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Antihydrogen production by two stage charge exchange

ATRAP Collaboration



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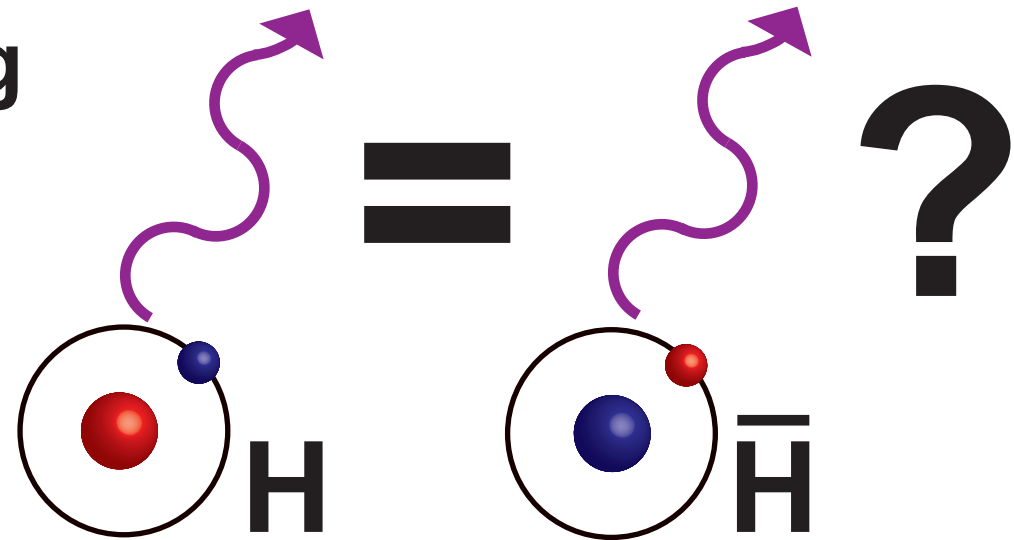


Much Cooler than LHC

Why antihydrogen?

CPT symmetry breaking

- ▶ compare 1S-2S line of $\bar{\text{H}}$ to H
- ▶ most precise measurement of CPT symmetry using leptons and baryons



Antigravity

- ▶ $g = \bar{g}$ to a part in 10^6
(indirect measurements)

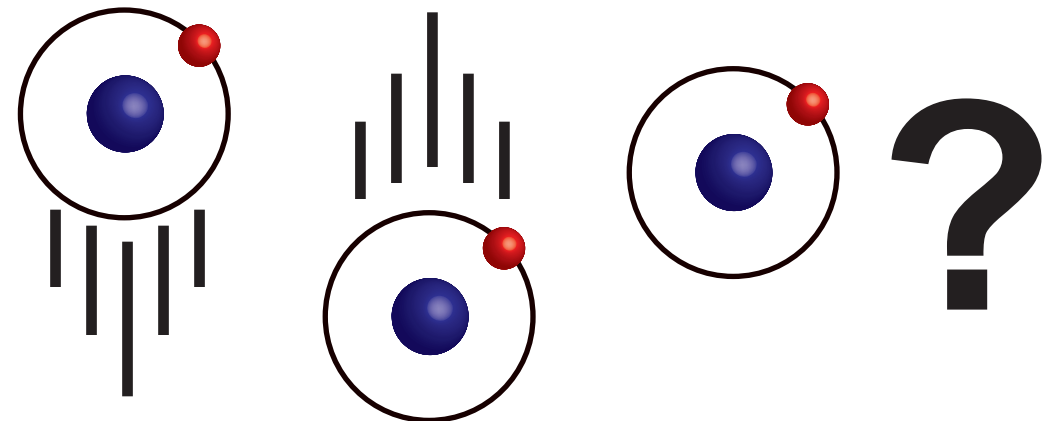
Pakvasa *et al.* Phys. Rev. D 39, 1761–1763 (1989)

Hughes, Holzscheiter.

Phys. Rev. Lett. 66, 854–857 (1991)

Gabrielse *et al.* Phys. Rev. Lett. 82, 3198 (1999)

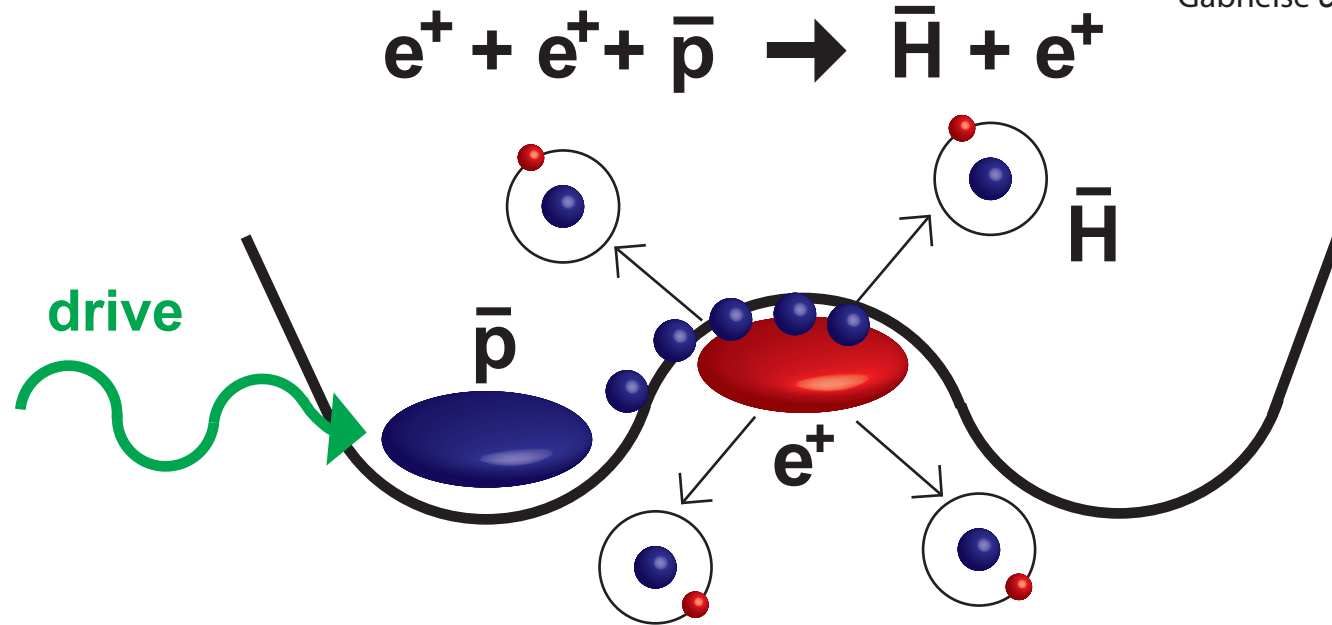
- ▶ Trapped $\bar{\text{H}}$ and $\bar{\text{H}}$ beam experiments are underway



$\bar{\text{H}}$ formation & trapping

Three Body Recombination in a nested Penning trap

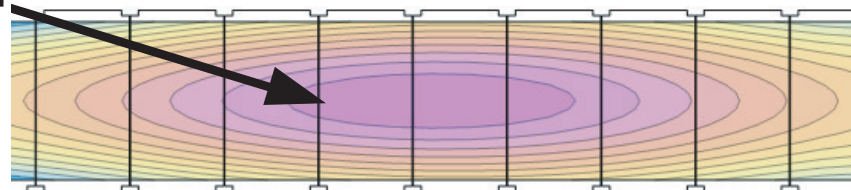
Gabrielse *et al.* Phys. Lett. A 129, 38 (1988)



