ALPHA Antihydrogen Symmetry Tests

CINP Town Hall Meeting, CAP Edmonton
June 13, 2015

Makoto C. Fujiwara
TRIUMF

For ALPHA-Canada
Many thanks to Garth, CINP, LRP committee

In Canadian SAP context, we are a part of Fundamental Symmetries program within CINP (Chair: Gerald Gwinner)
- EDMs, TRINAT, Fr, TITAN, Canadian Penning Trap
- Off-shore nuclear experiments: Qweak, Moller, Trek
- Share physics goals & experimental techniques

ALPHA also has interdisciplinary components
- AMO, Plasma, Low Temperature, High Energy (IPP)
- This is a strength, not weakness!

Makoto Fujiwara, ALPHA
What is Fundamental Symmetries?

- My working definition:
  Fun. Sym. \approx Fundamental Physics with low energy tools
- Address questions in Precision & Symmetry Frontiers
- Exploit ingenious techniques
  - Radioactive ions&atoms, UCN, laser, traps, antimatter
  - Many projects require continuous R&D
    - Cannot easily predict physics reach e.g. from (Luminosity) x (Cross section)
  - Excellent for HQP training

Very strong area in Canadian SAP

- Showcased, e.g. by SSP 2015, FunSym 2010
• **Motivations: “Big Picture”**

• **Recent achievements with ALPHA**
  – Trapping, microwaves, charge neutrality

• **Plan**
  – ALPHA-2, ALPHA-g

• **For details: ALPHA invited talks at this CAP**
  – Thompson: Atomic physics [Tue, afternoon]
  – Fujiwara: Fundamental symmetries [Wed, afternoon]
• Atomic hydrogen: 75% of known universe; Simplest atom; one of best studied systems
  – 1s-2s level: 2 466 061 413 187 035 (10) Hz \( \Delta \nu/\nu \sim 10^{-15} \)
  – Hyperfine splitting: 1 420 405 751.768 (1) Hz \( \sim 10^{-13} \)

• Antihydrogen: stably confined by ALPHA (2010)
  \( \rightarrow \) Comparison of H and anti-H: “Textbook” experiment

• Many experimental challenges in production, trapping, spectroscopy, detection of anti-H \( \rightarrow \) continuous R&D

• Subatomic physics technique: a key in all of ALPHA physics; advantage in competitive field
What is Fundamental (Particle) Physics? (Grossman)

“Simple answer”: The SM, including Higgs, works extremely well!

Many open (recently exacerbated) issues, in particular:
- Naturalness of Higgs mass & Cosmological constant
- Require fine-tuning by $O(30), O(120)$? Multiverse?
- Hopefully, LHC & precision expt’s will solve them soon!

But, “$L=?$” really the right question to ask?
Is (effective) Quantum Field Theory correct description of Nature?
Where do you look when asking Big Questions?
Where do you look when asking Big Questions?

Makoto Fujiwara, ALPHA
CPT and Gravity tests with Antihydrogen

• Test of CPT
  – CPT: a fundamental property of local, relativistic QFT
  – CPT theorem demands H & Anti-H spectra be identical
  – Violation of CPT would force fundamental change in theory, incl. validity of QFT

• Test of Gravity (not in SM) in regimes previously untested

• Anti-H probes fundamental framework of physics (QFT+GR), rather than specific models within it
  – Probability for finding violation is low!
  – Expt’s are hard and competitive!

• High risk business!
ALPHA and ALPHA-Canada

ALPHA
- Since 2005
- 16 institutions
- ~40 physicists
ALPHA and ALPHA-Canada

U Calgary recently joined TRIUMF Consortium (leading ALPHA-g CFI)

ALPHA
• Since 2005
• 16 institutions
• ~40 physicists

ALPHA-Canada
• >1/3 of ALPHA: largest group in ALPHA (largest Can. fraction offshore?)
• 10 Faculty/Scientists/Staff (8 grant eligible; 5.2 FTE)
• Excellent HQP training
• Leadership in particle detection, uWave spectr., laser cooling

Makoto Fujiwara, ALPHA
Producing & Trapping Antihydrogen

\[10^{-12}\]  

