Fine structure constant determinations

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"Metrology of simple systems and fundamental tests"
Quantum metrology and fundamental constants

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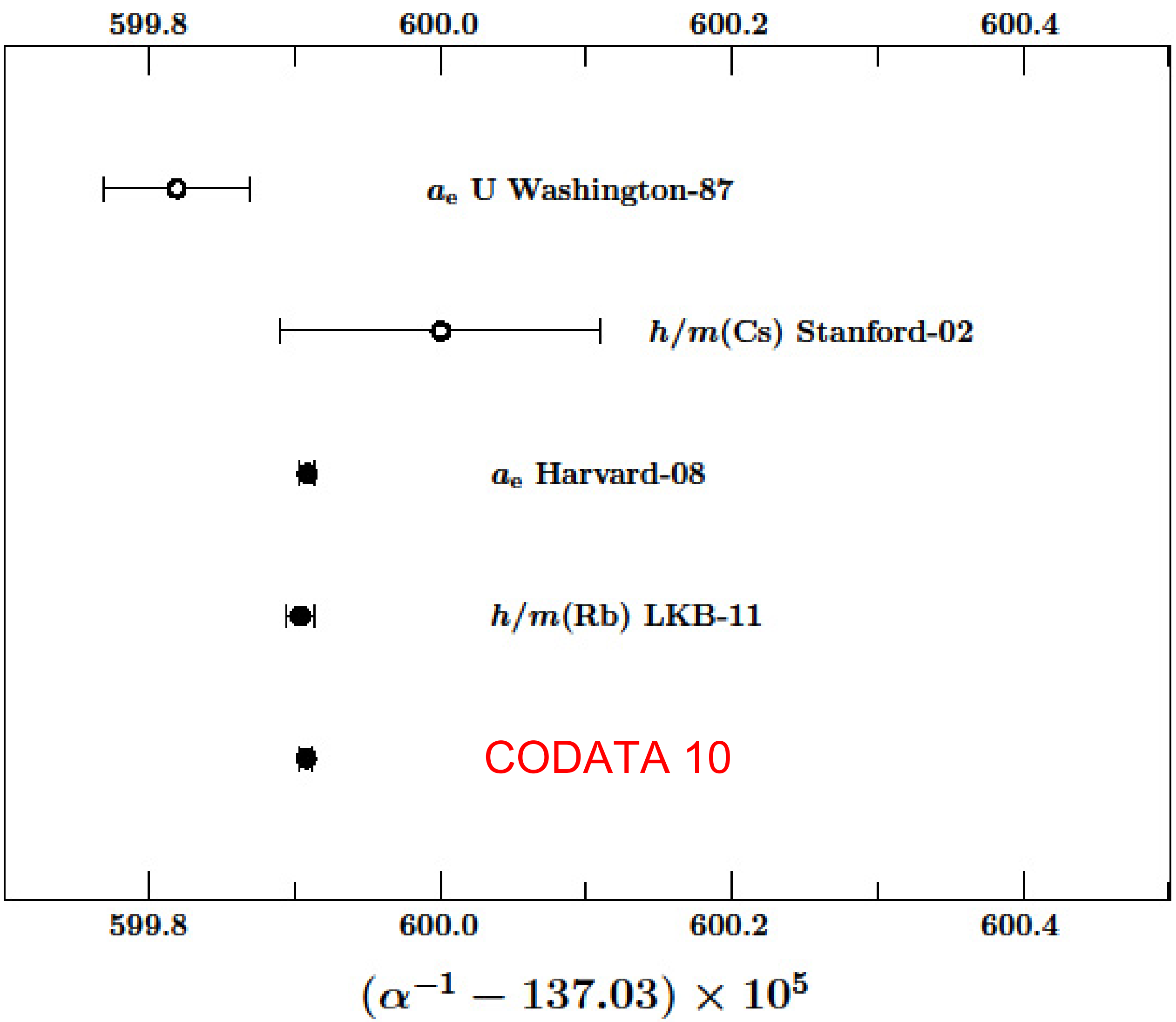
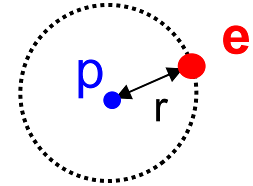
Present status of the knowledge of the fine structure constant



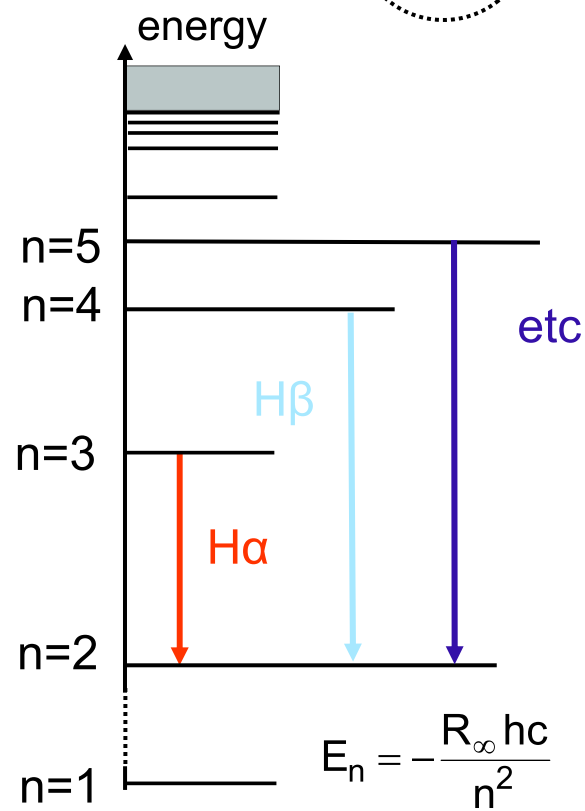
Codata 2010 arXiv:1203.5425v1 [physics.atom-ph]

A bit of history



A brief history : 19th century

Optical spectrum
(Balmer 1885)



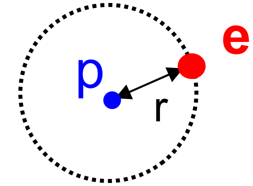
Bohr (1913)

Balmer-Rydberg formula
(1889)

$$\boxed{\frac{1}{\lambda} = R\left(\frac{1}{n^2} - \frac{1}{p^2}\right)}$$

n and p integers
R : Rydberg constant

A bit of history



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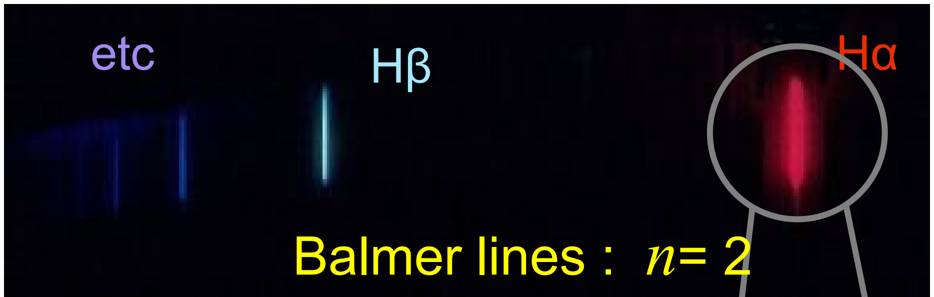

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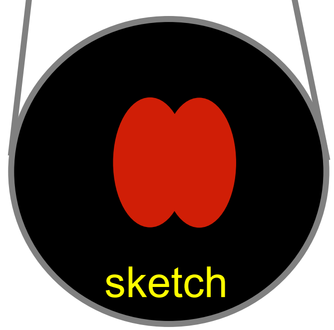
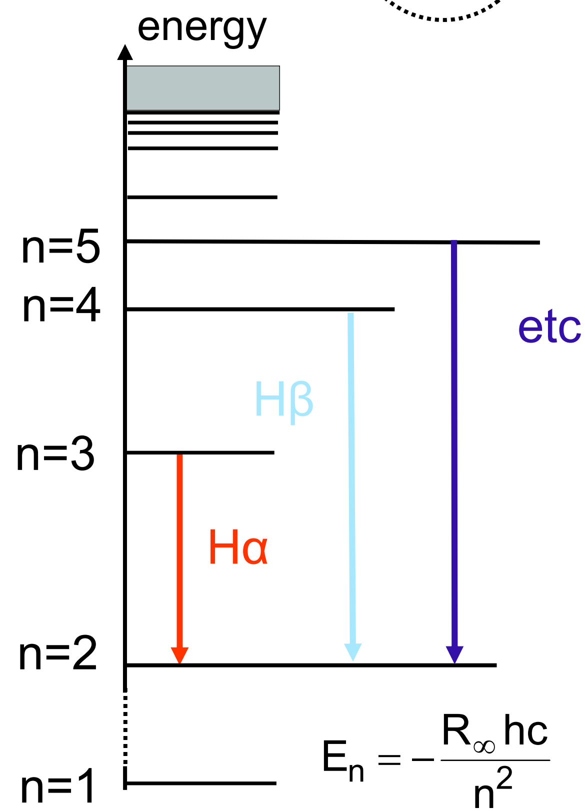


Fine structure : two lines !!



Bohr (1913)

A bit of history

1905 : Special theory of relativity
1913 : Bohr model description of H atom
1916 : A. Sommerfeld tried to include special relativity in the Bohr model to explain the fine structure observed in H

Werten der Konstanten e, m_H und L. Wir wollen diesem System der *strahlungstheoretischen universellen Einheiten* ein System von *spektroskopischen Einheiten* gegenüberstellen.

Von Bohr wurde bereits betont, daß die Rydbergsche Zahl[1]) in der Grenze für ein hohes Atomgewicht

(46) $$N_\infty = \frac{2\pi^2 m e^4}{c h^3}$$ Rydberg constant

Wir fügen den Bohrschen Gleichungen (46) und (47) die charakteristische Konstante unserer Feinstrukturen

(49) $$\alpha = \frac{2\pi e^2}{c h}$$ Fine Structure constant

Messungen ergaben für $\Delta\nu_H$ einen Wert, der, wenn man die Grenzen recht weit steckt, zwischen 0,35 und 0,37 liegt. Wir werden daher mit

(50) $$\Delta\nu_H = 0{,}360 + \Theta \cdot 0{,}010$$ Hγ (Paschen series)

rechnen, wo Θ ein positiver oder negativer echter Bruch ist, der aber vermutlich der 0 näher liegt als der 1. Trotz dieser beträchtlichen Unsicherheit werden wir zu einigen bemerkenswerten Folgerungen über die universellen Einheiten gelangen.

Zunächst ergibt sich wegen $\Delta\nu_H = N\alpha^2/16$ f.s. scaled as α^4

(51) $$\alpha^2 = (5{,}25 + \Theta \cdot 0{,}15)\cdot 10^{-5}, \quad \alpha = (7{,}25 + \Theta \cdot 0{,}10)\cdot 10^{-3}$$

Value of α from f.s.

1916. № 17.
ANNALEN DER PHYSIK.
VIERTE FOLGE. BAND 51.

1. *Zur Quantentheorie der Spektrallinien;*
von A. Sommerfeld.

$$\begin{cases} e = (4{,}76 + \eta\cdot 0{,}05)\cdot 10^{-10}, \\ h = (6{,}51 + \eta\cdot 0{,}11)\cdot 10^{-27}, \\ \alpha^2 = (5{,}30 + \eta\cdot 0{,}04)\cdot 10^{-5}, \\ \Delta\nu_H = 0{,}363 + \eta\cdot 0{,}0025, \\ m_H = (1{,}64 + \eta\cdot 0{,}02)\cdot 10^{-24}, \\ L = (6{,}08 - \eta\cdot 0{,}06)\cdot 10^{23}. \end{cases}$$

Codata 2012

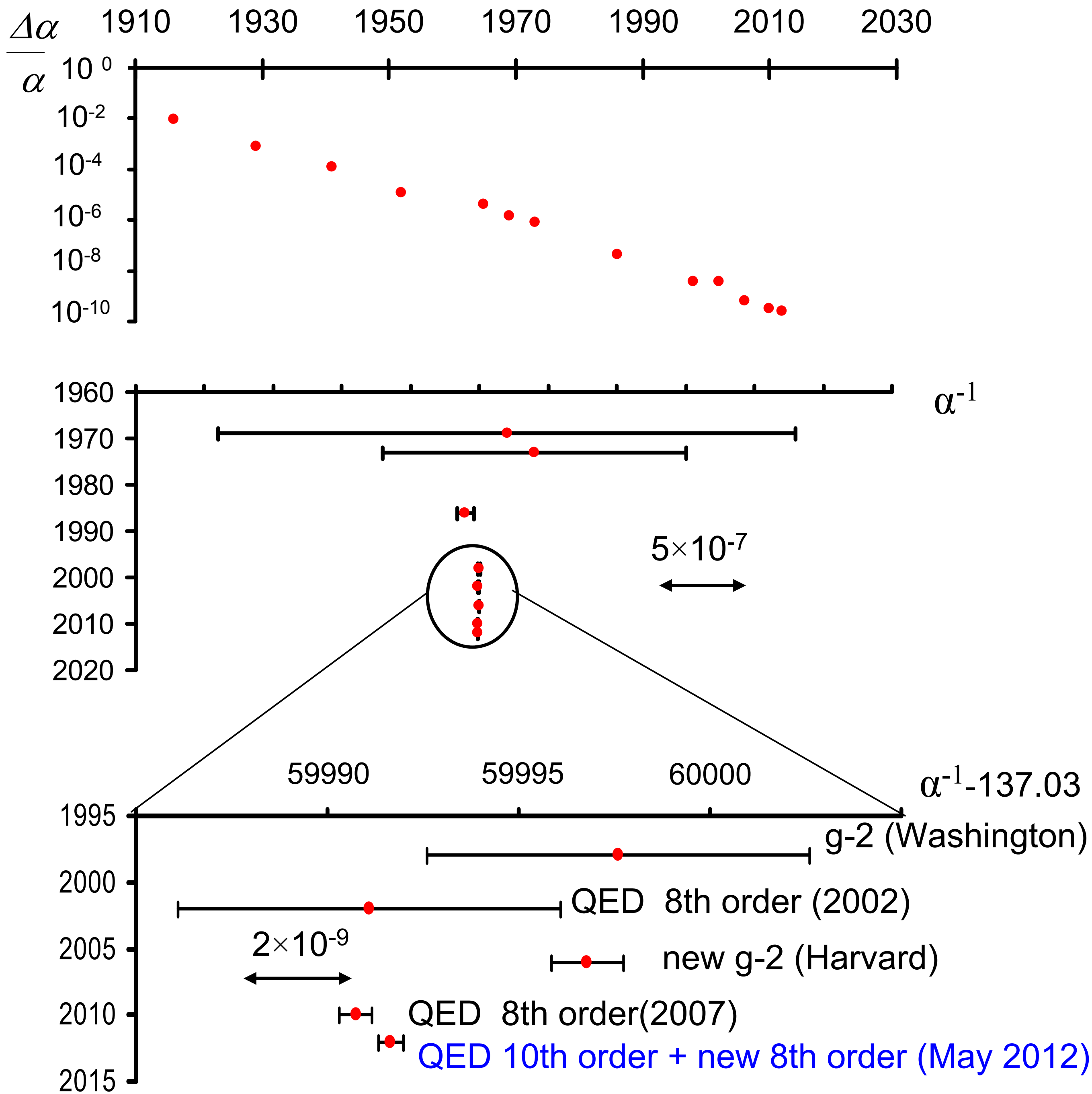
$e \times c = 4.8032\ldots 10^{-10}$ abs.e.m.u.