Antihydrogen Trapping

Make antihydrogen in a magnetic gradient neutral atom trap.
only ~ 0.4 K deep

Gabrielse *et al.* (ATRAP Collaboration)
Phys. Rev. Lett. 100, 113001 (2008)



two stage charge exchange

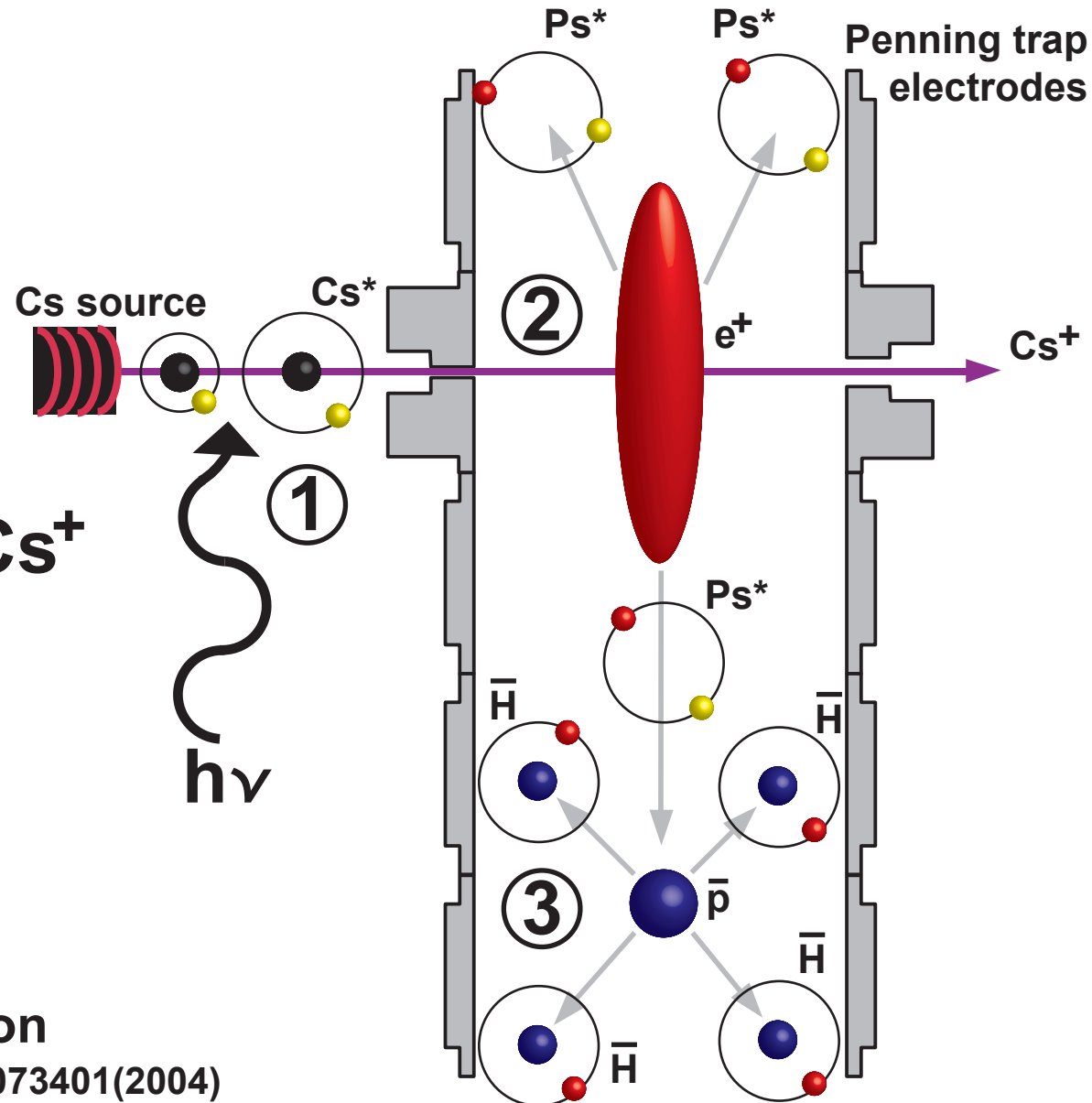
- ① $\text{Cs} + h\nu \rightarrow \text{Cs}^*$
- ② $e^+ + \text{Cs}^* \rightarrow \text{Ps}^* + \text{Cs}^+$
- ③ $\text{Ps}^* + \bar{p} \rightarrow \bar{\text{H}} + e^-$

Monte Carlo calculations

Hessels *et al.* PRA 57 1668(1998)

first laser-controlled $\bar{\text{H}}$ production

Storry *et al.* (ATRAP Collaboration) PRL 93 073401(2004)



$\bar{H}$ formation & trapping

three body recombination

- ☒ hot $\bar{p}$ create hot $\bar{H}$ ($\bar{p}$ must be driven into the e^+ cloud)
- ☒ $\bar{H}$ is easily ionized (TBR creates high n-state $\bar{H}$)
- ☒ successfully trapped!
ALPHA Collaboration - Nature Physics 7, 558–564 (2011)
ATRAP Collaboration - PRL 108. 113002(2012)

charge exchange

- ☒ potential for coldest $\bar{H}$ ($\bar{p}$ remain at rest)
- ☒ control over $\bar{H}$ n-state ($n_{\bar{H}} \cong n_{Cs^*}$)
- ☒ giving up solid angle

The York Positron Accumulator

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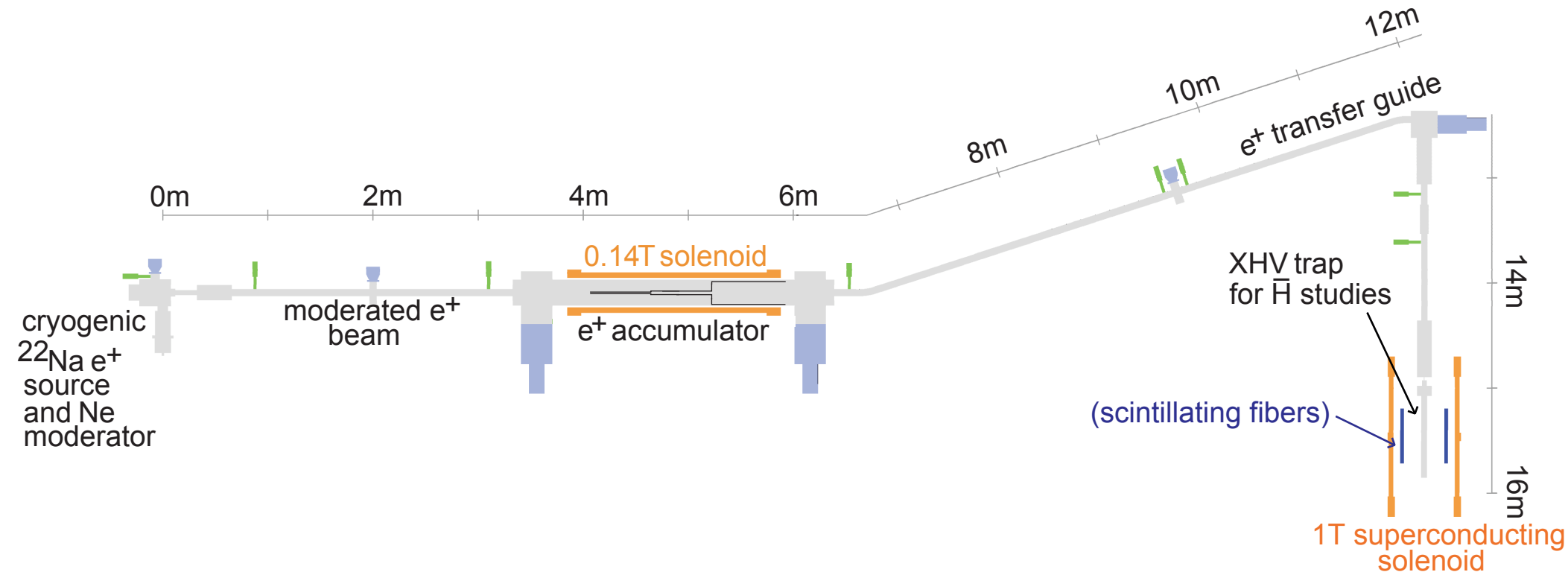
- positron accumulation via gas-buffer cooling