**AD**  
- p- Production (GeV)  
- Deceleration (MeV)  
- Trapping (keV)  
- Cooling (~ meV)

\[10^4 \text{ p}^-\]  
\[10^8 \text{ e}^+\]

\[10^{-9}\]  

**Na-22**  
- e+ Production (MeV)  
- Moderation  
- Accumulation (eV)  
- Cooling (~ meV)
Producing & Trapping Antihydrogen

$10^{-12}$

**AD**
- p- Production (GeV)
- Deceleration (MeV)
- Trapping (keV)
- Cooling (~ meV)

Superimpose Magnetic Trap

$U = -\mu \cdot \vec{B}$

Challenge: Antihydrogen $kT >> \mu \Delta B$ (trap depth)

$10^{-9}$

**Na-22**
- $e^+$ Production (MeV)
- Moderation
- Accumulation (eV)
- Cooling (~ meV)
• ALPHA optimized for particle detection
  – Distinctive feature among AD expt’s
  – Position sensitive annihilation detection with 37,000 channel Si strips
• Software & analysis
  – DAQ & all software incl. tracking, MC
  – Introduced blind analysis
  – Random Forest technique (variation of decision tree)
• Exotic atom physics
  – Canadian expertise: muonic, pionic, kaonic, antiprotonic atoms
  – Doing experiment with few atoms
• All this helps make us competitive! (so far)
Highlights of Recent ALPHA Results (briefly!)
Detected annihilations of 38 anti-H released from the trap

- Position sensitive detection to discriminate against:
  - Cosmic background
  - Bare antiprotons

"#1 Breakthrough in 2010" PhysicsWorld

2010: Antihydrogen Trapped (for 172 ms)

Letter to Nature, Nov. 17, 2010
2011: Confinement of Antihydrogen for 1000 s

- Increased trapping rates by x5 (hard to tweak zero)
  - Improved reconstruction (Calgary Ph.D.)
- Trapping time increased by x5000
- “Game changer”
  - Opens up many possibilities
- Detailed studies of dynamics

Cover, Nature Physics, July 2011 Issue
Principle author: Fujiwara

Makoto Fujiwara, ALPHA
2012: First Spectroscopy on Antihydrogen Atoms

Canadian-Led Initiative:
Mike Hayden (SFU), Walter Hardy (UBC)
Art Olin, MCF (TRIUMF) et al.
M. Ashkezari (SFU), T. Friesen (Calgary)
S. Stracka (TRIUMF)
2012: Microwave-induced Hyperfine Transition

- Developed at SFU/UBC
- Trap ~1 Anti-H/20 min
- Irradiate with $\mu$W
  - Drive transition: trapped $\rightarrow$ un-trapped
  - Look for annihilations
- Multivariate (blind) analysis
  - improved S/N by x10

Installation at CERN, July 2011

![Graph showing events over time with standard and multivariate analyses with improved S/N by x10]
Finally!

Principal author: Michael Hayden (SFU)

First spectroscopic measurements on anti-H!

- Precision limited: $O(10^{-3})$
- Demonstration of spectroscopy on a single anti-atom at a time
- “Historic!” – Nature Editor
- Annihilation detection: key
- Major Canadian-led success

Makoto Fujiwara, ALPHA
Latest Result: June 3, 2014
Charge Neutrality of Antihydrogen

Makoto Fujiwara, ALPHA
Latest result: Is Antimatter Neutral?
Nature Comm. 5, 3955 (2014)

• Why matter is neutral?
  – Anomaly cancellation, GUT?
  – Experimentally, proton + electron = neutral to $10^{-21}$
• CPT test: Is antiproton + positron neutral?
  – “Hidden” Canadian proposal!
• Result (Berkeley, York Ph.D.):
  – Anti-H neutral to $1.3 \times 10^{-8}$
• New limit on e+ charge
  – ALPHA’s first precision result!
  – X10 better from 2014 run?
  – Sensitivity to e+ mass?
“we congratulate NSERC for bravely recognizing the best and most basic research, and we applaud our prizewinners for adding an important milestone to the history of science.”

