

Low Energy Antiproton Experiments

Villars sur Ollon, September 2004

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- **Atomic-, Nuclear-, Particle-Physics**
- **Forces and Symmetries**
- **Discrete Symmetries**
- **Properties of Known Basic Interactions**
- **Hydrogen and Hydrogen-like Atoms**
- **Fundamental Constants**

⇒ only touching a few examples

Fundamental Interactions – Standard Model

Gravitation

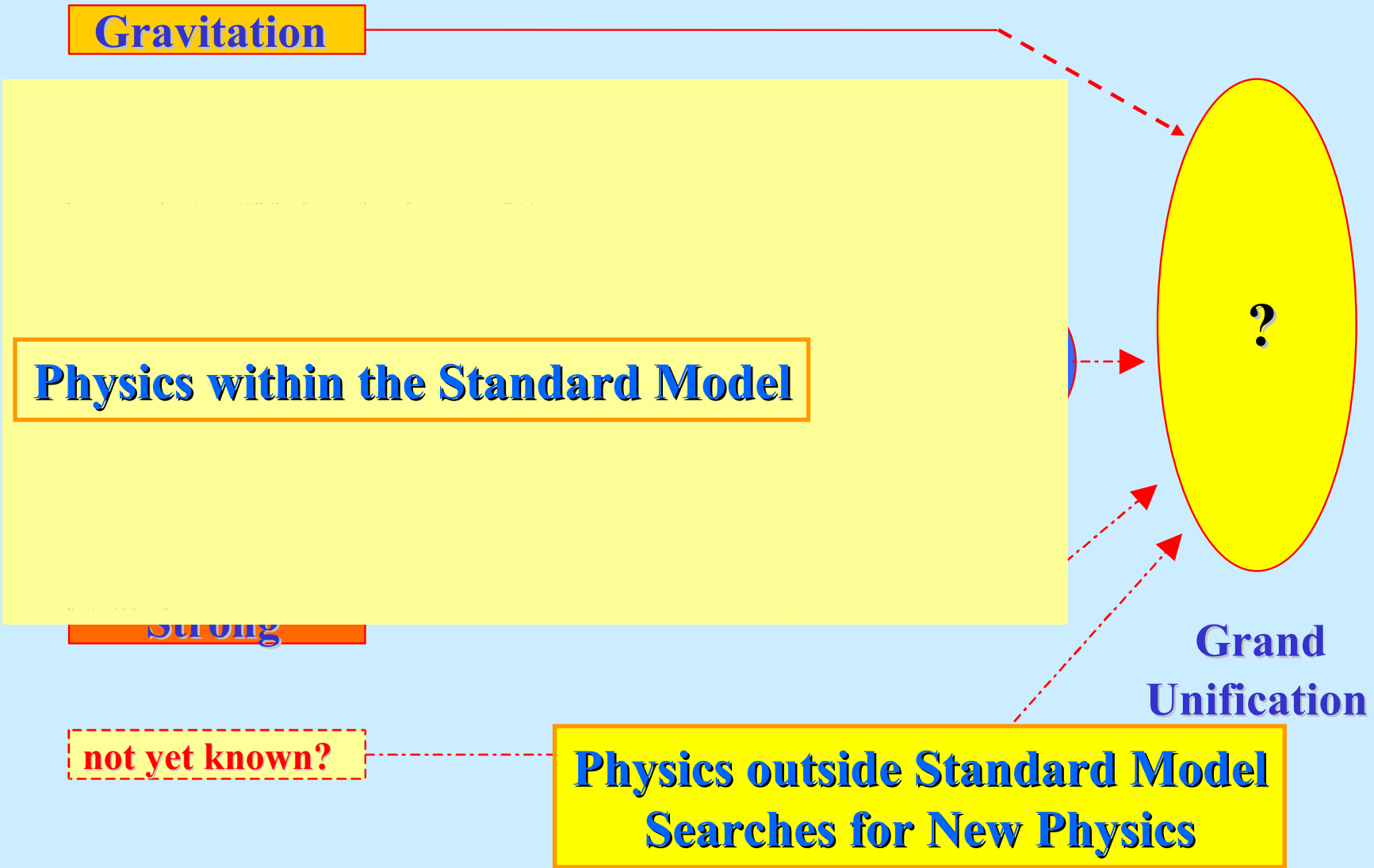
Physics within the Standard Model

Strong

not yet known?

**Physics outside Standard Model
Searches for New Physics**

**Grand
Unification**



What are we concerned with ?

fundamental := “ forming a foundation or basis a principle, law etc. serving as a basis”



Standard Model

- **3 Fundamental Forces**
 - Electromagnetic **Weak Strong**
- **12 Fundamental Fermions**
 - Quarks, Leptons
- **13 Gauge Bosons**
 - γ , W^+ , W^- , Z^0 , H, 8 Gluons

However

- **many open questions**
 - Why 3 generations ?
 - Why some 30 Parameters?
 - Why CP violation ?
 - Why us?
 -
- **Gravity not included**
- **No Combind Theory of Gravity and Quantum Mechanics**

What are we concerned with ?

fundamental := “ forming a foundation or basis a principle, law etc. serving as a basis”



Forces and Symmetries

Local Symmetries \Leftrightarrow Forces

- fundamental interactions

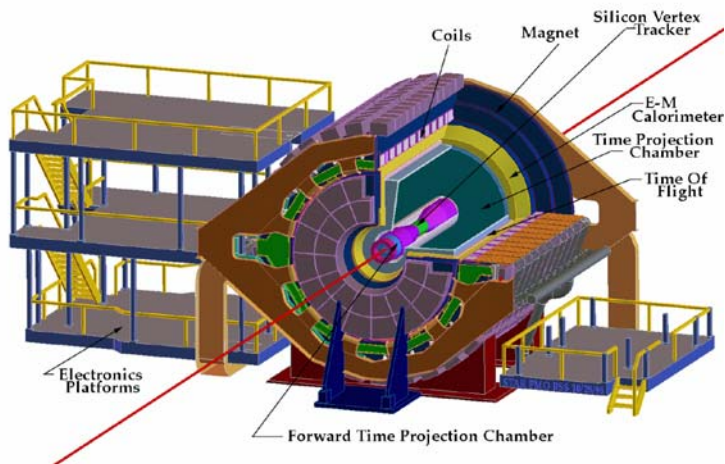
Global Symmetries \Leftrightarrow Conservation Laws

- energy
- momentum
- electric charge
-
- lepton number
- charged lepton family number
- baryon number
-

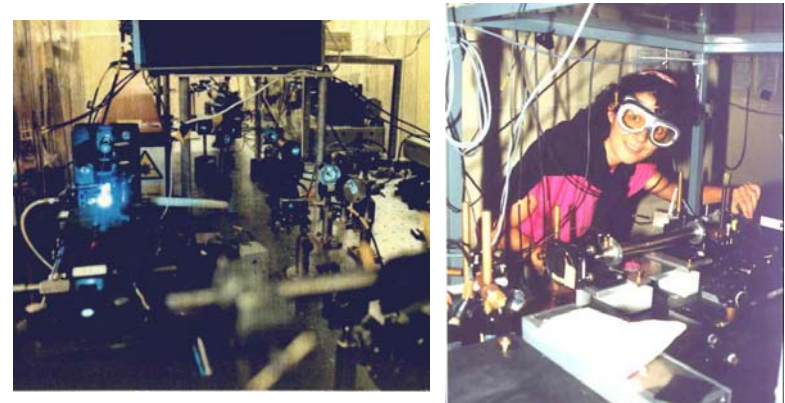
Possibilities to Test New Models



STAR Detector



**High Energies
& direct observations**



**Low Energies
& Precision Measurements**

Discovery of Deuterium

- A barely visible shadow in hydrogen spectral lines

- Reduced mass

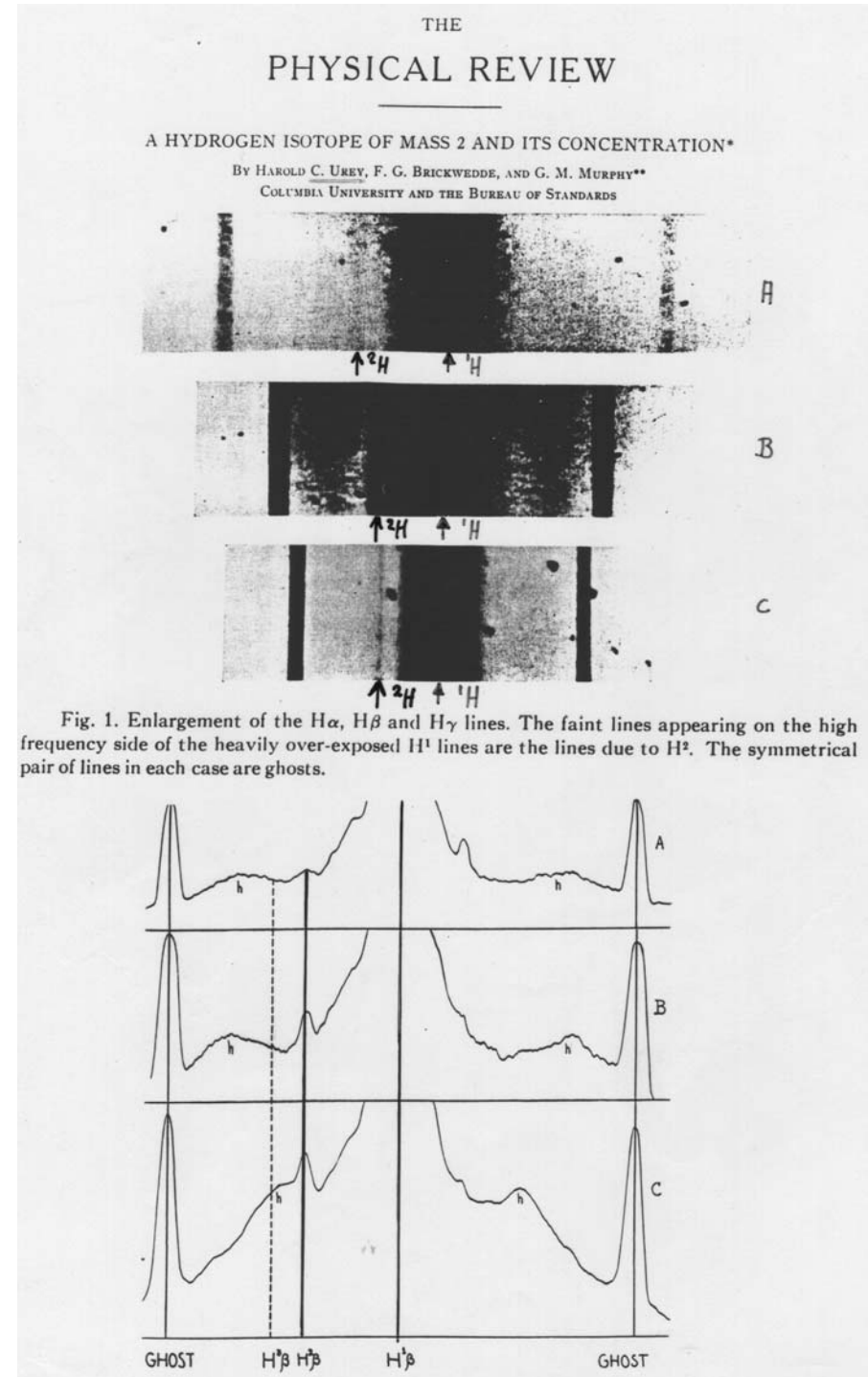
$$\mu_{\text{red}} = \frac{m_{\text{nucleus}} * m_{\text{electron}}}{m_{\text{nucleus}} + m_{\text{electron}}}$$

used for identification

- $\mu_{\text{red}}(\text{H}) - \mu_{\text{red}}(\text{D}) = 2,7 \cdot 10^{-4}$

- Significant impact

Urey, Columbia University, New York(1932)



Some Fundamental Systems in Atomic Physics

(With Precision Experiments)

* Single particles

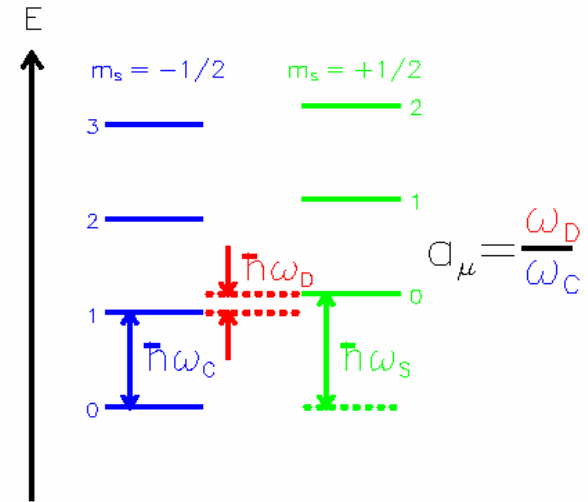
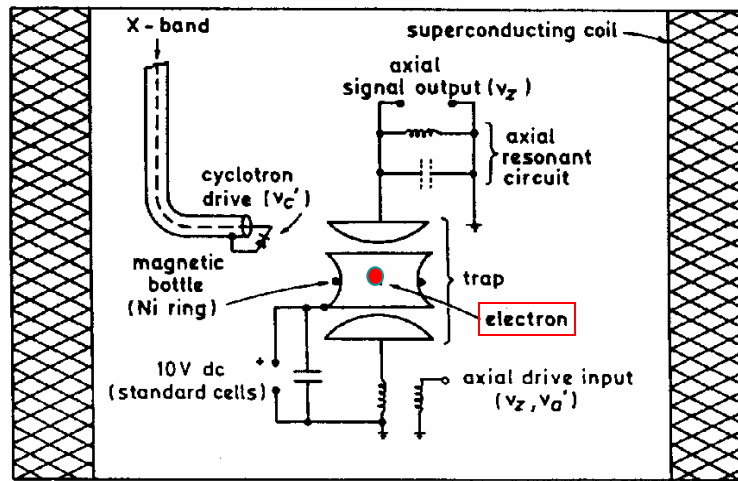
e^+, e^-	magnetic anomaly \Rightarrow fine structure constant α	<i>Dehmelt et al.</i> ('87) <i>Kinoshita et al.</i> ('98)
p, \bar{p}	charge - mass ratio \Rightarrow Test of CPT symmetry	<i>Gabrielse et al.</i> ('99)
n	search for edm \Rightarrow Test of CP / T symmetry	<i>Ramsey,</i> <i>Pendlebury et al.</i> ('99)
μ^+, μ^-	magnetic anomaly \Rightarrow Conf. St. Mod./New Physics ?	<i>Hughes, Roberts, Morse</i> <i>et.al.</i> ('04)

* Bound States

$H=(pe^-)$	hyperfine structure \Rightarrow clock 1s - 2s \Rightarrow Rydberg constant R_{∞}	<i>Essen, Hellwig et al.</i> ('71) <i>Hänsch, Biraben,</i> ('99) <i>Boshier et al.</i> ('95)
Cs	P violation experiments \Rightarrow Test of Standard Model	<i>Wieman et al.</i> ('99)
$Ps=(e^+e^-)$	(hyper)fine structure \Rightarrow Test of QED 1s - 2s $\Rightarrow m_e/m_{e^+}$	<i>Hughes et al.</i> ('84) <i>Mills et al.</i> ('83) <i>Chu et al.</i> ('93)
$M=(\mu^+e^-)$	hyperfine splitting, 1s - 2s \Rightarrow fundamental constants, CPT & search for new physics	<i>Hughes, Jungmann</i> <i>et al.</i> ('99, '00, '01)

Electron Magnetic Anomaly

$$a_e = \frac{(g_e - 2)}{2}$$



Experiment : $a_{e^+} = 1\,159\,652\,187.9 (4.3) \bullet 10^{-12}$

(Dehmelt et al. 1987) $a_{e^-} = 1\,159\,652\,188.4 (4.3) \bullet 10^{-12}$

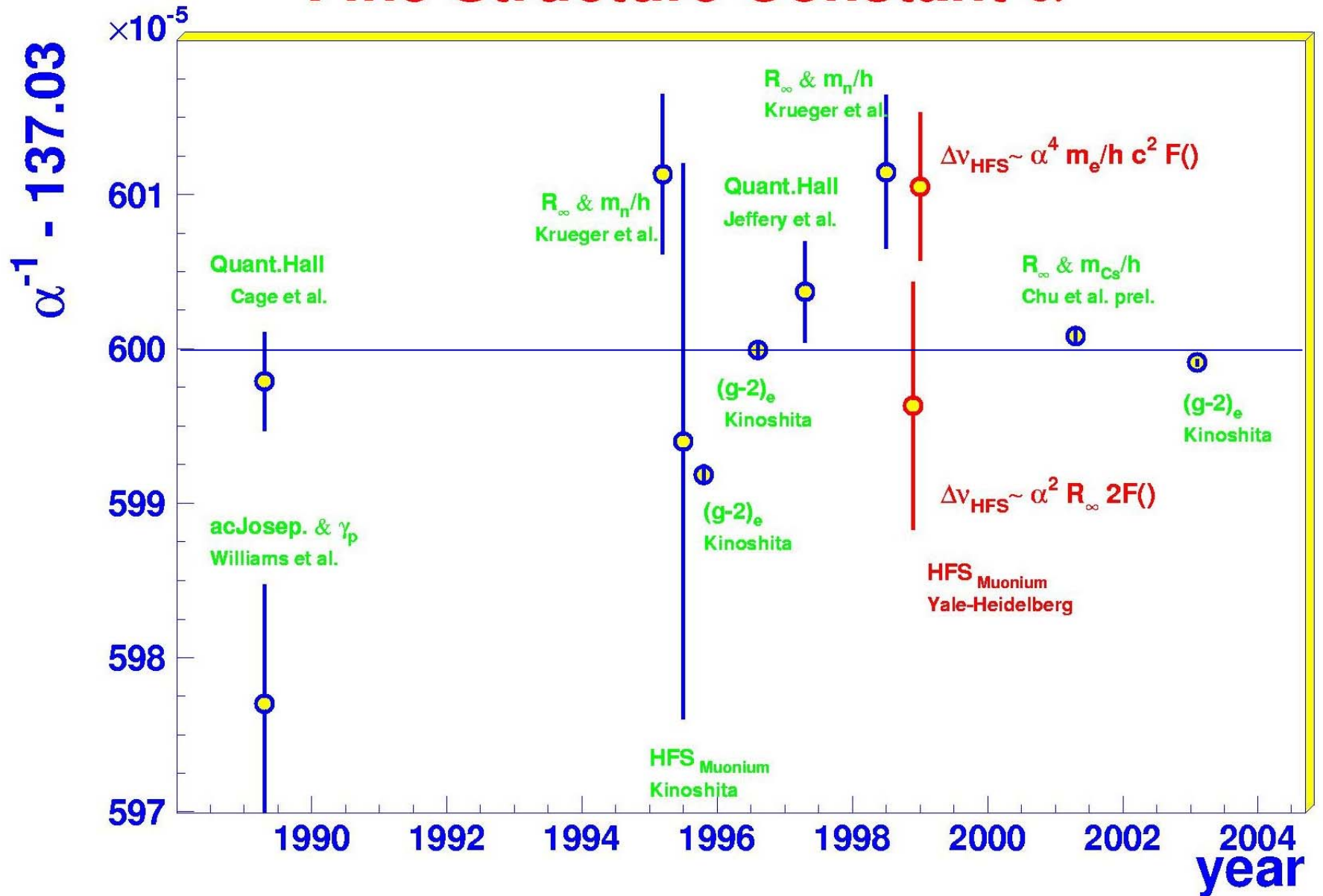
Theory: $a_{e^\pm} = 1\,159\,652\,156.4 (4.1)(22.9) \bullet 10^{-12}$ ← with α from Quantum Hall Effect

(Kinoshita et al. 1998) $= 0.5 \left(\frac{\alpha}{\pi}\right) - 0.328\,478\,965\dots \left(\frac{\alpha}{\pi}\right)^2 + 1.181\,241\,456\dots \left(\frac{\alpha}{\pi}\right)^3 - 1.409(38) \left(\frac{\alpha}{\pi}\right)^4 + \dots + \underbrace{4.40 \cdot 10^{-12}}_{\mu, \tau, \text{ hadrons}, W, Z}$

alternatively: $\rightarrow \alpha_{(g-2)}^{-1} = 137.035\,999\,93 (52)$

G. Gabrielse (sept. 2004): A factor of 4 improvement about to be published

Fine Structure Constant α



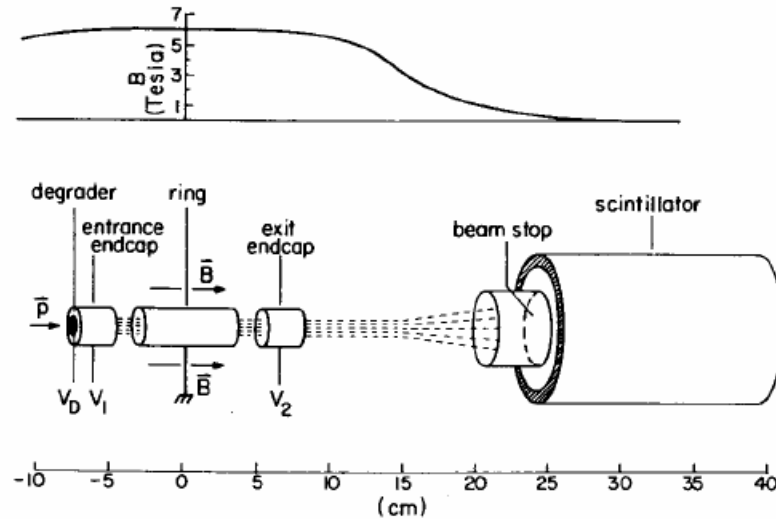
First Capture of Antiprotons in a Penning Trap: A Kiloelectronvolt Source

G. Gabrielse, X. Fei, K. Helmersen, S. L. Rolston, R. Tjoelker, and T. A. Trainor
Department of Physics, University of Washington, Seattle, Washington 98195

H. Kalinowsky and J. Haas
Institute für Physik, University of Mainz, West Germany

and

W. Kells
Fermi National Accelerator Laboratory, Batavia, Illinois 60510
 (Received 8 September 1986)



Special Relativity and the Single Antiproton: Fortyfold Improved Comparison of \bar{p} and p Charge-to-Mass Ratios

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 Department of Physics, Harvard University, Cambridge, Massachusetts 02138

H. Kalinowsky and G. Rouleau†
 Institut für Physik, Universität Mainz, 55099 Mainz, Germany

W. Jhe
 Department of Physics, Seoul National University, Seoul 151-742, Korea
 (Received 17 October 1994; revised manuscript received 3 April 1995)

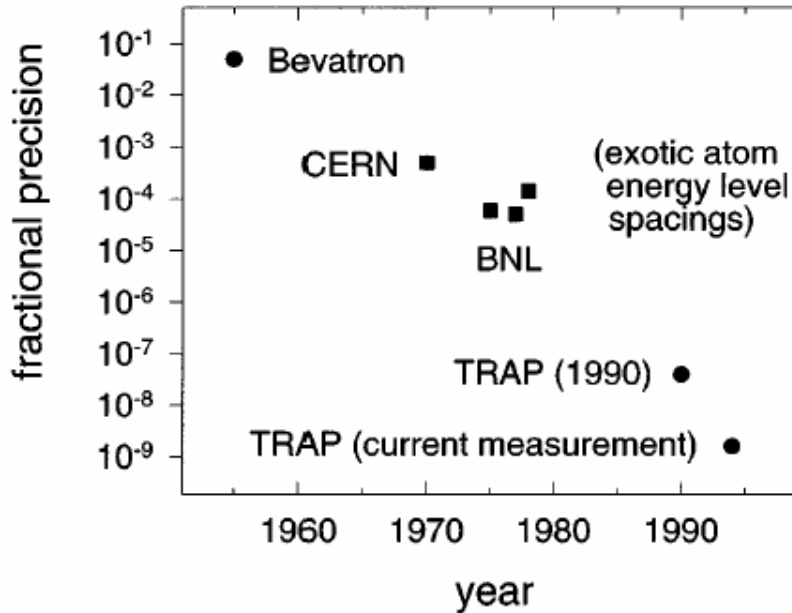


FIG. 1. Comparisons of charge-to-mass ratios (circles) and inertial masses (squares) for \bar{p} and p .

