Hyperfine structure of antiprotonic helium and the antiproton magnetic moment

Eberhard Widmann

ASACUSA collaboration

DISCRETE 2012

Lisbon, Dec. 6, 2012

Der Wissenschaftsfonds.

Project I-198-N20

Stefan Meyer Institute for Subatomic Physics, Vienna

Austrian Academy of Sciences

Exotic atom formation

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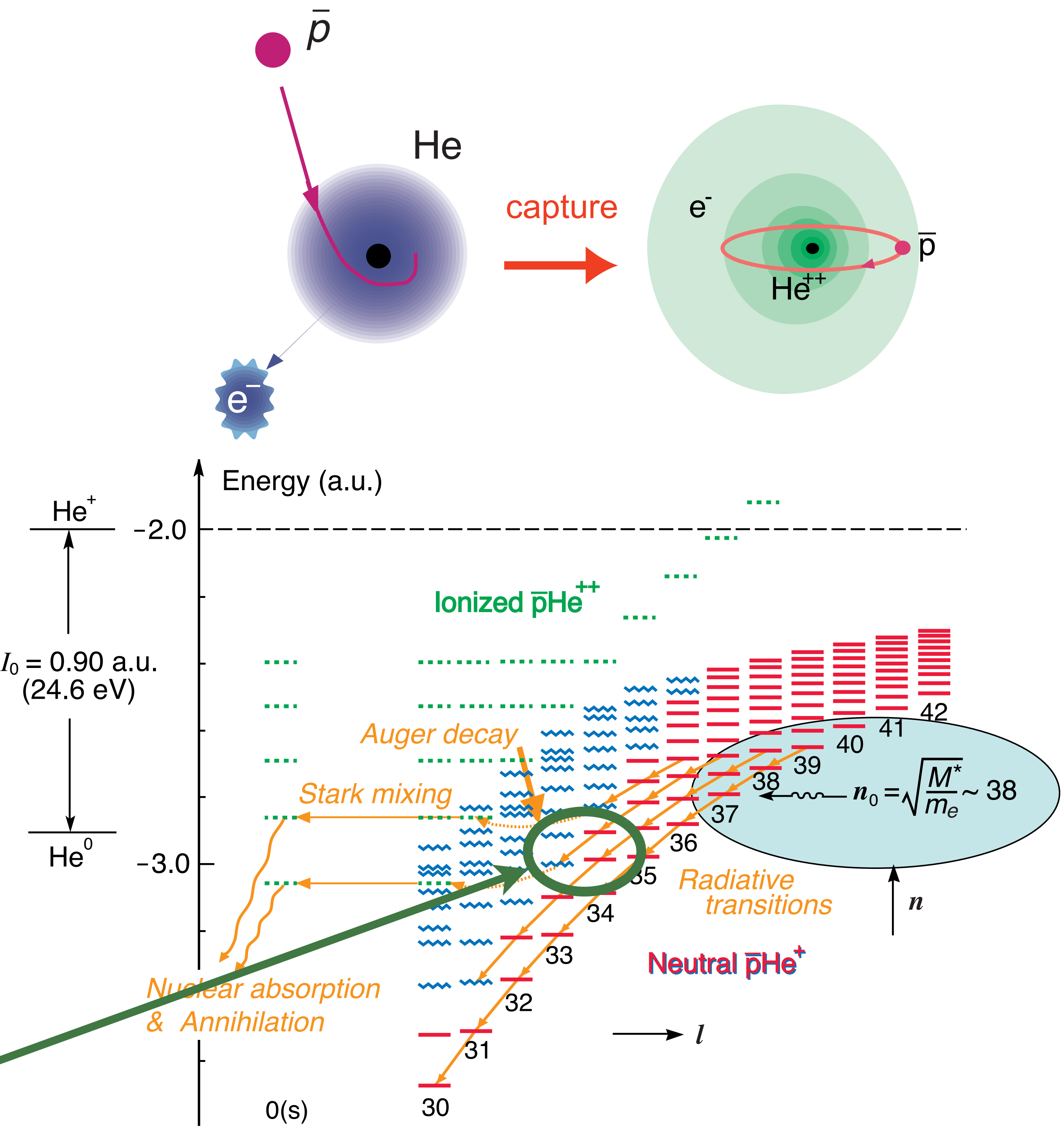
- stopping of negatively charged particles in matter
  - slowing down by ionization (normal energy loss)
  - end when kinetic energy < ionization energy
  - capture in high-lying orbits with n~√(M*/me)



laser transition:
forced annihilation

antiprotonic helium: τ ~ μs
τ ≤ ns

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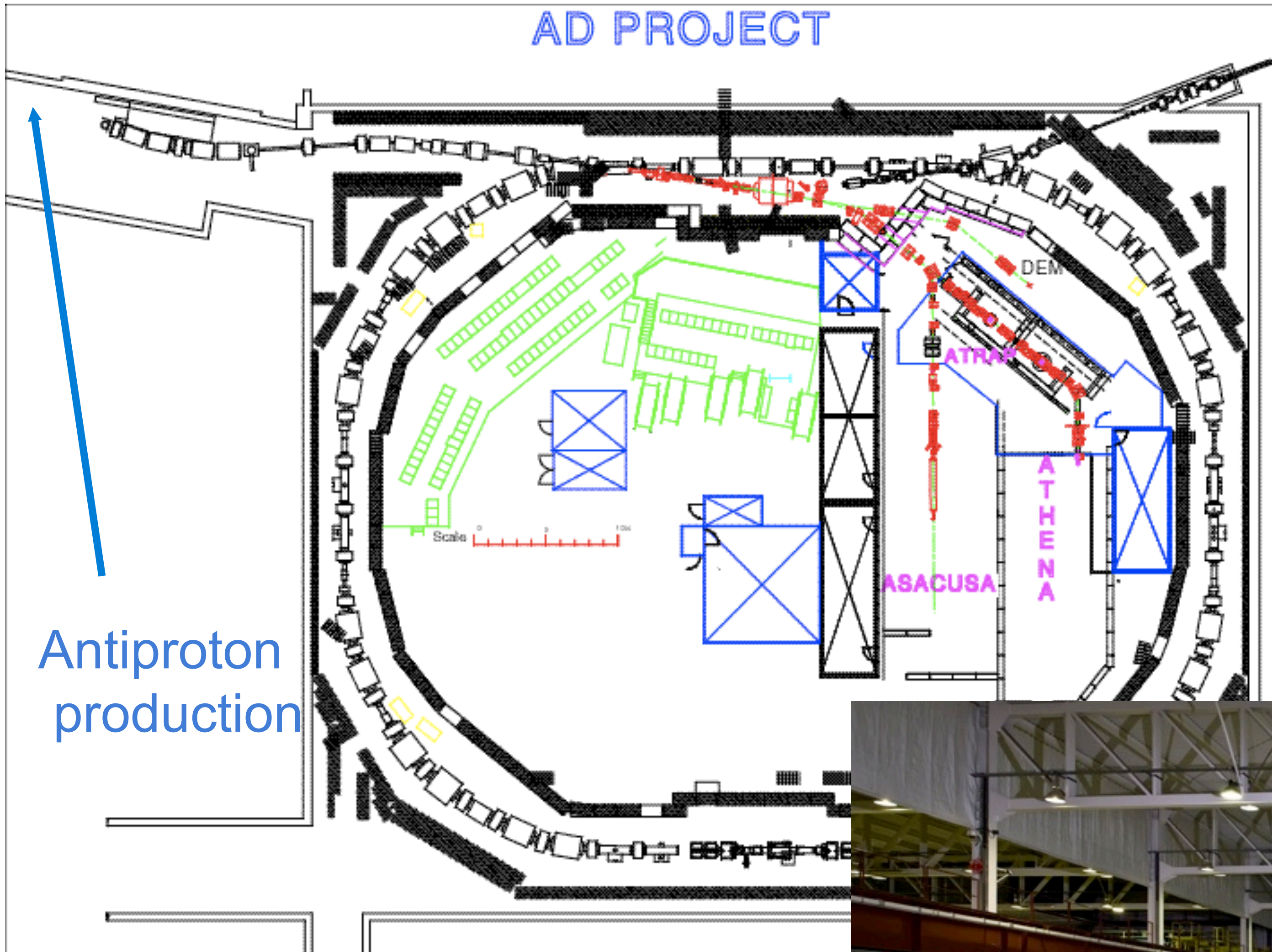
Current source: AD @ CERN



- All-in-one machine:
  - Antiproton capture
  - deceleration & cooling
  - 100 MeV/c (5.3 MeV)
- Pulsed extraction
  - 2-4 x 10^7 antiprotons per pulse of 100 ns length
  - 1 pulse / 85−120 seconds

ASACUSA collaboration @ CERN-AD

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Asakusa Kannon Temple
by Utagawa Hiroshige (1797-1858)

Atomic **S**pectroscopy **A**nd **C**ollisions
Using **S**low **A**ntiprotons

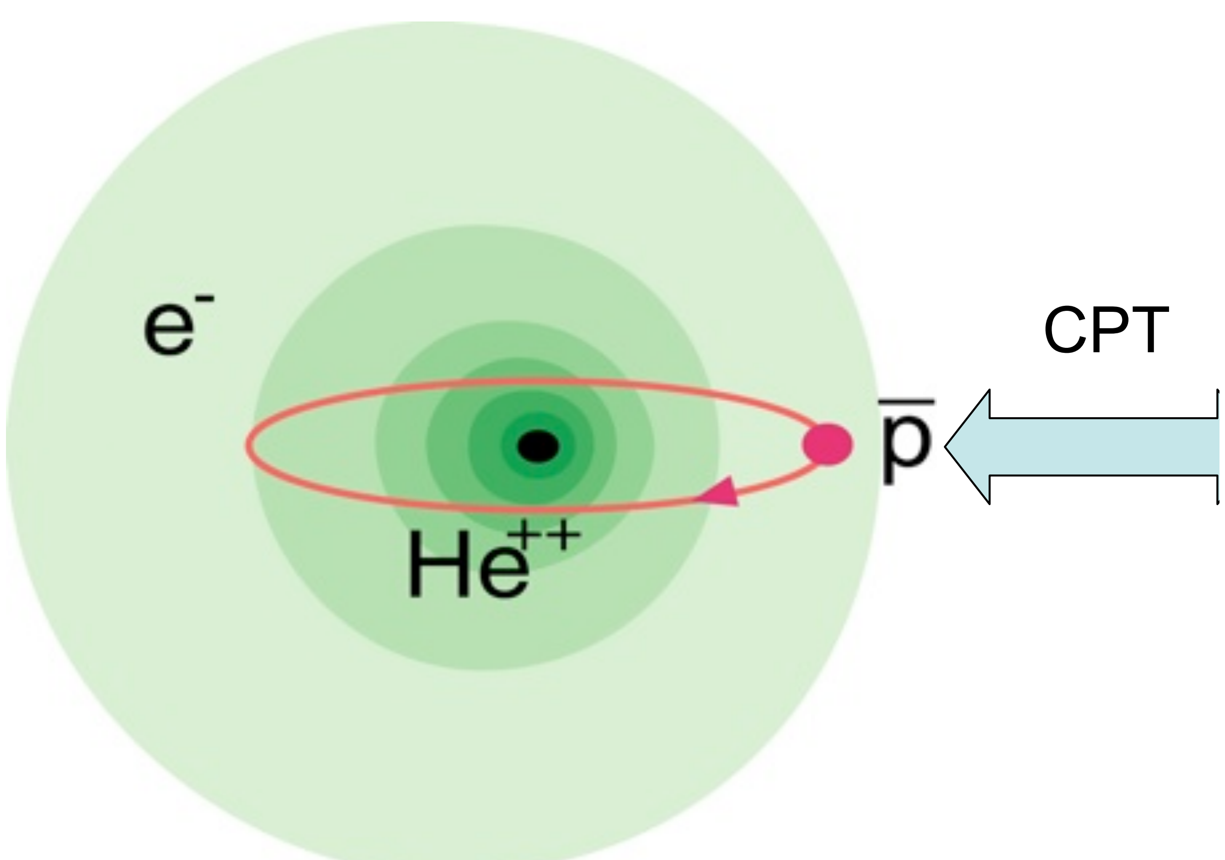
Spokesperson: R.S. Hayano, University of Tokyo

- University of Tokyo, Japan
  - Institute of Physics
  - Faculty of Science, Department of Physics
- RIKEN, Saitama, Japan
- SMI, Austria
- Aarhus University, Denmark
- Max-Planck-Institut für Quantenoptik, Munich, Germany
- Institute for Particle and Nuclear Physics, Wigner Center for Physics, Budapest, Hungary
- ATOMKI Debrecen, Hungary
- Brescia University & INFN, Italy
- University of Wales, Swansea, UK
- The Queen’s University of Belfast, Ireland