$h = 6.62606957(29) \times 10^{-34}$ J s

$\alpha^2 = 5.3251354528 \times 10^{-3}$

$\Delta\nu_H = 0.36551\ldots \text{cm}^{-1}$

History of
α determinations
(from
"CODATA xxxx")

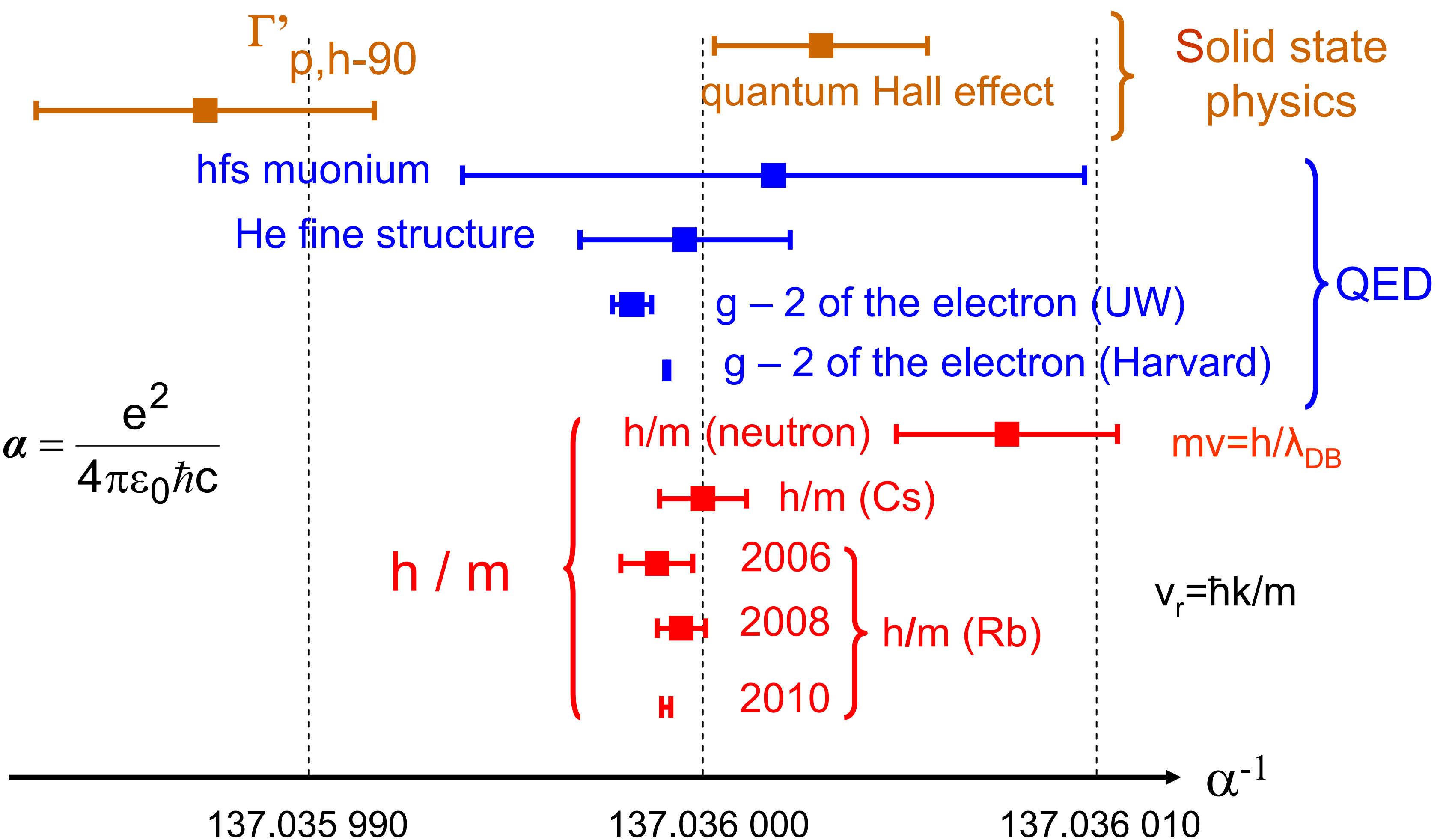


History of α determinations

Sommerfeld 1916 (~ 10^{-2}) :	$\alpha^{-1} = 137{,}4\ (1{,}3)$	H f.s. + indirect
Birge 1929 (~ 8.10^{-4}) :	$\alpha^{-1} = 137{,}29\ (11)$	indirect (e, h, c)
Birge 1941 (~ 1.10^{-4}) :	$\alpha^{-1} = 137{,}030\ (16)$	indirect (R_∞, e/m, F, N_A)
LSA 1952 (~ 1.10^{-5}) :	$\alpha^{-1} = 137{,}037\ 7\ (16)$	(LSA D f.s., a_e)
LSA 1965 (~ 4.10^{-6}) :	$\alpha^{-1} = 137{,}038\ 8\ (6)$	(H Lamb shift, muonium hfs, a_e) (H Ls 137,037, H hfs137,03552)
B.N.T. 1969 (~ 1.10^{-7}) :	$\alpha^{-1} = 137{,}036\ 02\ (21)$	(H hfs, γ_p, Josephson) mainly without QED (H Ls, a_e)
codata 1973 (~ 8.10^{-8}) :	$\alpha^{-1} = 137{,}036\ 04\ (11)$	(data selection + uncert. expansion)
codata 1986 (~ 4.10^{-8}) :	$\alpha^{-1} = 137{,}035\ 989\ 5\ (61)$	(data selection + uncert. expansion)
codata 1998 (~ 4.10^{-9}) :	$\alpha^{-1} = 137{,}035\ 999\ 76\ (50)$	(mainly, $a_{e\text{-}WS}$)
codata 2002 (~ 4.10^{-9}) :	$\alpha^{-1} = 137{,}035\ 999\ 11\ (50)$	($a_{e\text{-}Ws}$, h/m_{Cs})
codata 2006 (~ 7.10^{-10}) :	$\alpha^{-1} = 137{,}035\ 999\ 679\ (94)$	($a_{e\text{-}Hd}$)
codata 2010 (~ 3.10^{-10}) :	$\alpha^{-1} = 137{,}035\ 999\ 074\ (44)$	($a_{e\text{-}Hd}$, h/m_{Rb})
latest QED 2012 (~ $2.5.10^{-10}$)	$\alpha^{-1} = 137{,}035\ 999\ 166\ (34)$	($a_{e\text{-}Hd}$, 10th order QED)

Determinations of the fine structure constant

- dimension less (free of units)
- scales electromagnetic interaction (common to all methods : charge particle in e.m field)



$$\alpha = \frac{e^2}{4\pi\varepsilon_0 \hbar c}$$

General outline

Lecture I : less accurate determinations of α

- Quantum Hall effect
- Hydrogen fine and hyperfine structure
- Helium fine structure
- Exotic hydrogen-like atoms

Lecture II : most accurate determinations of α

- g-2 (lepton)
- h/m
- contribution of α in new SI

Quantum Hall effect (see v.K. Wed. 18th July) $\rightarrow$ α (1.8×10^{-8})

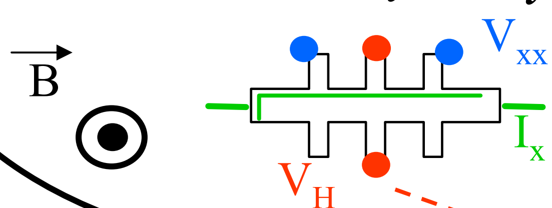
VOLUME 45, NUMBER 6 PHYSICAL REVIEW LETTERS 11 AUGUST 1980

New Method for High-Accuracy Determination of the Fine-Structure Constant Based on Quantized Hall Resistance

K. v. Klitzing
Physikalisches Institut der Universität Würzburg, D-8700 Würzburg, Federal Republic of Germany, and Hochfeld-Magnetlabor des Max-Planck-Instituts für Festkörperforschung, F-38042 Grenoble, France

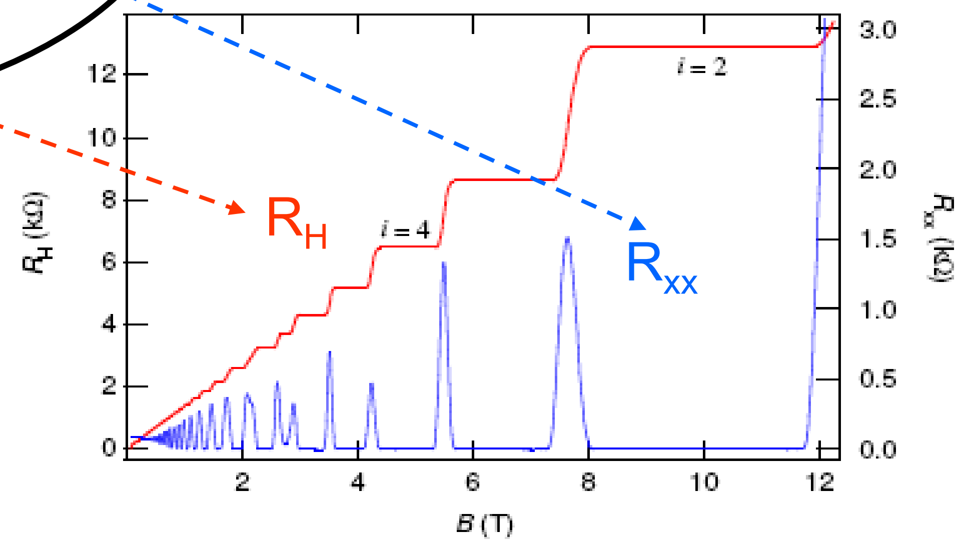
Q.H.E.