Murphy, Surko. Phys. Rev. A 46, 5696 (1992)

- nearly 100% efficient transfer into the 1T field

Comeau *et al.* (ATRAP Collaboration) New J. Phys. 14. 045006 (2012)

- up to 4×10^9 e^+ trapped and cooled in the cryogenic Penning trap



ATRAP cryogenic Penning trap

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$\bar{p}$ from the Antiproton Decelerator enter through the bottom of the trap, slowed in a Be degrader and trapped and cooled using e^- .

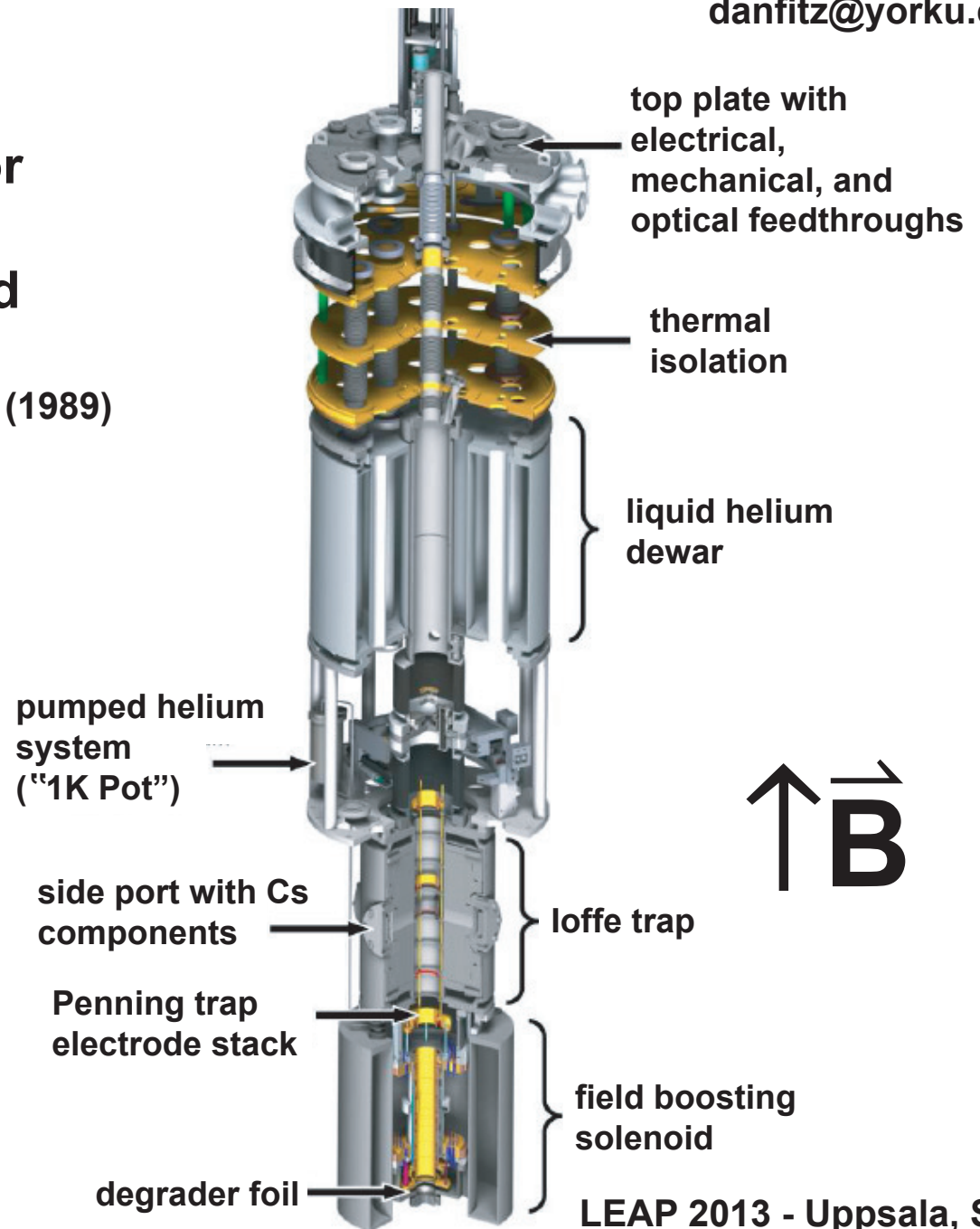
Gabrielse *et al.* Phys. Rev. Lett. 63, 1360–1363 (1989)

e^+ from the York positron accumulator enter through the top.

pumped helium system keeps the electrode stack at 1.2 K.

Wrubel *et al.* (ATRAP Collaboration)
NIM A 640, 232 (2011)

