Development towards a future experiment ALPHA-X (tentative title):

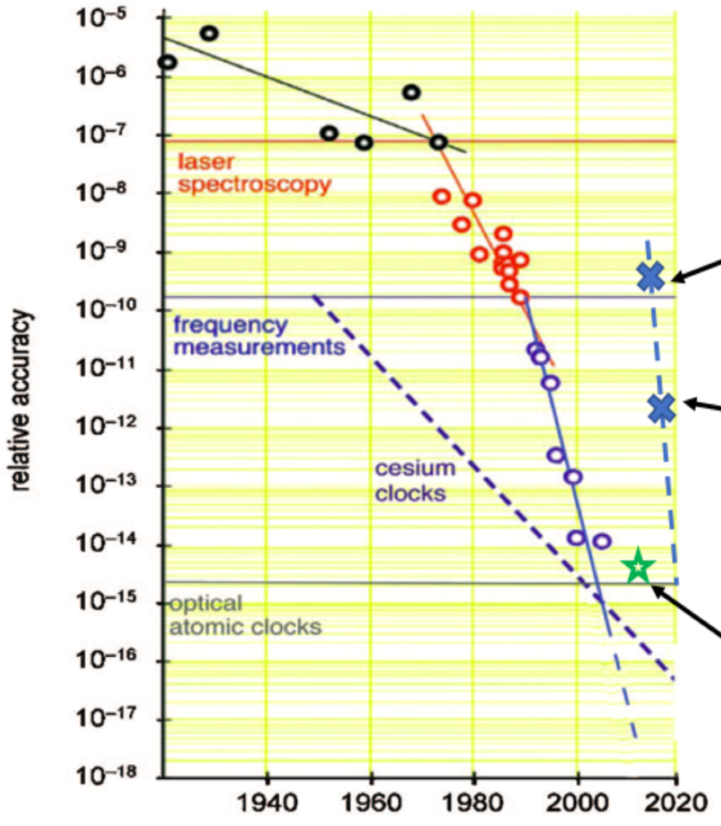
PP meeting: Sept 5, 2019

Not for distribution!

Ideas preliminary and unpublished

Introduction

- Current priority: ALPHA-g/2
  - Looking at future as well
  - Sounds crazy, but this is how we've operated in last 20 yrs!
- 20 years since Antiproton Decelerator at CERN started
  - Tremendous progress in anti-H studies
  - Reaching H precisions is in sight; we now want to think about going beyond



T. W. Hänsch, Rev. Mod. Phys. **78** 1297 (2005)

2×10^{-10}
ALPHA Collaboration
Nature **541**, 506–510 (2017)

2×10^{-12}
ALPHA Collaboration
Nature **557**, 71–75 (2018)

4.2×10^{-15}
C. G. Parthey et al.,
PRL **107**, 203001 (2011)

Project objectives (slightly modified)

- Develop a next generation anti-H experiment at CERN possibly to run after Long Shutdown 3 (2025/26)
- Prototype entirely new techniques for antihydrogen studies, using hydrogen as a proxy
  - Could possibly improve precisions on atomic H physics too, but this is beyond the scope of the initial proposal

Scientific Case

- Test of fundamental symmetries between matter & antimatter
- Take advantage of tremendous progress in quantum techniques in atomic physics over the past decades, e.g.:
  - Atomic fountain & atom interferometry [gravity tests, fine structure const]
  - Optical lattice/ion clocks [precision spectroscopy at 10^{-18} level]
  - Coherent manipulations of quantum states [laser cooling, quantum logic]
  - High phase space density regimes [molecules, Bose-Einstein Condensates]
- Most of these techniques have not been applied to hydrogen
  - Too difficult to handle, compared e.g. to alkali atoms
    - Laser to drive transitions (e.g. 1S-2P) are difficult (e.g. nW power versus 10's W)
    - Lack of convenient cold atomic source
- We will develop new techniques for with H prototype
  - Allows to test various new ideas; potential for tremendous gains!

Ultra-cold anti-H in micro Kelvin regime

- Want coldest Anti-H temperatures
  - Temperature a major limitation(e.g. TOF broadening)
  - Cold fountain needed to avoid radial blow up (20 mK ~ 20 m/s, still fast!)
- Laser cooling:
  - Recoil limit ~ order 1 mK
  - Sub-Doppler techniques hard for (anti)H
- Evaporative cooling
  - Used in MIT trap for BEC
  - Cannot work for anti-H (yet!)
- Adiabatic cooling
  - Only way to get to < mK regime?

