ASACUSA antihydrogen program: current status and prospects

T. Wolz on behalf of the ASACUSA collaboration

contact: tim.wolz@cern.ch

Studienstiftung des deutschen Volkes

GEFÖRDERT VOM Bundesministerium für Bildung und Forschung

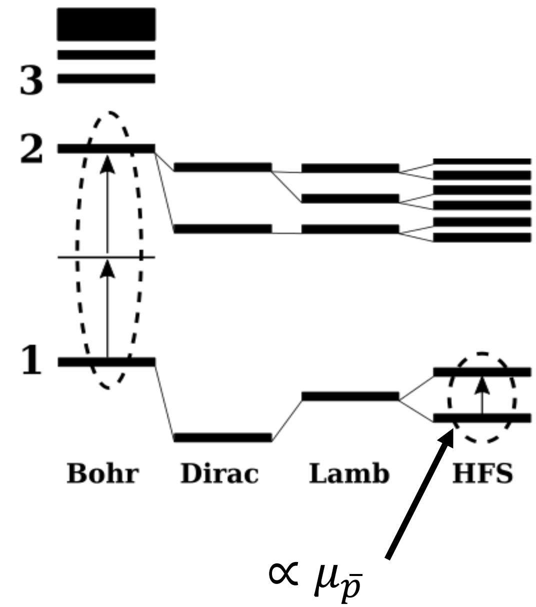
CPT symmetry tests and constraints on SME coefficients in antihydrogen

If CPT symmetry holds, matter and anti-matter properties should be exactly equal (mass) or opposite (charge, magnetic moment)

- CPT has been tested in various sectors
  - Comparison of electron / positron
  - Antiproton charge to mass ratio, magnetic moment
  - Anti-helium and anti-deuteron nuclei charge to mass ratios

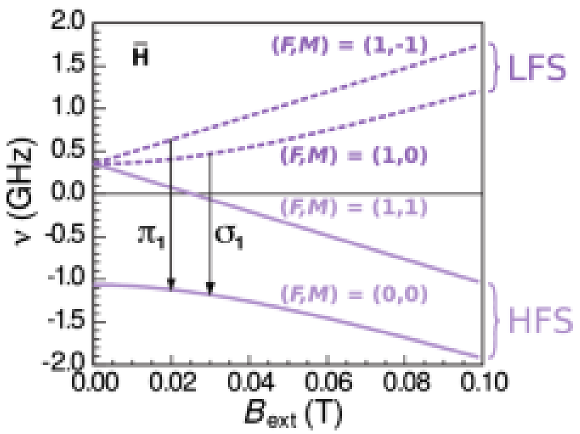
- Antihydrogen is the only atomic system made up entirely of antimatter
  - 1s→2s transition
  - Hyperfine splitting (10^{-4} relative precision in trap)
  - Lamb shift

- Low-energy atomic systems are good candidates to test Standard Model Extension (SME) coefficients → Lorentz violating terms included to the SM Lagrangian