~ 44 members

Antiprotonic Helium and CPT

- Three-body system He^{++}-e^--$\bar{p}$
  - $\bar{p}$ in highly excited, near circular states (n,l) ~ (38,37)
- Easy (automatic) formation
- Comparison to 3-body QED calculations with $m_{\bar{p}}$
  - 2 heavy centers: molecular calculations



$$E_{nr} = \left\langle -\frac{1}{2m_{13}}\nabla^2_{\mathbf{r}_1} - \frac{1}{2m_{23}}\nabla^2_{\mathbf{r}_2} - \frac{1}{m_3}\nabla_{\mathbf{r}_1}\nabla_{\mathbf{r}_2} + \frac{Z_1Z_3}{r_1} + \frac{Z_2Z_3}{r_2} + \frac{Z_1Z_2}{r_{12}} \right\rangle.$$

$$E_{rc} = \alpha^2 \left\langle -\frac{\nabla_i^4}{8m_e^3} + \frac{1}{8m_e^2}\left[Z_{\mathrm{He}}4\pi\delta(\mathbf{r}_{\mathrm{He}}) + Z_{\bar{p}}4\pi\delta(\mathbf{r}_{\bar{p}})\right] \right\rangle.$$

$$E_{rc-qed} = \alpha^2 \left\langle \frac{2a_e}{8m_e^2}\left[Z_{\mathrm{He}}4\pi\delta(\mathbf{r}_{\mathrm{He}}) + Z_{\bar{p}}4\pi\delta(\mathbf{r}_{\bar{p}})\right] \right\rangle,$$

$$E_{se} = \alpha^3 \left\langle \frac{4Z_i}{3}\delta(\mathbf{r}_i)\left\{\left[\ln\frac{1}{\alpha^2} - \ln\frac{k_0(n)}{\mathrm{Ry}} + \frac{5}{6} - \frac{3}{8}\right] + (Z_i\alpha)3\pi\left(\frac{139}{128} - \frac{1}{2}\ln 2\right) - \frac{3}{4}(Z_i\alpha)^2\ln^2\frac{1}{(Z_i\alpha)^2}\right\}\right\rangle.$$

$$E_{vp} = \alpha^3 \left\langle \frac{4Z_i}{3}\left[-\frac{1}{5} + (Z_i\alpha)\pi\frac{5}{64}\right] \right\rangle.$$

$$E_{RMC} = -\alpha^2 \left\langle \frac{\nabla^4_{\mathrm{He}}}{8m^3_{\mathrm{He}}} + \frac{\nabla^4_{\bar{p}}}{8m^3_{\bar{p}}} \right\rangle.$$

$$E_{ret} = \alpha^2 \sum_{i>j} \frac{Z_iZ_j}{2m_im_j} \left\langle \frac{\nabla_i\nabla_j}{r_{ij}} + \frac{\mathbf{r}_{ij}(\mathbf{r}_{ij}\nabla_i)\nabla_j}{r_{ij}^3} \right\rangle.$$

$$E_{two-loop} = \alpha^4 \left\langle \frac{Z_i}{\pi}\left[-\frac{6131}{1296} - \frac{49\pi^2}{108} + 2\pi^2\ln 2 - 3\zeta(3)\right]\delta(\mathbf{r}_i) \right\rangle$$

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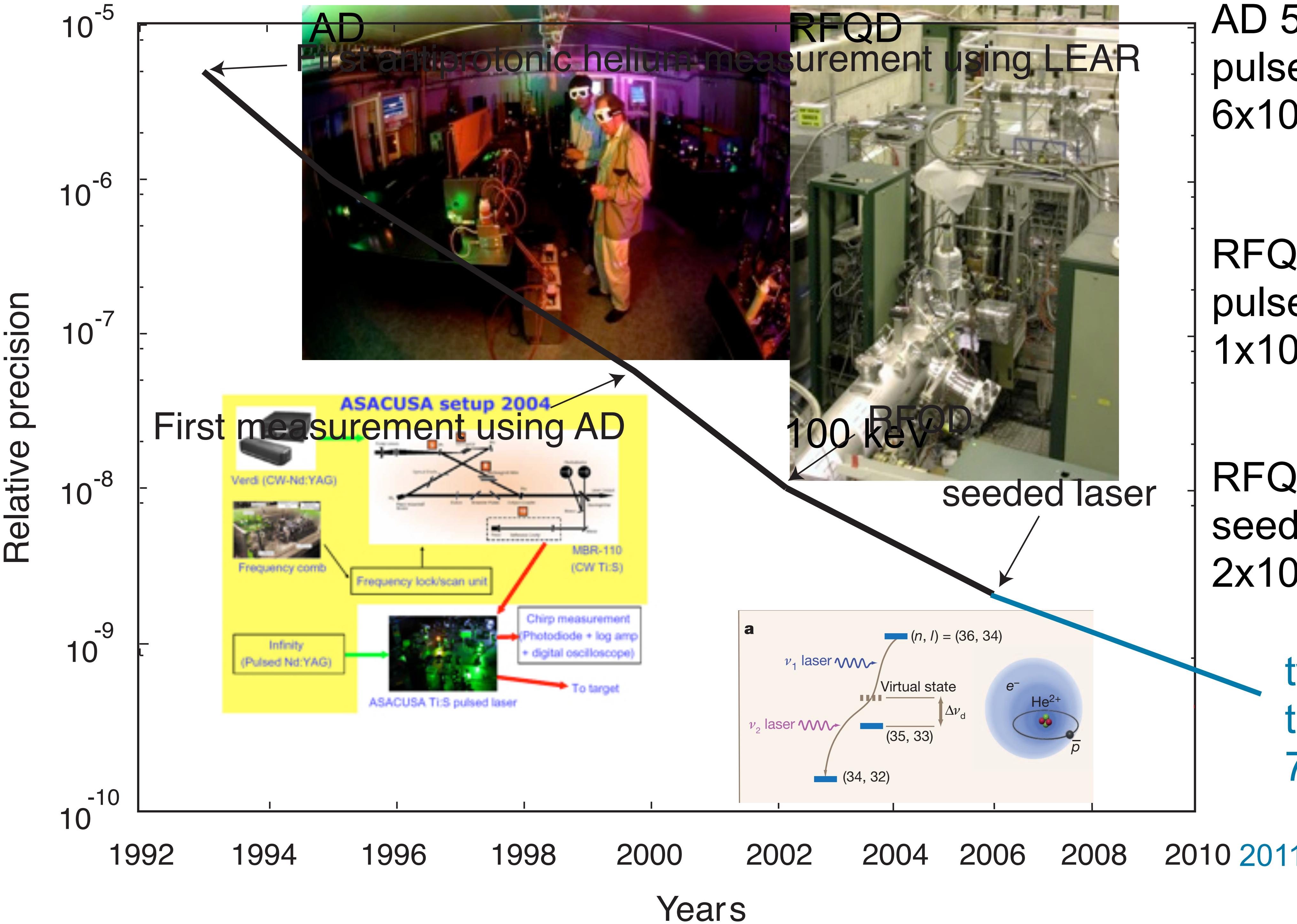
Progress in atomcule spectroscopy



AD 5.3 MeV, pulsed dye laser 6×10^{-8}

RFQD 100 keV, pulsed dye laser 1×10^{-8}

RFQD 100 keV, seeded laser 2×10^{-9}

two-photon transitions 7×10^{-10}

Experimental improvement: M. Hori *MPQ Munich*

Parallel theoretical improvement: V.I. Korobov *JINR Dubna*

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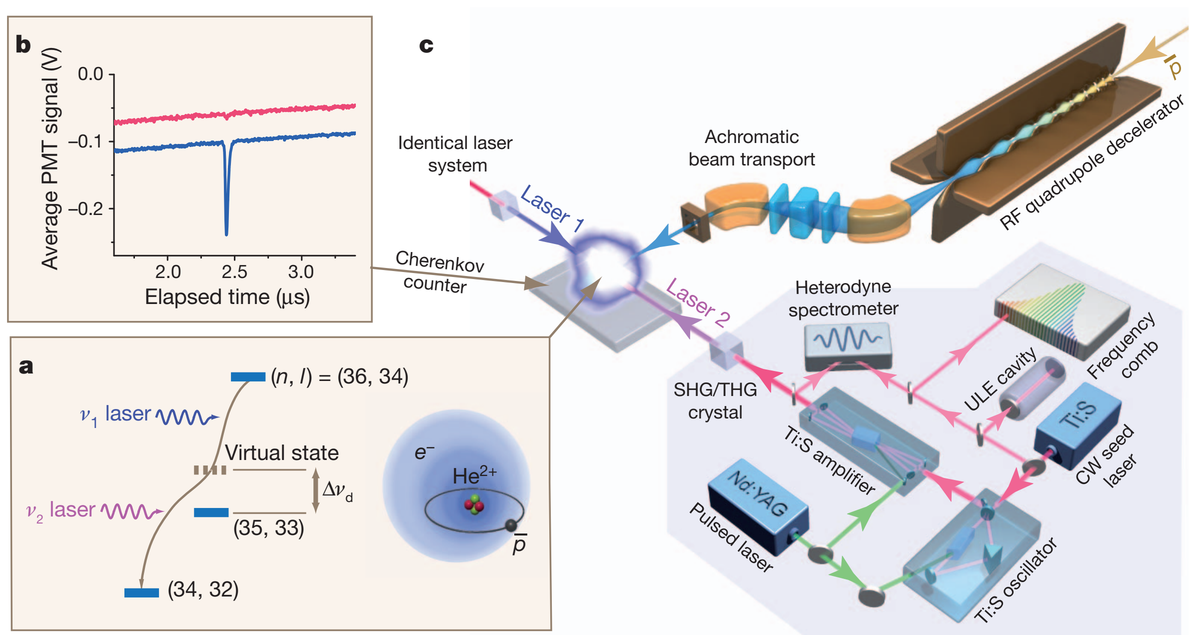
Two-photon spectroscopy of $p^{bar}He^{+}$

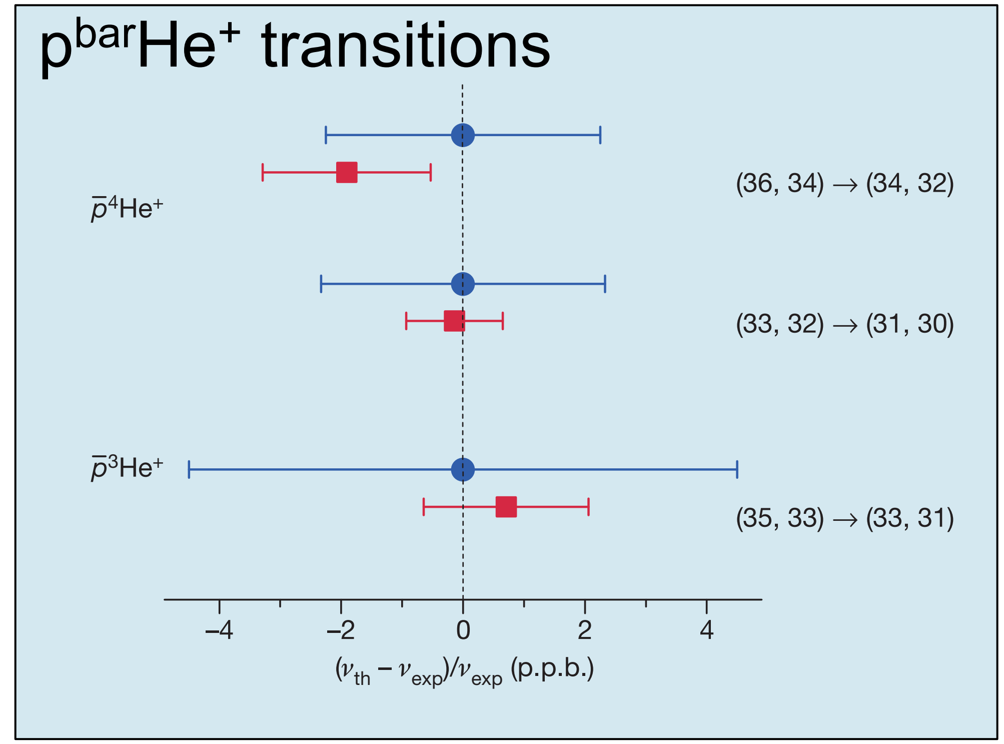


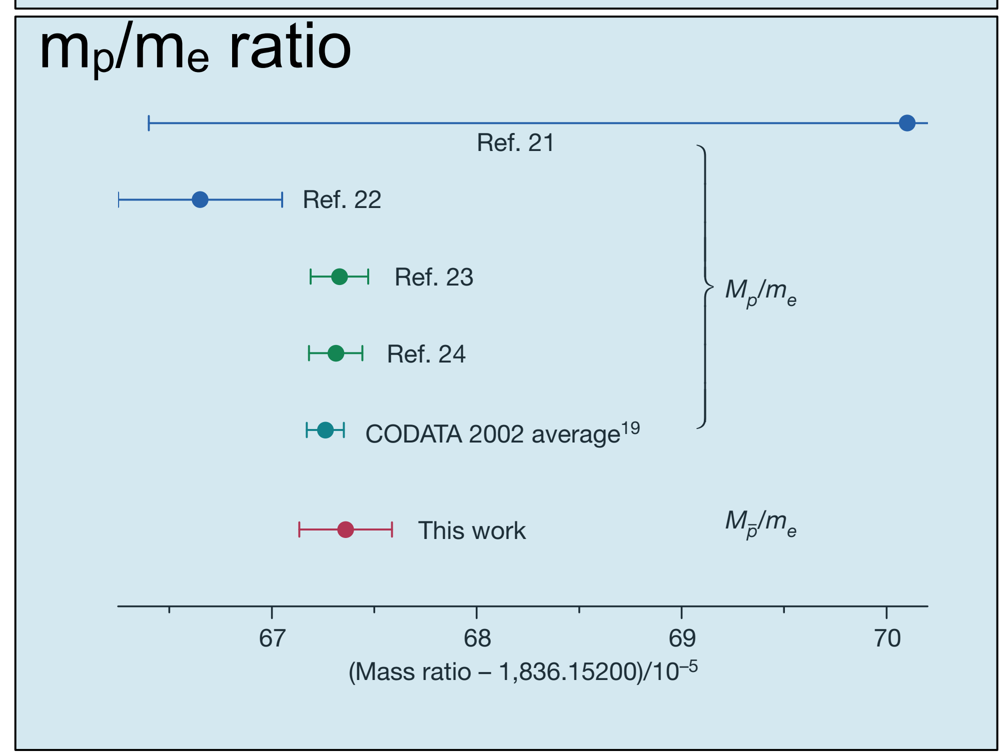
two-photon laser spectroscopy:
$m_{\bar{p}}/m_e$ = 1,836.1526736(23)(1.3 ppb)