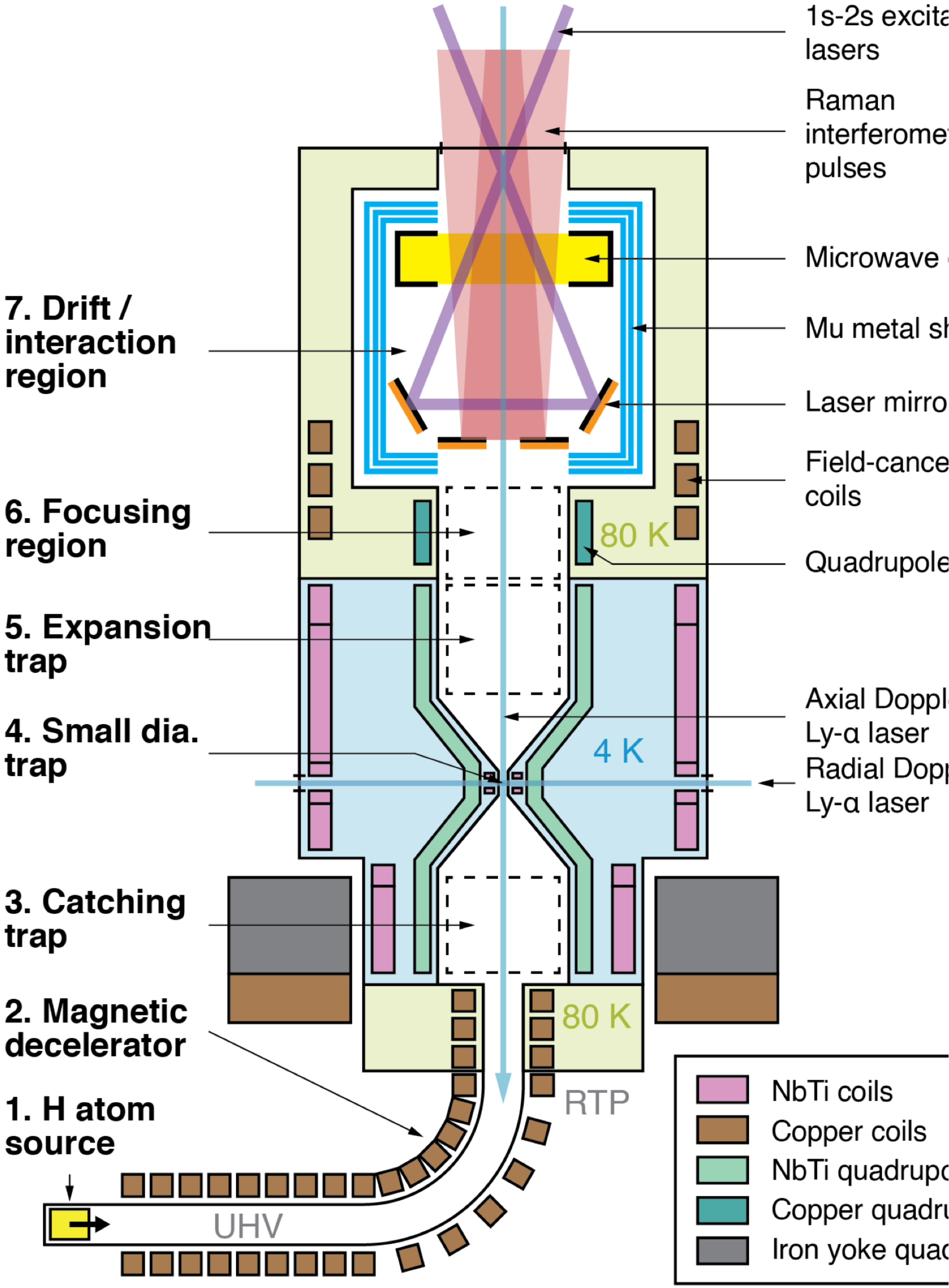
New Concept!

- Start with small, high density quadrupole trap (few mm radius)
  - Dynamically transferred from Octupole; now feasible due to laser cooling
- Laser cool in 3D → high phase space density (~100 um radius, 500 um length)
  - Allow densities 10^7 – 10^8 cm^{-3} (currently ~ 1 cm^{-3} in ALPHA)
- Expand to cool adiabatically

  → Can create a Hbar gas in micro-Kelvin regime!
- Launch into free space as fountain

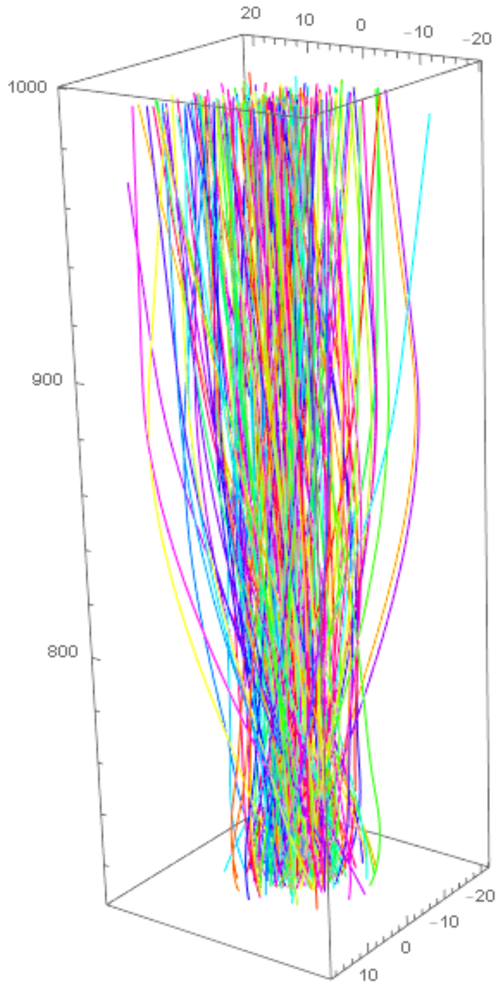
Concept

- Tight focusing quadrupole trap, laser cooling → expansion
  - Allows much better laser manipulations
    - Atomic fountain, interferometry, optical trapping
  - Higher densities ($10^7 - 10^8$ more dense than ALPHA 2)
    - Development towards antimatter molecules, BEC
  - Adiabatic cooling to micro K (currently 0.5 K)
  - Currently still in conceptual development stage
- Propose to build the trap at TRIUMF [~30 FTE-Yr]
  - Scale comparable to ALPHA-2 trap
  - Will hire a cryo/mechanical engineer + several tech's

