Advances in the Spectroscopy of the 1S-2S Transition in Antihydrogen

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for the ALPHA collaboration @ CERN

- CPT
- Spectrum of (Anti)hydrogen
- Trapping
- Laser cooling
- Old and new protocols
- Uncooled results, SME limit/sensitivity.
- 2022 prospects

This work was supported by: the European Research Council through its Advanced Grant programme (JSH); CNPq, FAPERJ, RENAFAE (Brazil); NSERC, NRC/TRIUMF, EHPDS/EHDRS, FQRNT (Canada); FNU (NICE Centre), Carlsberg Foundation (Denmark); JSPS Postdoctoral Fellowships for Research Abroad (Japan); ISF (Israel); STFC, EPSRC, the Royal Society and the Leverhulme Trust(UK); DOE, NSF(USA); and VR(Sweden).

Symmetries of special relativity

Rotations and translations in spacetime (Lorentz transformation).

Parity **x** → **-x** Time reversal t → -t Charge conjugation **matter → antimatter**

Discrete symmetries are broken in weak interactions.

CPT can be expressed as a Lorentz rotation by an imaginary angle.

CPT conserved in local Lorentz invariant field theories.

If CPT symmetry is broken, the cosmic matter-antimatter asymmetry can develop under equilibrium conditions (Dolgov).

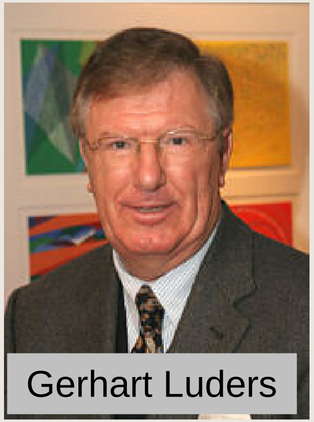
Test LT and CPT symmetry in different systems!

CPT predicts identical atomic spectra for H and $\bar{\text{H}}$.

SME is an extension of the standard model with LTV and CPTV terms allowing a sensitivity comparison for different measurements.

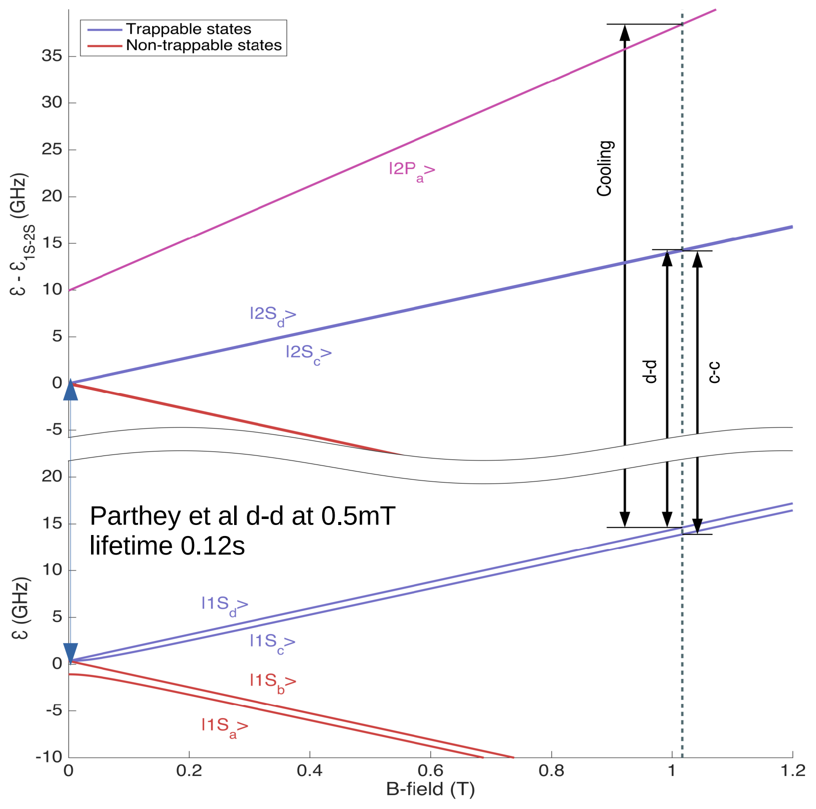
Matter-antimatter comparisons allow isolation of CPTV terms.