$$\left|\frac{M_{\bar{p}} - M_p}{M_p}\right| \approx \left|\frac{Q_{\bar{p}} - Q_p}{Q_p}\right| < 7\text{x}10^{-10}\ (90\%\text{CL})$$

with constraint
G. Gabrielse et al. Phys. Rev. Lett. 82 (1999) 3198

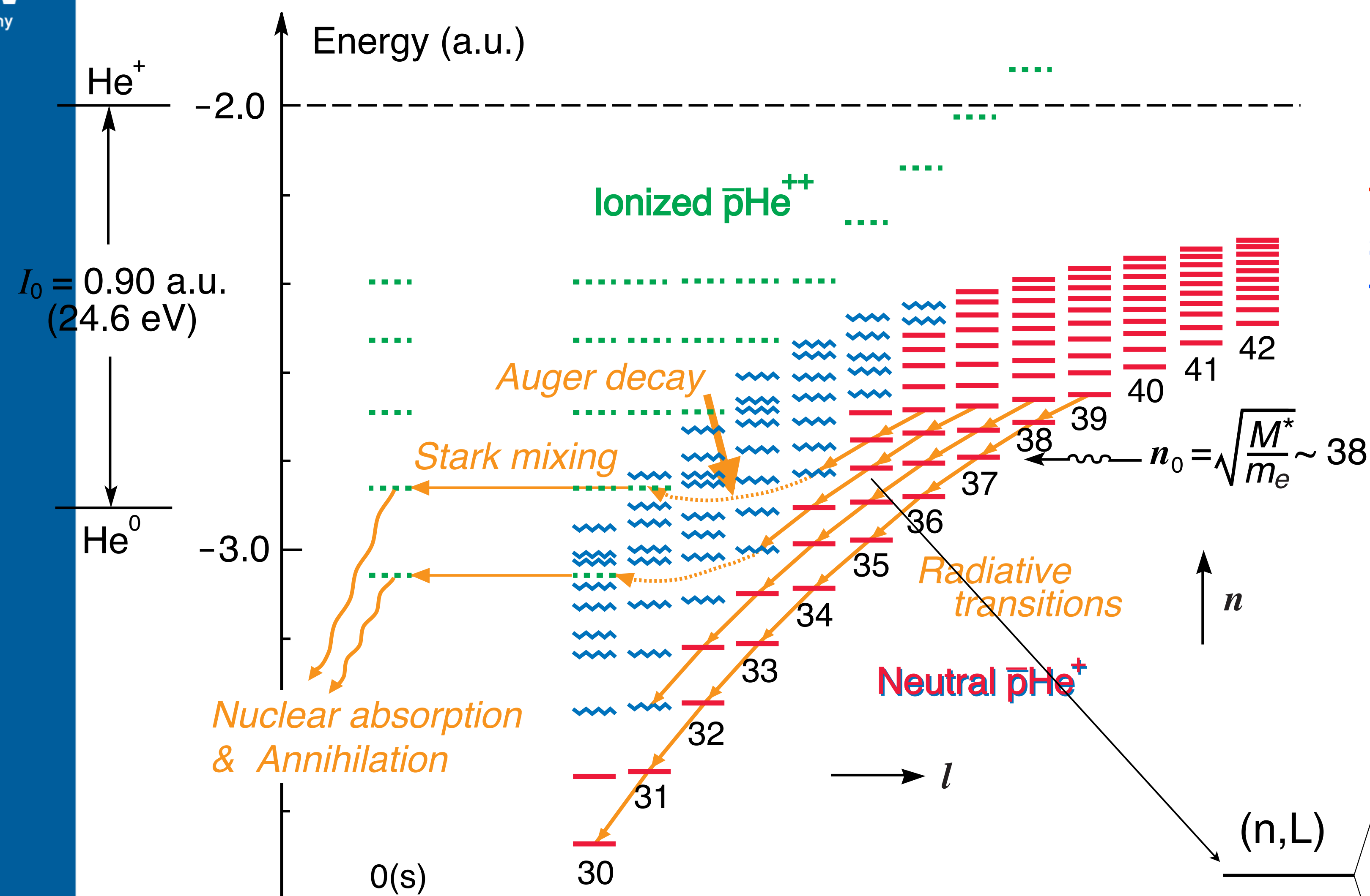
$$(Q_{\bar{p}}/M_{\bar{p}})/(Q_p/M_p) + 1 = 1.6(9) \times 10^{-10}$$





M. Hori et al. Nature 475, 484 (2011)
included in CODATA 2010 for proton

Antiprotonic helium „atomcule“ HFS

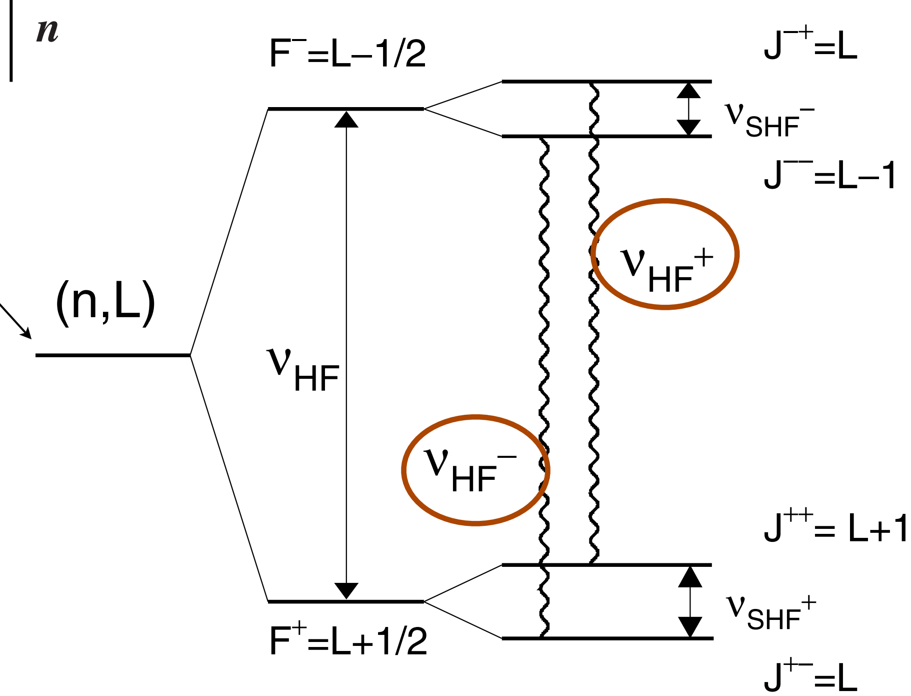


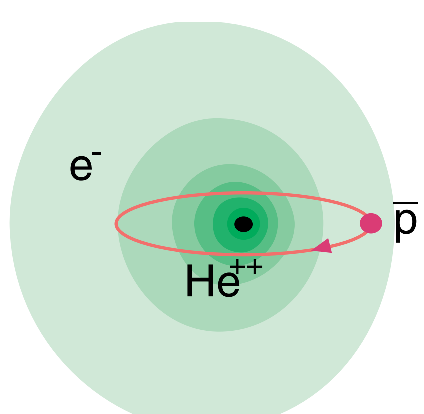
Metastable states

τ~ μs

short-lived states (Auger decay)

τ ≤ 10 ns





HFS: L_{pbar} - S_e, $\nu_{HF} \sim$ 10−15 GHz

SHFS: S_{pbar}, $\nu_{SHF} \sim$ 100 MHz

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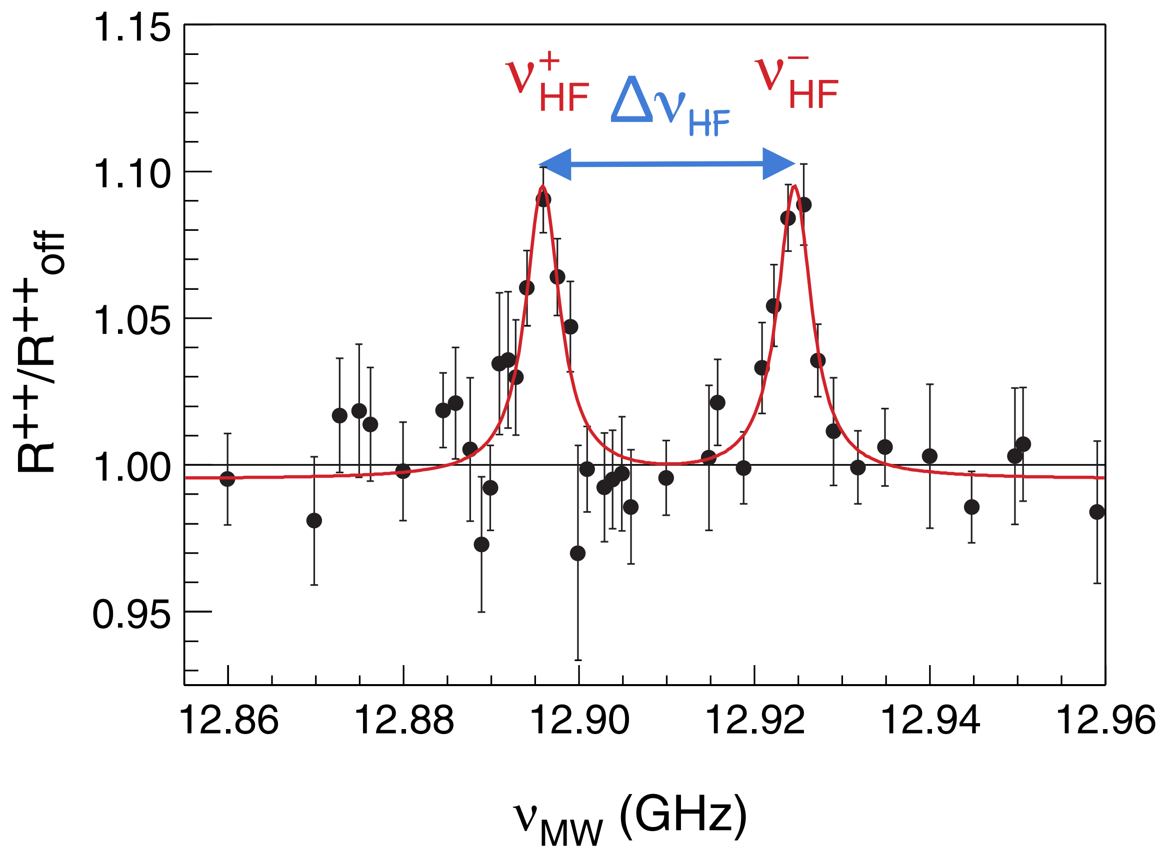
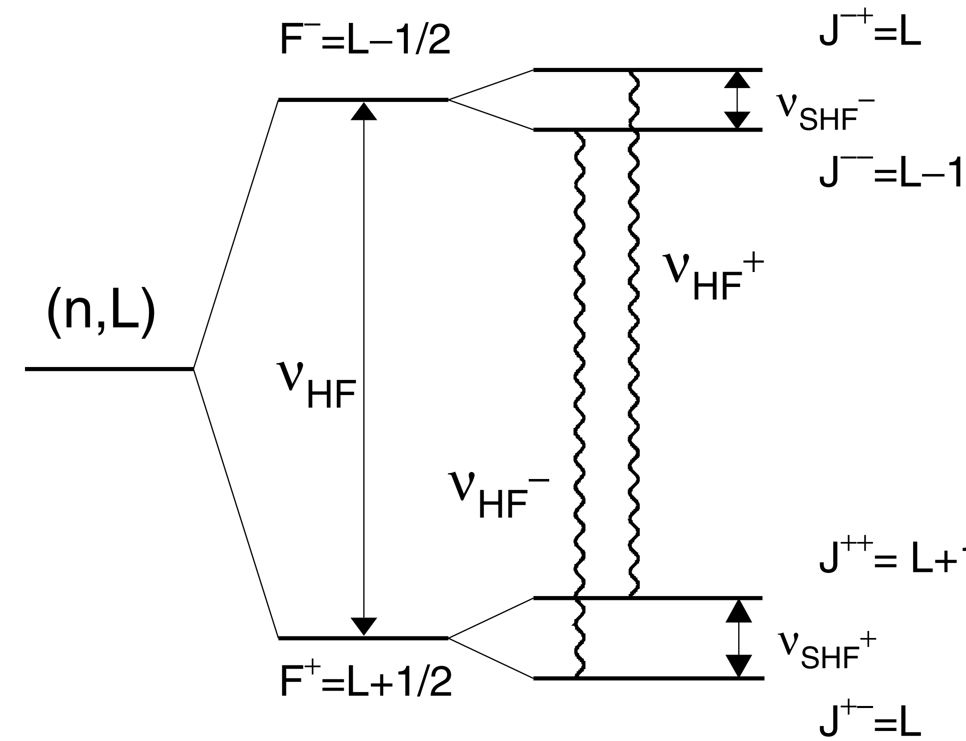
determination of $\mu_{\bar{p}}$