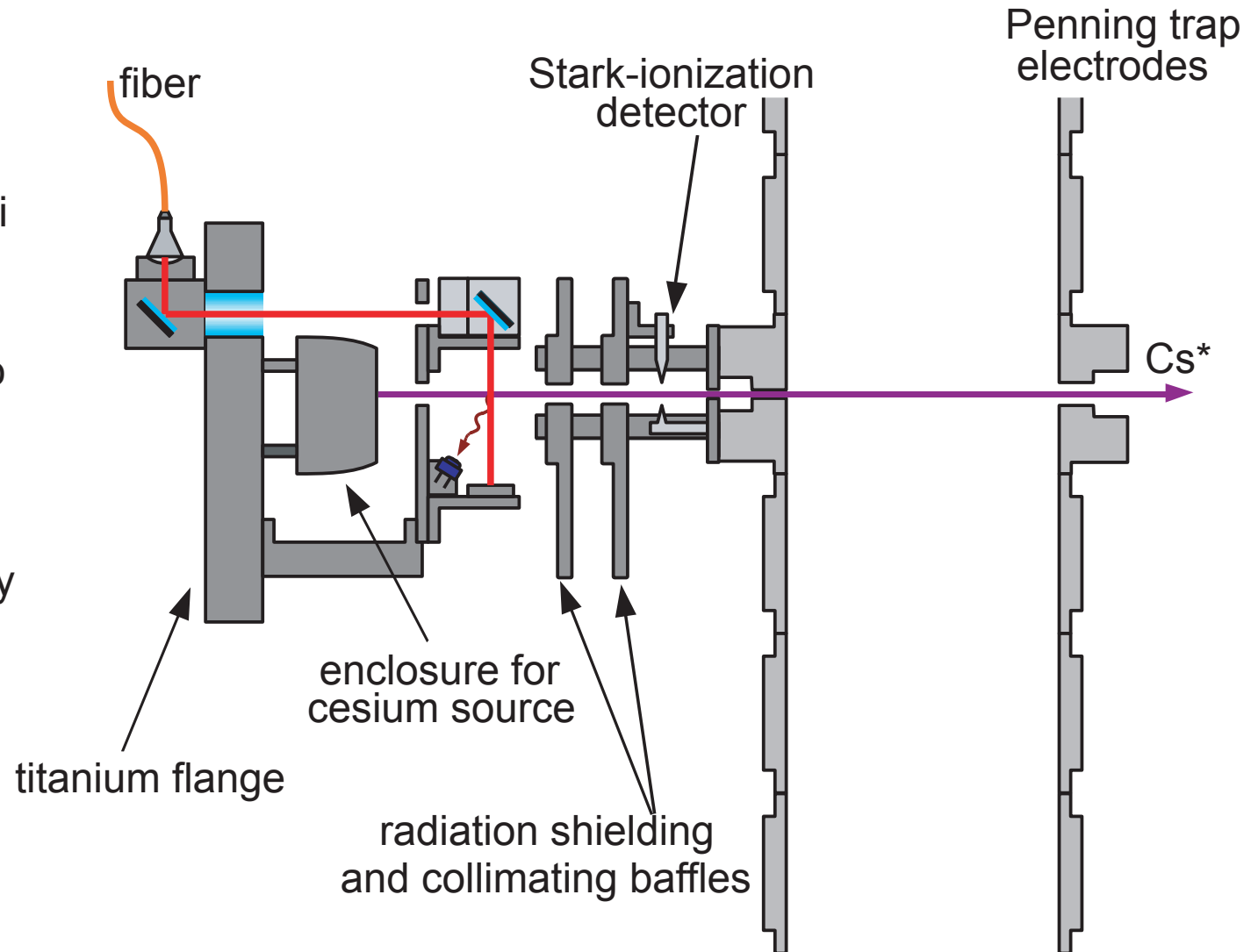
XHV trap $< 6 \times 10^{-17}$ Torr



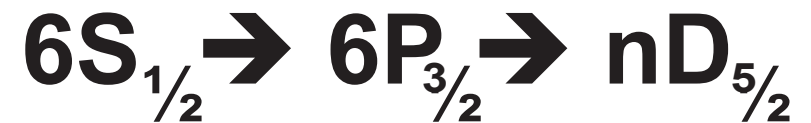
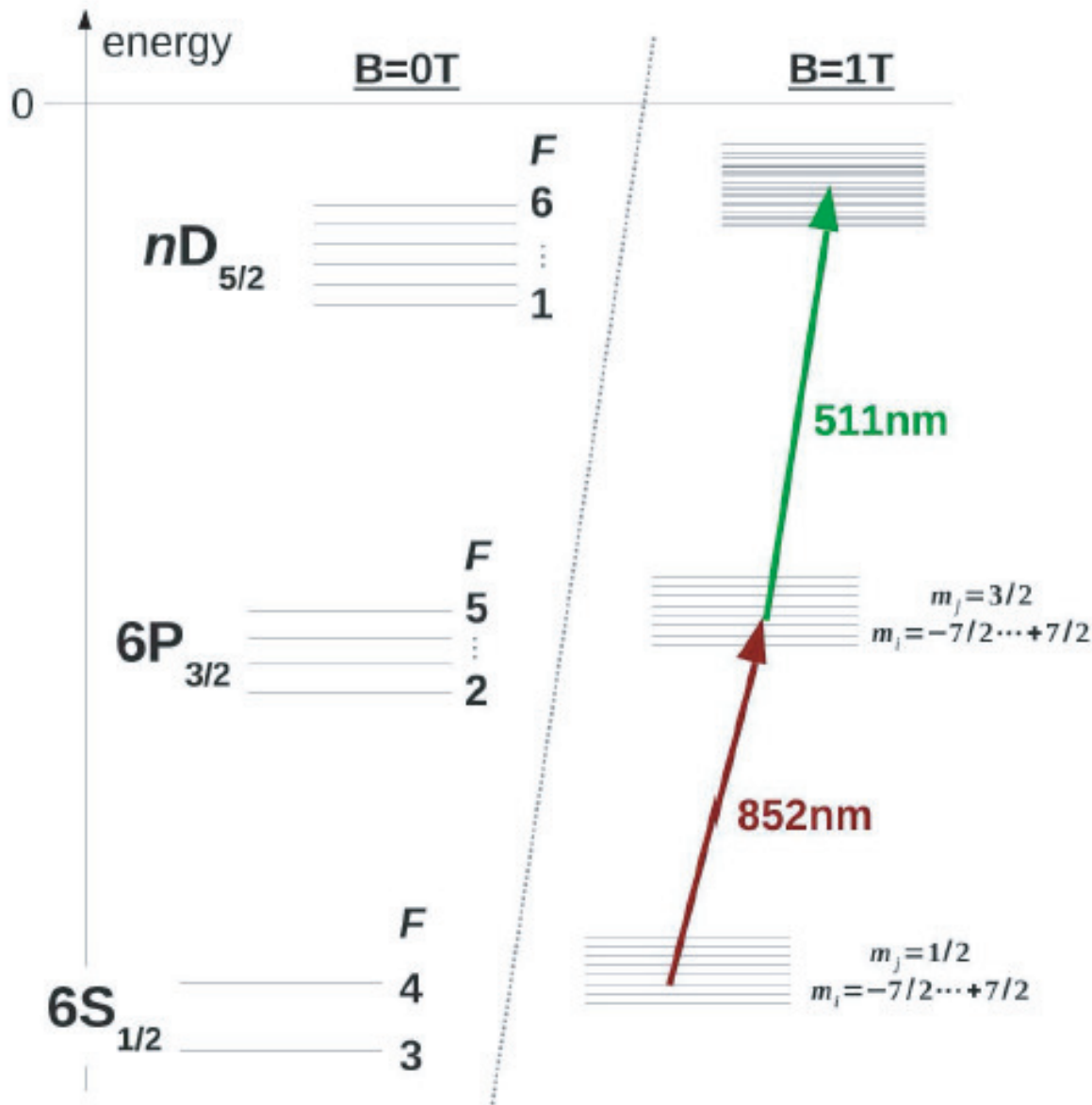
LEAP 2013 - Uppsala, SE

Rydberg cesium apparatus

- ▶ resistively heated Alkali metal dispenser
- ▶ Cs source heated up to 600 K within the XHV cryogenic trap.
- ▶ 4×10^6 Cs^{*}/s detected by Stark-ionization detector



cesium excitation



which Rydberg state is best?

