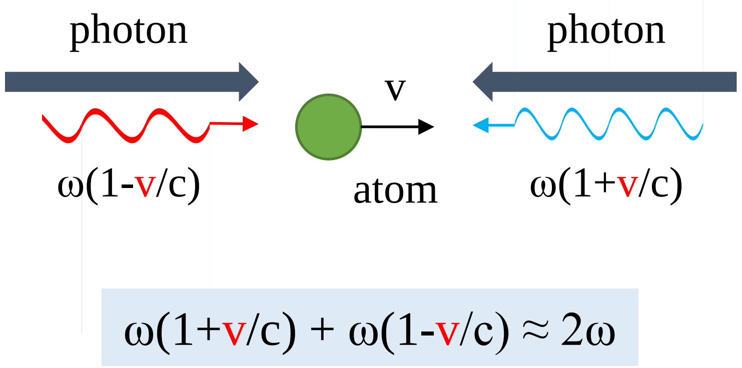
The 1S-2S transition of hydrogen

$f \sim 2.5 \times 10^{15} Hz$

long lifetime of metastable 2S state ~ 1/8sec
narrow natural linewidth ~ 1.3Hz

good for experiment
BUT, it's forbidden

note : Doppler-free two-photon transition (Hänsch, 1977)



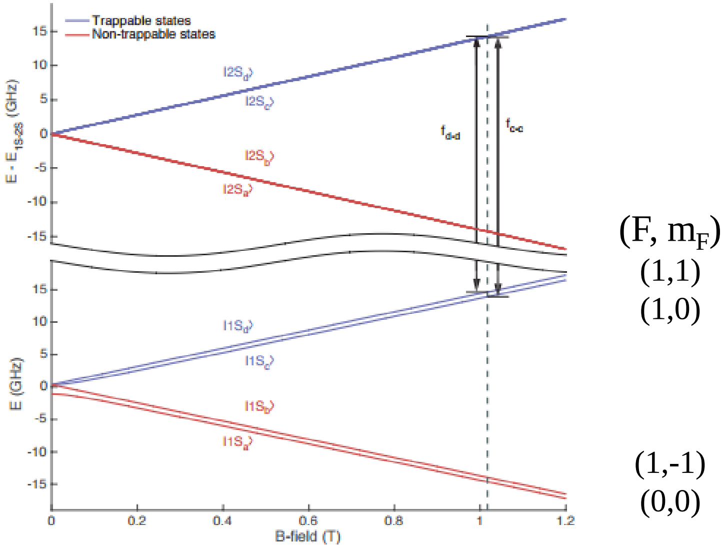
With co- and counter-propagating beams,
eliminates first-order Doppler broadening
reduces the line width to 1kHz

The fractional second-order Doppler shift
2×10^{-11} (for hydrogen)

2. ALPHA experiment

The 1S-2S transition of hydrogen

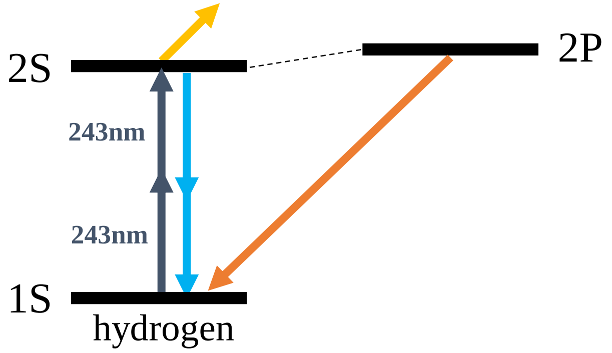
< Energy diagram >



a, b : untrappable high-field seeking states
d, c : trappable low-field seeking states

$$f_{d-d} = 2\ 466\ 061\ 103\ 064(2)\ kHz$$
$$f_{c-c} = 2\ 466\ 061\ 707\ 104(2)\ kHz$$

< Simplified level scheme >



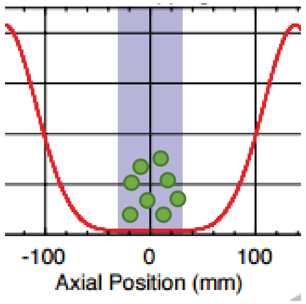
An atom in the 2S state can experience

1) a two-photon decay
   to same hyperfine state → trappable
2) a one-photon decay via 2P state
   to same spin → trappable
   or spin-flip → untrappable
3) ionization
   by a single additional photon → untrappable