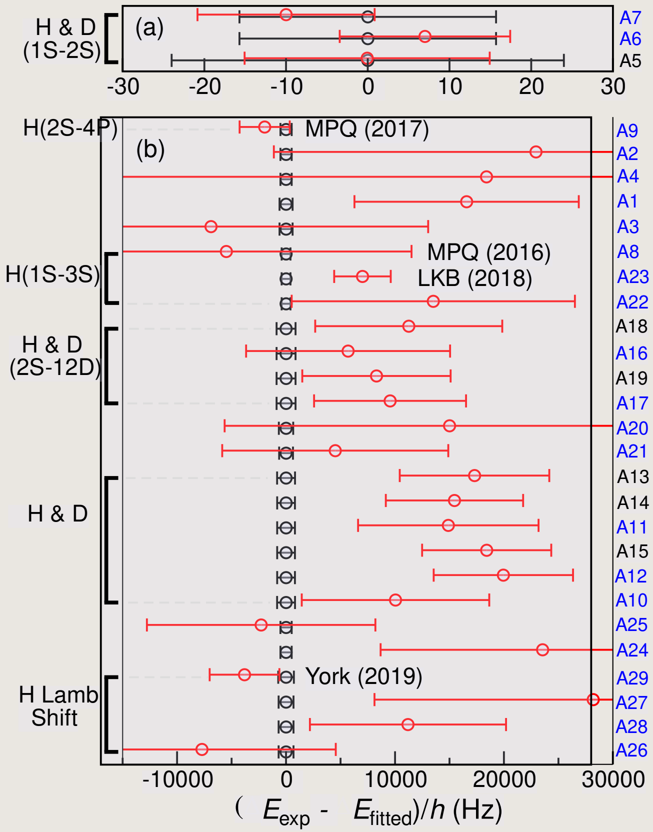
Julian Schwinger



Gerhart Luders

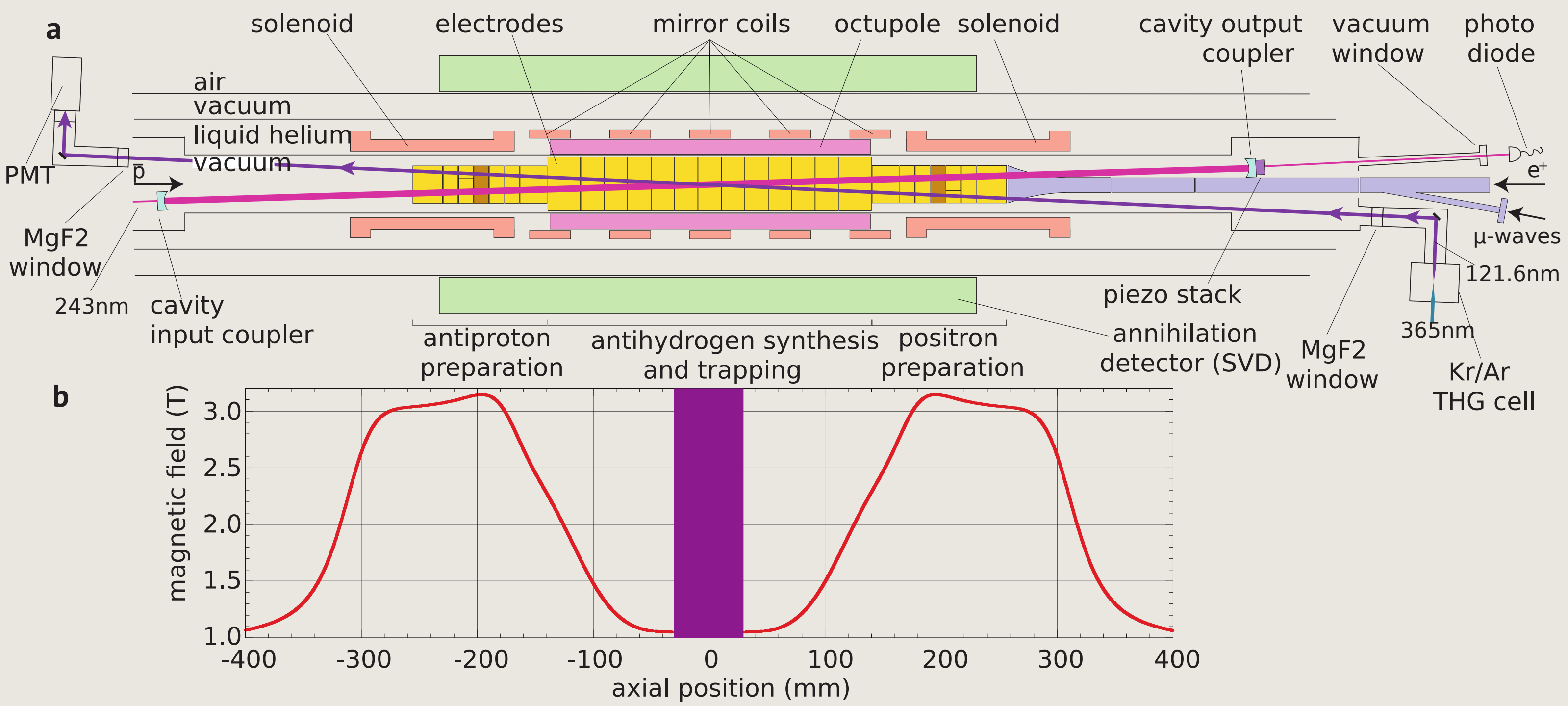
Hydrogen Spectrum





CODATA
Rev Mod Phys
93, 25010,2021

Antihydrogen Synthesis and Interrogation

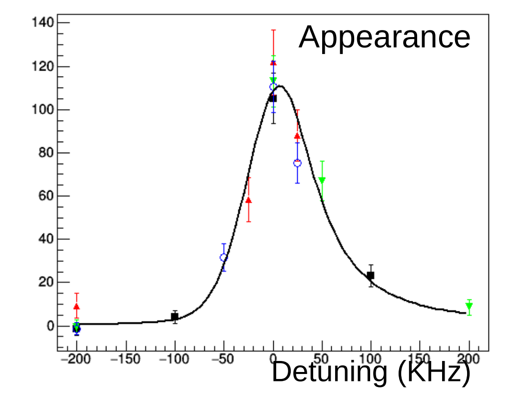


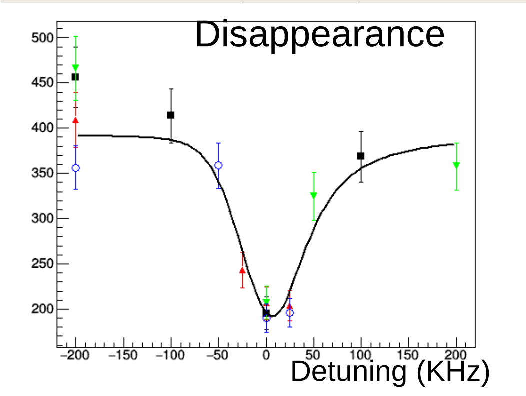
Cooling with Lyman α Laser

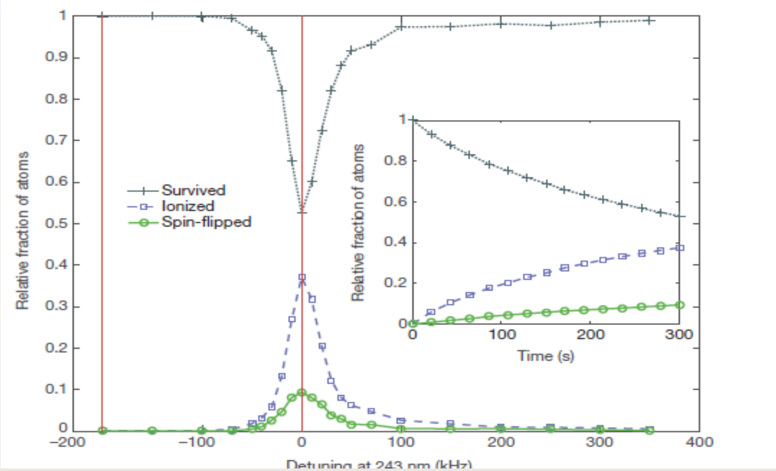
- Drive the $1S_d \rightarrow 2P_a$ transition detuned -220 MHz below the resonance.
- $\bar{H}$ moving toward the laser are slowed and the re-emitted photon is emitted isotropically leading to axial cooling.
