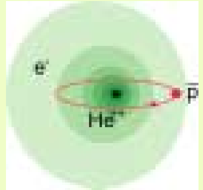
High Precision Laser and Microwave Spectroscopy of Antiprotonic Helium



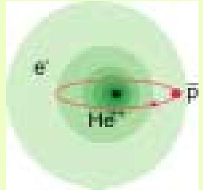
E. Widmann

ASACUSA collaboration

University of Tokyo

- High precision laser spectroscopy and CPT test for the proton/antiproton charge and mass
- Observation of hyperfine splitting and prospects of a CPT test for the proton/antiproton magnetic moment

ASACUSA collaboration @ CERN-AD



Asakusa Kannon Temple
by Utagawa Hiroshige (1797-1858)

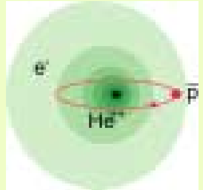
Atomic Spectroscopy And Collisions Using Slow Antiprotons

~ 40 members

- *University of Tokyo, Japan*
- *RIKEN, Saitama, Japan*
- *Tokyo Institute of Technology, Japan*
- *University of Tsukuba, Japan*
- *Institute for Molecular Science, Okazaki, Japan*
- *Tokyo Metropolitan University, Japan*
- *CERN, Switzerland*
- *University of Aarhus, Denmark*
- *University of Wales Swansea, UK*
- *KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary*
- *University of Debrecen, Hungary*
- *KVI, Groningen, The Netherlands*
- *PSI Villigen, Switzerland*
- *Ciril -Lab. Mixte CEA-CNRS, Caen Cedex, France*
- *GSI, Darmstadt, Germany*
- *Institut für Kernphysik, Universität Frankfurt*
- *Universität Freiburg, Germany*
- *St. Patrick's College, Maynooth, Ireland*
- *The Queen's University of Belfast, Ireland*

Spokesman: R.S. Hayano, University of Tokyo

ASACUSA: Study of Antiprotonic Atoms: Spectroscopy, collisions, dE/dx, atomic formation



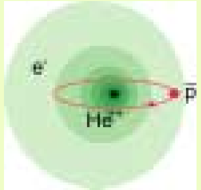
Ultimate test of the
3-body quantum theories

- Bound-state QED
  - $\bar{p}He^{+}$ spectroscopy
- Continuum 3-body system
  - $\bar{p}$ - H collision, etc.

CPT test
- $\bar{p}$ mass, charge
  - $\bar{p}He^{+}$ spectroscopy (+ 3-body theory)
  - protonium and $\bar{p}He^{++}$ spectroscopy

+ many more byproducts

Antiprotonic Helium Group



- E.W., R.S. Hayano, T. Ishikawa, J. Sakaguchi, T. Tasaki, H. Yamaguchi
  - Department of Physics, University of Tokyo
- J. Eades, M. Hori
  - CERN, Geneva, Switzerland
- D. Horvath
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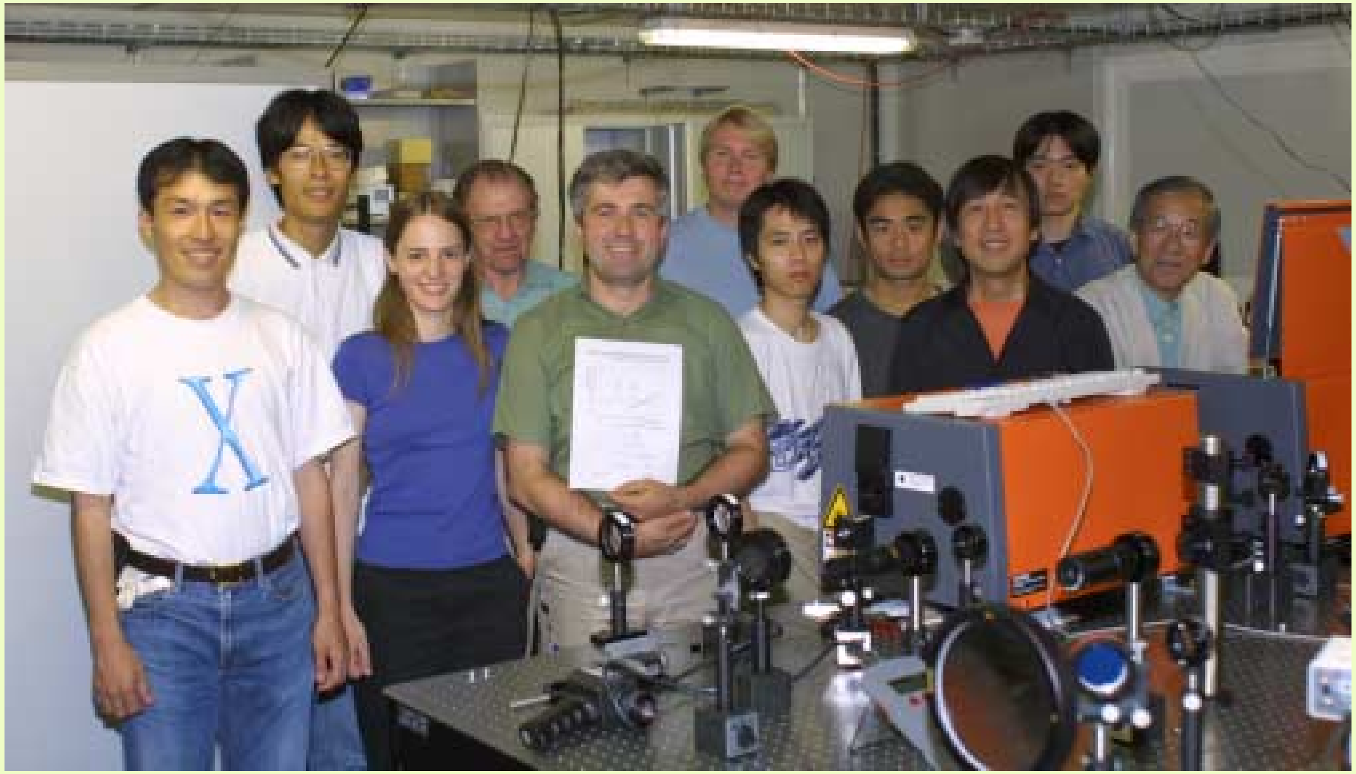
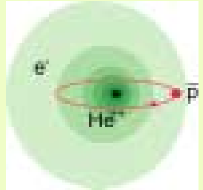
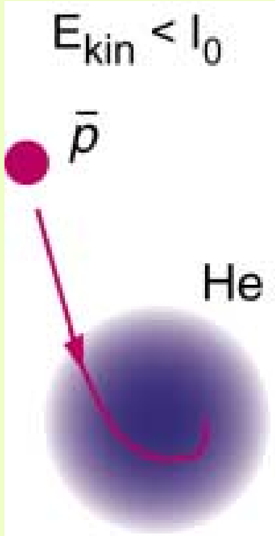
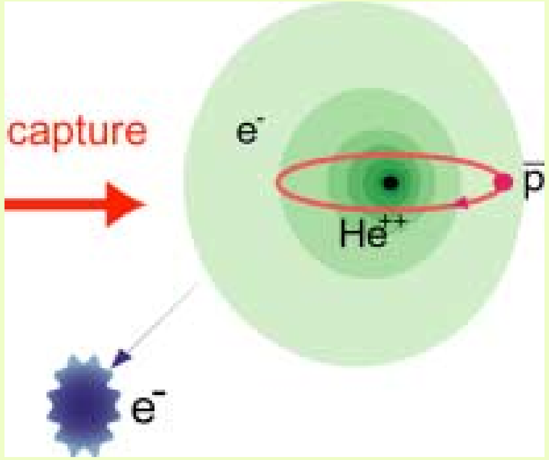
- B. Juhasz
  - University of Debrezen, Hungary
- H.A. Torii
  - Institute of Physics, University of Tokyo
- T. Yamazaki
  - RIKEN, Saitama, Japan

