Stimulated decay and formation of antihydrogen atoms

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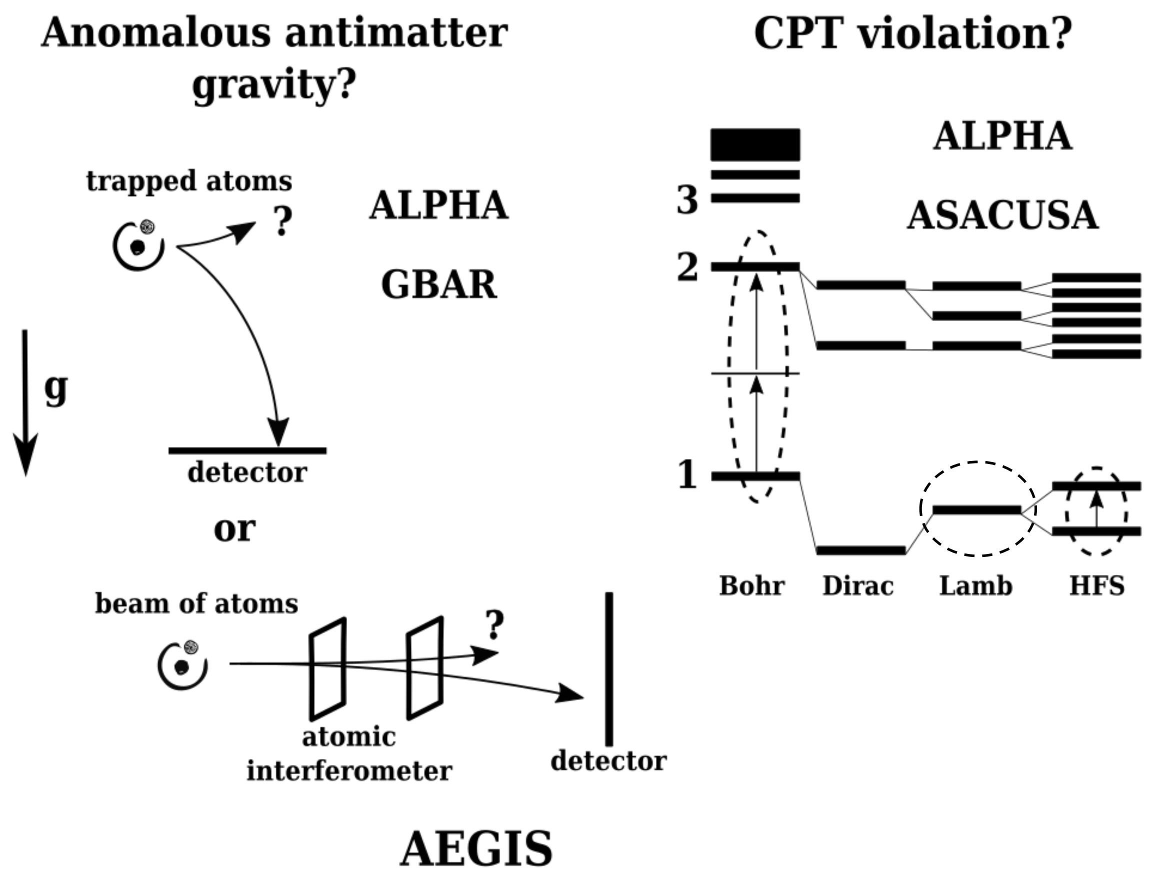
Outline

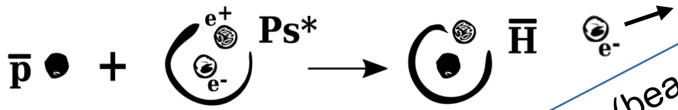
- Antiproton Decelerator (AD) facility at CERN
  - Physics investigated
  - Antihydrogen production mechanisms
- Stimulated deexcitation to enhance fraction of ground state atoms
  - Electric and magnetic field mixing
  - Light induced Rydberg state mixing
- Stimulated radiative recombination
- Proof-of-principle of deexcitation light sources
- Rydberg atomic hydrogen test beam at CERN
- Summary and outlook

Antihydrogen physics program at CERN's Antiproton Declerator



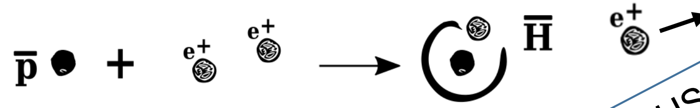
Precision measurements require cold anti-atoms in ground state

Charge exchange reaction (CE)



AEGIS (beam)
GBAR (trap)

