First lecture:
Precision measurement in atomic physics

Second lecture:
Laser spectroscopy of simple atoms

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How precise?

- Magnetic moment of electron,

  g_e (exp) = 2.00231930436146(56)

- Rydberg constant = $\frac{2\pi^2 m_e e^4}{h^3 c}$

  = 109,737.31568639(91)

- Electric dipole moment of electron

  $|d_e| < 8.7\times10^{-29}$ e·cm

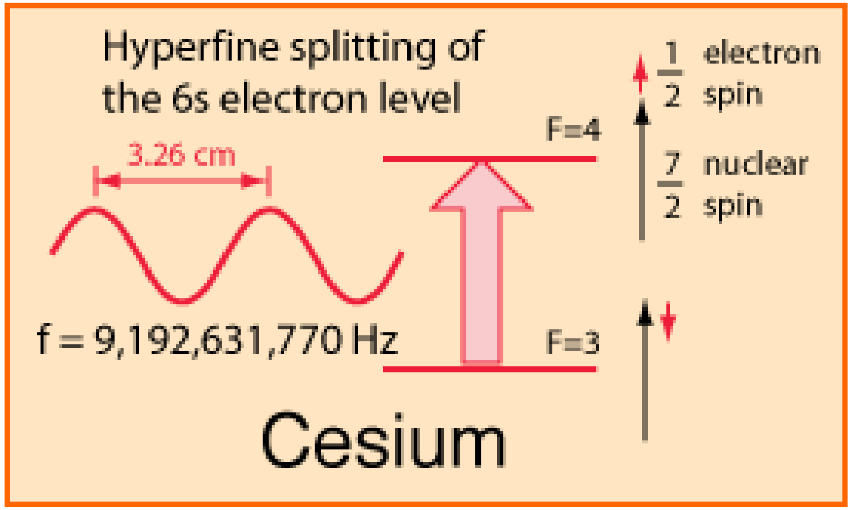
- Time variation of fine structure constant

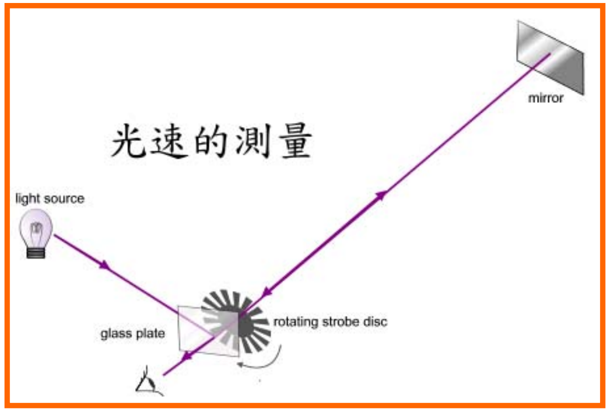
  $\delta\alpha/\alpha$ = $(-1.6 \pm 2.3)\times10^{-17}$/year $\quad \alpha = e^2/\hbar c \approx 1/137$

[1] D. Hanneke et al., *Phys. Rev. Lett.* **100,** 120801 (2008)
[2] Th. Udem et al., *Phys. Rev. Lett*. **79**, 2646 (1997)
[3] The ACME Collaboration, Science **343**, 269 (2014)
[4] T. Rosenband *et al.*, *Science* **319**, 1808 (2008)

Classical measurements

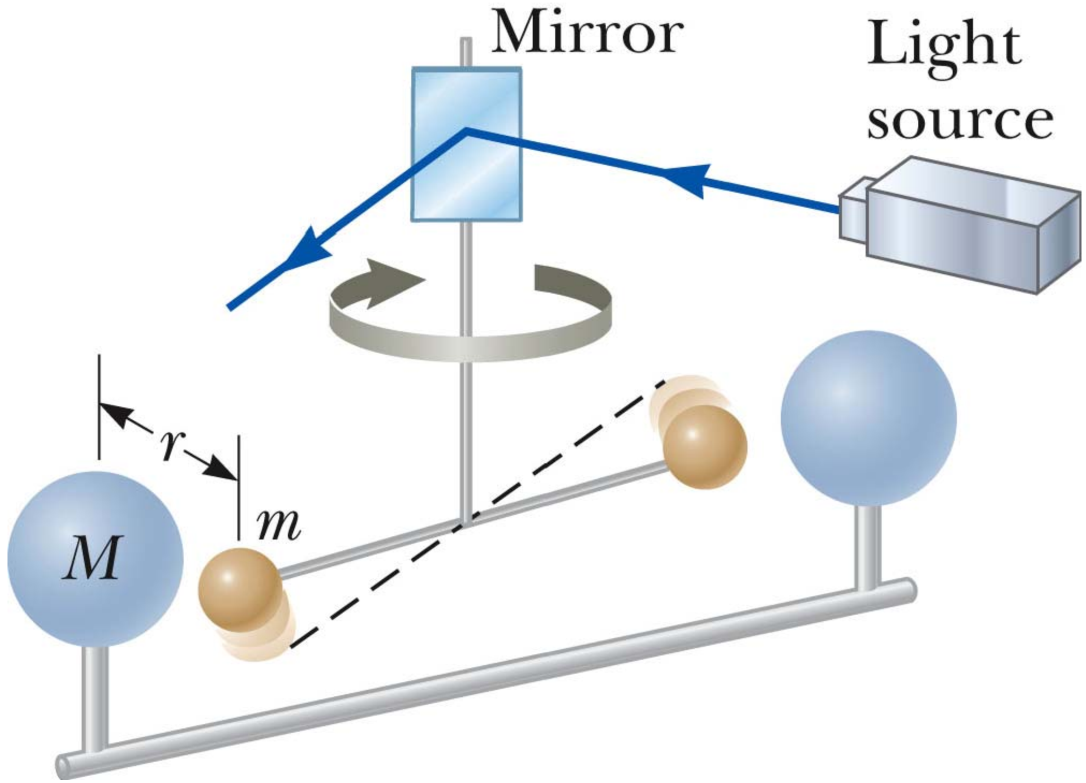
- Time, Length, Mass, Charge
- Definition of Unit
- Good Tools





Example

- Cavendish 1798, G = 6.74×10^{-11}
- G = $(6.674 \pm 0.001) \times 10^{-11}$, $\delta G/G \sim 100$ ppm



Outline

- Historical Review:
  Precision measurement lead to new physics
- Modern approach: resonance and frequency measurement
- Selected topics

Resonance Method

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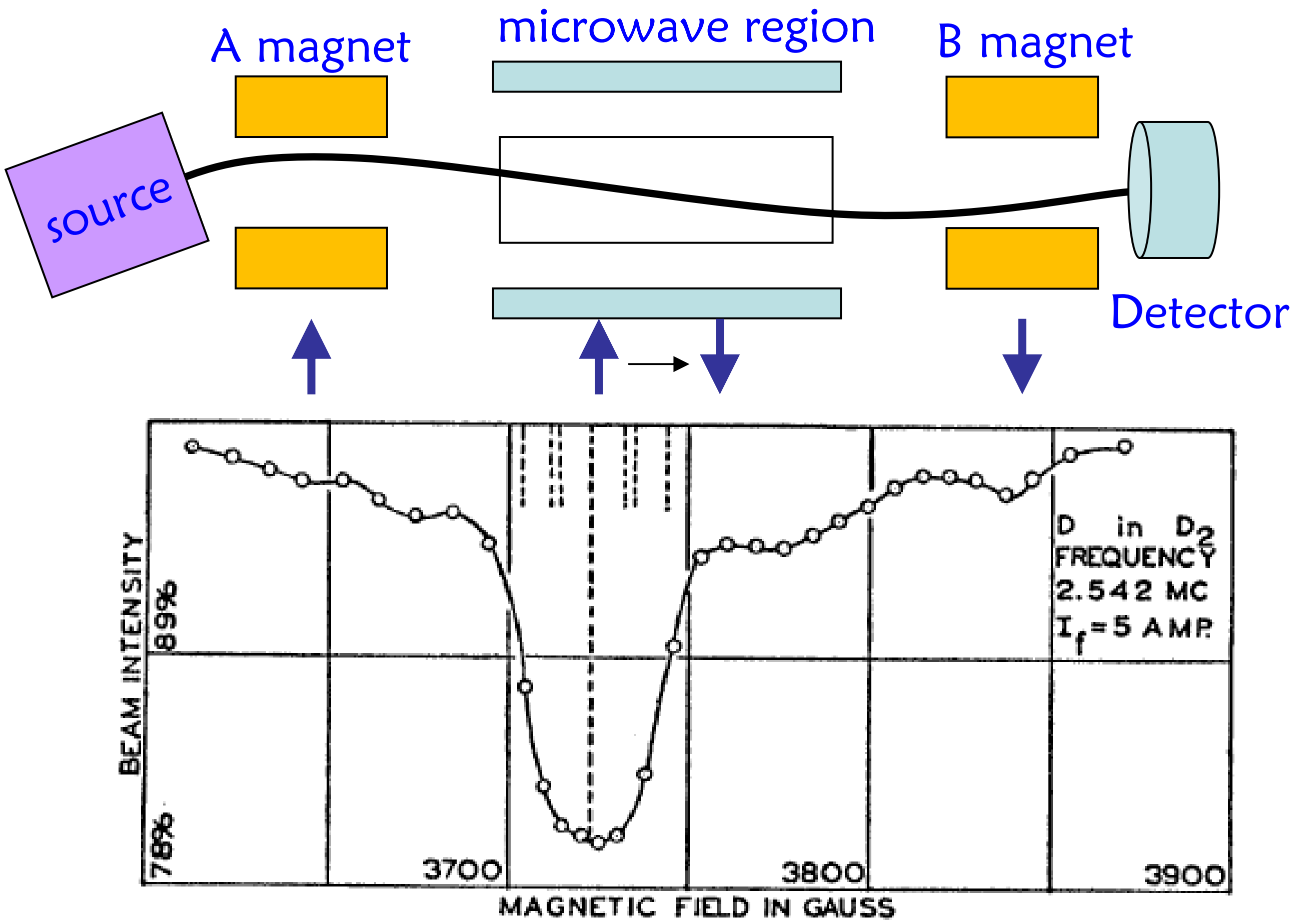
- First Motivated by Stern-Gerlach experiment, 1922
- First atomic spectroscopy by resonance method
  NMR, Rabi and Ramsey, 1934-1939

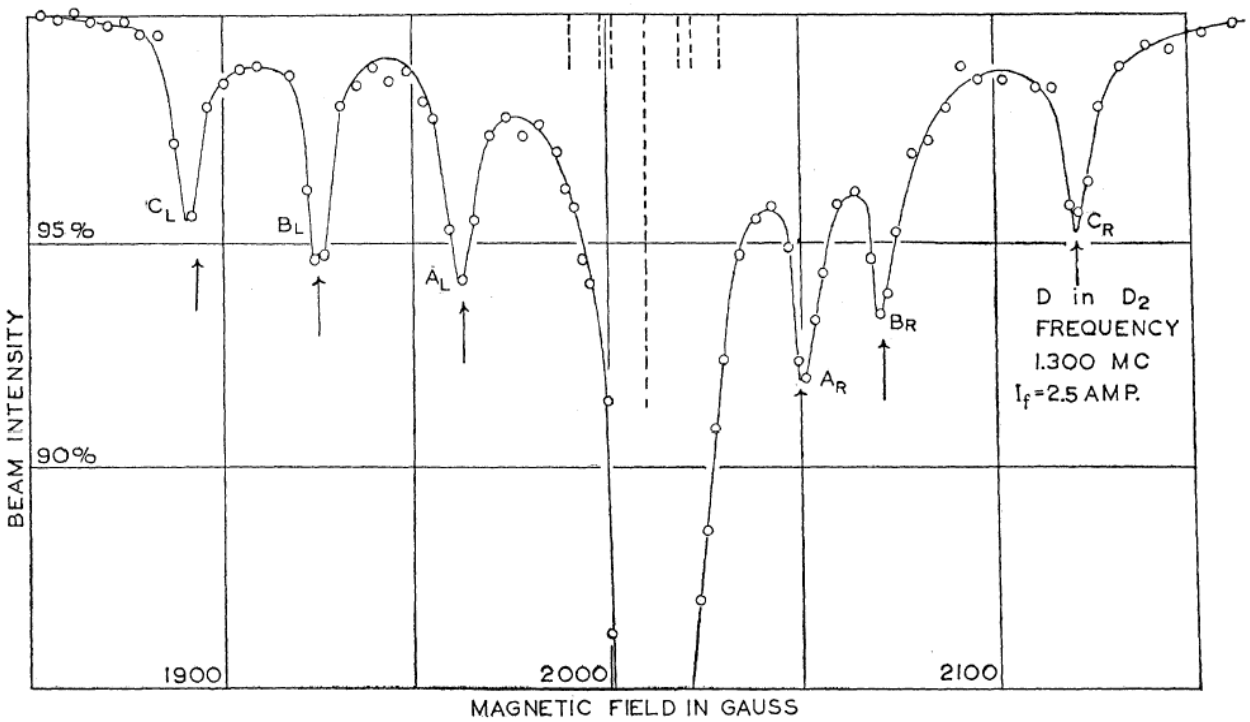


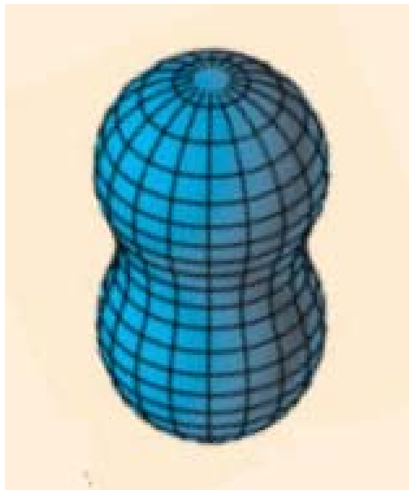
NMR for Deuteron

Isidor Isaac Rabi

Norman F. Ramsey

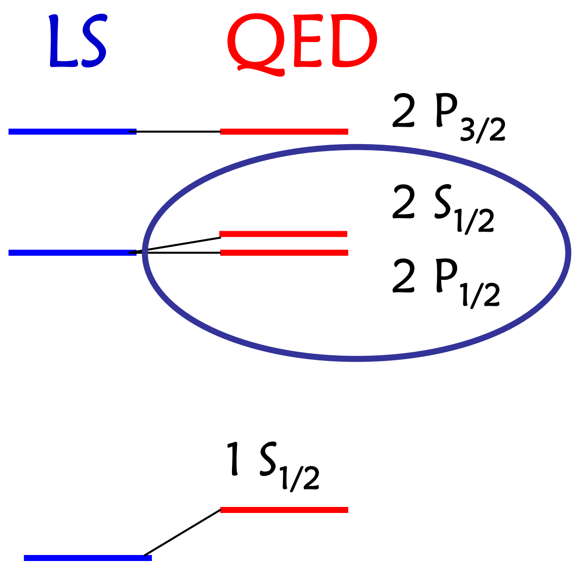
- Electric Quadrupole moment of Deuteron discovered
- Nuclear force is Non-central! Tensor force

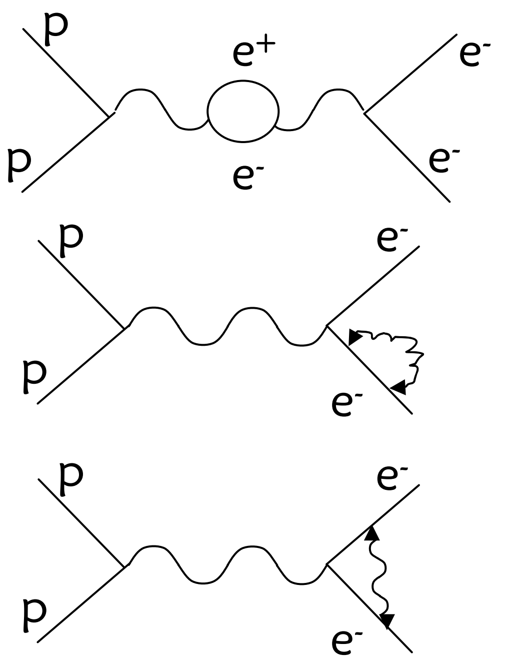


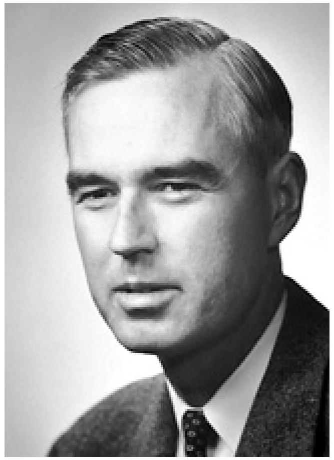


J. M. Kellogg, I. I. Rabi, N. F. Ramsey, and J. R. Zacharias Phys. Rev. 57, 677 (1940)

The Lamb Shift

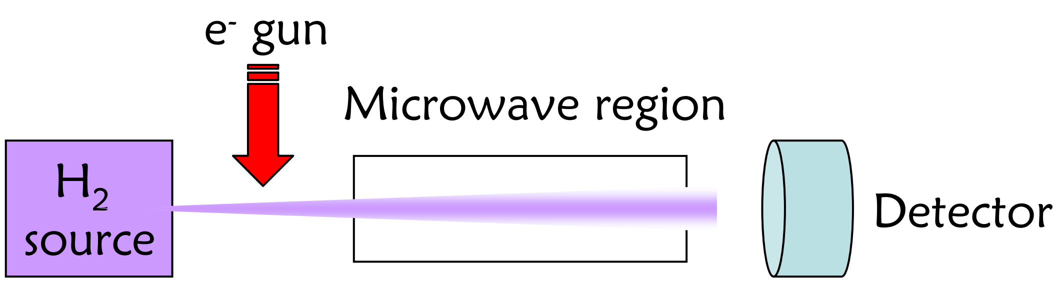






1947 by Lamb ~1060 MHz
now: 1057.846(4) MHz

Willis Eugene Lamb
Nobel Prize in 1955
"for his discoveries concerning the fine structure of the hydrogen spectrum"



QED

- Quantum Electrodynamics
- The most precisely tested theory

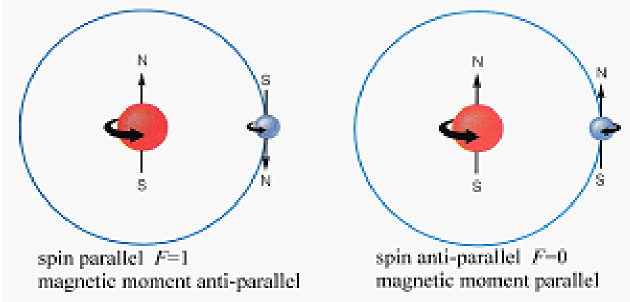
Sin-Ichiro Tomonaga (朝永振一郎), Julian Schwinger, Richard P. Feynman
Nobel Prize in Physics 1965

"for their fundamental work in quantum electrodynamics, with deep-ploughing consequences for the physics of elementary particles"

Selected topics in precision measurement

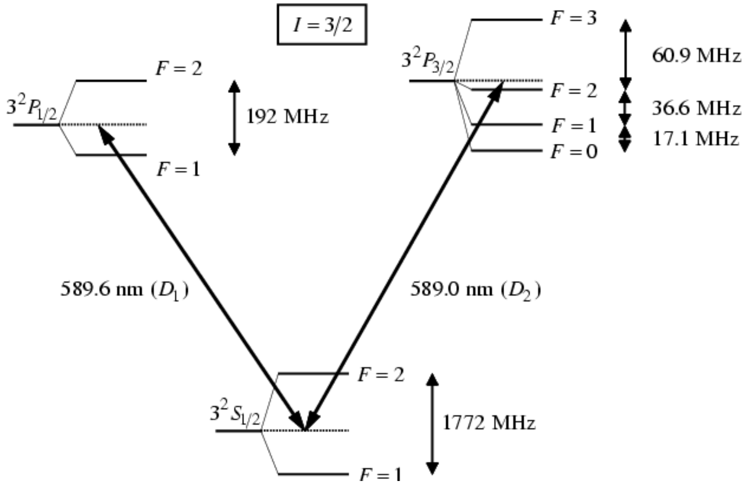
- Hyperfine structure: probing nuclear moment
- Test QED: the g-2 of electron and muon
- New source of CP violation: electric dipole moment of electron and nucleon
- Strong interaction: size of proton
- Time and frequency standard: making a better clock
- Constancy of fundamental constant: can speed of light change?