- ▶ lifetime increases with n
- ▶ cross sections scale with n^4
- ▶ higher n states more easily ionized by e^+ space charge
- ▶ excitation probability decreases with increasing n

$$n \approx 42$$

Cs in a magnetic field

$$H = H_0 + \overbrace{\zeta(r)\vec{L} \cdot \vec{S}}^{H_{\text{FS}}} + \overbrace{a(\vec{I} \cdot \vec{J})}^{H_{\text{HFS}}} + \underbrace{\frac{1}{2}\alpha(\vec{L} + g_e\vec{S} + g_I\vec{I}) \cdot \vec{B}}_{H_{\text{para}}} + \underbrace{\frac{1}{8}\alpha^2 r^2 \sin^2\theta B^2}_{H_{\text{dia}}}$$

no solution for arbitrary field strength!

$6S_{1/2} \rightarrow 6P_{3/2}$

- ▶ H_{dia} is negligible for small n
- ▶ in 1T field, $H_{\text{HFS}} \approx H_{\text{para}}$
- ▶ energy levels given by Breit-Rabi formula

$6P_{3/2} \rightarrow nD_{5/2}$

- ▶ H_{dia} no longer negligible
- ▶ H_{dia} couples states with $\Delta l \pm 2$
- ▶ energy levels given by
 - Hamiltonian diagonalization
 - semi-classical method