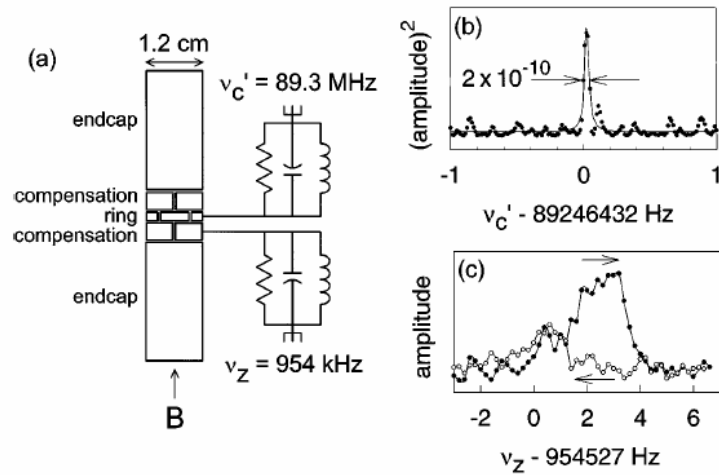


FIG. 2. Open access Penning trap electrodes and detection circuits in (a), with the cyclotron (b), and axial (c) signals from one trapped \bar{p} .

⇒
**Proton and Antiproton
 q/m compare to 0.1 ppb**

Clock Comparisons
 ⇒
**Proton and Antiproton
 gravitational acceleration
 equal to 1 ppm**

Hydrogen-like Atoms

	Positronium e^+e^-	Muonium μ^+e^-	Hydrogen pe^-	Muonic Helium4 $(\alpha\mu^-)e^-$	Muonic ..Hydrogen.. $p\mu^-$	Pionic ..Hydrogen.. $p\pi^-$	Antiprotonic Helium4 $(\alpha\bar{p})^+$
$\Delta\nu_{1S-2S}$ [THz]	1233.6	2455.6	2466.1	2468.5	4.59×10^5	5.88×10^5	1.46×10^7
$\delta\nu_{1S-2S}$ [MHz]	1.28	.145	1.3×10^{-6}	.145	.176	3.5×10^7	10^{11}
$\Gamma = \frac{\Delta\nu_{1S-2S}}{\delta\nu_{1S-2S}}$	9.5×10^8	1.7×10^{10}	1.9×10^{15}	2.6×10^{12}	2.7×10^3	1.7×10^4	10^2
$\Delta\nu_{HFS}$ [GHz]	203.4	4.463	1.420	4.466	4.42×10^7	--	--
$\delta\nu_{HFS}$ [MHz]	1200	.145	4.5×10^{-22}	.145	.145	--	--
$\Gamma = \frac{\Delta\nu_{HFS}}{\delta\nu_{HFS}}$	1.7×10^2	3.1×10^4	3.2×10^{24}	3.1×10^4	3.1×10^8	--	--

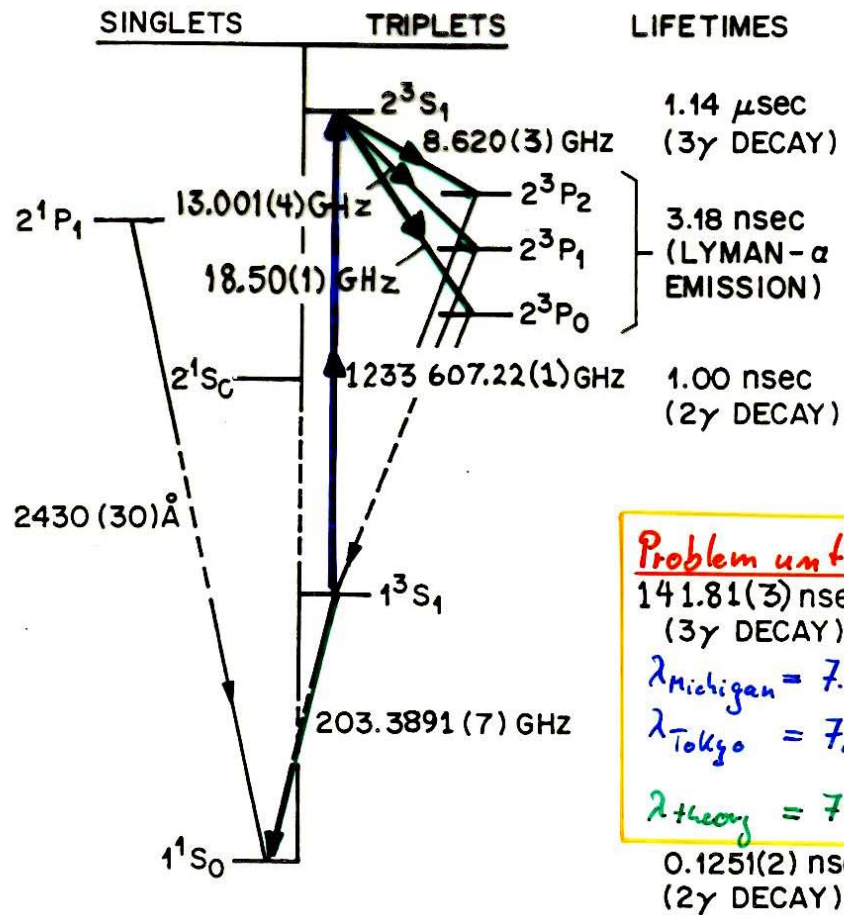
leptonic

hadronic

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POSITRONIUM SPECTROSCOPY



Laser spectroscopy 1s-2s

(Chu, Mills et al.)

$m_{e^-} = m_{e^+}$ at 10^{-8} level

Problem until recently:

141.81(3) nsec
(3 γ DECAY)

$\lambda_{\text{Michigan}} = 7.0482(16) \mu\text{s}^{-1}$

$\lambda_{\text{Tokyo}} = 7.0398(29) \mu\text{s}^{-1}$

$\lambda_{\text{theory}} = 7.03830(7) \mu\text{s}^{-1}$

0.1251(2) nsec
(2 γ DECAY)

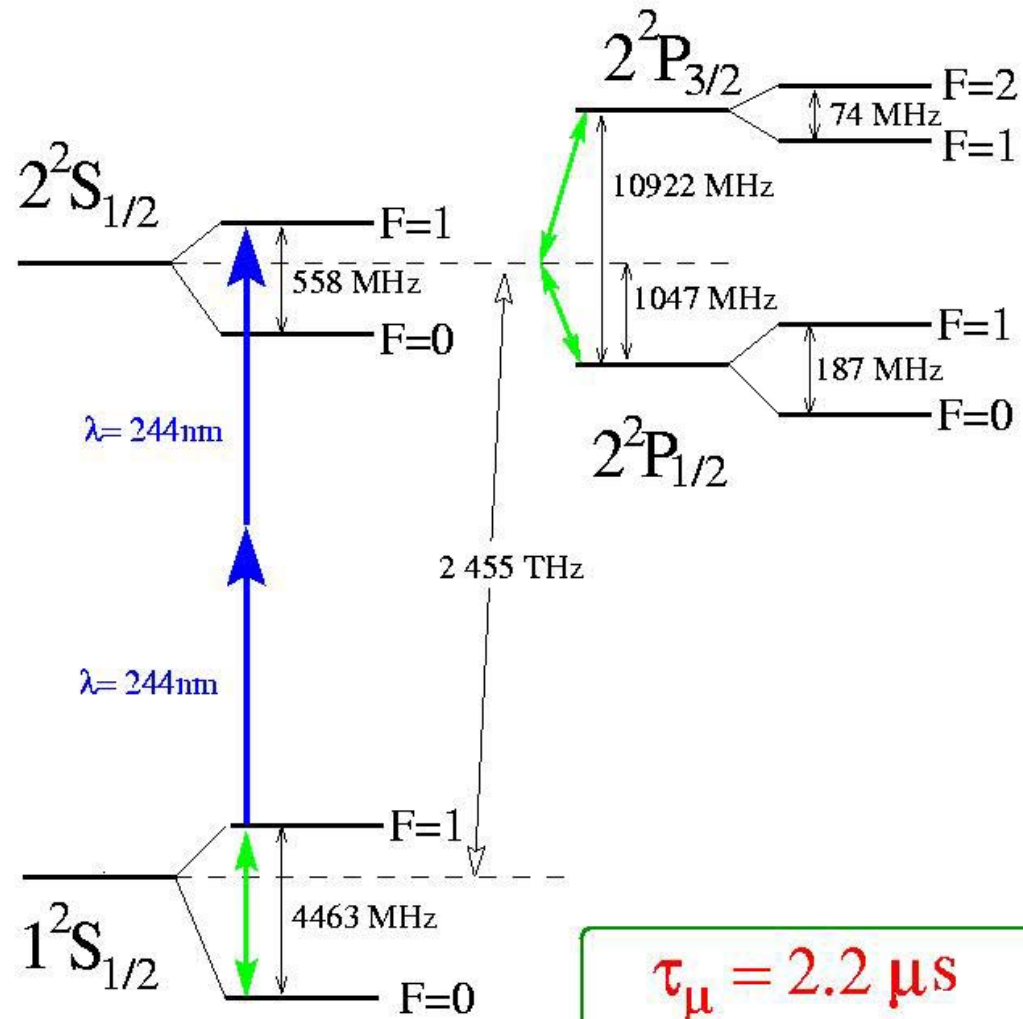
Fig. 1 Energy levels of the n=1 and n=2 states of positronium. The quantities with error estimates in parentheses are measured values. [A.P.Mills & S.Chu, 1990]

All measurements in agreement with theory (now)!

Hydrogen-like Atoms

	Positronium e^+e^-	Muonium μ^+e^-	Hydrogen pe^-	Muonic Helium4 $(\alpha\mu^-)e^-$	Muonic ..Hydrogen.. $p\mu^-$	Pionic ..Hydrogen.. $p\pi^-$	Antiprotonic Helium4 $(\alpha\bar{p})^+$
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Muonium ($M=\mu^+e^-$) Energy Levels n=1 and n=2



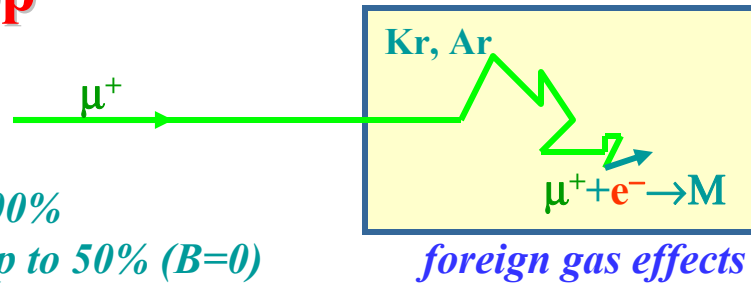
(not to scale)

$\tau_\mu = 2.2 \mu\text{s}$
 $\min \Delta\nu_{\text{nat}} = 145 \text{ kHz}$

Methods of Muonium Production

• Gas Stop

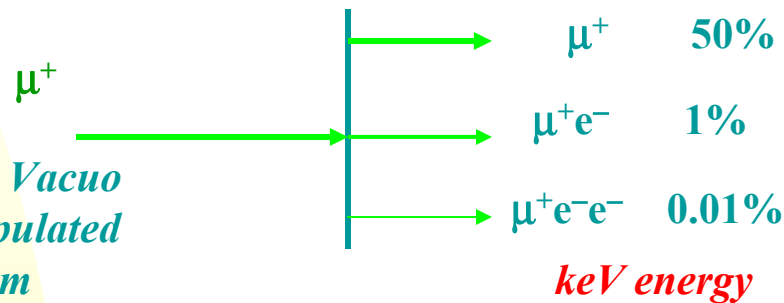
Yields up to 100%
Polarization up to 50% ($B=0$)
100% ($B \gg 1T$)



1960: Discovery of the atom
(V. Hughes et al.)

• Beam Foil

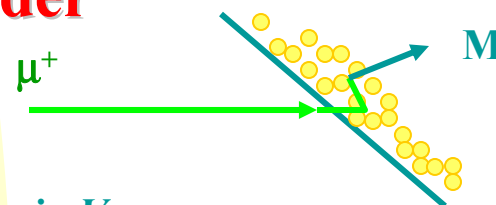
Muonium in Vacuo
 $n=2$ state populated
fast muonium



1980: Enable excited state spectroscopy
(LAMPF, TRIUMF)

• SiO₂ Powder

thermal Muonium in Vacuo
Yields up to 12%
Polarization 39(9)%



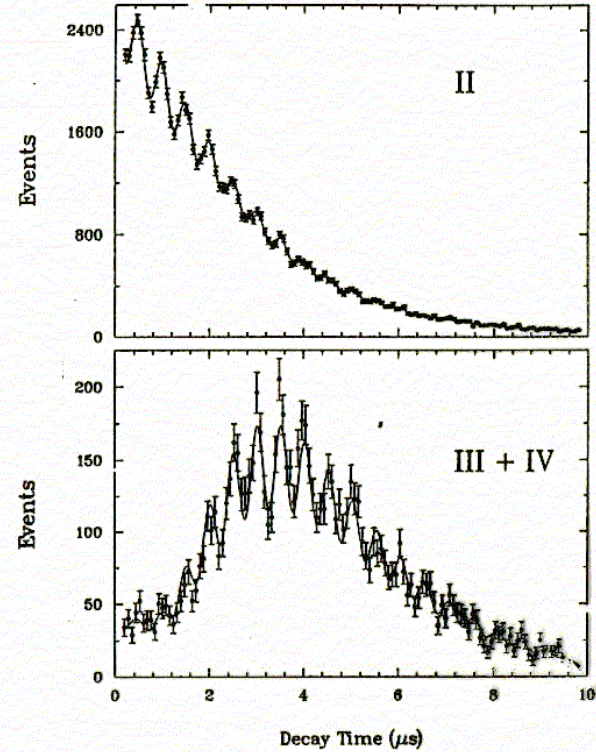
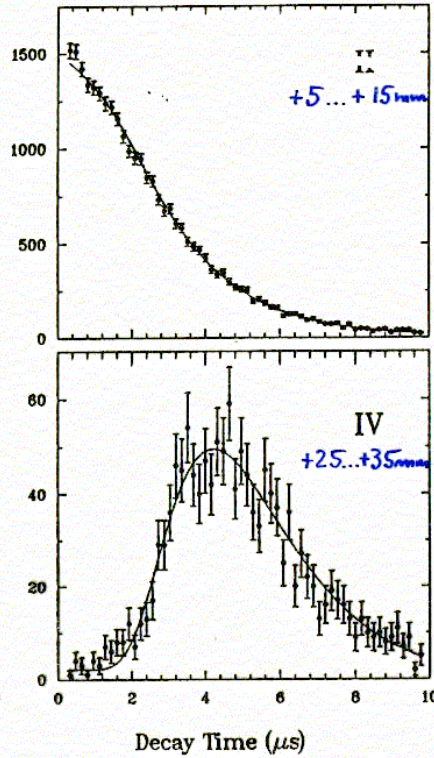
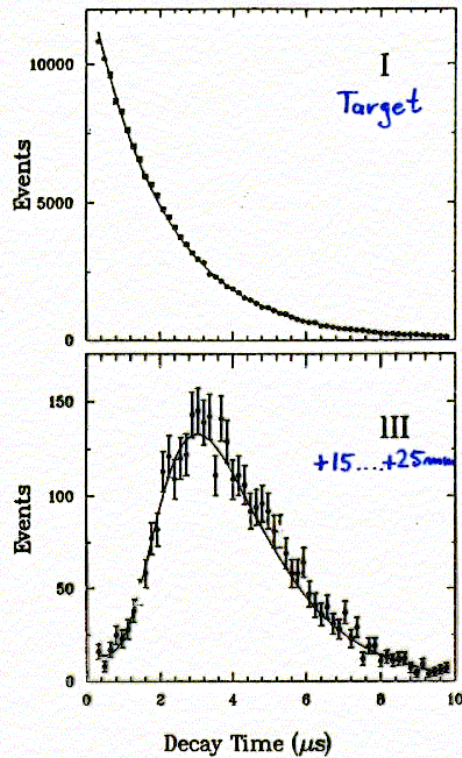
$M(2s) / M(1s) < 10^{-4}$
velocity $1.5 \text{ cm} / \tau_\mu$

1986: Enable vacuum spectroscopy
(TRIUMF, KEK, PSI, LAMPF)

1988:

$B=0$

$B=.140(3) \text{ mT}$



Muonium yield: $\approx 12(2)\%$ per stopped μ^+

Polarization: $39(9)\%$

Diffusion in SiO_2

powder:

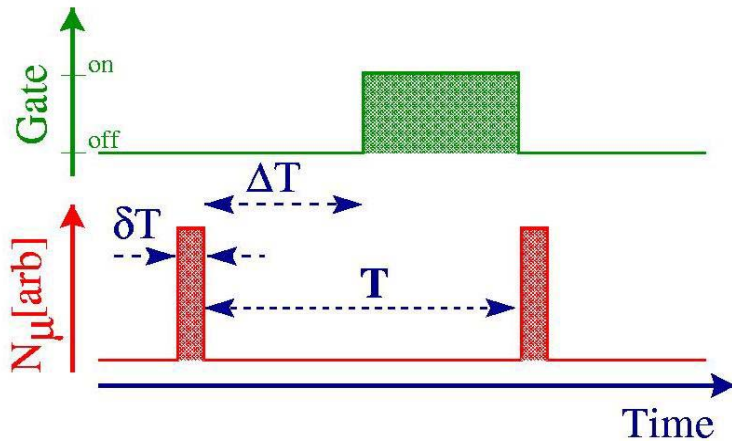
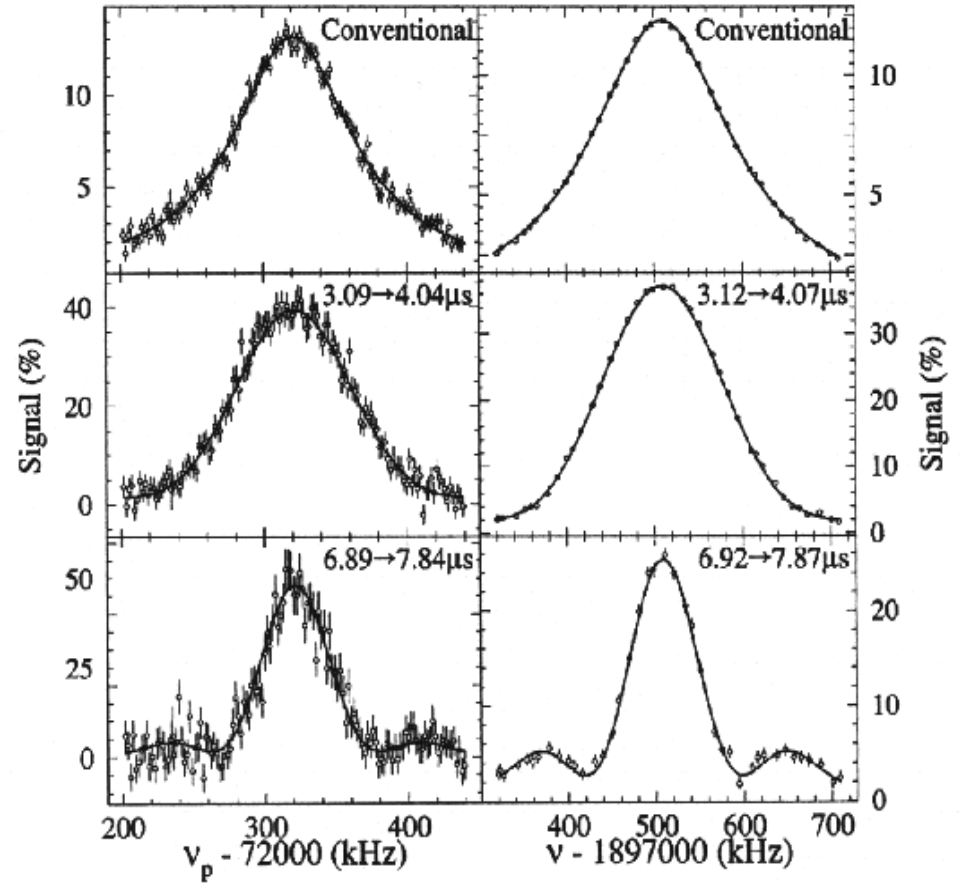
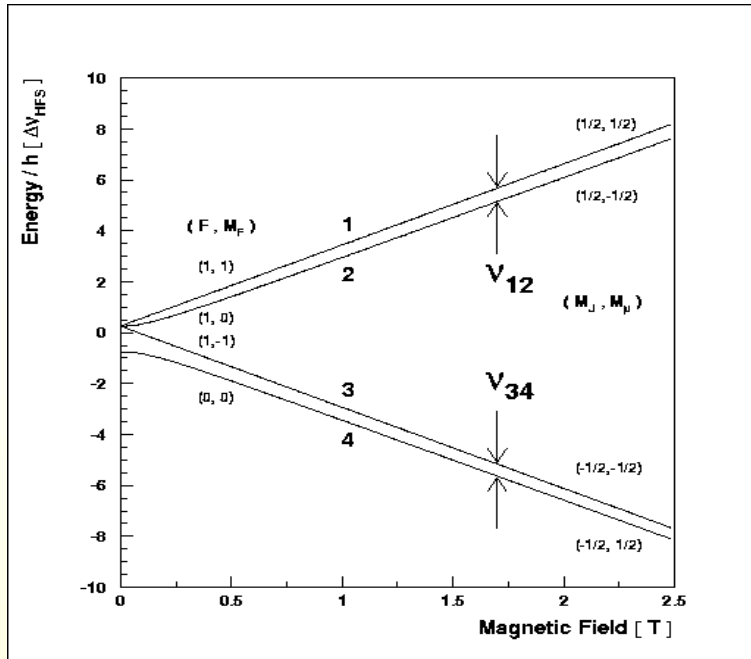
$$D = 1068(81) \frac{\text{cm}^2}{\text{sec}}$$

Temperature:

$$T = 296(10) \text{ K} \approx \bar{v} = 7.4(1) \frac{\text{mm}}{\mu\text{sec}}$$

Muonium Hyperfine Structure

Yale - Heidelberg - Los Alamos



$$\Delta v_{\text{exp}} = 4\,463\,302\,765(53) \text{ Hz} \quad (12 \text{ ppb})$$