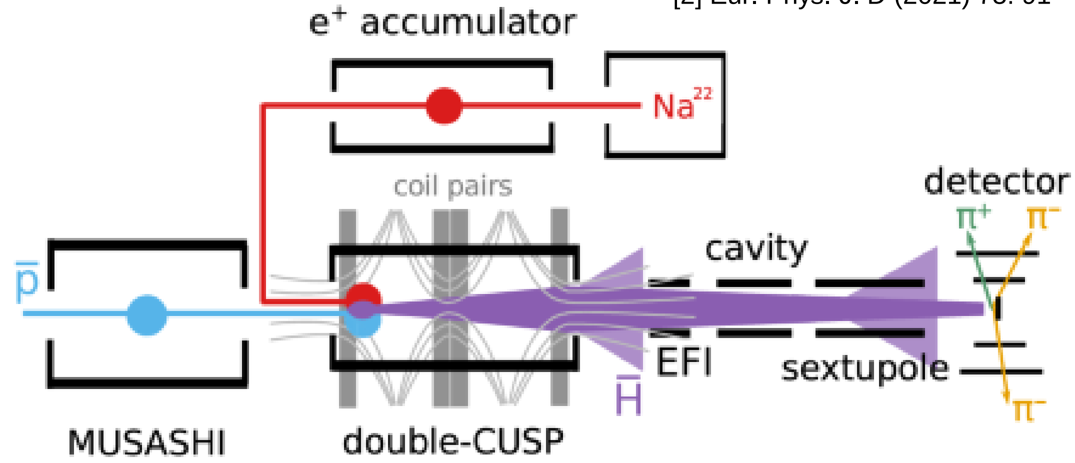


→ Antiproton magnetic moment is known to ppb level (Nature 550, 371–374)
→ At 10^{-5} level first order corrections of HFS include magnetic and electric form factors of antiproton
→ HFS sensitive to antiproton structure at 30 ppm precision level

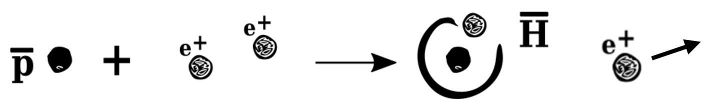
GS HFS measurement in a beam within ASACUSA



ASACUSA experimental scheme 2021
[2] Eur. Phys. J. D (2021) 75: 91



- Positrons from a radioactive source are accumulated and mixed with initially trapped antiprotons in a double CUSP-trap