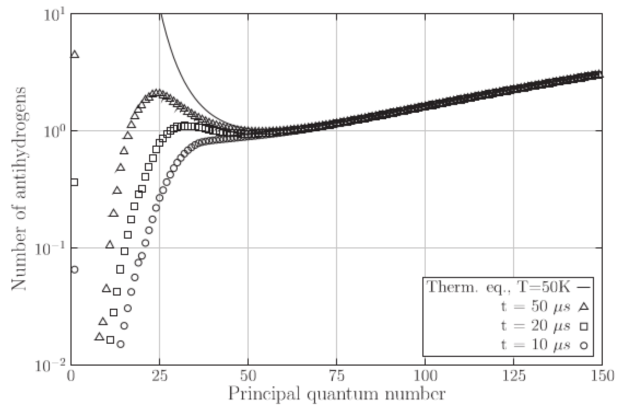
Three-body recombination



ASACUSA (beam)
ALPHA (trap)

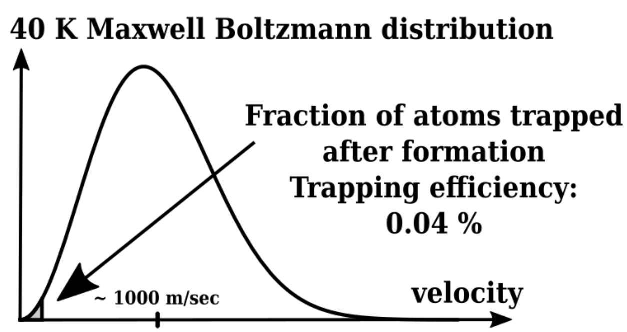
Atomic lifetimes of the order of milliseconds

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



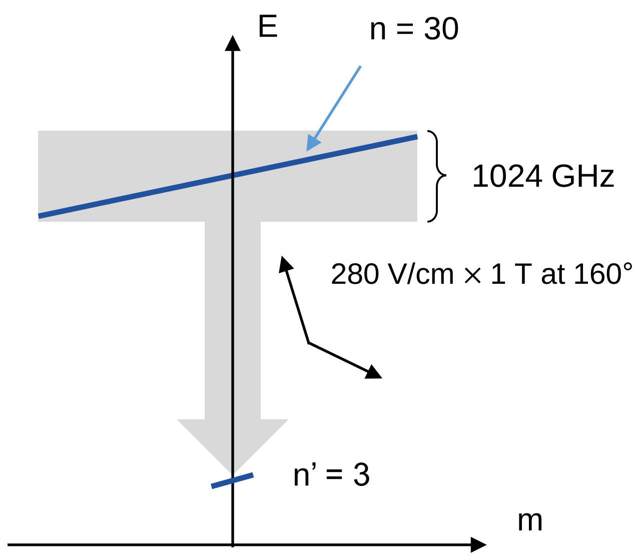
Phys. Rev. A 90, 032704 (2014)

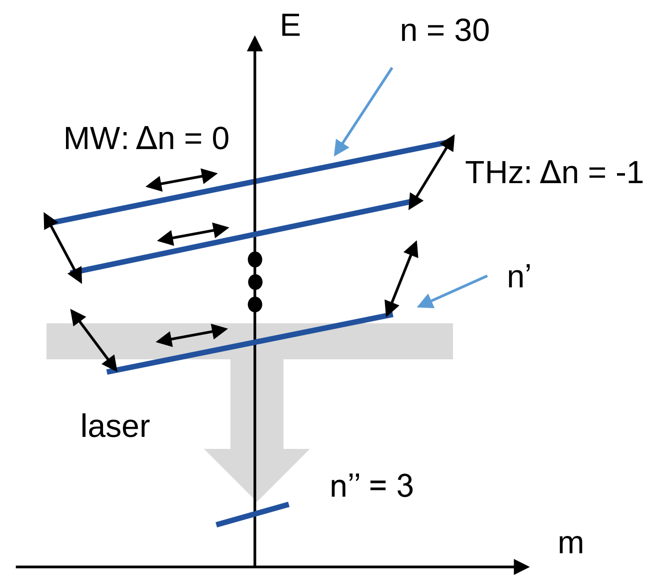
Temperatures of the order of 40 Kelvin



New ideas are needed to increase the number of ground state atoms available!