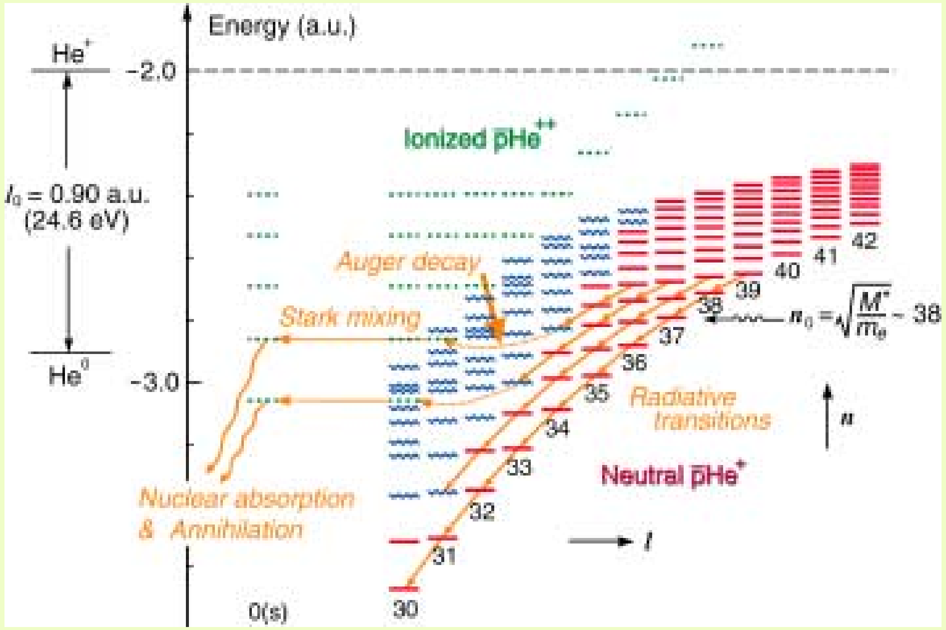


p̄He⁺ "Atomcule"
a naturally occurring trap for antiprotons



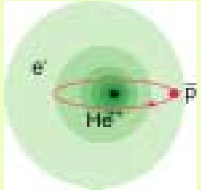


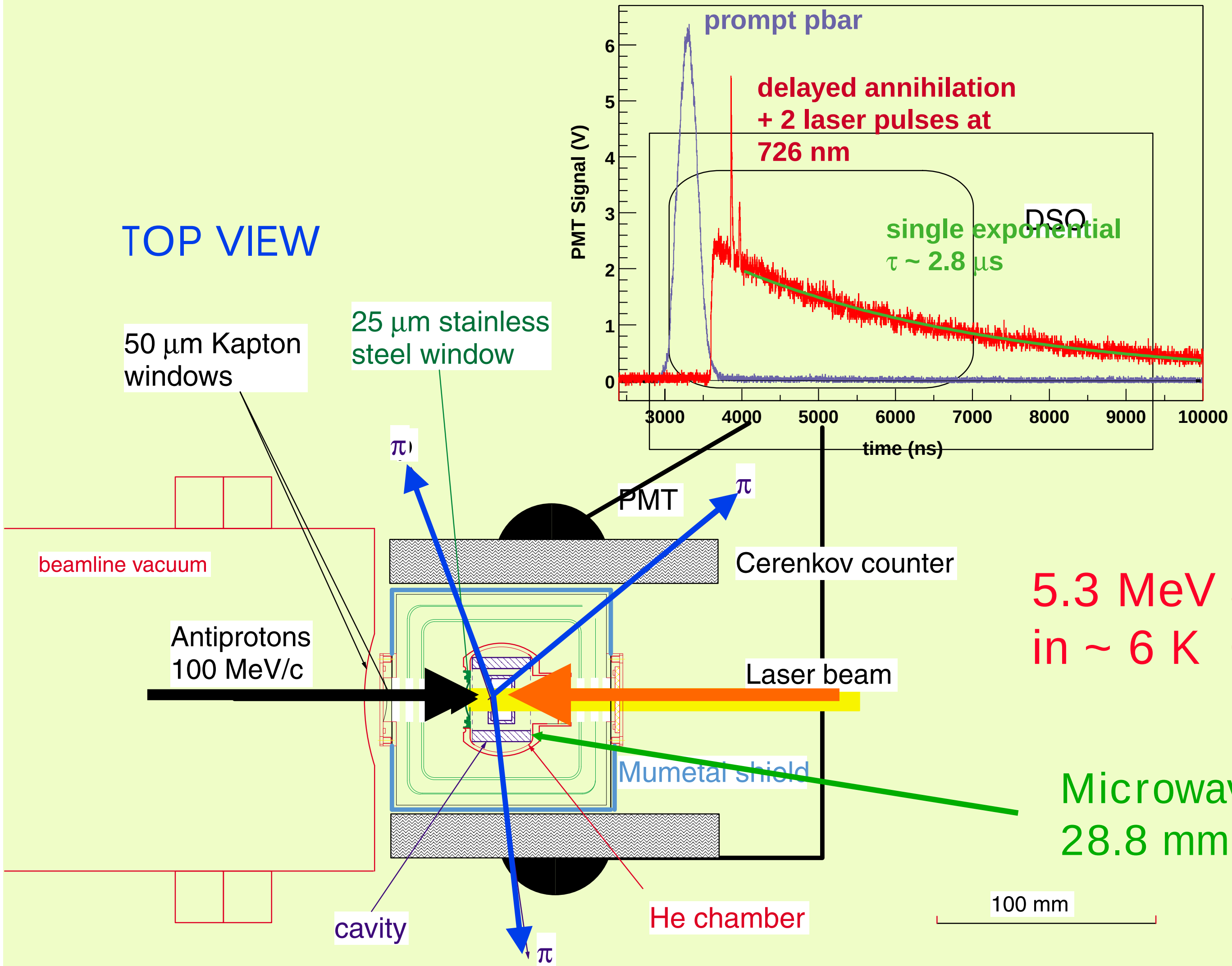




- Characteristics of both atom and molecule -> "atomcule"
- 3-body system
- 2 heavy "nuclei" with Z=1 and Z=-1
- electron can be treated by Born-Oppenheimer approximation
- ~ 3% of stopped antiprotons survive with average lifetime of ~ 3 μs

Experimental Setup at AD



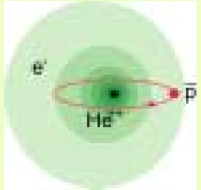


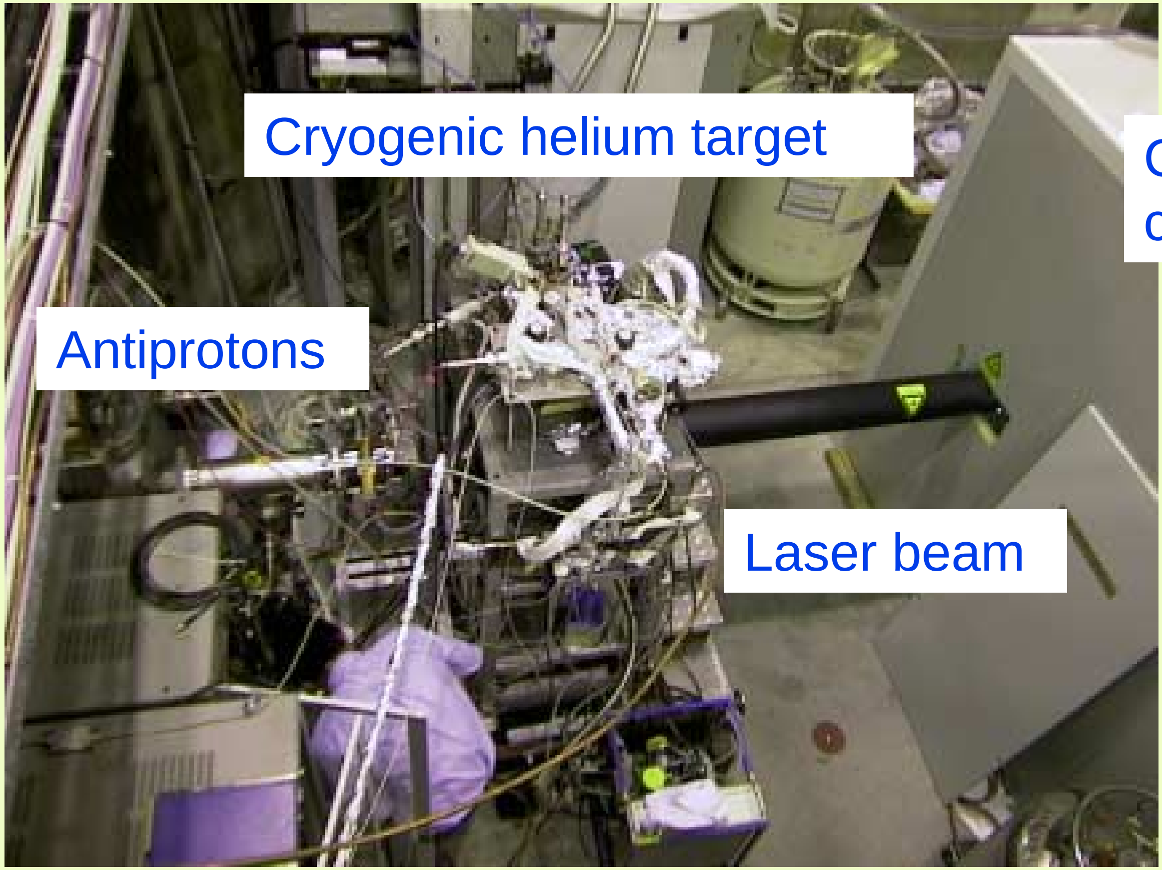
Analog Measurement of Delayed Annihilation using Cerenkov counters and digital oscilloscope