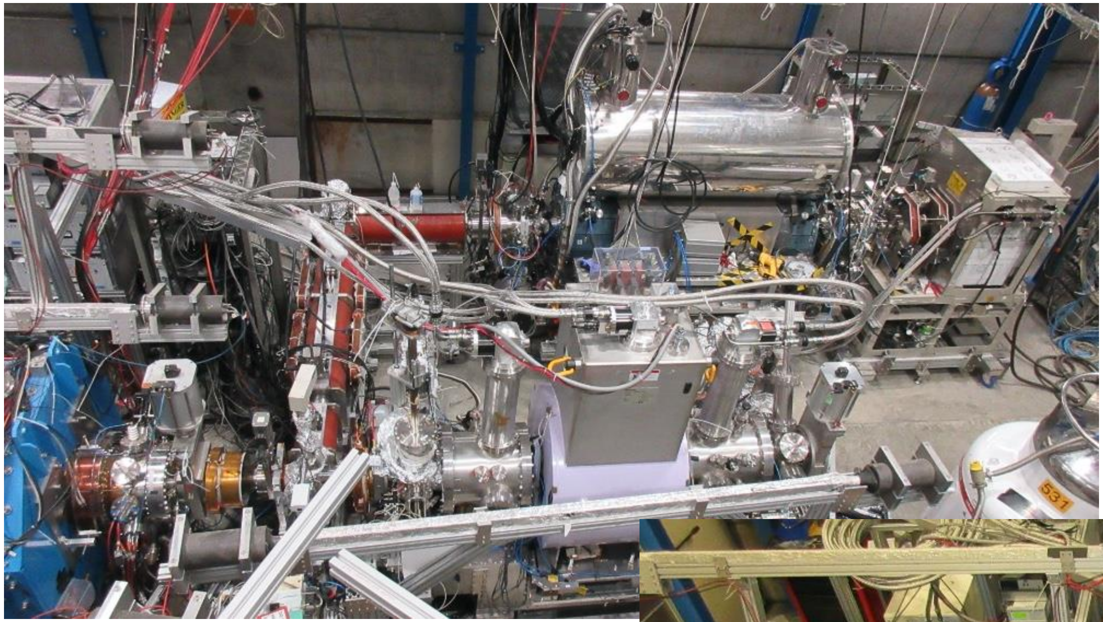


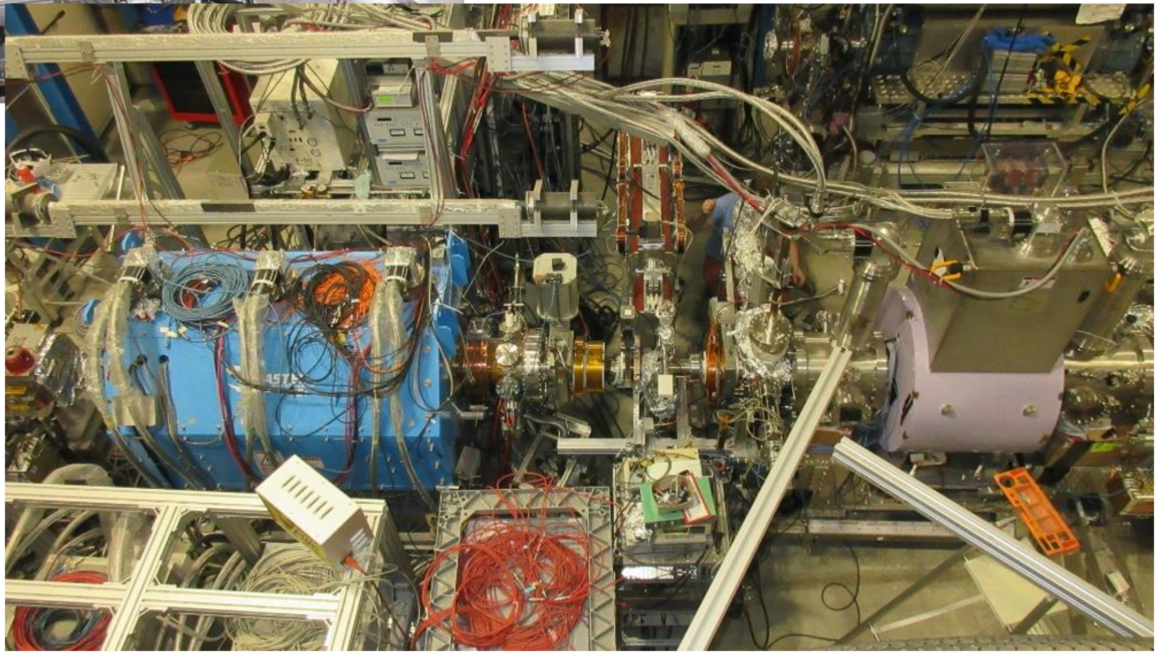
- The polarized beam enters a MW cavity for spectroscopy measurements
- A field ionizer allows to study the quantum states within the beam
- A superconducting sextupole defocuses HFS (produced inside the cavity) before detection

→ Antihydrogen beam (~100 atoms) detected away from the trap formation region in 2014

[1] Nat Commun 5, 3089 (2014)

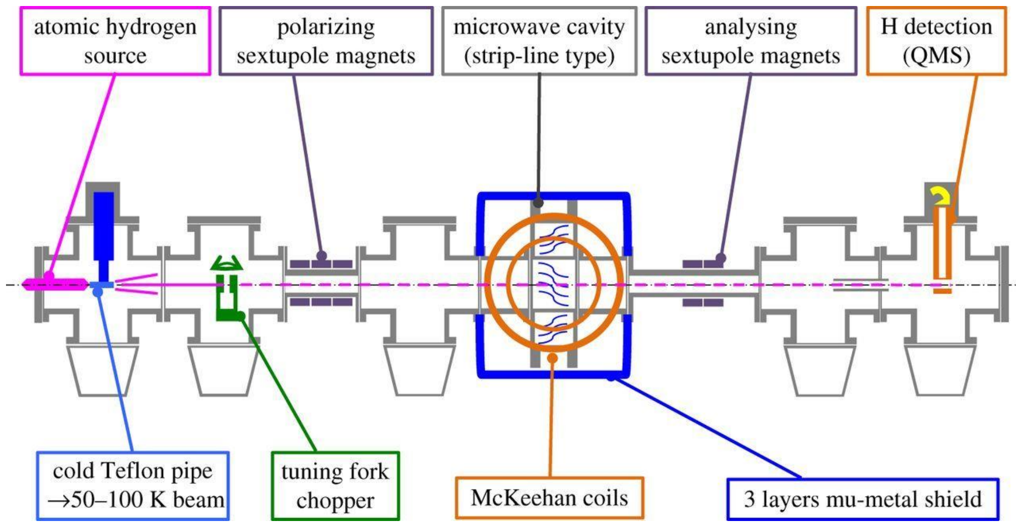
GS HFS measurement in a beam within ASACUSA