- $\nu_{SHF}{}^+$, $\nu_{SHF}{}^-$ most sensitive, but impossible to measure (power requirement)
- $\Delta\nu_{HF} = \nu_{HF}{}^- - \nu_{HF}{}^+ = \nu_{SHF}{}^+ - \nu_{SHF}{}^-$: sensitive to $\mu_{\bar{p}}$
- sensitivity factors from theory (D. Bakalov and E.W., PRA 76 (2007) 012512)
  - $S(F,J)= \partial E_{nFLJ} / \partial\mu_{\bar{p}}\,|_{\mu_{\bar{p}} = -\mu_p}$
  - $S(\nu_{_{HF}}{}^+) = S(F^-J^{--}) - S(F^+J^{+-})$

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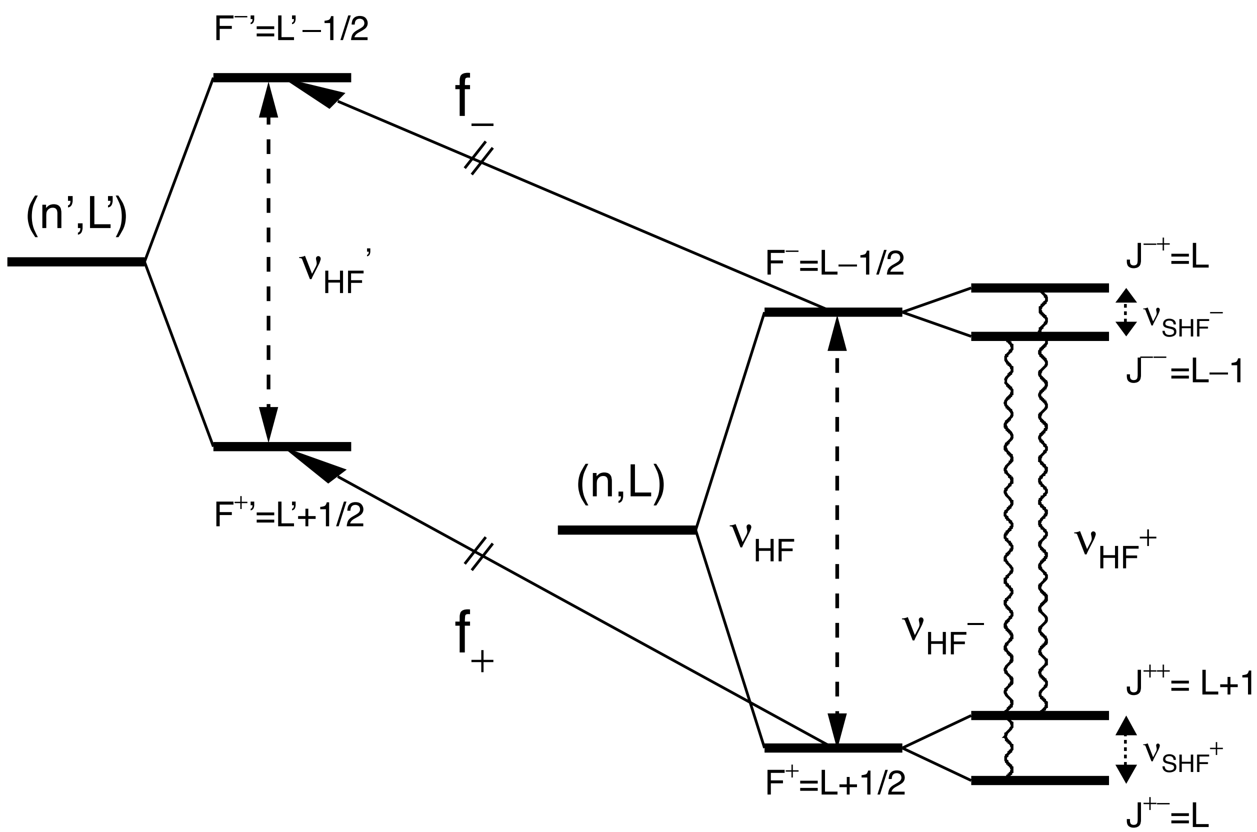
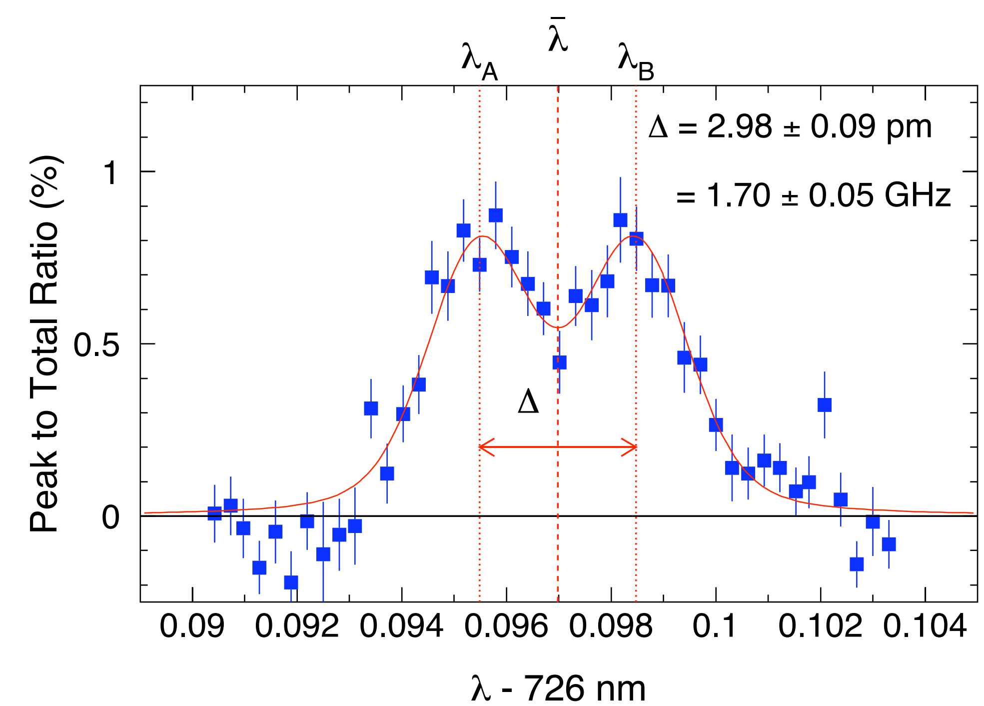
1st Observation of HFS in a laser transition





LEAR, E. W. et al. PLB 404 (1997) 15-19

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

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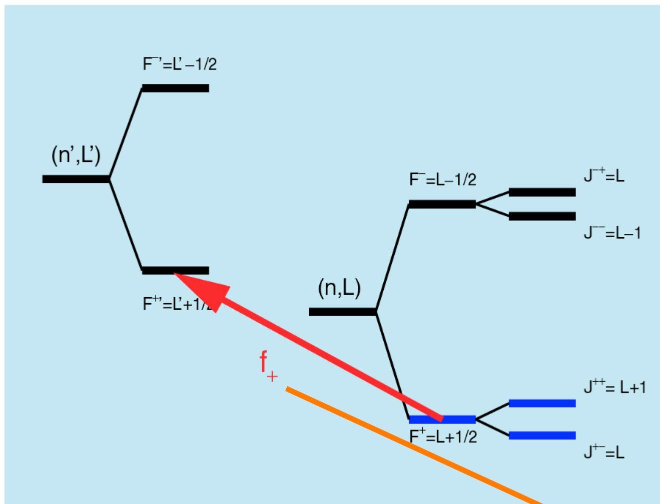
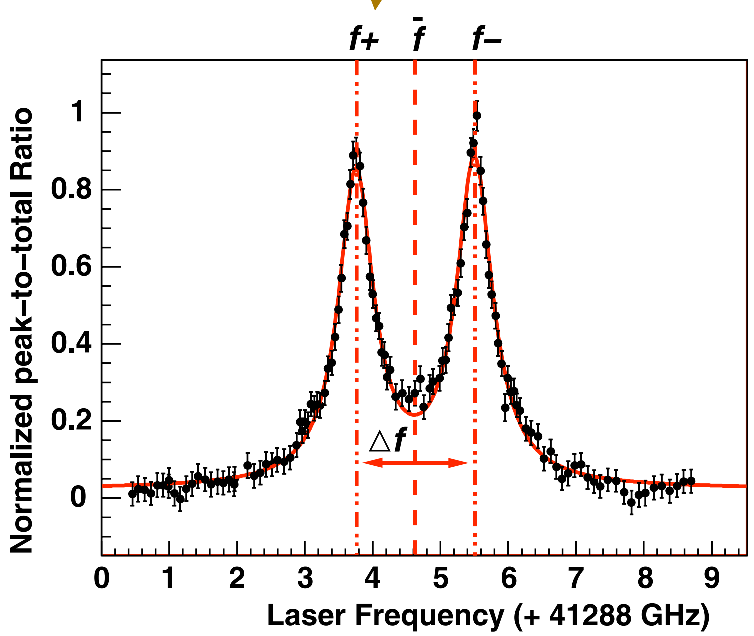
Laser-microwave-laser resonance experiment

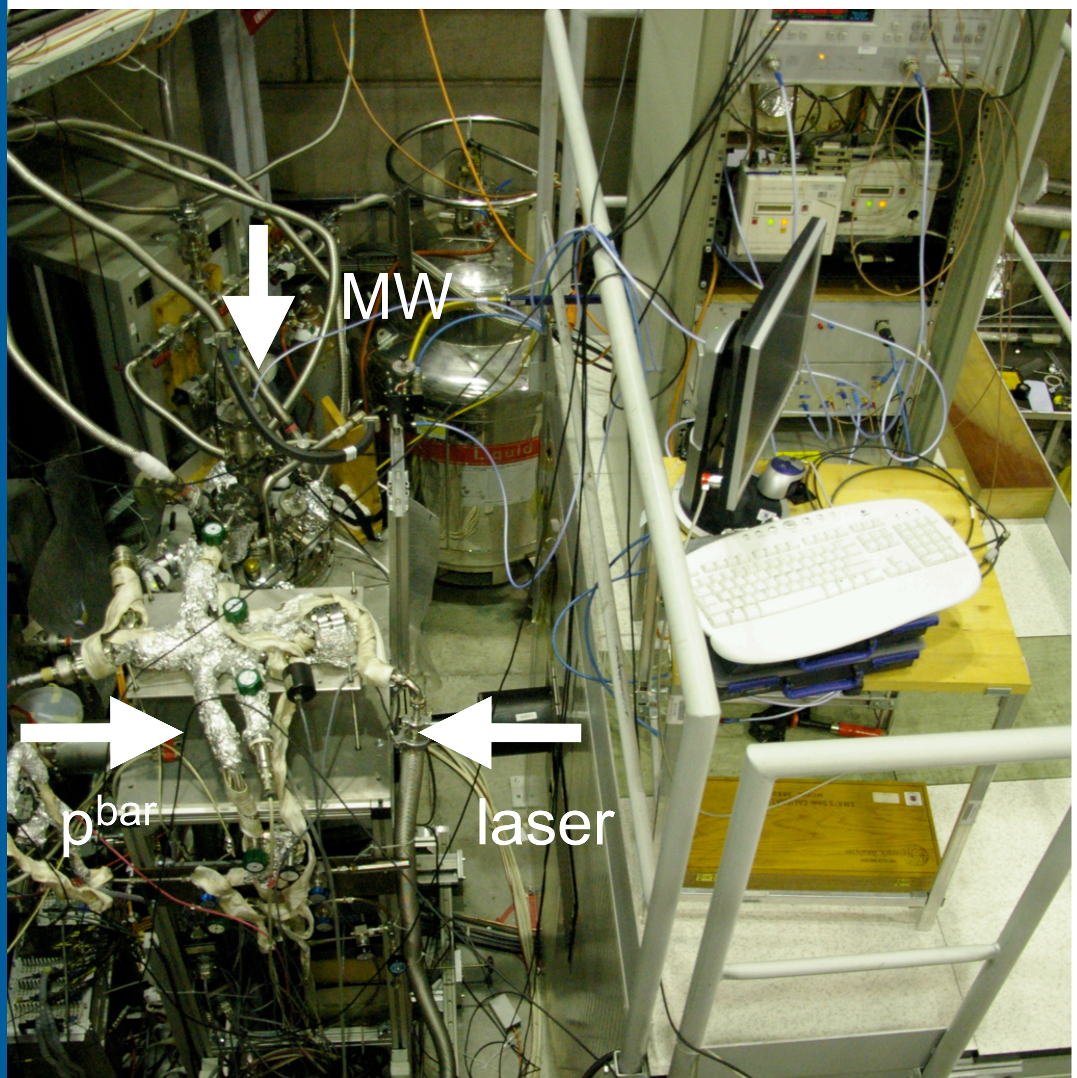
Parameters of (37,35) state:

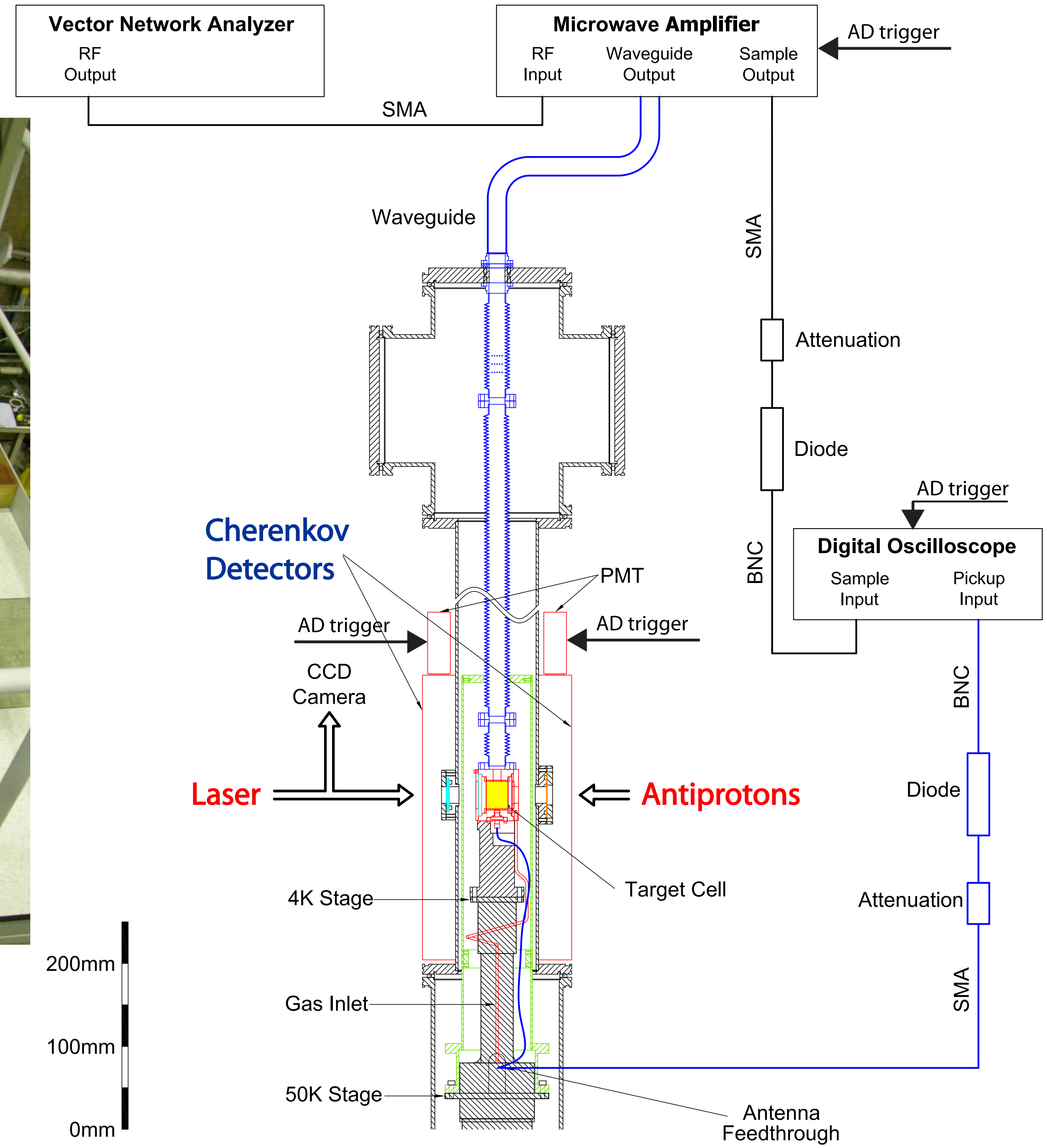


Step 1: depopulation of F^+ doublet with f_+ laser pulse

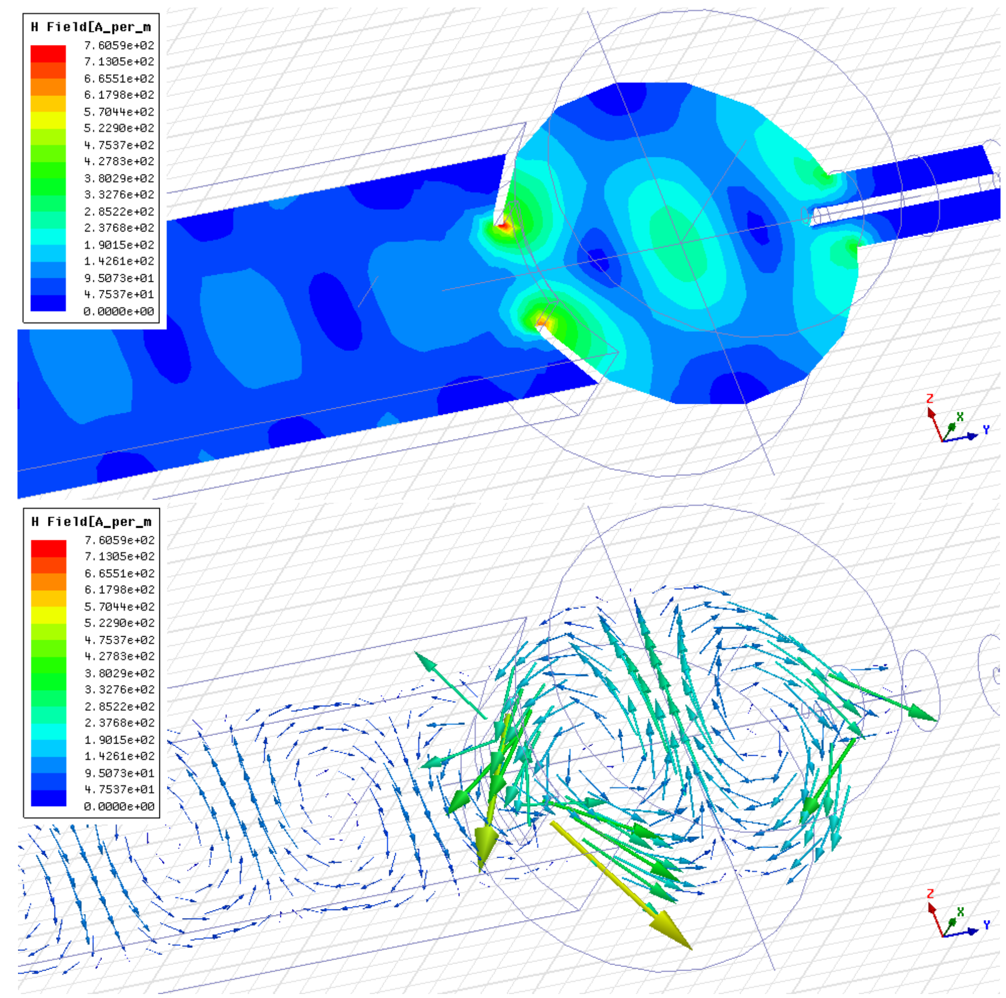


Experimental setup





Microwave cavity



- 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

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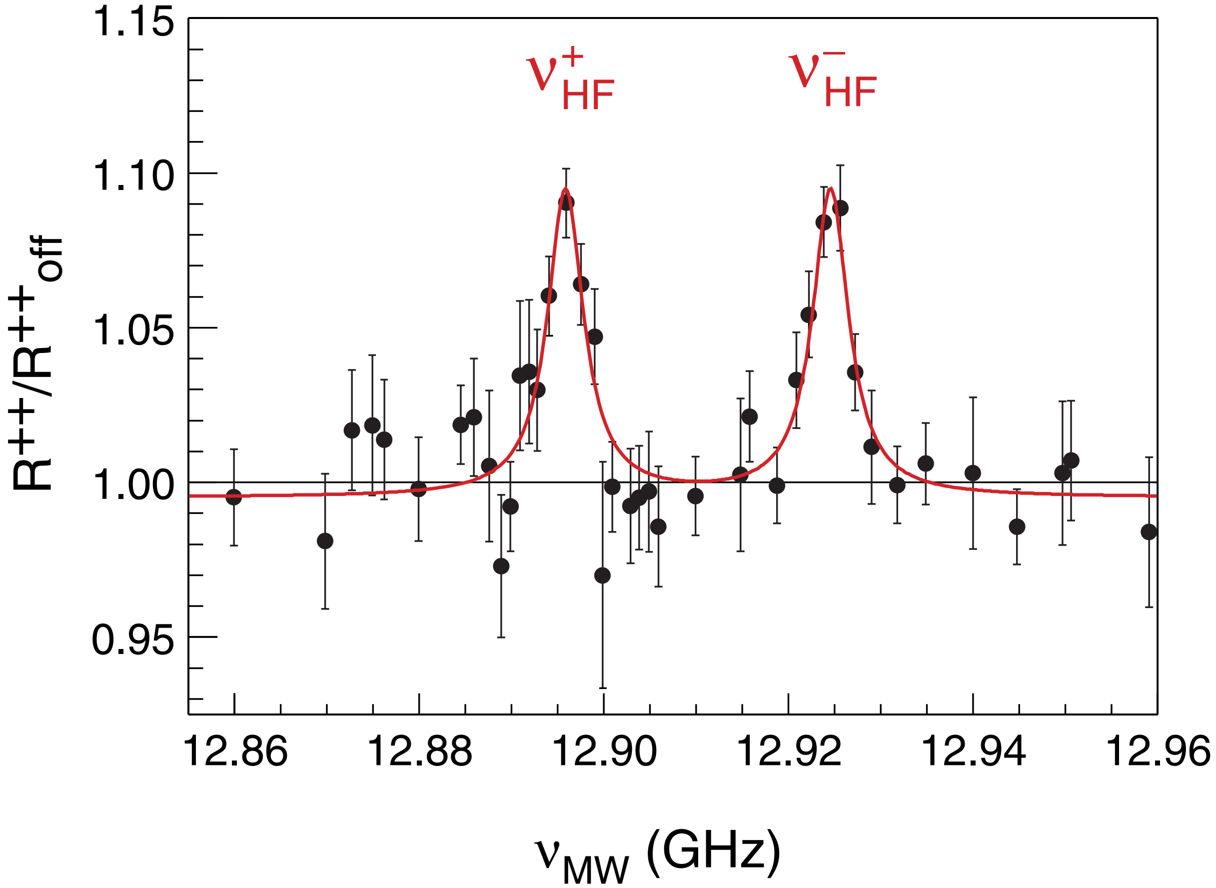
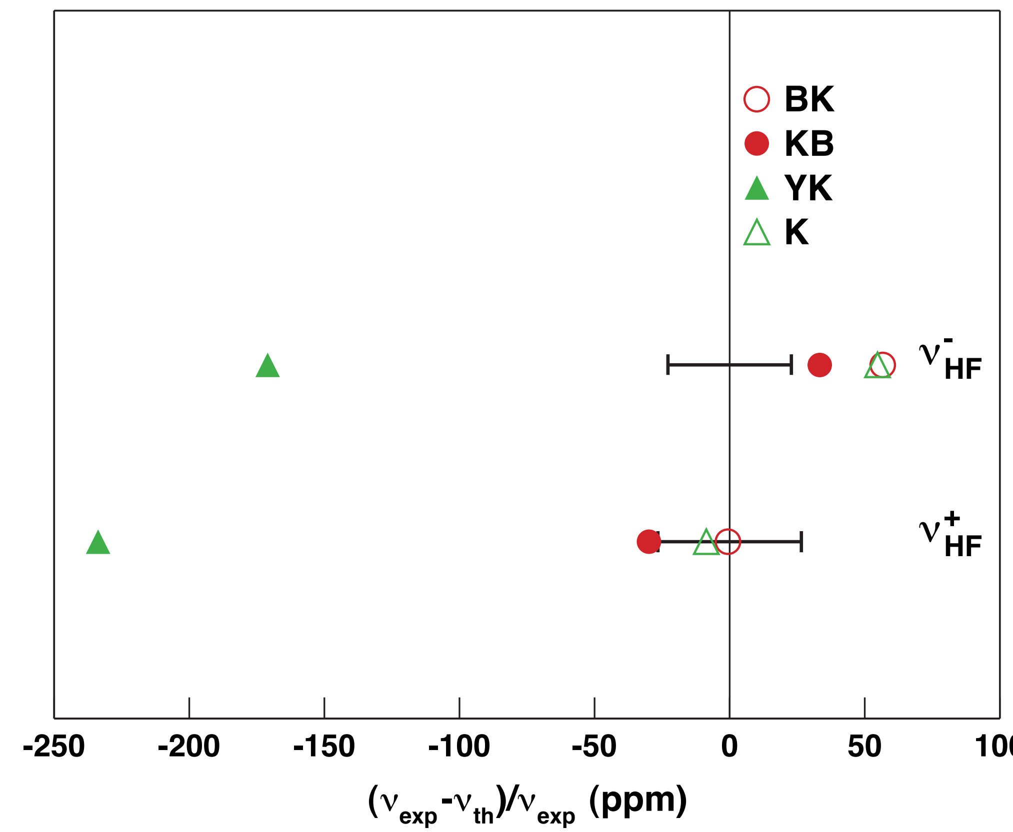
First observation of HFS MW transition