- Coupling of the motions from our trapping fields leads to 3D cooling.

2016 Measurement Procedure

- Excite the 2-photon transition between the 1S and 2S d-d hyperfine states. This is Doppler free (first order).
- 2S state lifetime is 0.12 sec; 3rd photon can ionize the $\bar{H}$. The ion annihilates on electrodes. Blocking potential inhibits axial escape.
- With lower probability 2Sd state can decay to untrapped 1S state which also annihilates.







- Illuminate 3 stacks of $\bar{H}$ & single frequencies spanning d-d.
- 4 sets/21 trials of -200 kHz, 0 kHz detunings with 2 others.
- Normalize for number of $\bar{H}$ and cavity power.
- 10 week campaign

f_{dd}=2 466 061 103 079.4 (5.4) kHz (2 ppt)


nature
International journal of science

Letter | OPEN | Published: 04 April 2018

Characterization of the 1S–2S transition in antihydrogen

M. Ahmadi, B. X. R. Alves, [...] J. S. Wurtele

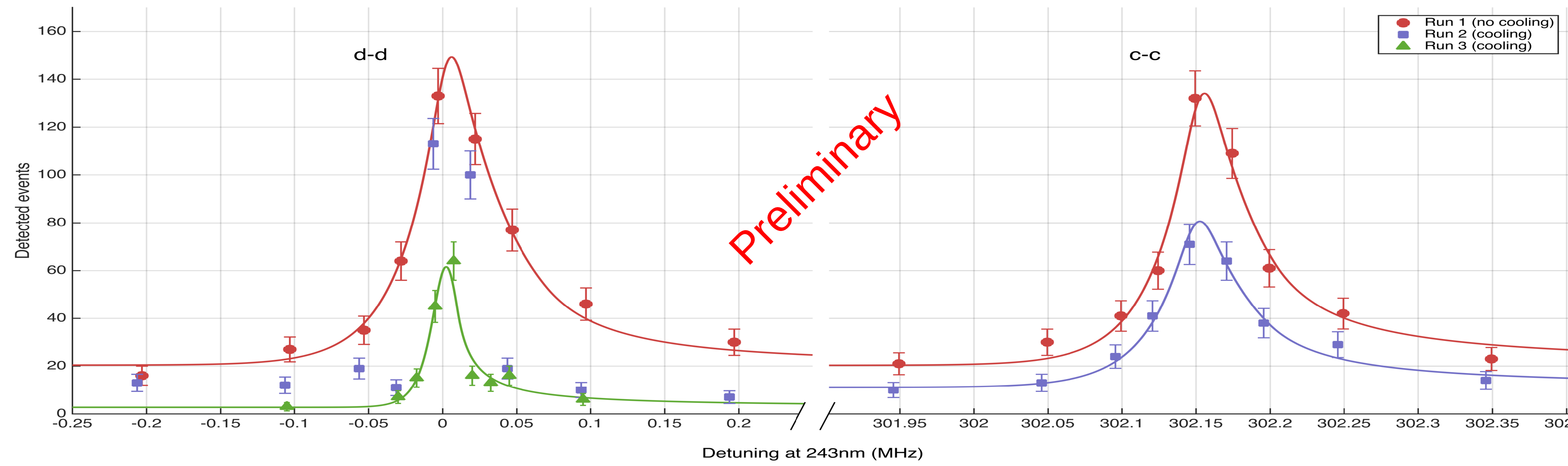
Nature 557, 71–75 (2018) | Download Citation