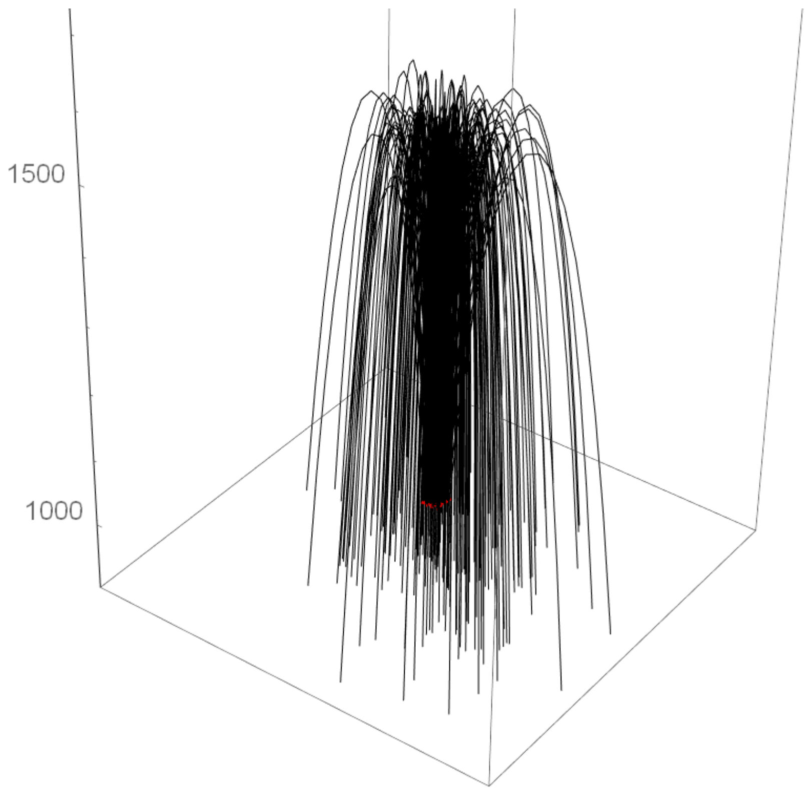


Fountain simulation example:

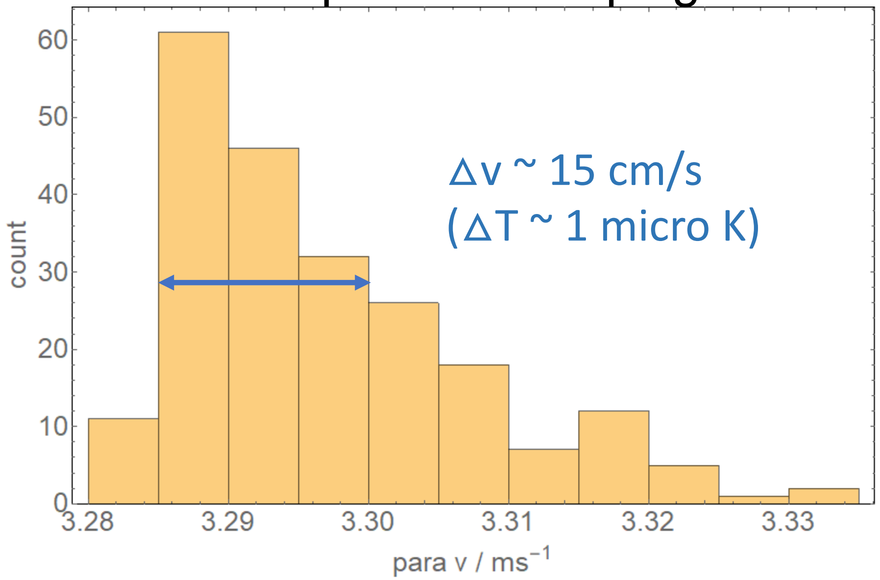
Magnetic focusing



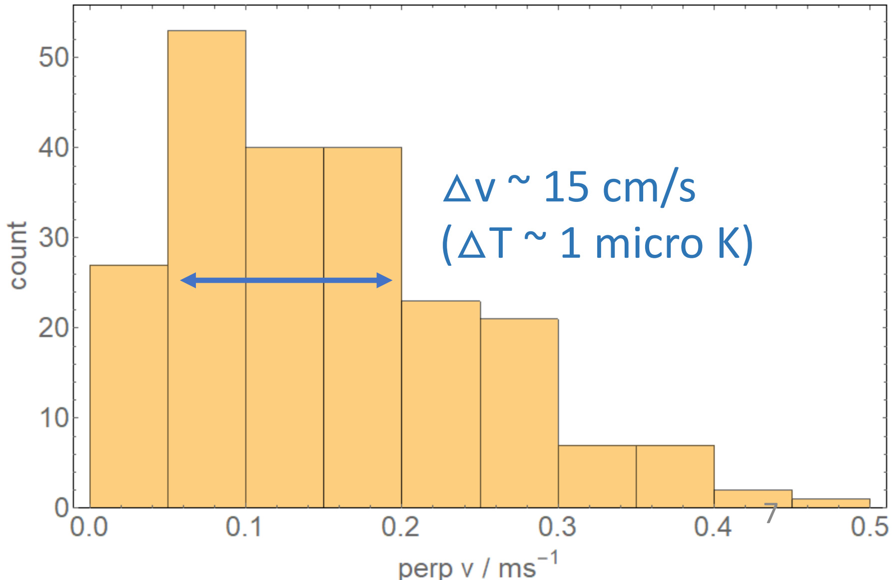
Tracks in the fountain



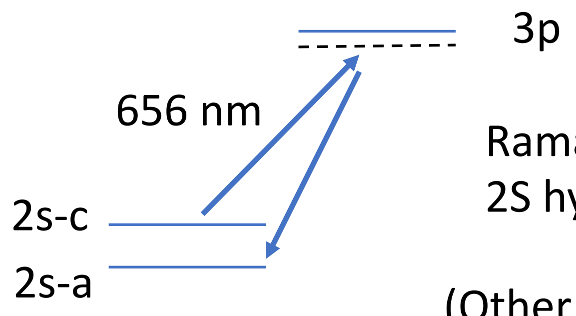
Vertical speed of escaping atoms



Horizontal speed of escaping atoms



Physics 1: Gravity via atom interferometry (AI):