excitation lasers

852 nm $6S_{1/2} \rightarrow 6P_{3/2}$

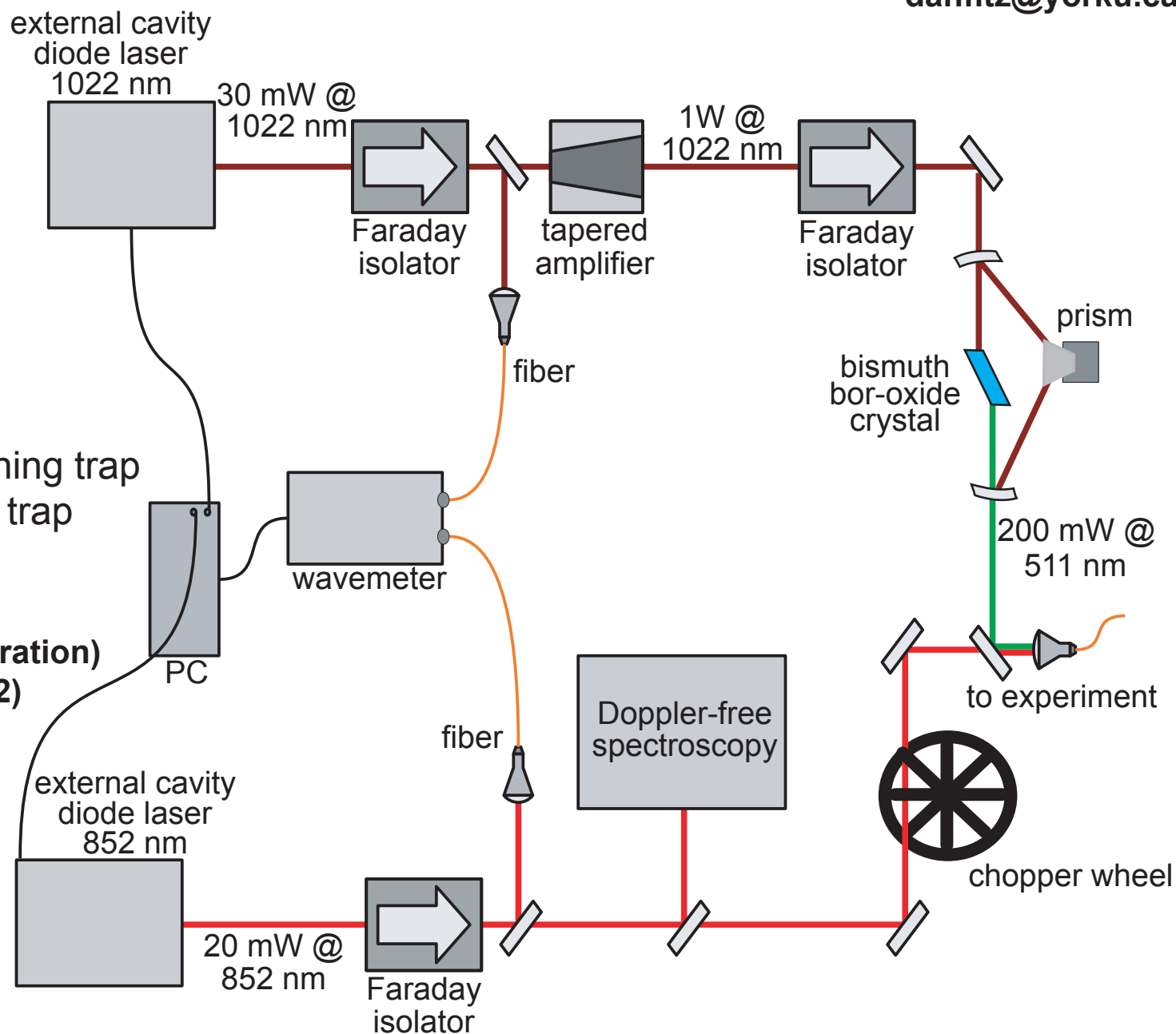
511 nm $6P_{3/2} \rightarrow nD_{5/2}$

- ▶ tunability > 10 GHz
20 < n < ionization

- ▶ excitation in the 1T Penning trap
as well as the 3.2T Ioffe trap

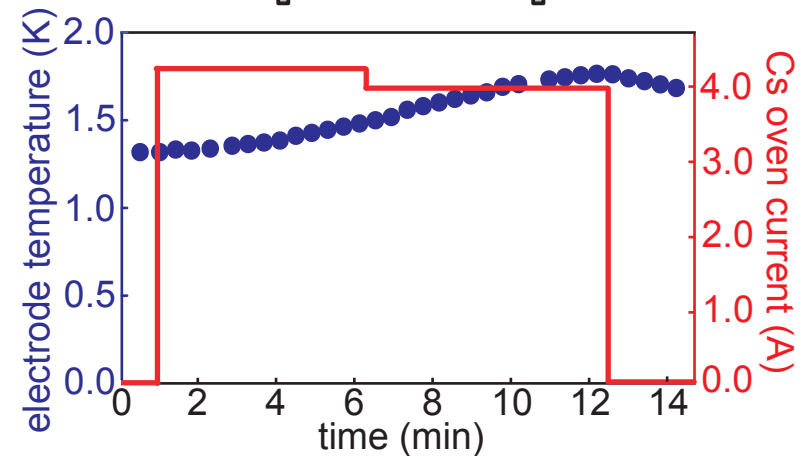
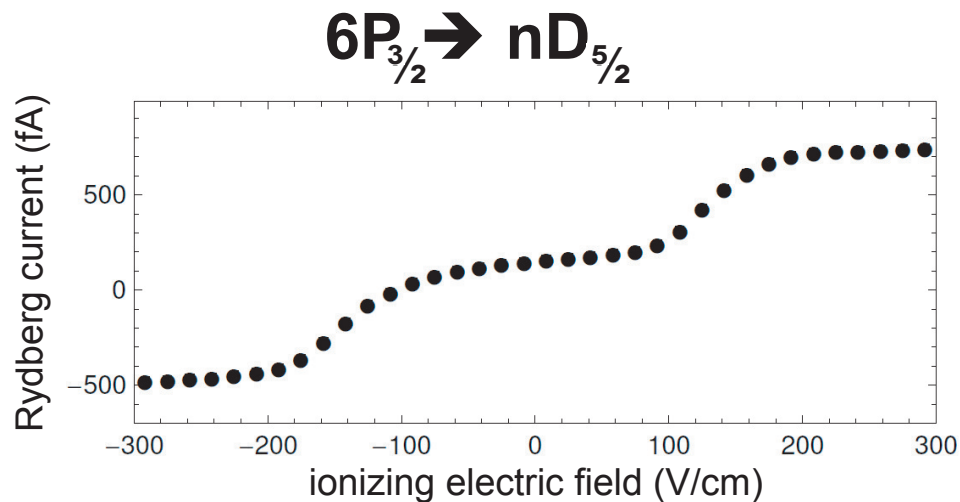
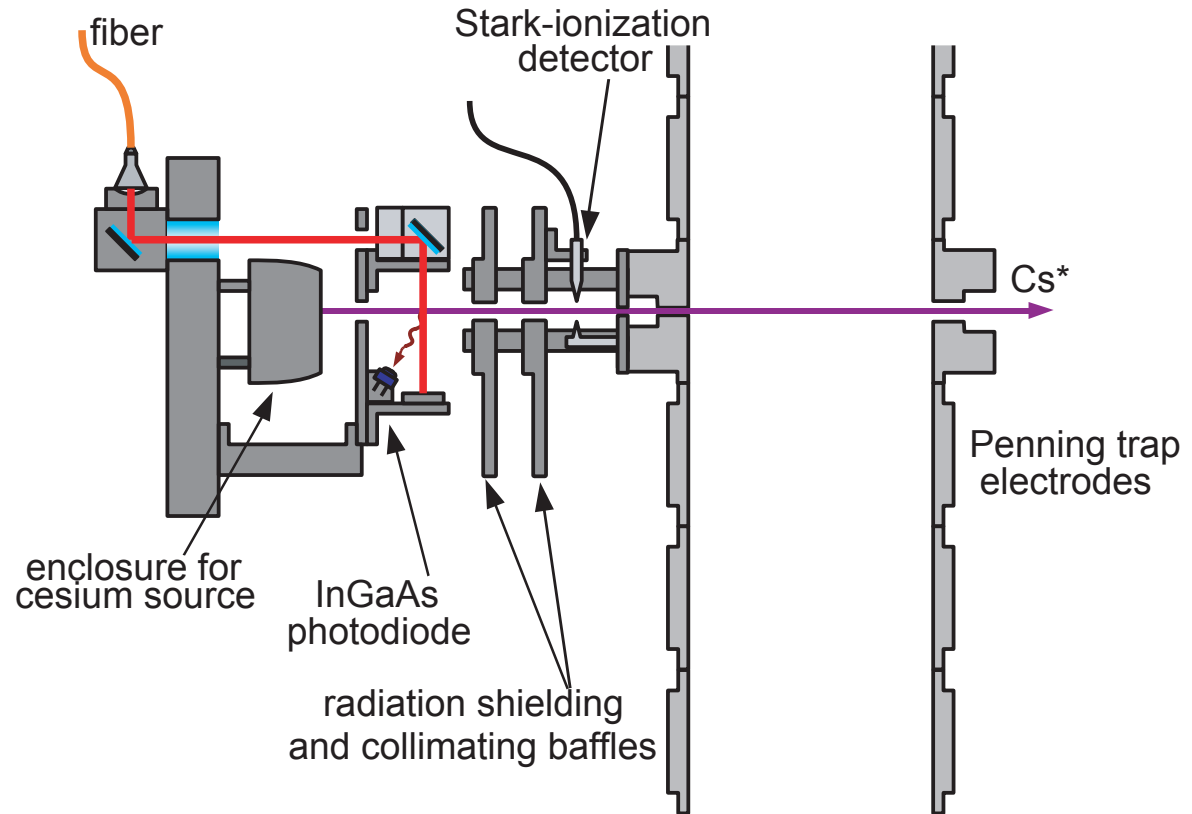
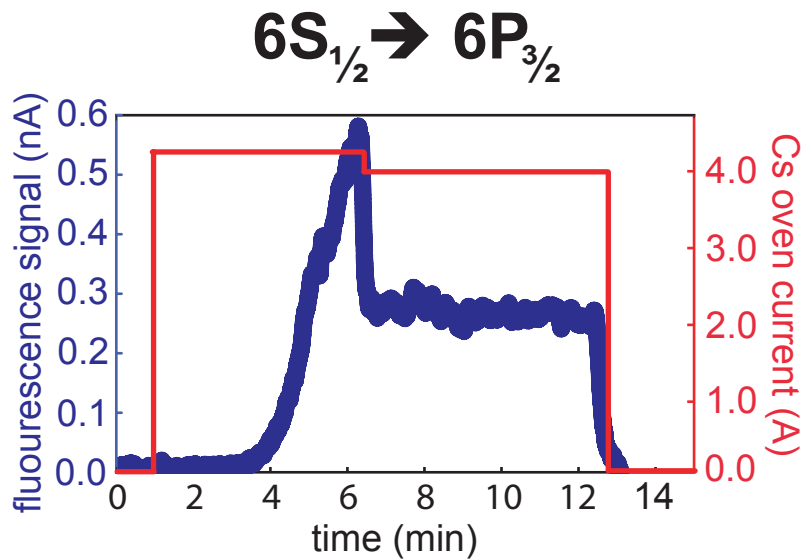
- ▶ linewidth ~ 1 MHz

Müllers *et al.* (ATRAP Collaboration)
New J. Phys. 14. 055009 (2012)