Experimental accuracy: ~ 3 x 10^{-5}

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

E.W. et al. PRL 89 (2002) 243402

- Comparison to theory favours most recent results of both groups
  - Korobov, Bakalov JPB 34 L519 2001
  - Kino et al. Proc. APAC 2001
- Difference < 6 x 10^{-5}
- Corresponds to theoretical uncertainty
  - Omission of terms $O(\alpha^2)$~5x10^{-5}

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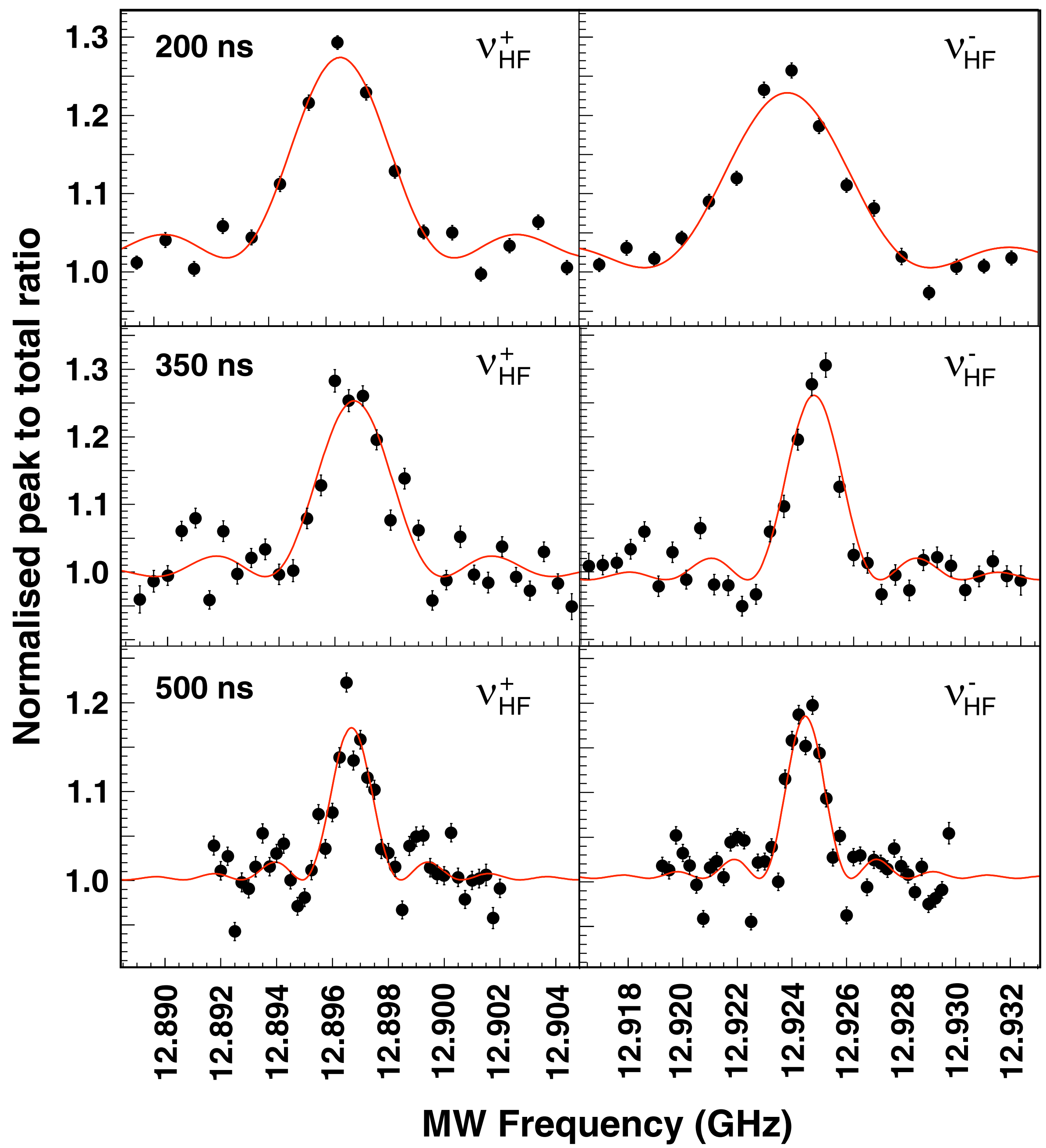
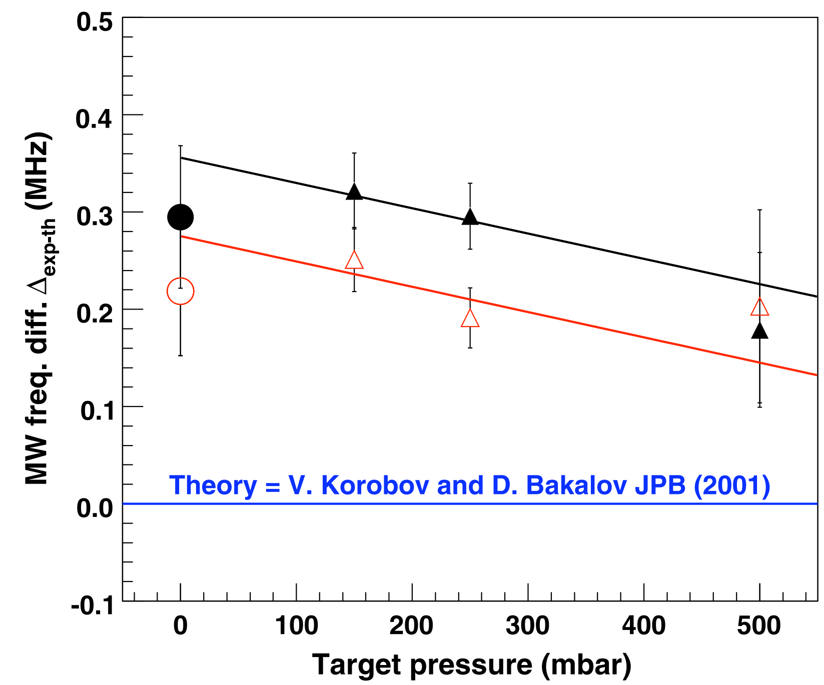
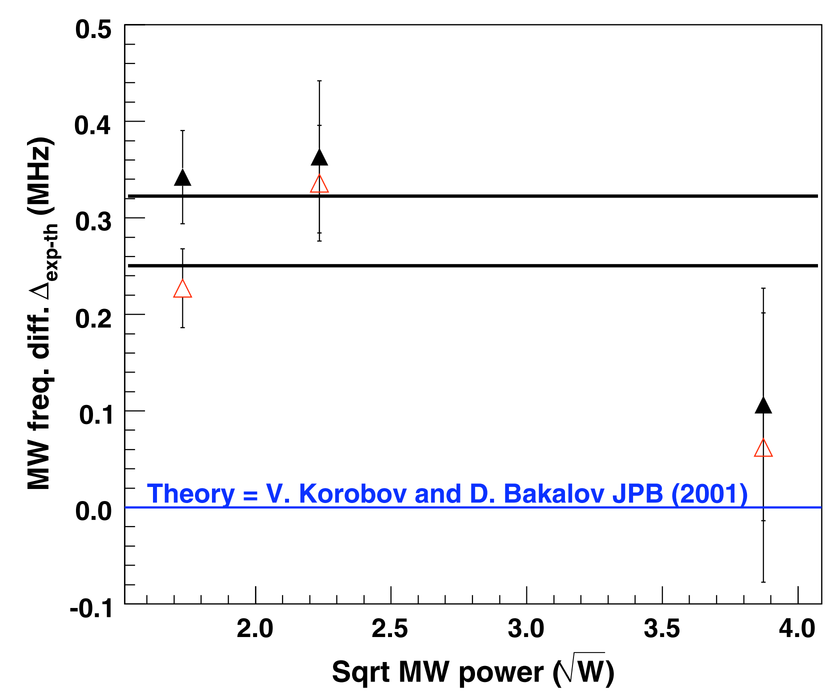
Systematic studies in ^{4}He