Raman scattering between 2S hyperfine states

(Other 2S-nP transition possible)

- ALPHA-g precision goal: 10^{-2}
  - Likely need AI for better precision
- Pioneering AI proposal by Joel, Holger et al. (PRL 2014)
  - Also considered LyA schemes
  - Laser is difficult in both cases
- We propose 2S state Raman interferometer (Haench, AGE): ← Francis
- Advantages:
  - Laser (2S-3P) 656 nm more readily available
  - "State labeling" → can use hotter atoms
  - Fountain is much colder, focused

- Challenges (see later)
  - Creation of 2S state
  - Detection of 2S-c vs 2S-a states
- Holger: Statistical precision:

  $\sim 10^{-4}$ /sqrt(#atoms)

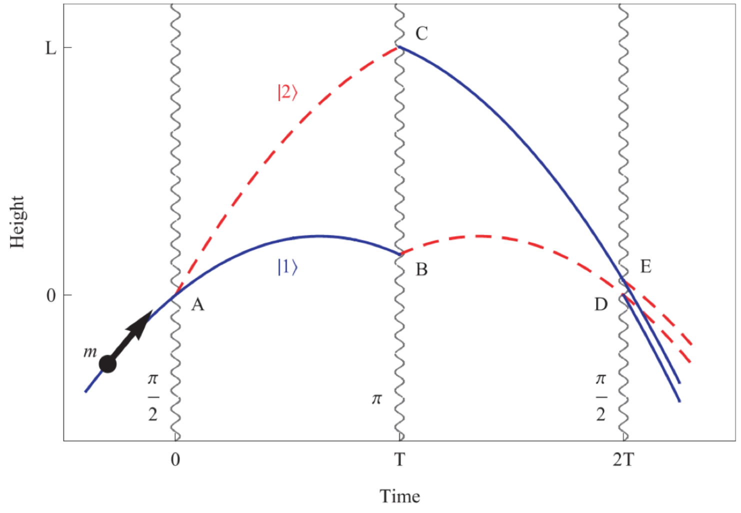
  e.g. 10^{-6} for 10,000 atoms
  - Systematics with B field a key
    - 10^{-4} to 10^{-5} seems plausible?

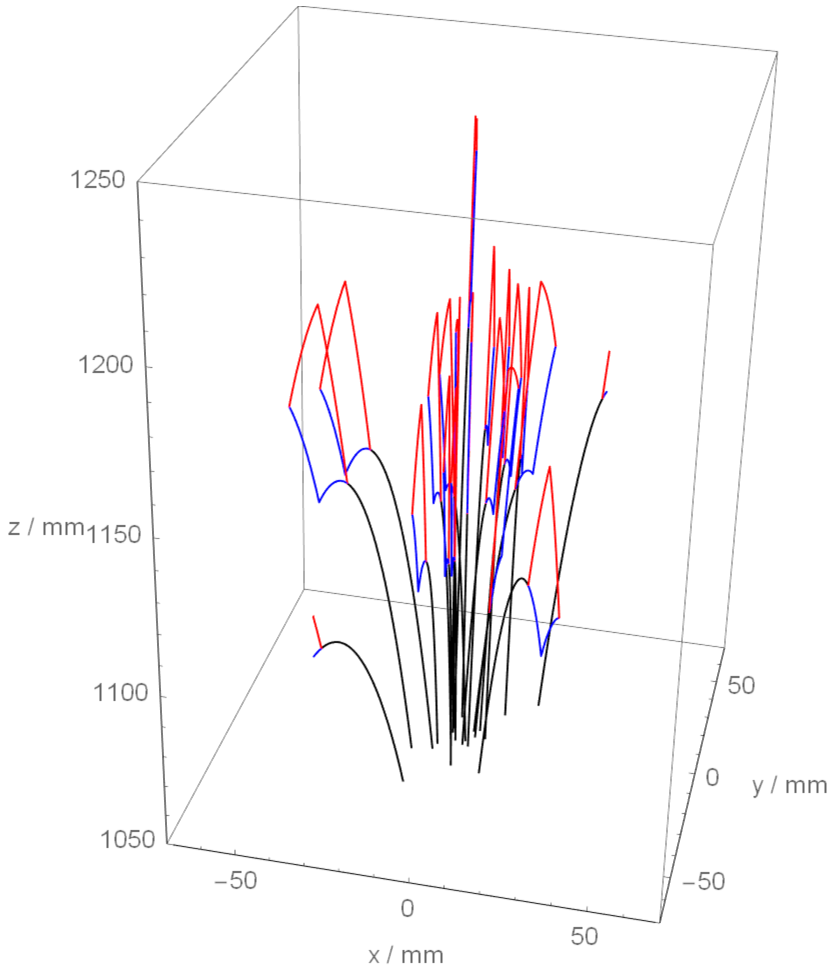
Atom Interferometer simulation

$$\Delta\phi_{\text{las}} = \Big(\phi_L(\mathbf{r}_A, 0) - \phi_L(\mathbf{r}_C, T)\Big) - \Big(\phi_L(\mathbf{r}_B, T) - \phi_L(\mathbf{r}_D, 2T)\Big)$$

$$= k_{\text{eff}} \cdot (r_D - r_C - r_B + r_A) - \omega_{\text{eff}}(2T - T - T + 0)$$

$$= k_{\text{eff}} g T^2$$





Physics 2: Hyperfine splitting via Ramsey Resonance: (synergy with UCN)