--- Message from Dr. John Polanyi to the ALPHA-Canada team

Also, 2011 APS John Dawson Award for Anti-H Trapping
Plan (1)

Precision Spectroscopy with ALPHA-2
• Constructed w/ major Canadian contributions: RTI+TRIUMF&Calgary
• Commissioning successful Dec 2014: > x2 anti-H trapping rates
• New Canadian initiative: Lyman-alpha spectroscopy and cooling
• First physics run in July 2015; will run for several years
Plan (2)

Antimatter Gravity studies with ALPHA-g
ALPHA-\(g\): Antimatter Gravity Experiment

- Does antimatter fall down with \(g\)?
  - Experimental question!
  - (e.g. Lykken et al, arXiv:0808.3929)
  - Already 2 dedicated exp’ts at AD
  - We can do it better in a trap?
- Originally Canadian initiative now adopted by entire ALPHA
  - Laser cooling essential: UBC/Calgary
  - CPT test via uWaves: SFU/UBC
  - TPC tracker, cosmic veto: TRIUMF/York
- \$6.9M approved (CFI + Ontario)
  - Waiting for other matching funds
  - Total Cdn contributions: >\$12M cash
Laser cooling
[Donnan, MCF, Robicheaux, J. Phys. B. 46, 205302 (2013)]
- Cooling on 1 dimension
- Use coupling of degrees of freedom for 3-D cooling
- Cooling from 500 mK to 20 mK

Anti-H energy
Time evolution
(0-200 s)

Anti-atomic fountain & Anti-atom interferometer
ALPHA-g Staged Approach

Stage 1: Sign of $g$
- Should be “immediate” once ALPHA-g is commissioned

Stage 2: $\sim 1\%$ meas. of $g$
- Laser cooled anti-H
- Also uWave CPT

Stage 3: Anti-atom fountain & Interferometer

Preliminary simulations

$g(\text{anti-H/H})=0.99$

$g(\text{anti-H/H})=1.01$
Rare Isotope Physics!

\[ ^1H \rightarrow ^{-1}H \]
Recall proton radius puzzle: 7 sigma effect

Atomic H 1s-2s (Laser)
  - $r_p$ shift at $\sim$1 MHz

Hyperfine splitting (uWaves)
  - Proton structure shift (Zemach) at 60 kHz

ALPHA initial goals
  - 1s-2s: 100 kHz
  - HFS: 1 kHz

→ Already sensitive to antiproton internal structure
ALPHA Resources
Faculty FTE commitment as of 2015

<table>
<thead>
<tr>
<th>Name</th>
<th>Institution</th>
<th>FTE</th>
<th>Main contributions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Makoto Fujiwara</td>
<td>TRIUMF</td>
<td>100%</td>
<td>Detectors, Analysis, Traps</td>
</tr>
<tr>
<td>David Gill</td>
<td>TRIUMF</td>
<td>50%</td>
<td>Detectors, Analysis</td>
</tr>
<tr>
<td>Walter Hardy</td>
<td>UBC</td>
<td>70%</td>
<td>Microwaves, Cryogenics</td>
</tr>
<tr>
<td>Michael Hayden</td>
<td>SFU</td>
<td>30%</td>
<td>Microwaves, Cryogenics</td>
</tr>
<tr>
<td>Scott Menary</td>
<td>York</td>
<td>80%</td>
<td>Detectors, Analysis</td>
</tr>
<tr>
<td>Takamasa Momose</td>
<td>UBC</td>
<td>30%</td>
<td>Lasers, Cooling</td>
</tr>
<tr>
<td>Art Olin</td>
<td>TRIUMF/UVic</td>
<td>85%</td>
<td>Detectors, Software, Cryo</td>
</tr>
<tr>
<td>Robert Thompson</td>
<td>Calgary</td>
<td>75%</td>
<td>Lasers, Traps</td>
</tr>
<tr>
<td><strong>Total Grant-Eligible FTE</strong></td>
<td><strong>5.2</strong></td>
<td></td>
<td>(Not including expected hires)</td>
</tr>
</tbody>
</table>