$$R_H(i) = \frac{R_K}{i} = \frac{h}{i\,e^2}$$

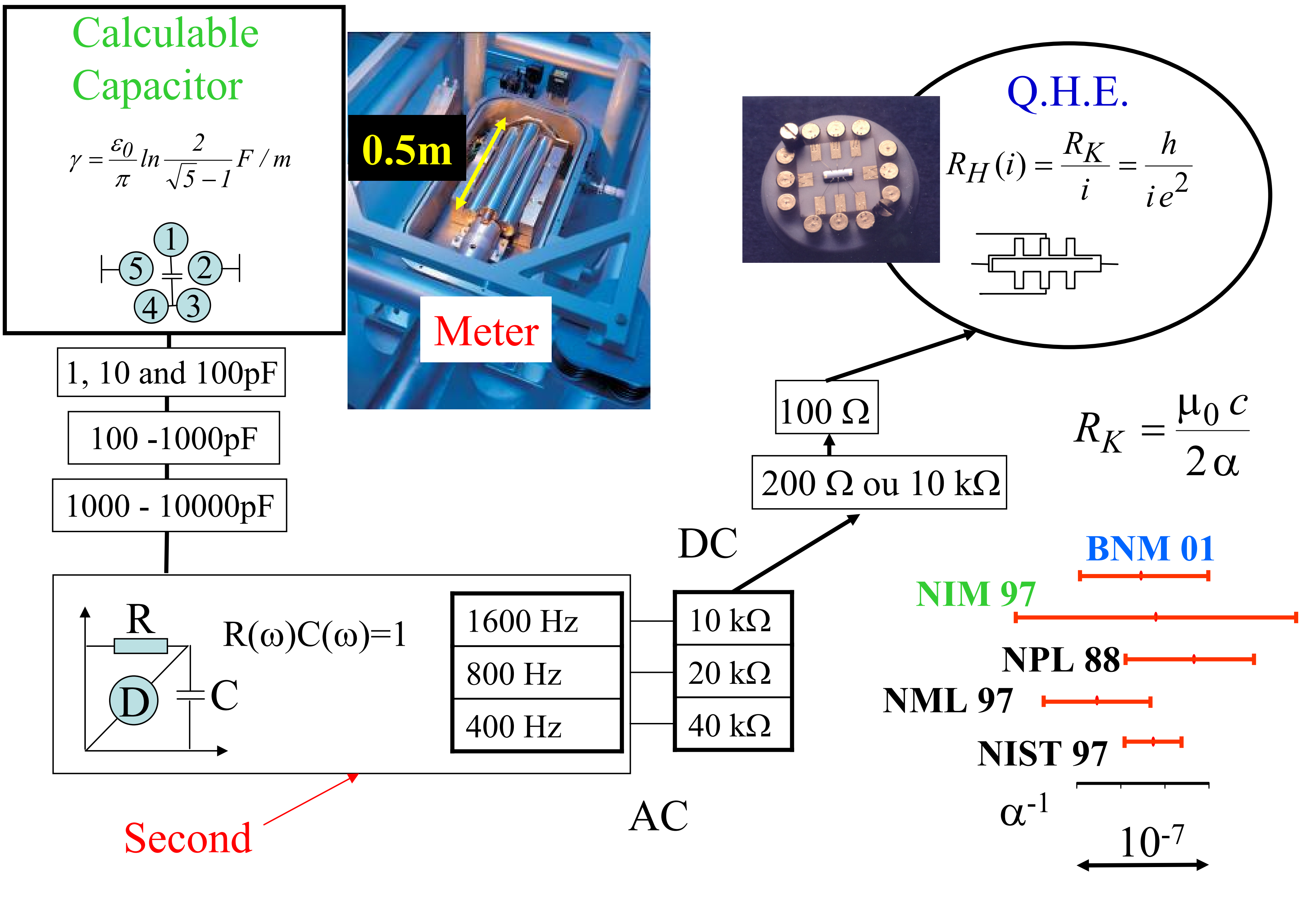


$$\boxed{R_K = \frac{h}{e^2} = \frac{\mu_0\,c}{2\,\alpha}}$$

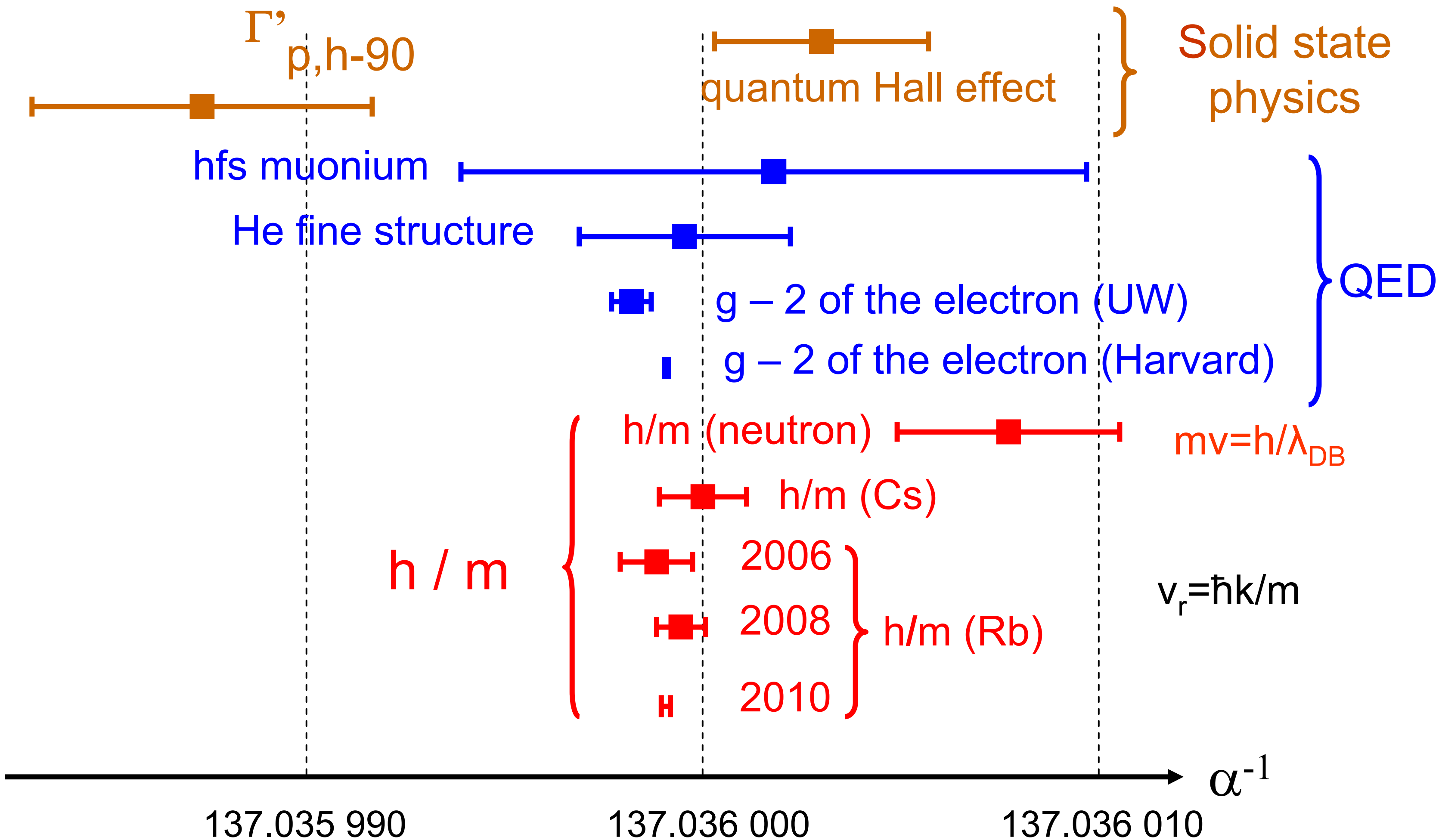
Nobel prize 1985



Quantum Hall effect (see v.K. Wed. 18th July) $\rightarrow$ α (1.8×10^{-8})



Quantum Hall effect (see v.K. Wed. 18 July) → α (1.8×10^{-8})



2012 : → Universality of R_K : Graphene, GaAs/AlGaAs (see Tzalenchuk talk Thurs 19 July)

→ QED correction negligible

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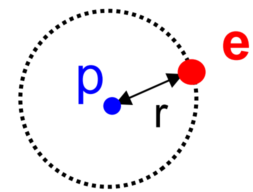
Hydrogen fine structure



1913: N. Bohr $$R_\infty = \frac{mc^2\alpha^2}{2\hbar c}$$

1916: A Sommerfeld tried to include special relativity in the Bohr model to explain the fine structure observed in H

→ *$\alpha = v_e/c$ velocity of the electron on the 1st orbit of Bohr model to the velocity of light*

$$\alpha = \frac{e^2}{4\pi\varepsilon_0\hbar c}$$ Fine structure constant

→ *angular momentum quantization $k \neq n$*

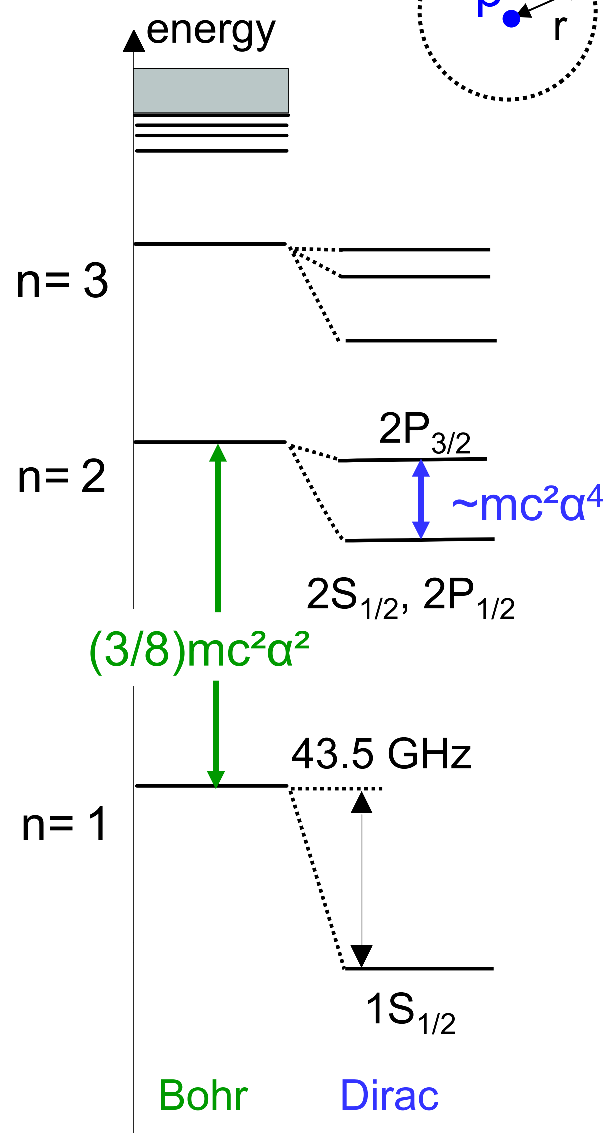
→ *failed because spin of the electron is missing*

1928 : Dirac equation combines more recent equation describing H spectrum (wave function) (Schrödinger eq.) and the relativity.

→ positron (anti-electron)

→ spin of the electron

The fine structure constant introduced by A. Sommerfeld is still the relevant parameter for the H spectroscopy



$$E_n = -\frac{R_\infty hc}{n^2}$$

e^- spin
relativity

Quantum ElectroDynamics (QED)

Electrodynamics : interaction between charge and field

QED : quantization of the field
$\Rightarrow$ photon : field quantized in term of quantum harmonic oscillators
$\Rightarrow$ quantum harmonic oscillators $E_n=(n+1/2)\hbar\omega$
ground state: zero energy = 1/2 $\hbar\omega$ renormalization $\Rightarrow$ 0
Heisenberg principle $\Delta E \Delta t \sim \hbar$ $\Rightarrow$ fluctuations

QED vacuum is subject to fluctuations around zero average-field

$\Rightarrow$ spontaneous emission : quantum state = atom + field = not a stationary state
Vacuum fluctuations$\rightarrow$ spontaneous emission

$\Rightarrow$ energy (E) carried out by the electron in vacuum =
E of electron + E in the e.m. field =electron + cloud of photons = renormalization of the electron mass (self energy~$\Delta m/m$)

$\Rightarrow$ Quantum vacuum : continuously appearing and disappearing pair of "virtual" particles (particle anti-particle) (vacuum polarization~ε_r)

Observations QED vacuum : anomaly of the gyromagnetic factor of the electron, Lamb shift (~1948)

Hydrogen hyperfine structure

Hyperfine structure in atoms results from the small magnetic moment of the nucleus

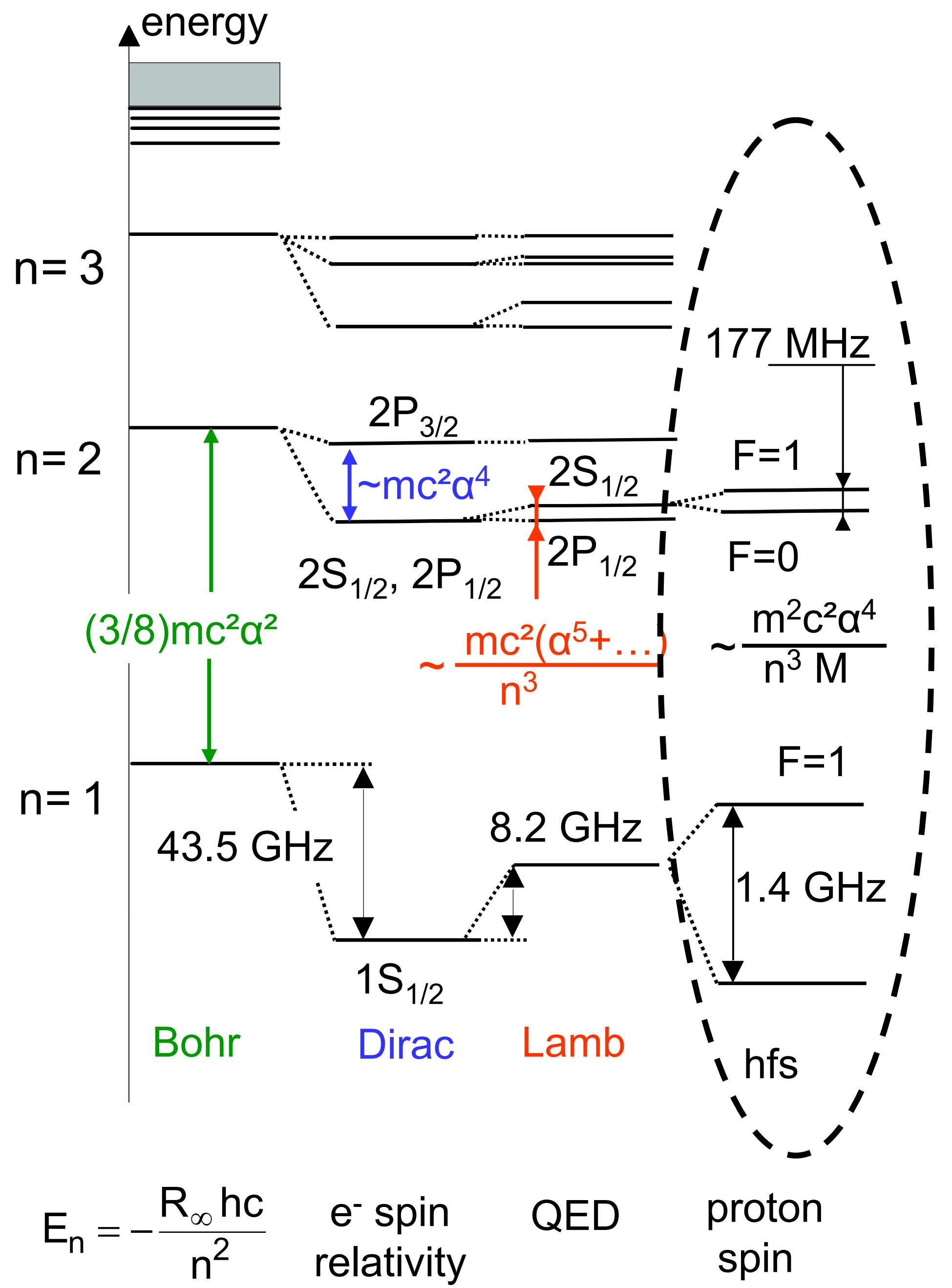
The electron and the proton have both a spin, that is an intrinsic angular momentum.

$S = 1/2$ for the electron

$I = 1/2$ for the proton

The total momentum is : $\vec{F} = \vec{S} + \vec{I}$

This leads to a splitting of all hydrogen energy levels which varies roughly as $1/n^3$



The 1S hyperfine structure of hydrogen

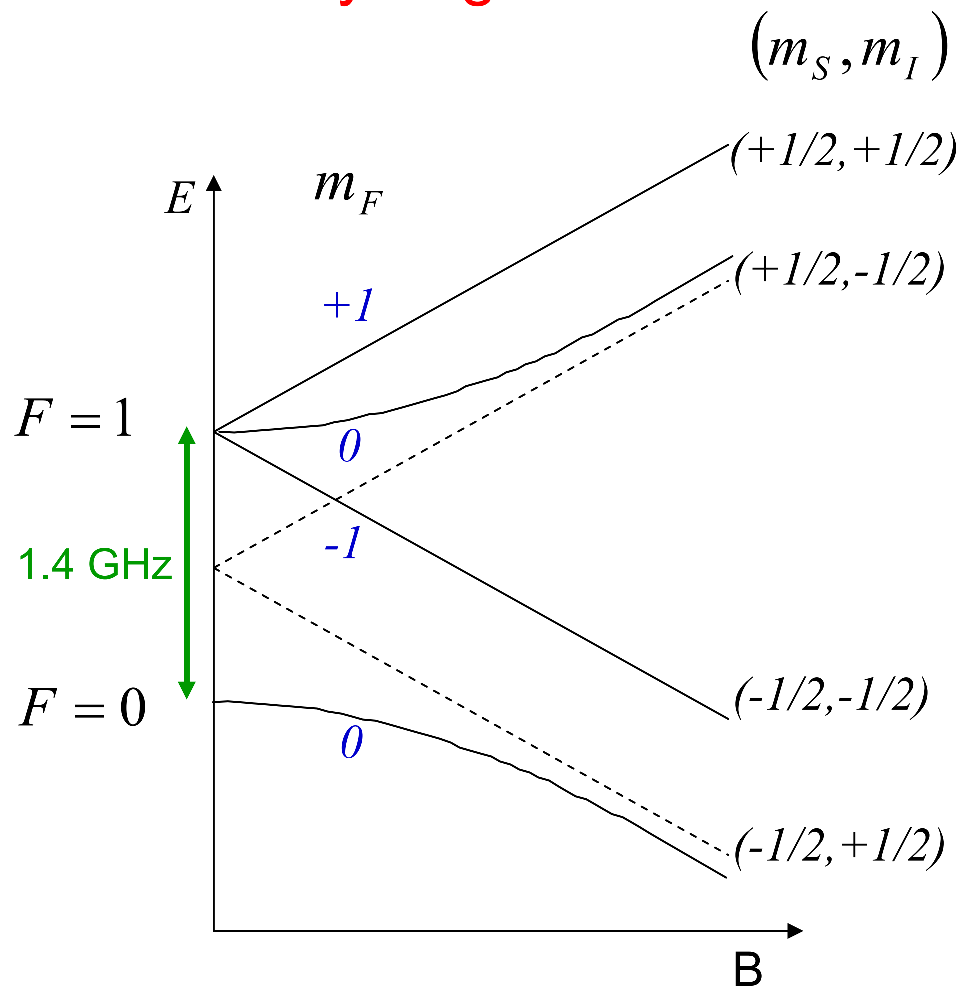
In an applied magnetic field B, the F = 1 hyperfine level is split in three Zeeman sublevels.