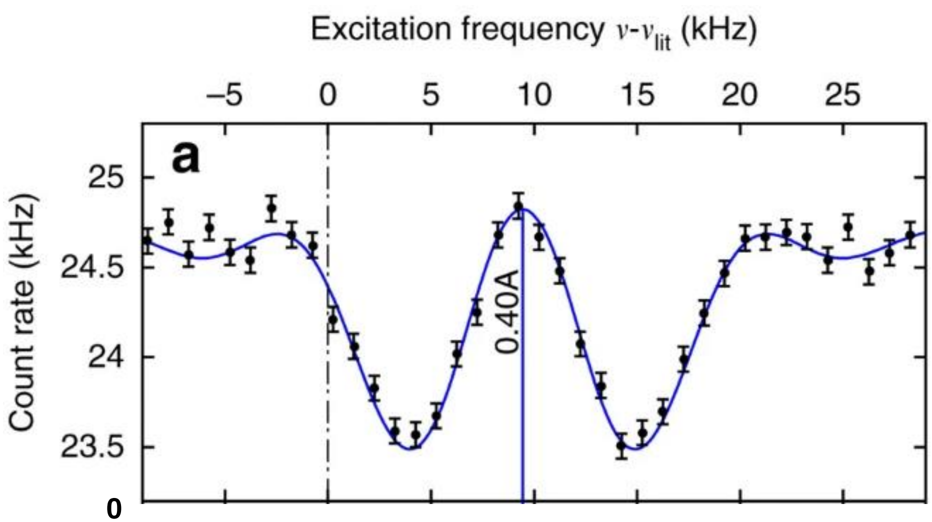




3ppb precise proof-of-principle measurement of the ground-state hyperfine splitting

[3] Nat Commun 8, 15749 (2017)

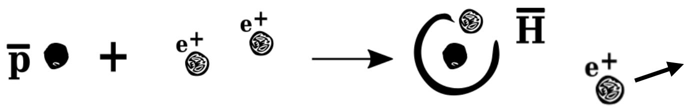




- → A proof-of-principle on hydrogen yielded a 3ppb precise measurement of HFS in hydrogen
- → σ_1 transition measured with a 2.7×10^{-9} relative precision
- → SME sensitive π_1 transition has been measured with approximately 60 Hz precision

Three body recombination, produced states and their temperature

Three-body recombination formation mechanism:



⚠

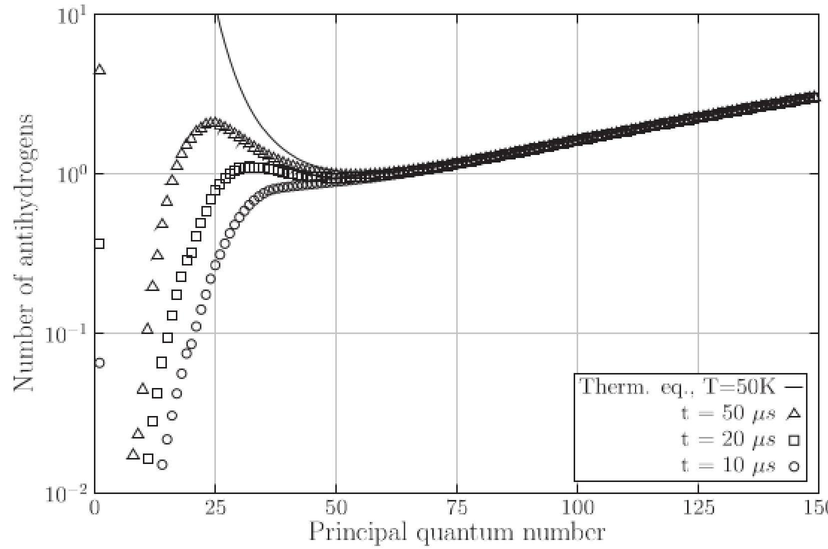
Rydberg lifetimes are of the order of milliseconds