5.3 MeV antiprotons are stopped in ~ 6 K 0.5 – 3 bar He gas

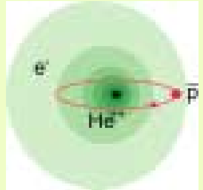
Microwave cavity 12.91 GHz:
28.8 mm diameter, 24.5 mm length

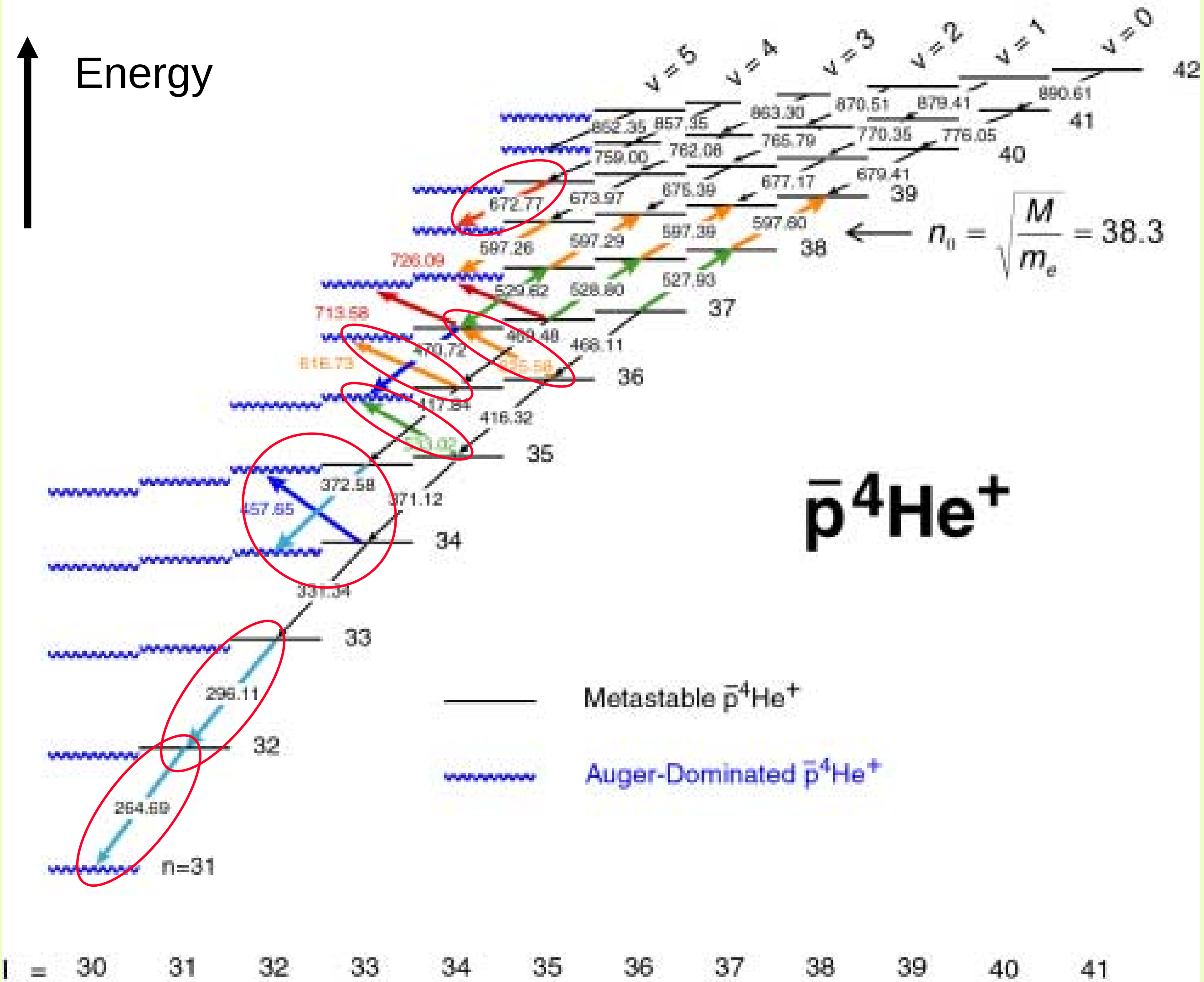
Setup at AD - area





Observed transitions in ^{4}He





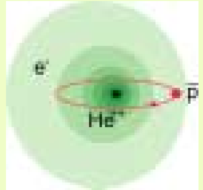
Angular Momentum →

- Spectroscopy method: forced annihilation by laser transition meta-stable to short-lived state
- LEAR: 10 transitions in ^{4}He, 3 in ^{3}He observed
  - First experimental proof that exotic particle is captured around

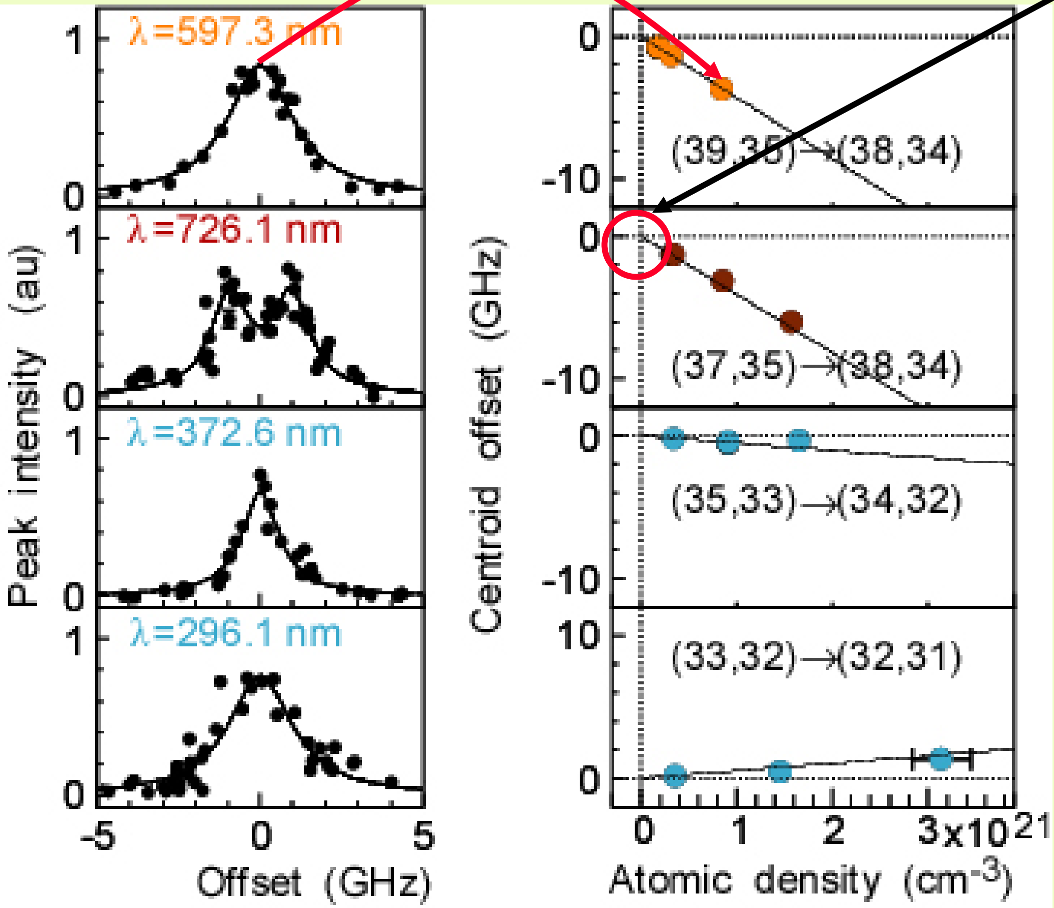
$$n_0 = \sqrt{M / m_e}$$

- AD: 8 new transitions in ^{4}He, 4 new in ^{3}He
  - Last transitions in v=0, 1 (UV) and v=4 cascade observed
- Systematic studies possible