- Nuclear magnetic moment
- F = I + J
- a and b constant



$$\Delta E_{HFS} = \tfrac{1}{2} aK + \tfrac{1}{4} b \frac{\tfrac{3}{2}K(K+1) - 2I(I+1)J(J+1)}{I(2I-1)J(2J-1)}$$

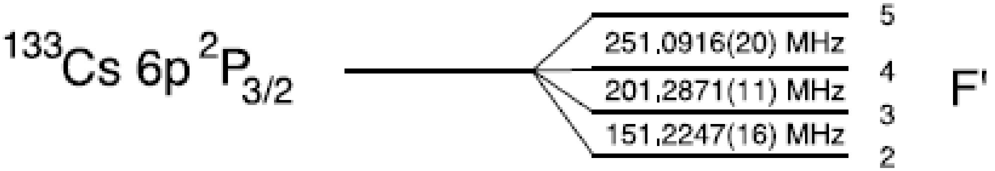
$$K = F(F+1) - J(J+1) - I(I+1)$$

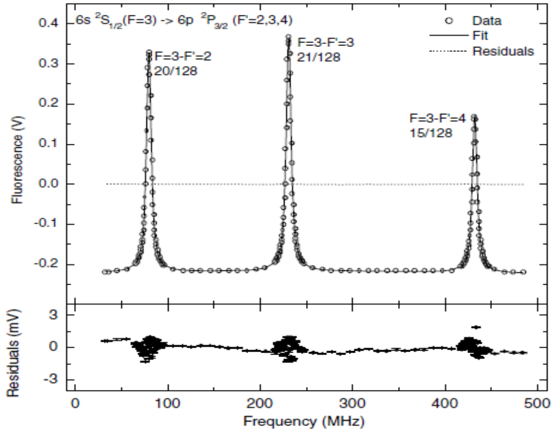


Magnetic octupole moment

- Observe magnetic octupole moment of ^{133}Cs

V. Gerginov, A. Derevianko, and C. E. Tanner, PRL 91, 072501 (2003)





$$H_{\text{dipole}} = a I \cdot J, \qquad H_{\text{quadrupole}} = b \frac{3(I \cdot J)^2 + \frac{3}{2}(I \cdot J) - I(I+1)J(J+1)}{2I(2I-1)J(2J-1)},$$

$$H_{\text{octupole}} = c \frac{\{10(I \cdot J)^3 + 20(I \cdot J)^2 + 2(I \cdot J)[-3I(I+1)J(J+1) + I(I+1) + J(J+1) + 3] - 5I(I+1)J(J+1)\}}{I(I-1)(2I-1)J(J-1)(2J-1)}$$

$$\Delta\nu_{54} = 5a + \frac{5}{7}b + \frac{40}{7}c \; + \; (-0.000520 \text{ MHz}),$$

$$\Delta\nu_{43} = 4a - \frac{2}{7}b - \frac{88}{7}c \; + \; (+0.000119 \text{ MHz}),$$

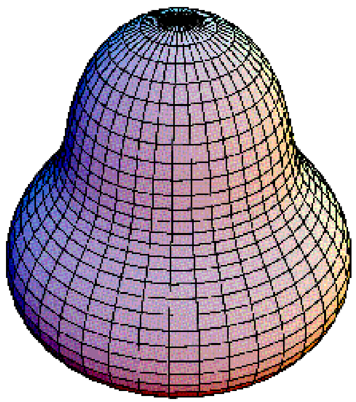
$$\Delta\nu_{32} = 3a - \frac{5}{7}b + \frac{88}{7}c \; + \; (+0.000401 \text{ MHz}),$$

a (MHz)	b (MHz)	c (kHz)
50.288 27(23)	−0.4934(17)	0.56(7)

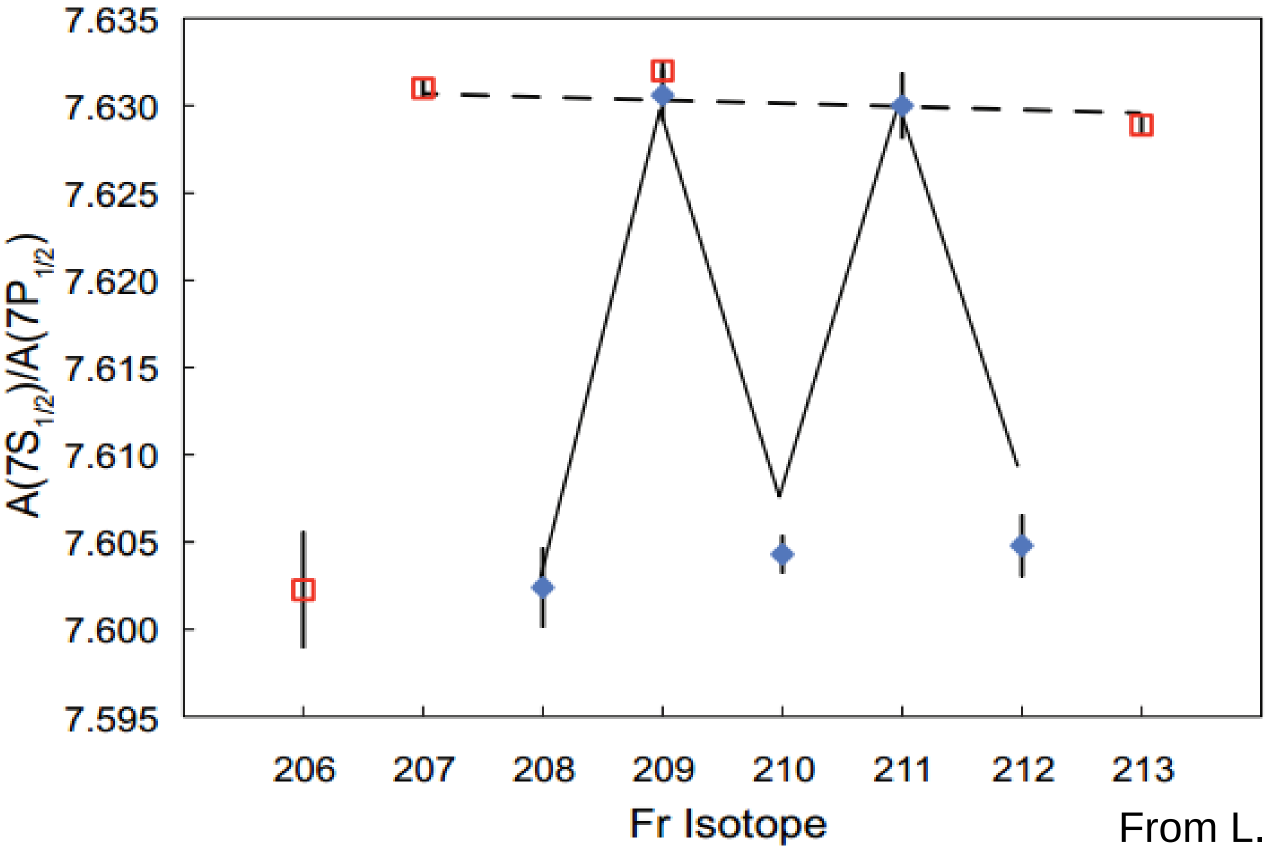
- Observe magnetic octupole moment of ^{87}Rb from spectroscopy of hyperfine intervals

  V Gerginov, C E Tanner, W R Johnson, Can. J. Phys., 87(1): 101-104 (2009)

- Large deformation for some heavy nuclei
- Comparison to nuclear shell model



Hyperfine anomaly

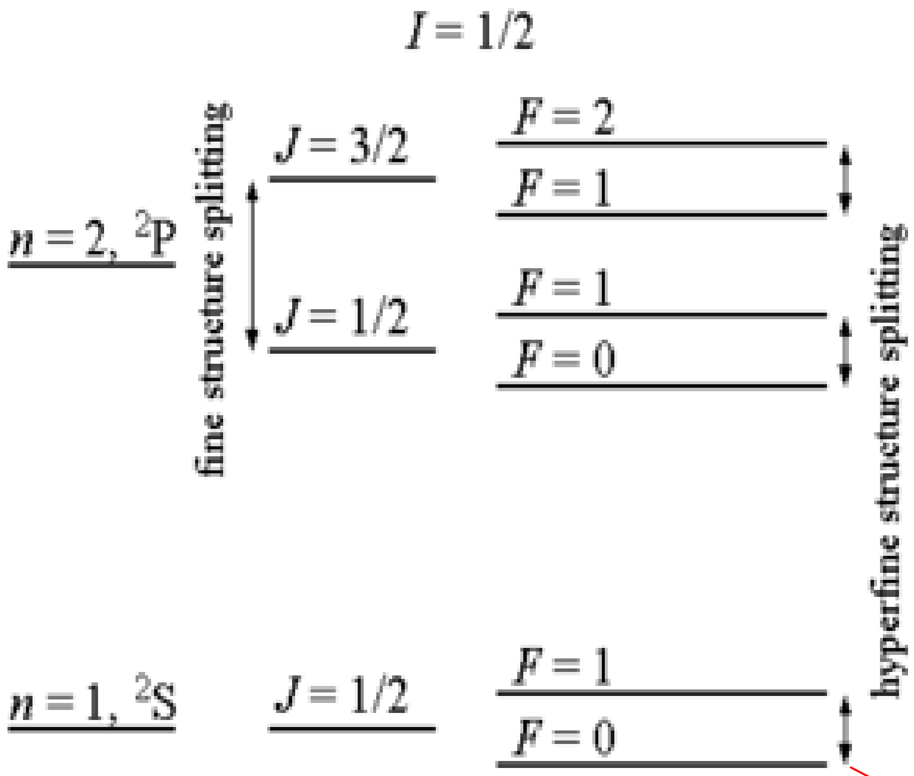


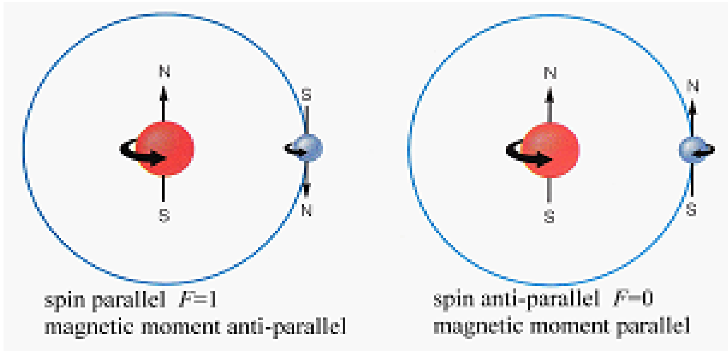
From L. Orozco, UMD

Blue points: Grossman et al., PRL **83**, 935–938 (1999)
Red points: new measurements at TRIUMF (error as of May 30, 2013)
Dashed line: magnetization radius = charge radius, normalized to ^{211}Fr
^{213}Fr ground state: Duong, et al. Europhys. Lett., **3**(2), 175-182 (1987)
^{206}Fr ground state: Voss, et al. To be published.

- Measure hyperfine constant of isotopes
- Magnetic radius $\neq$ electric radius

Hydrogen HFS





E_{HFS} = 1420.4057517667(9) MHz = 21 cm

$$E_F^N = \frac{8}{3\pi}\alpha^3 \mu_B \mu_N \frac{m_e^3 m_N^3}{(m_N + m_e)^3}$$

HFS and Zemach moment

calculable — unknown

$$E_{HFS} = (1 + \Delta_{QED} + \Delta_R + \Delta_S)E_F$$

where $E_F = \frac{8}{3\pi}\alpha^3 \mu_B \mu_p \frac{m_e^3 m_p^3}{(m_e + m_p)^3}$ = known

$$\Delta_S = \Delta_Z + \Delta_{pol}$$

$$= -2\alpha m_e <r>_Z (1 + \delta_Z^{rad}) + \Delta_{pol}$$

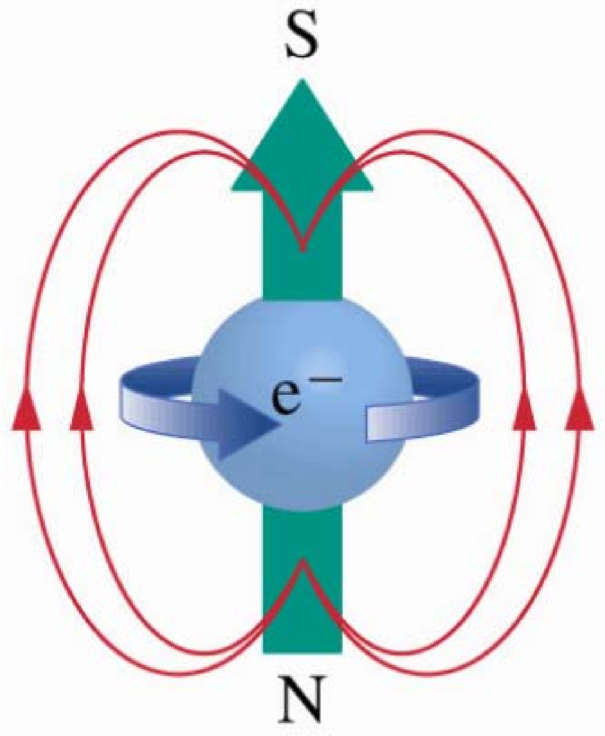
calculable

$$<r>_Z = -\frac{4}{\pi}\int_0^\infty \frac{dQ}{Q^2}\left[\frac{2G_E G_M}{g} - 1\right]$$

Zemach moment,
to be precisely determined

What is g-factor?

The magnetic moment of the electron is proportional to the electron spin



$$m_s = +\frac{1}{2}$$

$$\frac{|\bar{\mu}|}{\mu_B} = g \cdot \frac{|\bar{s}|}{\hbar}$$

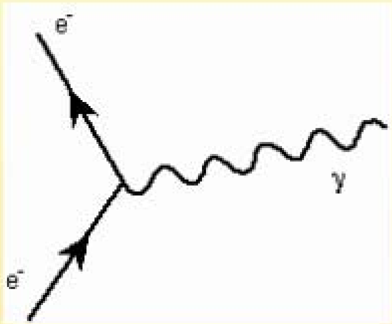
- Classical non-relativistic g=1
- In QM, Dirac Theory predict g=2

In reality, g= 2.002319304

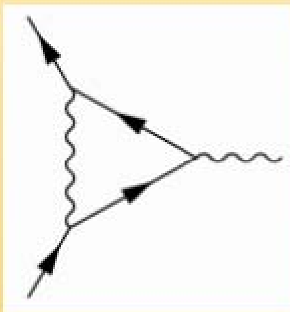
QED and g factor

- Vacuum is not real vacuum

0th order:

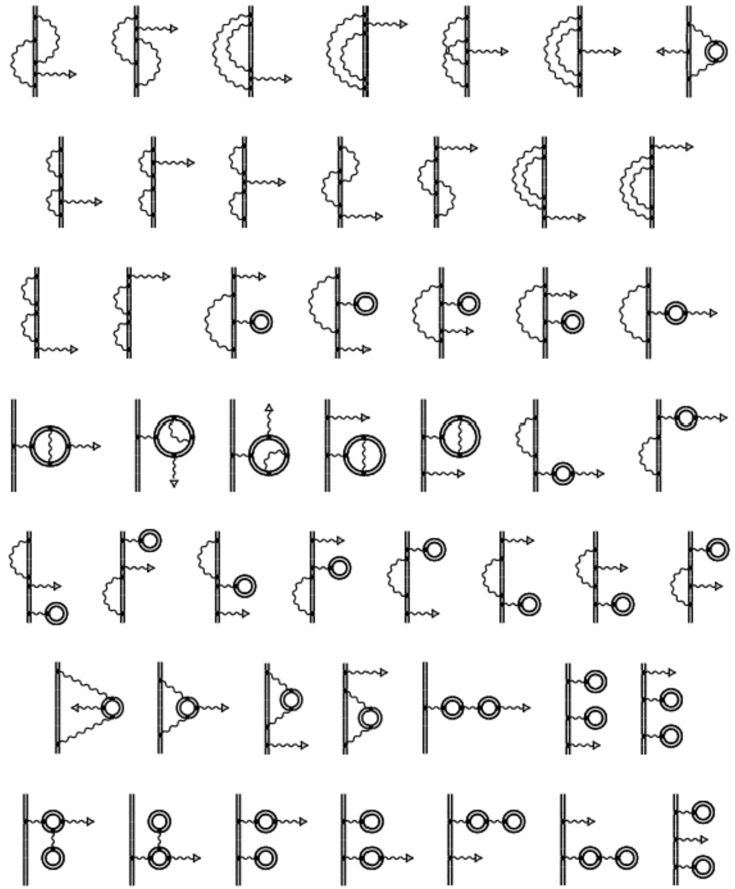


1st order:



+ …

and a lot more….



Why measure g factor

- Test QED
- Search for structure of electrons
- g can be expanded as a function of α

$$\frac{g}{2} = 1 + C_2\left(\frac{\alpha}{\pi}\right) + C_4\left(\frac{\alpha}{\pi}\right)^2 + C_6\left(\frac{\alpha}{\pi}\right)^3 + \ldots\ldots$$

$$+ a_{\mu\tau} + a_{hadronic} + a_{weak}$$

$$\alpha = e^2/\hbar c \approx 1/137$$

$\alpha^{-1} = 137.035\,999\,074\,(44)$

D. Hanneke, S. Fogwell, and G. Gabrielse, *PRL* **100,** 120801 (2008)

Measure electron in bound system

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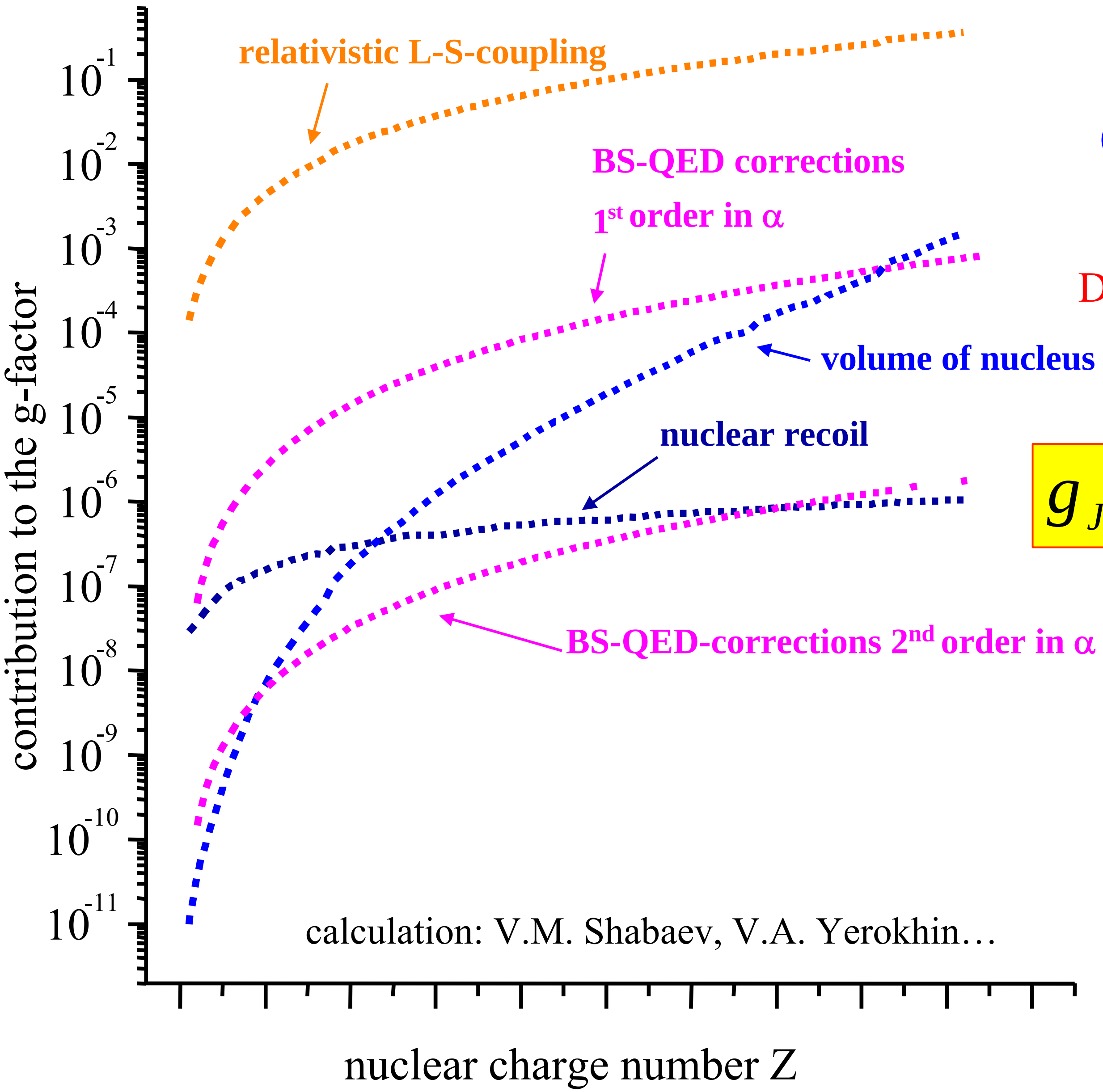