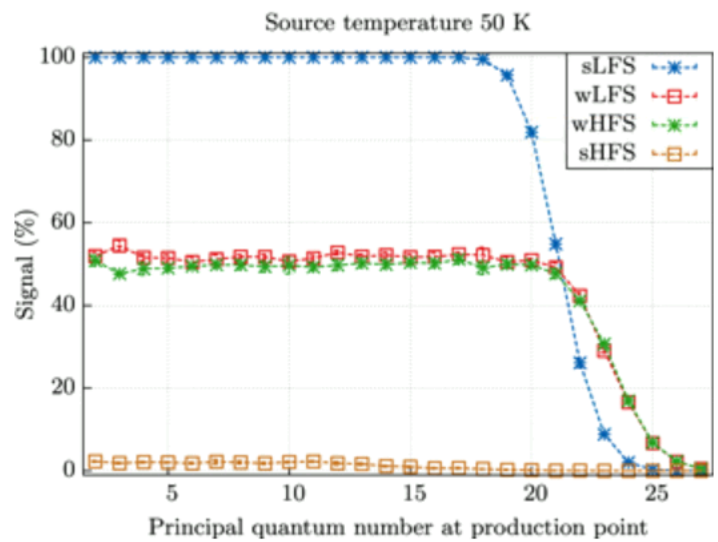
$$\tau_{n,l} \approx \left(\frac{n}{30}\right)^3 \left(\frac{l+1/2}{30}\right)^2 2.4\,\mathrm{ms}$$

Detection of anti-atoms at the end of the beamline is a complex interplay between:

- Quantum state distribution
- Temperature
- Trajectory
- Spontaneous decay
- Background

[4] Phys. Rev. A 90, 032704 (2014)

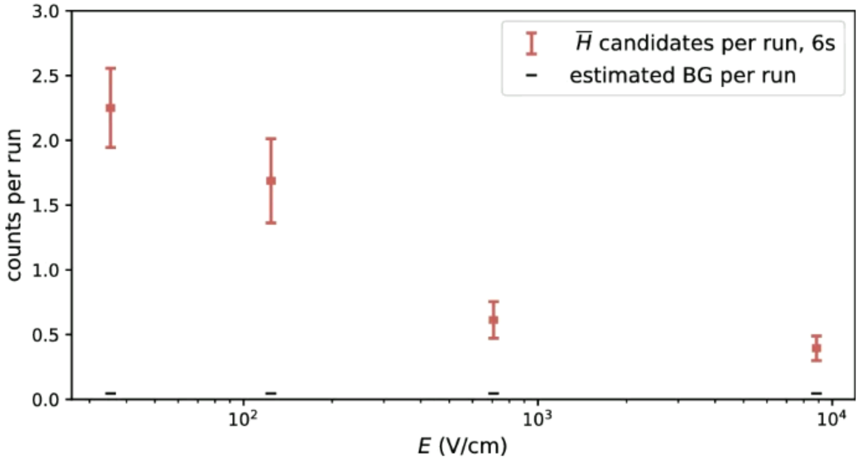




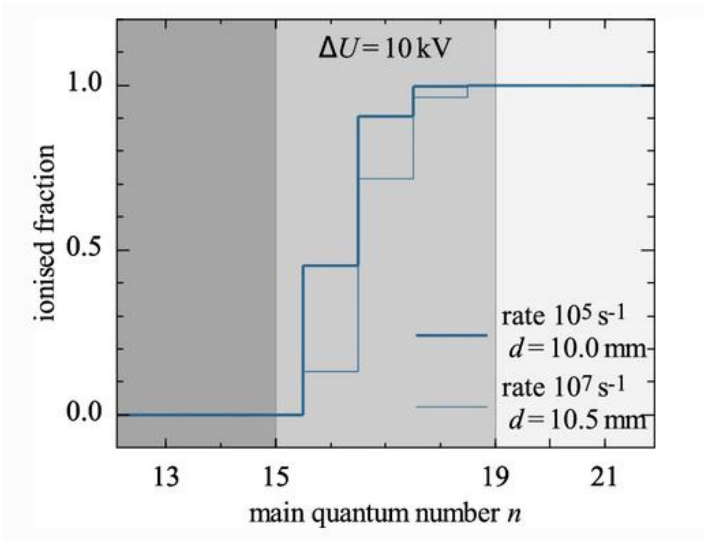
[5] J. Phys. B: At. Mol. Opt. Phys. 48 184001 (2015)