2018 Measurements

Runs 1 and 2: Stack for 8-11 hours > 1000 trapped $\overline{\mathrm{H}}$/run. Cycle through 9 frequencies with 2s exposures for both d-d and c-c 100 times alternating scan direction.

Runs 2 and 3: + Laser-cool 1S d states during stacking and for 5hr after.

Run 3: + reduce scan range and exposure time. d-d only.



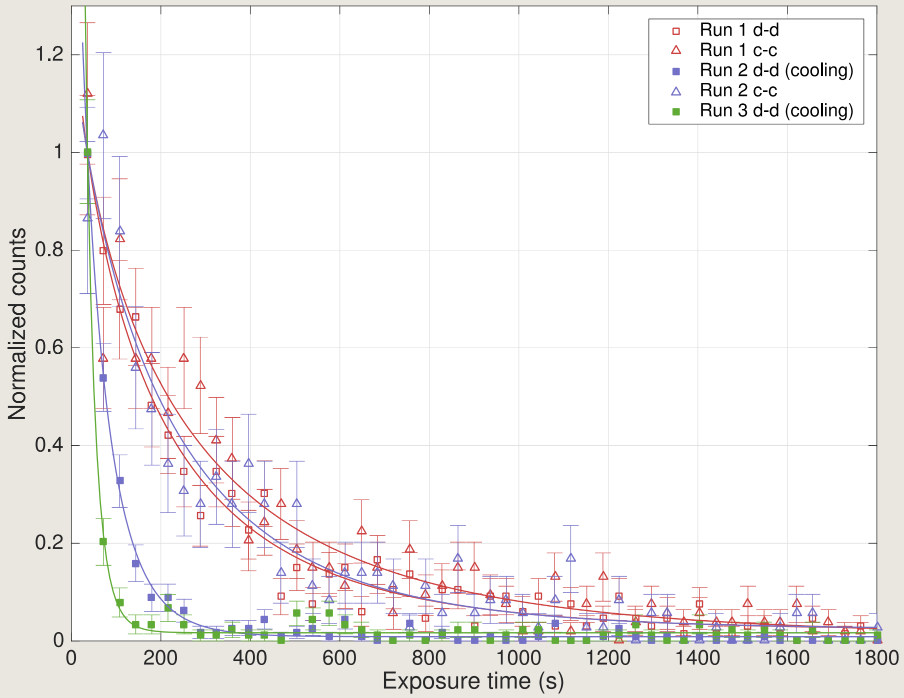
Depletion Rates

Annihilations/cycle vs exposure time

- **sensitive to cavity power**
- **sensitive to trapped $\bar{H}$ energy distribution**
- **run 2 vs run 3 depletion ?**