QED of free electron (exp. Dehmelt et al., Gabrielse et al. theo. Kinoshita)

Dirac value

Nuclear correction

$$g_J = 2 + a_e + a_b + b + c$$

Relativistic correction

QED of bound electron

Measure g in free space

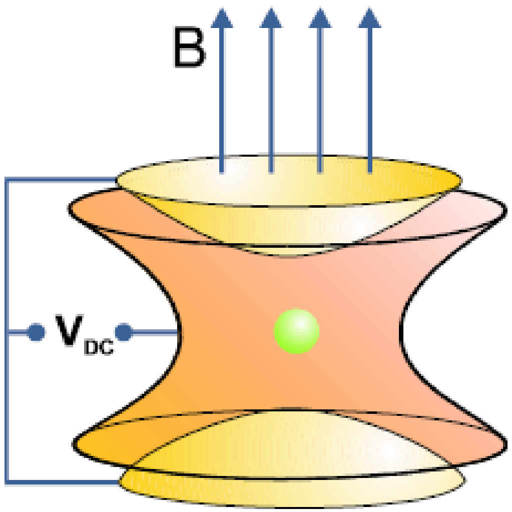
Spin precession (Larmor) frequency

$$\hbar\omega_L = m_s g \cdot \mu_B \cdot B \qquad \mu_B = \frac{e\hbar}{2m}$$

Calibration of magnetic field by cyclotron frequency:

$$\hbar\omega_C = \frac{q}{M} B$$

$$g = 2\frac{\omega_L}{\omega_C}\frac{q}{e}\frac{m}{M} = 2\frac{\omega_L}{\omega_C}$$



Measurement performed on a single electron in Penning trap

Current status

g-2 experiment of electron and muon:

g_e (exp) = 2.00231930436146(56)
g_e (th) to determine fundamental constant

g_μ (exp) = 2.0023318<u>416</u>(12)*
g_μ (th) = 2.0023318<u>367</u>(13)*

} 5 σ deviation

G.W. Bennett et al., *Phys Rev Lett* 92, 161802 (2004)

Size of proton

- Fundamental quantity bothering for decades
- Very important for nuclear calculation
- Lattice QCD not able to calculate precisely

Charge radius of proton by electron scattering

$$\left(\frac{d\sigma}{d\Omega}\right)_{Rosenbluth} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \left\{ \left(\frac{G_E^2(Q^2) + \frac{Q^2}{4M^2} G_M^2(Q^2)}{1 + \frac{Q^2}{4M^2}} \right) + \frac{Q^2}{2M^2} \cdot G_M^2(Q^2) \cdot \tan^2(\theta/2) \right\}$$

$$\Rightarrow \quad < r_c^{\ 2} > = -6 \frac{dG_E(Q^2)}{dQ^2}\bigg|_{Q^2=0}$$

- Simon et al, (1980) R_{rms} = 0.862(12) fm
- I. Sick, (2003). R_{rms} = 0.895(18) fm

Nuclear size effect

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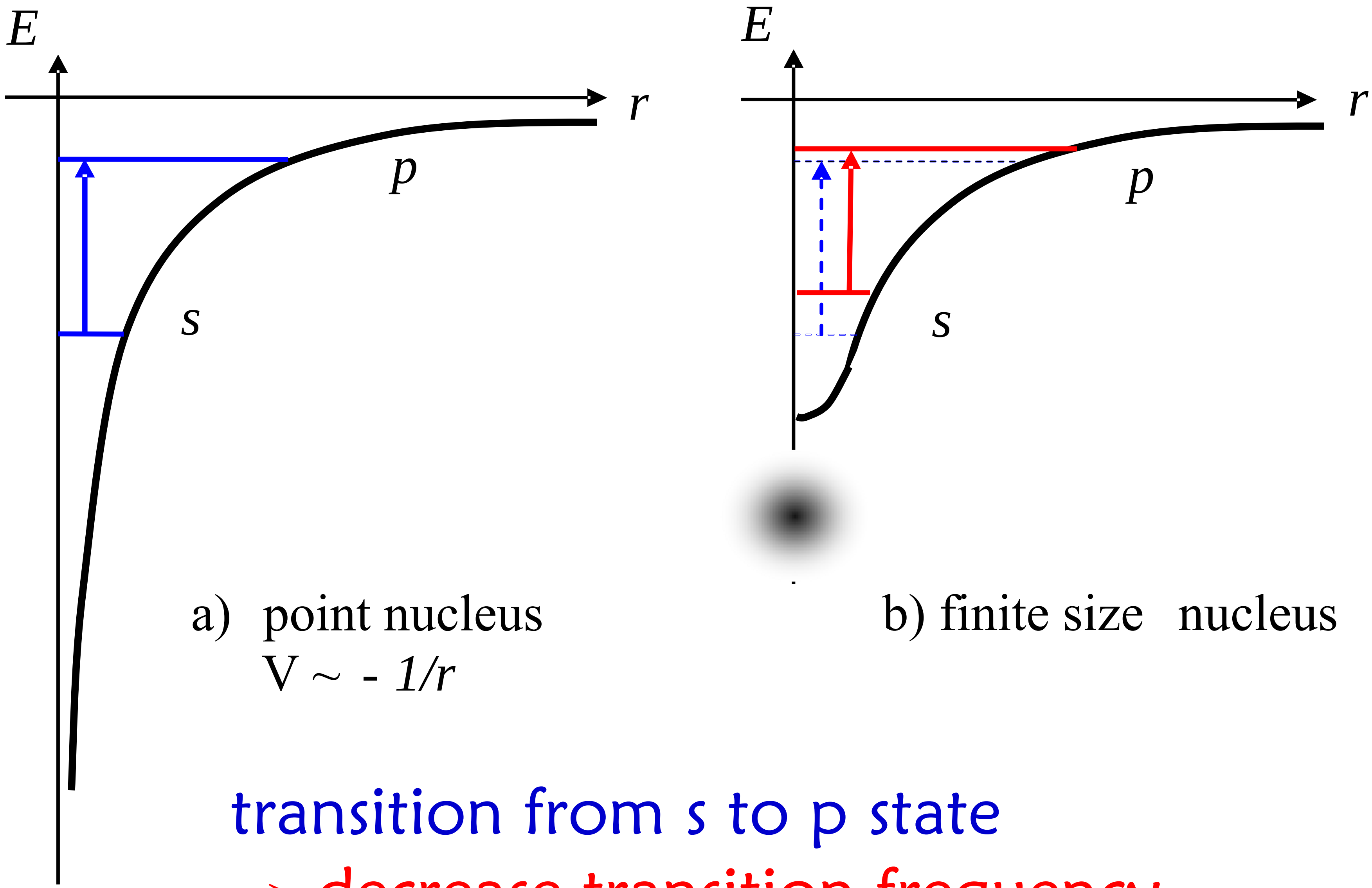

a) point nucleus
V ~ - *1/r*

b) finite size nucleus

transition from s to p state

→ decrease transition frequency

Laser spectroscopy method

- Measure H transition frequency 1s $\rightarrow$2s at 121 nm, uncertainty: (th) 16 kHz, (exp) 22 kHz

$\rightarrow$ charge radius of proton R_{rms} = 0.883(14) fm

Lack of precision (only1~2%) very annoying!

Kirill Melnikov and Timo van Ritbergen, Phys. Rev. Lett. **84**, 1673(2000)

Nuclear size effect

$$E(nS) \approx \frac{-R_\infty}{n^2} + \frac{L_{1S}}{n^3} \qquad L_{1S} = (8172 + 1.56 \cdot r_p{}^2)MHz$$

- Two unknowns: R_∞ and r_p

0.883(14) fm, hydrogen spectroscopy, ENS Paris

C. Schwob et al., Phys. Rev. Lett. **82**, 4960 (1999).

K. Melnikov and T. van Ritbergen, Phys. Rev. Lett. **84**, 1673(2000).

0.890(14) fm, hydrogen spectroscopy, MPI Garching

T. Udem et al. Phys. Rev. Lett. **79**, 2646, (1997).

0.862(12) fm, original electron scattering result

G.G. Simon et.al. Nucl. Phys. A **333**, 381 (1980)

0.895(18) fm, re-analysis of world data

I. Sick, Phys. Lett. **B 576**, 62-67 (2003)

0.879(8) fm, new experiment by GSI

J. C. Bernauer et al., Phys. Rev. Lett. **105**, 242001 (2010)

Optical frequency measurement

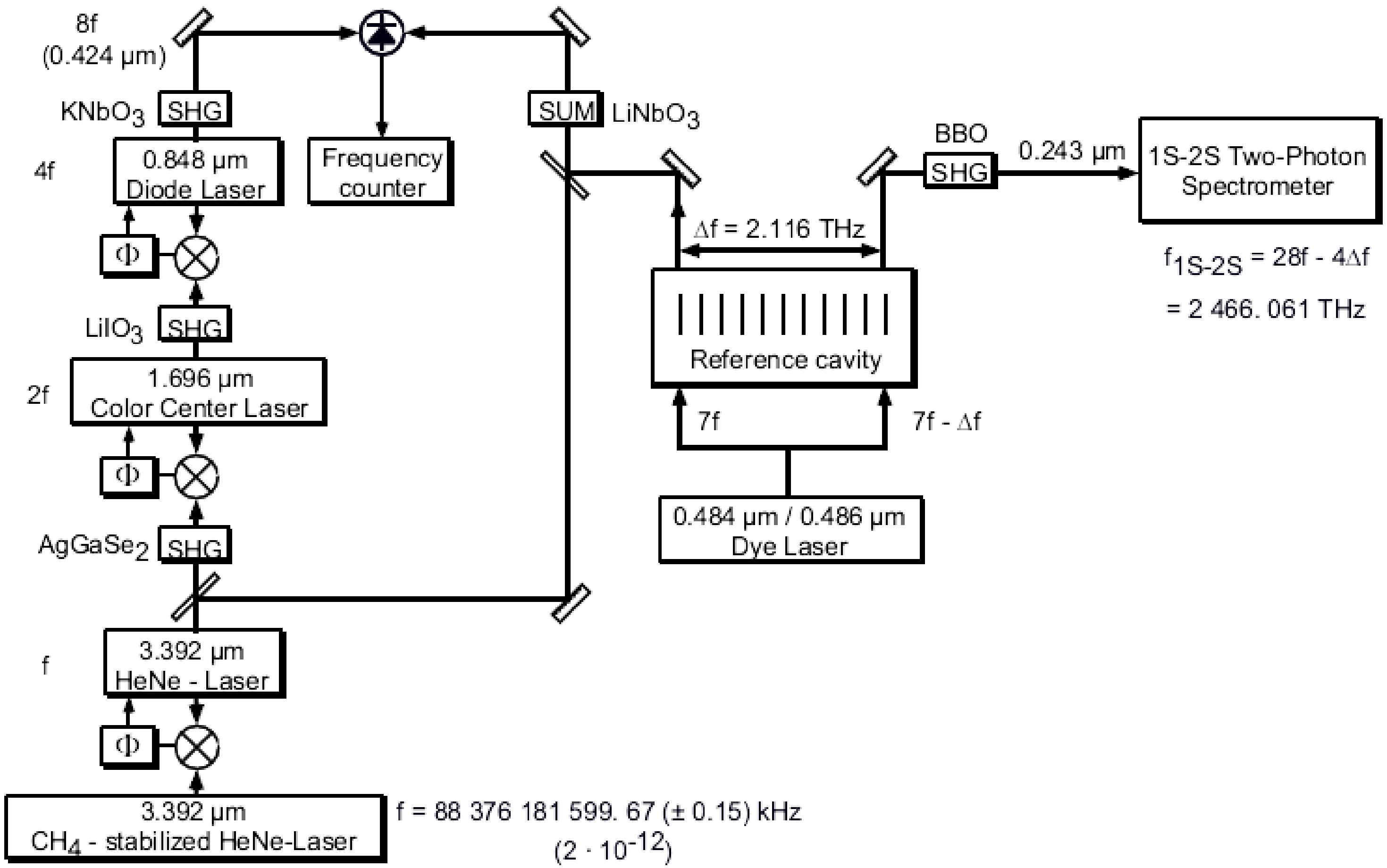

Fig. 4. The first 1992 Garching frequency chain for the measurement of the $1S - 2S$ transition in atomic hydrogen (Φ: phase-locked loop, SHG: second harmonic generation)

Frequency chain

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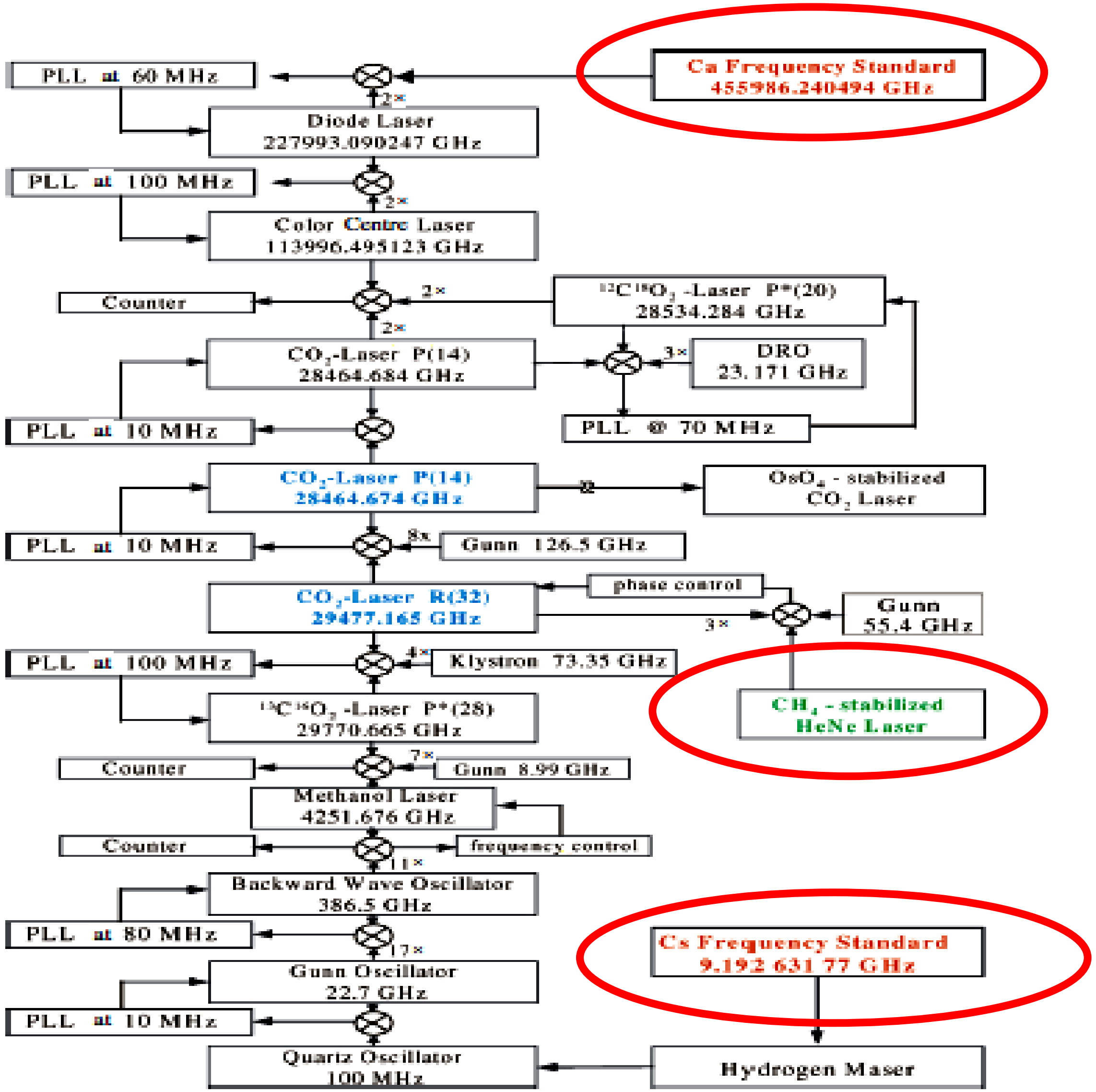
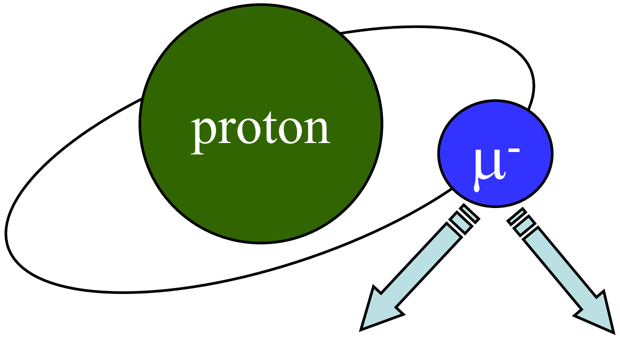


Figure 5. The PTB harmonic frequency chain was the first to achieve a phase-coherent connection between the caesium primary standard and an optical-frequency reference in the visible range. In this case, the target was the calcium optical frequency standard at 457 THz (657 nm). (Adapted with permission from [96].)

Muonic atom result



muon decay $\mu^- \rightarrow e^- \nu \bar{\nu}$

- $m_\mu / m_e \sim 200$
- Bohr radius $a_0 = \dfrac{4\pi\varepsilon_0 \hbar^2}{m_e e^2}$
- Energy level $E_n = -\dfrac{e^4}{2(4\pi\varepsilon_0\hbar)^2}\dfrac{m_e}{n^2}$
- Wave function $\Psi(r) \sim a_0^{-3/2} e^{-r/a_0}$
- Energy shift due to nuclear size $\sim |\Psi(0)|^2 \langle r^2 \rangle$
- Sensitivity $\sim (m_\mu / m_e)^2$