3. Results

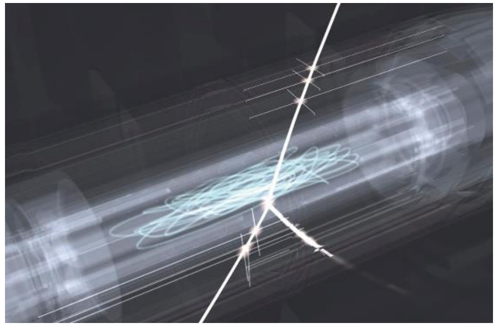
Experimental process

producing $\overline{H}$ in the atom trap
pulsing axial electric fields



holding for 600s

ramping down the fields
to release



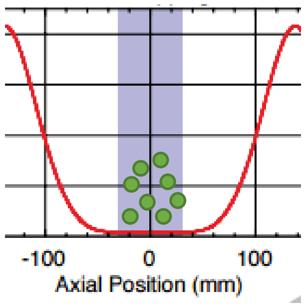
300s exposure of both the c-c & d-d transition, by illuminating the laser
1) On resonance : an expected resonance frequency ($\delta = 0$)
2) Off resonance : detuning 200kHz below ($\delta = -200kHz$)
3) No laser : without laser radiation

11 sets of
three types of trial

3. Results

Experimental process

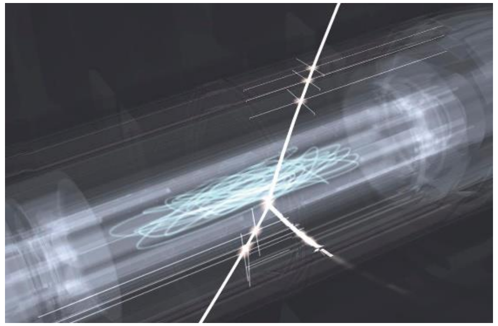
producing $\overline{H}$ in the atom trap
pulsing axial electric fields



300s
c-c transition

300s
d-d transition

ramping down the fields
to release



The vertex detector

Reconstruction efficiency 0.376 ± 0.002	Reconstruction efficiency 0.688 ± 0.002
Cosmic background rate $0.0043 \pm 0.0003 s^{-1}$	Cosmic background rate $0.042 \pm 0.001 s^{-1}$

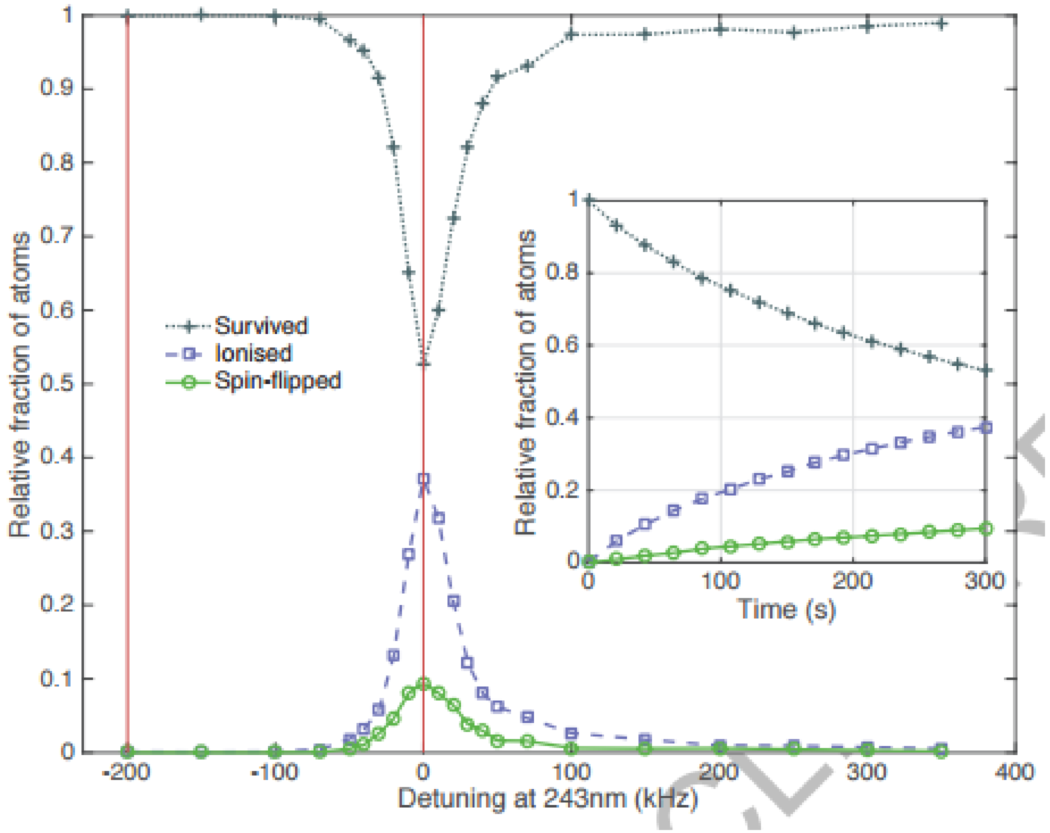
note : Multivariate analysis algorithm
used for cosmic ray rejection