Rydberg cesium excitation

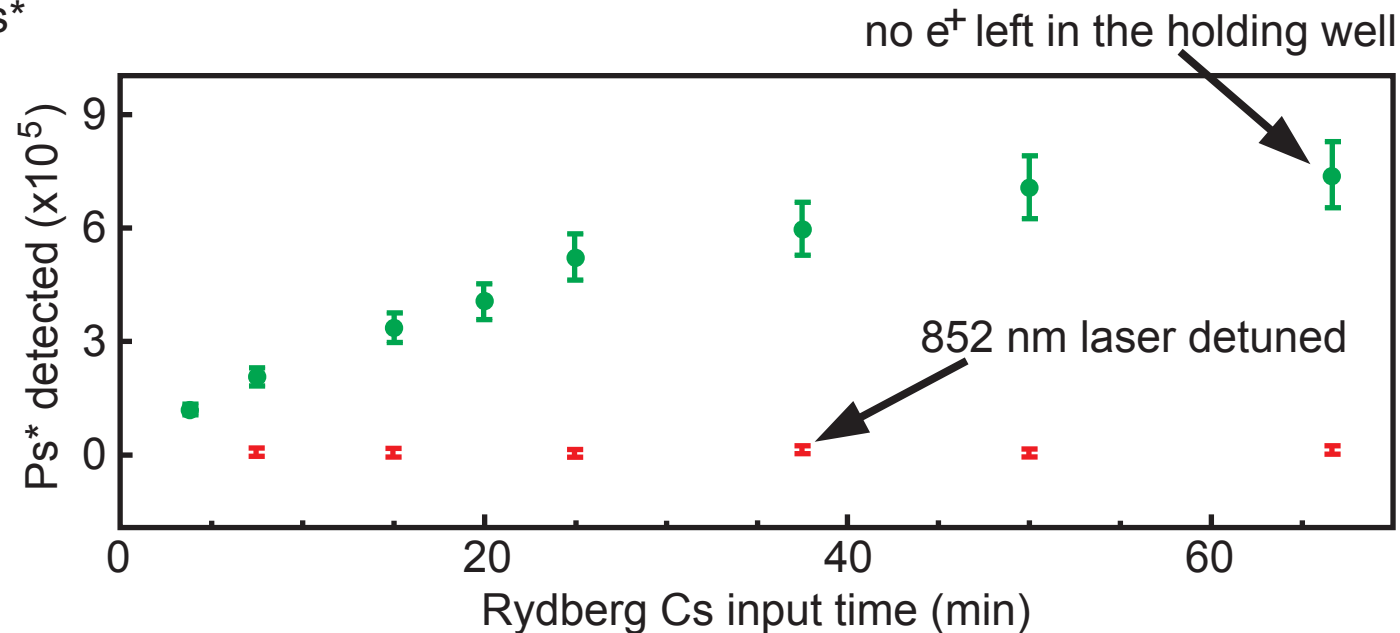
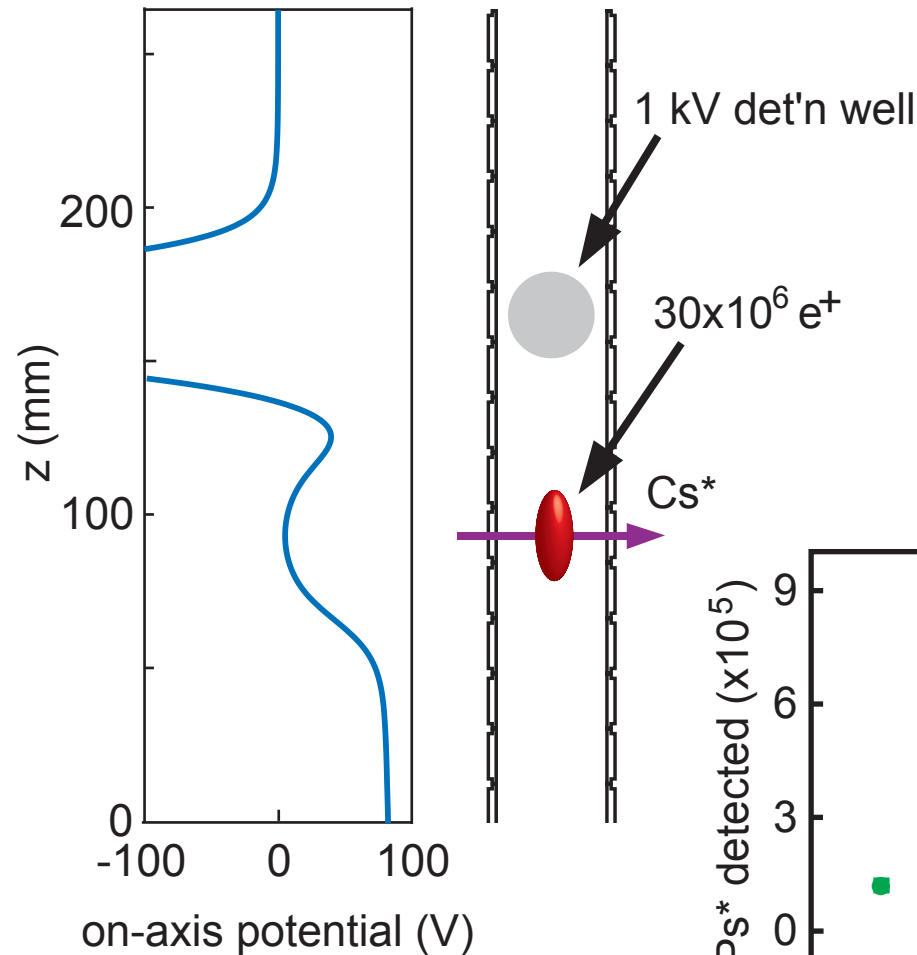
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positronium production



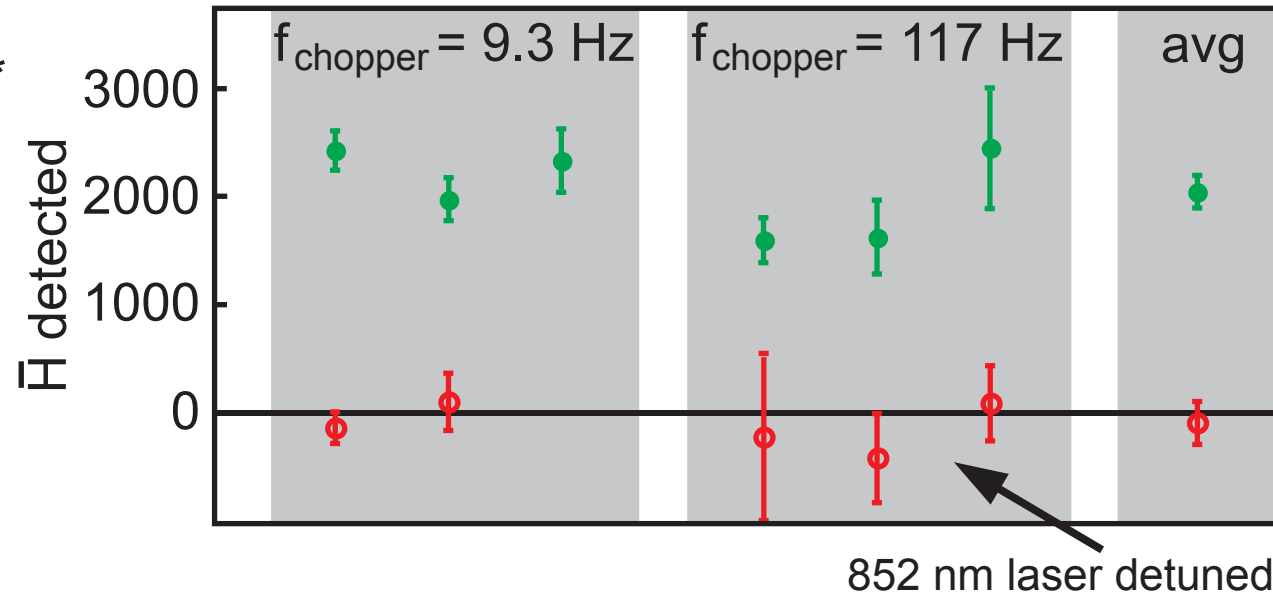
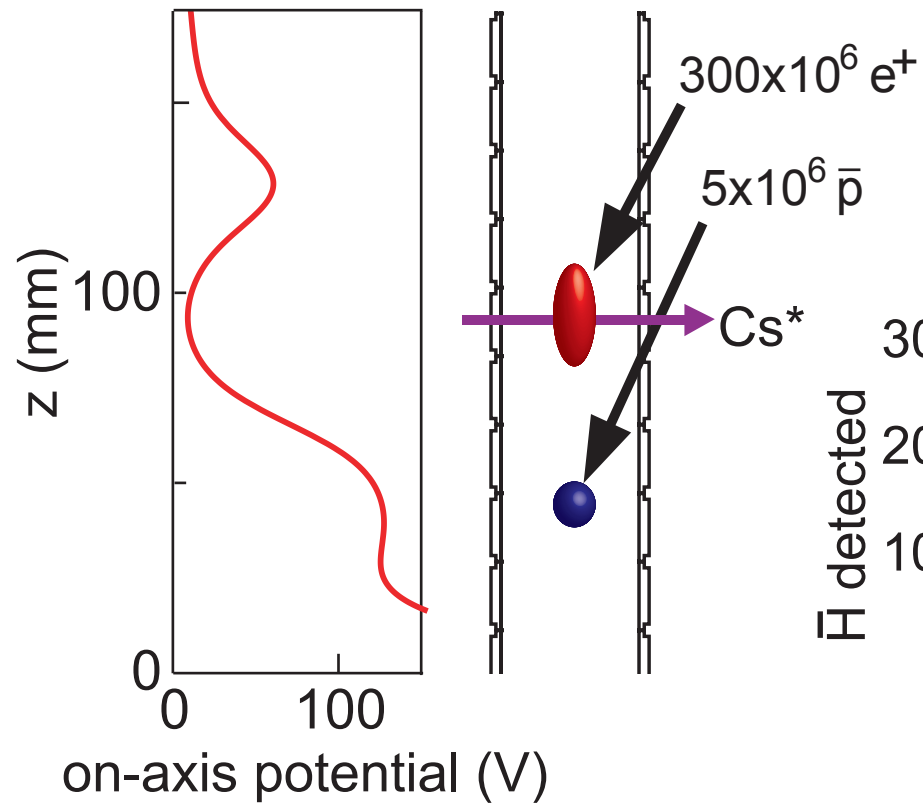
- ▶ Ps^* exits the e^+ cloud isotropically
- ▶ some travel axially and are ionized in the detection well
- ▶ detection well is dumped and e^+ are counted using annihilation γ
- ▶ over 2×10^6 atoms/sr produced