$r_p = 0.84184(67)$ fm

Pohl et al., Nature **466**, 213, 2010

$r_p = 0.84087(39)$ fm

Antognini et al., Science **339**, 417, 2013

Need more experimental verification of atomic QED calculations

Frequency standard

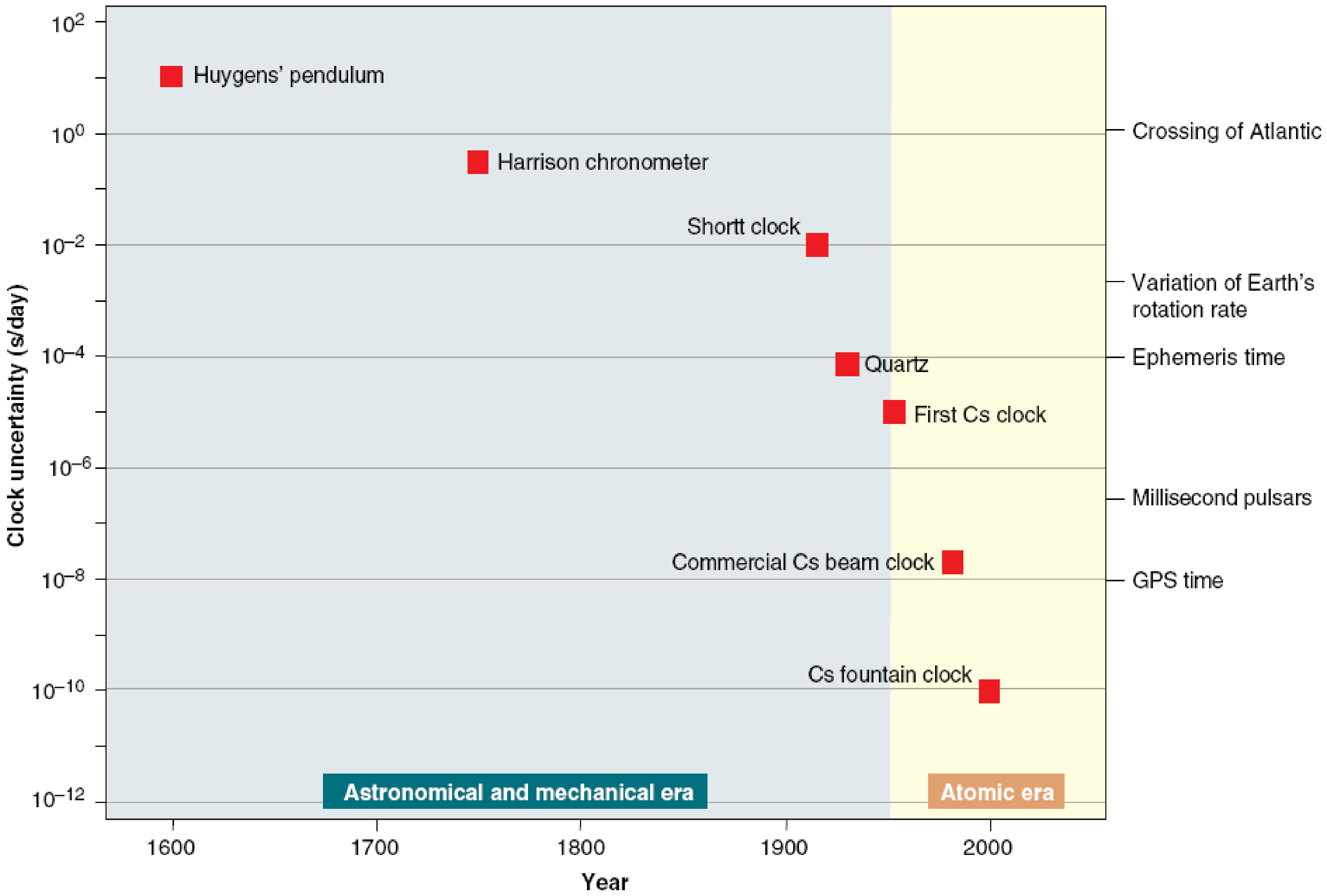
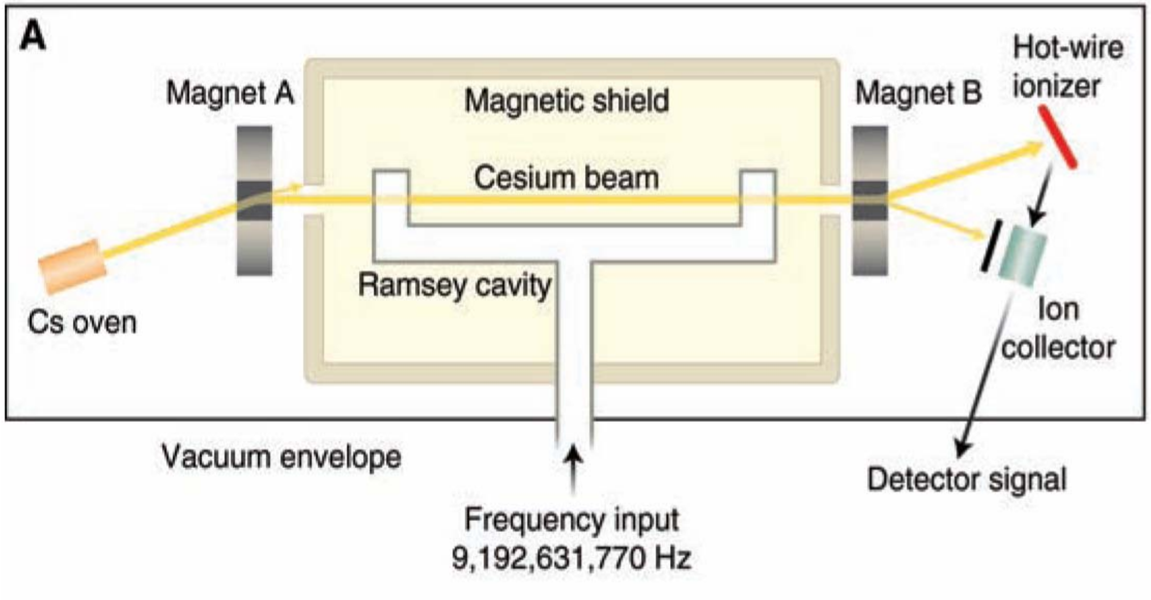


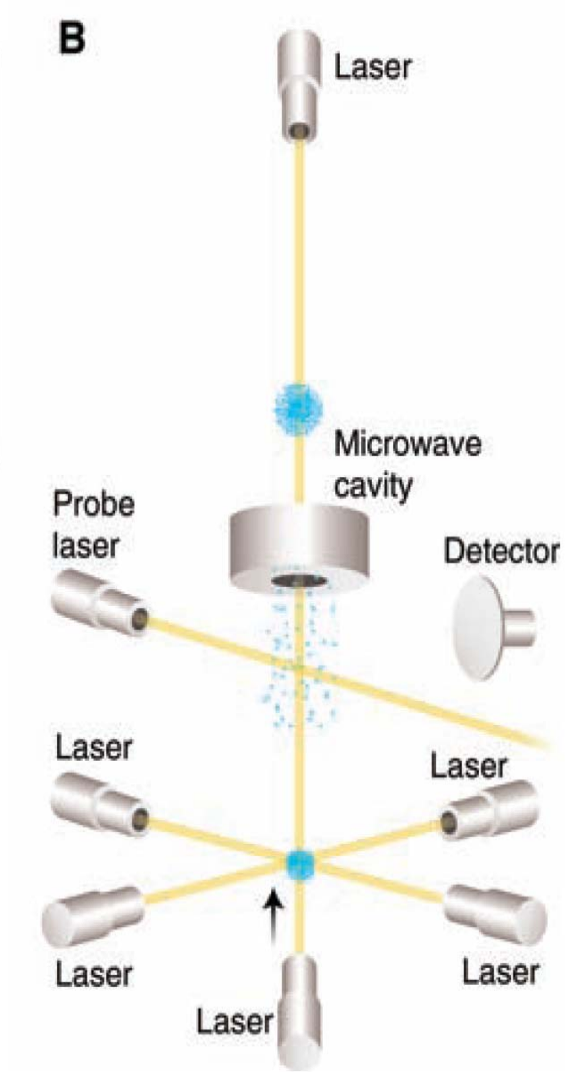
Figure: S.A. Diddams et al.,Science 306, 1318, 2004

Why better clock?

- When you measure something very precisely, new physics will come out by itself!
- Applications:
  - GPS
  - Test special relativity, gravitational red-shift
  - Gravitational wave radiation in binary pulsar
  - Test linearality of quantum mechanics
  - Variation of fundamental constant

Microwave Cs clock





A: Microwave resonance of Cs beam

$\delta\nu/\nu_0 = 3\times10^{-15}$

state selection, interaction time

B: Cs fountain clock

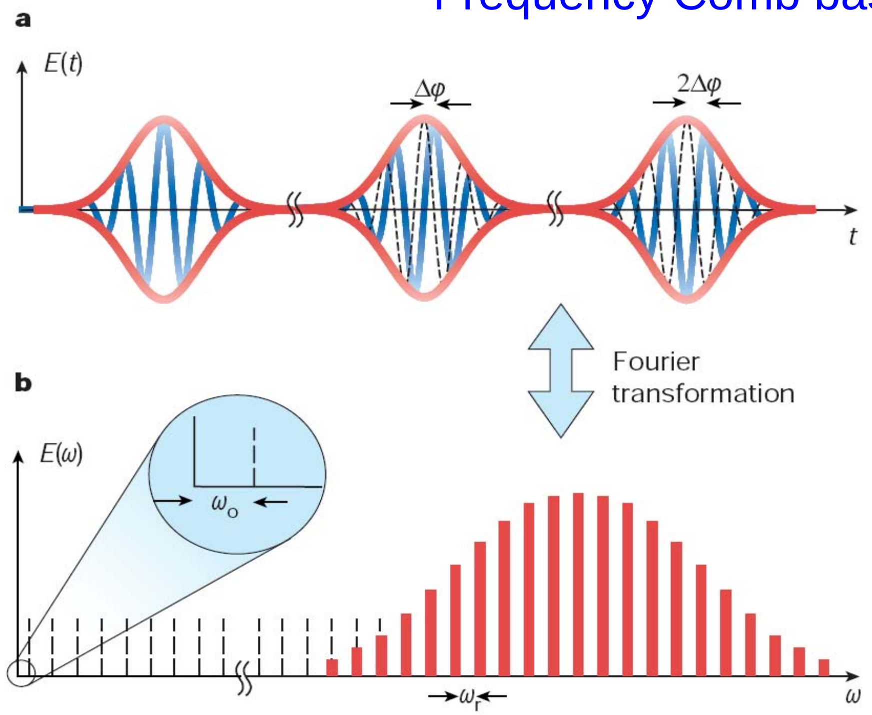
$\delta\nu/\nu_0 = 4\times10^{-16}$

> To improve $\delta\nu/\nu_0$?

NIST Cs fountain

- Frequency comb: pioneering work by T.W. Hänsch and J. Hall made frequency measurement possible

Frequency Comb basics



Picture from Th. Udem, R. Holzwarth, T.W. Hänsch, Nature 416, 233, 2002

$\omega_n = n\,\omega_r + \omega_{offset}$

ω_r : 50MHz ~ 1GHz

ω_r:
Determined by cavity length

ω_{offset}:
measured by f-2f technique

- Trapped ions: Hg^+, Ca^+, Sr^+, Yb^+, Ba^+, In^+, Al^+.....
  - Long interaction time, can be laser cooled
  - Single ion detection, poor S/N
- Trapped neutral atoms: Ca, Sr, Yb, Mg, H.....
  - Large number of atoms, very high S/N
  - Complicated systematics
- Precision ~ $10^{-17} – 10^{-18}$ ($Hz^{1/2}$)

Permanent electric dipole moment

- 1957 Landau first pointed out the electric dipole moment (EDM) of a fundamental particle would suggest P and T violation

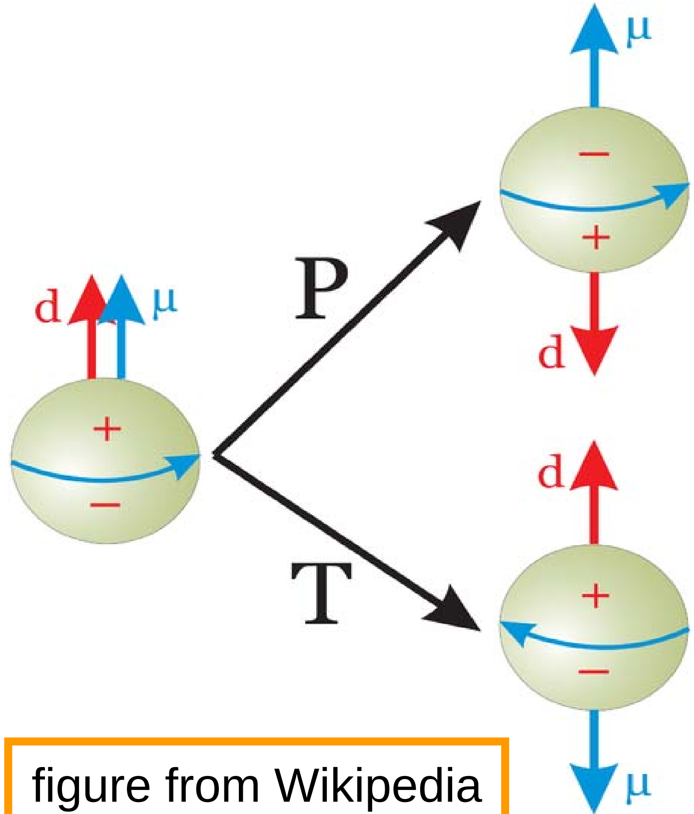


figure from Wikipedia

d: electric dipole moment
= vector
u: spin or magnetic moment
= pseudo-vector, (like **r** x **p**)

Neutron EDM: history

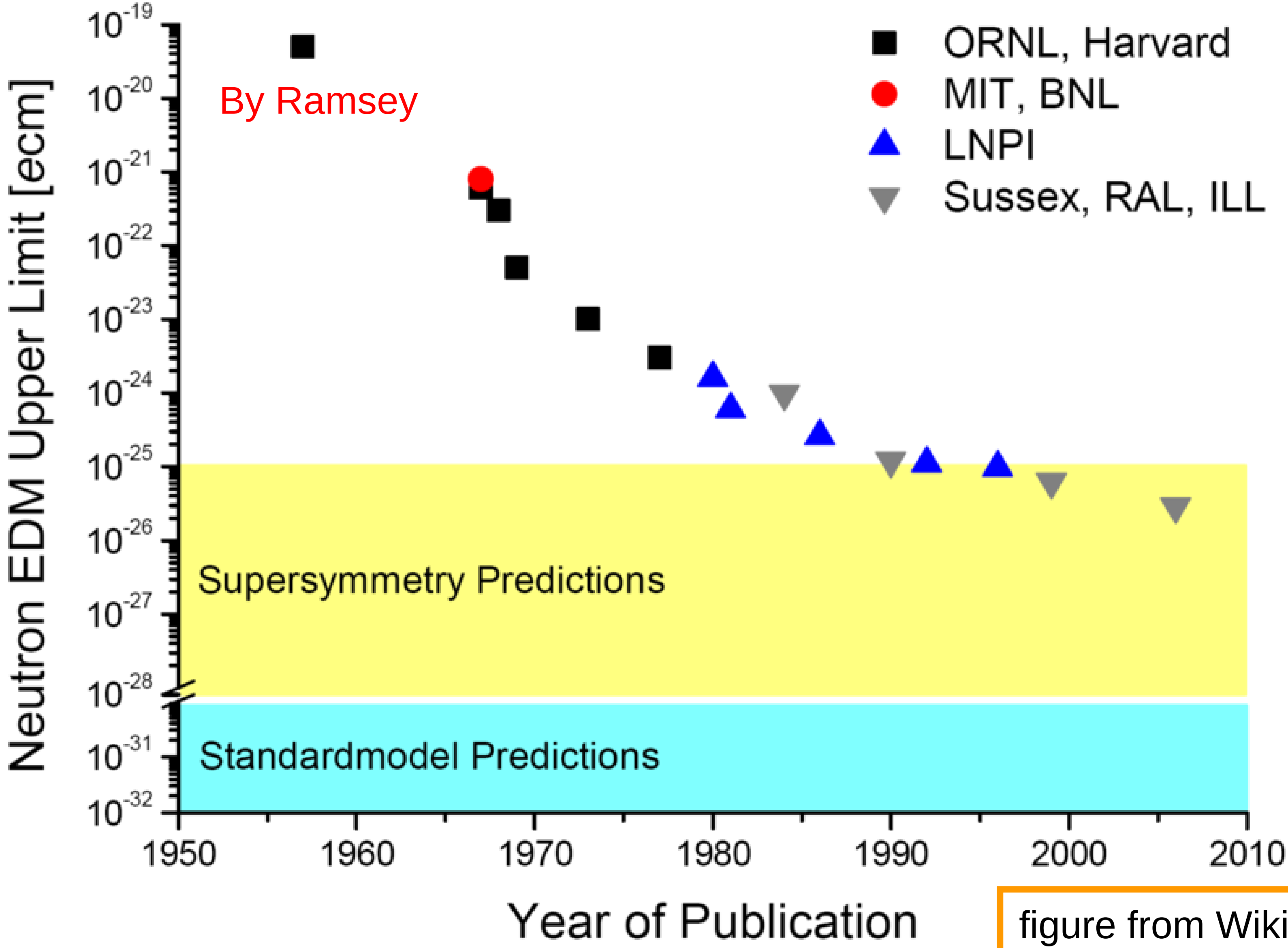


figure from Wikipedia

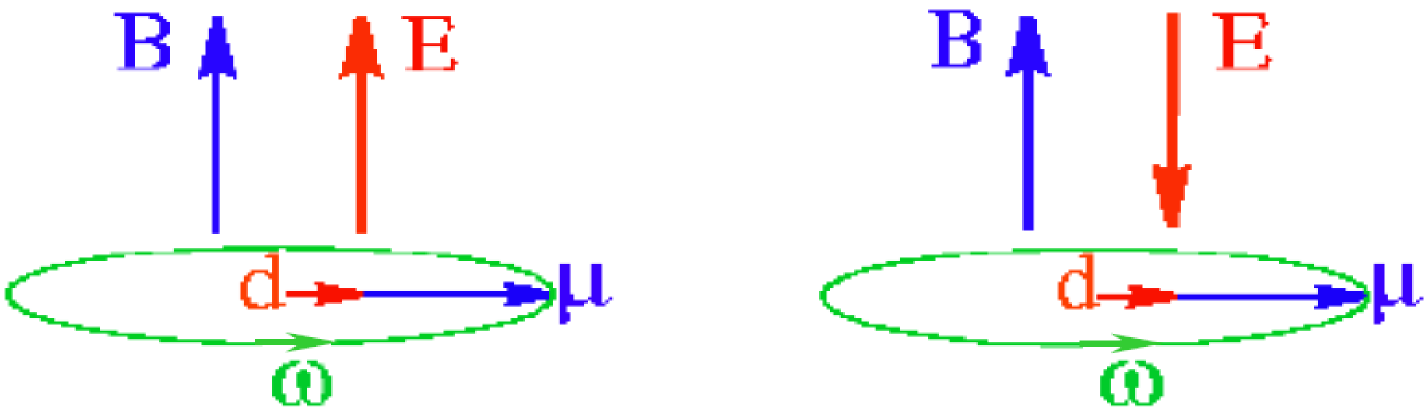
CP violation without strangeness

- Matter–antimatter asymmetry suggest another source of CP violation
  - Electron: intrinsic ?
  - Quark: intrinsic ?
  - Neutron/proton:
    from quark EDM ? New interaction?
  - Atoms, molecules:
    large enhancement factors

Atoms: Tl, Cs, Hg, Xe, Rn, Ra, Fr
Molecule: PbO, YbF, ThO
Ions, solid state systems, etc…

How to measure EDM

$$H = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E}$$



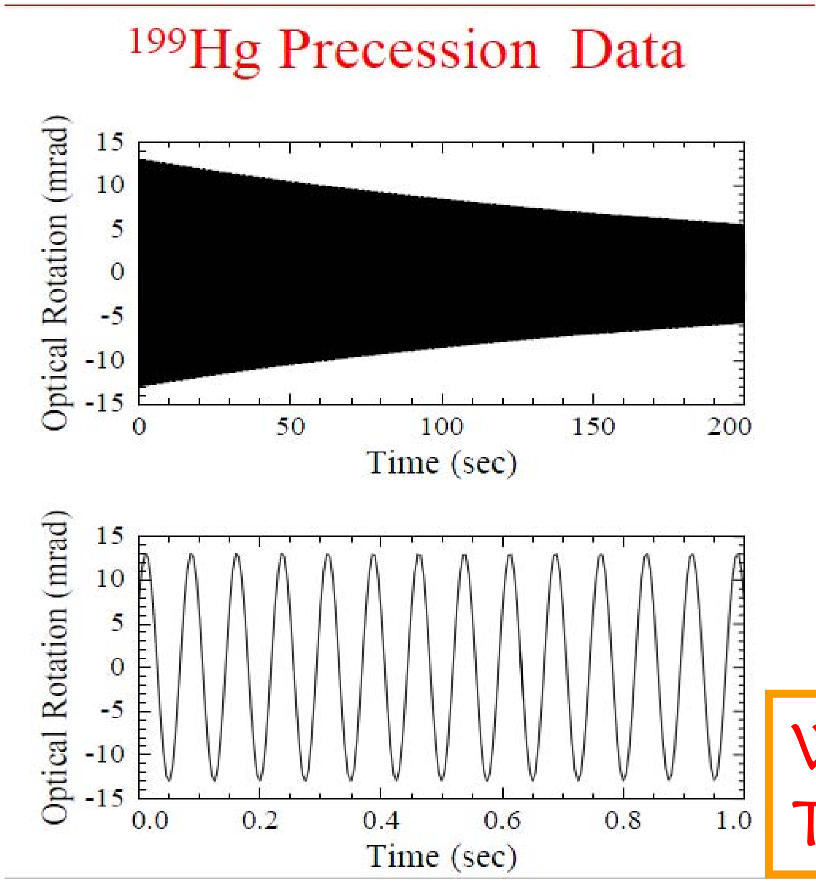
$$\omega_1 = \frac{2\mu B + 2dE}{\hbar} \qquad \omega_2 = \frac{2\mu B - 2dE}{\hbar}$$

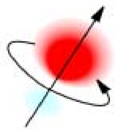
$$\omega_1 - \omega_2 = \frac{4dE}{\hbar}$$

figure from M. Romalis, Princeton

Problem:
reverse E field cause leakage current,
huge noise from B field

Current status





Typical value

E ~ 10 kV/cm

ω~ 10Hz, $\delta\omega$ ~ nHz

Sensitivity approaching
some Standard Model extension

What if someone observes EDM?
Theories ready with many parameters

figure from M. Romalis, Princeton

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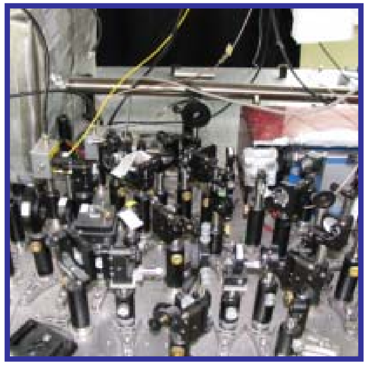
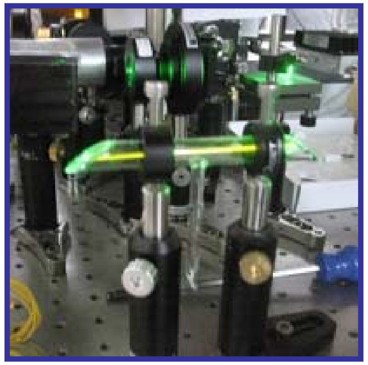
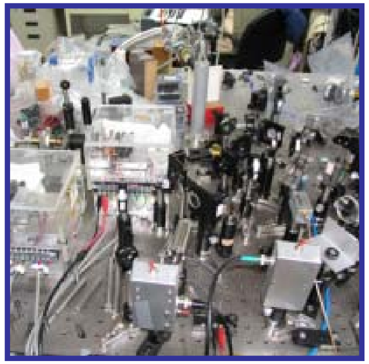
Second lecture:

Laser spectroscopy of simple atoms

work performed at NTHU Physics







Precision spectroscopy of simple atoms

- Hydrogen: exact solution exist
- Helium: numerical method
- Lithium: numerical method

Remain as input for atomic calculation

- Magnetic moment of nucleus
- Charge radius of nucleus

Motivation

- Calculable atomic structure: precision measurement test fundamental physics
- Advances in atomic theories, e.g. in H, He, Li, He^+, Li^+, Be^+ etc…
- New experimental techniques, e.g.: cold atoms by atom and ion trap, frequency comb, exotic atoms, etc…
- What fundamental physics to study?