Antihydrogen detection in excited states away from the trap formation region

[2] Eur. Phys. J. D (2021) 75: 91
(2016 run)



- Antihydrogen quantum state distribution measured via electric field ionization after a ~1.8 m flight path
- Increasing electric field strengths probe stronger bound levels
- Signal over background significantly decreases for strong bound levels



- A given electric field probes a range of principal quantum numbers due to blue and red shift of hydrogenic substates

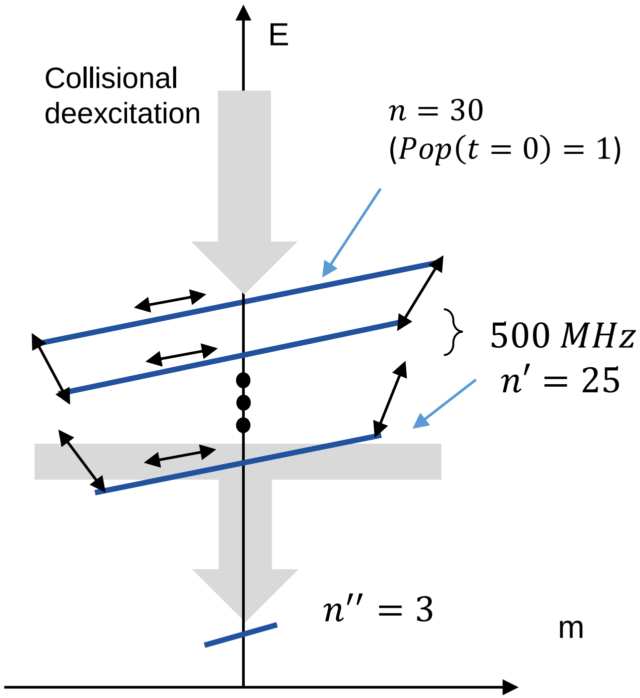
→ Most states detected exhibit principal quantum numbers above 30 and higher

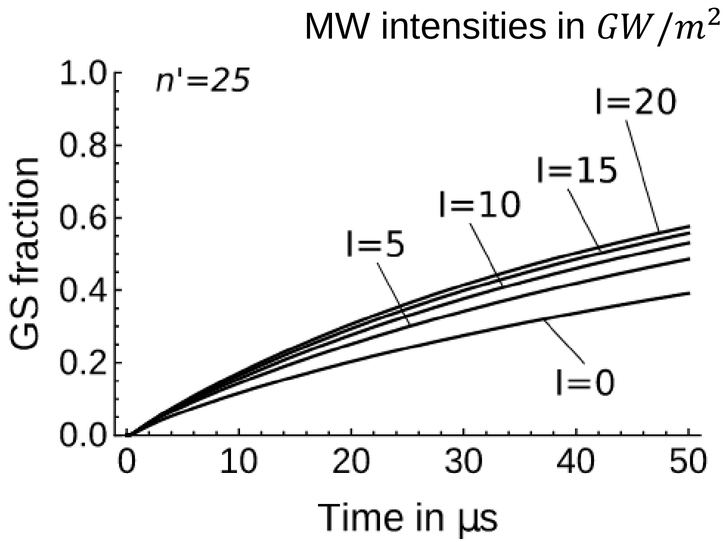
→ New ideas are needed to enhance the number of ground state atoms ideally right after formation