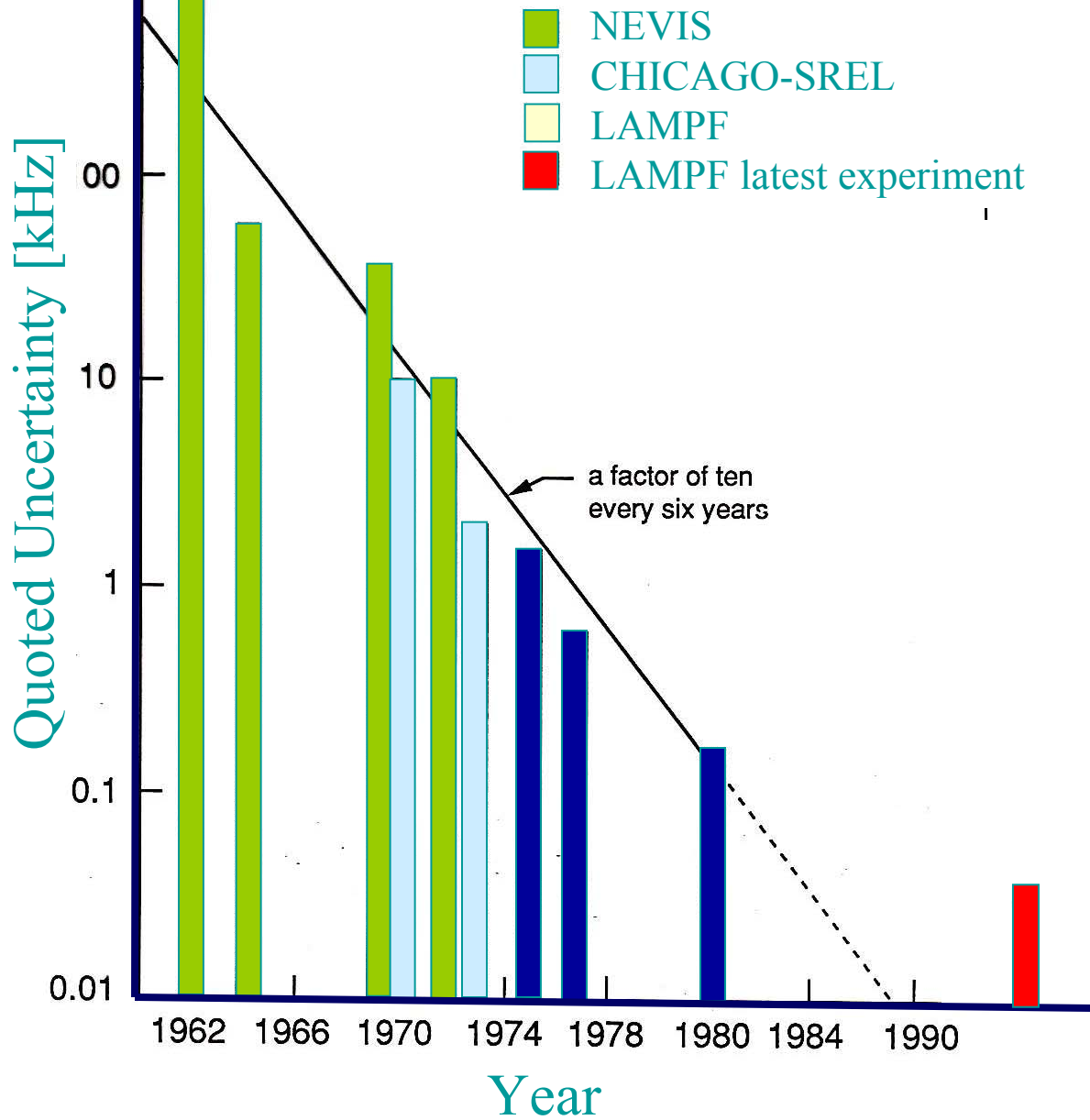
$$\Delta v_{\text{theo}} = 4\,463\,302\,649(520)(34)(<100) \text{ Hz}(<120 \text{ ppb})$$

$$\mu_{\mu}/\mu_p = 3.183\,345\,13(39) \quad (120 \text{ ppb})$$

$$m_{\mu}/m_e = 206.768\,273(24) \quad (120 \text{ ppb})$$

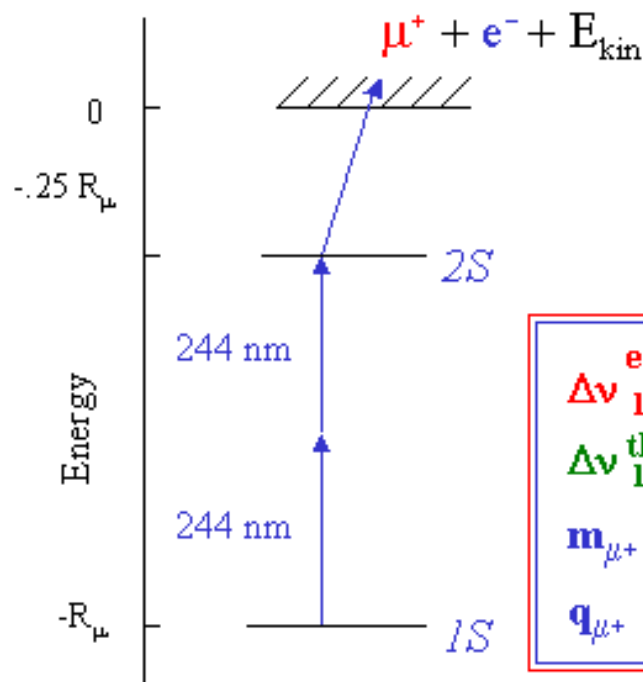
$$\alpha^{-1} = 137.036\,010\,8(5\,2) \quad (39 \text{ ppb})$$

History of Muonium Ground State Hyperfine Splitting Measurements



Muonium 1S-2S Experiment

Heidelberg - Oxford - Rutherford - Sussex - Siberia - Yale

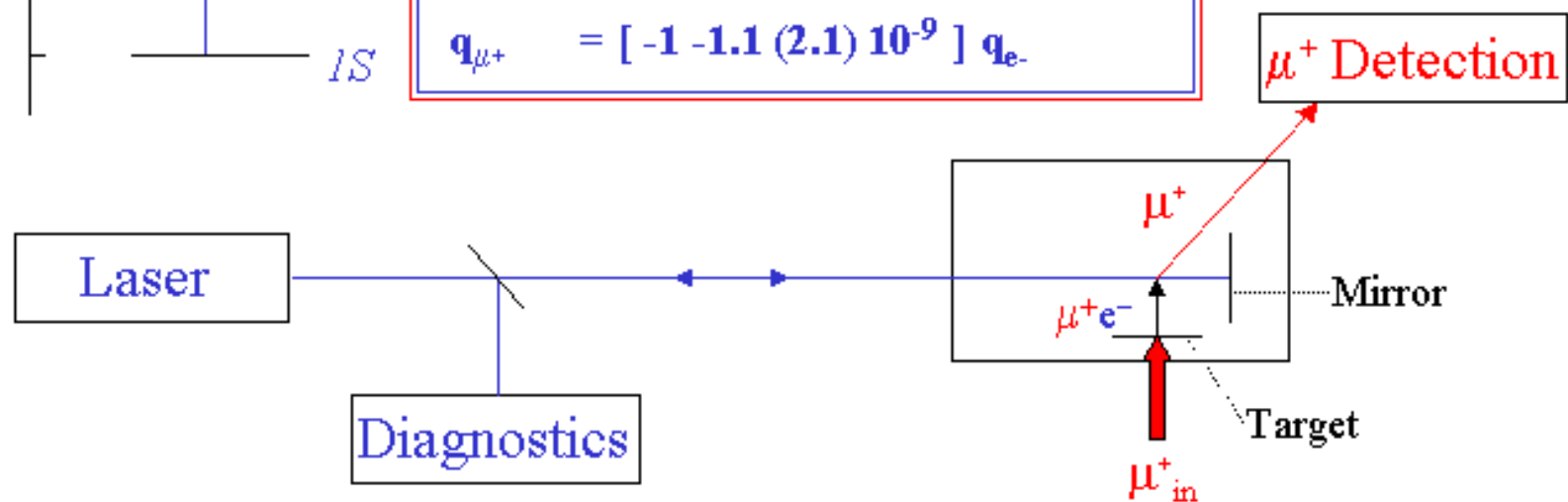
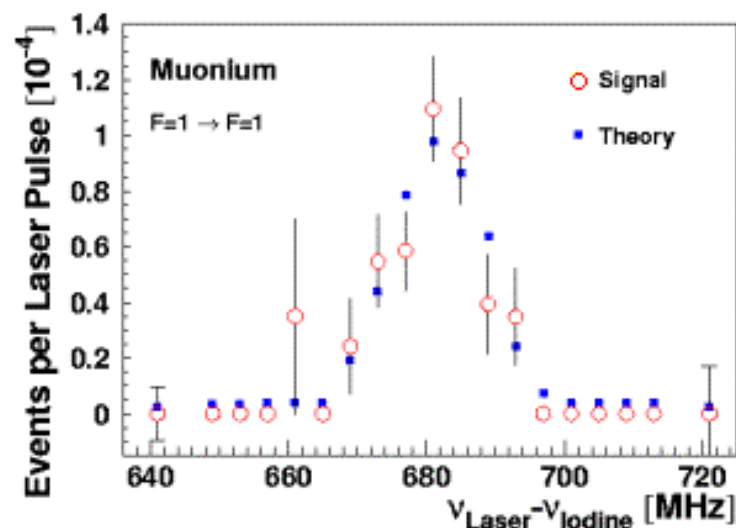


$$\Delta\nu_{1s-2s}^{\text{exp}} = 2455\,528\,941.0(9.1)(3.7) \text{ MHz}$$

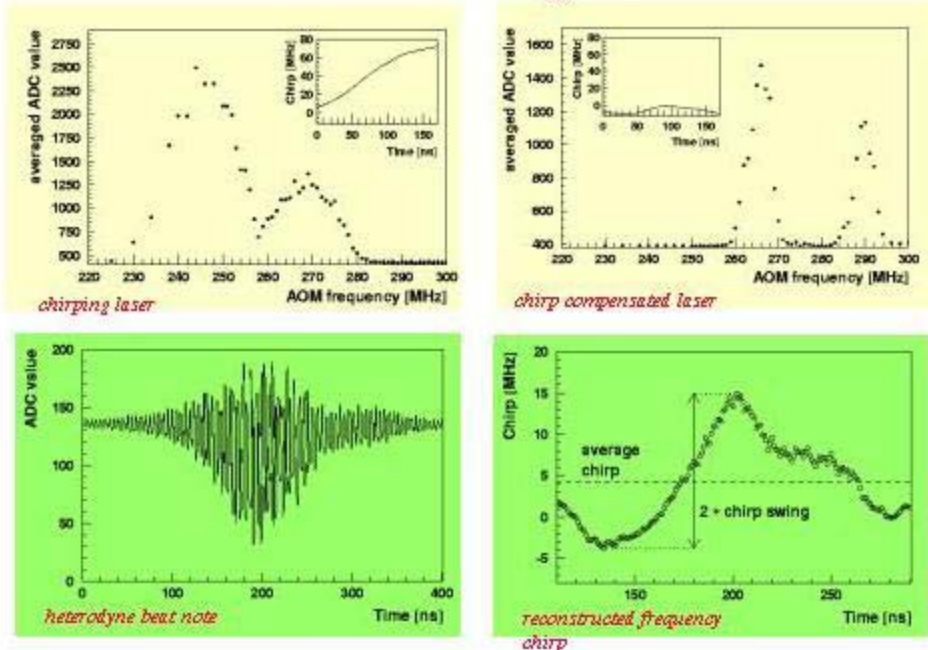
$$\Delta\nu_{1s-2s}^{\text{theo}} = 2455\,528\,935.4(1.4) \text{ MHz}$$

$$m_{\mu^+} = 206.768\,38(17) m_e$$

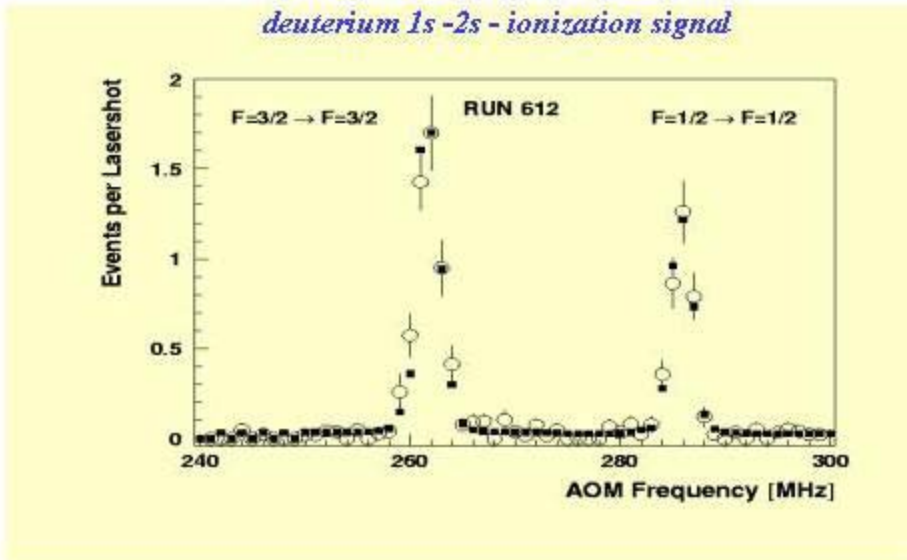
$$q_{\mu^+} = [-1 -1.1(2.1) 10^{-9}] q_e$$



Deuterium Signals



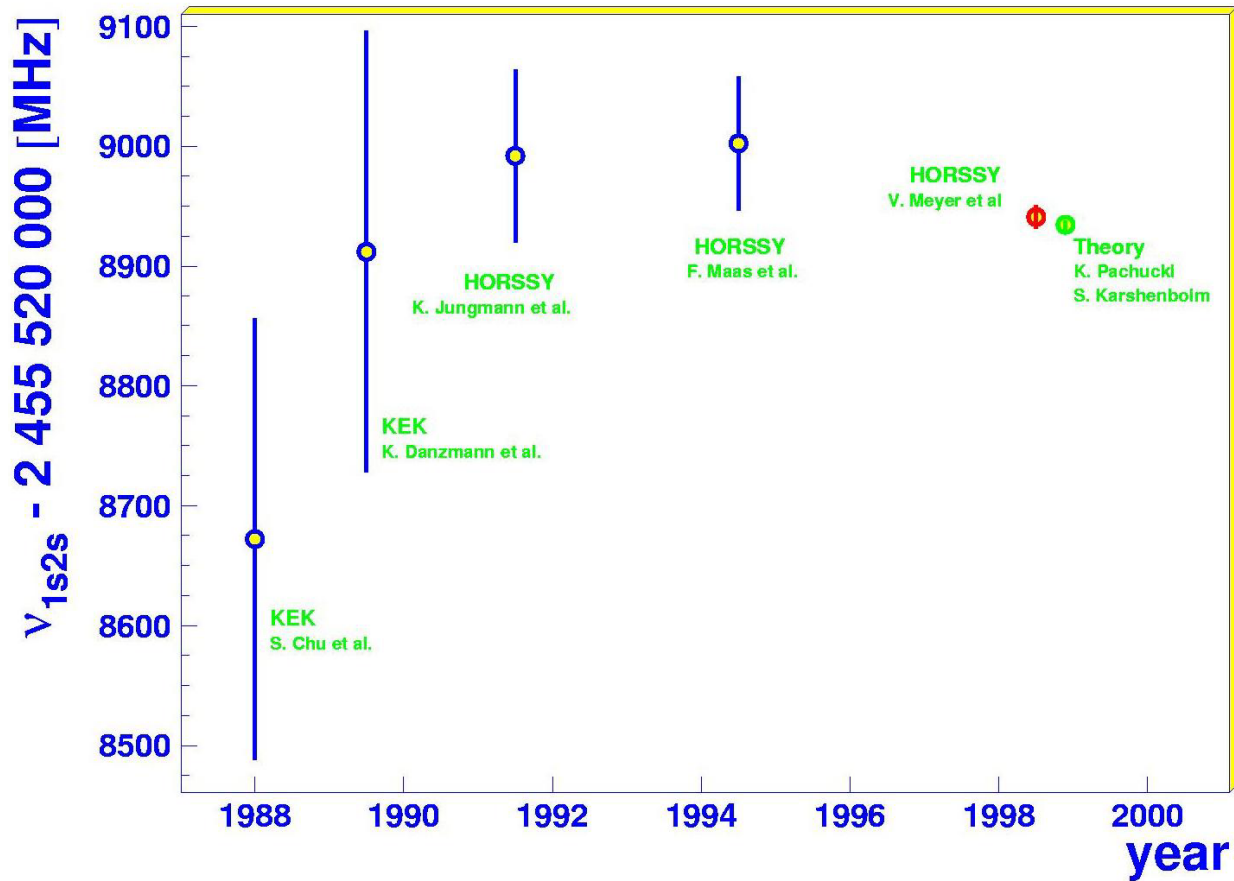
deuterium 1s-2s - ionization signal



$$\Delta\nu_{1s2s}(\text{exp}) = 2\,466\,732\,397.1(8.5) \text{ MHz}$$

$$\Delta\nu_{1s2s}(\text{theo}) = 2\,466\,732\,397.14(8) \text{ MHz}$$

Muonium 1s-2s Interval



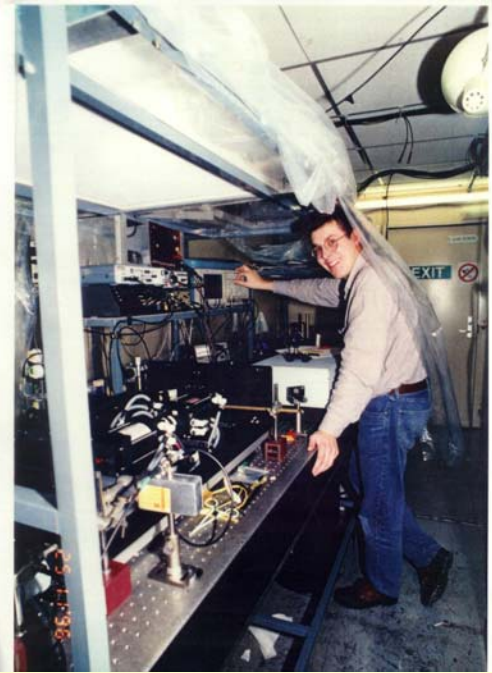
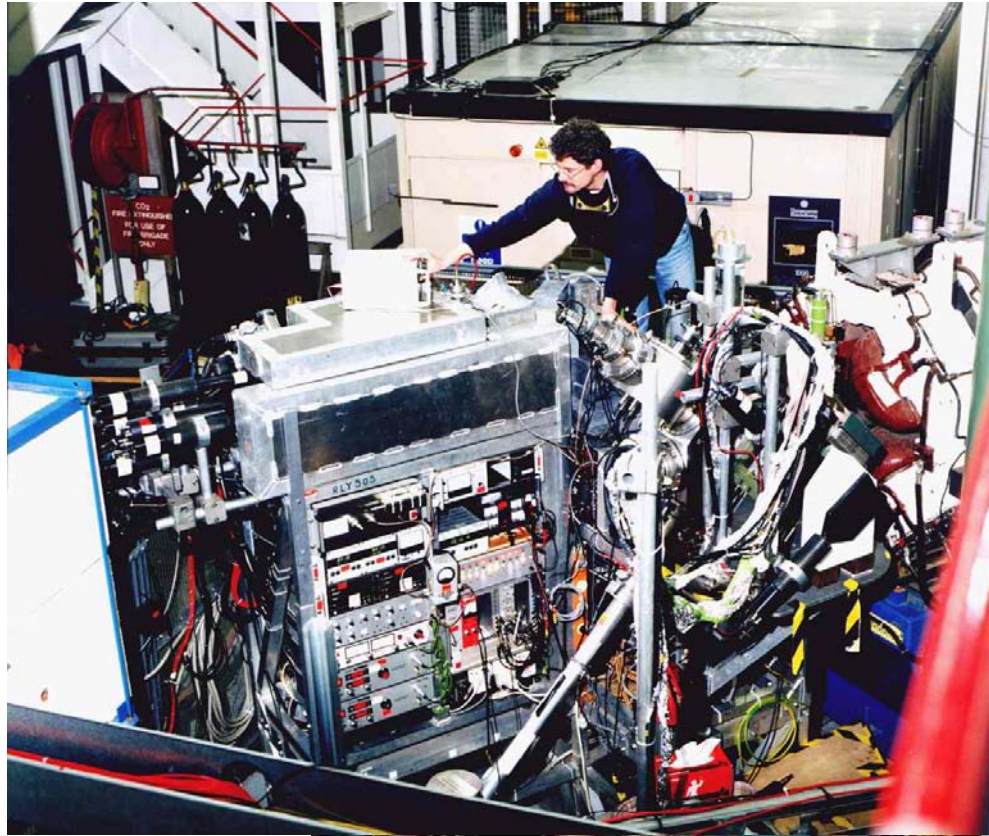
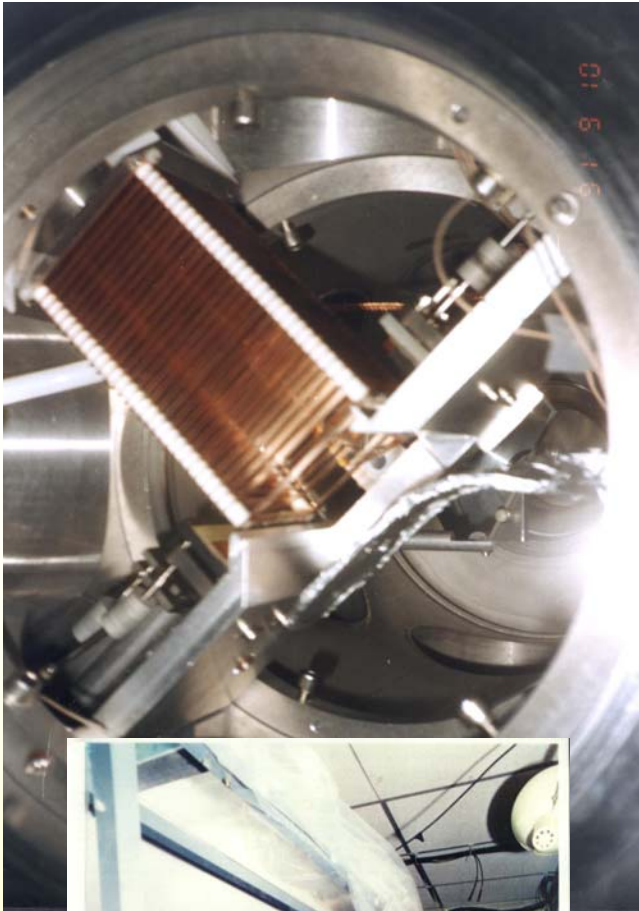
Results:

$$\Delta v_{1s-2s}^{\text{exp}} = 2455\,528\,941.0(9.1)(3.7) \text{ MHz}$$

$$\Delta v_{1s-2s}^{\text{theo}} = 2455\,528\,935.4(1.4) \text{ MHz}$$

$$m_{\mu^+} = 206.768\,38(17) m_e \quad (0.8 \text{ ppm})$$

$$q_{\mu^+} = [-1 -1.1(2.1) 10^{-9}] q_{e^-} \quad (2.2 \text{ ppb})$$



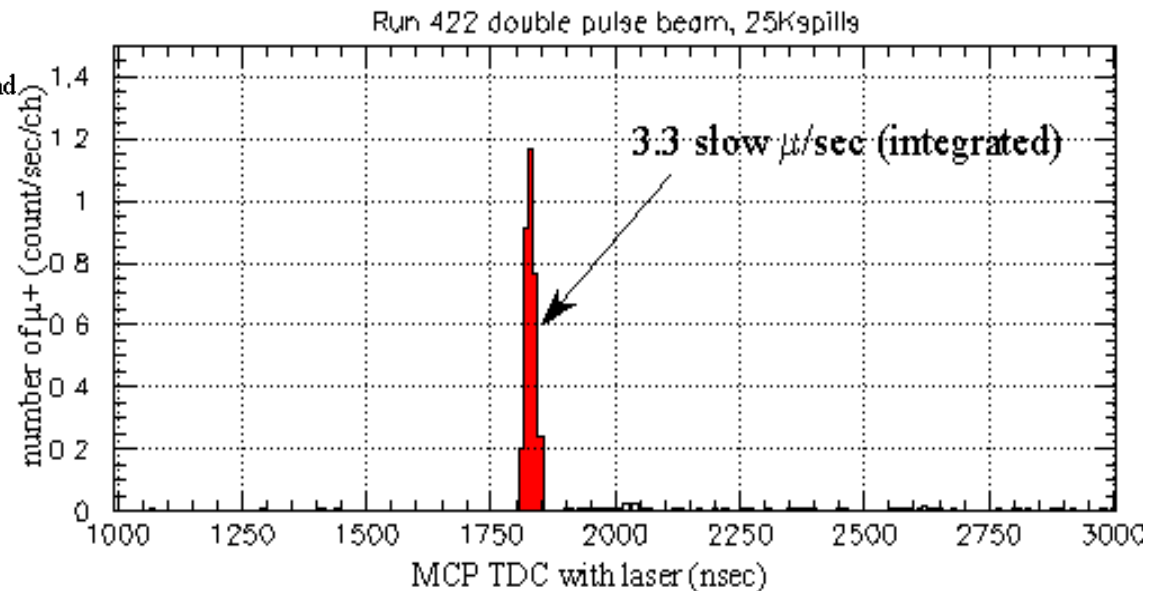
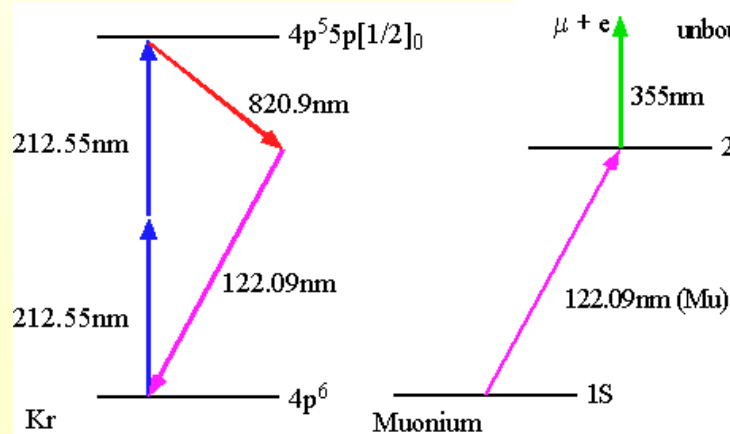
**Muonium
1s-2s
At RAL
1987 -2000**