UME 63, NUMBER 6 PHYSICAL REVIEW LETTERS 7 AUGUST 1989

rf Spectroscopy in an Atomic Fountain

Mark A. Kasevich, Erling Riis, and Steven Chu
Department of Physics, Stanford University, Stanford, California 94305

Ralph G. DeVoe
IBM Almaden Research Center, San Jose, California 95120
(Received 15 May 1989)

Laser-cooled sodium atoms pushed up on a vertical trajectory by radiation pressure are observed to turn around due to gravity. The relatively long time the atoms spent freely falling in this "atomic fountain" allowed the ground-state hyperfine splitting to be measured with a linewidth of 2 Hz. After a 1000-sec integration time, the center of the line was resolved to ±10 mHz. The absolute splitting was measured to be 1 771 626 129(2) Hz.

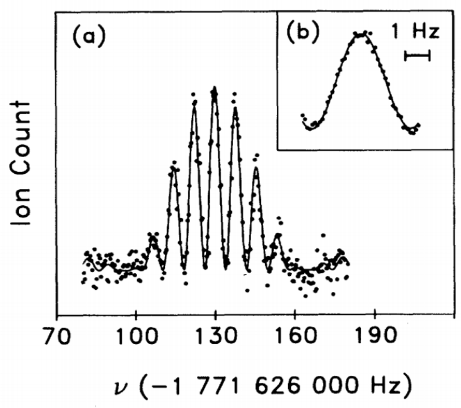


FIG. 3. (a) The observed Ramsey line shape for two 32-msec $\pi/2$ pulses separated by 125 msec. (b) The central fringe obtained with two 3.2-msec $\pi/2$ pulses separated by 255 msec.

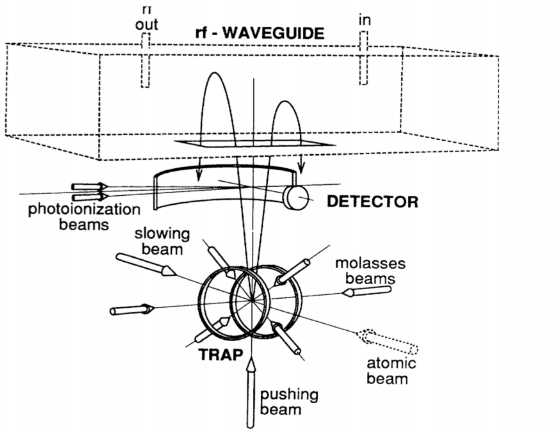


FIG. 1. Perspective view of the experimental setup for the atomic fountain. The atoms, initially confined to a small volume in the trap region, follow a ballistic trajectory through the waveguide and back to the detection region. A curved metal shield electrostatically focuses the photoionized atoms onto the detector. The waveguide is impedance matched to 50 Ω in

For anti-H fountain of 1 m
(between ground state c→a)
Linewidth ~ 0.5 Hz ($4x10^{-10}$)
For 10^4 atoms: stat error ~5 mHz
($4x10^{-12}$)

Systematic being evaluated:

B field ~ $2x10^{-10}$?
Doppler ~ $5x10^{-10}$?
Cavity phase error ?

(In Chu exp, Doppler/phase error ~$1.4x10^{-10}$ for v_radial ~4 cm/sec Na; our atoms would be a few times hotter)

2S hyperfine measurement should be possible too (either via RF or optical Raman)

Physics 3 (future develp't): Molecular ions: Hbar$_2^-$ (2 pbars & 1 e+)

- Interesting for CPT tests
  - Myers, PRA 98, 010101 (R): propose Hbar$^+$ + Pbar collisions in GBAR
- H_2^- ion "clock" at 10^{-17} precision? [PRL113, 023004]
  - Natural linewidth much narrower than 1s-2s (10^{-15})
  - Potential for higher precision CPT test than anti-H atom

  (HbarDbar- ion would be even better (due to dipole moment), if anti-deuteron available!)
- Associative ionization in optical trap?
  - H(2S) + H(2S) → H_2^+ + e^-: Theory PRA 85, 042710 (2012)
    - Xsection ~ 3 x 10^{-11} cm^2 if extrapolated to 10 mK?
  - More realistic value, 5x10^{-13} cm^2? [Svante]
  - 1000 Hbar(2S) at 10 mK in our small trap→ Density ~ 3x10^7/cm^3
  - ~2 molecular ions formed per trial? Recall; need just 1 ion (in a Paul trap) for a clock!
- Challenges:
  - Excite and trap 1000 Hbars(2S) *simultaneously* (see below)
  - Detection: catch in Penning trap, and release?
- Other reactions? E.g. laser induced association (Taka)

PRA 85, 042710 (2012)