Atomic structure (Hydrogen)

- non-relativistic

$$En = -\alpha^2 mc^2 \left(\frac{1}{2n^2} \right) = \frac{-13.6eV}{n^2}$$

- relativistic correction

$$-\alpha^4 mc^2 \frac{1}{4n^2} \left[\frac{2n}{(l+1/2)} - \frac{3}{2} \right]$$

- spin-orbit interaction (L·S, fine structure)

$$-\alpha^4 mc^2 \frac{1}{4n^2} \left[\frac{2n}{(j+1/2)} - \frac{3}{2} \right]$$

- nuclear moment (HFS)

$$\left(\frac{m}{m_p} \right) \alpha^4 mc^2 \frac{4\gamma_p}{3n^2} [f(f+1) - 3/2]$$

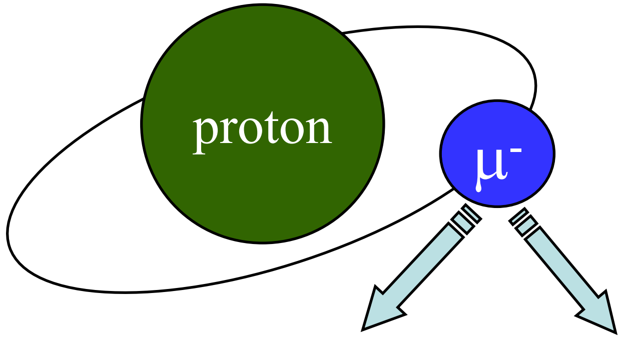
- QED effect (Lamb shift)

$$\alpha^5 mc^2 \frac{1}{4n^3} \left\{ k(n,l) \pm \frac{1}{\pi (j+1/2)(l+1/2)} \right\}$$

- nuclear size effect

$$\frac{2\pi}{3} Ze^2 |\psi(0)|^2 \langle r^2 \rangle_{proton}$$

Muonic atom result



muon decay $\mu^- \rightarrow e^- \nu \bar{\nu}$

- $m_\mu / m_e \sim 200$
- Bohr radius $a_0 = \frac{4\pi\varepsilon_0 \hbar^2}{m_e e^2}$
- Energy level $E_n = -\frac{e^4}{2(4\pi\varepsilon_0\hbar)^2}\frac{m_e}{n^2}$
- Wave function $\Psi(r) \sim a_0^{-3/2} e^{-r/a_0}$
- Energy shift due to nuclear size~ $|\Psi(0)|^2 \langle r^2 \rangle$
- Sensitivity ~ $(m_\mu / m_e)^2$

$r_p = 0.84184(67)$ fm

Pohl et al., Nature **466**, 213, 2010

$r_p = 0.84087(39)$ fm

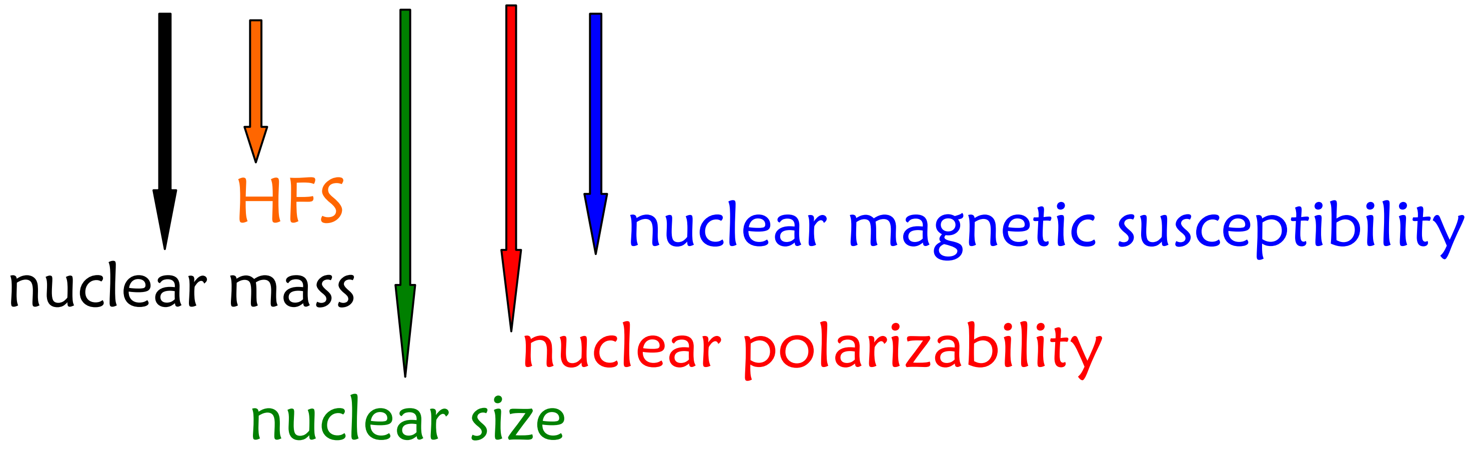
Antognini et al., Science **339**, 417, 2013

Need more experimental verification of atomic QED calculations

Hydrogen isotope shift

- Measure isotope shift (H-D), 1s - 2s at 121 nm

$\Delta\nu$ = 670 994.33464(15) MHz



Reference:
[1] Kirill Melnikov and Timo van Ritbergen, Phys. Rev. Lett. **84**, 1673(2000)
[2] A. Huber, Th. Udem, B. Gross, J. Reichert, M. Kourogi, K. Pachucki, M. Weitz, and T.W. Hänsch. Phys. Rev. Lett. **80**, 468 (1998)

Precision of Theory

Total transition frequency (optical):

- QED effects
- H: ~10 kHz, He: ~1 MHz, Li: > 10 MHz

Isotope shift:

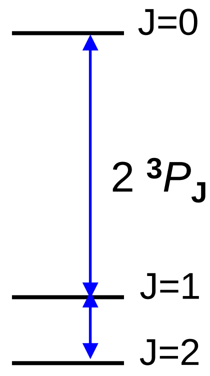
- Nuclear charge radius
- H: ~1 kHz, He: ~1 kHz, Li: ~10 kHz

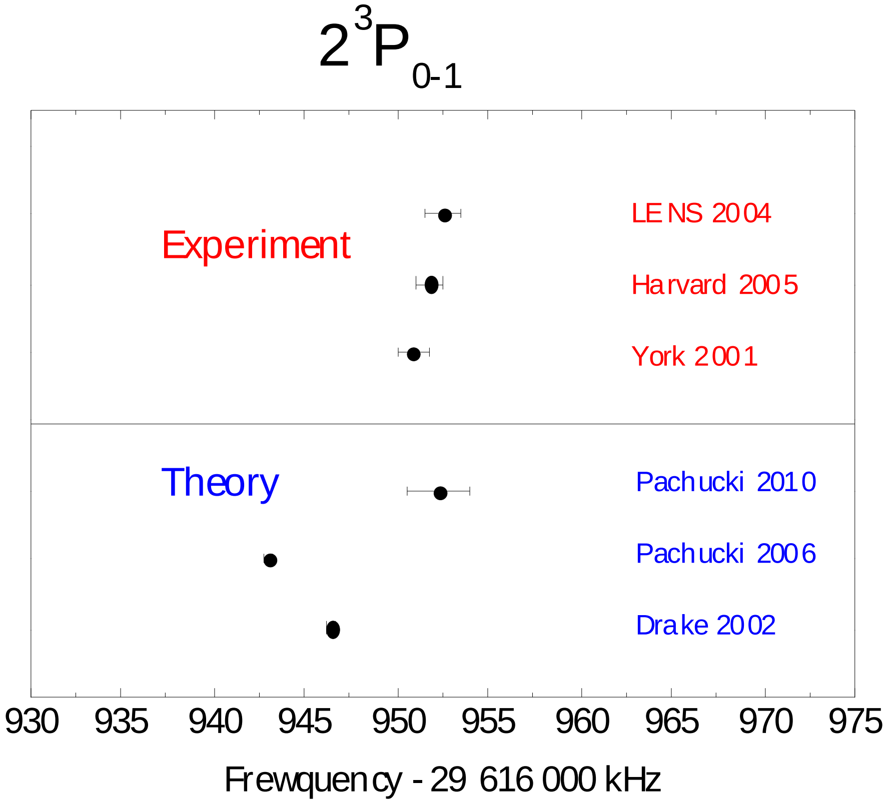
Fine and hyperfine structure :

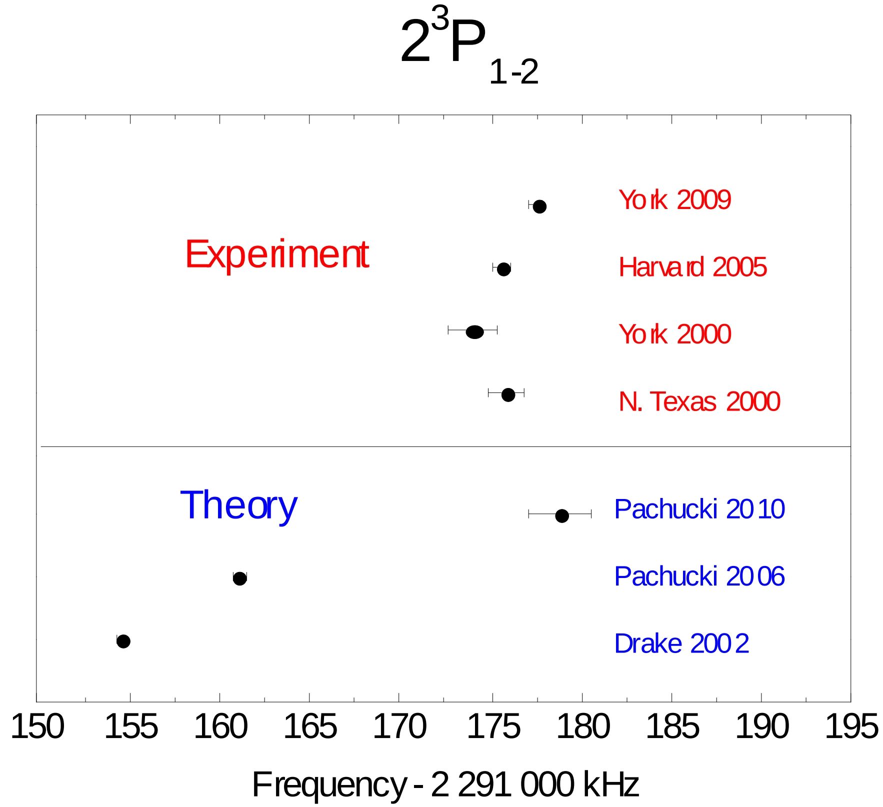
- State mixing, find hyperfine constant
- H: <1 kHz, He: <1 kHz, Li: several kHz

Previous attempt for helium FS

- uncertainty of theory and exp ~ 1 kHz
- Discrepancy = 10 kHz and 20 kHz for 10 years
- Include high-order terms ($\alpha^5 Ry$)



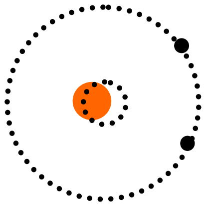




Isotope shift

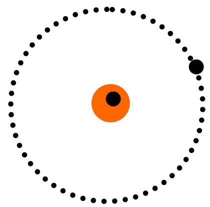
Isotope Shift $\delta\nu = \delta\nu_{MS} + \delta\nu_{FS}$

Mass shift: due to nucleus recoil



$$\delta\nu_{MS} \propto \frac{A - A'}{AA'}$$

Field shift: due to nuclear size



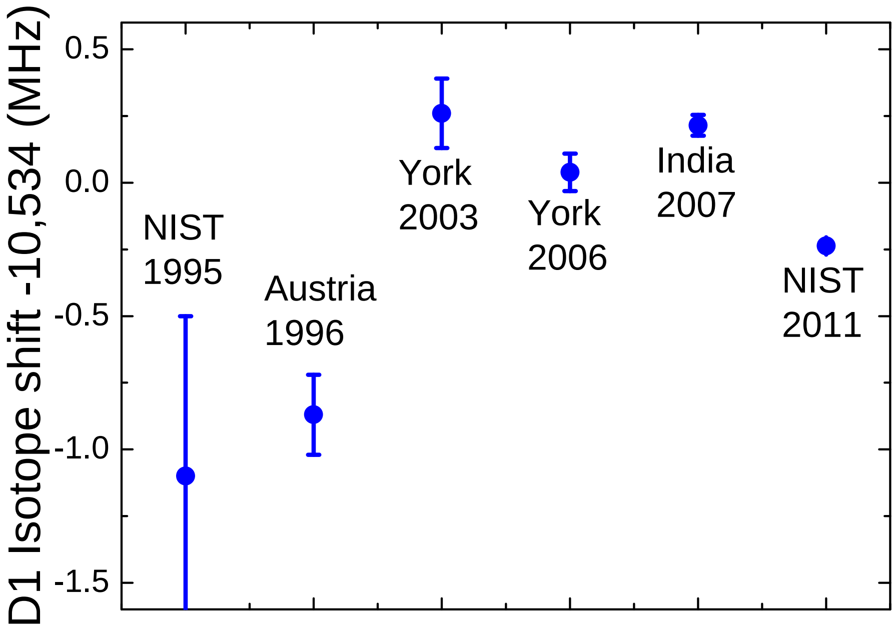
$$\delta\nu_{FS} \propto [\Psi(0)]^2 \times \delta < r_c^2 >$$

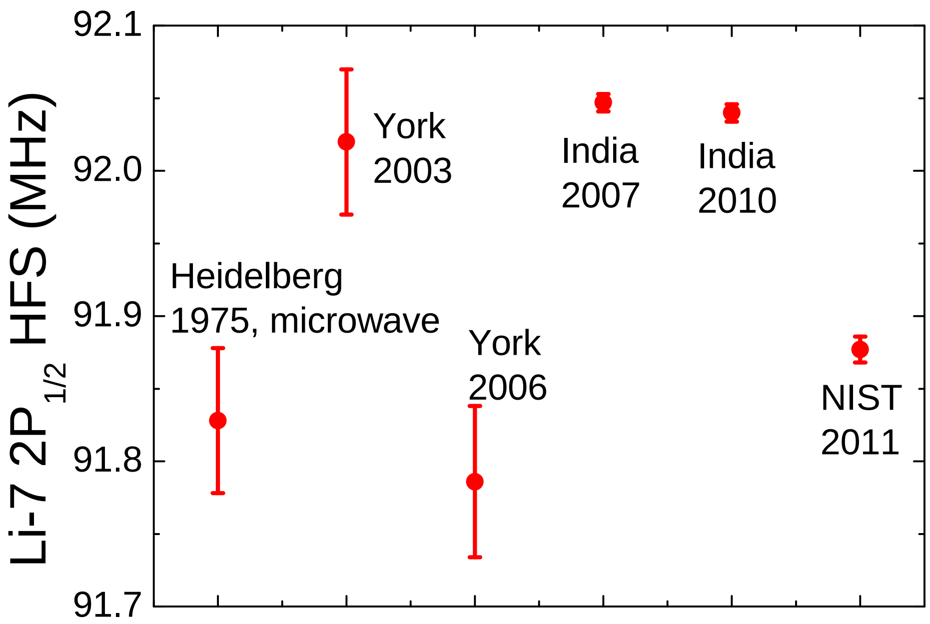
Nuclear mass precisely known

Atomic structure $\Psi(0)$ calculable,
H, He, Li.

This method widely used in H-D, ^{4}He-^{3}He, and ^{6}Li-^{7}Li and determine the difference in the nuclear size