THz and microwave radiation can be used to mix and deexcite the inital Rydberg states to rapidly populate the ground state

total THz intensity: $10\,\frac{W}{m^2}$
laser intensity: $100 * 10^5\; W/m^2$

[6] Phys. Rev. A 101, 043412 (2020)

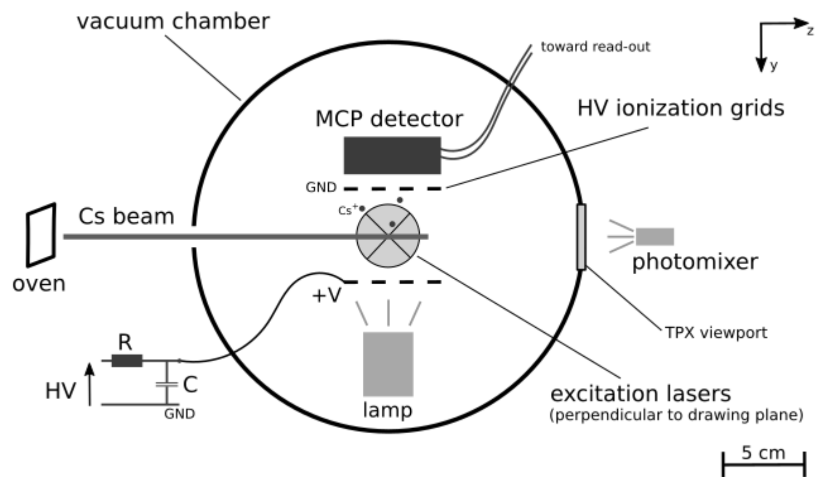


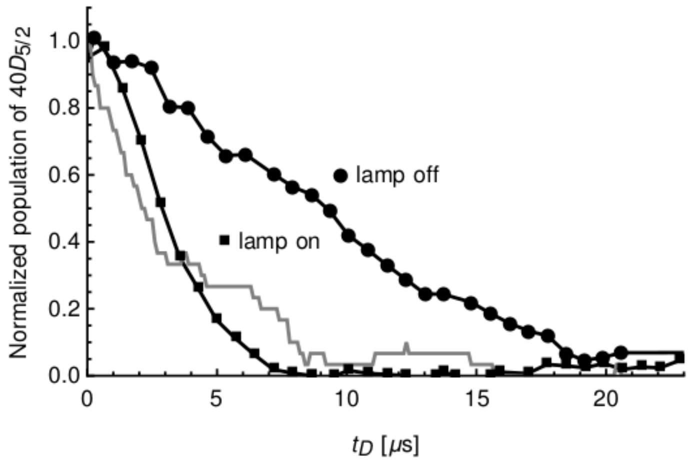


→ Initially populated levels are mixed relying on THz and microwave light

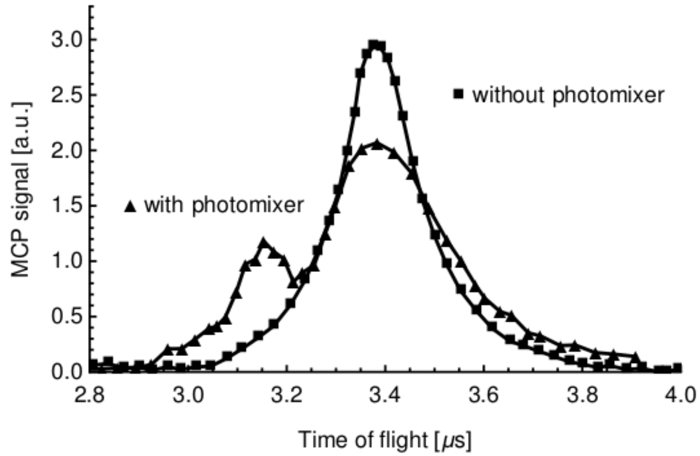
→ <u>Close to unity ground state fraction after a few ten microseconds</u> which is consistent with experimental requirements

A proof-of-principle of Rydberg state mixing has been performed on a beam of excited cesium atoms [8]





Population of $40D_{5/2}$ level as a function of the FI delay with respect to the excitation laser as stimulated by a BB lamp. Simulation data for a BB spectrum of 1200K is indicated in grey.