Stimulated deexcitation increases the number of GS atoms available





- State mixing via electric and magnetic fields
- Deexcitation via broadband laser

- Applicable to CE formation mechanism

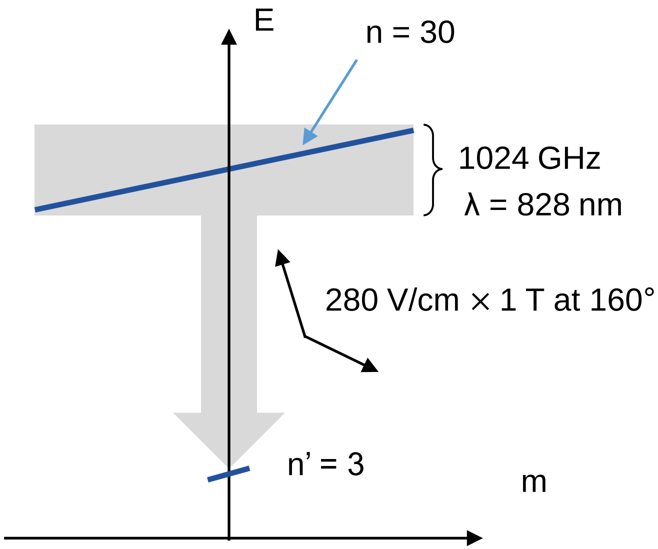
- State mixing and deexcitation through MW and THz light
- Deexcitation via narrowband laser

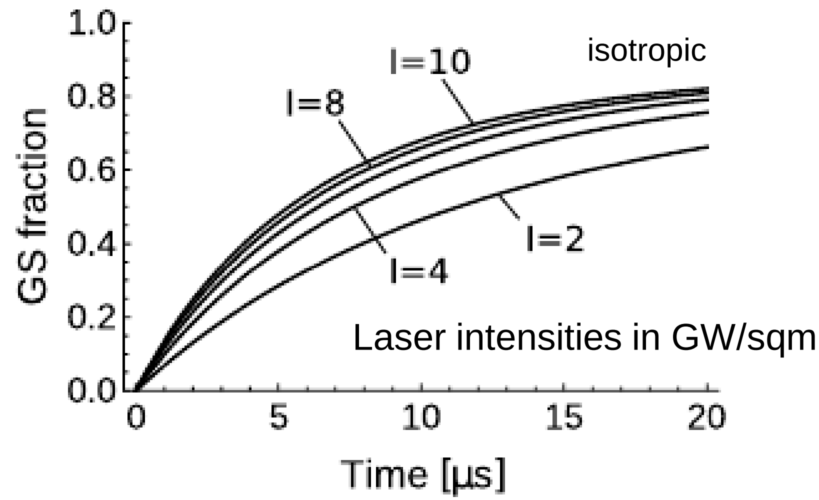
- Applicable to both CE and 3BR formation mechanism

[1] Phys. Rev. A 99, 013418 (2019)

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

Crossed electric and magnetic field mixing of Rydberg states



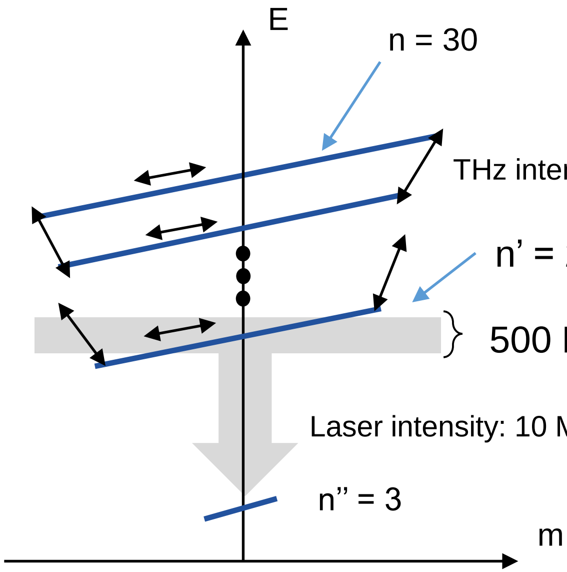


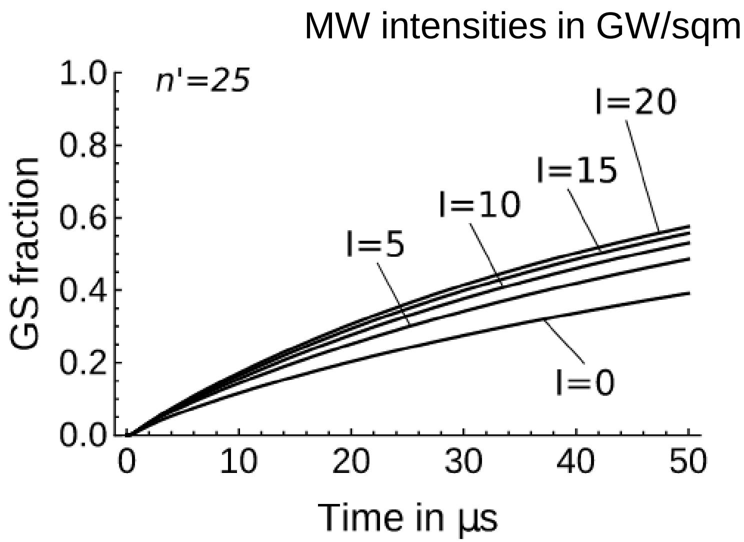
→ Ideal field mixing for the n=30 substates is found for an additional electric field of 280 V/cm