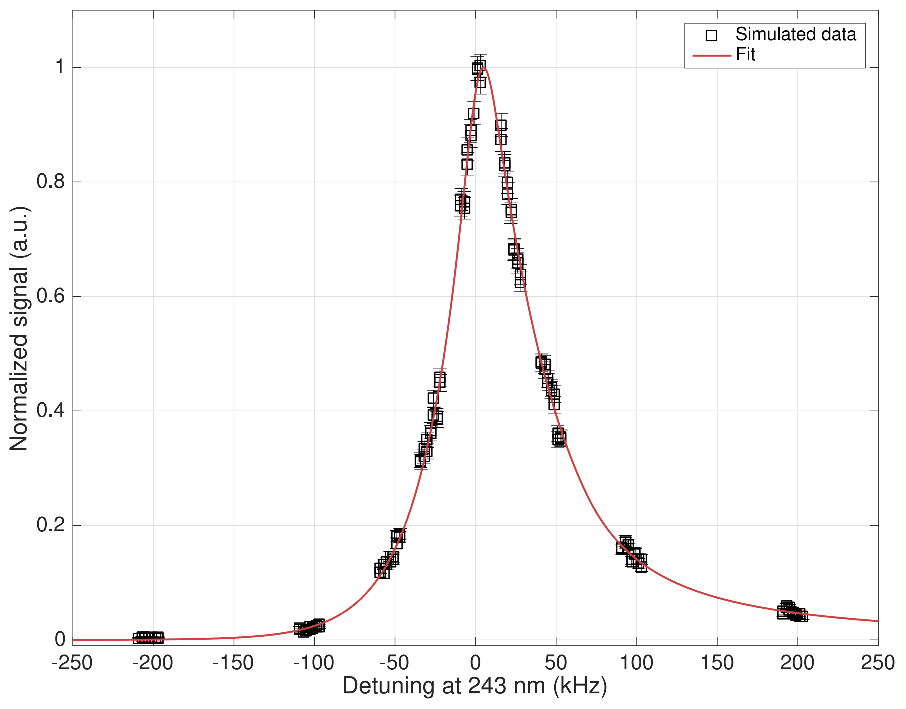
Useful for validation of simulation

Rapid depletion and small # of on-resonance bins made us decide in advance not to publish cooled run frequencies.



Lineshape determination

- Detailed simulation to assess effects of laser power and trap field.
- Simulated lineshape with full hydrogen physics fit with double exponential - Gauss convolution with blue tail.
- Same lineshape fit to data varying position and amplitude.
- Shift from central field frequency is ~7 kHz and we attribute a 2.5 kHz systematic to this value.



Results for Uncooled States

- First measurement of $f_{1Sc-2Sc}$ transition
  - Agrees with calculated value for hydrogen $(5.0)_{stat}(3.8)_{syst}$ kHz, $(8.4)_{stat}(3.9)_{syst}$ kHz.
- Remeasurement of $f_{1Sd-2Sd}$ transition with different systematics
  - Agrees with previous measurement and hydrogen value $(4.6)_{stat}(3.6)_{syst}$ kHz.
- Measurement of 2S hyperfine splitting using our $\bar{\text{H}}$ ground state splitting value to 0.5 MHz.

Preliminary

- Combining our d-d results with older measurements of antihydrogen and hydrogen we constrain the combination of CPT-symmetry violating parameters $a^{NR}_{2,e} + a^{NR}_{2,p} =$ **(0.4 ± 1.2)** $\times 10^{-9}$ GeV^{-1} in the non-minimal standard model extension.
- Comparison of $\bar{\text{H}}$ c-c results with new H measurements especially at higher field would test different more sensitive SME parameters.

Outlook

2022 Campaign aiming for order of magnitude improvement

- Line narrowing from laser cooling: FWHM 14$\pm$4kHz vs 58$\pm$12kHz
- Reduced 243nm cavity power and optimized frequency choice
- Increase in 121nm power from 8nJ (10Hz) to 130nJ(50Hz)
- Systematics studies enabled by scanning protocol efficiency
  - trap magnetic fields, cavity power variations…
- Improved metrology
  - Temperature stability, H maser, Cs fountain clock in 2023
- Increased antiproton availability from ELENA ring.

Thank you for your attention!

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