In a high field, electronic and nuclear moments are decoupled.

In an inhomogeneous magnetic field, atoms undergo a force

$$F_x = \overrightarrow{\mu_p} \cdot \frac{\partial \vec{B}}{\partial x}$$

(see Helmerson talk Friday 20 July)



→ deflection of an atomic beam

I.I. Rabi, J.M.B. Kellogg and J.R. Zacharias, Phys. Rev. 46, 157 and 163 (1934)

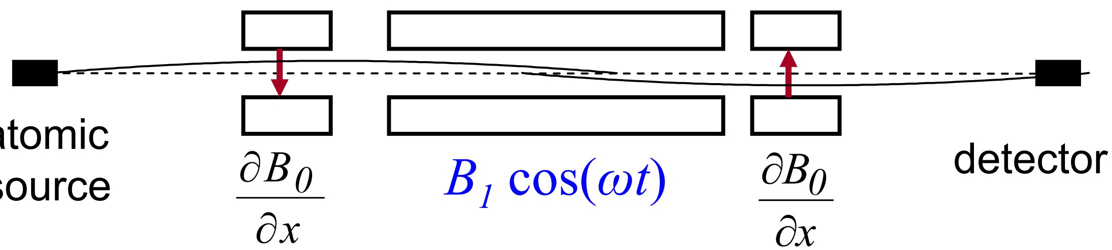
→ refocusing of an atomic beam (Columbia)

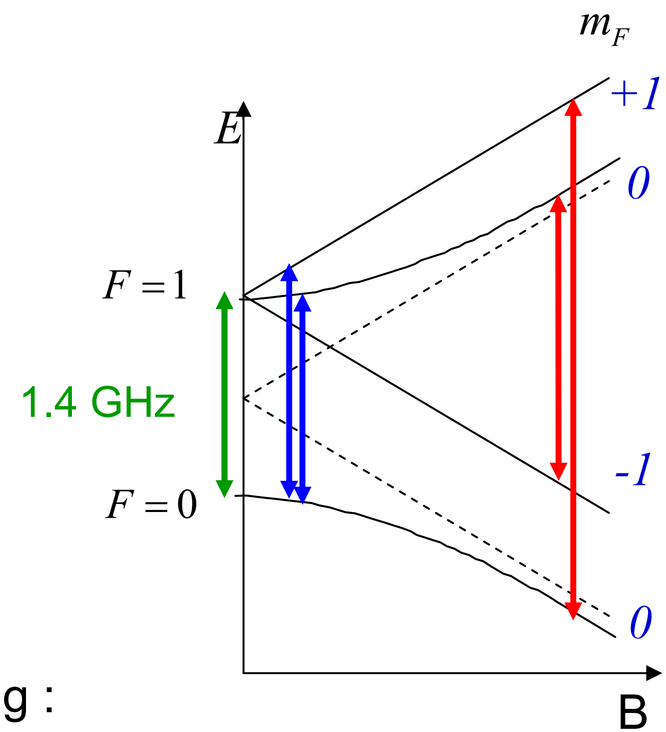
J.M.B. Kellogg, I.I. Rabi and J.R. Zacharias, Phys. Rev. 50, 472 (1936)

Atomic beam magnetic resonance (after the II w. war ...)

Principle of the method :

- two magnets to deviate the atomic beam and select a given state
- an oscillatory field to induce a transition between two states





First accurate measurement of the 1S hyperfine splitting :

J.E. Nafe, E.B. Nelson and I.I. Rabi, Phys. Rev. 71, 914 (1947); 73, 718 (1948); 75, 1194 (1949); 76, 1858 (1949).

in hydrogen $\Delta\nu_H$ = 1420. 410 (6) MHz
in deuterium $\Delta\nu_D$ = 327. 384 (3) MHz

Disagreement with theoretical predictions $\rightarrow$ $g \neq 2$

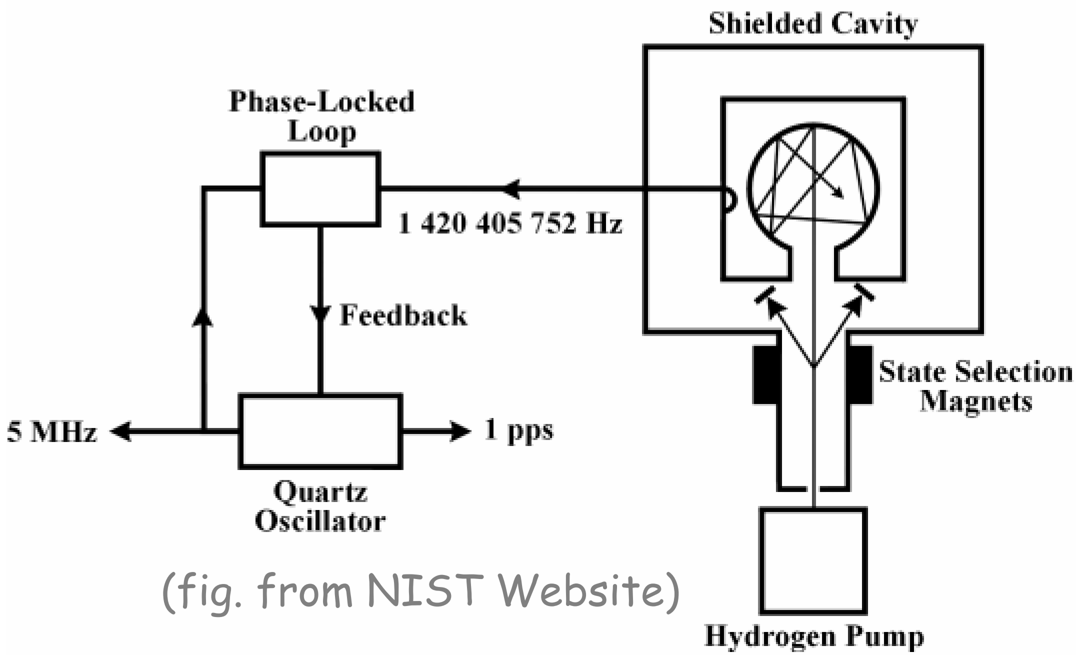
G. Breit, Phys. Rev. 72, 984 (1947)
J. Schwinger, Phys. Rev. 73, 416 (1948) and 76, 790 (1949)

The hydrogen maser

It gives by far the most accurate measurement of the hydrogen hyperfine structure

$F = 1$ states are selected and focused in a storage bulb

The atomic system oscillates at the $\Delta\nu_H$ frequency



(fig. from NIST Website)

First measurement by H.M. Goldenberg, D. Kleppner and N.F. Ramsey (1960)

Combined value of precise measurements : $\Delta\nu_H$ = 1420 405 751. 7667 (9) Hz
$\Delta\nu_D$ = 327 384 352. 5219 (17) Hz

For a review, see : N.F. Ramsey in Rev. Mod. Phys. 62, 541 (1990)

The 2S hyperfine structure of hydrogen

- It has been measured early by an atomic beam magnetic resonance method ...

J.W. Heberle, H.A. Reich and P. Kusch, Phys. Rev. 101, 612 (1956)
H.A. Reich, J.W. Heberle and P. Kusch, Phys. Rev. 104, 1585 (1956)

$\Delta\nu_H$ (2S) = 177 556.86 (5) kHz (Columbia)
$\Delta\nu_D$ (2S) = 40 924.439 (20) kHz

- and recently remeasured more precisely

N.E. Rothery and E.A. Hessels, Phys. Rev. A 61, 044501 (2000)

$\Delta\nu_H$ (2S) = 177 556. 785 (29) kHz (York)

It is not exactly equal to $\Delta\nu_H$ (1S) / 8

- The most accurate measurement is now an optical measurement !

N. Kolachevsky et al., Phys. Rev. Lett. 102, 213002 (2009)

$\Delta\nu_H$ (2S) = 177 556 834.3 (6.7) Hz (Garching)

The hyperfine structure of hydrogen : discussion

The 1S and 2S hyperfine structures in hydrogen and deuterium $\Delta\nu_H$ and $\Delta\nu_D$ have been measured very precisely ($\sim 10^{-12}$ for the 1S)

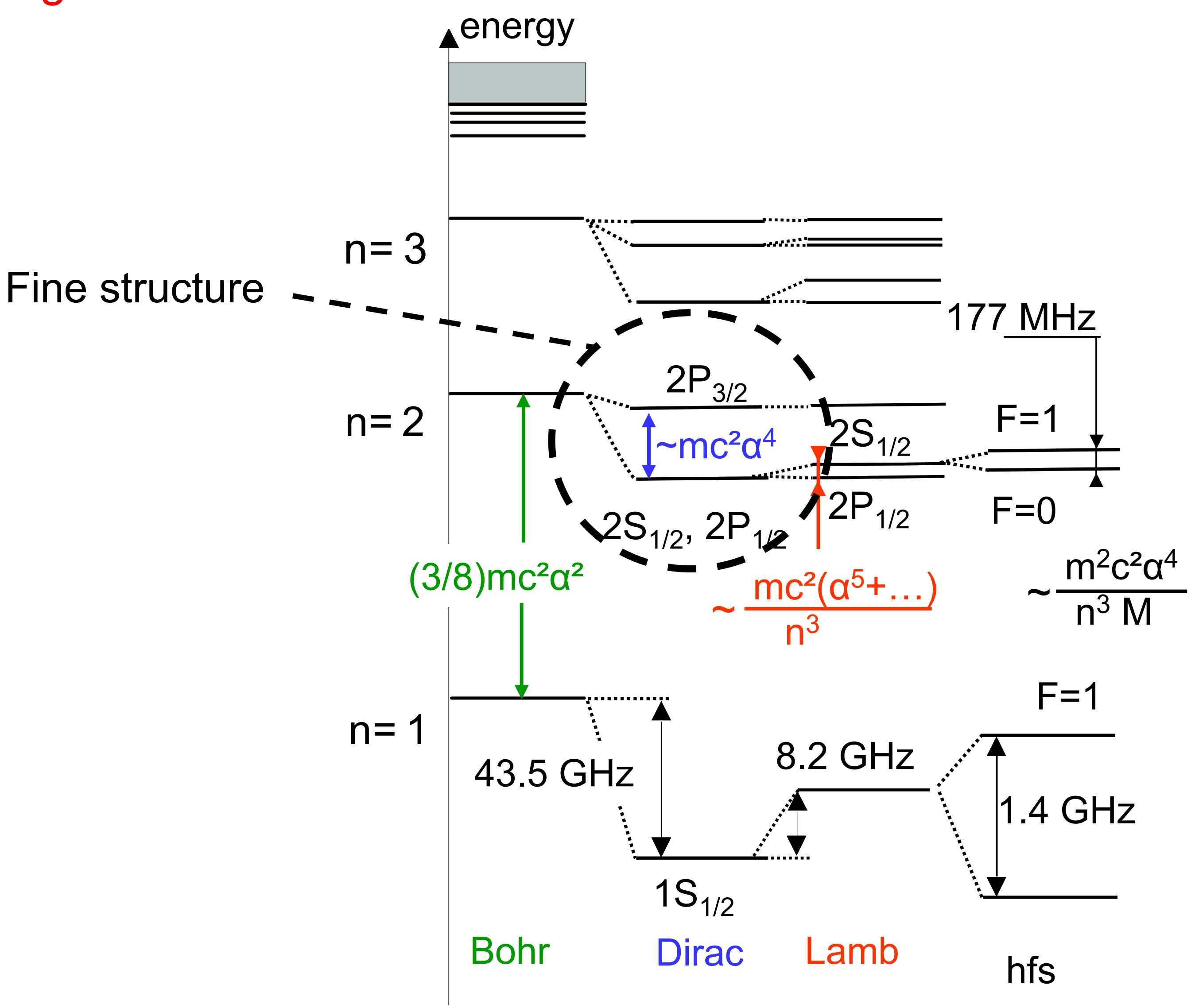
But, the comparison of their predicted and measured values cannot provide a competitive value of α because of the relative uncertainty of the theory ($\sim 10^{-6}$) due to the internal structure of the proton (or deuteron) :

- Proton charge radius : contradictory values (H, scatt., μp)
- Spin of the proton : « spin crisis » , proton spin not only due to the 3 quarks

An accurate value of α is needed to test all QED calculations

To overcome this limitation, a possibility is to study purely leptonic systems : positronium and muonium (see after)

Hydrogen levels



$$E_n = -\frac{R_\infty hc}{n^2}$$

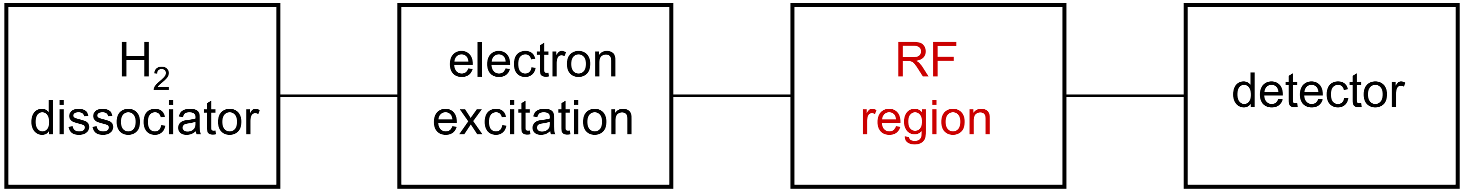
e⁻ spin relativity

QED

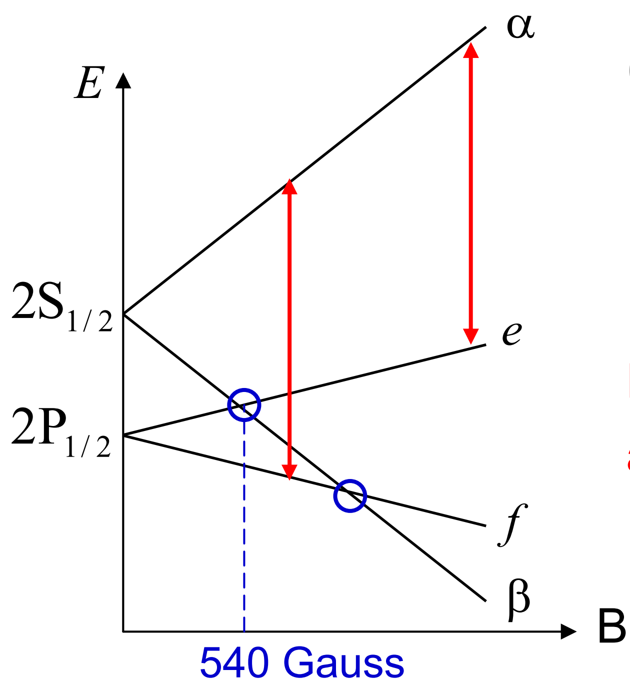
proton spin

Hydrogen fine structure : Lamb and Retherford experiment (I)