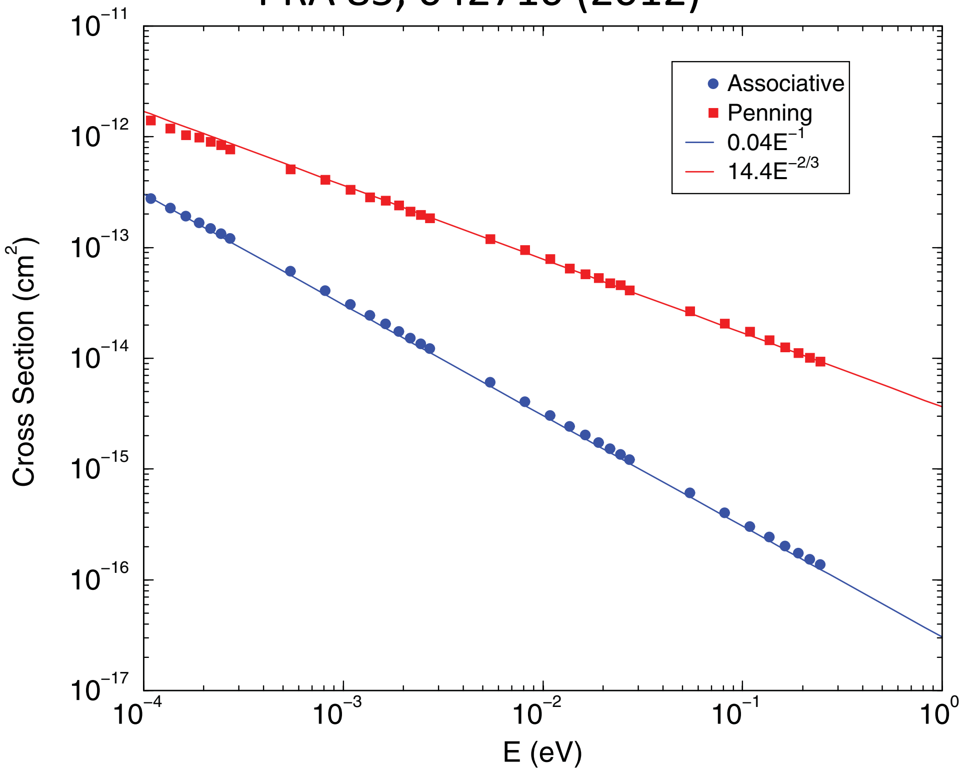
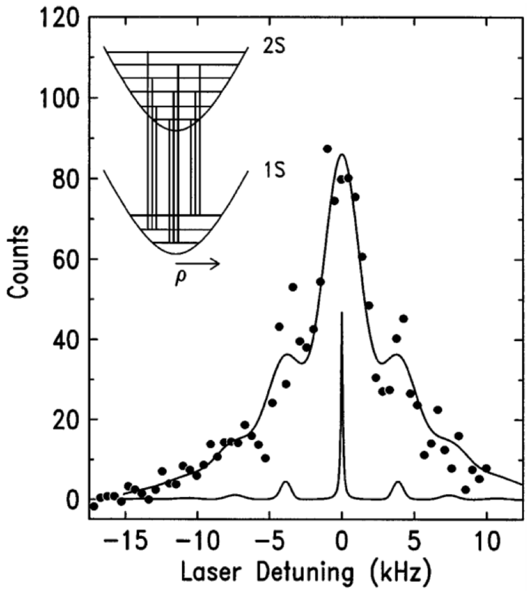


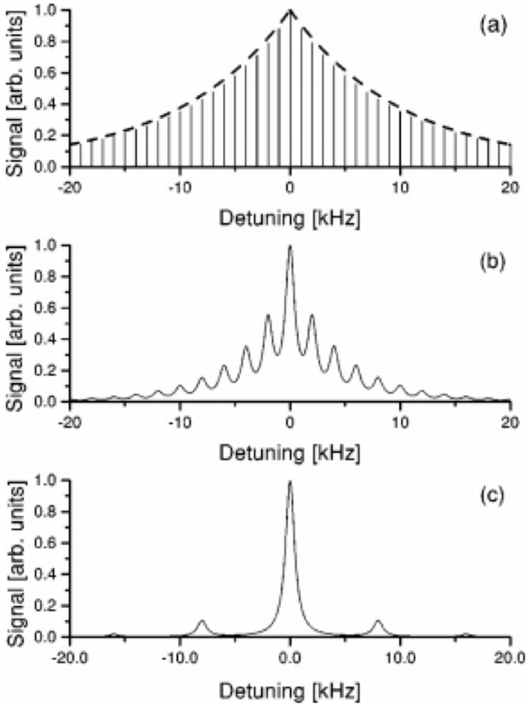
FIG. 5. (Color online) Associative and Penning ionization cross sections for H(2s) + H(2s) approaching on the $^3\Sigma_u^+$ state. Also included is a curve fit ($0.04E^{-1}$) to the associative ionization cross section and a curve fit ($14.4E^{-2/3}$) to the Penning ionization cross section. These calculations include all contributions for $v_{max} = 100$ and $j_{max} = 100$.