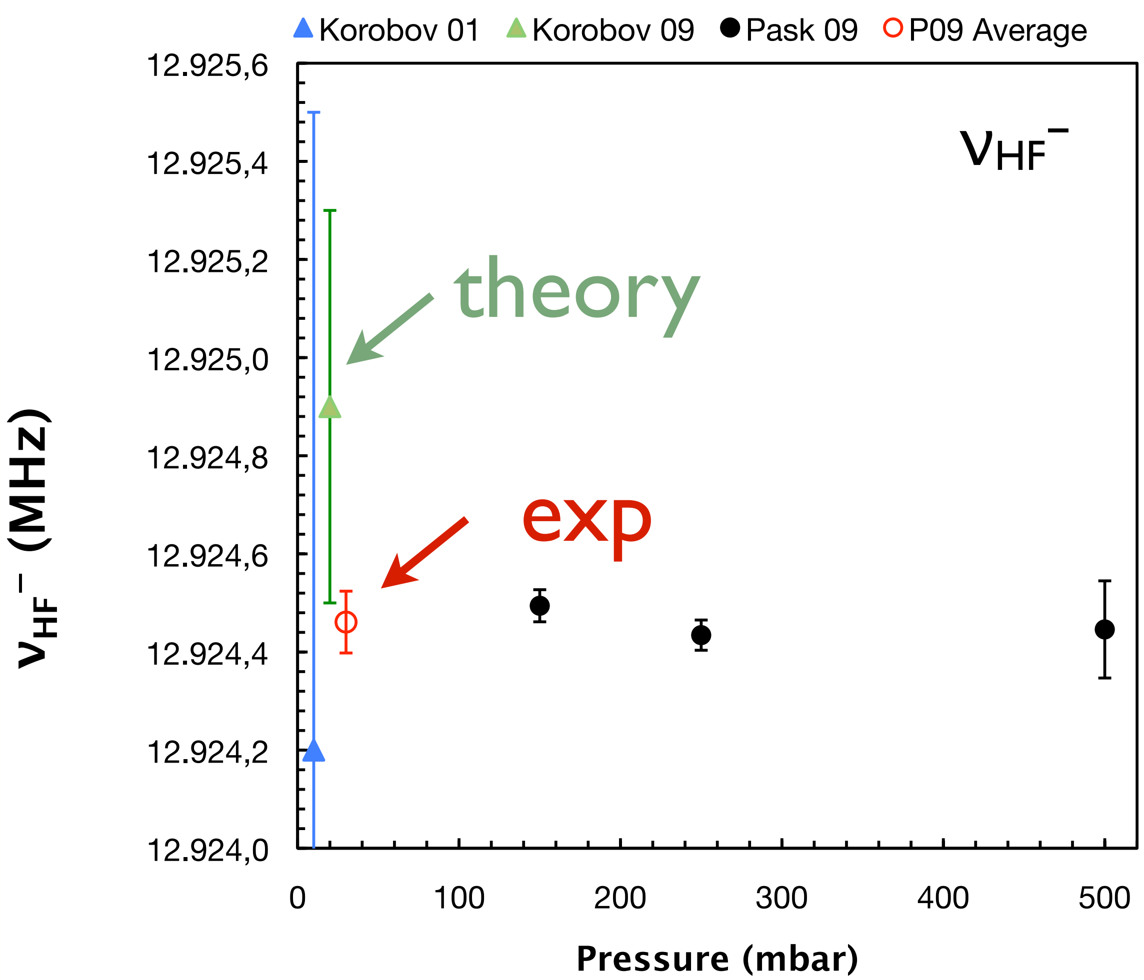
Time between laser shots

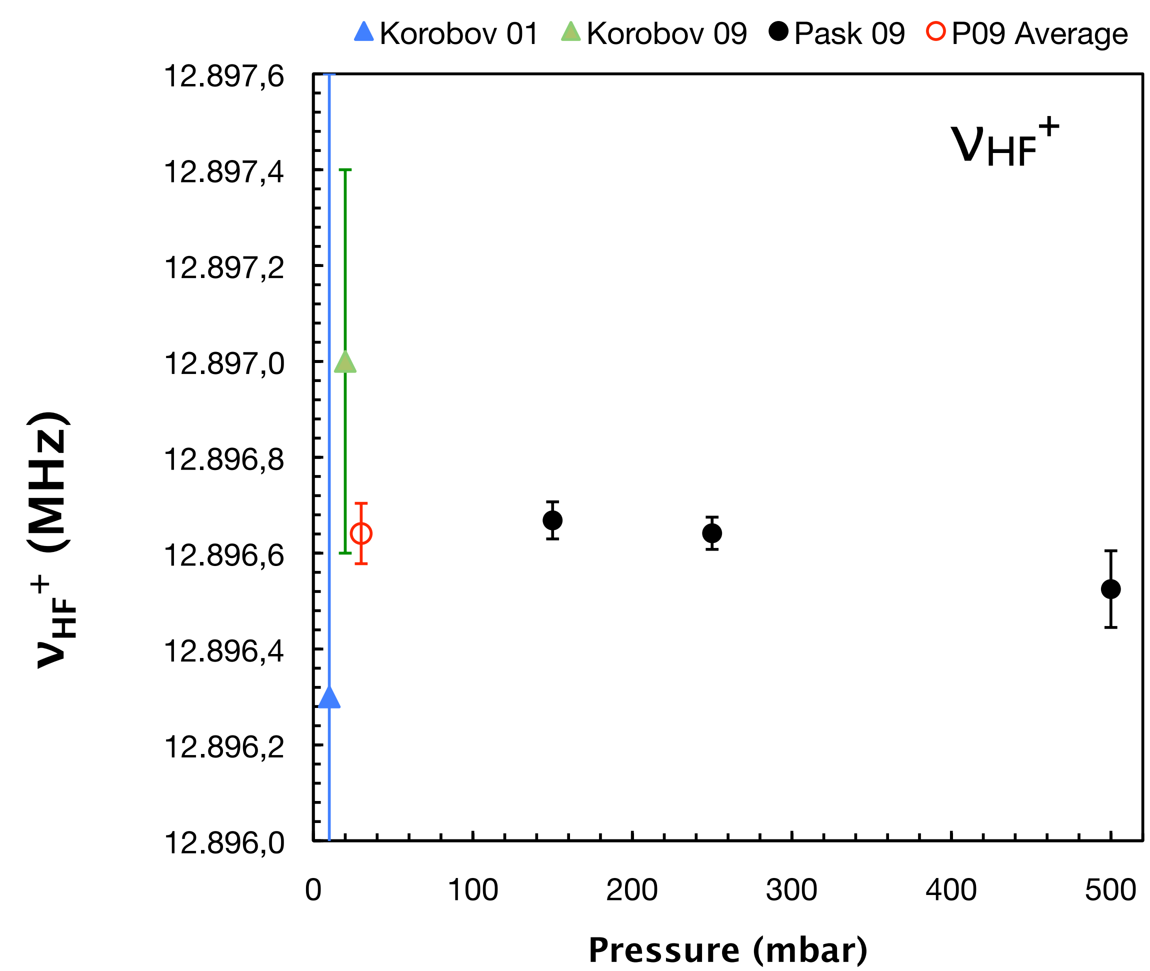




Target pressure, MW power

Comparison to theory in ^{4}He





accuracy exp: ν_{HF} : 5 ppm
th: 50 ppm

S. Friedreich, et al., *Hyperfine Interactions*, *199*, 337–346 (2011)

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Sonntag, 09. Dezember 12

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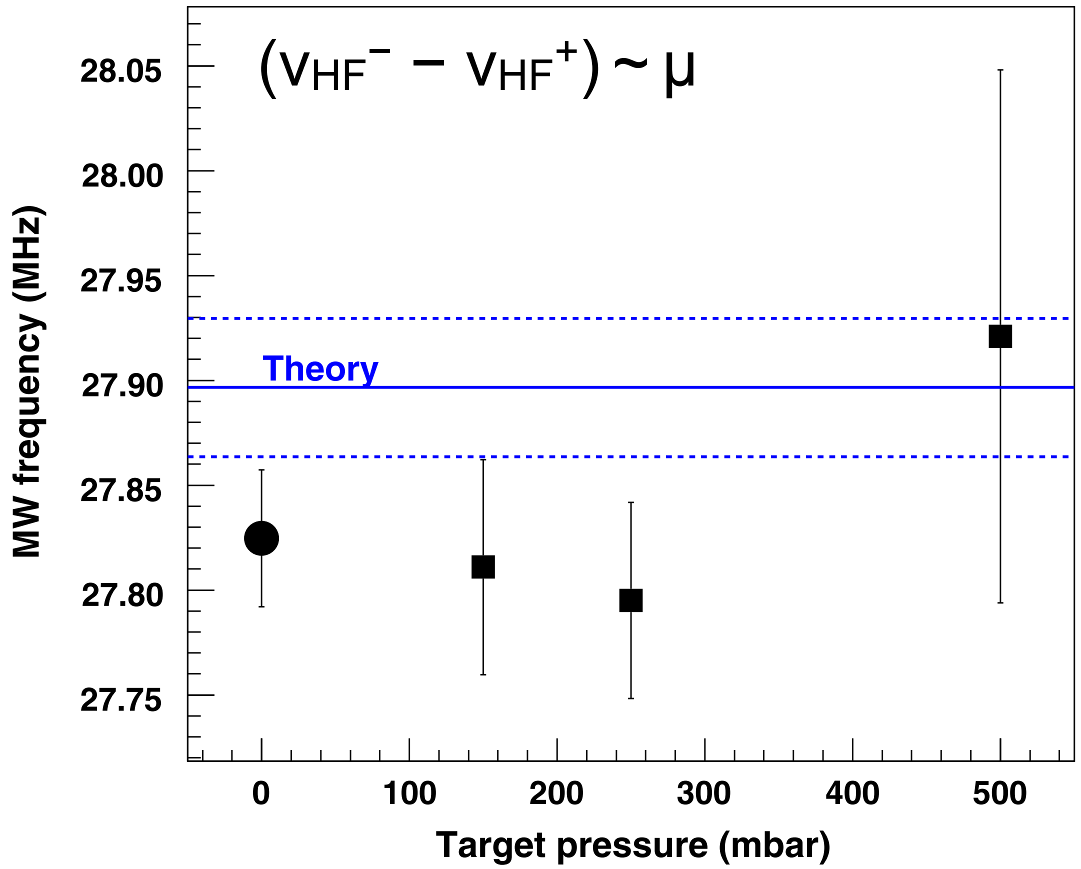
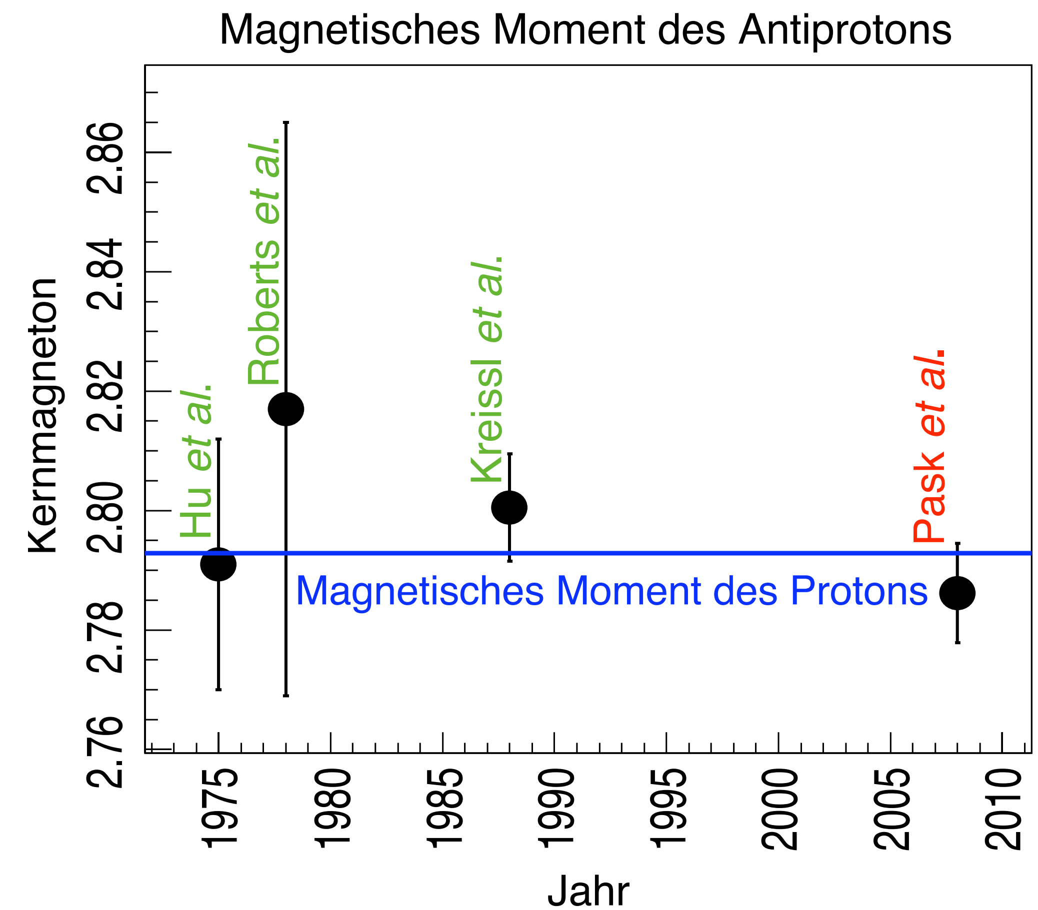
Magnetic moment of the antiproton