Principle



- Thermal dissociation of molecular hydrogen in an oven $\rightarrow$ H (1S)
- Crossed electronic bombardment of the atomic beam $\rightarrow$ H (2S)
- Quenching of the metastable state by a RF in various magnetic fields
- Detection of the metastable atoms through electron ejection from a metal target



(the hyperfine splitting is omitted on the diagram)

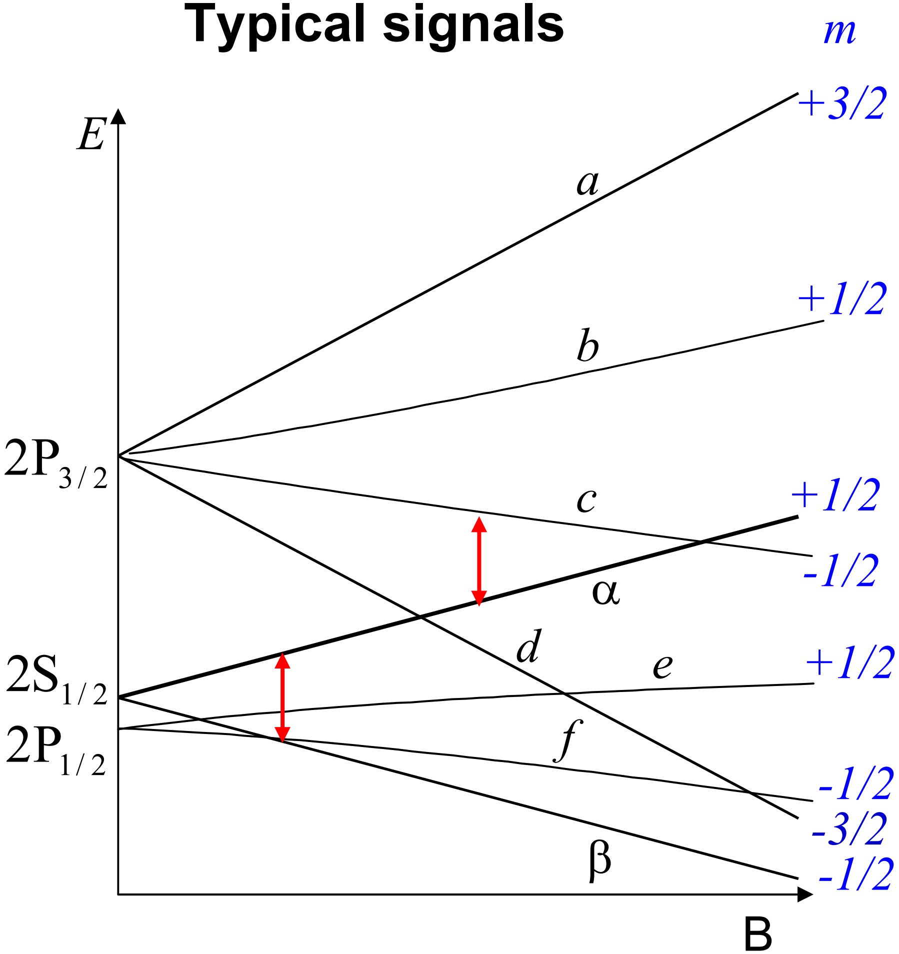
Due to βe and βf level crossings, and to the motional electric field seen by the atoms, the atomic beam is polarized

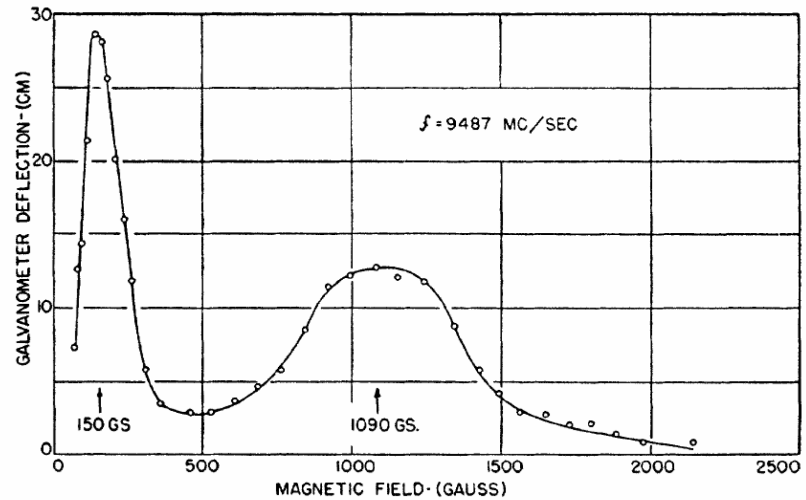
RF transitions are induced between $2S_{1/2}$ (α) state and the various sublevels of $2P_{1/2}$ and $2P_{3/2}$

They are detected through the decrease of the 2S beam intensity

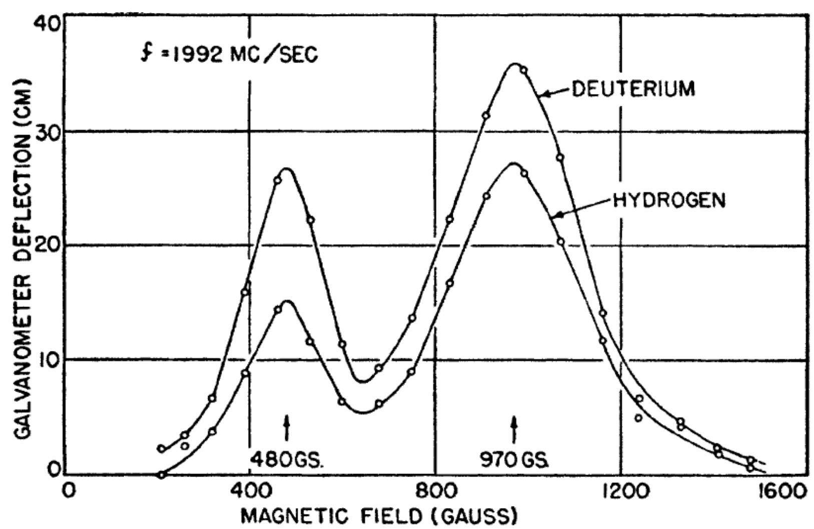
Hydrogen fine structure : the Lamb and Retherford experiment (II)

Typical signals





Observed resonance curves



fixed RF frequency and various B field values

Hydrogen fine structure : the Lamb and Retherford experiment (II)

THE

PHYSICAL REVIEW

A journal of experimental and theoretical physics established by E. L. Nichols in 1893

SECOND SERIES, VOL. 79, No. 4 AUGUST 15, 1950

Fine Structure of the Hydrogen Atom.* Part I

WILLIS E. LAMB, JR., AND ROBERT C. RETHERFORD†
Columbia Radiation Laboratory, Columbia University, New York, New York

(Received April 10, 1950)

The fine structure of the hydrogen atom is studied by a microwave method. A beam of atoms in the metastable $2^2S_{1/2}$ state is produced by bombarding atomic hydrogen. The metastable atoms are detected when they fall on a metal surface and eject electrons. If the metastable atoms are subjected to radiofrequency power of the proper frequency, they undergo transitions to the non-metastable states $2^2P_{1/2}$ and $2^2P_{3/2}$ and decay to the ground state $1^2S_{1/2}$ in which they are not detected. In this way it is determined that contrary to the predictions of the Dirac theory, the $2^2S_{1/2}$ state does not have the same energy as the $2^2P_{1/2}$ state, but lies higher by an amount corresponding to a frequency of about 1000 Mc/sec. Within the accuracy of the measurements, the separation of the $2^2P_{1/2}$ and $2^2P_{3/2}$ levels is in agreement with the Dirac theory. No differences in either level shift or doublet separation were observed between hydrogen and deuterium. These results were obtained with the first working apparatus. Much more accurate measurements will be reported in subsequent papers as well as a detailed comparison with the quantum electrodynamic explanation of the level shift by Bethe.

Among the topics discussed in connection with this work are (1) spectroscopic observations of the H_α line, (2) early attempts to use microwaves to study the hydrogen fine structure, (3) existence of metastable hydrogen atoms, their properties and methods for their production and detection, (4) estimates of yield and r-f power requirements, (5) Zeeman and hyperfine structure effects, (6) quenching of metastable hydrogen atoms by electric and motional electric fields, (7) production of a polarized beam of metastable hydrogen atoms.

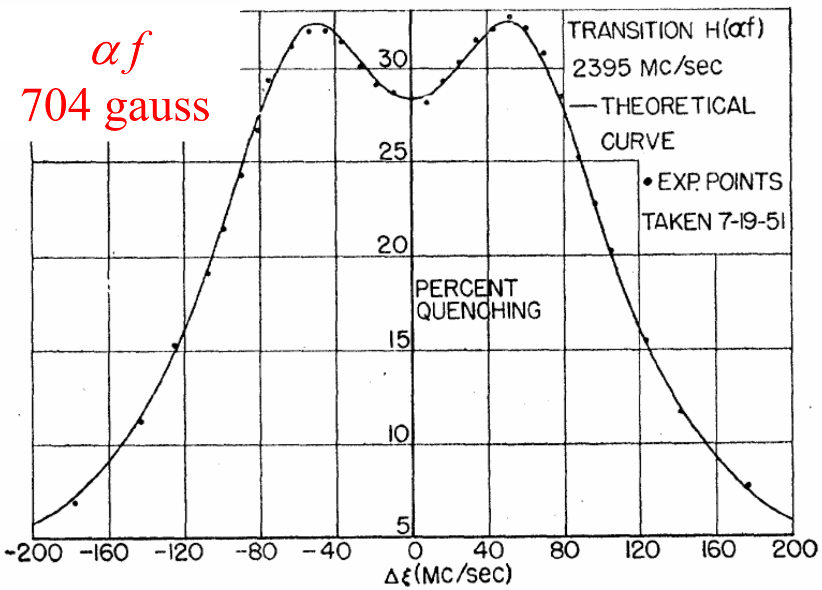
"$2S_{1/2}$ lies higher $2P_{1/2}$ about 1000 Mc/sec" → Nobel prize 1955

Hydrogen fine structure : the Lamb and Retherford experiment (III)

Detailed analysis of the line profiles

(the hyperfine splitting is visible on the signal)

αf
704 gauss



Results

for the $2S_{1/2} - 2P_{1/2}$ interval

in hydrogen and deuterium :

δ_H = 1057.77 (10) MHz

δ_D = 1059.00 (10) MHz

References

W.E. Lamb Jr. and R.C. Retherford, Phys. Rev. 79, 549 (1950)
Phys. Rev. 81, 222 (1951)
W.E. Lamb Jr, Phys. Rev. 85, 259 (1952)
W.E. Lamb Jr. and R.C. Retherford, Phys. Rev. 86, 1014 (1952)
S. Triebwasser, E.S. Dayhoff and W.E. Lamb Jr, Phys. Rev. 89, 98 (1953)
E.S. Dayhoff, S. Triebwasser and W.E. Lamb Jr, Phys. Rev. 89, 106(1953)

The fine structure of hydrogen : discussion

One can determine the n = 2 fine structure of hydrogen from the combination of measurements involving 2P states

The derived value of $1/\alpha$ is : 137.036003(41) (accuracy 3 x 10^{-7}) (Codata 2012)
It is not competitive since it is limited by the large natural width of the 2P levels (~ 100 MHz)

The fine structure constant is used as a cross check of the consistency of the data

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- Helium fine structure
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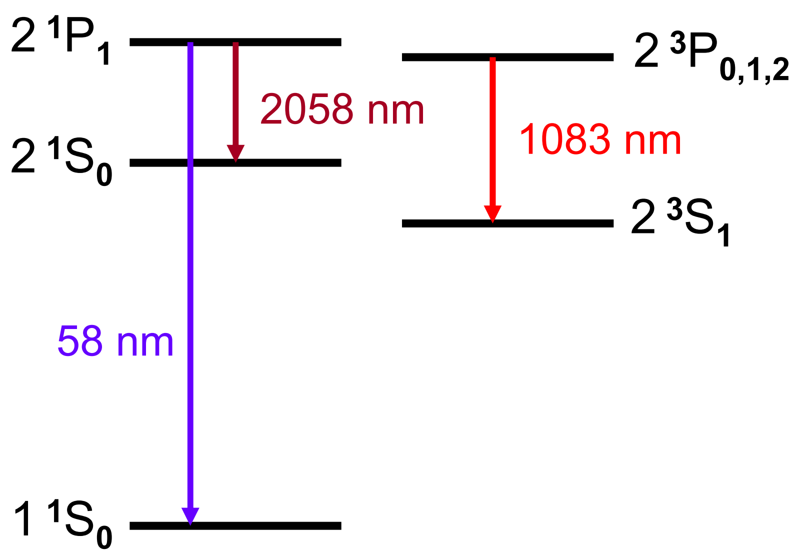
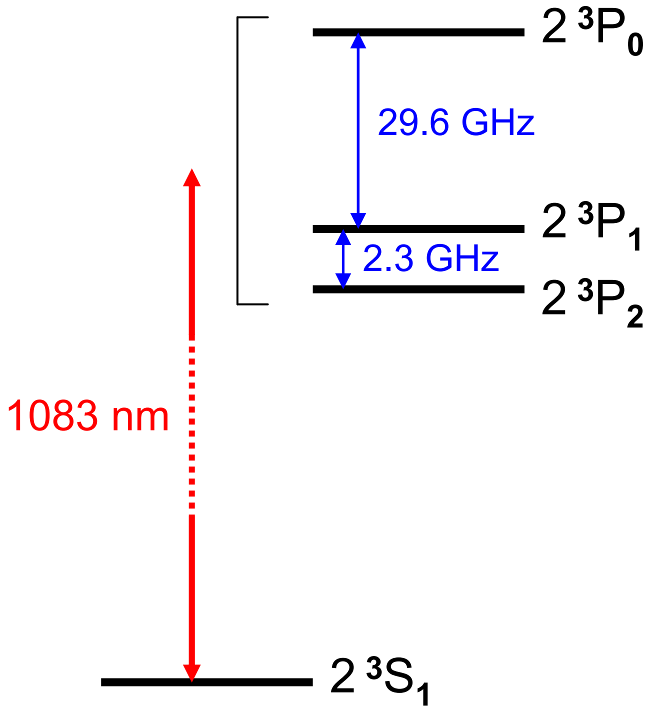
Helium fine structure

Helium :

- ✓ simplest multi electron atom → calculations can be performed
- ✓ the 1^1S_0 and $2\,^3S_1$ states are metastable
- ✓ ^{4}He : nuclear spin 0 → no hyperfine structure
- ✓ The lifetime of 2^3P states are longer compared to hydrogen ($\Delta\nu$=1.6MHz / 100MHz) since they cannot easily decay to the ground state



The spectroscopy of helium atom : fine structure



A lot of experiments have been performed in ^{4}He to measure the fine structure intervals of the $2\,^3P$ manifold

Metastable $2\,^3S$ atoms are populated by discharge either in a cell or in an atomic beam

$2\,^3P_J$ states are optically excited using a laser diode source at 1083 nm

Frequency intervals have been determined either from optical line structures or by microwave techniques

The spectroscopy of helium atom : fine structure

various experimental methods

- Laser fluorescence technique with an atomic beam (LENS, Florence) combines sub-Doppler laser spectroscopy and direct microwave measurement

G. Giusfredi *et al.*, Can. J. Phys. <u>83</u>, 301 (2005)

- Separated oscillatory field microwave measurement of the $2\,^3P_1$-$2\,^3P_2$ interval uses an optical pulse in a thermal beam followed by two RF pulses (York U.)