Physics 4: 1S-2S spectrspy with uK anti-H

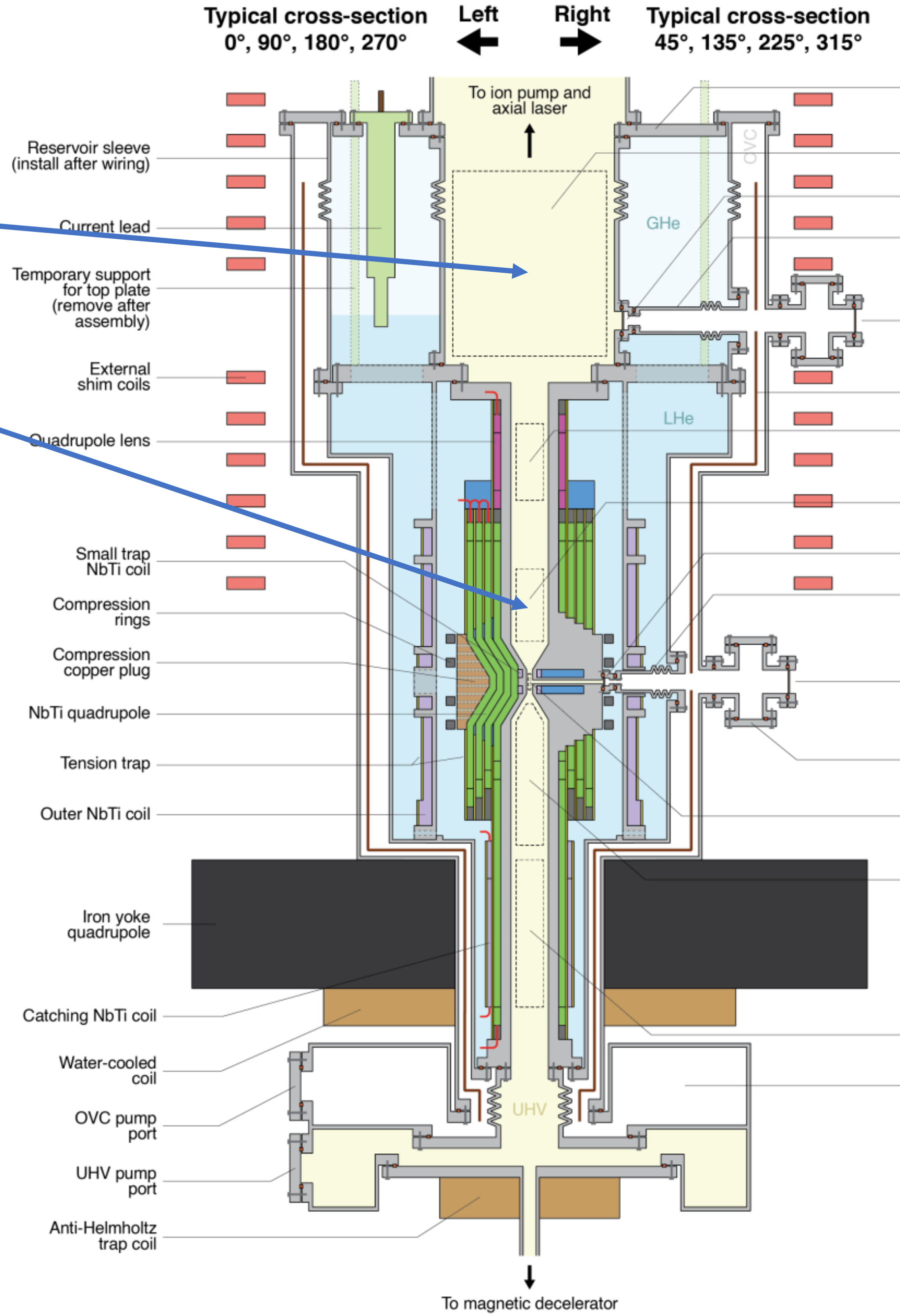
- Some options:
  - Fountain volume: ~ 1 uK, near zero field (low density; likely need recycling of atoms)
  - Expansion volume: ~10 uK, harmonic trap (similar volume as ALPHA-2 trap)
- 1 uK Hbar, laser waist 0.5 mm → TOF broadening ~ 20 Hz! (cf. current H error: 10 Hz)
- “Lamb-Dicke” or “Ramsey” spectroscopy in harmonic trap?



Cesar PRL 77, 255 (1996)



Cesar PRA 59, 4564 (1999)



Many other possibilities

- Optical, microwave trapping
  - These were original motivations
- Optical trapping in 2S state?
  - AC polarizability much bigger than 1S state
  - Convenient loading scheme via 1S-2S excitation
  - “magic wavelengths” e.g. for 2S-3S transition near 1371 nm
  - Looked all great until a factor 10^3 mistake discovered in polarizability!
- Microwave trap (Taka)
  - Trapping volume large, no need for B field
- 1S-2S spectroscopy in optical trap [Crivelli]
  - Likely will not work as proposed due to the missed effect of 2S-2P mixing
- Currently, these ideas are not as promising as the fountain for different reasons, but could be revisited in the future

- Charge neutrality in fountain [PRL 100, 120407]

  Precision of 10^{-20}???

  (need a ground state AI)

Tremendous opportunities!

Project

1. Atomic hydrogen source, decelerator [UBC]
2. Superconducting magnets [Calgary/BNL]
3. **Cryogenic hydrogen trap [Calgary/TRIUMF]**
4. Microwave systems [SFU]
5. Laser systems [UBC]
6. **Detector/Data acquisition [York/TRIUMF]**
7. **Upgrade to UCN/CMMS liquid Helium facility [TRIUMF]**

UCN Lq. He facility expansion (Alexey Koveshnikov): Required to run superconducting trap

- 2nd compressor
  - Current He capability: ~55 L/hr
  - By adding a 2nd compressor, will increase by ~15 L/hr to 70 L/hr
- Cost (USD)
  - RSX compressor: $250K
  (Refurbished one maybe ½ the price)
  - Various materials: $20K
- Resources
  - Cryo engineer: 3 months-FTE
  - Tech: 5-6 months-FTE
  - Design office: ~1 week*
  - Elec. Service: ~2 week*
  - Plant group (water cooling package; He piping): ~ 4 weeks*
- Transfer line to the experiment
  - 300K USD hardware
  - 3 month cryo engineer
  - 3 month tech
- This is essential to reduce operational cost