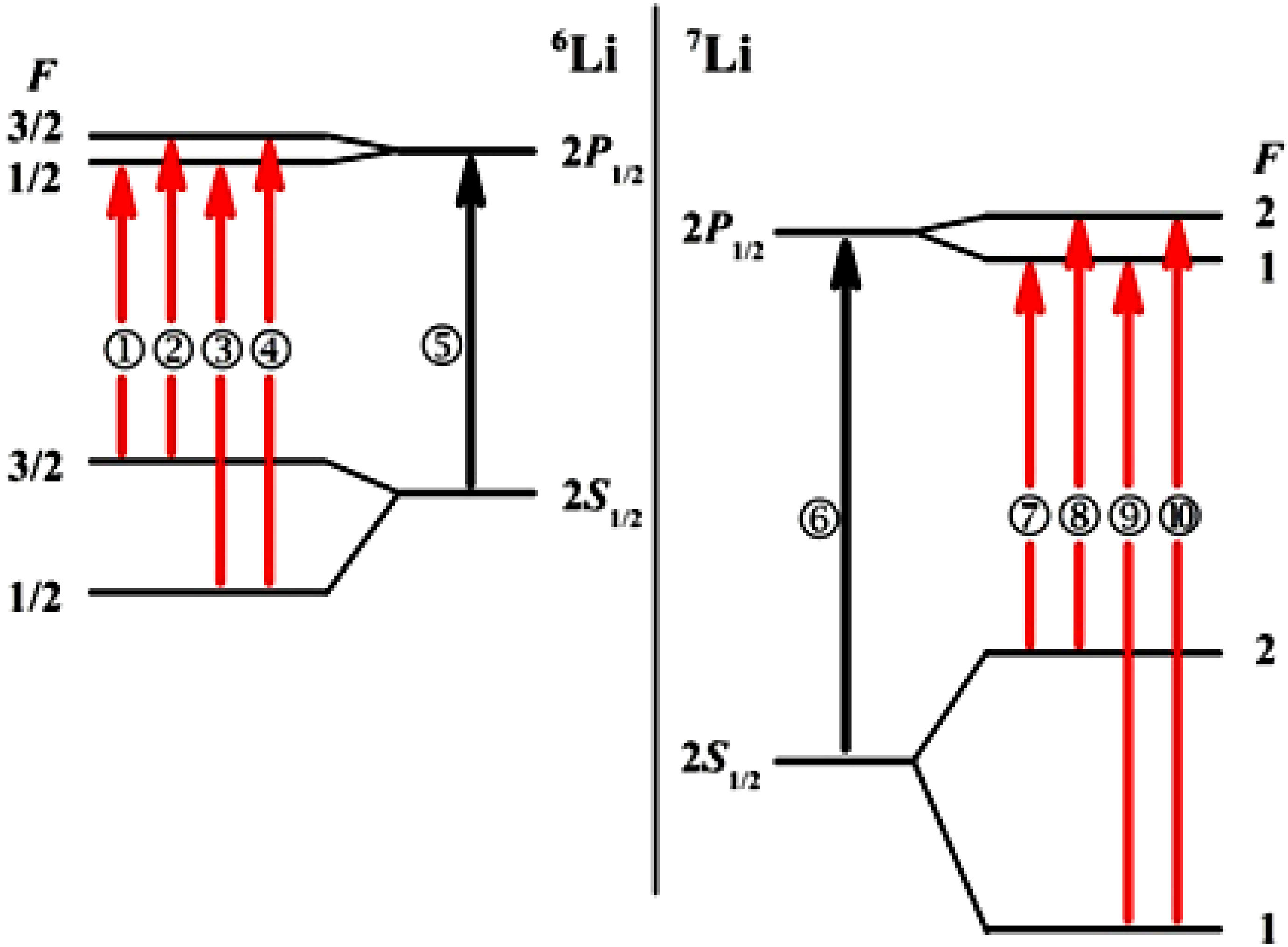
Discrepancy in lithium D1 line



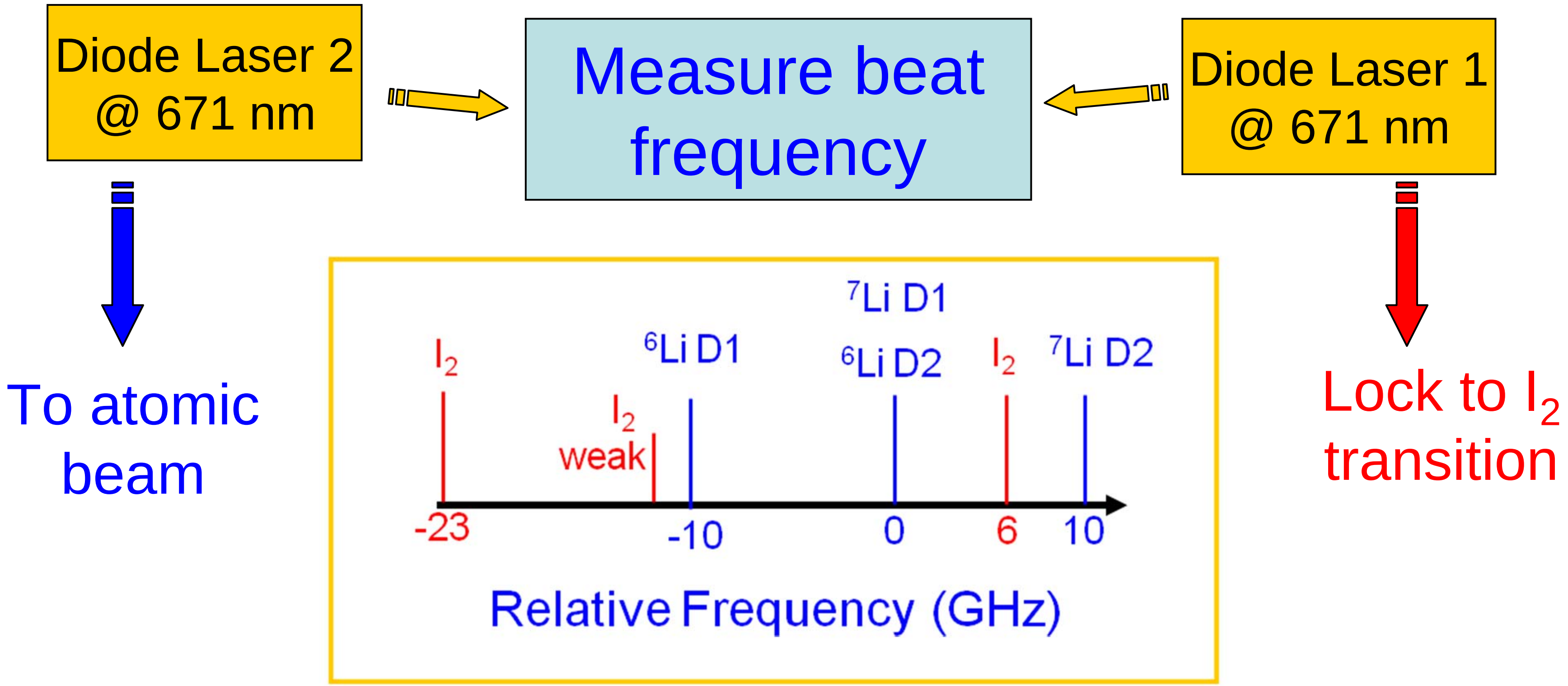


- Isotope shift: different velocity may cause systematic effect
- FS and HFS in one isotope: almost immune to beam alignment

- Spectroscopy of lithium D lines at NTHU



Our approach



Iodine spectrometer

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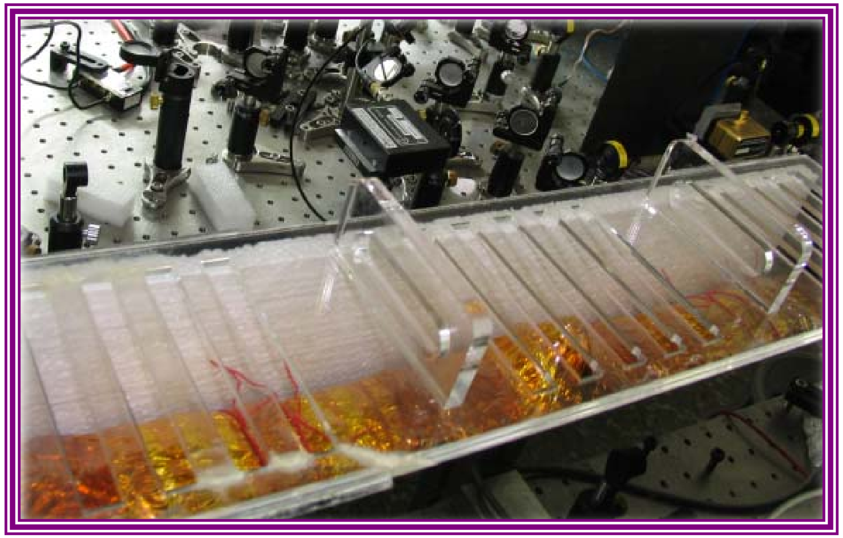
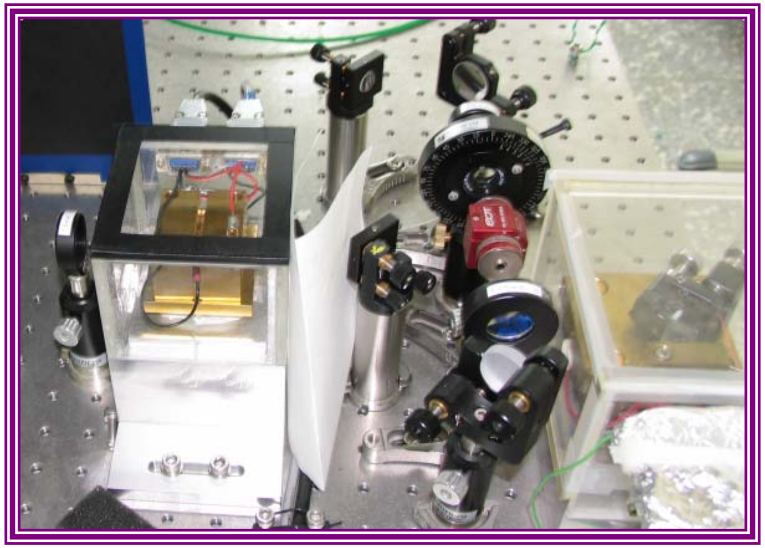
- Frequency modulation transfer saturation spectroscopy





Absolute frequency measurement

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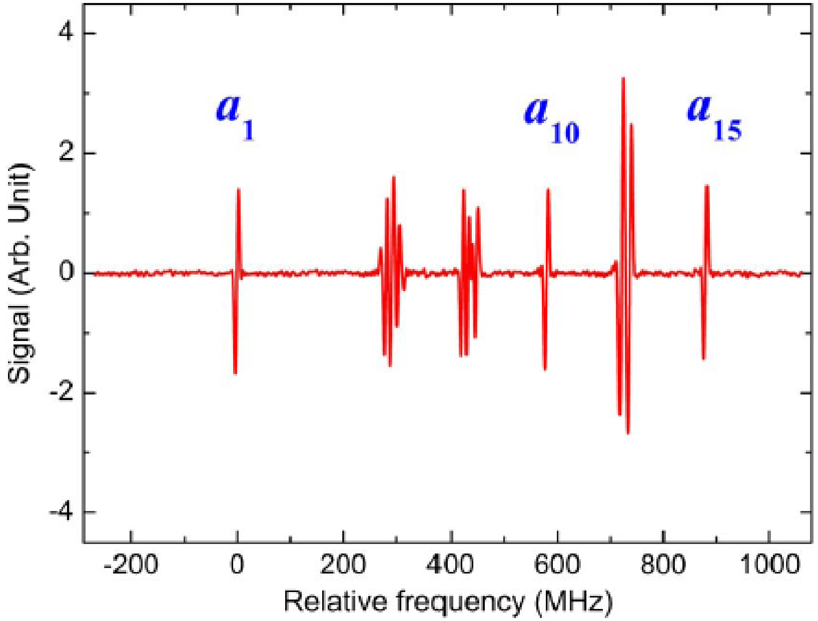
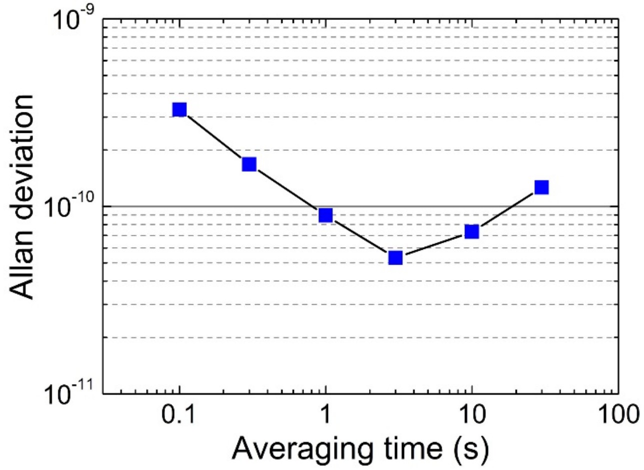
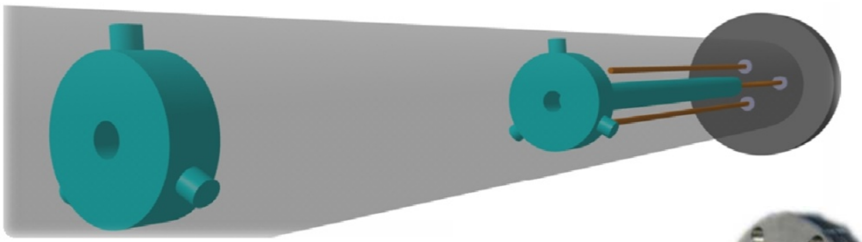


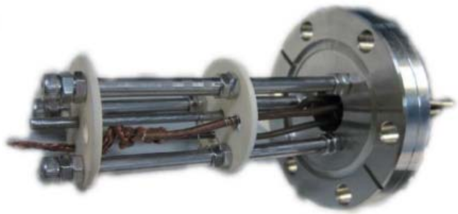


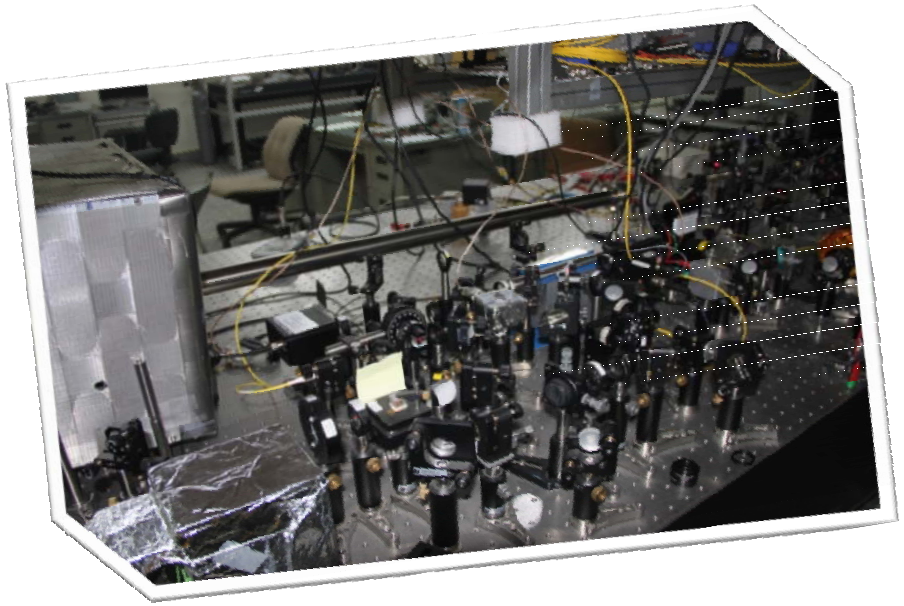
	Measured[a]	Calculated	*Measured – Calculated*
a_1	446,806,191,890(25)	446,806,194,569	–2, 679
a_{10}	446,806,778,950(35)	446,806,781,526	–2, 576
a_{15}	446,807,072,638(24)	446,807,075,266	–2, 628
$a_{15} - a_1$	880,748(35)	880,697	51(35)
$a_{15} - a_{10}$	293,688(42)	293,740	–52(42)
$a_{10} - a_1$	587,060(43)	586,957	103(43)

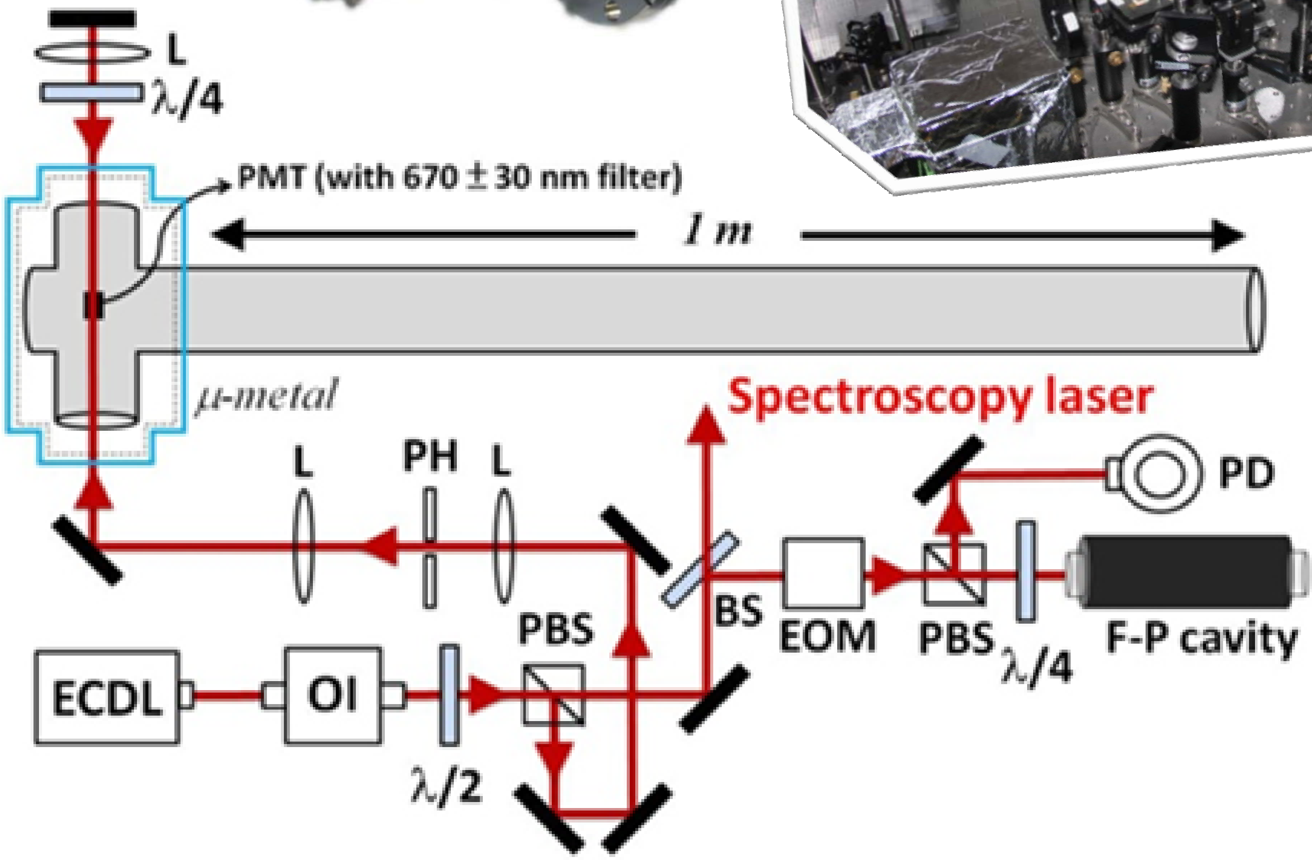
Y.-C. Huang et al., *Appl. Opt.* **52**, 1448-1452 (2013)