3. Results

Simulation setup

Calculate the two-photon excitation probability as a function of laser detuning(δ) during a 300s exposure of both the c-c & d-d transitions assuming 1W of circulating laser power in cavity

transit time broadening, AC Stark shift, Zeeman effect



Simulation results

1) asymmetric due to residual Zeeman effect
2) compared to off resonance,
the fraction of $\overline{H}$ removed by on-reson. Laser
0.47 (at 300s)

3. Results

Experimental results

producing $\overline{H}$ in the atom trap → holding for 600s → ramping down the fields

Efficiency = 0.688

Table1. Detected events during 1.5s ramp down

Type	Number of detected events	Background	Uncertainty
Off resonance	159	0.7	13
On resonance	67	0.7	8.2
No laser	142	0.7	12

→ survived(trapped) atoms

1) Off resonance ~ no laser
   no laser-related side effects leading to H loss

2) On ~ Off resonance

$$159 - 67 = 92 \pm 15\ counts$$

$\therefore \frac{92}{0.688} \approx 134$ atoms removed by On-res. laser

$\therefore \frac{92}{159} \approx (58 \pm 6)\%$ of trapped atoms removed

→ consistent with hydrogenic rate estimates (simulation results)

3. Results

Experimental results

producing $\overline{H}$ in the atom trap → holding for 600s → ramping down the fields

Efficiency = 0.376

Table 2 | Detected events during the 300 s hold times for each transition, and their sum

Type	Number of detected events	Expected Background	Uncertainty
d-d off res.	15	14.2	3.9
d-d on res.	39	14.2	6.2
No laser	22	14.2	4.7
c-c off res.	12	14.2	3.5
c-c on res.	40	14.2	6.3
No laser	8	14.2	2.8
d-d+c-c off res.	27	28.4	5.2
d-d+c-c on res.	79	28.4	8.9
No laser (sum)	30	28.4	5.5

→ lost(untrapped) atoms

1) Comparing with background
   Off resonance & No laser ~ background(28)
   Only On resonance type is different(79)

2) On ~ Off resonance

$$79 - 27 = 52 \pm 10\ counts$$

$$\therefore \frac{52}{0.376} \approx 138 \text{ atoms removed by On-res. Laser}$$

→ consistent with the result before(134)

Assuming no exotic asymmetries in the spectrum, 400kHz resolution as a test of CPT symmetry !

3. Results

Limitations

A stronger statement must await a detailed measurement of transition line shape.

There are the uncertainties which can become important for smaller detunings.

the long-term average laser frequency ~ 8×10^{-13} (frequency comb)
the laser linewidth at two-photon frequency ~ $10kHz$
the trap's minimum magnetic field strength ~ $28.46 \pm 0.01\ GHz$
the frequency uncertainty for c-c ~ $\pm 6400Hz$ (resulting from field uncertainty)
for d-d ~ $\pm 350Hz$

→ A straightforward extension of the current technique
should provide a measurement of the line shape in the near future

4. Conclusion

- As a first laser-spectroscopic measurement on antimatter, ALPHA observed 1S-2S transition in magnetically trapped atoms of antihydrogen in the ALPHA-2 apparatus at CERN.

- ALPHA determined the frequency of transition, driven by two photons from a laser at 243nm, is consistent with that expected for H in the same environment at a relative precision of about 2×10^{-10}. The sensitivity is ~ $2 \times 10^{-18} GeV$, which is approaching the absolute precision of the CPT test in the neutral kaon system of ~ $5 \times 10^{-19} GeV$.

- Improved trapping rate bodes well for many other future antihydrogen experiments, such as microwave hyperfine transitions, Lyman-alpha light and gravitational studies.

- It can potentially have a significant sensitivity to the internal structure of the antiproton, at a level relevant to the current puzzle in the proton charge radius.