→Should be discussed in context of overall He upgrade at TRIUMF

*Missed from the list Proj. Init. Sheet

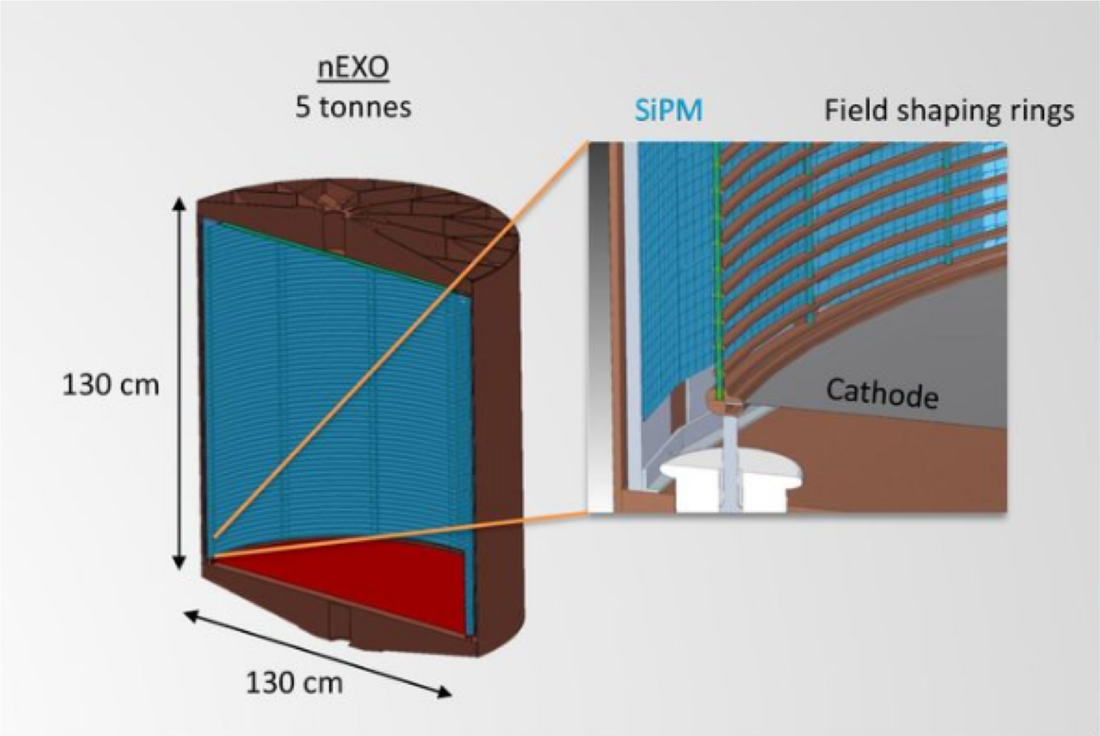
Detection/Data acquisition

- Minor support requested for:
  - Photon detection with SiPMs (in line with Fabrice's group interest; see next)
  - Environmental monitoring via MIDAS
    - We will probably use a commercial system for experimental control to be compatible with ALPHA
  - Some electronics development for magnetometry readout etc.

Development at TRIUMF Detector group (mostly for Dark Matter, Neutrino)

- SiPM at low temperatures (Stefan)
  - Our cryostat at TRIUMF currently goes down only to 80K
- MCP, Si detector at low temp.
- Wave-length shifter + SiPM for Ly-beta? (102 nm)
- “3D digital SiPM”? Processing chip and SiP on board
- Preamp at 4K? Heating? UHV?

- SiPM walls?
  - nEXO experiment: ~4 m^2 SiPM coverage ($5-10M)



Why TRIUMF?

- ALPHA one of the high priorities of PP dept
  - TRIUMF supports R&D for off site expts, e.g. HK, SuperCDMS, nEXO
- Existing infrastructures at TRIUMF as a National Lab
  - Scale of the project is beyond what can be easily handled by one university
  - Access to a liquid helium facility
  - Cryogenic, vacuum, photon detection expertise
- Synergies with other programs
  - Interest in expanding cryo/atom expertise in Sci/Tech Dept
  - UCN, ISAC fundamental symmetries, FrEDM fountain?
  - Photon detection
  - Can bring in new prospective
  - New fundamental physics initiatives
- We realize space is limited
  - Currently looking at old compression room outside Meson hall
    - Possibly share with other projects like nEXO
- Could produce high profile results on-site
  - Atomic hydrogen fountain/interferometry demonstration will be very significant!!!

Relationship to Broader Community

- General interest in quantum technologies
- Canadian Subatomic Long Range Plan recommendations
- TRIUMF Five Year Plan PPAC (including quantum sensing and fountain initiative): “high priority”
- Awards, recognitions for students and faculty
- Strong support from universities
- Will be working with TRIUMF Innovations for commercialization opportunities

Funding

- Univ’s cap secured for $4.6M (a total project, $11.6M)
  - No TRIUMF commitments assumed so far
  - Requesting provincial matching
  - 20% from vendor discount, possibly international partners
  - Some TRIUMF in-kind support would be highly appreciated!
- Timeline
  - Driven by our desire to develop a new expt at CERN after LS3 (2025/26)
  - Design & construction will be staged
    - Start immediately with well-defined sub-systems (H beam, lasers etc)
    - Work on finalizing trap design in the meantime