→ Close to unity ground state fraction after a few microseconds which is consistent with experimental requirements

CERN's AD
Deexcitation
Stim. rad. rec.
Proof of prin.
Rydberg beam
Summary

Light induced Rydberg state mixing





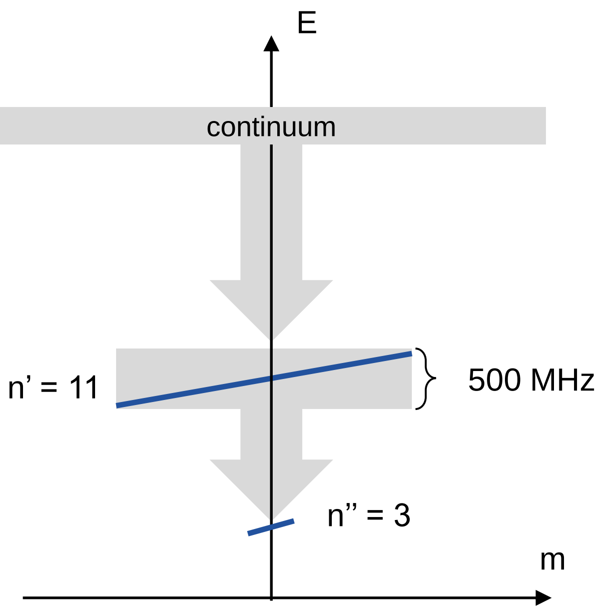
→ Initially populated levels are mixed relying on THz and microwave light

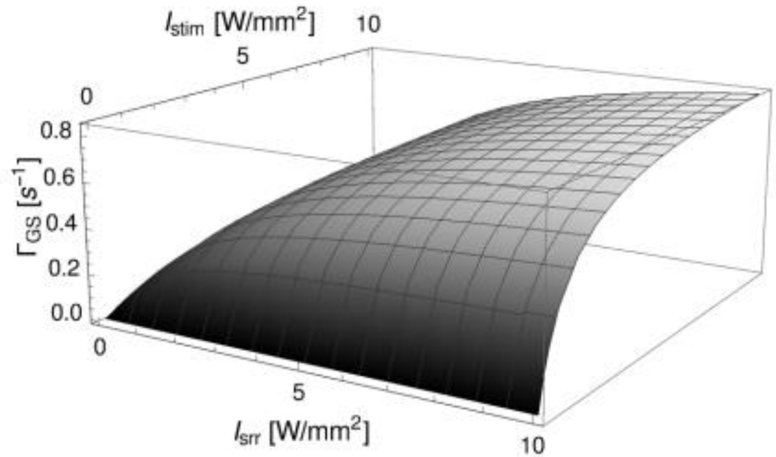
→ <u>Close to unity ground state fraction after a few ten microseconds</u> which is consistent with experimental requirements

Stimulated radiative recombination

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

Hyperfine Interact. 76, 189 (1993)