Precise Measurement of Transition Wavelength and CPT test for Mass and Charge

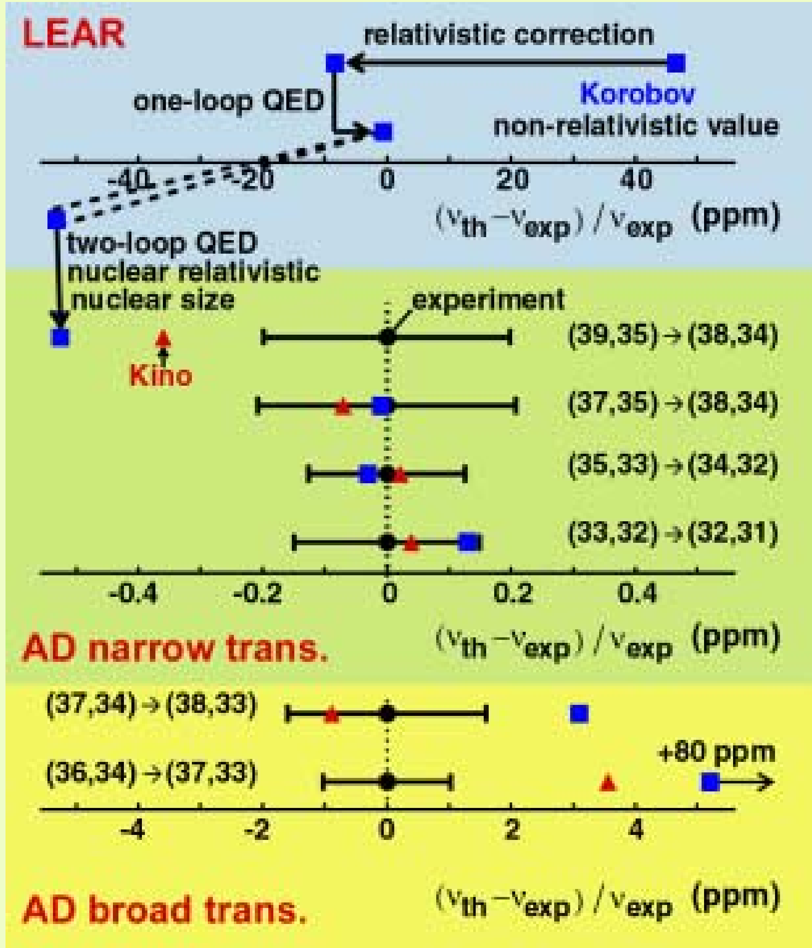


Zero-density values compared to state-of-the-art three-body QED calculations

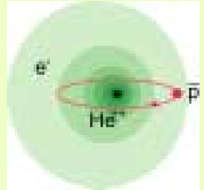


Resonance scans

Shift of line center with density



CPT test of proton/antiproton charge and mass



- Scaling factor for energy levels

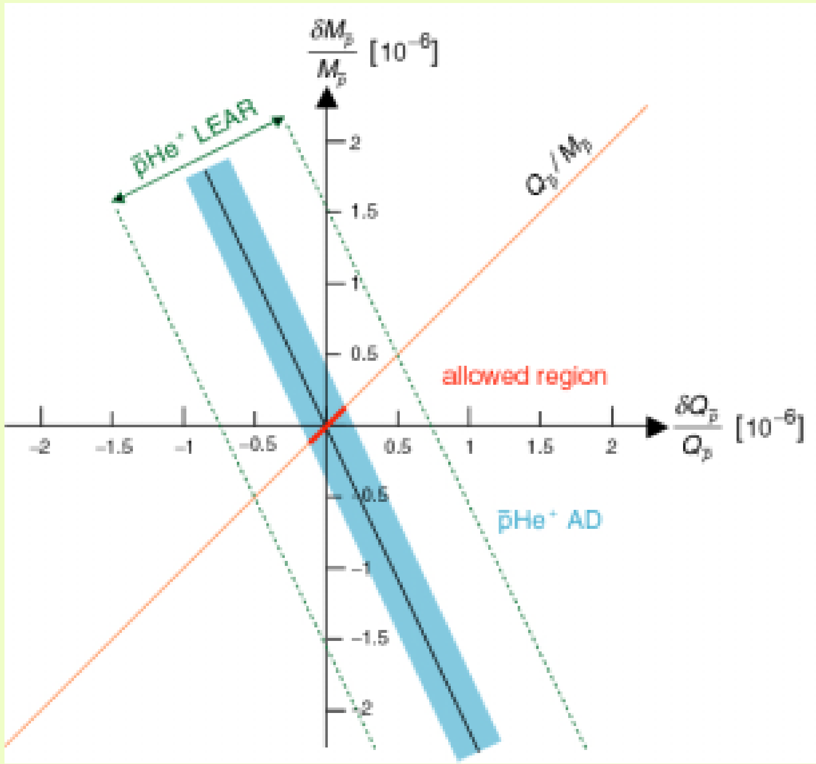
$$Ry_\infty(\bar{p}) = \frac{M_{\bar{p}}}{m_e}\left(\frac{Q_{\bar{p}}}{e}\right)^2 Ry_\infty$$

- Theory uses numerical values of proton
- Deviation between experiment and theory for ΔE

$$\Delta_{\text{exp-th}} = f_M \frac{M_{\bar{p}} - M_p}{M_p} + f_Q \frac{Q_{\bar{p}} - Q_p}{Q_p}$$
$$\approx (f_M + f_Q)\delta M \approx (f_M + f_Q)\delta Q$$

  - Since Q/M of proton/antiproton is equal to ~ 9×10^{-11} (Gabrielse 1999)

- Simple estimate: f_M=1, f_Q=2
- Accurate calculation (Kino) that vary M,Q keeping Q/M const:
  - $f_{M+}f_Q$=2.5 ... 5 depending on transition

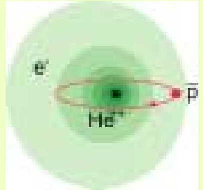


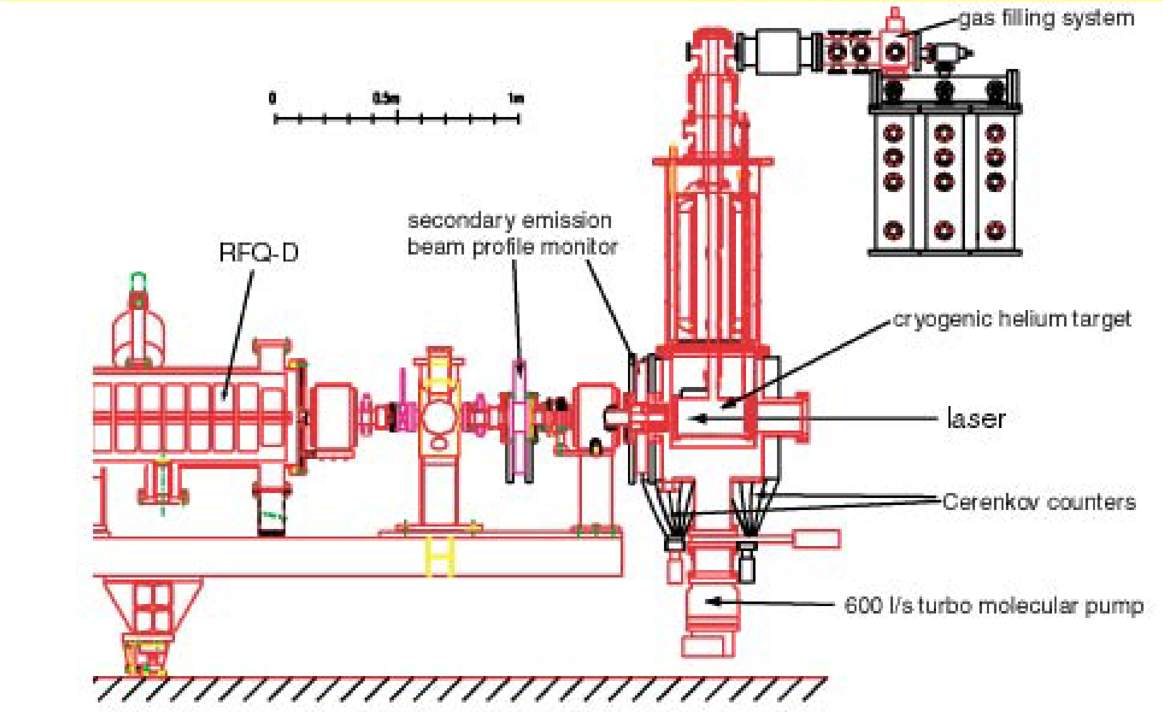
Average of 4 measurements yields

$$\left|\frac{M_{\bar{p}} - M_p}{M_p}\right| \approx \left|\frac{Q_{\bar{p}} - Q_p}{Q_p}\right| < 6\times10^{-8}$$