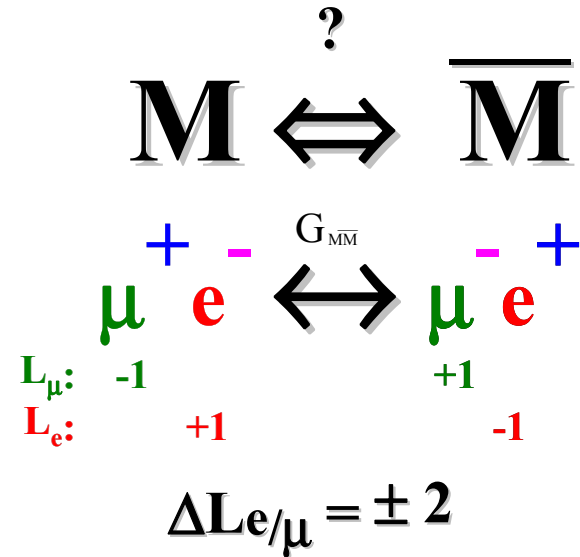
Future Possibilities for Muonium Spectroscopy

- **No Precision Experiment Activities known at this time**
- **Exploitation of Laser Spectroscopy to obtain “Slow Muons” Condensed Matter Science**

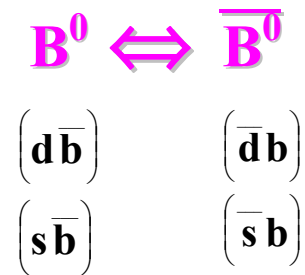
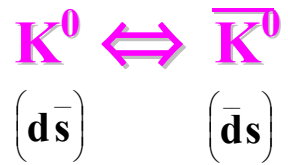
(K. Nagamine et al. @RAL)



Muonium–Antimuonium Conversion

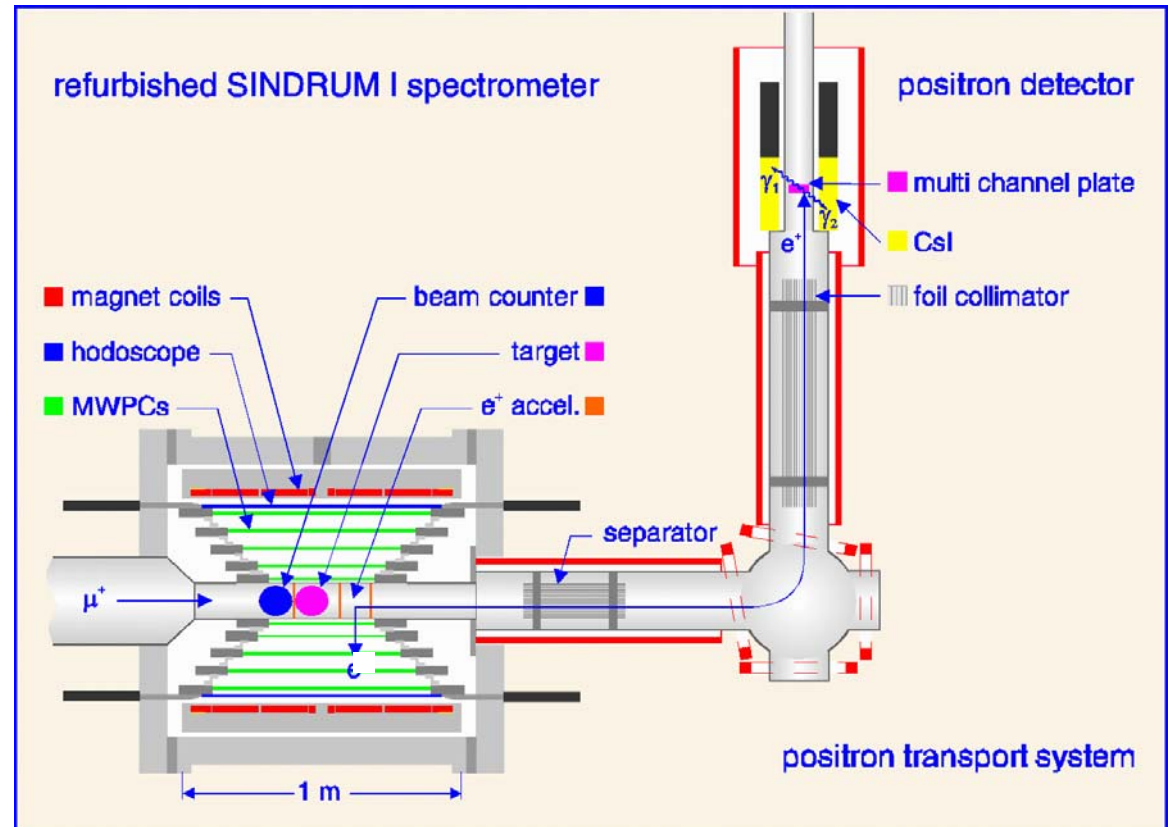
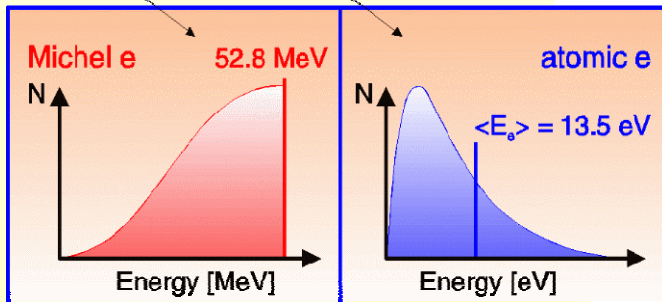
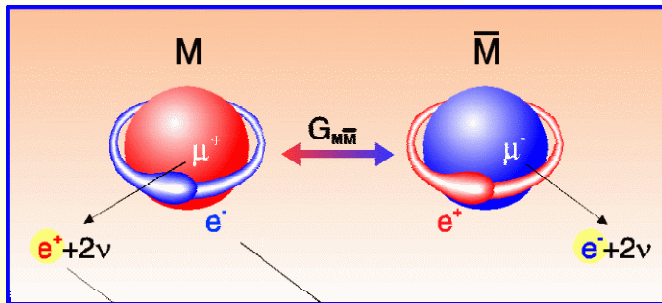
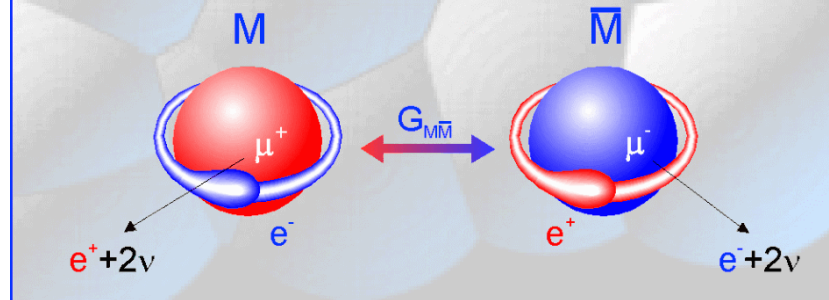


Four oscillations well established in quark sector

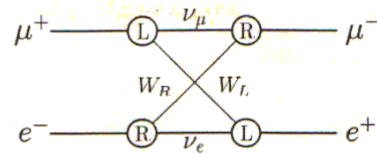


The MACS - $M\bar{M}$ collaboration

Heidelberg - Aachen - UNIZ - PSI - Dubna - Tbilisi - Yale



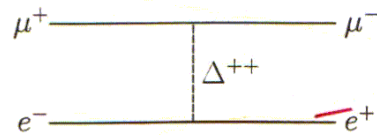
● Left-Right-symmetric models with heavy Majorana neutrinos



$G_{MM} \leq 10^{-5} \cdot G_F$

Halprin (1982)
Swartz (1989)

● Left-Right-symmetric models

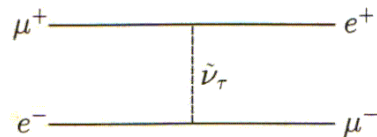


$G_{MM} \geq 2 \cdot 10^{-4} G_F$ ($m_{\nu_\mu} \leq 170 \text{keV}/c^2$)

P. Herczeg, R.N. Mohapatra (1992)

*Small room left for $m_{\nu_\mu} > 40 \text{keV}/c^2$
(85 keV/c^2)*

● SUSY models with broken R-parity



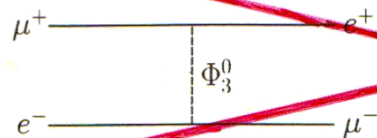
$G_{MM} \leq \text{present limit}$

$|\lambda_{312} * \lambda_{321}| \lesssim 1.5 \cdot 10^{-4} @ \tilde{m} = 100 \text{GeV}$

R.N. Mohapatra (1992)

bound 15 times improved A. Halprin, A. Masiero (1993)

~~● GUT Z_8 -models with 4th generation of heavy particles~~

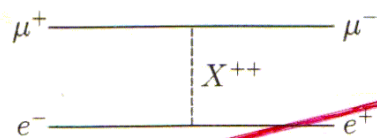


~~$G_{MM} \approx \text{present limit}$~~

~~$G_{MM} \text{ not below } 10^{-2} G_F$~~

~~G. Wong, W. Hou (1994)~~

● GUT models with dileptonic gauge boson



$G_{MM} \leq 1.8 \cdot 10^{-3} G_F$ ($m_{X^{++}}/g_{3l} \geq 1.1 \text{TeV}/c^2$)

331 model $m_{X^{++}} < 600 \text{GeV}/c^2$

H. Fujii, K. Sasaki et al. (1994)

$m_{X^{++}}/g_{3e} \geq 2.6 \text{TeV}/c^2$ 95%

331 model $m_{X^{++}} > 850 \text{GeV}/c^2$

"not attractive any more" "Higgs octet?"

The World according to Escher

P

matter

C

anti-matter

T



mirror image

time →

← time



anti-particle
 e^+

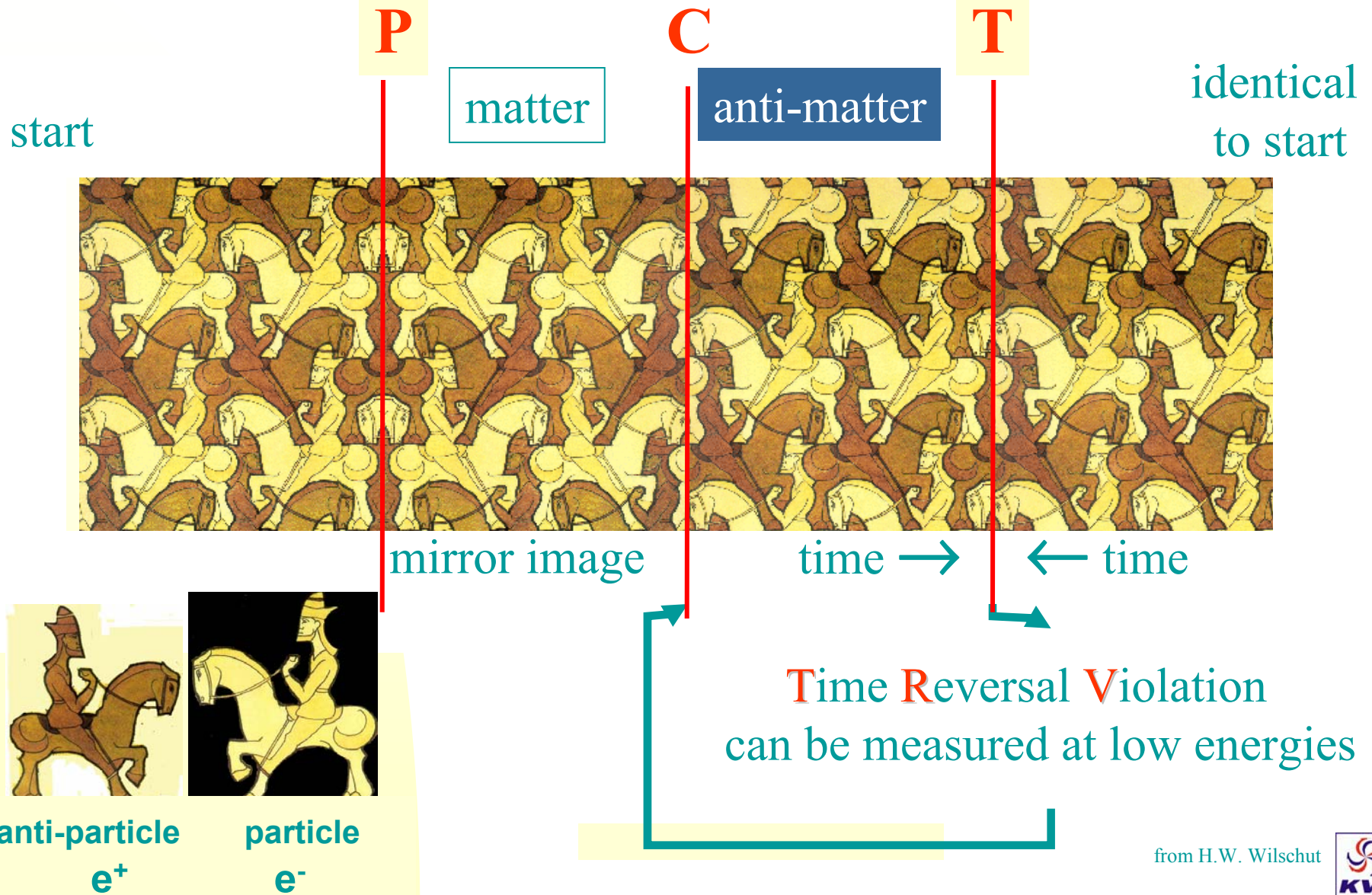


particle
 e^-

from H.W. Wilschut



The World according to Escher



CPT – Violation

Lorentz Invariance Violation

What is best CPT test ?

often quoted:

- $K^0 - \bar{K}^0$ mass difference (10^{-18})
- $e^- - e^+$ g- factors ($2 \cdot 10^{-12}$)

- **We need an interaction with a finite strength !**

New Ansatz (Kostelecky)

- K $\approx 10^{-21}$ GeV
- n $\approx 10^{-30}$ GeV
- p $\approx 10^{-24}$ GeV
- e $\approx 10^{-27}$ GeV
- μ $\approx 10^{-23}$ GeV
- **Future:**
Anti hydrogen $\approx 10^{-??}$ GeV

CPT tests

$$r_K = \frac{|m_{K^0} - m_{\bar{K}^0}|}{m_{K^0}} \leq 10^{-18}$$

$$r_e = \frac{|g_{e^-} - g_{e^+}|}{g_{avg}} = 1.2 \cdot 10^{-3} \cdot \frac{|a_{e^-} - a_{e^+}|}{a_{avg}} \leq 2 \cdot 10^{-12}$$



Are they comparable- Which one is appropriate



⇒ Use common ground, e.g. energies

generic CPT and Lorentz violating DIRAC equation

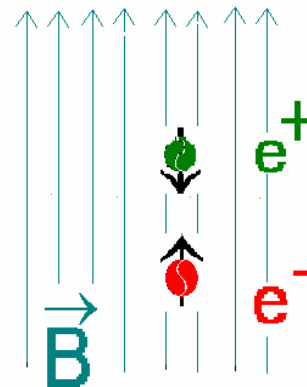
$$(i\gamma^\mu D_\mu - m - a_\mu \gamma^\mu - b_\mu \gamma_5 \gamma^\mu - \frac{1}{2} H_{\mu\nu} \sigma^{\mu\nu} + ic_{\mu\nu} \gamma^\mu D^\nu + id_{\mu\nu} \gamma_5 \gamma^\mu D^\nu) \psi = 0$$

$$iD_\mu \equiv i\partial_\mu - qA_\mu$$

a_μ, b_μ break CPT

$a_\mu, b_\mu, c_{\mu\nu}, d_{\mu\nu}, H_{\mu\nu}$ break Lorentz Invariance

Leptons in External Magnetic Field



$$\Delta\omega_a = \omega_a^{l^-} - \omega_a^{l^+} \approx -4b \frac{1}{3}$$

$$r_l = \frac{|E_{spin\ up}^{l^-} - E_{spin\ down}^{l^+}|}{E_{spin\ up}^{l^-}} \approx \frac{\hbar\Delta\omega_a}{m_l c^2}$$

Bluhm, Kostelecky, Russell, PhysRev. D57,3932 (1998)

For g2 Experiments :

$$r_l = \frac{\hbar\omega_c}{m_l c^2} \cdot \frac{|a_{l^-} - a_{l^+}|}{a_{avg}}$$

Dehmelt, Mittleman, Van Dyck, Schwinberg, hep/9906262

⇒ electron $r_e \leq 1.2 \cdot 10^{-21}$ muon $r_\mu \leq 3.5 \cdot 10^{-24}$

CPT

relates to various phenomena among which

- **Lorentz Invariance, preferred reference frame**
- **Particle – Antiparticle properties**
- **Spin**
- **Fermions and Bosons only**
- **.....**

CPT and Lorentz Invariance from Muon Experiments

Muonium:

new interaction below

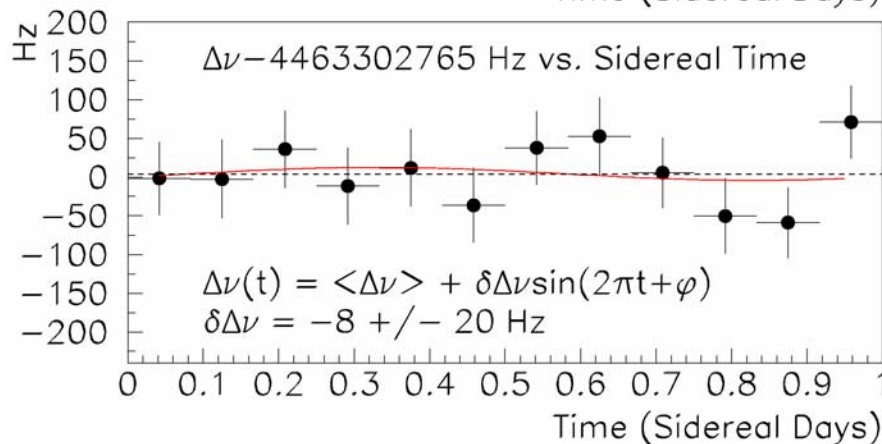
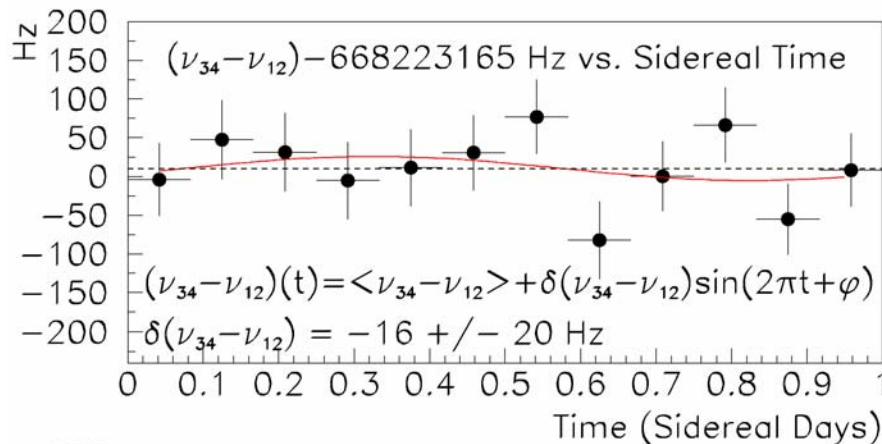
$$2 * 10^{-23} \text{ GeV}$$