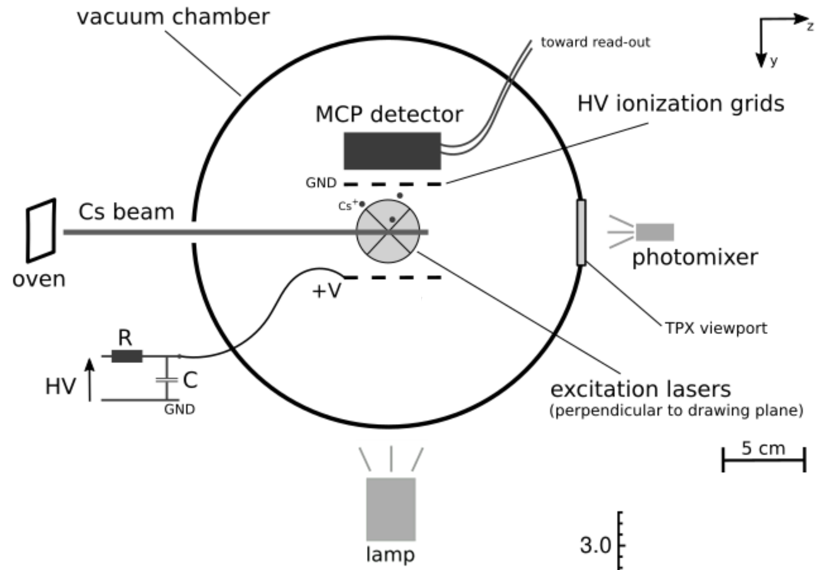


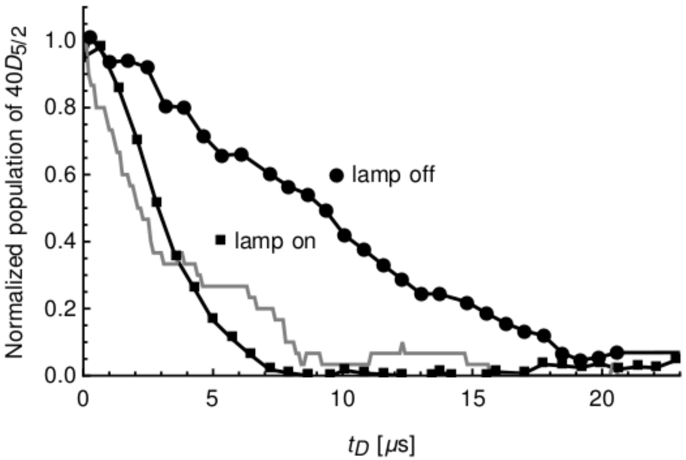
10 K positrons with density of 10^8 per ccm

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

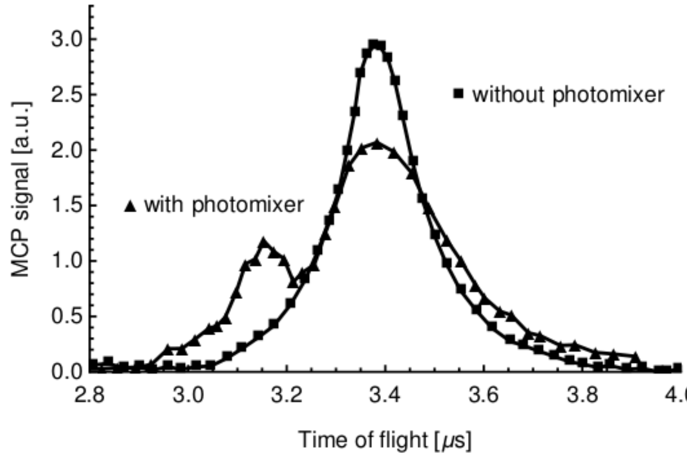
→ <u>One anti-atom per antiproton per second in ground state</u> is an improvement over the current state-of-the-art

Rydberg state mixing in a beam of excited cesium atoms





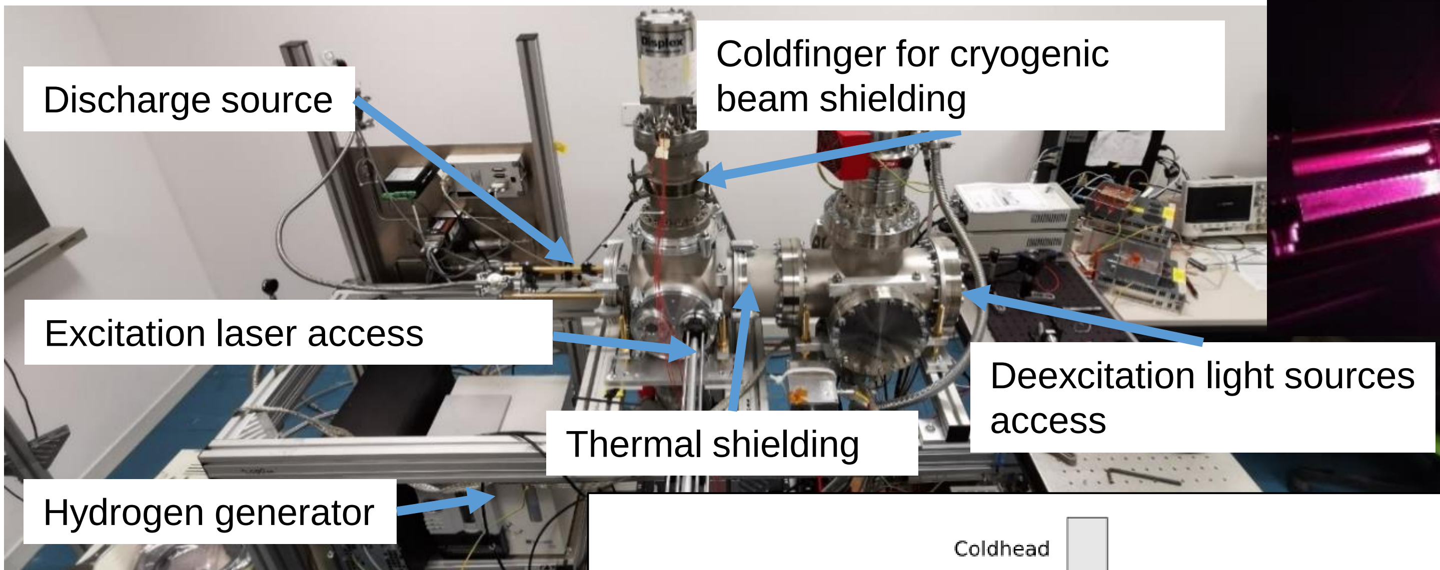
Population of $40D_{5/2}$ level as a function of the FI delay with respect to the excitation laser as stimulated by a BB lamp. Simulation data for a BB spectrum of 1200 K is indicated in grey.