T. Pask et al. / Physics Letters B 678 (2009) 55–59

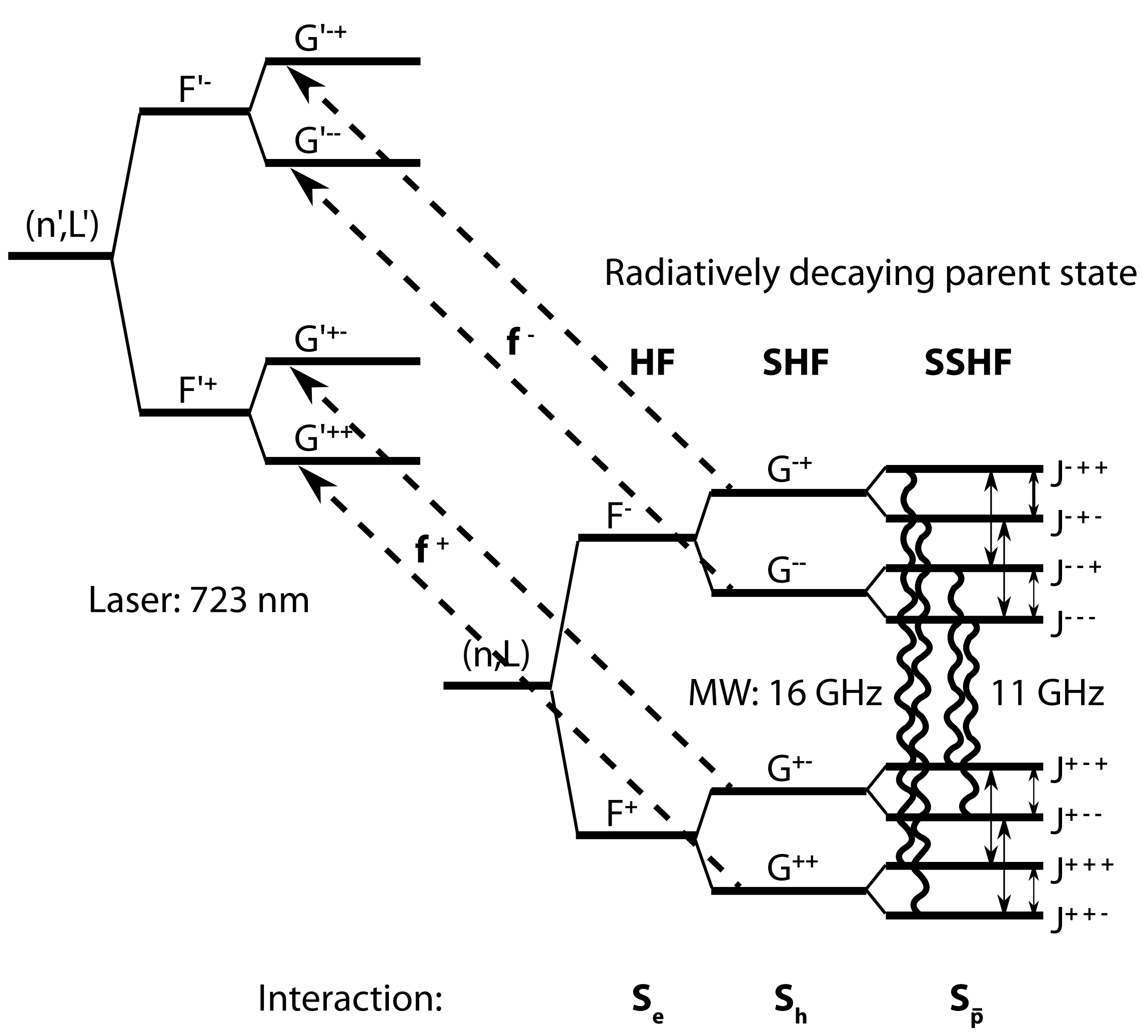
$$\mu_s^{\bar{p}} = -2.7862(83)\mu_N$$

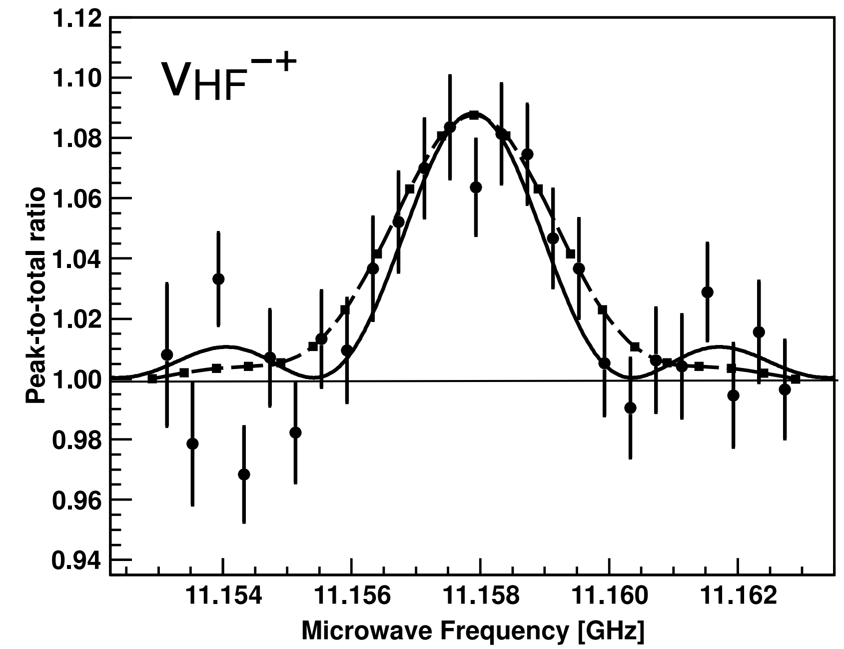
$\bar{p}$ MAGNETIC MOMENT — References — History since 1990

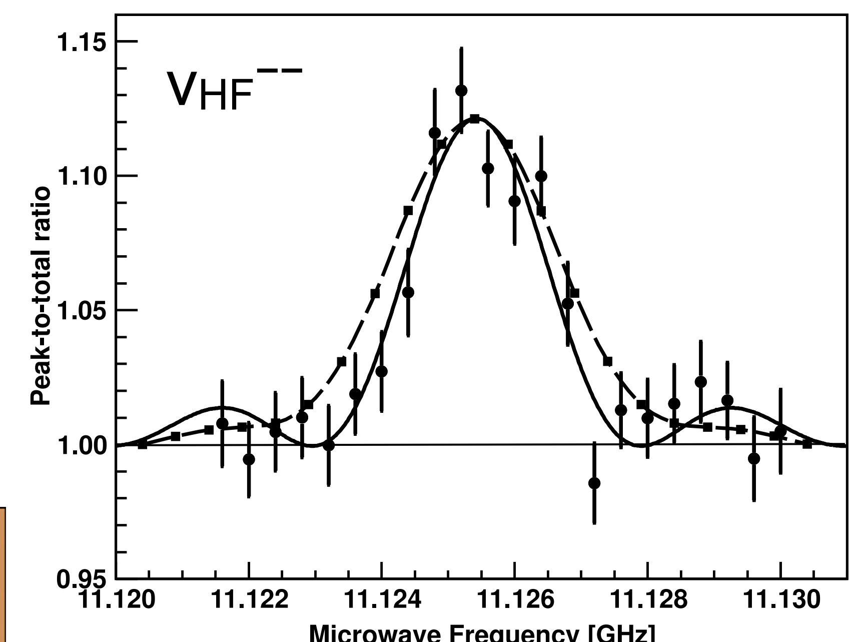
A few early results have been omitted.

VALUE (μ_N)	DOCUMENT ID		TECN	COMMENT
−2.793±0.006	**OUR AVERAGE**			
−2.7862±0.0083	PASK	09	CNTR	$\bar{p}$ He$^+$ hyperfine structure
−2.8005±0.0090	KREISSL	88	CNTR	$\bar{p}$ ^{208}Pb 11→10 X-ray
−2.817±0.048	ROBERTS	78	CNTR	
−2.791±0.021	HU	75	CNTR	Exotic atoms

HFS of antiprotonic ^{3}He







Contents lists available at ScienceDirect
Physics Letters B
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ELSEVIER

First observation of two hyperfine transitions in antiprotonic ^{3}He

S. Friedreich[a,*], D. Barna[b,c], F. Caspers[d], A. Dax[b], R.S. Hayano[b], M. Hori[b,e], D. Horváth[c,f], B. Juhász[a], T. Kobayashi[b], O. Massiczek[a], A. Sótér[e], K. Todoroki[b], E. Widmann[a], J. Zmeskal[a]

Physics Letters B, 700 (2011) 1–6

Agreement th-exp <5x10^{-5}
(~theory error)

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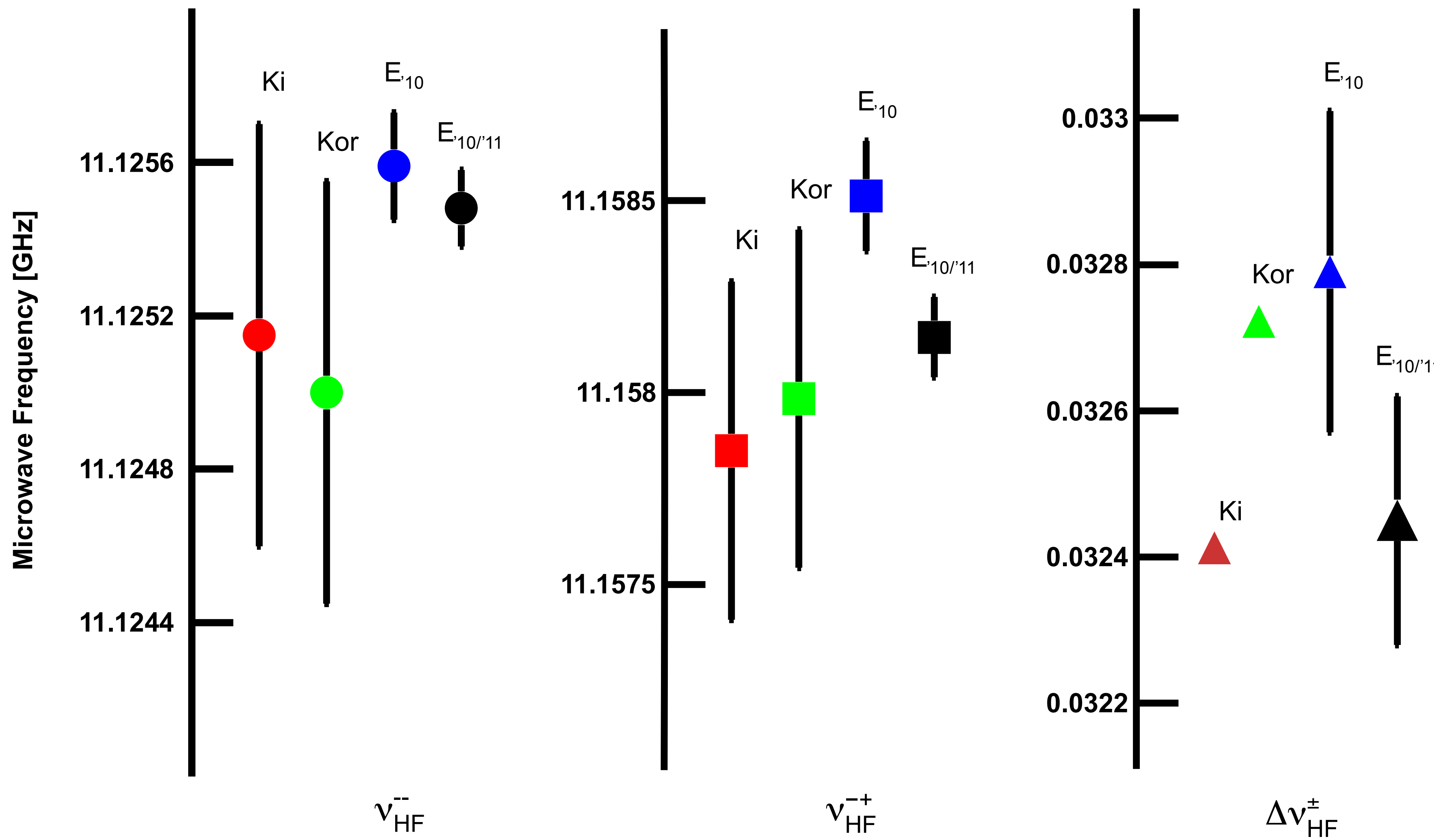
Comparison theory-experiment ^{3}He

exp. error:	13 ppm	16 ppm	0,7%
theory error	50 ppm	50 ppm	50 ppm



Kor: V. Korobov, Phys. Rev. A 73 (2006) 022509.
Ki: Y. Kino, et al., Hyperfine Interactions 146–147 (2003) 331.
E_{10}: S. Friedreich et al., Physics Letters B 700 (2011) 1–6
$E_{10/11}$: S. Friedreich, Ph.D. *(article in preparation)*

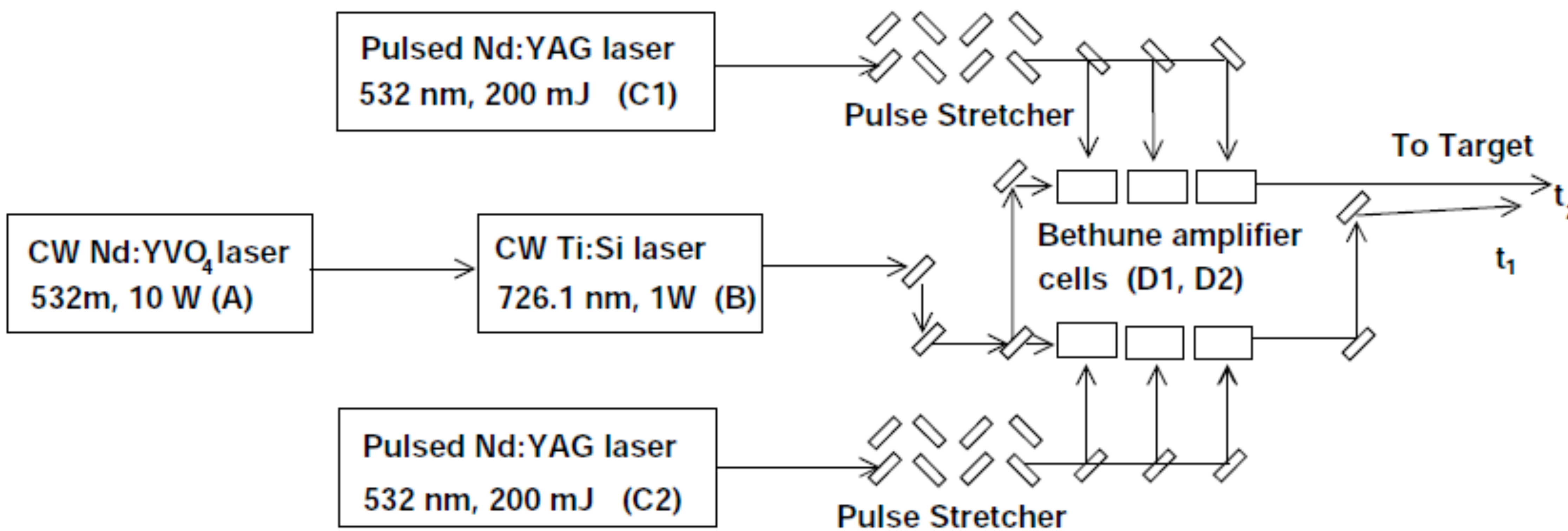
Summary and Outlook

- Atoms containing antiprotons offer exciting possibilities for tests of fundamental symmetries & interactions
- Precision spectroscopy of antiprotonic helium & three-body bound state QED
  - determine mass, charge *(rel. error $7x10^{-10}$)*, magnetic moment *(rel. error $2.9x10^{-3}$)* of the antiproton to highest precision
  - contribute to fundamental constants if CPT is assumed
- ultimate test of CPT with antiprotons
  - antihydrogen
- CERN-AD is currently unique in the world
- More low-energy antiprotons needed
  - ELENA upgrade at CERN (recently approved, start 2017)
  - FLAIR at FAIR (next decade)

New laser system

- Reduction of line width
  - Fourier limit
- Higher signal-to-noise
  - laser pulse > Auger lifetime

- Laser stability
  - pulse-amplified cw laser
  - narrow linewidth <100MHz
  - arbitrary time difference between
  - the two laser pulses



M. Hori, A. Dax

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