Muon g-2:

new interaction below

$$4 * 10^{-22} \text{ GeV (CERN)}$$

15 times better expected
from BNL when analysis
will be completed

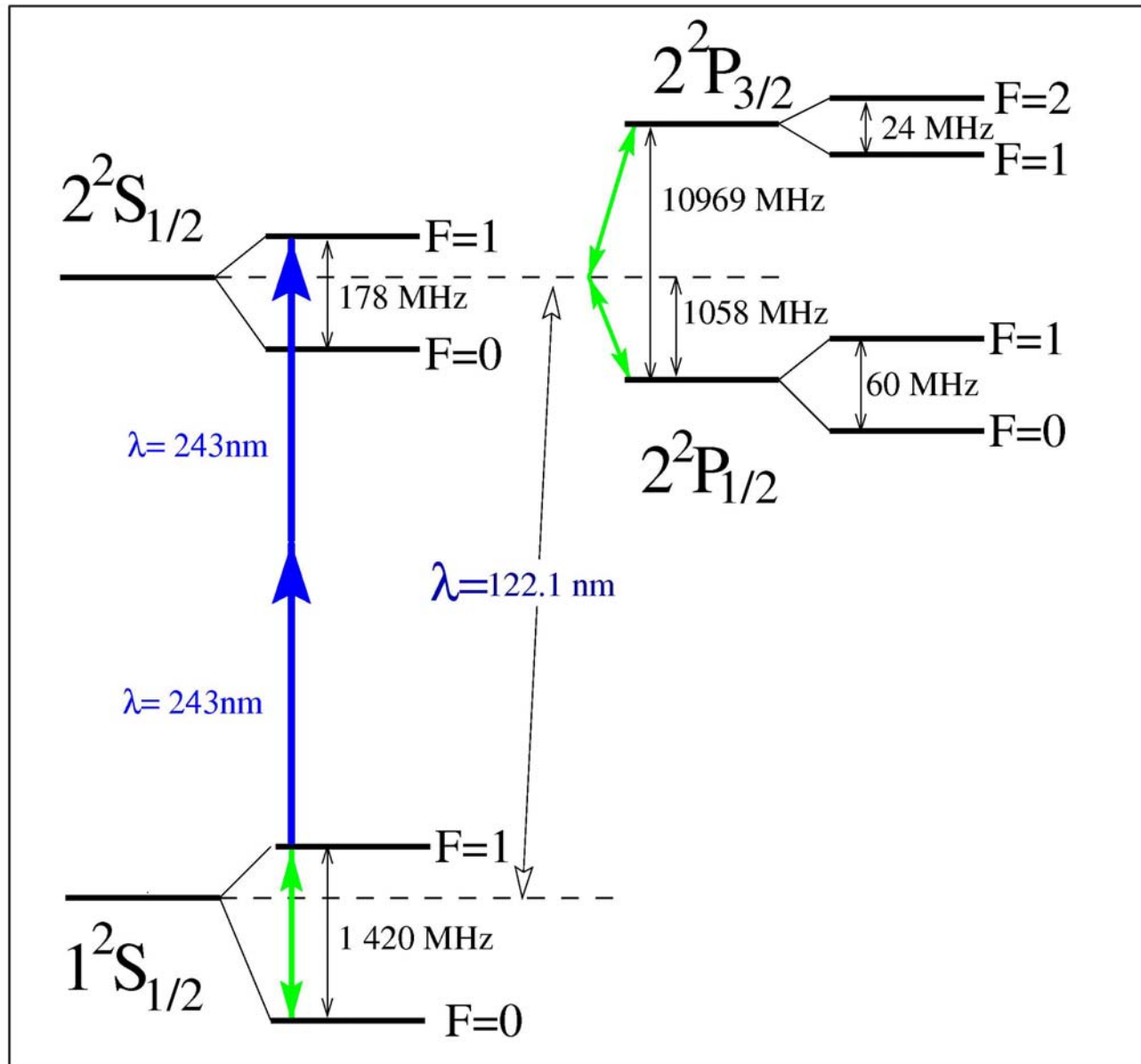


V.W. Hughes et al., Phys.Rev. Lett. 87, 111804 (2001)

Hydrogen-like Atoms

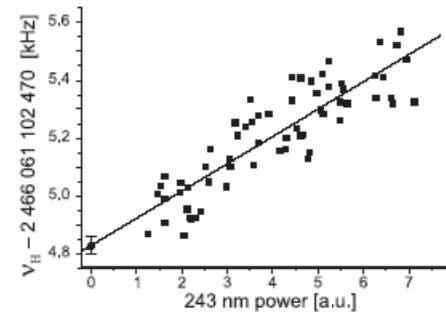
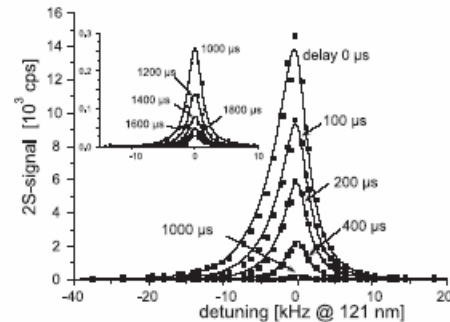
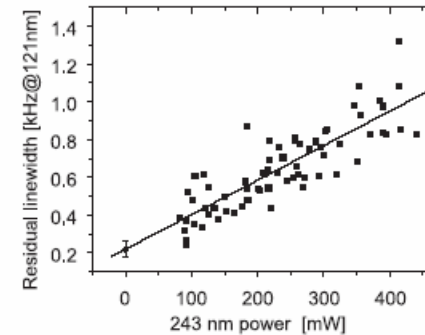
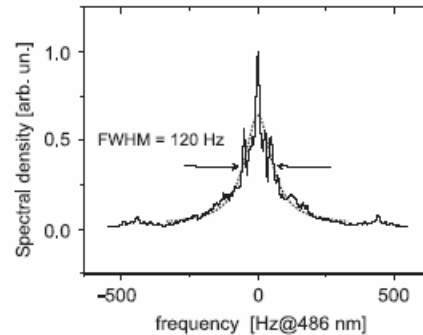
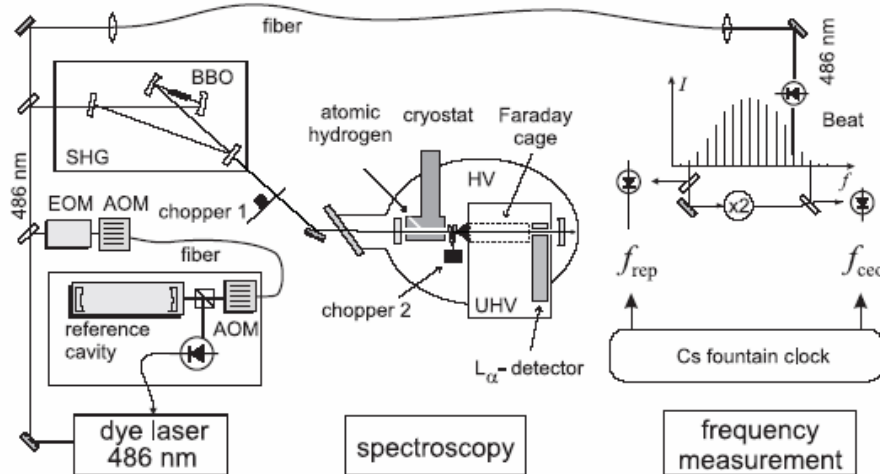
	Positronium e^+e^-	Muonium μ^+e^-	Hydrogen <u>pe^-</u>	Muonic Helium4 $(\alpha\mu^-)e^-$	Muonic ..Hydrogen.. $p\mu^-$	Pionic ..Hydrogen.. $p\pi^-$	Antiprotonic Helium4 $(\alpha\bar{p})^+$
$\Delta\nu_{1S-2S}$ [THz]	1233.6	2455.6	2466.1	2468.5	4.59×10^5	5.88×10^5	1.46×10^7
$\delta\nu_{1S-2S}$ [MHz]	1.28	.145	1.3×10^{-6}	.145	.176	3.5×10^7	10^{11}
$\Gamma = \frac{\Delta\nu_{1S-2S}}{\delta\nu_{1S-2S}}$	9.5×10^8	1.7×10^{10}	1.9×10^{15}	2.6×10^{12}	2.7×10^3	1.7×10^4	10^2
$\Delta\nu_{HFS}$ [GHz]	203.4	4.463	1.420	4.466	4.42×10^7	--	--
$\delta\nu_{HFS}$ [MHz]	1200	.145	4.5×10^{-22}	.145	.145	--	--
$\Gamma = \frac{\Delta\nu_{HFS}}{\delta\nu_{HFS}}$	1.7×10^2	3.1×10^4	3.2×10^{24}	3.1×10^4	3.1×10^8	--	--

Atomic Hydrogen

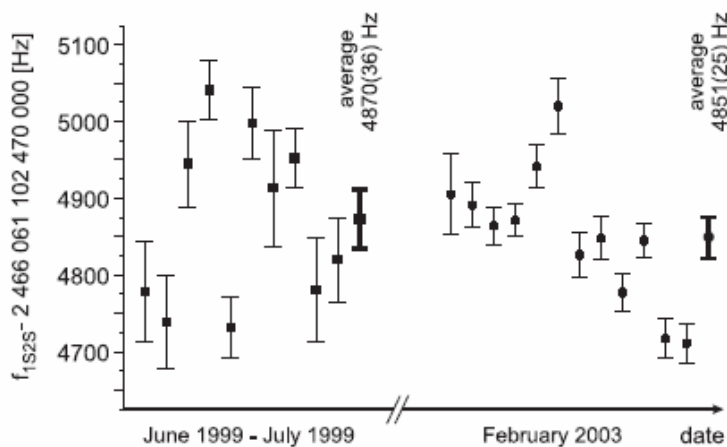


Hydrogen Laser spectroscopy

Haensch et al.



44 months



$$f_{1S-2S} = 2\,466\,061\,413\,187.29(37) \text{ kHz.}$$

$$1.8 \times 10^{-14}$$

$$\dot{\alpha}/\alpha = \partial/\partial t(\ln \alpha) = (-0.9 \pm 2.9) \times 10^{-15} \text{ yr}^{-1}$$

$\chi^2/df \approx 4.2$ $\chi^2/df \approx 9$

Hydrogen Laser Spectroscopy Accuracy

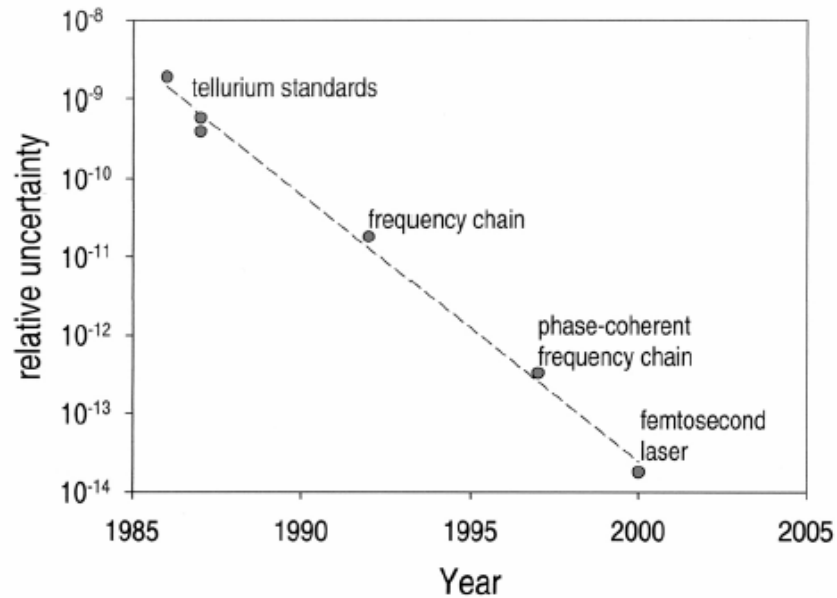


Figure 7. Improvements in 1S–2S measurement accuracy, showing the method of frequency metrology used at each stage.

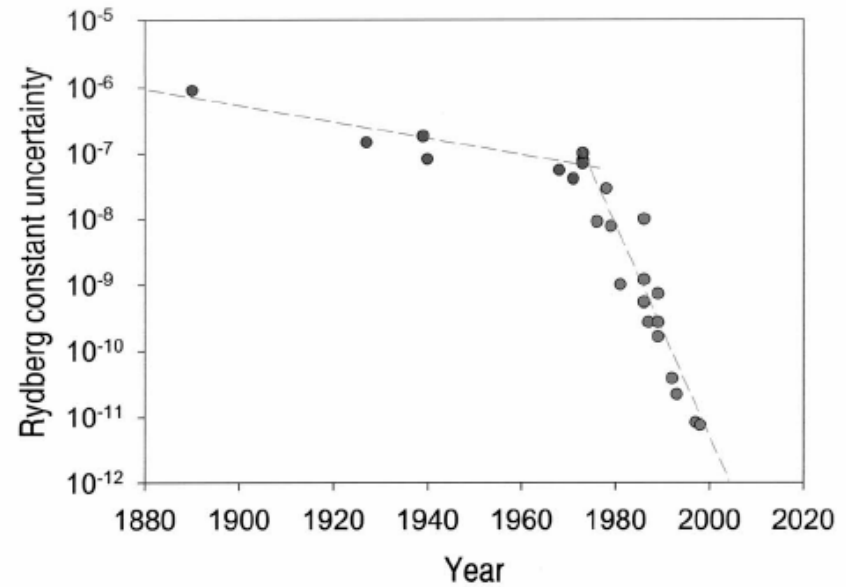


Figure 9. Improvement in the uncertainty of Rydberg constant measurements. The dashed lines are guides to the eye showing the change brought about by laser spectroscopy.

Hydrogen Laser spectroscopy

Haensch, Biraben et al.

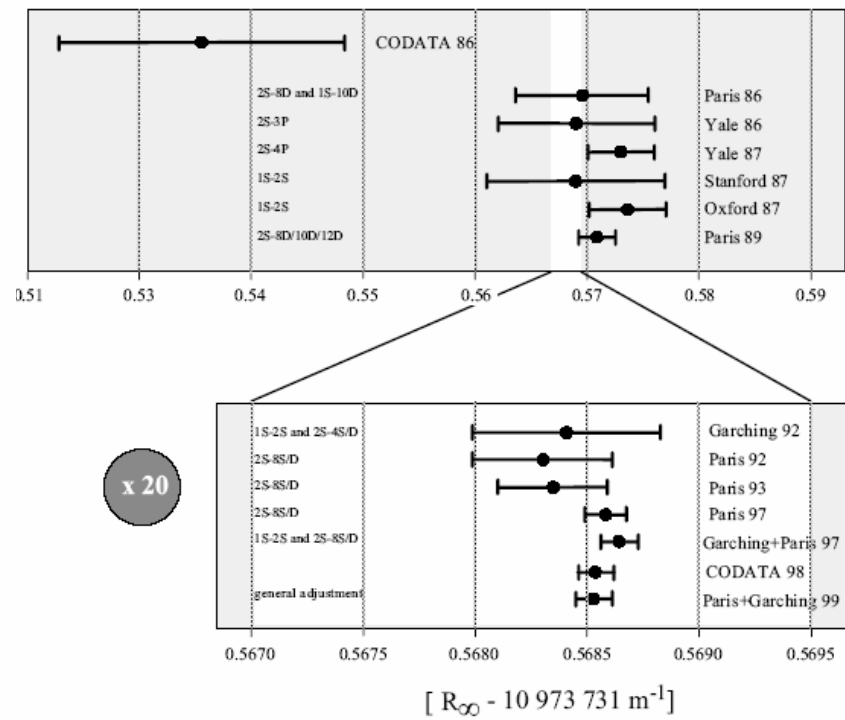
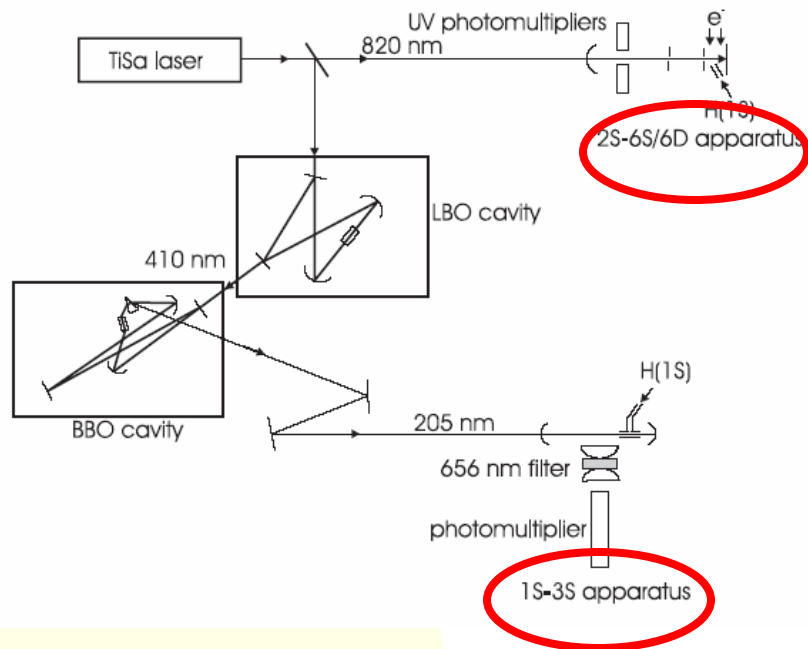
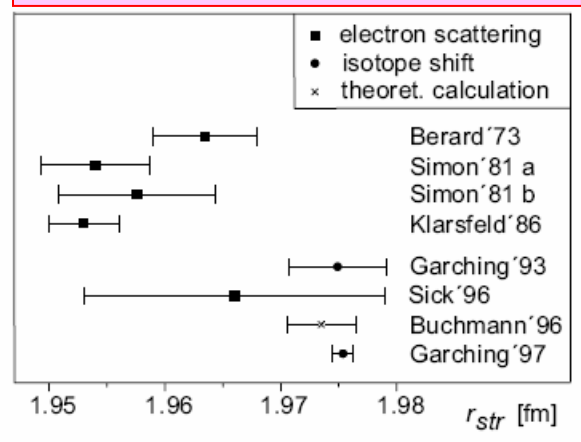


Fig. 14. A history of measurements of the Rydberg constant

“Deuteron Radius”



Hydrogen-like Atoms

	Positronium e^+e^-	Muonium μ^+e^-	Hydrogen pe^-	Muonic Helium4 $(\alpha\mu^-)e^-$	Muonic ..Hydrogen.. $p\mu^-$	Pionic ..Hydrogen.. $p\pi^-$	Antiprotonic Helium4 $(\alpha\bar{p})^+$
$\Delta\nu_{1S-2S}$ [THz]	1233.6	2455.6	2466.1	2468.5	4.59×10^5	5.88×10^5	1.46×10^7
$\delta\nu_{1S-2S}$ [MHz]	1.28	.145	1.3×10^{-6}	.145	.176	3.5×10^7	10^{11}
$\Gamma = \frac{\Delta\nu_{1S-2S}}{\delta\nu_{1S-2S}}$	9.5×10^8	1.7×10^{10}	1.9×10^{15}	2.6×10^{12}	2.7×10^3	1.7×10^4	10^2
$\Delta\nu_{HFS}$ [GHz]	203.4	4.463	1.420	4.466	4.42×10^7	--	--
$\delta\nu_{HFS}$ [MHz]	1200	.145	4.5×10^{-22}	.145	.145	--	--
$\Gamma = \frac{\Delta\nu_{HFS}}{\delta\nu_{HFS}}$	1.7×10^2	3.1×10^4	3.2×10^{24}	3.1×10^4	3.1×10^8	--	--

Hydrogen Laser spectroscopy

Haensch, Biraben et al.

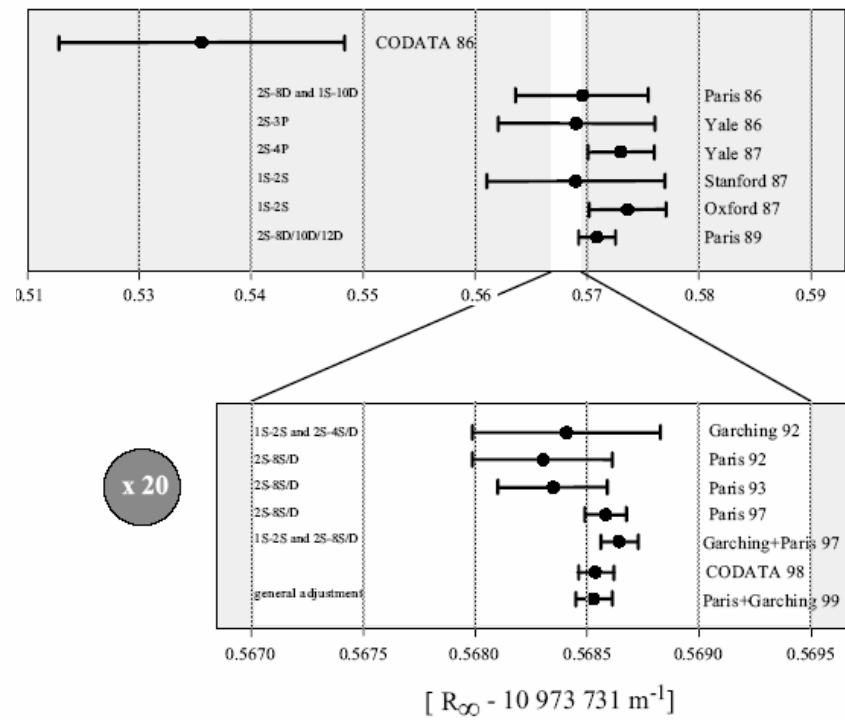
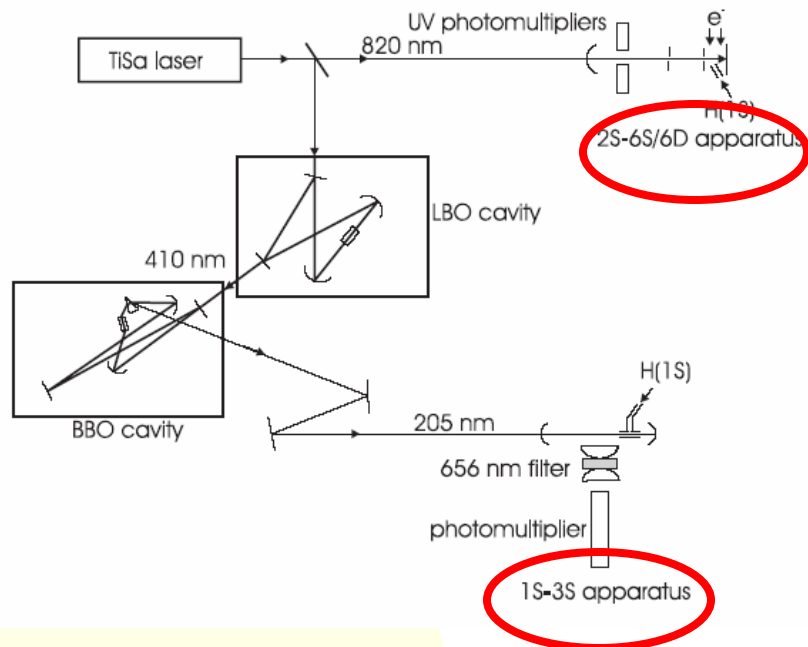
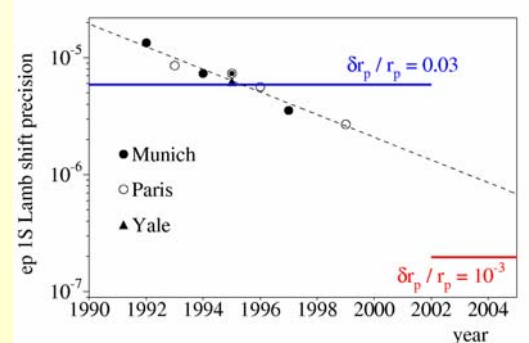


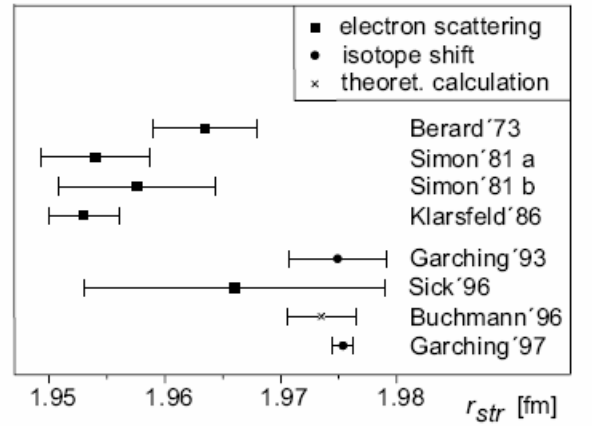
Fig. 14. A history of measurements of the Rydberg constant

“Proton Radius”



Muonic Hydrogen Lamb Shift

“Deuteron Radius”