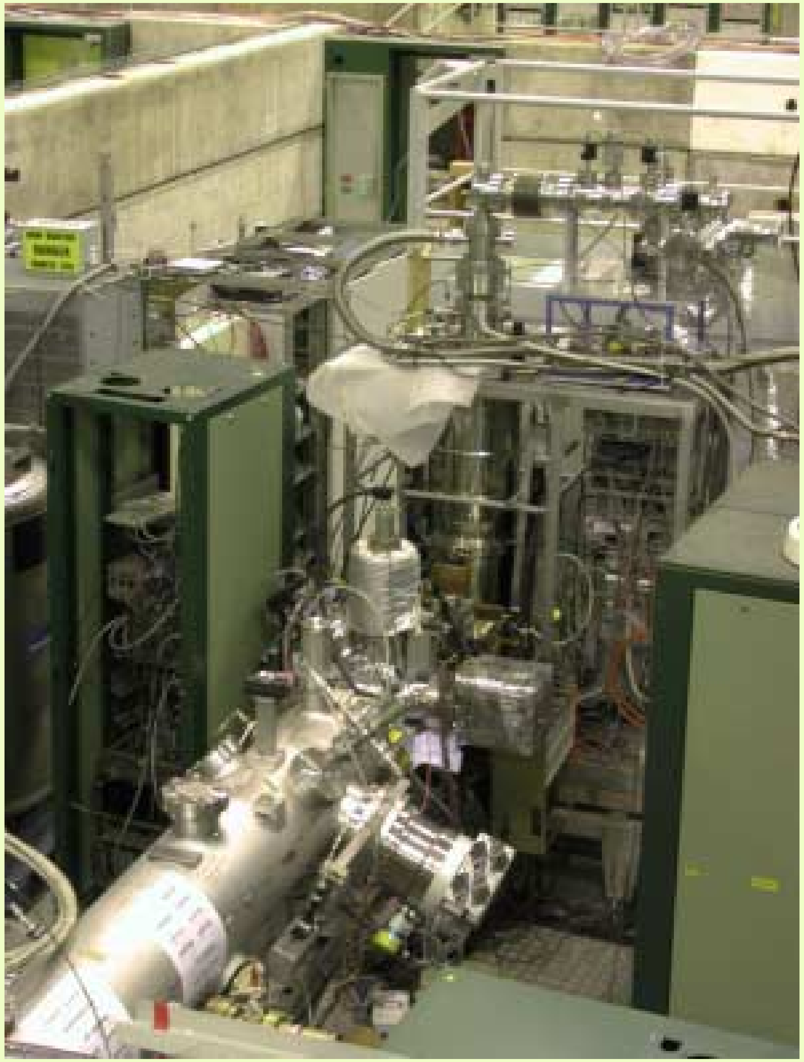
Factor 8 better than LEAR

Laser Spectroscopy at Ultra-low Density: Radio Frequency Quadrupole Decelerator

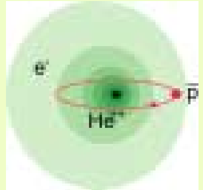


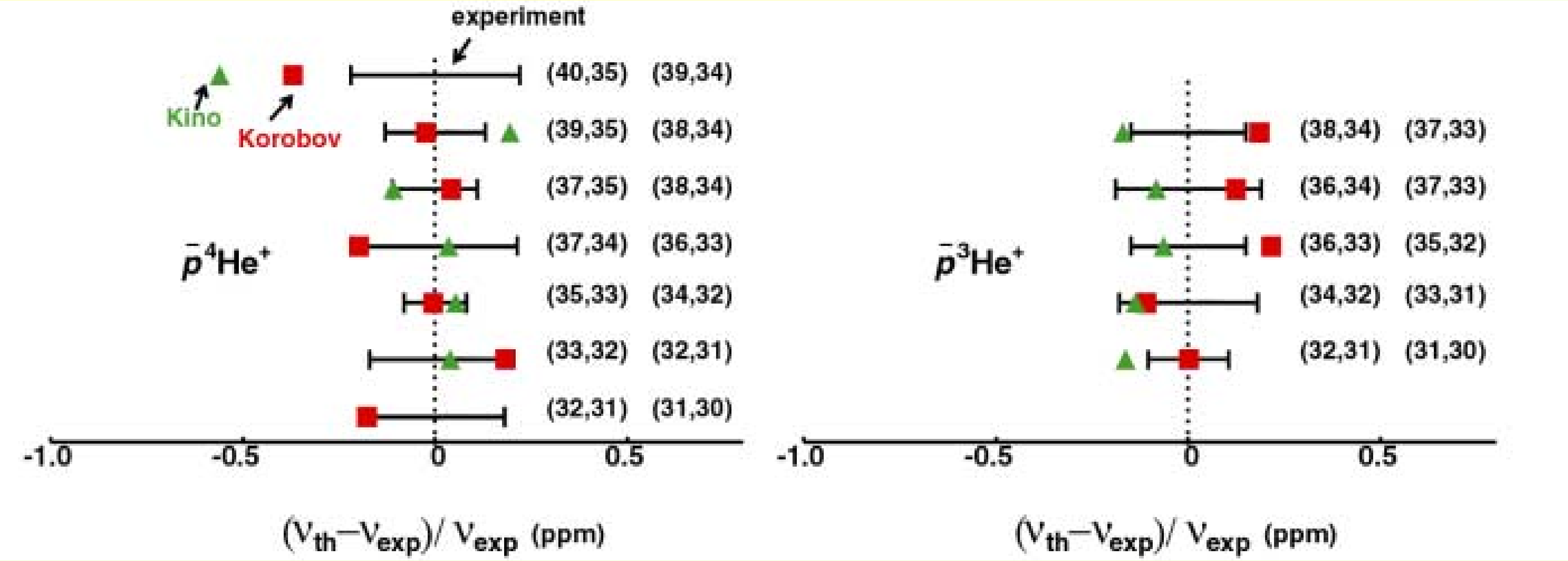


- RFQD: 5.3 MeV -> 20 – 120 keV (eff.~40%)
- Differential pumping + ultra-thin beam window (~ 1 µm Mylar)
- high efficiency of stopping antiprotons at ultra-low densities (p < 1 mbar, T~20 K)



Preliminary comparison to theory 2001



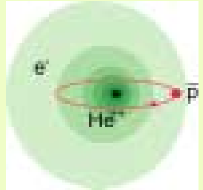


- Only data taken with RFQD at density 5×10^{17} cm^{-3} (factor 1000 lower than ever)
- Previous discrepancy removed, but new one exists
  - Problems for calculations for high-n, low-l states?
- Average over all data gives factor 3 better value for CPT test

$$\left|\frac{M_{\bar{p}} - M_p}{M_p}\right| \approx \left|\frac{Q_{\bar{p}} - Q_p}{Q_p}\right| < 1.8 \times 10^{-8}$$

PRELIMINARY

Details of QED corrections: 597 nm line



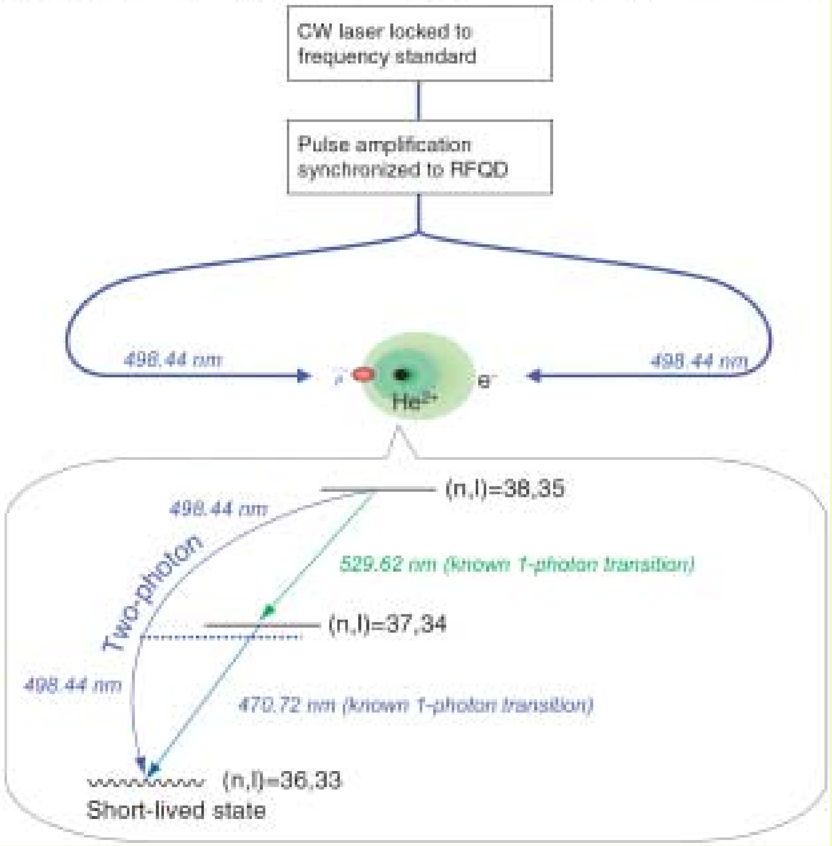
Quantity	Value	error			
Non-relativistic energy	501’972’376	(3)	MHz		
Relativistic corrections (e^-)	-27’556	(3)	MHz		
Rel. QED corrections	233		MHz		
Self energy	3’815		MHz		
Vacuum polarization	-123		MHz		
RMC	37		MHz		
Retardation	-35		MHz		
Two-loop corrections	1		MHz		
Finite size effect	2		MHz		
α^4 corrections	-3	(3)	MHz		
Total Korobov	501’948’718	(5)	MHz	(10)	ppb
Value Kino	501’948’828	(8)	MHz	(16)	ppb
Experiment 2000	501’949’010	(100)	MHz	(200)	ppb
Experiment 2001 PRELIM.	501’948’850	(50)	MHz	(100)	ppb

- Kino, Korobov use different variational expansions
- Deviation Korobov – Kino ~ 200 ppb >> estimated theoret. error !!
- QCD effects (finite size etc.) play no role

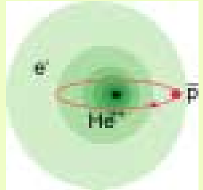
Outlook - 2-photon transitions in $p He^+$

- Current precision (50 – 100 MHz) seems limit for pulsed laser system
  - pulse-amplified cw-laser needed
- Go to ultra-low density using RFQD:
  - antiprotons with 10 - 100 keV to be stopped in ~mbar helium gas **done**
  - Elimination of collisional shift and broadening
- Doppler-free two-photon spectroscopy
  - $\Delta n = \Delta l = 2$ transitions
    - virtual intermediate state close to real one
  - state of the art: 10 MHz
  - Gives 1 ppb for CPT test of M and Q
  - Proton mass only known to 2.1 ppb!