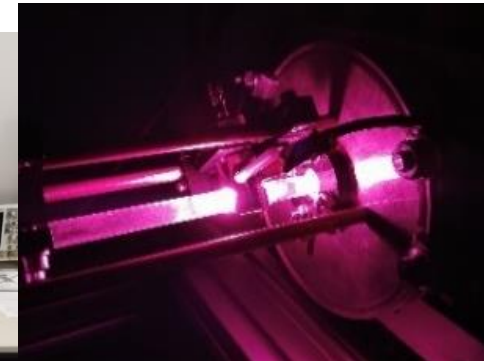


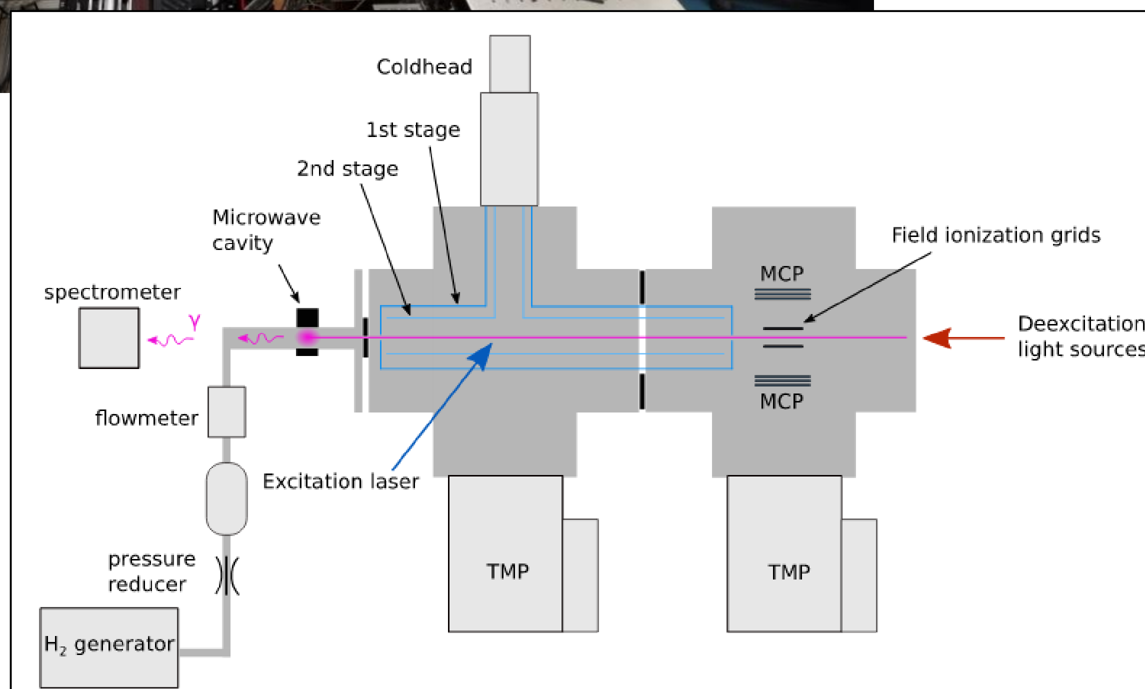
Stimulated $36S_{1/2} \rightarrow 36P_{3/2}$ transfer stimulated by a photomixer (97 GHz, spectral width 5 MHz).

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

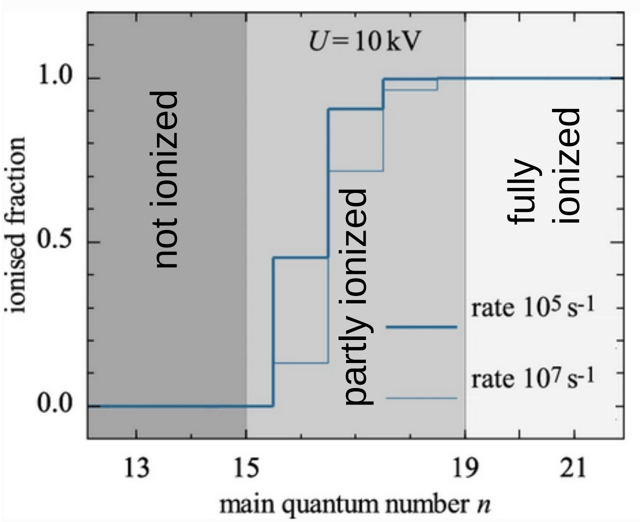
Rydberg beamline at CERN for hydrogen proof-of-principle