- **Anticipated new hires**
  - CRC-2 Chair, U. Calgary
  - Replacement for Art Olin, Andy Miller, TRIUMF
Doing research in Geneva/CERN is expensive! Common fund!
Development & operation of 2 complex devices
$200K/FTE comparable with other successful SAP projects

<table>
<thead>
<tr>
<th>Funding source/grants</th>
<th>Amount</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CFI-related</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CFI Innovation Fund 2015</td>
<td>$6.13M</td>
<td>Announced</td>
</tr>
<tr>
<td>AB, BC, ON provincial matching</td>
<td>$6.13M</td>
<td>In review</td>
</tr>
<tr>
<td>CFI Infrastructure Operating Fund</td>
<td>$368K/yr</td>
<td>Only after infrastructure completion</td>
</tr>
<tr>
<td><strong>NSERC</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operating grant</td>
<td>$1.4M/yr</td>
<td>Optimum</td>
</tr>
<tr>
<td>Operating grant</td>
<td>$800K/yr</td>
<td>Minimum</td>
</tr>
<tr>
<td>Capital</td>
<td>$150K/yr</td>
<td>Minor upgrades at level of RTI1</td>
</tr>
</tbody>
</table>
HQP records
• 4 Ph.D. completed
• 2 Ph.D. final stage
• 2 Ph.D. new
• 3 M.Sc. completed
• 3 M.Sc. current
• 2 PDF completed
• 2 PDF current
• ~5 undergrad
(Total ~23)

Request
• 5 PDF
• 10 grad student
(one per faculty)
• 5 man-term/yr undergrad
• Operation of 2 facilities: ALPHA-2 & ALPHA-g
• Labor intensive: we run 6-7 months a year at AD,
• Fundamental Symmetries: vibrant subfield of Canadian SAP

• ALPHA has made significant progress since its inception in 2005, and in 2011-16 period
  – Strong Canadian leadership in SAP and spectroscopy
  – Expect more breakthroughs before 2016!

• We have ambitious, exciting program for next decade, with ALPHA-2 and ALPHA-g

• CERN is committed to antiproton physics
  – ELENA ring + AD upgrade: >50M CHF

• Great public interest; please make use of it!
Our hard-working HQPs recognized

CERN Homepage
“Andrea Gutierrez, Ph.D. student from UBC”

Hydomako Thesis (Calgary) published as book: Springer “Best of Best” Thesis Series (20 downloads, since Jan.)
Thank you!

Merci!
Backup Slides
My key message

- The days of “guaranteed” discoveries or of no-lose theorems in particle physics are over, at least for the time being ....
- .... but the big questions of our field remain wild open (hierarchy problem, flavour, neutrinos, DM, BAU, .... )
- This simply implies that, more than for the past 30 years, future HEP’s progress is to be driven by experimental exploration, possibly renouncing/reviewing deeply rooted theoretical bias
- An approach that few years back would have raised eyebrows, but that today is legitimate and well motivated
CPT test benchmark

Neutral Kaon limit

Planck Suppression $\sim m_p^2/M_{\text{Planck}}$

$\Delta f \sim 10-100 \text{ kHz}$

Proton radius puzzle

Makoto Fujiwara
http://www.cern.ch

(June 2011)
ALPHA experiment traps antimatter atoms for 1000 seconds

Andrea Gutierrez, a PhD student from UBC, transfers liquid helium from a storage dewar into the cryostat containing the superconducting magnetic trap used by the ALPHA experiment.

In a paper published by *Nature Physics*, the ALPHA experiment at CERN reports that it has succeeded in trapping antimatter atoms for over 16 minutes: long enough to begin to study their properties in detail. ALPHA
CERN Bulletin

November, 2012

ALPHA-2: the sequel

While many experiments are methodically planning for intense works over the long shutdown, there is one experiment that is already working at full steam: ALPHA-2. Its final components arrived last month and will completely replace the previous ALPHA set-up. Unlike its predecessor, this next generation experiment has been specifically designed to measure the properties of antimatter.