J.S. Borbely *et al.*, Phys. Rev. A <u>79</u>, 060503 (2009)

- Doppler-free saturation spectroscopy in a cell (Harvard U.)

T. Zelevinsky, D. Farkas and G. Gabrielse, Phys. Rev. Lett. <u>95</u>, 203001 (2005)

- Electro-optic laser technique in an atomic beam (North Texas U.)
  uses modulated sidebands of a laser diode
  to measure fine structure and various Zeeman intervals

M. Smiciklas and D. Shyner, Phys. Rev. Lett. <u>105</u>, 123001 (2010)

All these measurements need very careful study of all systematic effects (Zeeman, pressure, 2nd order Doppler ...)

Helium fine structure : discussion

All these accurate measurements of the fine structure of the 2 ^{3}P level of helium are in good agreement each with others

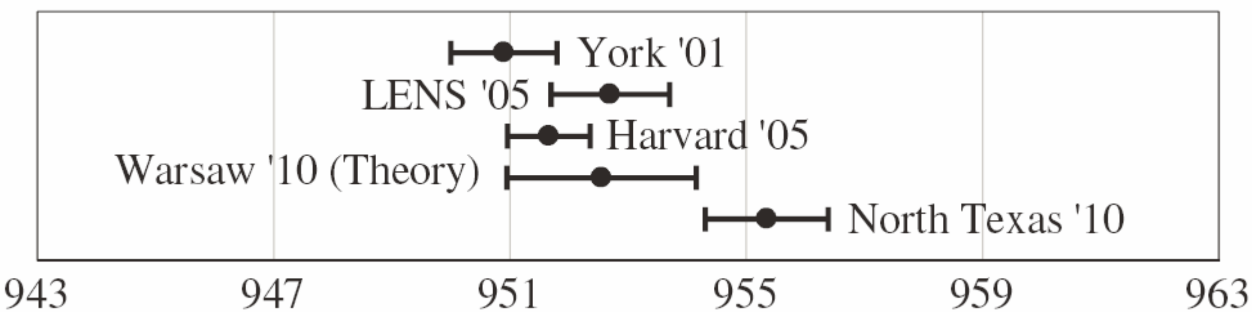
They give a test of QED theory of the electron - electron interaction in bound systems

G.W.F. Drake and Z.-C. Yan, Can. J. Phys. 86, 45 (2008)

Until recently there were two inconsistent calculations which disagreed with experimental results by ~ 15 kHz and more

Recent calculations up to $\alpha^5 R_\infty$ terms finally resolved this discrepancy

K. Pachucki and V.A. Yerokhin, Phys. Rev. Lett. 104, 070403 (2010)



2 $^3P_0$ - 2 $^3P_1$ interval – 29 646 000 (kHz)
from M. Smiciklas and D. Shyner (2010)

If the validity of the theory is assumed, experimental fine structure measurements in helium give an independent determination of α

with an uncertainty of 2 x 10^{-8} mainly due to uncalculated high-order QED terms

Simple stable atoms : discussion

Hydrogen :

simplest atom → best calculable atom within limits

- QED corrections
- contributions of the proton (not elementary particle)
- “wide” natural line width of nP levels (fine structure)

Helium :

simplest multi electron atom → calculable within limits (larger than hydrogen)

- still QED contributions
- but natural line width of nP levels lower compare to hydrogen
- and no hyperfine structure (lower contribution from the nucleus)

Aim of the experiments :

test QED calculation, fine structure constant is used as an input in QED calculations

General outline

Lecture I : less accurate determinations of α

- Quantum Hall effect
- Hydrogen fine and hyperfine structure
- Helium fine structure
- Exotic hydrogen-like atoms

Lecture II : most accurate determinations of α

- g-2 (lepton)
- h/m
- contribution of α in new SI

Exotic hydrogen-like atom

Atom made of exotic particles, in our case the "nucleus" of the bound system is a lepton

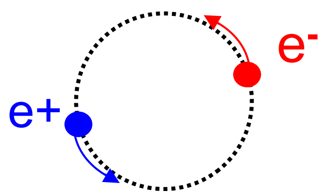
Lepton : elementary particle, fundamental constituent of the matter

→ no internal structure

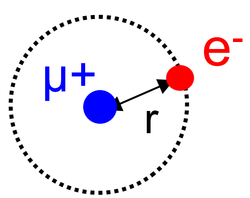
Charged lepton : spin 1/2, different masses

- Electron (e-), Positron (e+) (m_e)
- Muon (μ-, μ+) (~207 m_e) (lifetime 2.2 $\times 10^{-6}$s)
- Tau (τ-, τ+) (~3478 m_e) (lifetime 3×10^{-13}s)

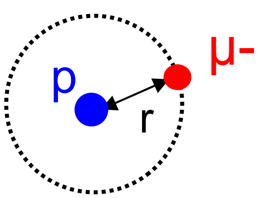
"Exotic hydrogen" atom :



positronium → α ?

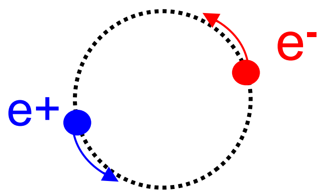


muonium → α ?



muonic hydrogen → r_p

The positronium e^+ - e^-



It is the lightest exotic hydrogen-like atom and a purely leptonic sytem
and allows to test relativistic two-body and QED corrections

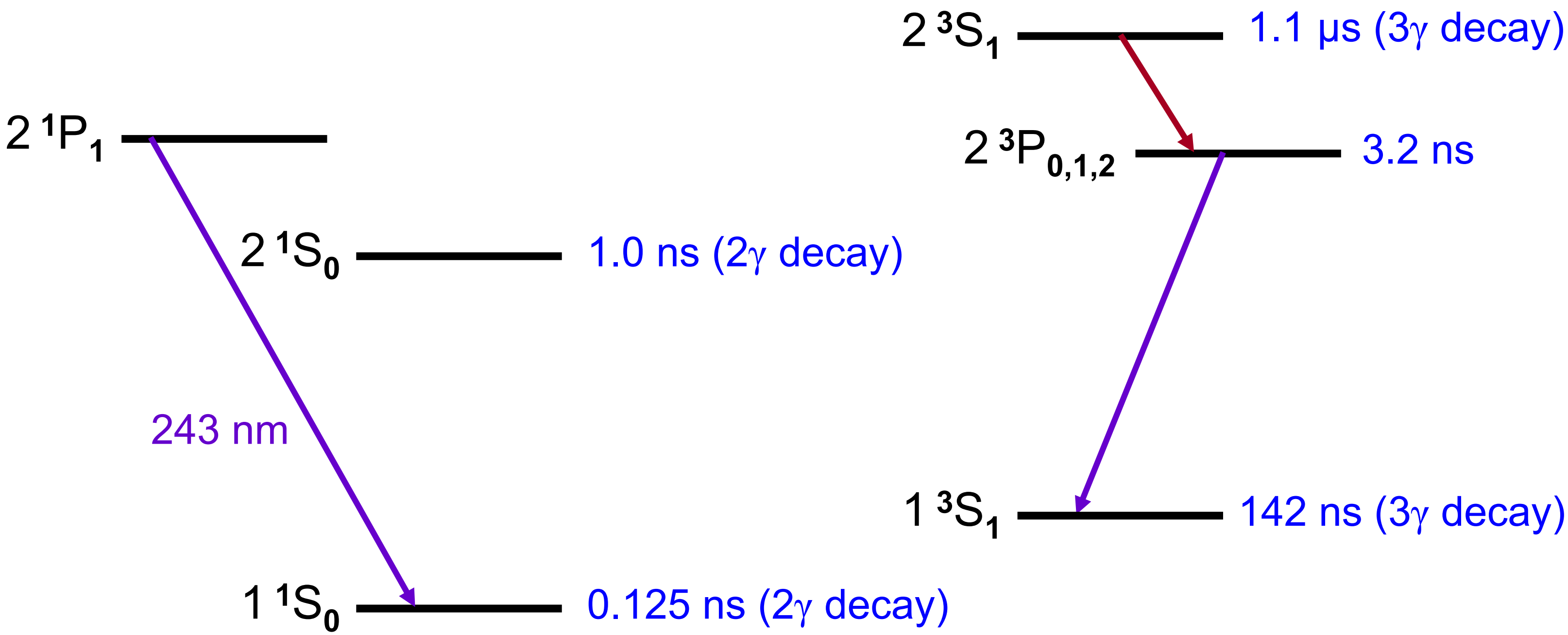
Electron and positron have same mass, same spin, but opposite charges

Energetic positrons are produced by radioactive sources
Positronium can be formed :

- by stopping energetic positrons in a gas or in a powder
- or by charge exchange of slow positrons in a thin foil or a gas target
- or by interaction of slow positrons with the surface of a solid in vacuum

The e+ - e- annihilation is responsible for specific terms in energy levels and limits the lifetimes

Energy levels and lifetimes in positronium



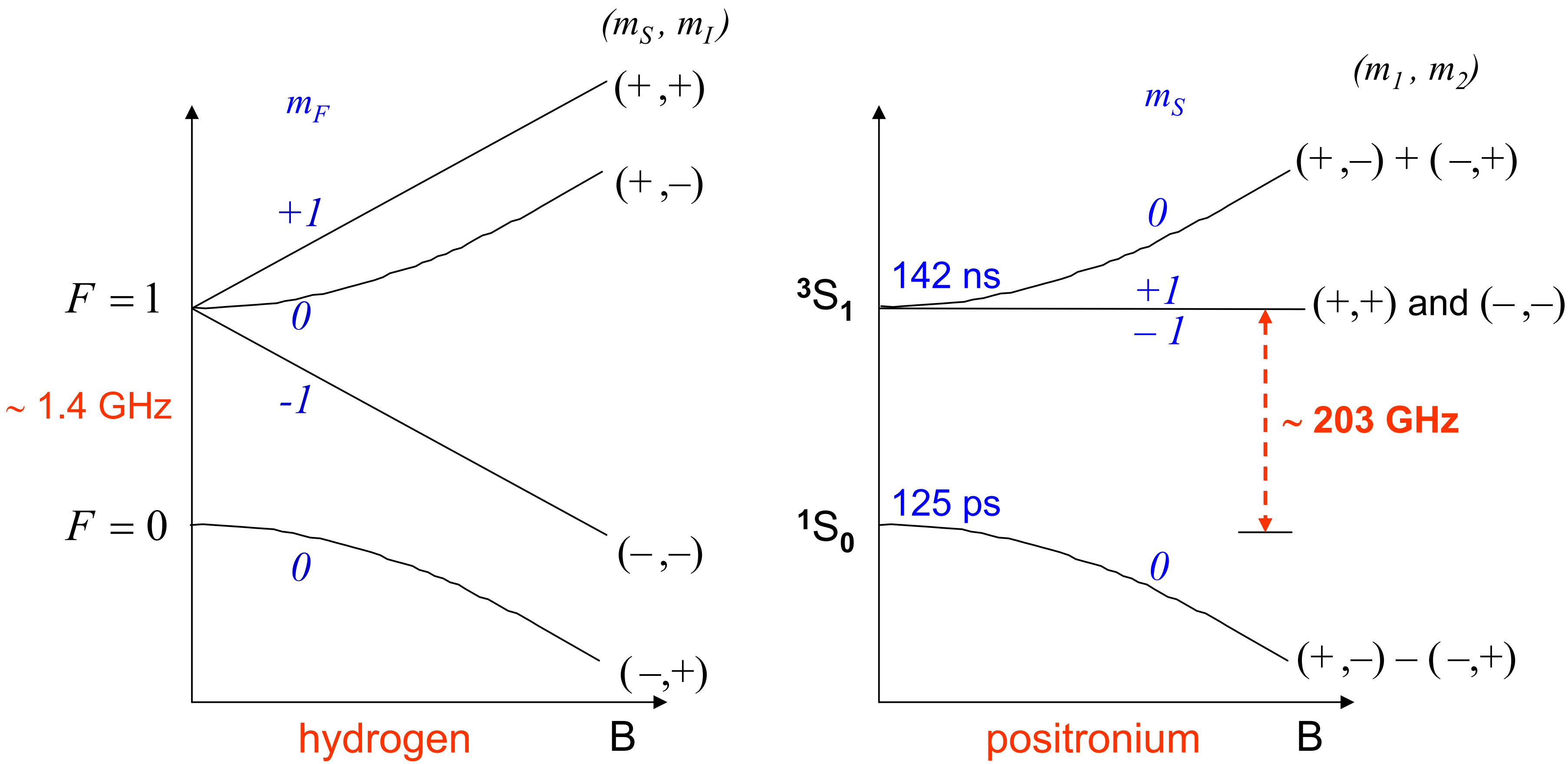
Parapositronium (singlets) Orthopositronium (triplets)

Lifetimes are much longer in orthopositronium

Because of present precision in theory and experiments, the experimental data which can be used to test QED predictions in positronium are :