(Anti-)Hydrogen Spectroscopy*

Hydrogen 1s-2s Saturation Intensity	I_s	= 0.9 W/cm ²
Excitation Rate	R_e	= $4\pi * 84 * (I/W/s * \text{cm}^2)^2 / \Delta\nu / \text{Hz}$
Photo Ionization Rate	R_p	= $9 * I/W/s * \text{cm}^2$
Zeeman shift	$\delta\nu_Z$	= $9.3 * B \text{ Hz/T}$
ac Stark shift	$\delta\nu_{ac}$	= $1.7 * I \text{ Hz / W} * \text{cm}^2$
Velocity at 1mK	V_{1K}	= 4 m/s
Time-of-flight broadening	$\Delta\nu_{TOF}$	= 3 kHz (1 mK, 600 μm beam diam.)
Lyman α detection efficiency	10^{-6}	= $\Omega * \text{eff}_{MCP} (= 10^{-4} * 10^{-2})$

10^{11} H-atoms (MIT Bose condens.)

$$\delta\nu/\nu_{1s2s} = 10^{-13} \text{ (1s integration time)}$$

* numbers verified with L. Willmann

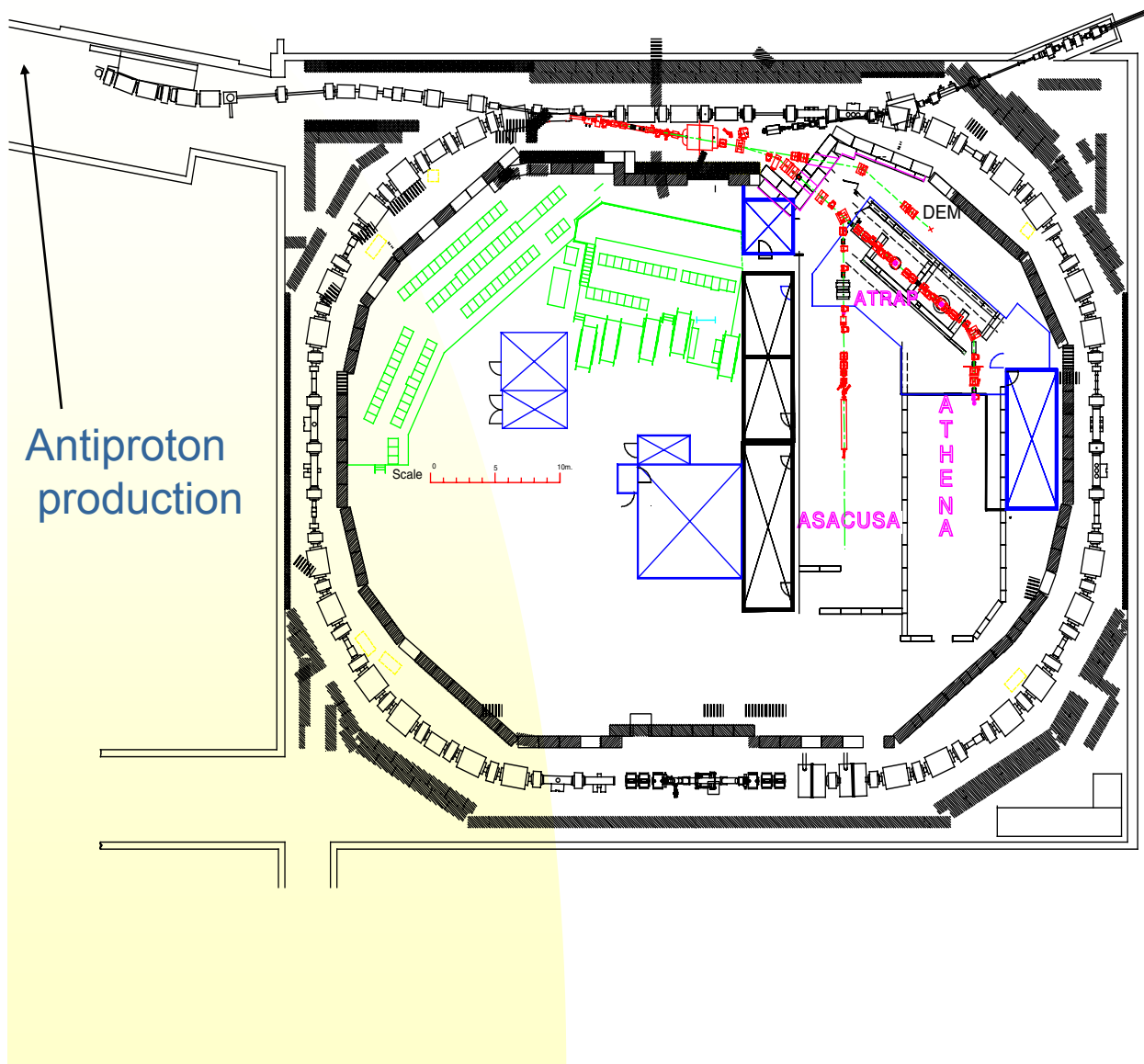
Just one Problem: Lyman- α detection via field quenching => atoms can be used once only
(all 1s, m_F states get equally populated)

How to scale line center accuracy in absence of systematic errors?

$$\delta\nu = \Delta\nu_{\text{exp.}} / (\text{Sign./Noise}) \approx \Delta\nu_{\text{exp.}} / \sqrt{N_{\text{particles}}}$$

Antiproton Decelerator (AD) at CERN

AD PROJECT



- Started operation July 6th, 2000
- Antiproton capture, deceleration, cooling
- Pulsed extraction
 - 2-4 x 10⁷ of 5 MeV antiprotons per pulse, ~100 ns length
 - 1 pulse / 100 seconds
- 3 Experiments
 - ATHENA & ATRAP (antihydrogen)
 - ASACUSA (antiprotonic helium, etc.)

Search Results -- Summary

TS=(antihydrogen)

DocType=All document types; Language=All languages; Databases=SCI-EXPANDED, SSCI, A&HCI; Timespan=1945-

379 results found

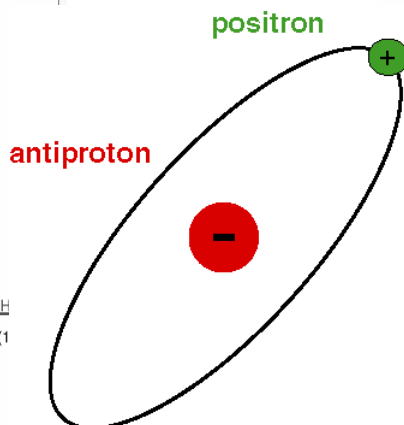
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Records 1 -- 10



Use the checkboxes to select individual records for marking, then click Submit to add them to the Marker

1. Gabrielse G, Speck A, Storry CH, et al.
First measurement of the velocity of slow antihydrogen atoms
PHYSICAL REVIEW LETTERS 93 (7): Art. No. 073401 AUG 13 2004
2. Oxley P, Bowden NS, Parrott R, et al.
Aperture method to determine the density and geometry of antiparticle plasmas
PHYSICS LETTERS B 595: 60-67 AUG 12 2004
3. Van Hooydonk G
Mexican hat curve for hydrogen and antihydrogen states in natural atom H
ACTA PHYSICA HUNGARICA NEW SERIES-HEAVY ION PHYSICS 19 (3-4): 385-388 2004
4. Gribakin GF, Knudsen H, Surko CM
Progress, challenges and perspectives in positron physics: Report on the XIII International Positron Workshop
PHYSICA SCRIPTA 70 (1): C1-C9 JUL 2004
5. Kuzmin SG, O'Neil TM
Polarization and trapping of weakly bound atoms in penning trap fields
PHYSICAL REVIEW LETTERS 92 (24): Art. No. 243401 JUN 18 2004
6. Strasburger K
Dependence of the static leptonic properties on the internuclear distance in the H-H and He-H systems
JOURNAL OF PHYSICS B-ATOMIC MOLECULAR AND OPTICAL PHYSICS 37 (1) 2211-2219 MAY 28 2004
7. Froelich P, Zygelman B, Saenz A, et al.
Hydrogen-antihydrogen molecule and its properties
FEW-BODY SYSTEMS 34 (1-3): 63-72 MAY 2004
8. Donets ED, Donets EE, Syresin EM, et al.
Formation of a high intensity low energy positron string
REVIEW OF SCIENTIFIC INSTRUMENTS 75 (5): 1563-1565 Part 2 MAY 2004
9. Amoretti M, Amsler C, Bonomi G, et al.
Dynamics of antiproton cooling in a positron plasma during antihydrogen formation
PHYSICS LETTERS B 590 (3-4): 133-142 JUN 24 2004
10. Armour EAG, Chamberlain CW, Liu Y, et al.
Collisions between low-energy antihydrogen and atoms
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH SECTION B-BEAM INTERACTIONS WITH MATERIALS AND ATOMS 221: 1-5 JUL 2004



Search Results -- Summary

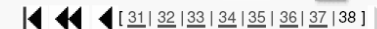
TS=(antihydrogen)

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371. NIEVES JF, SHANKER O
ANALYSIS OF MODELS FOR HYDROGEN-ANTIHYDROGEN OSCILLATIONS
PHYSICAL REVIEW D 30 (1): 139-146 1984
372. DEO BB, MAHARANA K
HYDROGEN-ANTIHYDROGEN OSCILLATIONS IN A FRACTIONALLY CHARGED PATTI-SALAM MODEL
PHYSICAL REVIEW D 29 (5): 1020-1021 1984
373. NEUMANN R, POTH H, WINNACKER A, et al.
LASER-ENHANCED ELECTRON-ION CAPTURE AND ANTIHYDROGEN FORMATION
ZEITSCHRIFT FUR PHYSIK A-HADRONS AND NUCLEI 313 (4): 253-262 1983
374. CAMPEANU RI, BEU T
HYDROGEN ANTIHYDROGEN INTERACTION POTENTIAL
PHYSICS LETTERS A 93 (5): 223-226 1983
375. SARKAR U, MISRA SP, PARIDA MK
HYDROGEN ANTIHYDROGEN OSCILLATIONS - SIGNATURE OF INTERMEDIATE MASS SCALES IN GUTS
PHYSICS LETTERS B 120 (1-3): 124-126 1983
376. MOHAPATRA RN, SENJANOVIC G
HYDROGEN-ANTIHYDROGEN OSCILLATIONS AND SPONTANEOUSLY BROKEN GLOBAL B-L SYMMETRY
PHYSICAL REVIEW LETTERS 49 (1): 7-10 1982
377. ARNELLOS L, MARCIANO WJ
HYDROGEN-ANTIHYDROGEN OSCILLATIONS, DOUBLE PROTON DECAY, AND GRAND UNIFIED THEORIES
PHYSICAL REVIEW LETTERS 48 (25): 1708-1711 1982
378. KOLOS W, MORGAN DL, SCHRADER DM, et al.
HYDROGEN-ANTIHYDROGEN INTERACTIONS
PHYSICAL REVIEW A 11 (6): 1792-1796 1975
379. JUNKER BR, BARDSLEY JN
HYDROGEN-ANTIHYDROGEN INTERACTIONS
PHYSICAL REVIEW LETTERS 28 (19): 1227& 1972

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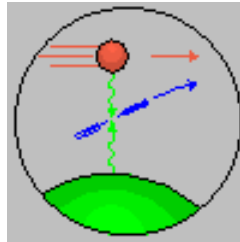
379 results found

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First experimental observations (at CERN) attributed to hot, fast antihydrogen.

"Production of Antihydrogen"

G.Baur et al. (includes D. Grzonka, W. Oelert, G. Schepers, and T. Sefzick, now part of ATRAP)
Phys.Lett. B 368 (1996) 251-258.



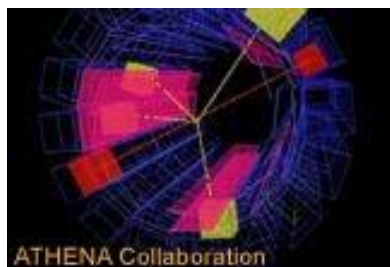
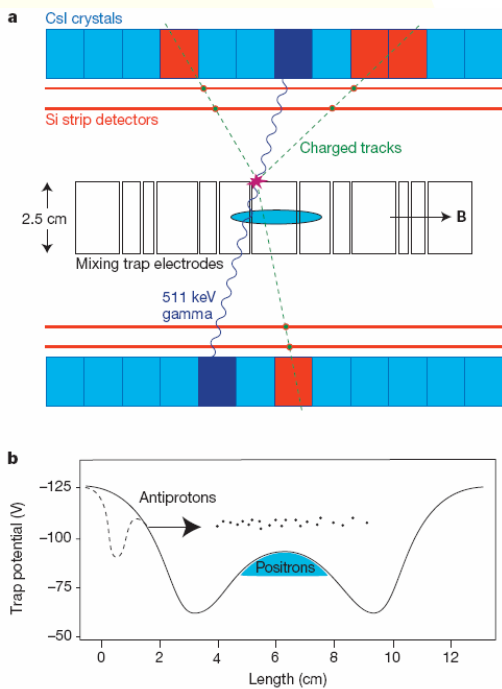
Second observations (at Fermilab, with improved setup and luminosity monitors) attributed to hot, fast antihydrogen atoms.

"Observation of Antihydrogen"

G. Blanford, et al.
Phys. Rev. Lett. **80**, 3037 (1998).

Production and detection of cold antihydrogen atoms

M. Amoretti*, C. Amsler†, G. Bonomi‡§, A. Bouchta‡, P. Bowe||, C. Carraro*, C. L. Cesar¶, M. Charlton#, M. J. T. Collier#, M. Doser‡, V. Filippini☆, K. S. Fine‡, A. Fontana☆☆, M. C. Fujiwara††, R. Funakoshi††, P. Genova☆☆, J. S. Hangst||, R. S. Hayano††, M. H. Holzschetter‡, L. V. Jørgensen#, V. Lagomarsino*‡‡, R. Landua‡, D. Lindelöf†, E. Lodi Rizzini§☆, M. Macri*, N. Madsen†, G. Manuzio*‡‡, M. Marchesotti☆, P. Montagna☆☆, H. Pruijs†, C. Regenfus†, P. Riedler‡, J. Rochet‡#, A. Rotondi☆☆, G. Rouleau‡#, G. Testera*, A. Variola*, T. L. Watson# & D. P. van der Werf#



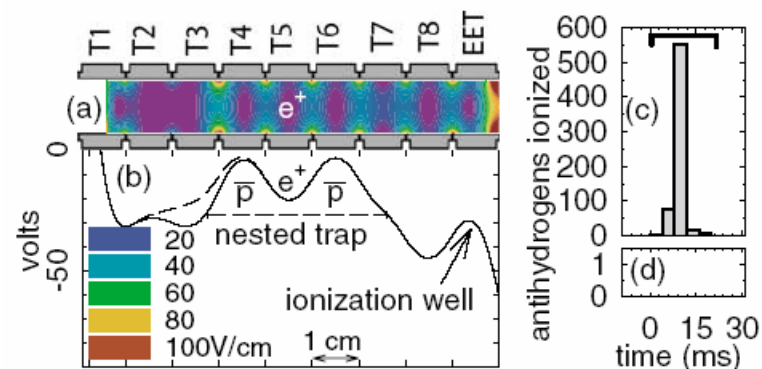
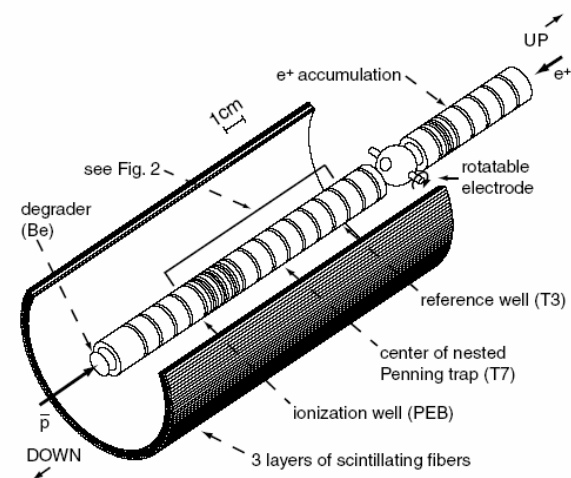
Scientists Create 'Star Trek' Antihydrogen in Quantity

By Alex Dominguez
Associated Press
posted: 02:59 pm ET
18 September 2002

Background-Free Observation of Cold Antihydrogen with Field-Ionization Analysis of Its States

G. Gabrielse,^{1,*} N. S. Bowden,¹ P. Oxley,¹ A. Speck,¹ C. H. Storry,¹ J. N. Tan,¹ M. Wessels,¹ D. Grzonka,² W. Oelert,² G. Scheepers,² T. Seifick,² J. Walz,³ H. Pittner,⁴ T. W. Hänsch,^{4,5} and E. A. Hessels⁶

(ATRAP Collaboration)



Physical Review Letters 89, 213401 online (2002)

High rate production of antihydrogen

ATHENA Collaboration

M. Amoretti^a, C. Amsler^b, G. Bazzano^{c,d}, G. Bonomi^e, A. Bouchta^e, P. Bowe^f,
C. Carraro^{a,g}, C.L. Cesar^h, M. Charltonⁱ, M. Doser^e, V. Filippini^{c,d}, A. Fontana^{c,d},
M.C. Fujiwara^{j,k}, R. Funakoshi^k, P. Genova^{c,d}, J.S. Hangst^f, R.S. Hayano^k,
L.V. Jørgensenⁱ, V. Lagomarsino^{a,g}, R. Landua^e, D. Lindelöf^b, E. Lodi Rizzini^{c,l},
M. Macri^a, N. Madsen^f, G. Manuzio^{a,g}, M. Marchesotti^e, P. Montagna^{c,d}, H. Pruys^b,
C. Regenfus^b, P. Riedler^e, A. Rotondi^{c,d}, G. Rouleau^e, G. Testera^a, A. Variola^a,
D.P. van der Werfⁱ

^a *Istituto Nazionale di Fisica Nucleare, Sezione di Genova, 16146 Genova, Italy*

^b *Physik-Institut, Zurich University, CH-8057 Zurich, Switzerland*

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Received 27 August 2003; accepted 14 October 2003

Editor: W.-D. Schlatter

Abstract

We show that antihydrogen production is the dominant process when mixing antiprotons and positrons in the ATHENA apparatus, and that the initial production rate exceeds 300 Hz, decaying to 30 Hz within 10 s. A fraction of 65% of all observed annihilations is due to antihydrogen.

Three-Dimensional Annihilation Imaging of Trapped Antiprotons

M. C. Fujiwara,^{1,2,*} M. Amoretti,³ G. Bonomi,⁴ A. Bouchta,⁴ P. D. Bowe,⁵ C. Carraro,^{3,6} C. L. Cesar,⁷ M. Charlton,⁵ M. Doser,⁴ V. Filippini,⁸ A. Fontana,^{8,9} R. Funakoshi,¹ P. Genova,^{8,9} J. S. Hangst,¹⁰ R. S. Hayano,¹ L. V. Jørgensen,⁵ V. Lagomarsino,^{3,6} R. Landua,⁴ E. Lodi-Rizzini,^{8,11} M. Marchesotti,⁸ M. Macri,³ N. Madsen,¹⁰ G. Manuzio,^{3,6} P. Montagna,^{8,9} P. Riedler,⁴ A. Rotondi,^{8,9} G. Rouleau,^{4,5} G. Testera,³ A. Variola,³ D. P. van der Werf,⁵ and Y. Yamazaki²

(ATHENA Collaboration)

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(Received 31 July 2003; published 13 February 2004)

We demonstrate three-dimensional imaging of antiprotons in a Penning trap, by reconstructing annihilation vertices from the trajectories of the charged annihilation products. The unique capability of antiparticle imaging has allowed, for the first time, the observation of the spatial distribution of the particle loss in a Penning trap. The radial loss of antiprotons on the trap wall is localized to small spots, strongly breaking the azimuthal symmetry expected for an ideal trap. Our observations have important implications for detection of antihydrogen annihilations.

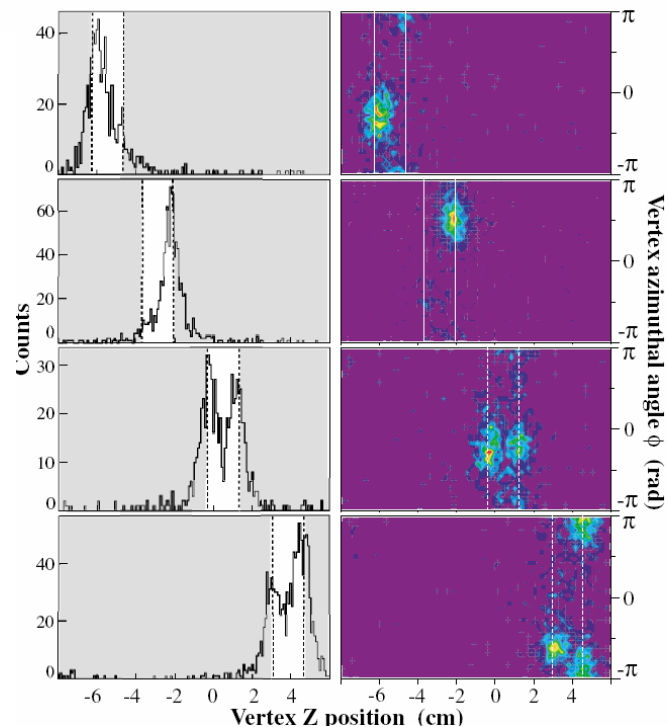


FIG. 4 (color). The projection of the annihilation distribution on the z axis (left column) and on the $z-\phi$ plane (right column) for four different confinement setups. The trap well positions are indicated by the unshaded regions, and the dimensions of the electrodes are depicted with dashed lines.