	LEAR	AD(2001)	Future
Collisional Shift	~500 MHz	1 MHz(RFQD)	=
Collision width	<500 MHz	1 MHz(RFQD)	=
Doppler width	300-600 MHz	=	10 MHz (2-photon)
Calibration	300 MHz	60 MHz	5 MHz (CW laser)
Laser band width	1200 MHz	300-800 MHz	10 MHz (pulse amplified CW laser)
Precision	500 ppb	60 ppb	< 1 ppb



“Hyperfine” structure of $\bar{p}He^+$



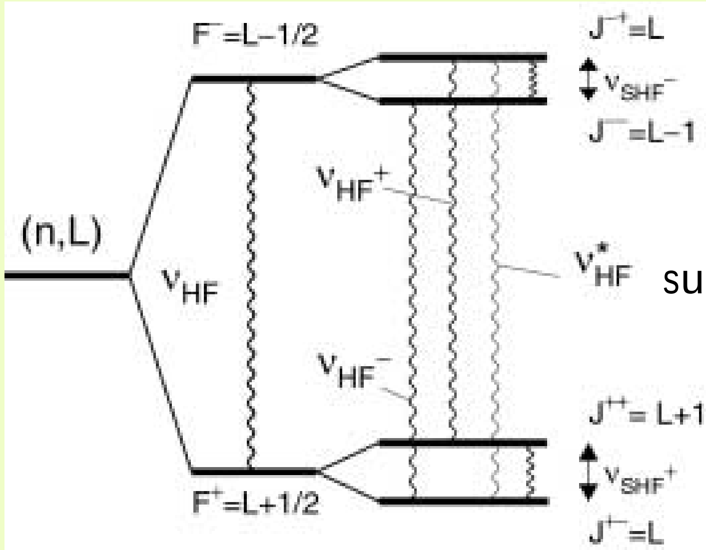
- interactions of magnetic moments:
  - electron: $\vec{\mu}_e = g\,\mu_B \vec{S}_e$
  - pbar: $\vec{\mu}_{\bar{p}} = [g_s(\bar{p})\vec{S}_{\bar{p}} + g_l(\bar{p})\vec{L}_{\bar{p}}]\mu_{\bar{N}}$
- Dominant splitting: “Hyperfine”:

$$\vec{L}_{\bar{p}} \cdot \vec{s}_e$$

  - sizeable because of large L of pbar.
- “Superhyperfine” splitting
  - Interaction antiproton spin with other moments
- Spin coupling scheme:

$$\vec{j} = \vec{L}_{\bar{p}} + \vec{S}_e$$

$$\vec{J} = \vec{j} + \vec{S}_{\bar{p}} = \vec{L}_{\bar{p}} + \vec{S}_e + \vec{S}_{\bar{p}}$$

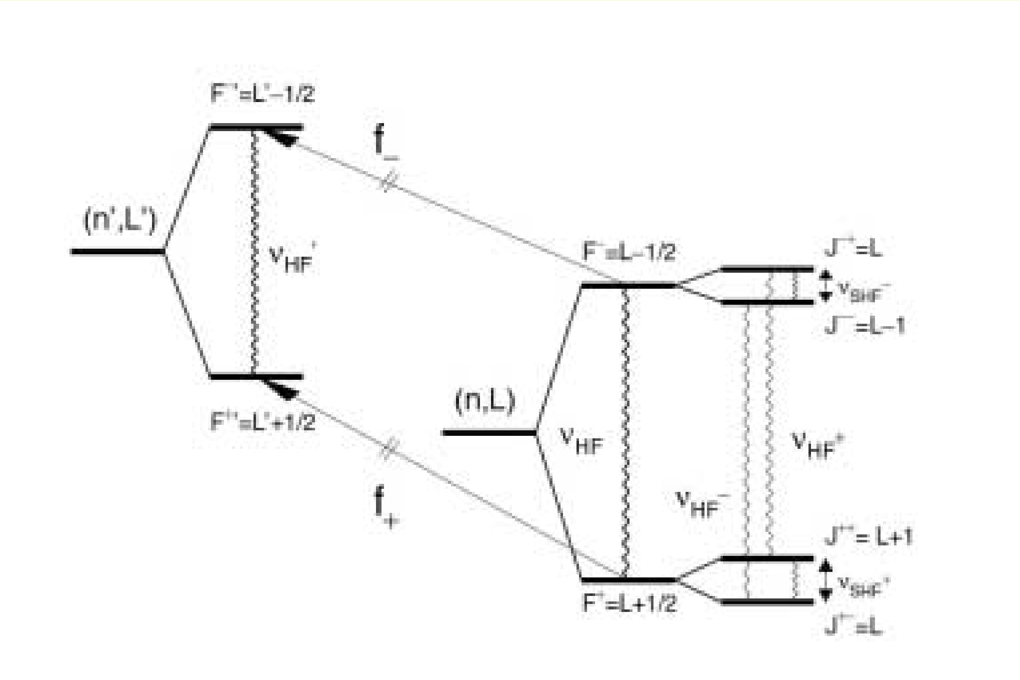


suppressed

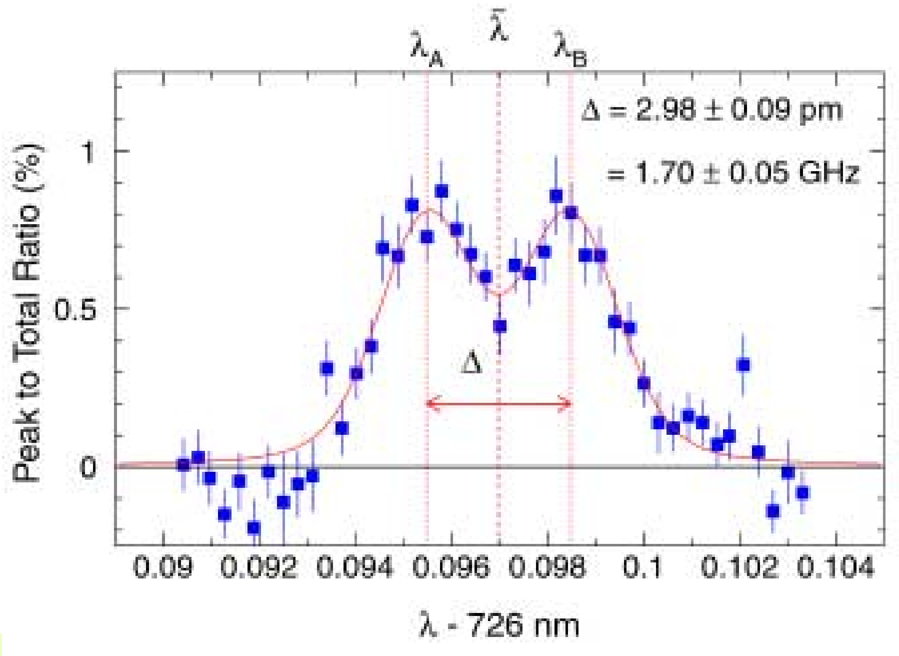
ν_{HF} ~ 10 … 15 GHz
ν_{SHF} ~ 50 … 150 MHZ

ν_{SHF} sensitive to magnetic moment of pbar (known to 3×10^{-3})
ν_{HF} sensitive with suppression factor 7×10^{-3}
Possible experimental resolution: 10^{-5} or better