Experimental setup

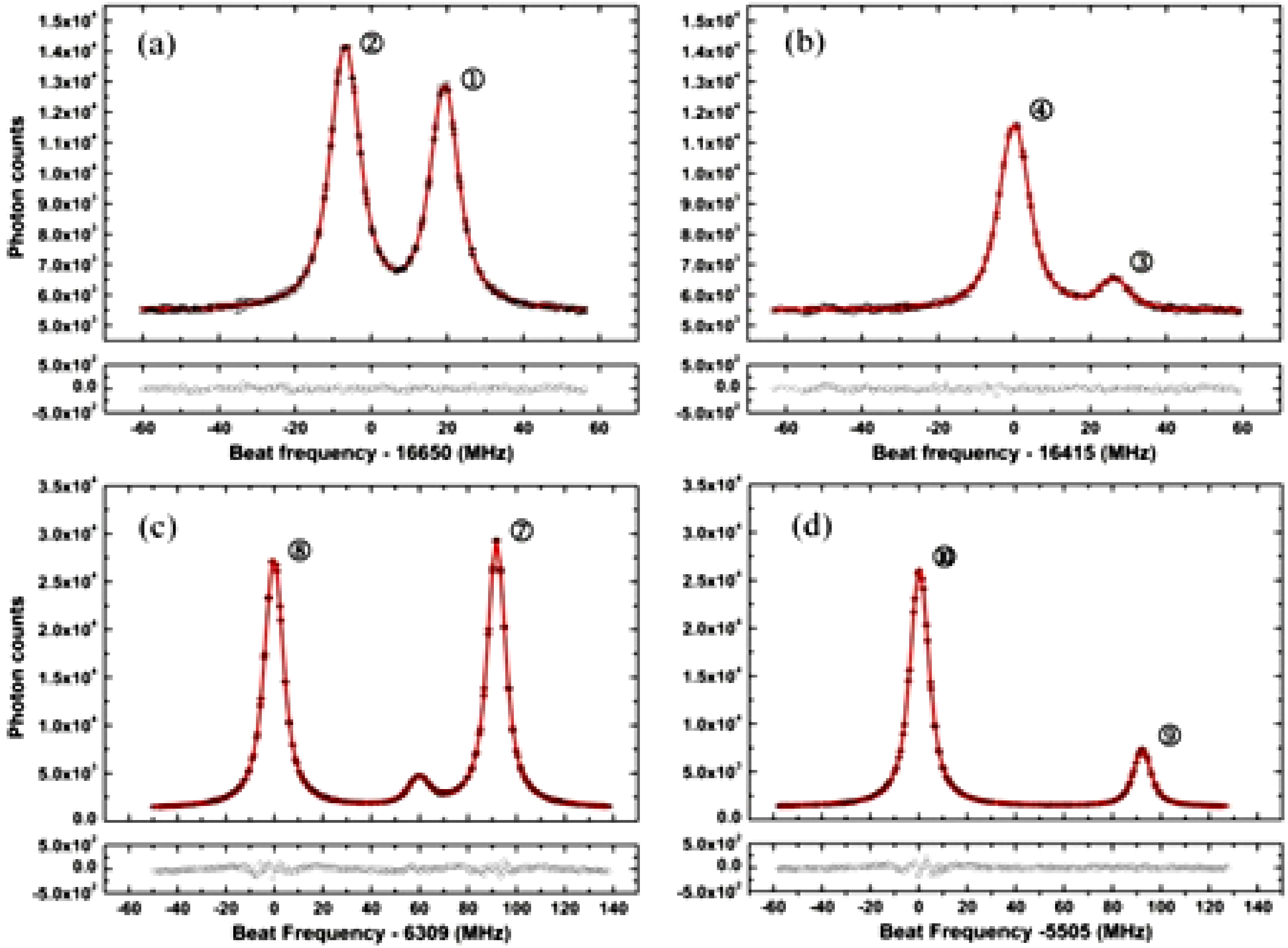








Typical signal for lithium-7



Laser power dependence

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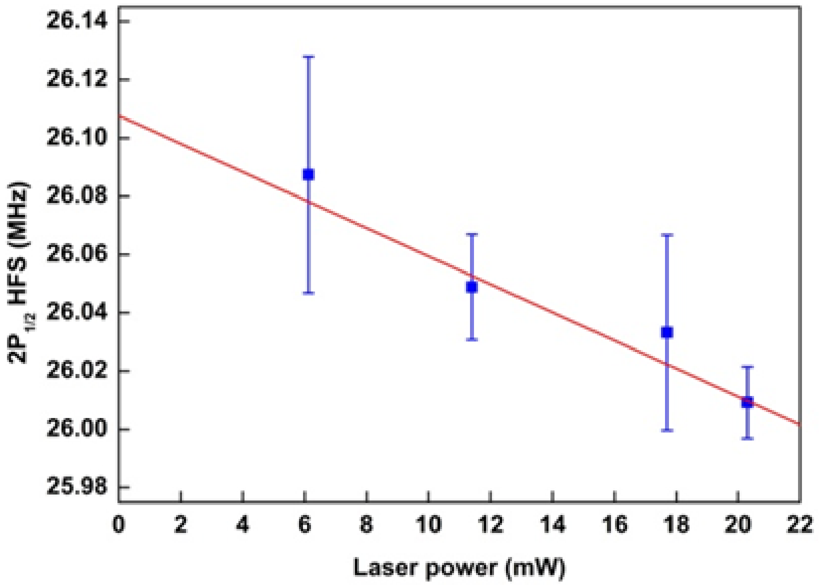
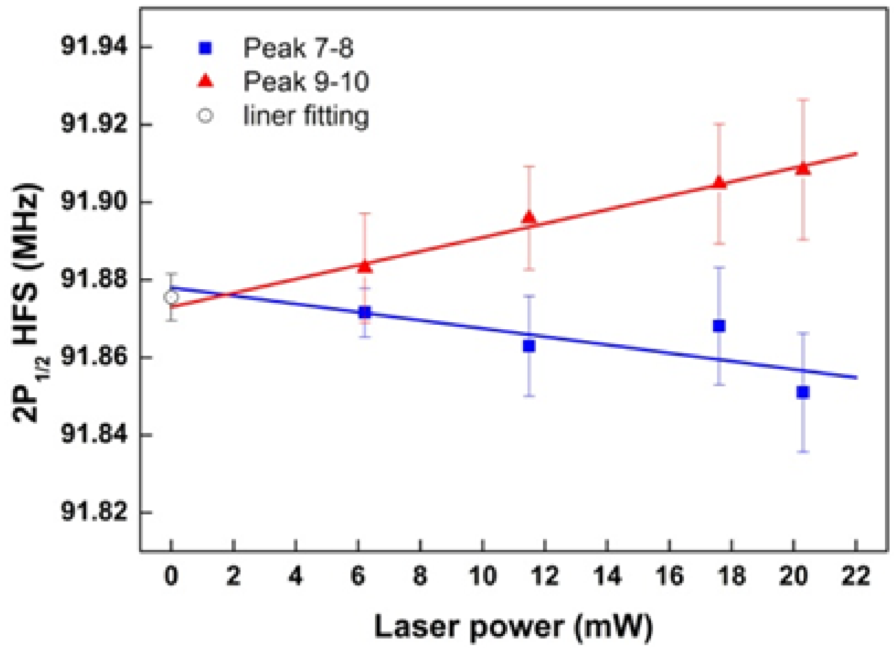
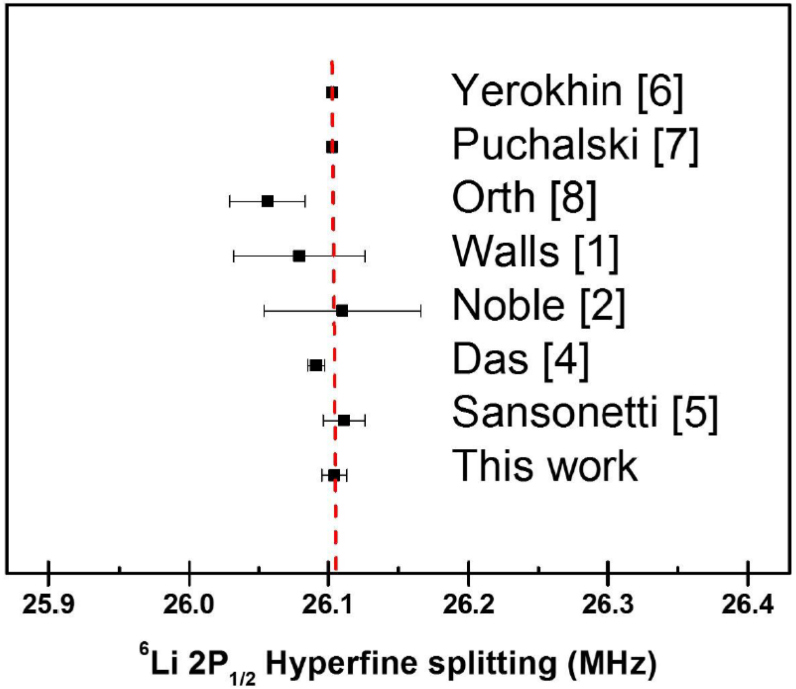
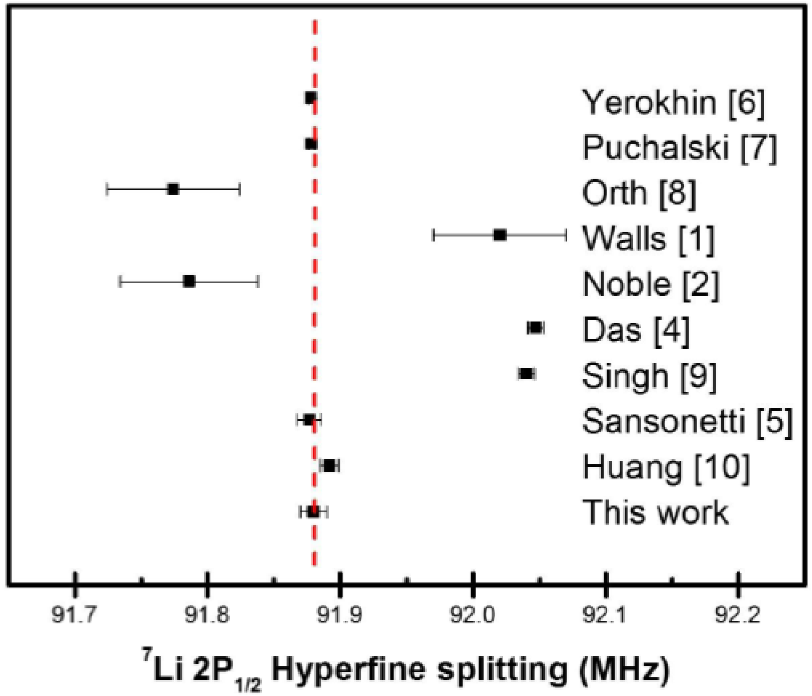


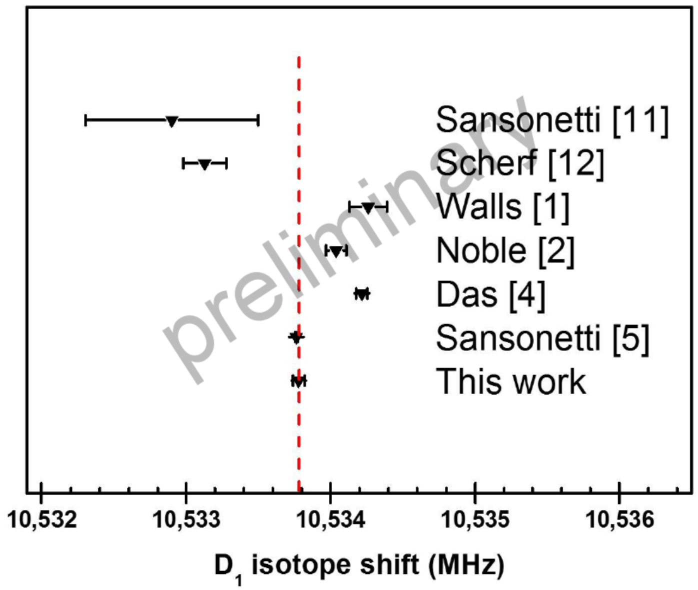


- AC Stark effect from other levels
- Photon momentum → cooling or heating
- Optical pumping

Results


Yerokhin [6]
Puchalski [7]
Orth [8]
Walls [1]
Noble [2]
Das [4]
Sansonetti [5]
This work
25.9
26.0
26.1
26.2
26.3
26.4
6Li 2P1/2 Hyperfine splitting (MHz)

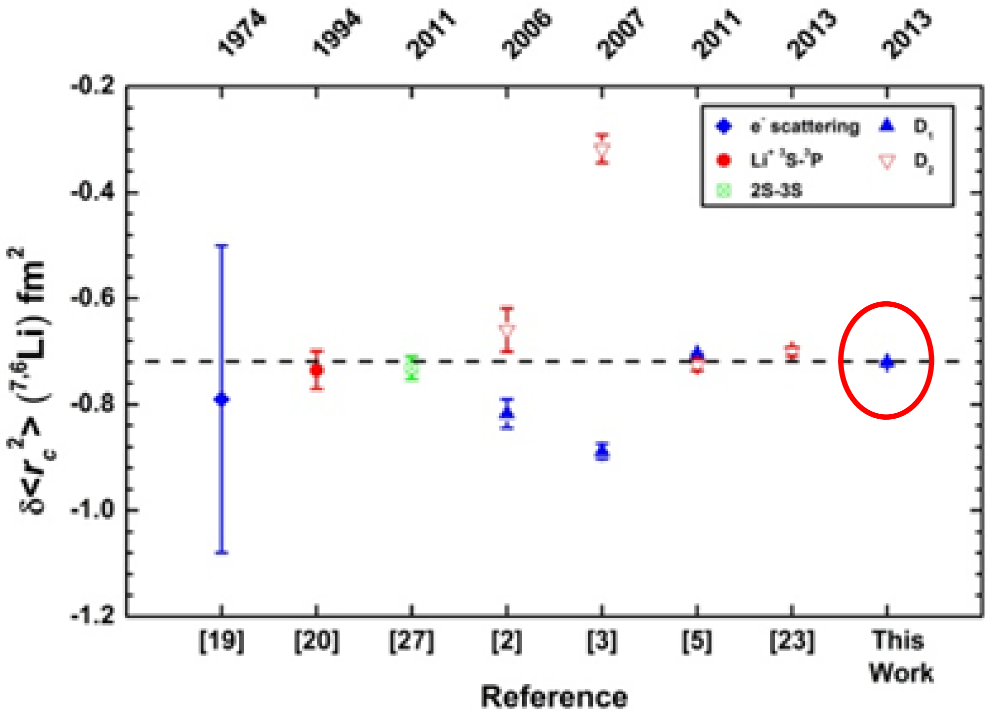

Yerokhin [6]
Puchalski [7]
Orth [8]
Walls [1]
Noble [2]
Das [4]
Singh [9]
Sansonetti [5]
Huang [10]
This work
91.7
91.8
91.9
92.0
92.1
92.2
7Li 2P1/2 Hyperfine splitting (MHz)


Sansonetti [11]
Scherf [12]
Walls [1]
Noble [2]
Das [4]
Sansonetti [5]
This work
preliminary
10,532
10,533
10,534
10,535
10,536
D1 isotope shift (MHz)

Results for charge radius

- IS, HFS in D1 of Li-6,7 measured

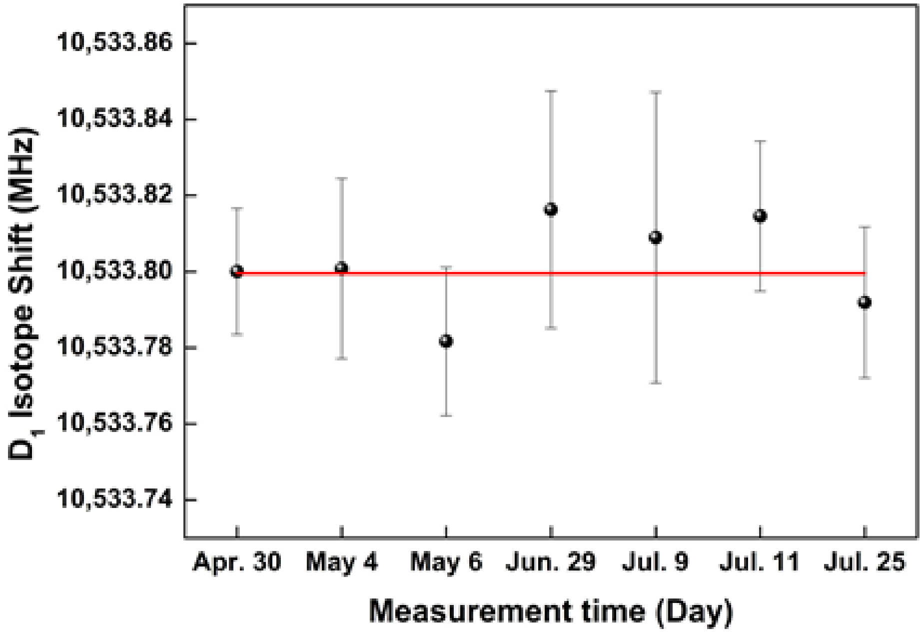
D_1 IS (MHz)	Reference	Year
10 533.800(8)	This work	2013
10 533.763(9)	Sansonetti	2011
10 534.215(39)	Das	2007
10 534.039(70)	Noble	2006
10 533.160(68)	Bushaw	2003
10 534.26(13)	Walls	2003
10 533.13(15)	Scherf	1996



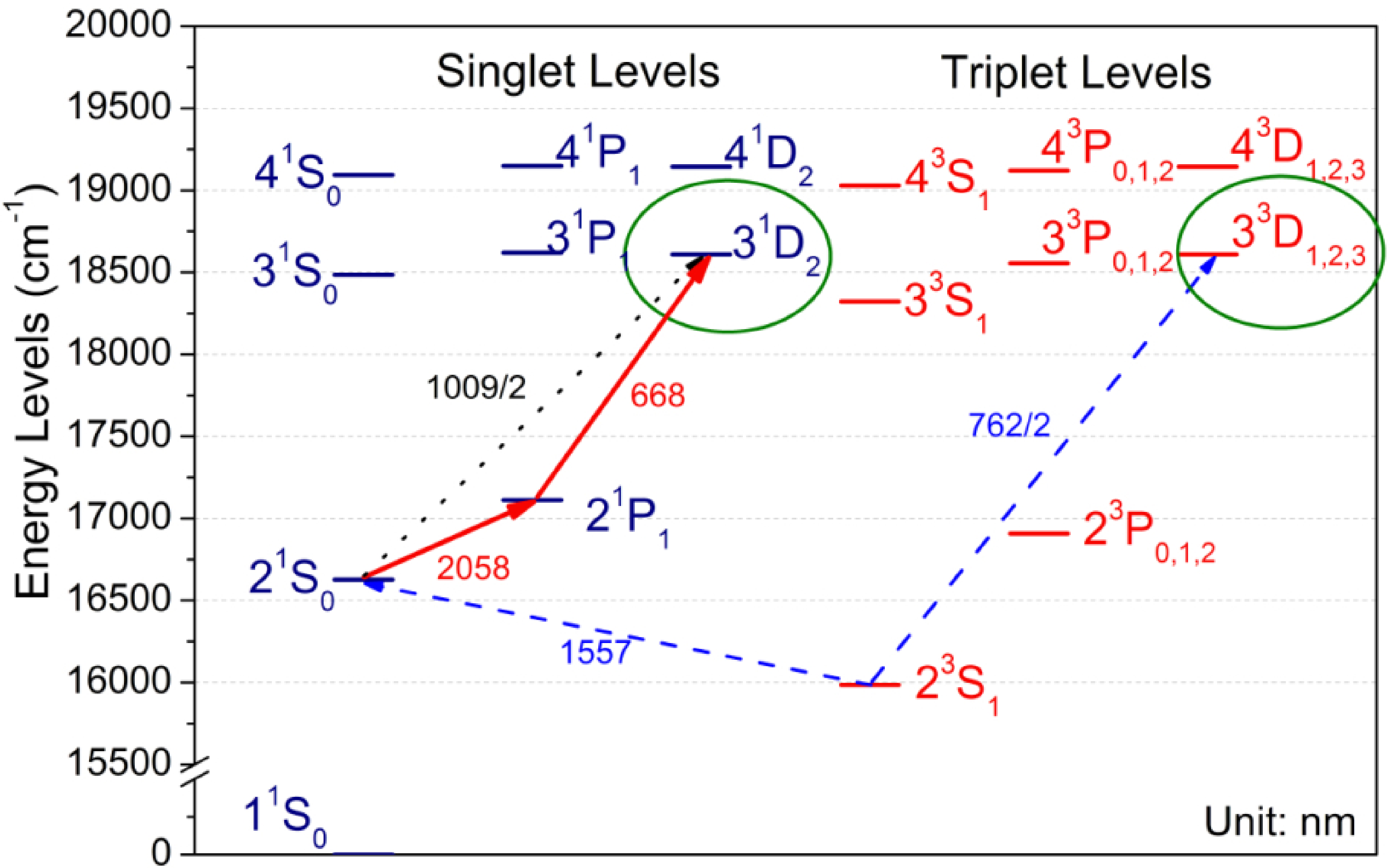
Y.-C. Huang et al., *J. Phys. B: At. Mol. Opt. Phys.* **46**, 075004 (2013)

Error Budgets

Source	^{7}Li		^{6}Li		Isotope shift
	$2S_{1/2}$	$2P_{1/2}$	$2S_{1/2}$	$2P_{1/2}$	
statistical	12	8	13	8	10
Reference laser instability	16	-	13	-	21
Laser power variation	1	0.5	1	0.5	1.5
First-order Doppler effect	2	<1	<1	<1	20
Zeeman shift	<1	<1	<1	<1	<1
Total	20	8	18	8	31



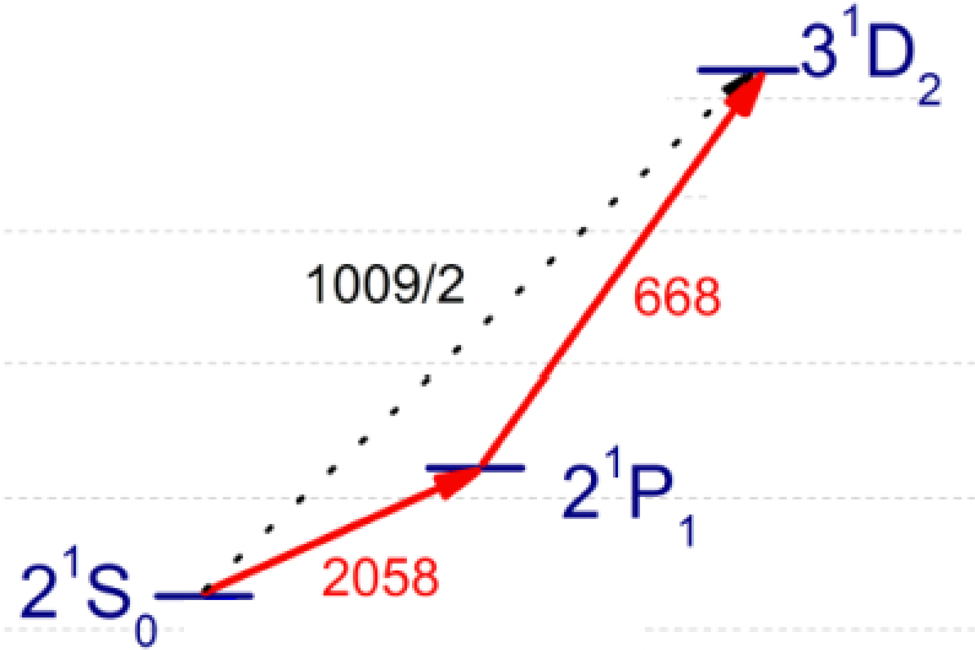
Helium spectroscopy



Motivation

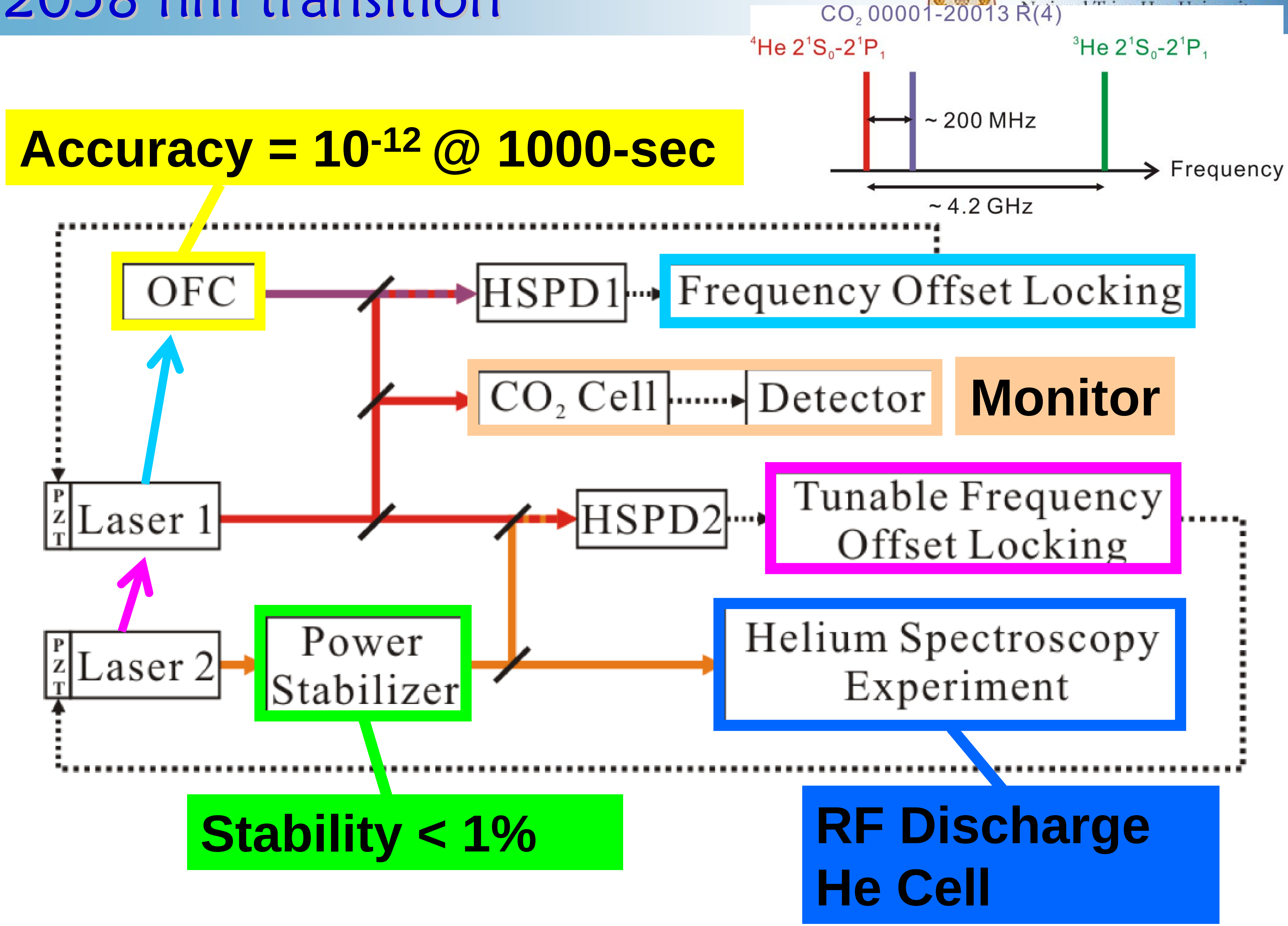
- Better theory
- Experiments mostly performed in triplet state
- Singlet-triplet forbidden transition probed