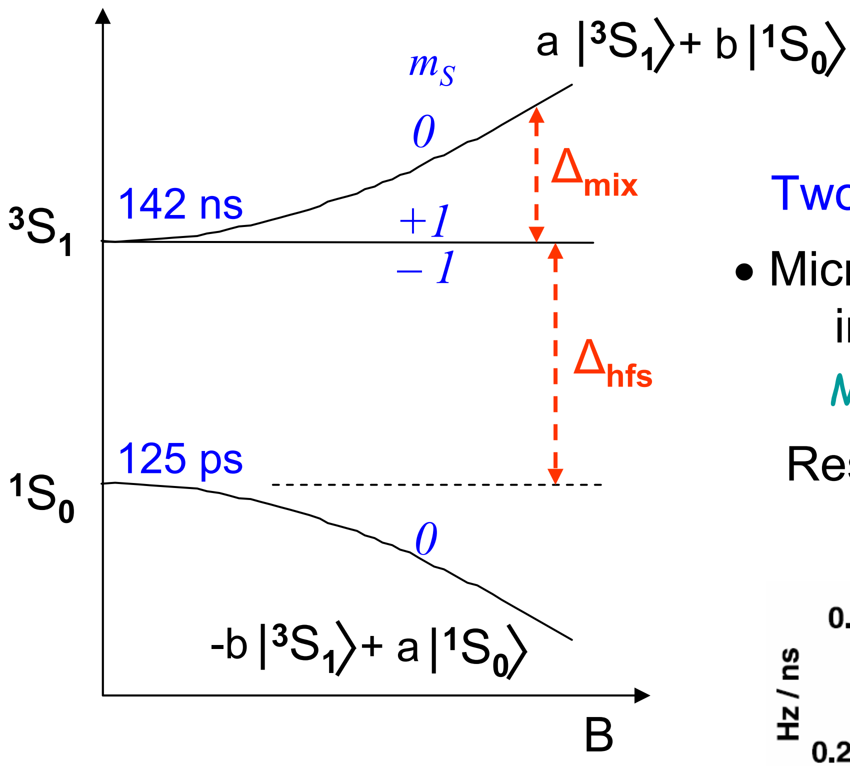
- the annihilation rates in triplet and singlet ground states
- the n = 1 hyperfine interval
- the n = 2 fine structure interval
- the 1S-2S triplet interval

The hyperfine structure of the ground state of positronium



e^+ and e^- have opposite gyromagnetic ratios so that $(+,+)$ and $(-,-)$ states have null magnetic momentum

Measurement of the hyperfine structure of positronium through the Zeeman splitting



Δ_{mix} is related to Δ_{hfs} by a simple formula

Two approaches :

- Microwave excitation at frequency Δ_{mix} (~ 3 GHz in 0.8 T) followed by an increase of 2γ decay

  M.R. Ritter *et al.*, Phys. Rev. A 30, 1331 (1984)

  Result : Δ_{hfs} = 203.389 10 (74) GHz (Yale)

  (3.9 σ from theory)

- Quantum oscillation

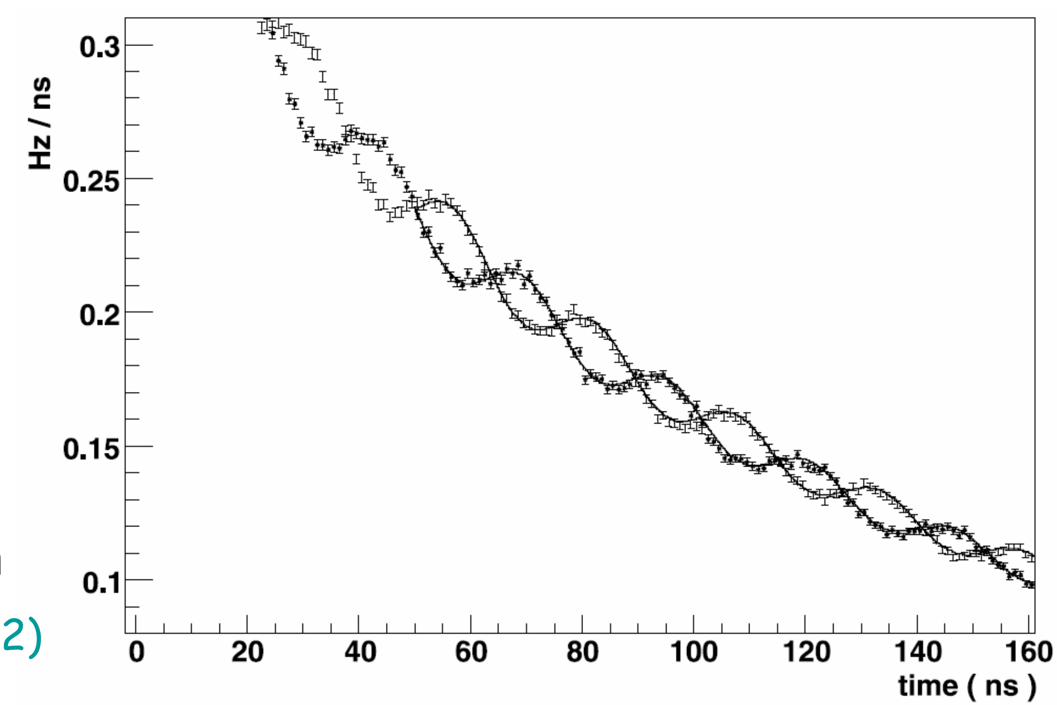
  Y. Sasaki and al. , (Tokyo)
  Physics Letters B 697, 121 (2011)

  Result : Δ_{hfs} = 203.324 (39) GHz

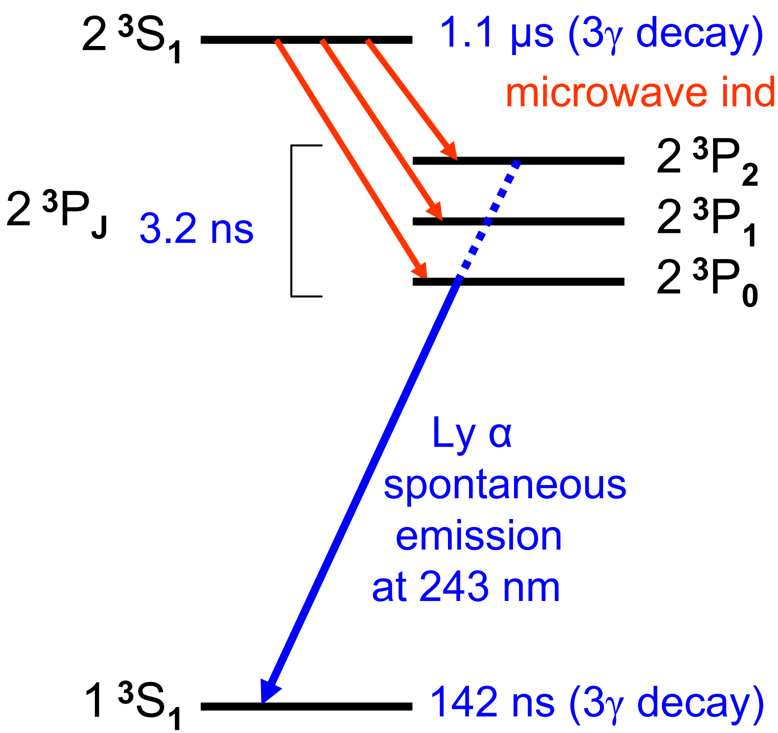
  less precise but could be improved

- and also direct THz excitation

T. Yamazaki *et al.*, arXiv (5 Apr. 2012)



Measurements of the n = 2 fine structure intervals in positronium



$2\,^3S_1$ and $2\,^3P_J$ states are all populated when positronium atoms are formed

The microwave transitions are detected through the increase of Ly α fluorescence

The measured frequencies are :

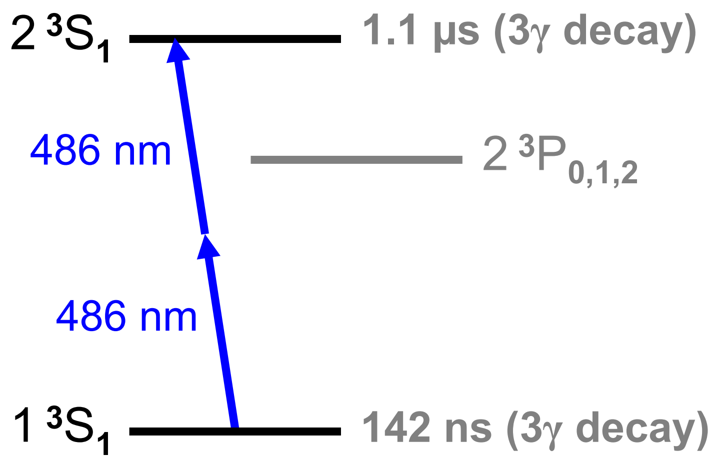
(Mainz)

	stat.	syst.
ν_0 = 18 499.65 MHz	(1.20)	(4.00)
ν_1 = 13 012.42 MHz	(0.67)	(1.54)
ν_2 = 8 624.38 MHz	(0.54)	(1.40)

D. Hagena, R. Ley, D. Weil and G. Werth, Phys. Rev. Lett. 71, 2887 (1993)

Agreement with recent calculated QED corrections in $R_\infty \alpha^4 \ln \alpha^{-1}$

Frequency measurement of the $1\,^3S_1 - 2\,^3S_1$ transition of positronium



The most sensitive to QED effects since they roughly scale as $1/n^3$

Doppler-free two-photon spectroscopy

n = 2 population is detected through positrons counting after laser ionization

This transition was measured fort the first time with a pulsed dye laser :

S. Chu, A.P. Mills JR and J.L. Hall, Phys. Rev. Lett. 52, 1689 (1984) (Stanford)

and later with cw excitation :

M.S. Fee, S. Chu et *al.*, Phys. Rev. A 48, 192 (1993)

Result : 1 233 607 216.4 (3.2) MHz accuracy 2.6 ppb

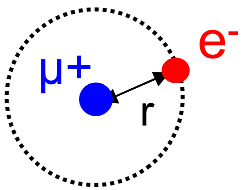
sufficient accuracy to test the $R_\infty \alpha^4$ QED corrections

Hydrogen 1S-2S : 2 466 061 413 187 035(10) Hz Phys. Rev. Lett. 107, 203001 (2011)

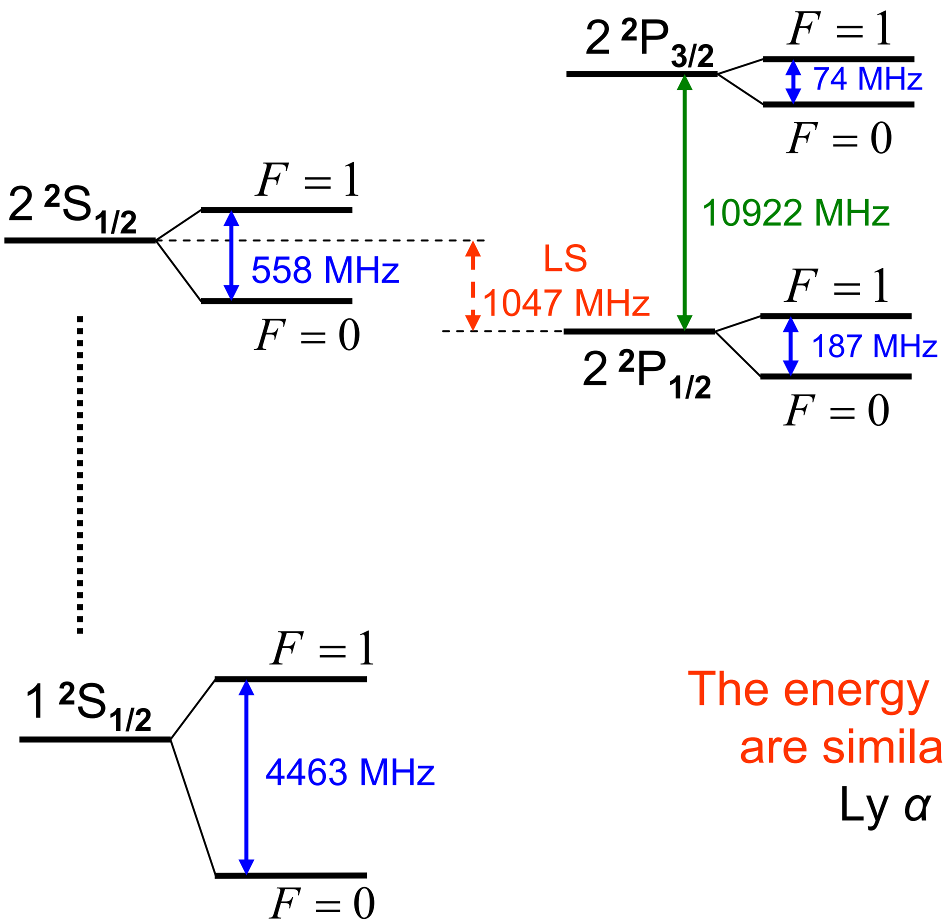
Presently another group plans to perform a new experiment in order to improve this accuracy by a factor 5 and then check recent QED calculations

P. Crivelli, C.L. Cesar and U. Gendotti, Can. J. Phys. 89, 29 (2011) (Rio)

The muonium μ^+ - e^-



Like electrons and positrons, muons are leptons, but their mass is ~ 207 times larger



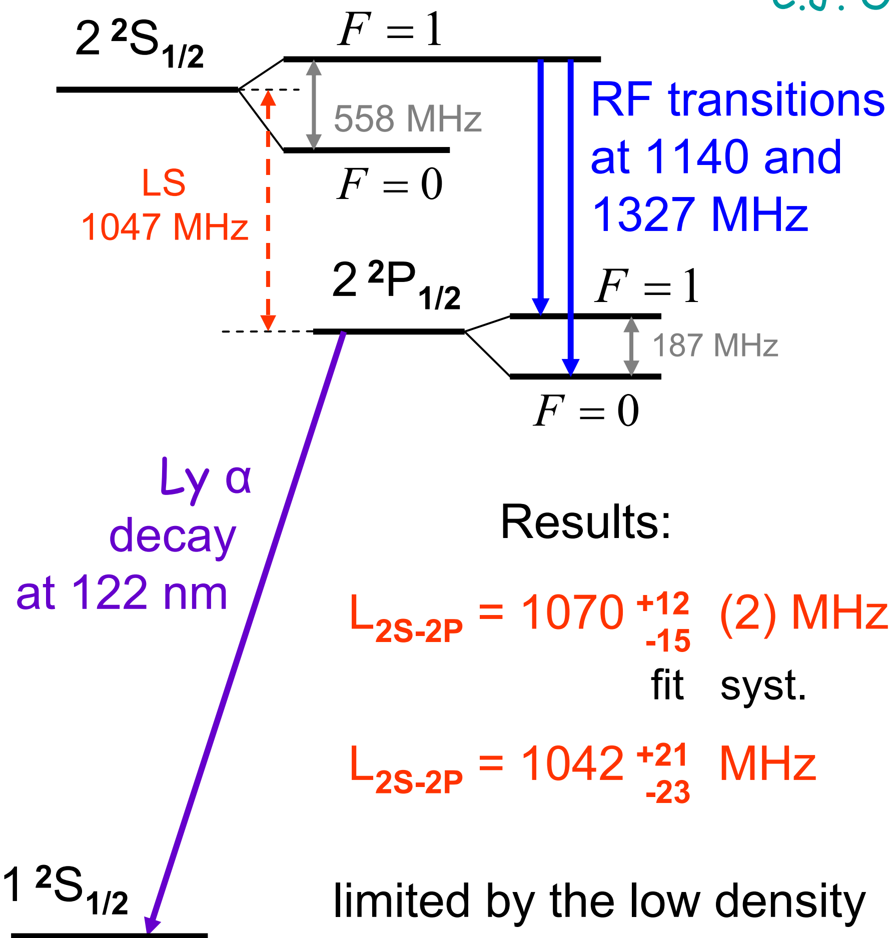
Production of muonium :