Observation of HFS in laser transition



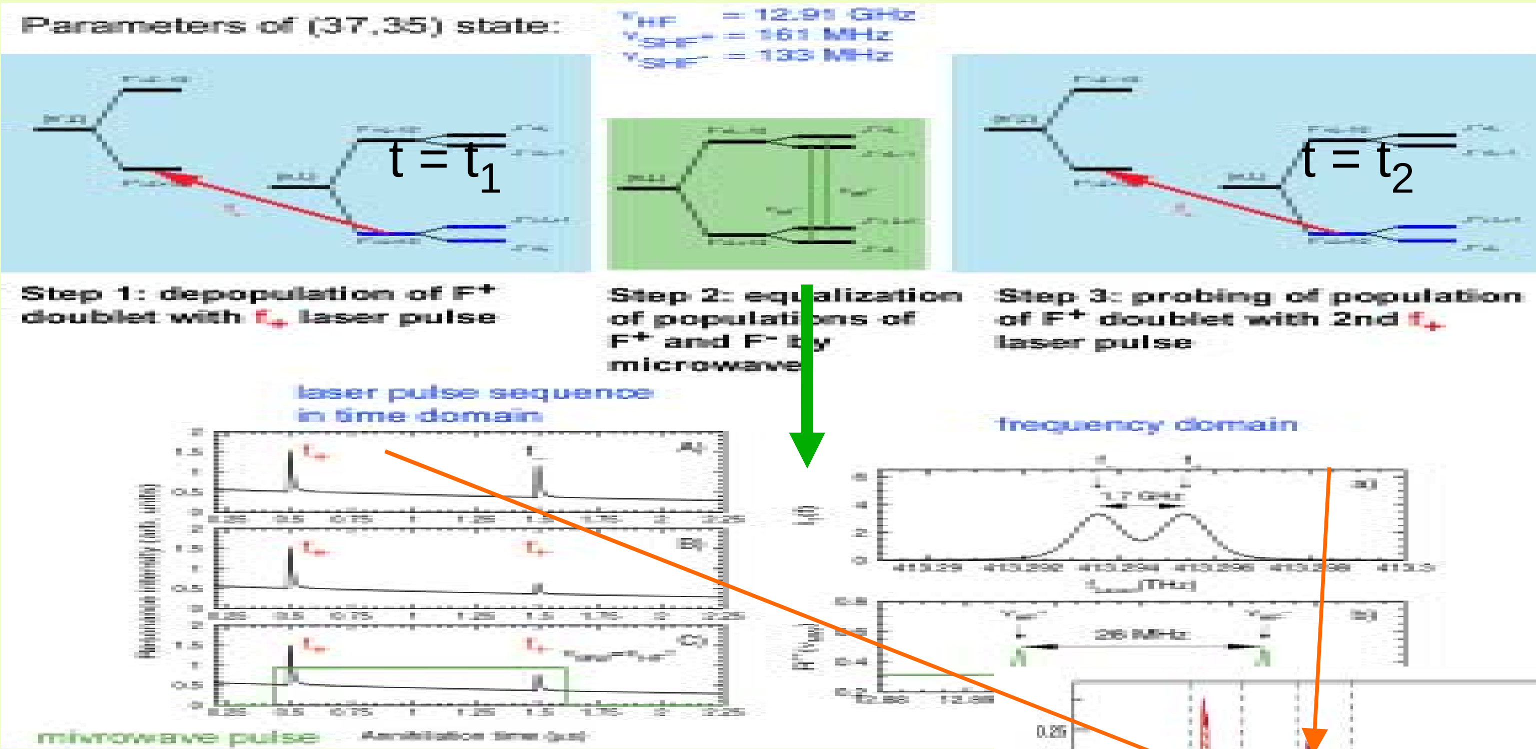
(n,l)=(37,35)->(38,34) @ LEAR

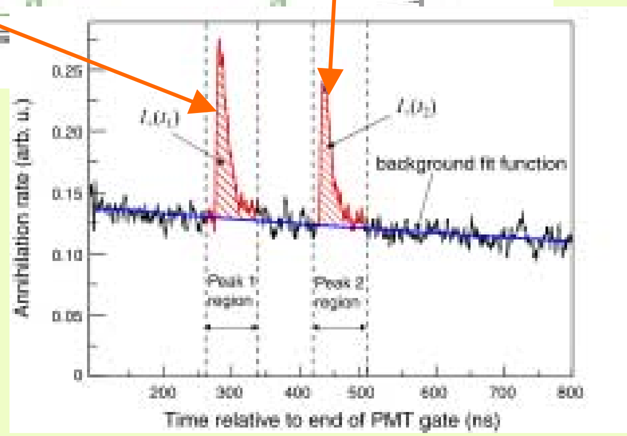


E. Widmann et al., PLB 404, 15 (1997)

- 1.7 GHz is difference of HF splitting of (37,35) and (38,34) state
- SHFS transitions cannot be observed due to Doppler broadening & laser bandwidth

Principle of laser-microwave-laser resonance experiment

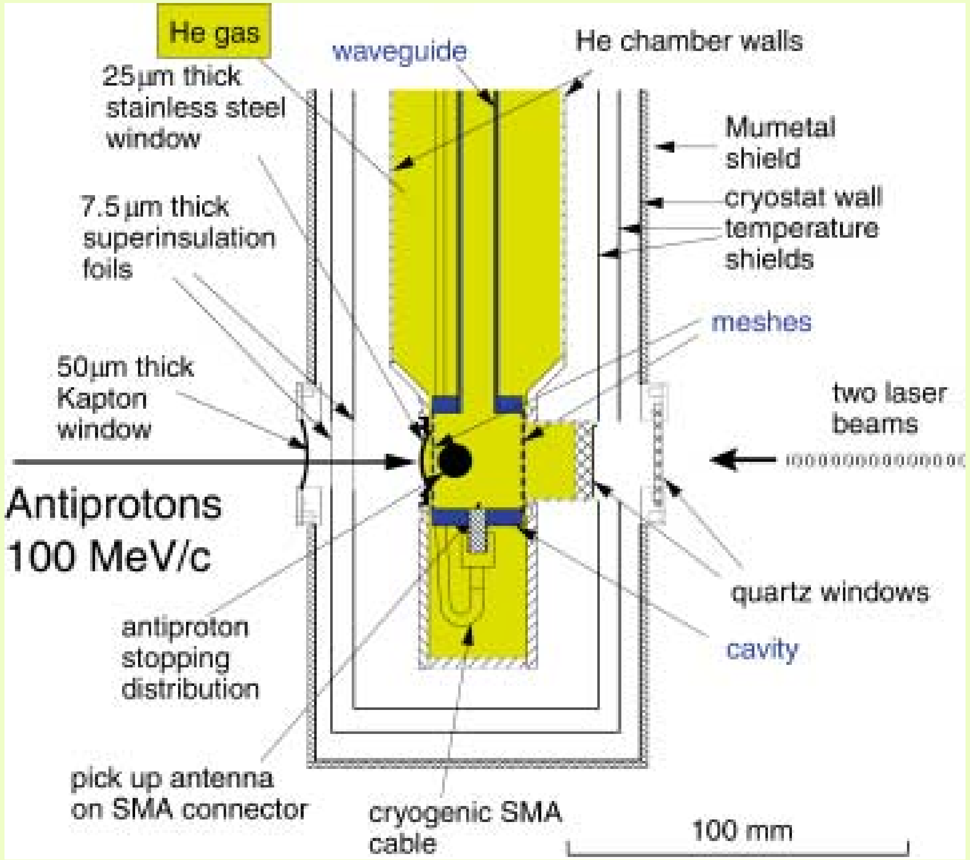




- Direct measurement of HF splitting by microwave radiation
- Area under laser spike is proportional to population
  - Measure $R^{++} = I(f=f^+,t_2) \,/\, I(f=f^+,t_1)$

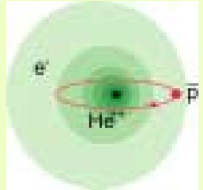
Microwave cavity for HFS measurement

- cavity for 13 GHz at < 10 K to reduce Doppler broadening
- Meshes to allow pbar and laser light to enter

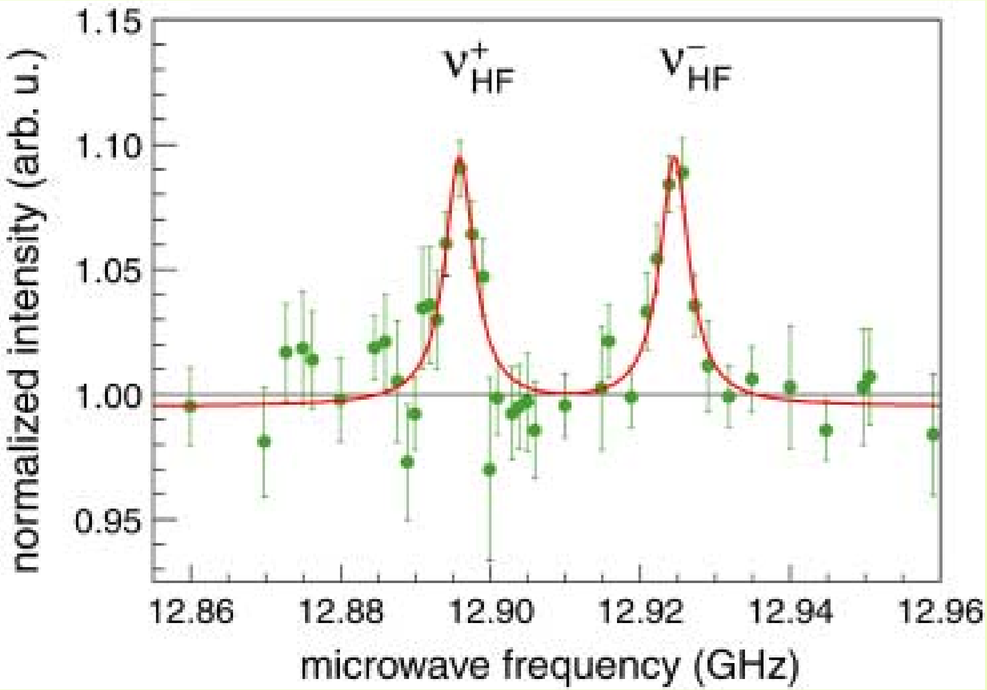


- low Q (~100) to avoid mechanical tuning
- tuning via synthesizer and stub tuner