The ALPHA collaboration is working at full speed to complete the ALPHA-2 set-up for mid-November – this will give them a few weeks of running before the AD shutdown on 17 December. “We really want to get some experience with this device this year so that, if we need to make any changes, we will have time during the long shutdown in which to make them,” says Jeffrey Hangst, ALPHA spokesperson. “Rather than starting the 2014 run in the commissioning stage, we will be up and running from the get-go.”

The first piece to arrive was the ALPHA-2 cryostat from the TRIUMF laboratory in Canada. This cryostat will hold 16 LHC current leads to power the eight superconducting magnets in the new ALPHA-2 atom trap.

The leads will allow the ALPHA-2 set-up to use less liquid helium. “These leads were provided by CERN, and use special technology developed specifically for the LHC,” explains Jeffrey. “As a small collaboration, we could never have afforded this technology on our own.”

Meanwhile, the final piece of the ALPHA-2 puzzle – the superconducting solenoid – is on its way. The leads will arrive in the next few weeks.

Our top priority

After three years of LHC running, we are still at the beginning of a long research programme with our flagship facility, and hopefully 4 July 2012 will go down in history as the date of one of many landmark discoveries spanning several years. CERN’s top priority for the next decade and more is the full exploitation of the LHC. With speculation about potential future facilities mounting in the light of the discovery of a new Higgs-like particle, it’s important to state that most clearly. Of course, this will rely on continued global collaboration, and it’s important that CERN engage constructively with other regions.

The first piece to arrive was the ALPHA-2 cryostat from the TRIUMF laboratory in Canada. This cryostat will hold 16 LHC current leads to power the eight superconducting magnets in the new ALPHA-2 atom trap.

Canadian contribution recognized!
Antimatter and Standard Model Extension (SME)

- **SME: Effective Field Theory** by Kostelecky et al.
  - Pospelov, Myers, Moore etc.
- **“Anti-CPT theorem”** Greenberg 2002
  - In local field theories, CPT violation does not happen without Lorentz violation

<table>
<thead>
<tr>
<th>Lorentz even</th>
<th>Lorentz odd</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CPT even</strong></td>
<td>SM</td>
</tr>
<tr>
<td></td>
<td>Most of BSM</td>
</tr>
<tr>
<td><strong>CPT odd</strong></td>
<td>Beyond EFT</td>
</tr>
<tr>
<td></td>
<td><strong>EFT</strong></td>
</tr>
<tr>
<td></td>
<td>(e.g. SME)</td>
</tr>
</tbody>
</table>

Well tested in Matter expt’s

Beyond EFT

Matter-Antimatter Comparisons

Lehnert@CPT’13 meeting

Makoto Fujiwara, ALPHA
Possible CPTV shift (Pospelov)

\[ \Delta E \sim \frac{m^{n+1}}{\Lambda^n_{CPTV}} \]

Small absolute energy \( \Delta E \) → probes high energy scale

For \( n=1, m=1 \text{ GeV}, \)
\( \Lambda_{CPTV} = M_{Pl} \sim 10^{19} \text{ GeV} \)

\( \Delta E_{CPT} \sim 10^{-19} \text{ GeV} \)
(\( \sim 10 \text{ kHz in frequency} \))

Neutral Kaon test at few 100 kHz

Antihydrogen studies potentially sensitive to Planck scale physics!
Compatibility of Penning and Neutral traps

Antiproton plasma manipulation

Pulsed source of antihydrogen (ATHENA)

Evaporative cooling of antiprotons

Annihilation-based plasma diagnosis

Anti-H production at 1 T field

Title and Authors

**The Coolest Antiprotons**

A new record low temperature for a cloud of antiprotons was measured at CERN in Geneva, announces a report in the 2 July Physical Review Letters. Researchers cooled a cloud of about 4,000 antiprotons down to 9 kelvin using a standard approach for cooling atoms that has never been used with charged particles or ions. The technique could provide a new way to create and trap antihydrogen, which could help researchers probe a basic symmetry of nature.

Antihydrogen, the antimatter counterpart of hydrogen, is composed of one antiproton and one positron (anti-electron). According to the CPT (charge parity-time) theorem, a fundamental pillar of the standard model of particle physics, hydrogen and antihydrogen should share many basic traits like mass.