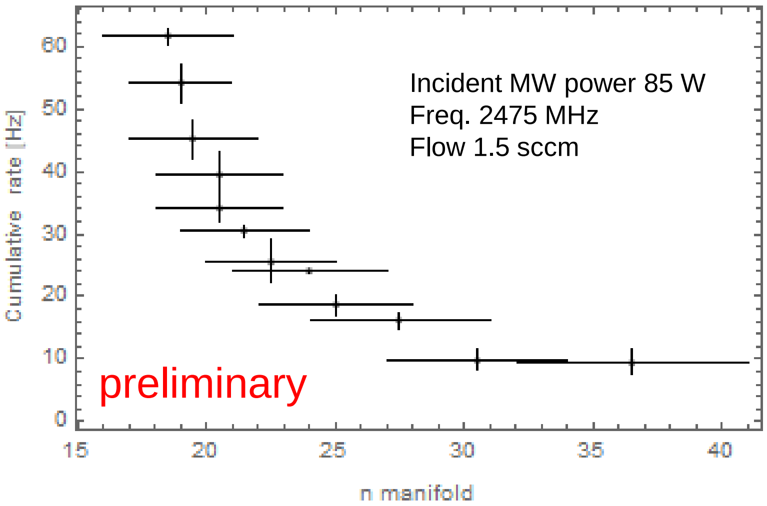






Rydberg state formation within a discharge plasma





→ Alternative to laser excitation: Obtain Rydberg atoms directly out of the plasma

- + Similar distribution of states as expected in antimatter experiments
- + Interesting from a plasma point-of-view
- - Field ionization complicates detecting a deexcitation signal
- - Rather low rates

Summary and outlook

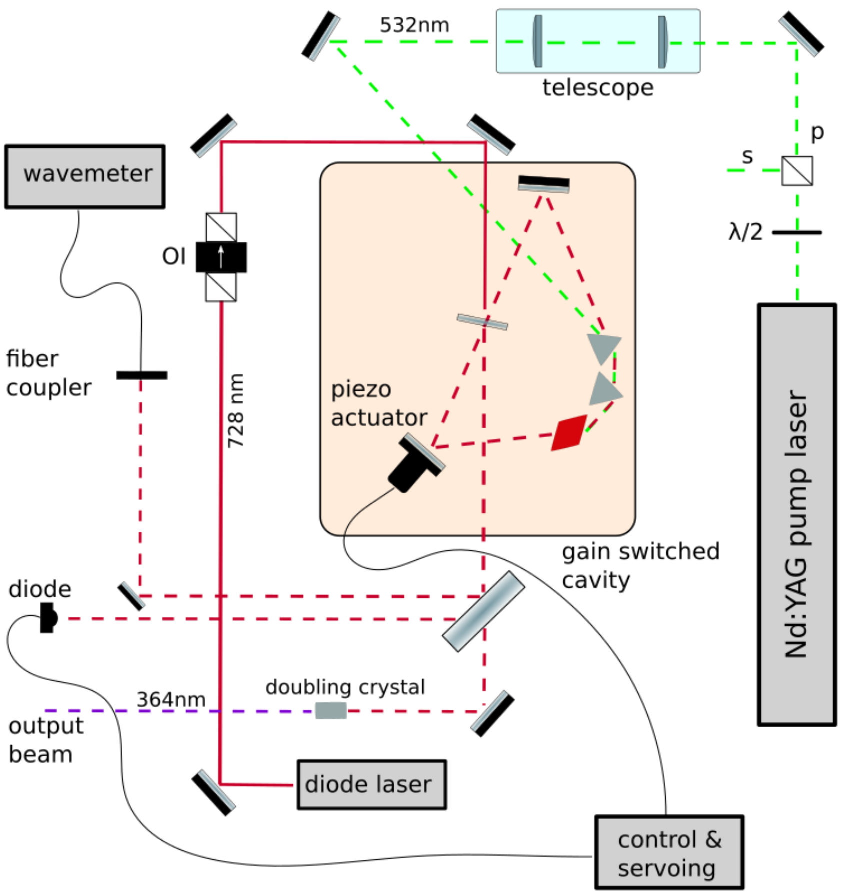
- Atomic antimatter physics is an interesting field of research and impressive results have been published in the last years
- Experiments rely on cold anti-atomic ground state samples still posing a major hurdle towards precision measurements
- Stimulated deexcitation has the potential to be a key technology addressing both main issues: number of atoms and their temperature in beam and trap experiments
- Schemes have been identified and simulated for both CE and 3BR formation mechanisms
- Deexcitation light sources have been tested on a Cs-Rydberg beam
- An atomic hydrogen beam has been set up at CERN for further tests and to develop a deexcitation laser before application at the AD