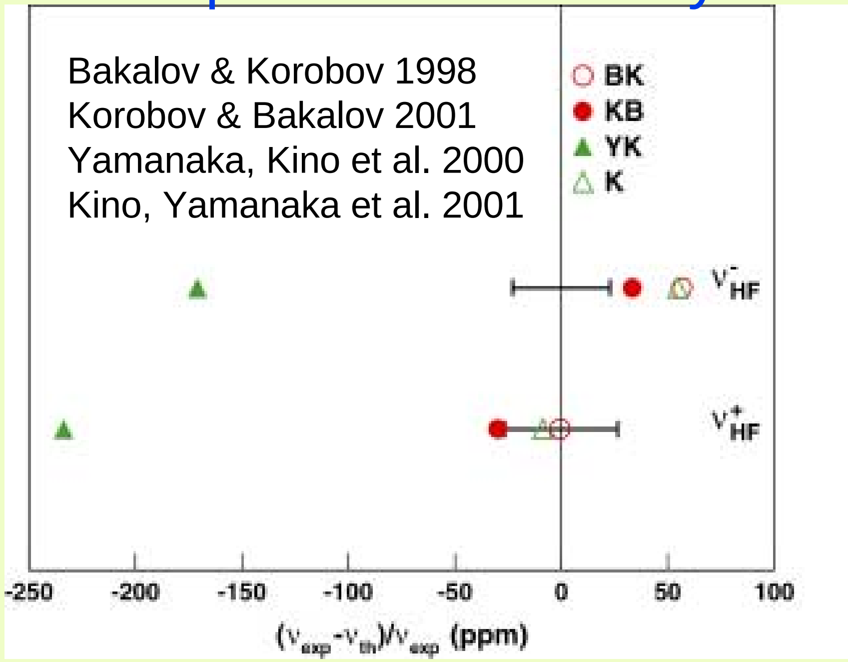
First Observation of Laser-Microwave-Laser Resonance



Resonance scan



Comparison to theory



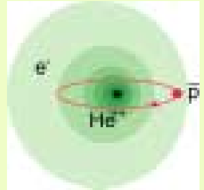
- Results about to be published
- Experimental accuracy: ~ 3×10^{-5}

ν_{HF}^+	12.895 96(34) GHz	27 ppm
ν_{HF}^-	12.924 67(29) GHz	23 ppm

- Comparison to theory favours most recent results of both groups
- Difference < 6×10^{-5}
- Corresponds to theoretical uncertainty

  Omission of terms $O(\alpha^2)$

Significance of HFS measurement

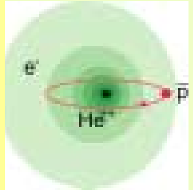


- Test of 3-body theory incl QED corrections
- Agreement ~ 6 x 10^{-5} : $|g_l(\bar{p}) - 1| < 6 \times 10^{-5}$
  - First determination ever of orbital g-factor of either proton or antiproton
- SHFS: antiproton magnetic moment
  - from laser-microwave-laser experiment the difference $\nu_{SHF}+ - \nu_{SHF}-$ can be determined
  - sensitive to μ_{pbar} with suppression factor (D. Bakalov, Nucl. Phys. A655 (1999) 301c)

$$\Delta\mu_{\bar{p}}^{exp} = \frac{\Delta\nu_{exp}}{\delta\nu / \delta\mu_{\bar{p}}} = \frac{3.4 \times 10^{-4}\ \text{GHz}}{0.0065\ \text{GHz}/\mu_N} = 0.05\mu_N;\ \text{PDG: } \mu_{\bar{p}} = 2.800 \pm 0.008\mu_N$$

  - Improvement in the determination of μ_{pbar} would require
    - Improvement of resolution by factor > 6: difficult
    - additional RF field of ~100 MHz (laser-mw-RF-laser resonance) or
    - Ultra-narrow band laser to resolve SHFS in laser transition, plus 100 MHz RF (laser-RF-laser resonance)
- Better way: Ground state hyperfine splitting of antihydrogen

Ground-State Hyperfine Structure of AntiHydrogen

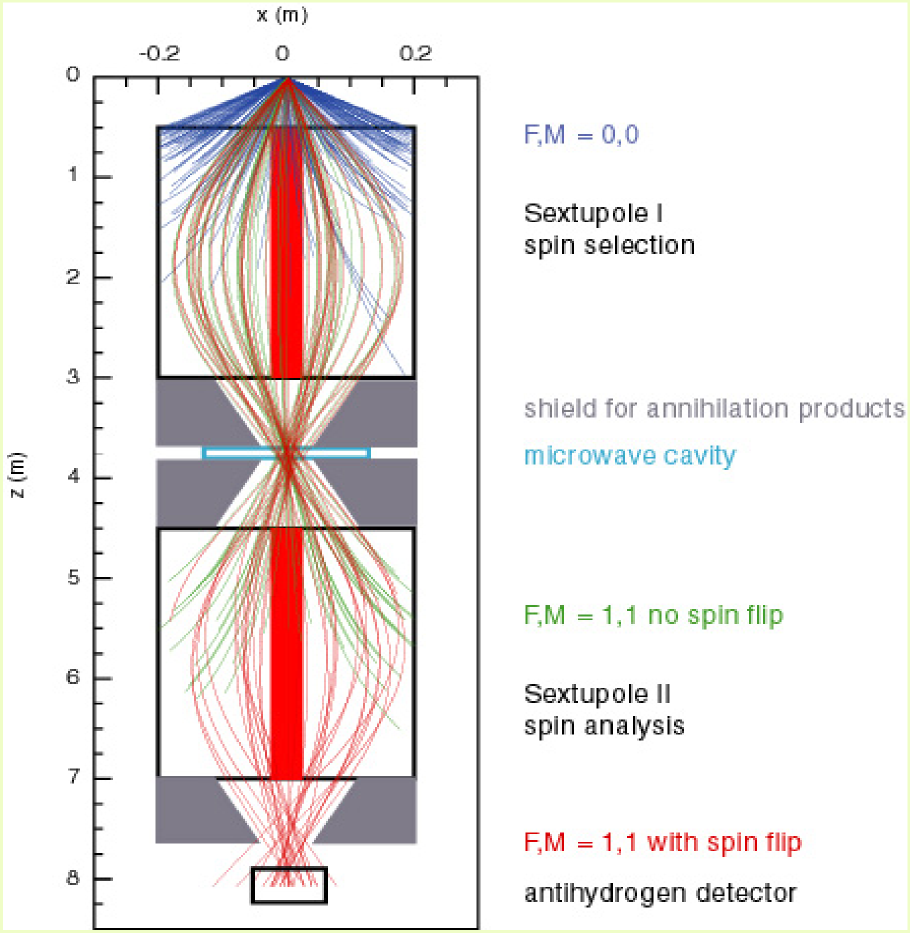


- One of the most accurately measured quantities in physics
  - hydrogen maser, Ramsey (Nobel price 1989)
- spin-spin interaction electron - (anti)proton
- Leading term: Fermi contact term

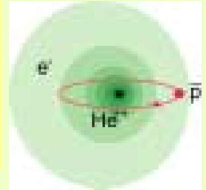
$$\nu_{HF} = \frac{16}{3}\left(\frac{M_p}{M_p + m_e}\right)^3 \frac{m_e}{M_p}\frac{\mu_p}{\mu_N}\alpha^2 Ry$$

- a measurement of ν_{HF} will directly give a value for the magnetic moment of pbar
- GS-HFS also tests form factors (structure) of (anti)proton!
  - finite size corrections ~ several ppm level

- GS-HFS can be done with atomic beams



Summary & Outlook



- Precision spectroscopy constitutes stringent test of 3-body theory including QED corrections
- Laser spectroscopy:
  - Comparison to theory, together with measured cyclotron frequency, allows to set CPT limit for pbar charge and mass

$$\left|\frac{M_{\bar{p}} - M_p}{M_p}\right| \approx \left|\frac{Q_{\bar{p}} - Q_p}{Q_p}\right| < 6\times10^{-8}$$

  - 8 times improvement over LEAR, further factor 3 expected from 2001 data
  - Limit can be pushed to ppb level by development of new laser system
- Hyperfine Structure
  - excellent agreement with 3-body QED calculations: $<6\text{x}10^{-5}$
  - 1st determination of orbital g-factor
  - Improvement needed to determine μ_{pbar}