First Laser-Controlled Antihydrogen Production

C.H. Storry,¹ A. Speck,¹ D. Le Sage,¹ N. Guise,¹ G. Gabrielse*,¹ D. Grzonka,² W. Oelert,² G. Schepers,²
T. Seifick,² H. Pittner,³ M. Herrmann,³ J. Walz,³ T.W. Hänsch,^{3,4} D. Comeau,⁵ and E.A. Hessels⁵

(ATRAP Collaboration)

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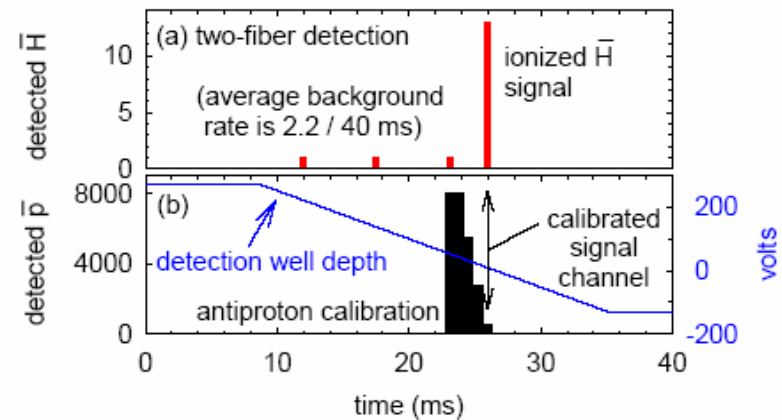
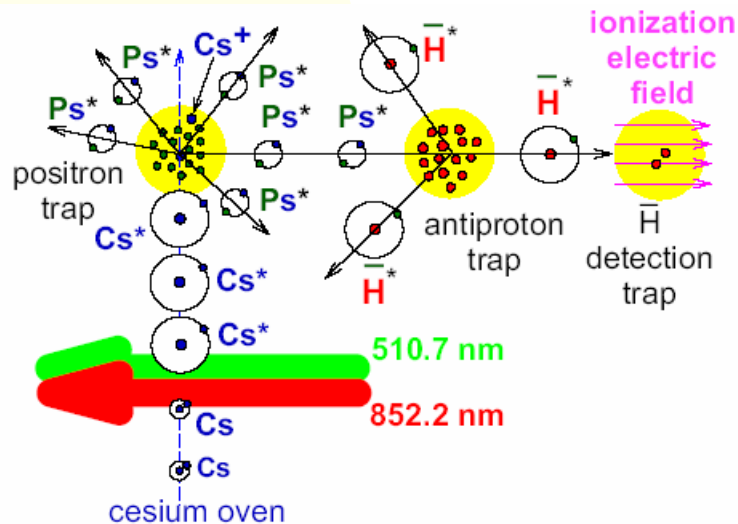
³Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, 85748 Garching, Germany

⁴Ludwig-Maximilians-Universität München, Schellingstrasse 4/III, 80799 München, Germany

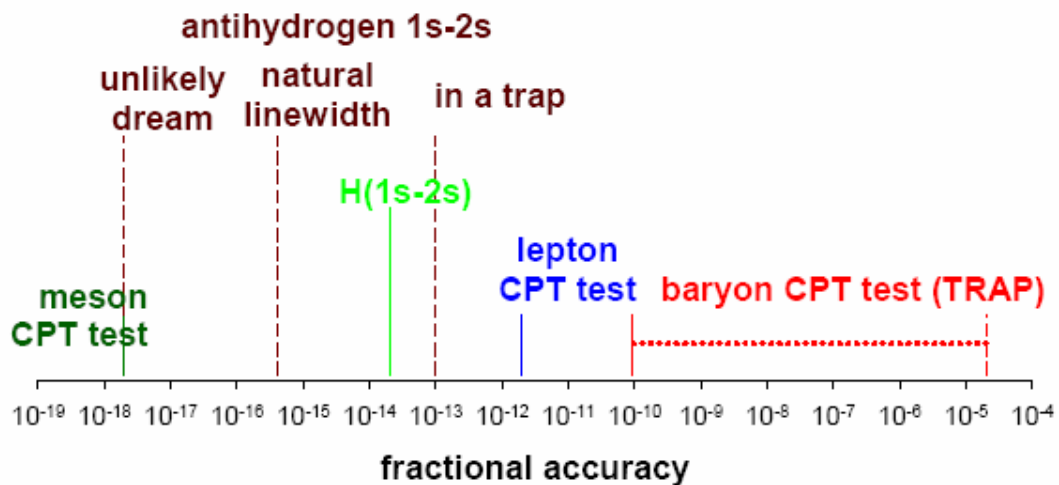
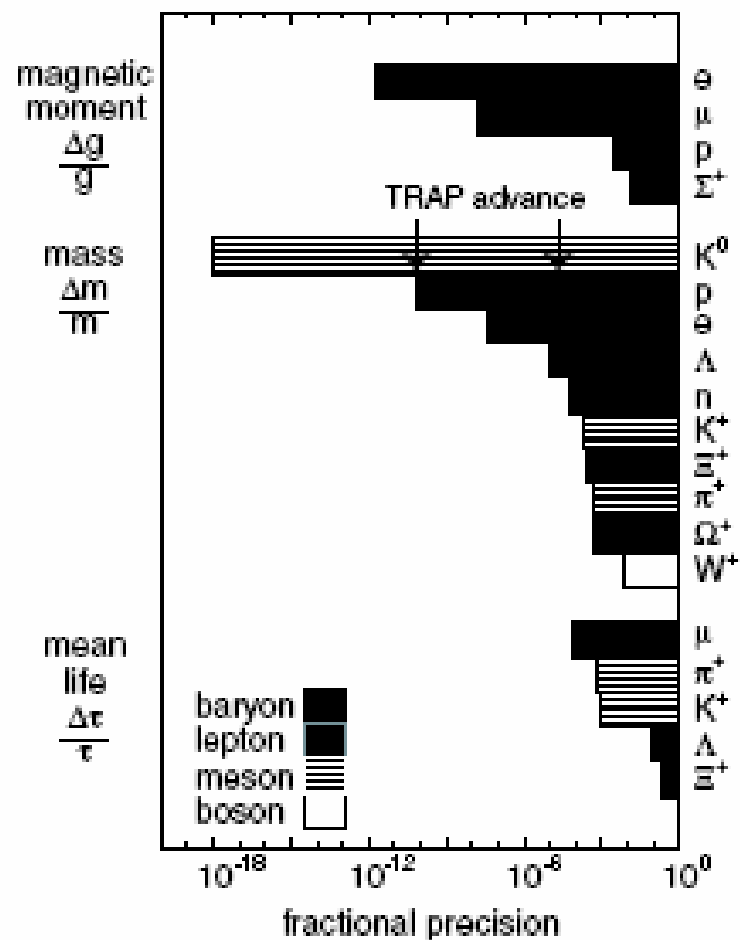
⁵York University, Department of Physics and Astronomy, Toronto, Ontario M3J 1P3, Canada

(Dated: Submitted to PRL: 17 August 2004)

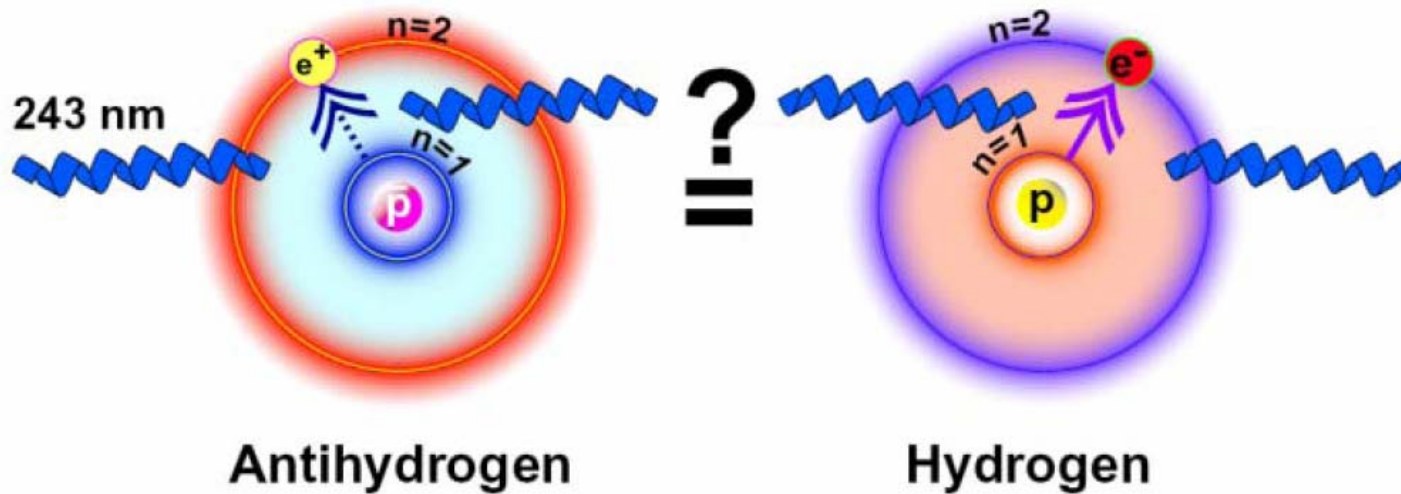
Lasers are used for the first time to control the production of antihydrogen (\bar{H}). Sequential, resonant charge exchange collisions are involved in a method that is very different than the only other method used so far – producing slow \bar{H} during positron cooling of antiprotons in a nested Penning trap. Two attractive features are that the laser frequencies determine the \bar{H} binding energy, and that the production of extremely cold \bar{H} should be possible in principle – likely close to what is needed for confinement in a trap, as needed for precise laser spectroscopy.



Antihydrogen CPT Tests



(Anti-)Hydrogen CPT tests



Laser spectroscopy 1s-2s

Microwave spectroscopy
1s Hyperfine Structure

$$\Delta V_{1s2s} = \frac{3}{4} * R_{\infty} + \epsilon_{\text{QED}} + \epsilon_{\text{nucl}} + \epsilon_{\text{weak}} + \epsilon_{\text{CPT}}$$

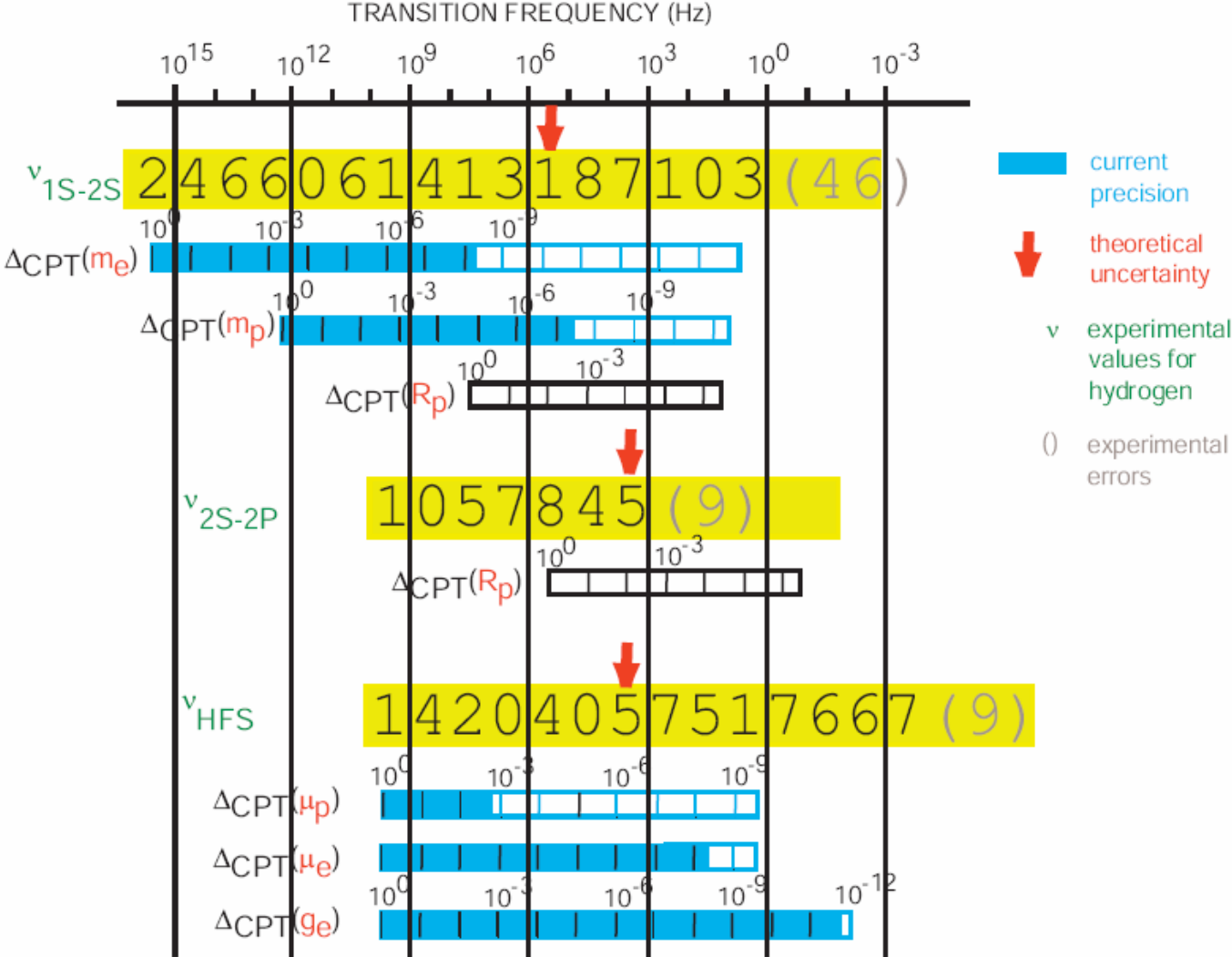
“Long distance” Interaction

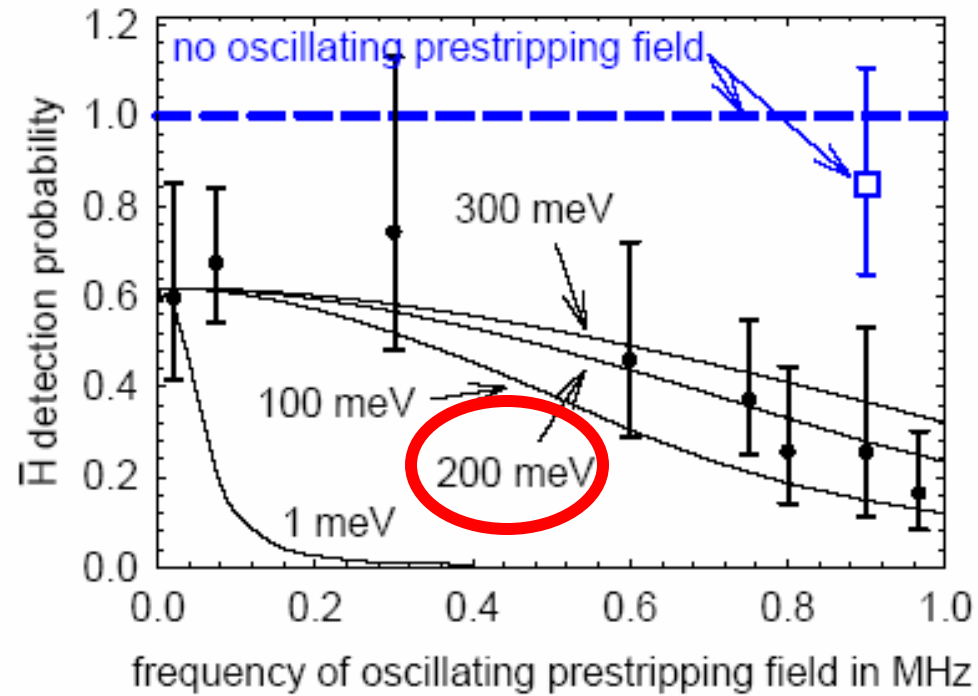
$$\Delta V_{\text{HFS}} = \text{cons.} * \alpha^2 R_{\infty} + \epsilon'_{\text{QED}} + \epsilon'_{\text{nucl}} + \epsilon'_{\text{weak}} + \epsilon'_{\text{CPT}}$$

“Contact” interaction

$$R_{\infty} = * m_e c^2 * \alpha^2 / 2 h$$

Measured quantities in hydrogen and relevance to CPT tests





Measurements indicate

$T \approx 2400$ K

needed for trapping

0.5 K

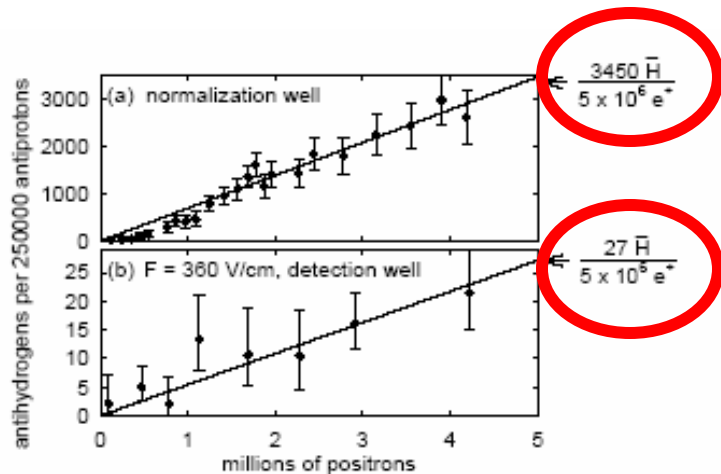


Fig. 20. \bar{H} produced from $2.5 \times 10^5 \bar{p}$ and detected in the normalization (a) and detection wells (b), the latter having survived a 360 V/cm field without ionizing. From (Gabrielse et al., 2004a).

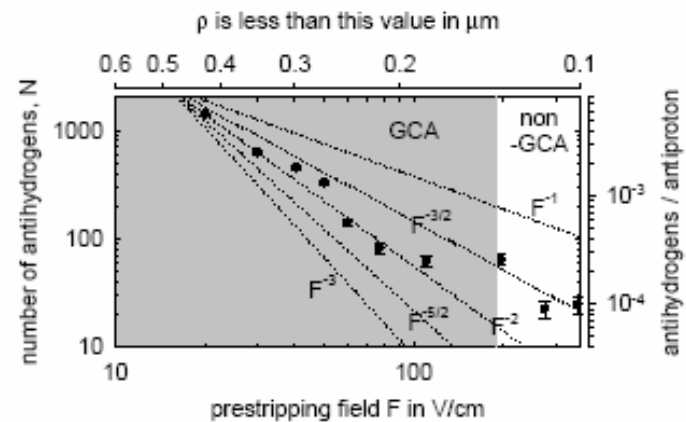


Fig. 21. Number N of \bar{H} that survive an ionization field $F = F_z$, for $2.5 \times 10^5 \bar{p}$ and $5 \times 10^6 e^+$, taken from measurements such as shown in Fig. 20. From (Gabrielse et al., 2004a).

$$\rho \leq \frac{a}{\sqrt{F}} \sqrt{\frac{e}{4\pi\epsilon_0}}$$

ρ mostly above .1 μm
 $n > 15$

(Anti-)Hydrogen Spectroscopy*

Hydrogen 1s-2s Saturation Intensity	I_s	= 0.9 W/cm ²
Excitation Rate	R_e	= $4\pi \cdot 84 \cdot (I/W/s \cdot \text{cm}^2)^2 / \Delta\nu / \text{Hz}$
Photo Ionization Rate	R_p	= $9 \cdot I/W/s \cdot \text{cm}^2$
Zeeman shift	$\delta\nu_Z$	= $9.3 \cdot B \text{ Hz/T}$
ac Stark shift	$\delta\nu_{ac}$	= $1.7 I \text{ Hz} / W \cdot \text{cm}^2$
Velocity at 1mK	V_{1K}	= 4 m/s
Time-of-flight broadening	$\Delta\nu_{TOF}$	= 3 kHz (1 mK, 600 μm beam diam.)
Lyman α detection efficiency	10^{-6}	= $\Omega \cdot \text{eff}_{MCP}$ (= $10^{-4} \cdot 10^{-2}$)

10^{11} H-atoms (MIT Bose condens.)

$$\delta\nu/\nu_{1s2s} = 10^{-13} \text{ (1s integration time)}$$

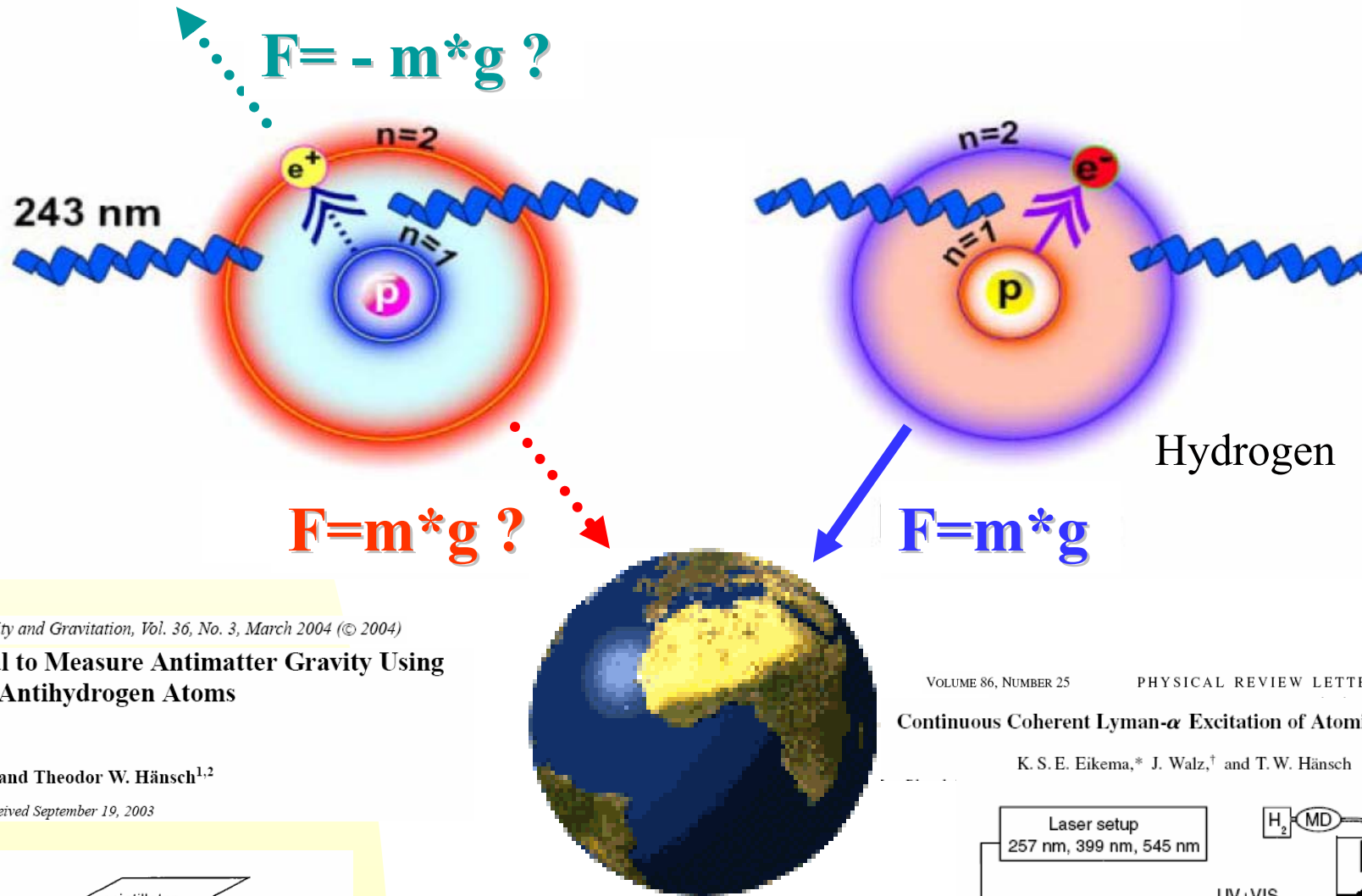
* numbers verified with L. Willmann

Just one Problem: Lyman- α detection via field quenching \Rightarrow atoms can be used once only
(all 1s, m_F states get equally populated)

How to scale line center accuracy in absence of systematic errors?

$$\delta\nu = \Delta\nu_{\text{exp.}} / (\text{Sign./Noise}) \approx \Delta\nu_{\text{exp.}} / \sqrt{N_{\text{particles}}}$$

(Anti-)Hydrogen Gravity Tests

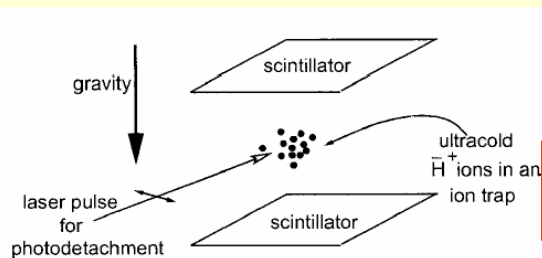


General Relativity and Gravitation, Vol. 36, No. 3, March 2004 (© 2004)