Anti-H production in atom trap
Trapped anti-H: Event Selection Criteria

Distributions of calibration samples

Main cut variables
1. Number of tracks
2. Vertex radius
3. Linear fit residuals

Cuts optimized for expected significance (p-value)

Cosmic rejection: 99.5%
Signal acceptance: 65%

All this studied without looking at the data
• Radial & axial deg. freedom largely decoupled
• Radial well decays faster than axial in trap shutdown \( \Rightarrow \) Hbar escapes radially
• \( t \) correlated with radial energy; \( z \) with axial energies: Orthogonal sensitivity

Nature Phys. 2011
Trapped antihydrogen dynamics
Nature Phys. 2011
Annihilation position distribution

- Sensitivity to direction dependent (anisotropic) energy distribution
- \( \text{Erad} \sim 0.5 \text{ K}, \text{Eax} \sim 1 \text{ mK} \) (could be possible by one dimensional cooling)
- Position sensitive detection (feature of anti-atoms), giving unexpected information!
Antimatter Gravity Measurement

• Gravity
  – Never measured with antimatter
  – Test of Weak Equivalence Principle

• Very difficult experiment since gravity is so weak
• Now plausible due to long confinement time

Confinement of antihydrogen for 1,000 seconds

The ALPHA Collaboration

Atoms made of a particle and an antiparticle are unstable, usually surviving less than a microsecond. Antihydrogen, made entirely of antiparticles, is believed to be stable, and it is this longevity that holds the promise of precision studies of matter-antimatter symmetry. We have recently demonstrated trapping of antihydrogen atoms by releasing them after a confinement time of 172 ms. A critical question for future studies is: how long can anti-atoms be trapped? Here, we report the observation of anti-atom confinement for 1,000 s, extending our earlier results by nearly four orders of magnitude. Our calculations indicate that most of the trapped anti-atoms reach the ground state. Further, we report the first measurement of the energy distribution of trapped antihydrogen, which, coupled with detailed comparisons with simulations, provides a key tool for the systematic investigation of trapping dynamics. These advances open up a range of experimental possibilities, including precision studies of charge-parity-time reversal symmetry and cooling to temperatures where gravitational effects could become apparent.
Microwave-induced Positron Spin Resonance (PSR)

Installation at CERN, July 2011

- Developed at SFU/UBC
- Trap ~1 Anti-H/20 min
- Irradiate with $\mu$W
  - Drive transition: \textit{trapped} $\rightarrow$ \textit{un-trapped}
  - Look for annihilations
- Multivariate (blind) analysis
  - improved S/N by x10
Careful Cross checks & Controls: e.g.

- Blind analysis
- “Decision tree” analysis to reject cosmic backgd
- Annihilation positions
- Different uWave powers
- Background studies, esp annihilations on residual gas

Microwave Results: Nature 2012

Makoto Fujiwara, ALPHA
Focused Canadian Contributions: Overview

**1s-2s Spectroscopy**
\[ \Delta f \sim 0.2 \text{MHz}, \Delta f/f \sim 10^{-10} \]

**Laser Cooling**
\[ T \sim 5 \text{ mK}^* \]

**Hyperfine Spectroscopy**
\[ \Delta f \sim 3 \text{ kHz}, \Delta f/f \sim 10^{-6} \]

---

**Particle Detection**

**Lyman alpha Laser**

**Microwave Techniques**

**ALPHA-2 Physics Goals**

**Pbar catching trap**

**Positron accumulator**

**Cryostat Electronics**

**e+ transfer**

**e+ detection**

**Theory**

**Particle theory Simulations**

Makoto Fujiwara, ALPHA
New apparatus for laser and microwave spectroscopy

Very complex design & construction job for cryostat

Unique Canadian contributions
  - Cryo-engineering
  - Precision welding
  - Canadian industry (PAVAC)
  - >3000 hours of machining at TRIUMF and Calgary
ALPHA-2 Si Vertex Detector

- Annihilation imaging
  - Key for single atom sensitivity
- Expanded & Improved for ALPHA-2
  - TRIUMF/York responsible for readout, DAQ, tracking/analysis software

Canadian students in Liverpool Si Clean Room

Annihilation of trapped pbar in ALPHA-2, Dec 2012
Lyman-alpha spectroscopy & cooling

M. Michan (Ph.D.), T. Momose, UBC

- **Laser cooling**
  - Provides cold, high density, spatially confined sample
  - Needed for gravity experiments

- **Pulsed Lyman-alpha spectroscopy**
  - Candidate for 1st laser exp.