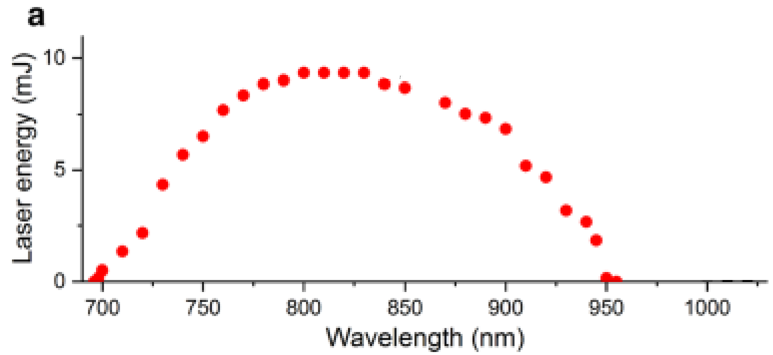
→ Stay tuned for first hydrogen deexcitation results!
→ Demonstrations on antimatter are planned throughout the upcoming beamtimes!

Thank you to C. Malbrunot (CERN), D. Comparat (LAC), M. Simon (SMI) and the entire ASACUSA and AEGIS collaboration.

Thank you for your attention.

Backup: Single mode emission laser 2s → Rydberg states



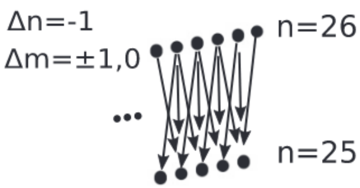


Appl. Phy. B 125:14 (2019)

λ [nm]	τ [ns]	E [mJ]	d [mm]
532	10	150	3
728	10	20	2
364	10	10	2

Backup: Intrinsic limitations, selection rules, frequencies and bandwidths

- General:
  - Relying on 3BR, methods of $E \times B$ field mixing cannot be easily applied
  - Accessibility of states and atomic selection rules



  - Inherent limit to the deexcitation times achievable

$$t_{\mathrm{deex}} = \frac{N}{N'} \times t_{N'}^{\mathrm{GS}}$$

initially pop. states (N); Lifetime to GS of states the pop. is coupled to ($t_{N'}^{\mathrm{GS}}$); # states one couples to (N')

- Specifics using light:
  - Ionization or culminated excitation of atoms (see plots on right)
  - Availability of light sources (in particular in the THz regime) → photomixing is an interesting technology
  - Technical issues (how do we bring in light, cryogenic environment, etc.)

High losses for $n > 35$ with THz

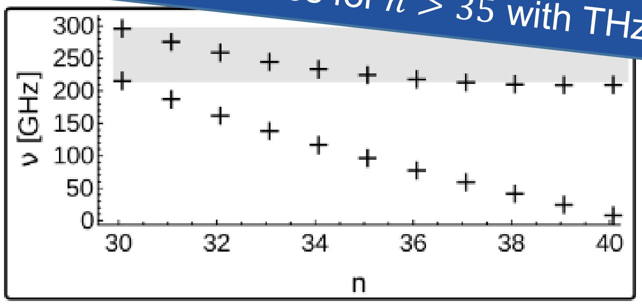


Fig. 1: Inter manifold transition frequencies in Rydberg antihydrogen [7]

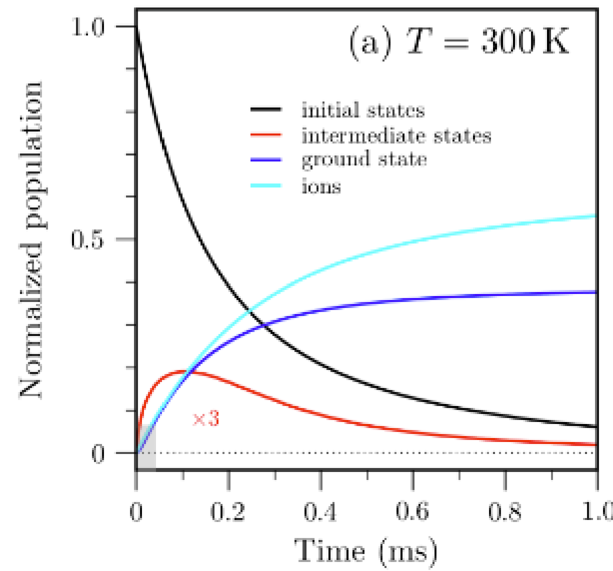


Fig. 2: States of trapped hydrogen for initial population of $n = 30, |m| < 15$ exposed to 300K BB spectrum [12]