- high energy proton beam incident on a target (ex. C)
- π^+ are created which decay in μ^+
- low energy muon beam incident on a gas target (ex. Ar) produces muonium atoms by electron capture

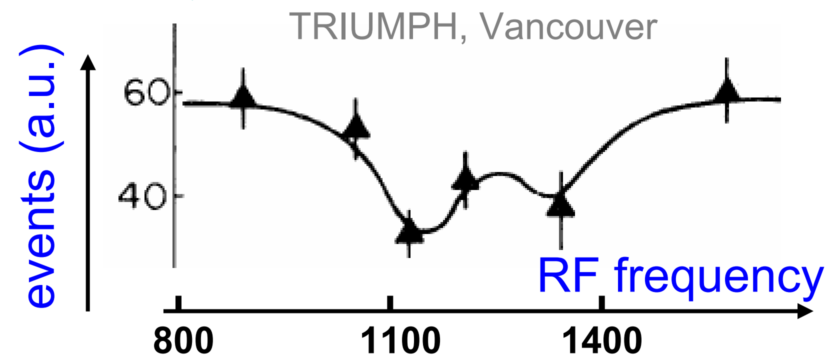
The energy levels of the muonium atom are similar to the ones of hydrogen

Ly α transition at 122 nm

RF measurement of the 2S Lamb shift in muonium



C.J. Oram et *al.*, Phys. Rev. Lett. 52, 910 (1984)



Results:

$$L_{2S-2P} = 1070\,^{+12}_{-15}\ (2)\ \text{MHz}$$

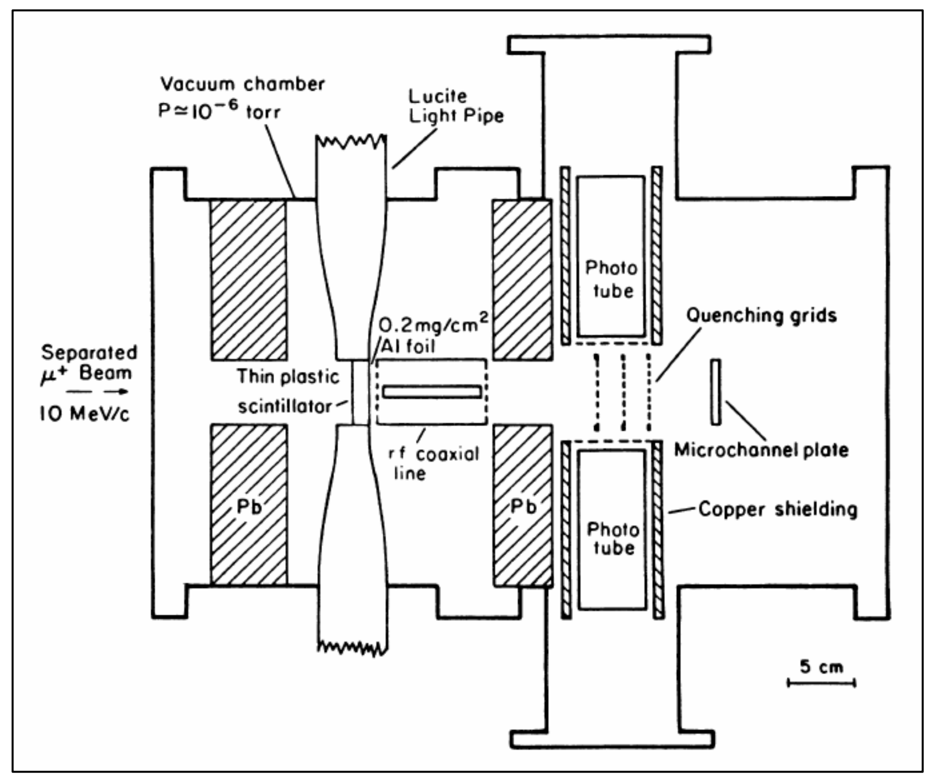
fit syst.

$$L_{2S-2P} = 1042\,^{+21}_{-23}\ \text{MHz}$$

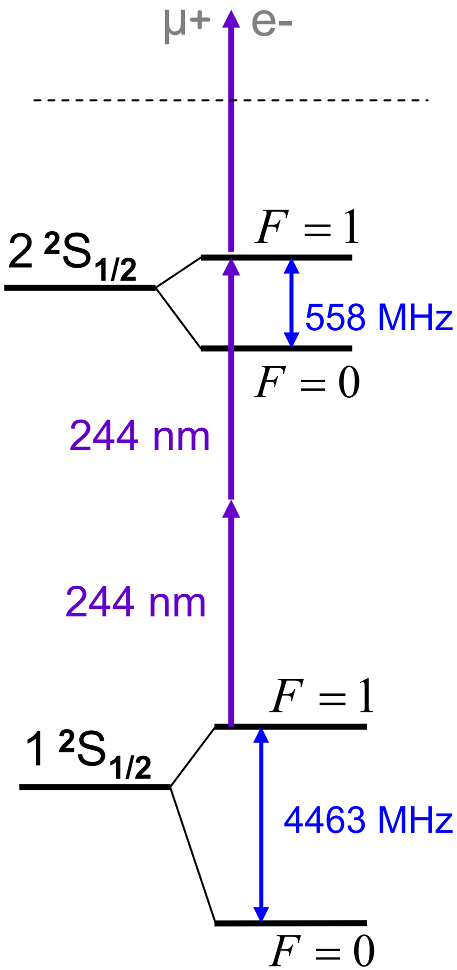
limited by the low density
of the muon beam

K.A. Woodle et *al.*,
Phys. Rev. A 41, 93 (1990)

LAMPF



Frequency measurement of the 1S-2S transition of muonium



First observation of the 1S-2S Doppler-free two-photon transition with a frequency doubled dye laser

S. Chu et al., Phys. Rev. Lett. 60, 101 (1988)

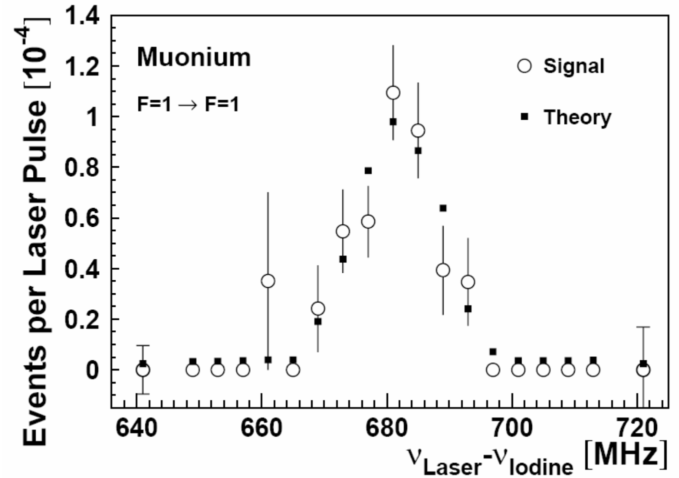
The 2S state is detected by photoionization (Stanford)

Frequency measurements :

F.E. Maas et al., Physics Lett. A 187, 247 (1994)

(Heidelberg, ...)

V. Meyer et al., Phys. Rev. Lett. 84, 1136 (2000)



Result : $\Delta\nu$(1S-2S) = 2 455 528 941. 0 (9.8) MHz

in good agreement with theory

The Lamb shift contribution can be deduced :

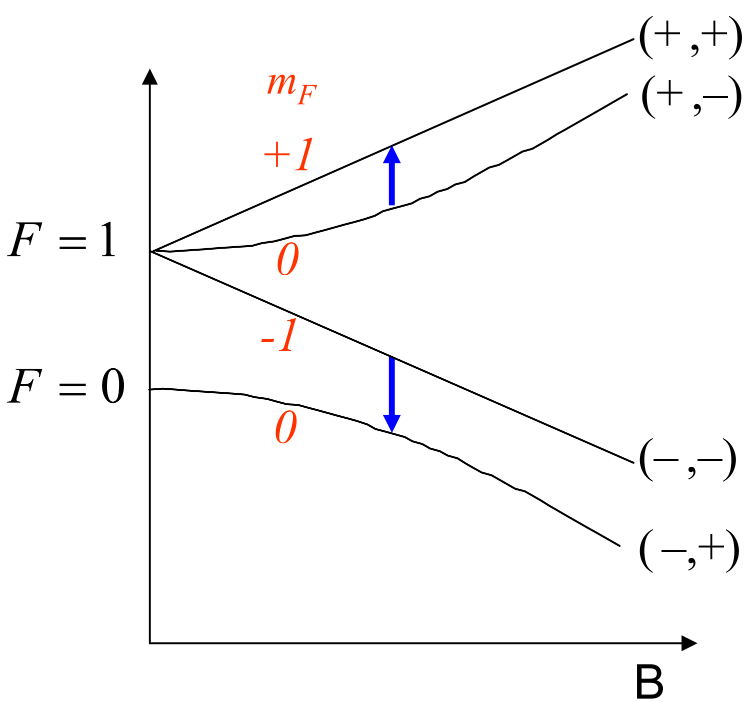
$\Delta\nu_{LS}$ = 7049.4 (9.9) MHz

The exp./ theory comparison gives the mass ratio : $m_{\mu+} / m_{e-}$ = 206.768 277 5 (24)
in agreement but less precise than the ratio deduced from the muon magnetic moment

Even using m_μ/m_e from μ magnetic moment, $\alpha_{\mu e}$ is not competitive

The 1S hyperfine structure of muonium

Experiments have been performed either in low or in high magnetic field



- Polarized muons are captured in a microwave cavity containing Kr gas inside a superconducting magnet
- Muonium is formed in states (+,-) and (-,-)
- Microwave magnetic resonance induces muon spin-flip transitions
- The transition signal is detected through the angular distribution of positrons produced by the μ+ decay

Results : $\Delta\nu_{hfs}$ = 4 463 302 765 (53) Hz   12 ppb

$\mu_{\mu+} / \mu_{e-}$ = 3.183 345 13 (39)   120 ppb

Most precise results obtained in muonium

W. Liu *et al.*, Phys. Rev. Lett. 82, 711 (1999)

(Yale,...)
at LAMPF

Muonium / positronium : discussion

Positronium :

Lightest exotic hydrogen-like atom
Large natural line width limited by e^+ - e^- annihilation (ns)
Complicated QED calculations (small mass…)

Muonium :

Natural line width limited by muon lifetime (2.2μs)
more sensitive to QED corrections (radius smaller VP more important)
Less complicated QED compared to positronium

A good agreement is found for both atoms between experimental results and theoretical predictions but tests in muonium are more stringent

In particular, the study of hyperfine structure of muonium allows to deduce values either of $m_{\mu+} / m_{e-}$ or the fine structure constant α, using other experimental data and/or theoretical predictions

$m_{\mu+} / m_{e-}$ = 206.768 267 0 (55) $u_r = 27\ 10^{-9}$

$1/\alpha$ = 137.035 996 3 (80) $u_r = 58\ 10^{-9}$

see discussion in : W. Liu *et al.*, Phys. Rev. Lett. 82, 711 (1999)

Structureless nucleus atom is a good idea, but the resulting value for the fine structure constant is not competitive (theoretical/experimental limitations)

Lecture I : conclusion

Limitation on the determination of α from :

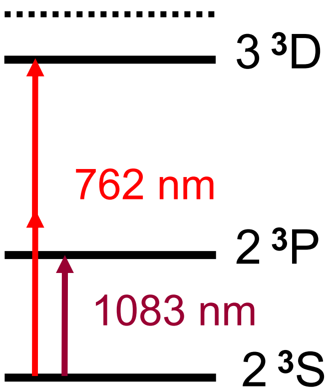
- R_K : system of unit ohm : $kg \cdot m^2 \cdot s^{-3} \cdot A^{-2}$ ($\Delta\alpha/\alpha \sim 2.10^{-8}$)
- Atomic fine structure, hyperfine structure : line width, QED, nucleus ($\Delta\alpha/\alpha \sim 3.10^{-7}$)
- Exotic atom : QED, experiments (S/N, line width) ($\Delta\alpha/\alpha \sim 6.10^{-8}$)

Need to simplify the studied (atomic) system to get rid of the structure resulting from the bounding with the other particle but can not get rid of the QED…

$\Rightarrow$ free electron (elementary particle no structure, …) : anomaly of the gyro magnetic ratio of the electron (Lecture II)

$\Rightarrow$ no more bound system ? No hidden but still in the competition, h/M method (lecture II)

Other spectroscopic measurements in helium



Precise frequency measurements of optical energy intervals provide a test of two-electron Lamb shift calculations

Optical transitions from the metastable $2\,^3S_1$ state allow the determination of both the $2\,^3S$ and $2\,^3P$ Lamb shifts and the ionization energy

• Absolute frequency measurements of the $2\,^3S_1$-$2\,^3P_{0,1,2}$ transitions at 1083 nm, with a frequency comb, give access to the $2\,^3S$ - $2\,^3P$ and $2\,^3P$ Lamb shifts (Florence)

f_0 = 276 764 094 746.9 (1.3) kHz
f_1 = 276 734 477 805.0 (0.9) kHz
f_2 = 276 732 186 818.4 (1.5) kHz

P. Cancio Pastor *et al.*,
Phys. Rev. Lett. 92, 023001 (2004)
and 97, 1399 03 (2006)
and 108, 143001 (2012) !

• Measurement of the two-photon $2\,^3S_1$-$3\,^3D_1$ transition at 762 nm (Paris) provides the ionization energy of the $2\,^3S$ state and a precise determination of the $2\,^3S$ Lamb shift through theoretical calculations on the $3\,^3D_1$ level

f = 786 823 850 002 (56) kHz

C. Dorrer *et al.*, Phys. Rev. Lett. 78, 3658 (1997)

Theoretical uncertainty of these Lamb shifts : 3000 kHz