- **Lyman-alpha source (122 nm)**
  - Requires 4 Wave Mixing (4WM) or 3rd Harmonic Generation in gas

**UBC Development**

- Broad band (~6 GHz) source demonstrated (Summer 2012)!!!
- 0.15 µJ per pulse (measured via H absorption): Sufficient for initial exp.

**Narrowband (<200 MHz) source being developed**

- 1st spectroscopy at 10^-7 level
- Allows cooling from 0.5 K to 20 mK [Simulations: J. Phys. B. 2013]

Makoto Fujiwara, ALPHA
• Ly-α laser: spectroscopy on atomic-H demonstrated @ UBC!
• Sufficient power obtained for 1st optical probing of anti-H

• Further optimizations
  – 4WM → THG
  – Narrowing
  – Laser will be shipped to CERN, June, 2014

• Light transport & control system at under construction at CERN
High Precision NMR of Antihydrogen
Ashkezari, Dunlop (SFU), Friesen (Calgary), Evetts (UBC): Hayden, Hardy

- **Nuclear Magnetic Resonance**
  - Antiproton spin flip
  - Broad maximum at 0.65 T
  - **Insensitive B field homogeneity!**
  - Initially at 10 kHz ($10^{-5}$)
    \[ \Rightarrow <100 \text{ Hz} \; (10^{-7}) \]
  - Complementary to laser exp.

- **655 MHz Resonator development (Dunlop, Evetts)**
  - Challenge: compatibility with trap/plasma requirements
  - Simulations with Laxdal, TRIUMF
  - Prototyping at SFU/UBC

---

**Resonator Prototype at SFU (Q ~ 300)**

- PRL 42, 1042 (1979)
  - Hardy et al. UBC

**Diagram:**

- Energy vs. $B_0$ (T)
- Resonator prototype at SFU (Q ~ 300)
High Precision NMR of Antihydrogen

HPQ: Ashkezari (SFU), Friesen (Calgary), Capra (York), Evetts (UBC): Hayden, Hardy, Thompson, Olin, Fujiwara

Nuclear Magnetic Resonance

- Insensitive to B field inhomogeneity at magic field 0.65 T!
- Design criteria for ALPHA-2
- Probe internal structure of anti-nucleon
- Measured for H by Hardy+ at UBC

Systematic effects from simulations

<table>
<thead>
<tr>
<th>Effects</th>
<th>Initial stage</th>
<th>With cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transit time: transverse</td>
<td>$2 \times 10^{-6}$</td>
<td>$1 \times 10^{-7}$</td>
</tr>
<tr>
<td>Transit time: axial</td>
<td>$2 \times 10^{-7}$</td>
<td>$5 \times 10^{-8}$</td>
</tr>
<tr>
<td>Doppler broadening</td>
<td>$1 \times 10^{-7}$</td>
<td>$1 \times 10^{-8}$</td>
</tr>
<tr>
<td>Resonator stability</td>
<td>$8 \times 10^{-8}$</td>
<td>$6 \times 10^{-9}$</td>
</tr>
<tr>
<td>Octupole field reproducibility</td>
<td>$2 \times 10^{-9}$</td>
<td>$1 \times 10^{-10}$</td>
</tr>
<tr>
<td>Mirror fields reproducibility</td>
<td>$1 \times 10^{-10}$</td>
<td>$1 \times 10^{-10}$</td>
</tr>
<tr>
<td>Solenoidal field reproducibility</td>
<td>$1 \times 10^{-10}$</td>
<td>$1 \times 10^{-10}$</td>
</tr>
</tbody>
</table>

RF Resonator needed

- Challenge: compatibility with trap/plasma requirements
- Simulations with TRIUMF RF
- Prototyping at SFU/UBC

Resonator Prototype at SFU (Q ~ 300)