antihydrogen production



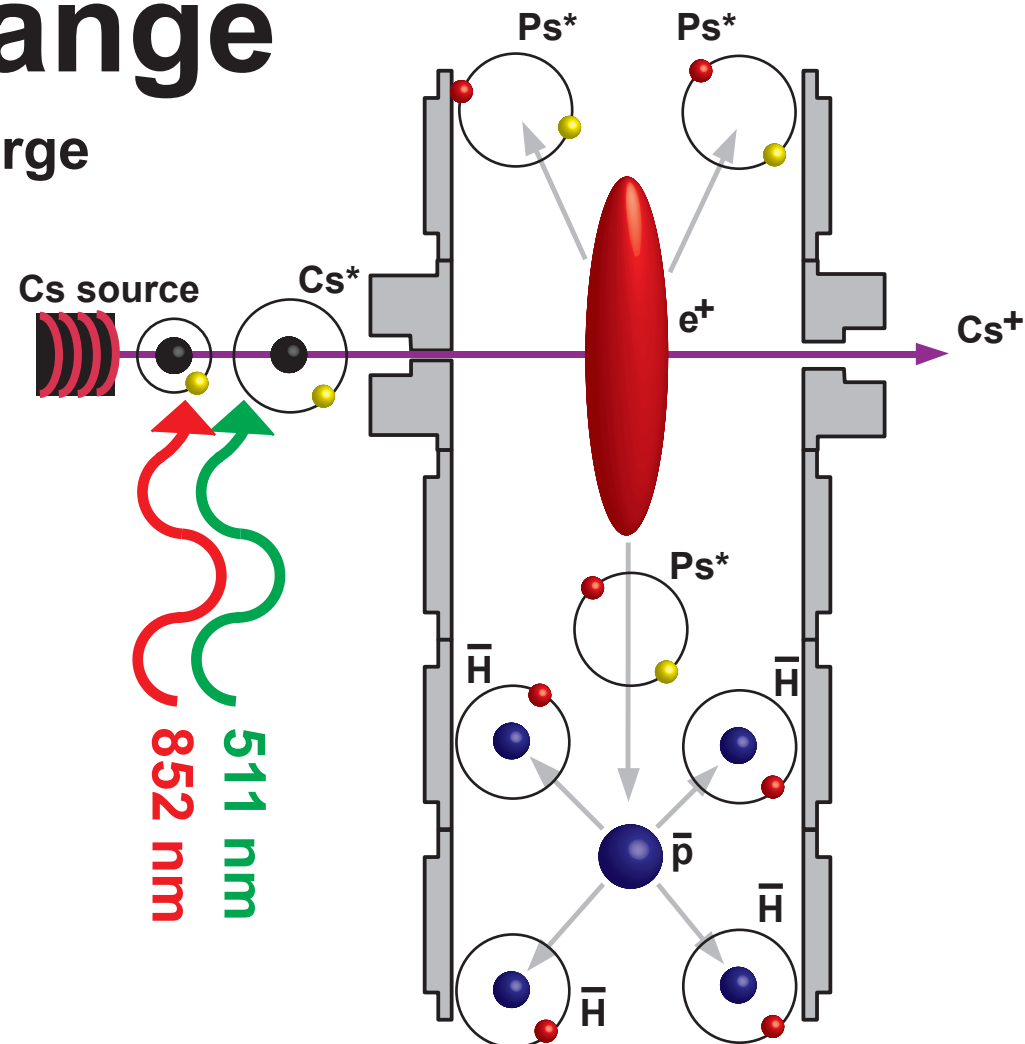
- ▶ 852 nm laser is chopped
- ▶ laser-off $\bar{p}$ counts are subtracted from laser-on $\bar{p}$ counts
- ▶ 2000 $\bar{H}$ atoms detected per 20 min trial
- ▶ two chopper frequencies used to eliminate non- $\bar{H}$ loss mechanisms.



summary

two stage Rydberg charge exchange

- ▶ promising method for producing large numbers of cold, trappable $\bar{\text{H}}$
- ▶ large numbers of e^+ and $\bar{\text{p}}$ loaded into an XHV cryogenic trap with a 600 K Cs^* source
- ▶ a powerful, tunable laser system can be used with or without the Ioffe trap
- ▶ millions of Ps^* and thousands of $\bar{\text{H}}$ created per trial



trap the cold $\bar{H}$

- ▶ Need to produce Ps^* and $\bar{H}$ in the Ioffe trap magnetic field
- ▶ adiabatic cooling of $\bar{p}$ to 3.5 K will allow for more trappable $\bar{H}$
Gabrielse *et al.* (ATRAP Collaboration) PRL 106, 073002 (2011)

thank you!

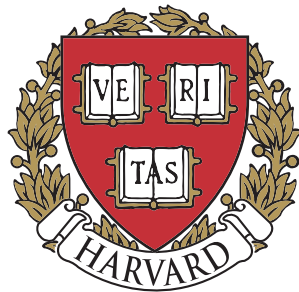
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NSF and AFOSR of the U.S.

funded by: BMBF, DFG, and DAAD of Germany

NSERC, CRC, and CFI of Canada