Stimulated $36S_{1/2} \rightarrow 36P_{3/2}$ transfer stimulated by a photomixer (97 GHz, spectral width 5 MHz).

[7] Eur. Phys. J. D 75:27 (2021)

Summary and ASACUSA-CUSP future physics program

- Antihydrogen atoms are detected in a field free environment ideal for in-beam precision spectroscopy
- Measurements are limited by the number of ground-state atoms available
- Deexcitation techniques have been identified that, together with other upgrades, should enable a measurement

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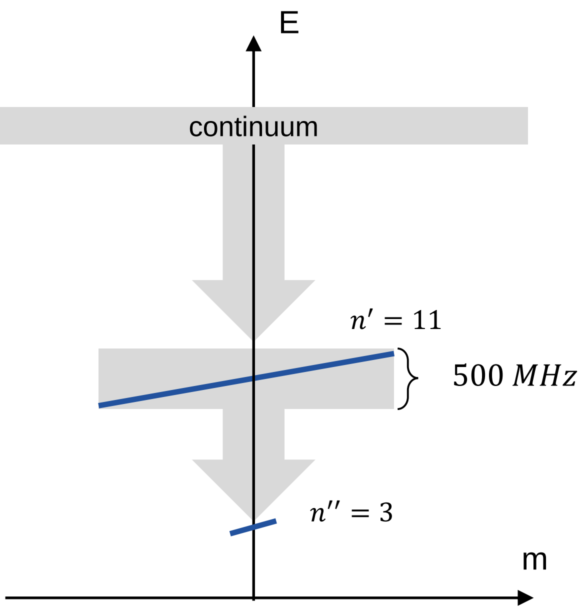
- Commission LS2 upgrades and ELENA beamline: trap antiprotons, produce antihydrogen
  - CUSP trap electrodes
  - New cold bore for CUSP trap
  - New techniques toward colder and more reproducible plasma conditions
- Proton source toward matter mixing experiments
- Collisional deexcitation of atoms to enhance the ground state fraction
- Stimulated deexcitation
  - THz technology and lasers
  - Deexcitation laser
  - Proof-of-principle on hydrogen before installation into the AD
- Measurement of quantum state distribution inside the beam

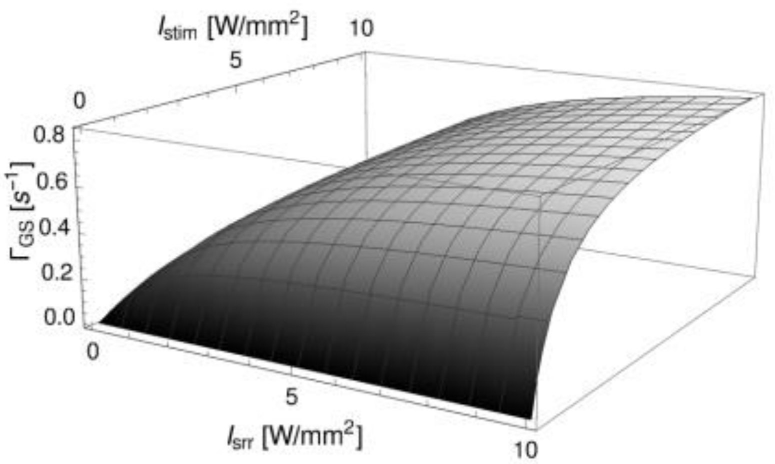
→ Stay tuned for spectroscopy experiments with ground state antihydrogen beam

Thank you for your attention.

Backup: Stimulated radiative recombination to directly form ground state anti-atoms

[6] Phys. Rev. A 101, 043412 (2020)





10K positrons with density of 10^8 per ccm

→ First simulation of stim. radiative recombination in a magnetic field and in combination with stimulated deexcitation

→ <u>One anti-atom per antiproton per second in ground state</u> is a tremendous improvement over the current state-of-the-art