A Proposal to Measure Antimatter Gravity Using Ultracold Antihydrogen Atoms

Jochen Walz¹ and Theodor W. Hänsch^{1,2}

Received September 19, 2003



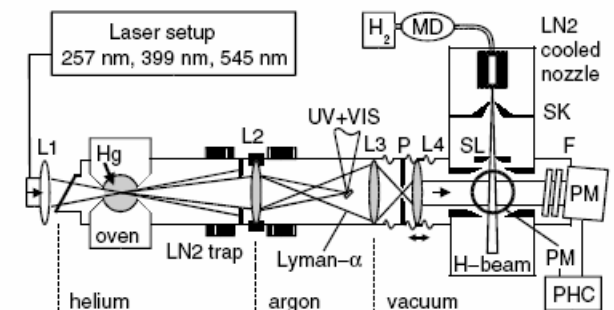
Lyman - α laser required

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PHYSICAL REVIEW LETTERS

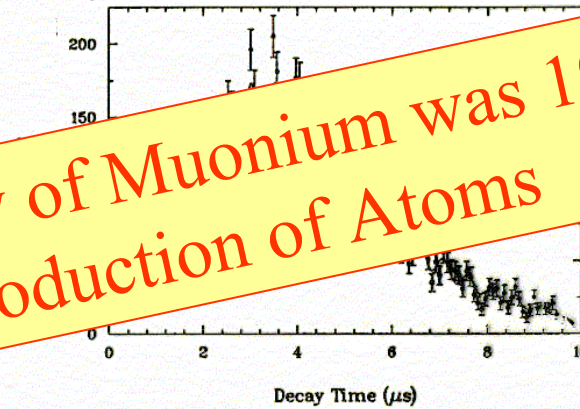
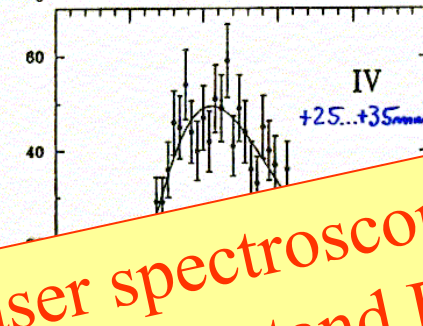
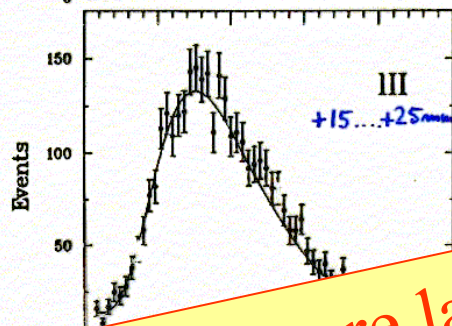
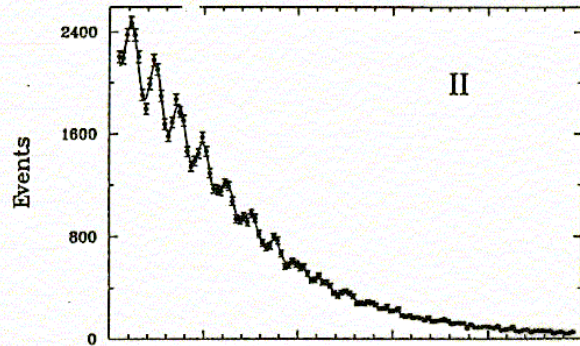
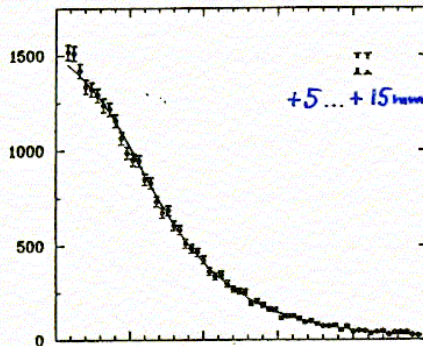
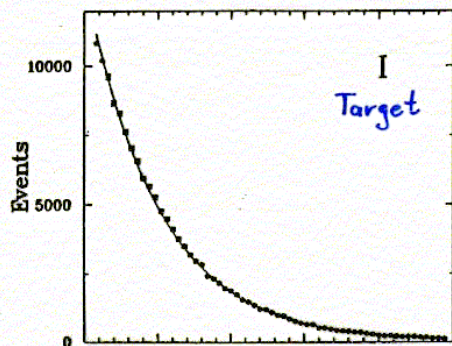
Continuous Coherent Lyman- α Excitation of Atomic Hydrogen

K. S. E. Eikema,* J. Walz,[†] and T. W. Hänsch



$B=0$

$B = .140(3) \text{ mT}$



We are about to begin laser spectroscopy of Muonium was 1988:
 Begin to Understand Production of Atoms

Production yield: $\approx 12(2)\%$ per stopped μ^+

Polarization: $39(9)\%$

Diffusion in SiO_2
powder:

$$D = 1068(81) \frac{\text{cm}^2}{\text{sec}}$$

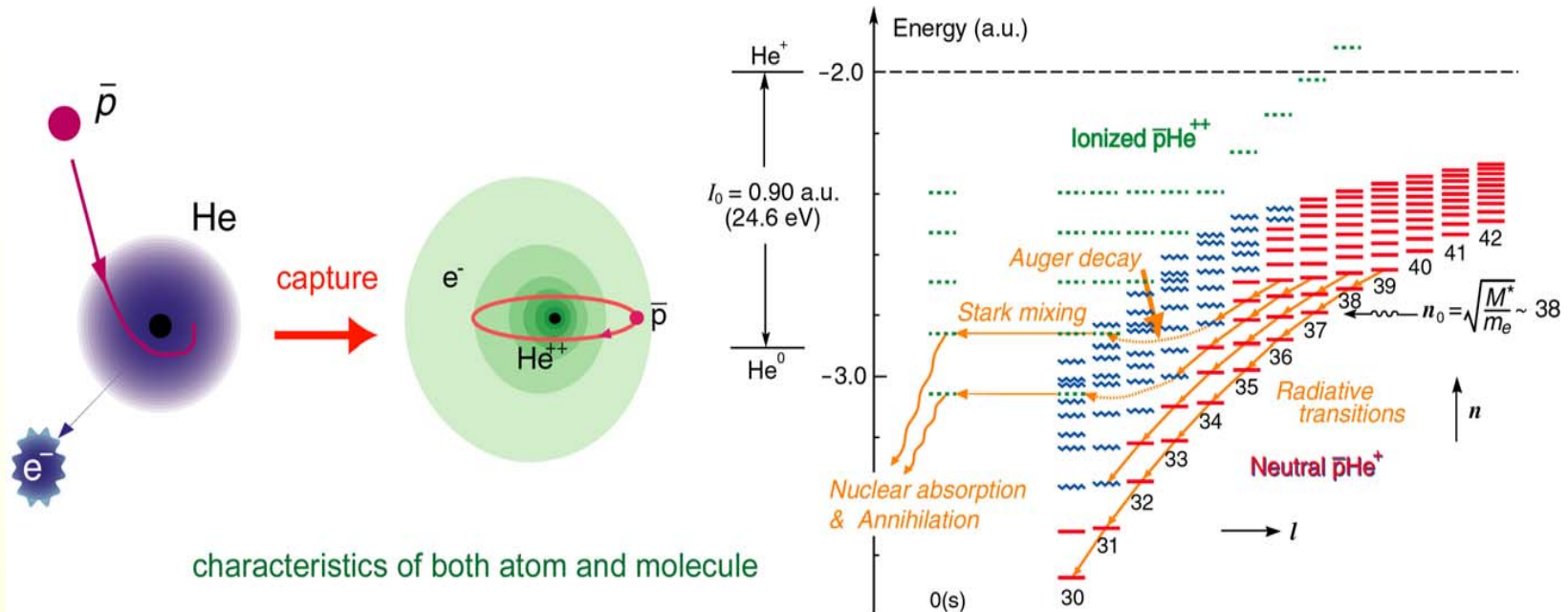
Temperature:

$$T = 296(10) \text{ K} \approx \bar{v} = 7.4(1) \frac{\text{mm}}{\mu\text{sec}}$$

Hydrogen-like Atoms

	Positronium e^+e^-	Muonium μ^+e^-	Hydrogen pe^-	Muonic Helium4 $(\alpha\mu^-)e^-$	Muonic ..Hydrogen.. $p\mu^-$	Pionic ..Hydrogen.. $p\pi^-$	Antiprotonic Helium4 $(\alpha\bar{p})^+$
$\Delta\nu_{1S-2S}$ [THz]	1233.6	2455.6	2466.1	2468.5	4.59×10^5	5.88×10^5	1.46×10^7
$\delta\nu_{1S-2S}$ [MHz]	1.28	.145	1.3×10^{-6}	.145	.176	3.5×10^7	10^{11}
$\Gamma = \frac{\Delta\nu_{1S-2S}}{\delta\nu_{1S-2S}}$	9.5×10^8	1.7×10^{10}	1.9×10^{15}	2.6×10^{12}	2.7×10^3	1.7×10^4	10^2
$\Delta\nu_{HFS}$ [GHz]	203.4	4.463	1.420	4.466	4.42×10^7	--	--
$\delta\nu_{HFS}$ [MHz]	1200	.145	4.5×10^{-22}	.145	.145	--	--
$\Gamma = \frac{\Delta\nu_{HFS}}{\delta\nu_{HFS}}$	1.7×10^2	3.1×10^4	3.2×10^{24}	3.1×10^4	3.1×10^8	--	--

pHe⁺ Atom – a naturally occurring trap for antiprotons

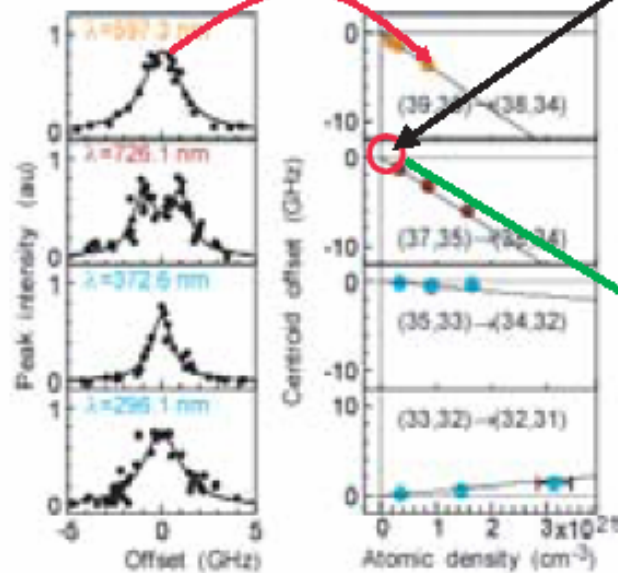


- Serendipitously discovered by Tokyo group at KEK
- 3-body system, Metastable
- ~ 3% of stopped antiprotons survive with average lifetime of ~ 3 μ s
- Precision laser spectroscopy by ASACUSA:
 - best test of 3-body QED theories
 - proton-antiproton mass & charge comparison, 60 ppb (PDG 2002)

Hayano, Yamazaki et al.

CPT Test with Antiprotonic Helium

5 MeV 1 π mm mrad beam



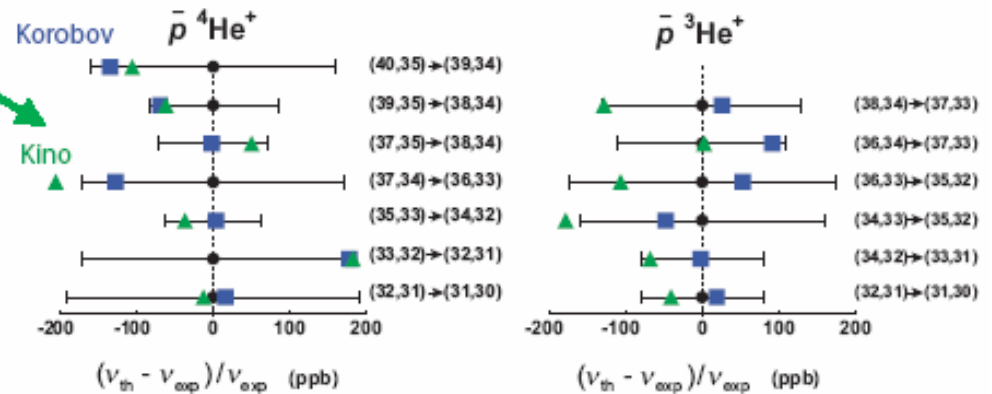
Resonance scans

Shift of center with density

- Zero-density values compared to state of-the-art three-body QED calculations
- \bar{p} mass and charge CPT limit: **60 ppb**

100 keV 100 π mm mrad beam

With RFQD: direct measurement at zero density (in "vacuum"): CPT limit 10 ppb

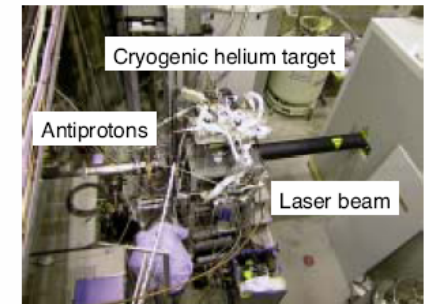
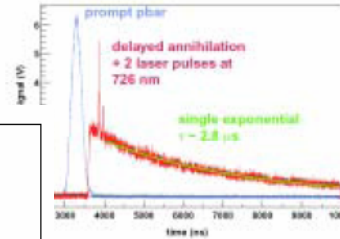
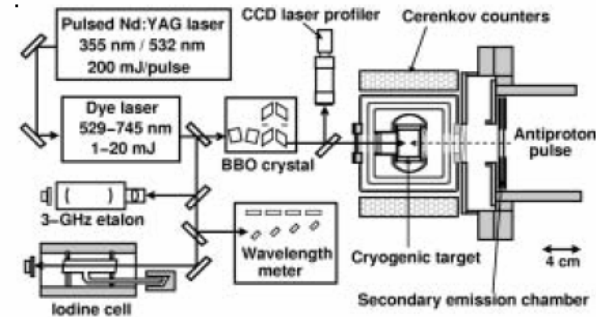


Exp. Accuracy 1.3×10^{-7}

Exp. Accuracy 6×10^{-8}

CPT test in Antiprotonic Helium

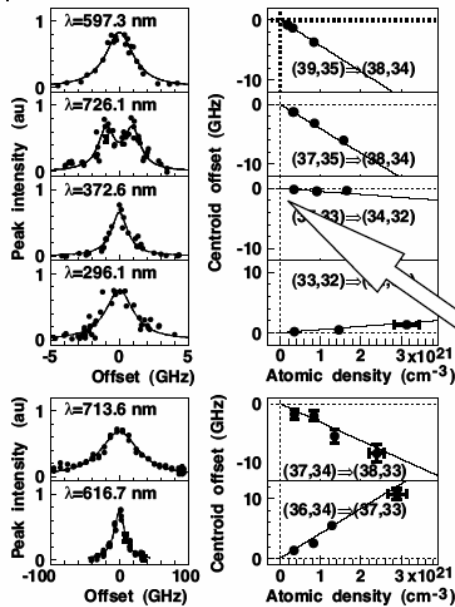
Method



R.S. Hayano, @Future AD Physics Program

The first PRL from AD

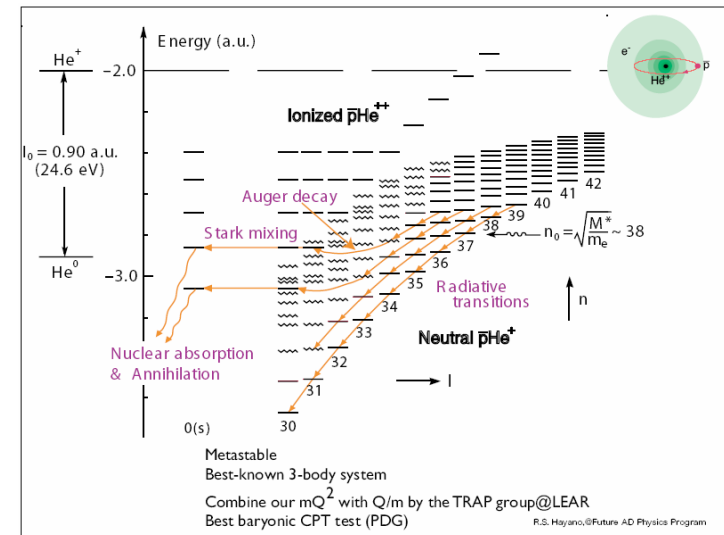
Hori et al. PRL 87 (2001) 093401



- “Phase-I” experiment - no RFQD
- Extrapolation to “vacuum” needed

$$\frac{|Q_p + Q_{\bar{p}}|}{Q_p} \sim \frac{|M_p - M_{\bar{p}}|}{M_p} < 6 \times 10^{-8}$$

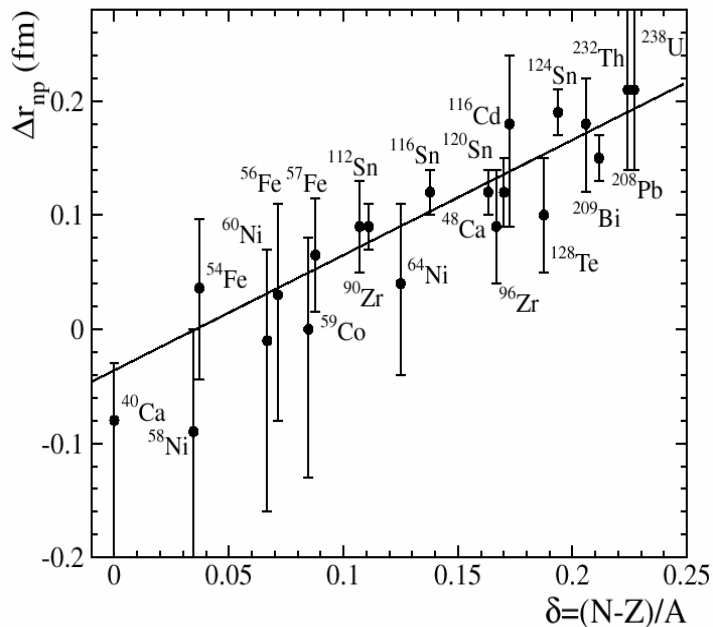
R.S. Hayano, @Future AD Physics Program



R.S. Hayano, @Future AD Physics Program

Antiprotonic Radioactive Atoms

Process	Observable	Deduced quantity	Physics
Capture in high orbit (atomic x-sections), cascade	Antiprotonic x-rays O(MeV)	Annihilation orbit, energy shifts	Matter distributions, neutron vs. protons on nuclear surface, ...
Annihilation ($n > 7$) on peripheral nucleon	De-excitation γ , particles, daughter activity	n vs. p annihilation	



VOLUME 87, NUMBER 8

PHYSICAL REVIEW LETTERS

20 AUGUST 2001

Neutron Density Distributions Deduced from Antiprotonic Atoms

A. Trzcina'ska, J. Jastrzebski, and P. Lubin'ski
Heavy Ion Laboratory, Warsaw University, PL-02-093 Warsaw, Poland

F. J. Hartmann, R. Schmidt, and T. von Egidy
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B. Klos
Physics Department, Silesian University, PL-40-007 Katowice, Poland
(Received 28 March 2001; published 2 August 2001)

Highest Uncertainty Arising from Theory

Where is Slow Antiproton Physics in 2004 ?

- **Driven by ambitious goals – CPT, Gravity,
Nuclear Properties, Medical,**
- **Antiprotonic Helium and Antihydrogen somewhat central**
 - **Antiprotonic Helium at KEK, LEAR, AD**
 - **Antihydrogen at CERN, FERMILAB (fast) and CERN (slow)**
- **There is slow Antiproton Facility available: AD**
- **AD produced beautiful results**
 - **Antiprotonic Helium**
 - **Antihydrogen**
- **Central now:**
 - **Learn to produce Antihydrogen (still highly excited / high velocities)**
 - **Prepare spectroscopy**
 - **Plasma Physics, Collision Physics, basic Atomic and Molecular Physics**
 - **Antimatter-Matter Interactions**
 - **.....**

Future Dreams & Plans

FLAIR Physics Topics with Antiprotons

- **Spectroscopy for tests of CPT and QED**
 - Antiprotonic atoms (pbar-He, pbar-p), antihydrogen

Low-energy
High-brilliance
Beams
- **Gravitation of antimatter**
 - Trapped and laser-cooled antihydrogen
- **Atomic collisions**

USR

 - Ionization, energy loss, antimatter-matter collisions
- **Antiprotons as hadronic probes**

DC beam,
availability of
RI

 - X-rays of light antiprotonic atoms: low-energy QCD
 - X-rays of neutron-rich nuclei: nuclear structure (halo)
 - Antineutron interaction
 - Strangeness -2 production
- **Medical applications: tumor therapy**

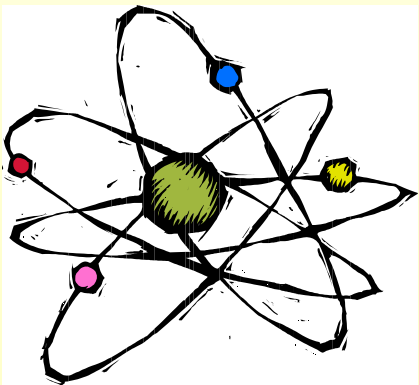
Higher energy



Atomic Physics Aspects of the Standard Model

Atomic Physics can be expected to continue to

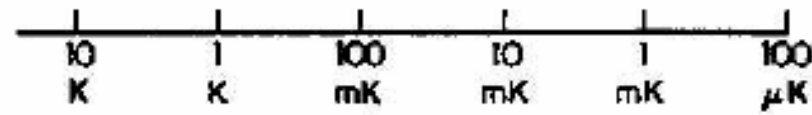
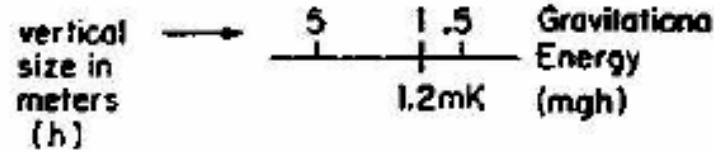
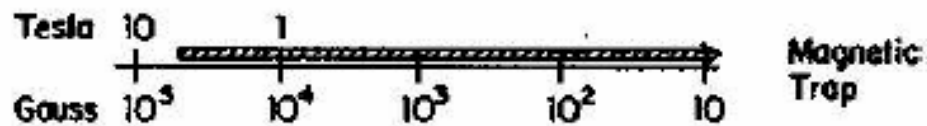
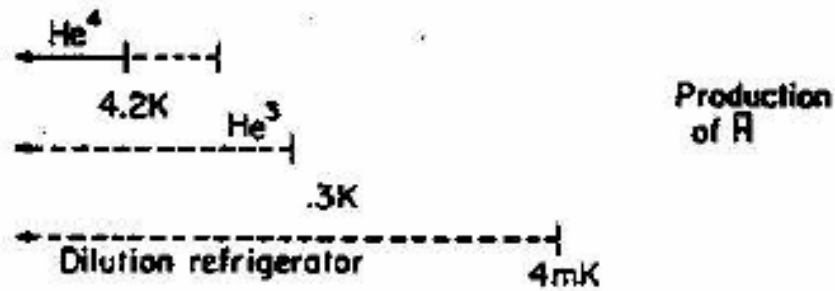
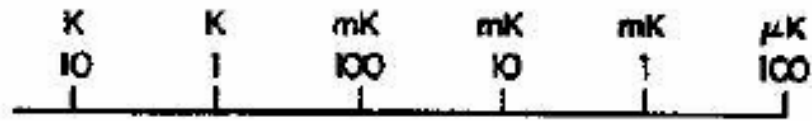
- ★ *provided sensitive tests of Standard Theory*
- ★ *contribute to the Development of Modern Fundamental Physical Concepts*
- ★ *search for new Phenomena*
- ★ *provide most accurate parameters*
- ★ *provide state of the art tools and techniques*
- ★ *show that every system has its own benefits*
- ★ *be good for surprises*



Antiproton contributions to this field just started –

Precision takes Time Care and Particles

Thank YOU !



Energy in °K