R. van Rooij et al., Science **333**, 196 (2011)

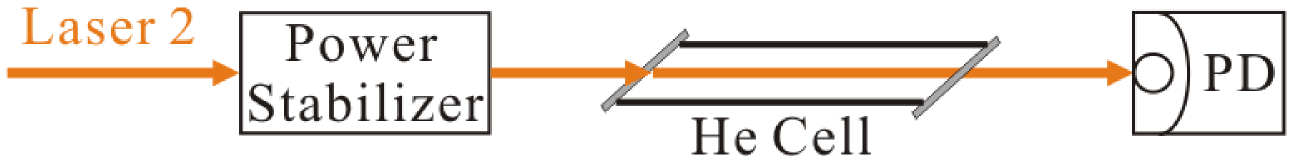


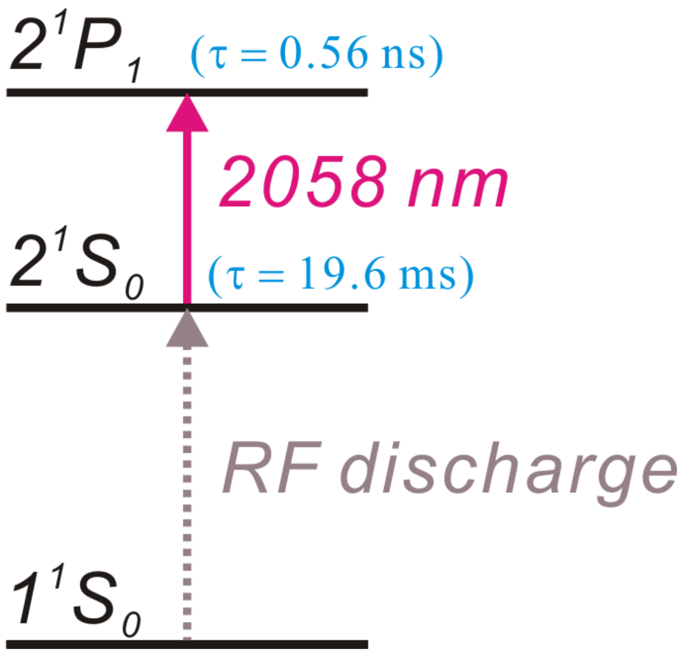
2058 nm transition

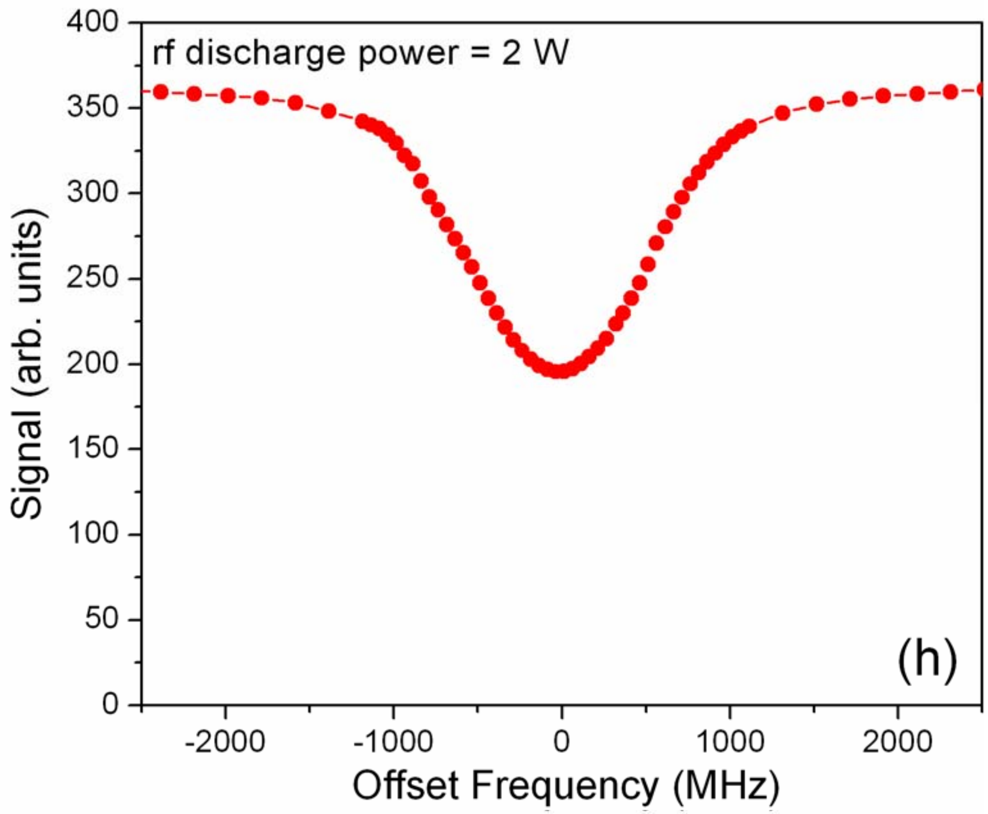
Department of Physics



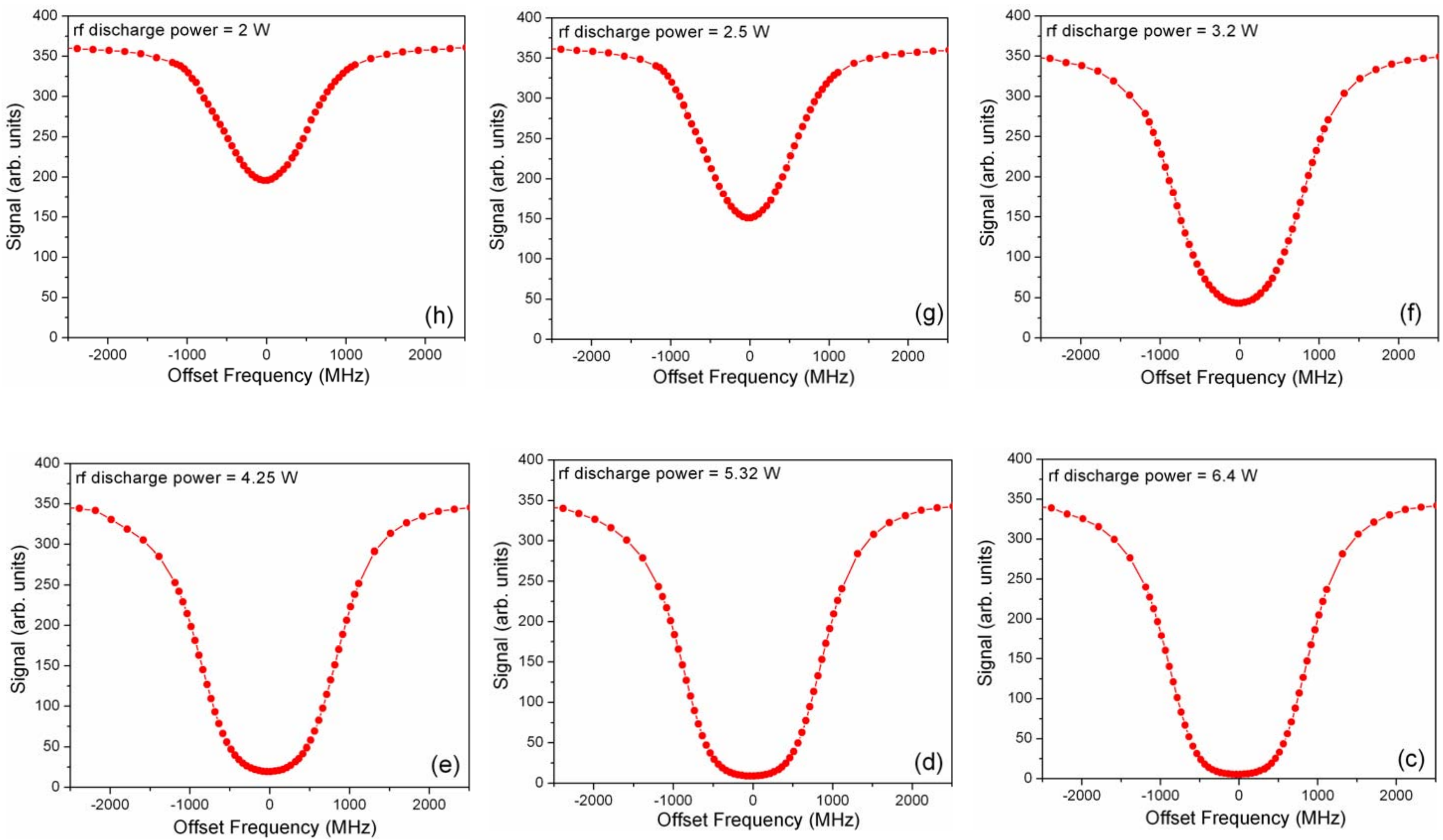
Direct Absorption Spectrum



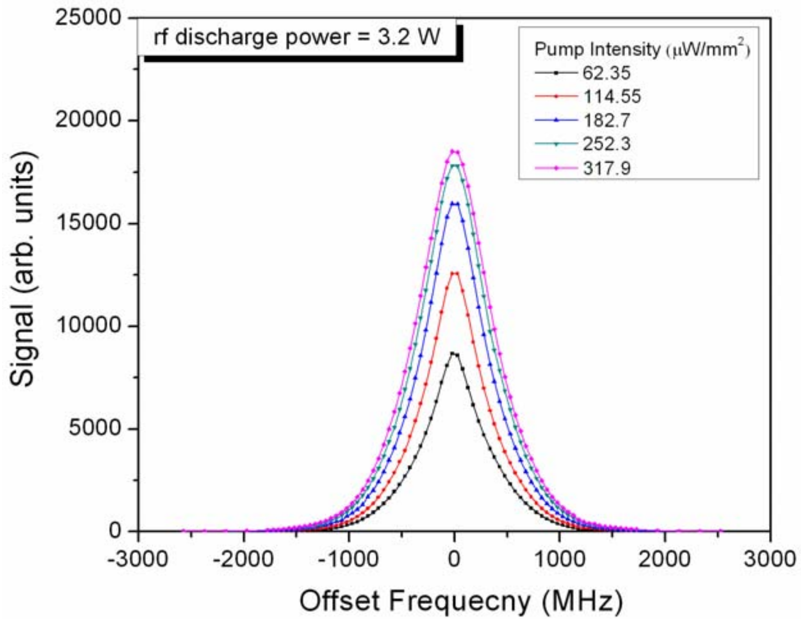


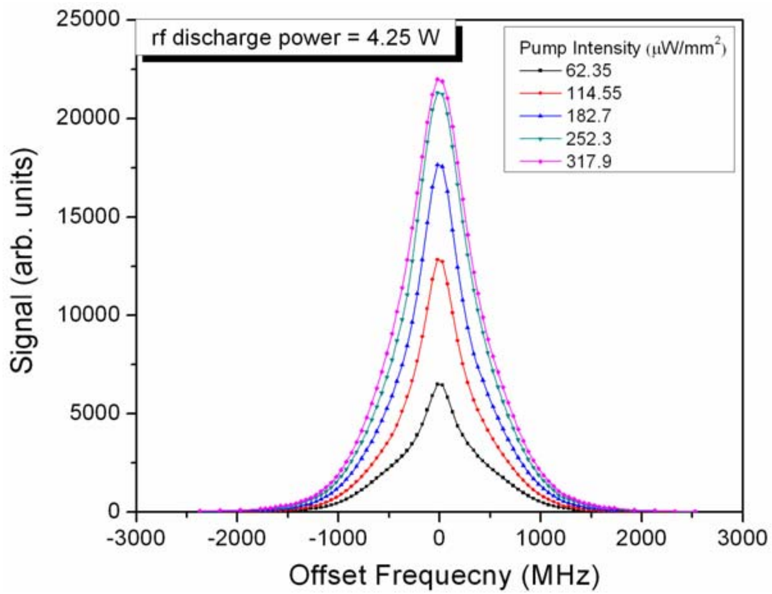


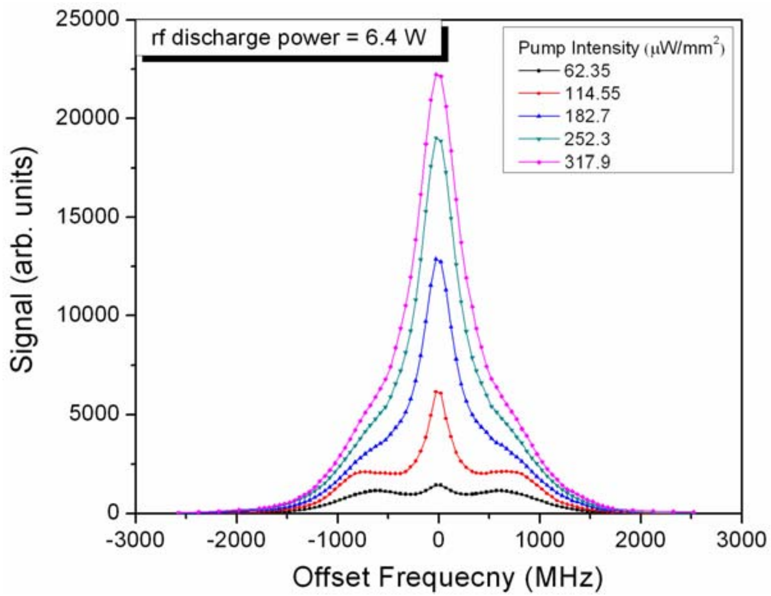
Direct Absorption Spectrum



Saturated Absorption Spectrum







Simulation of Saturated Absorption Spectra

Without Pump

$$I(\nu) = \mathrm{I}_0 \times Exp[-\kappa \times z]$$

$$\kappa = n_0 h \nu \alpha_0 \times \sqrt{\frac{m}{2\pi kT}} \times Exp\left[-\frac{mc^2(\nu-\nu_0)^2}{2kT{\nu_0}^2}\right] \times \frac{c}{\nu_0} \times \frac{\pi\Gamma_0}{2}$$

With Pump

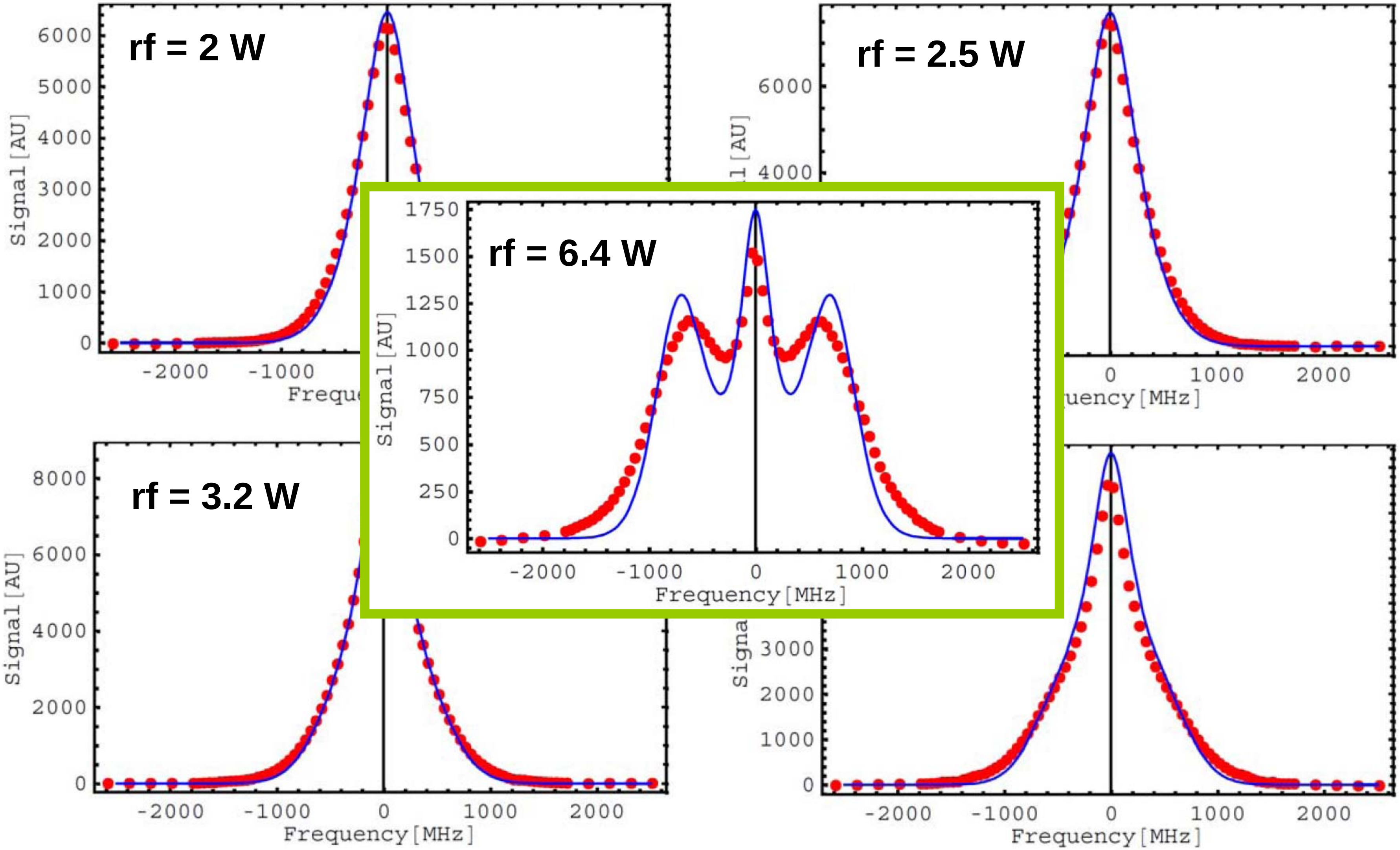
$$I(\nu)' = \mathrm{I}_0 \times Exp[-\kappa' \times z]$$

$$\kappa' = n_0 h \nu \alpha_0 \times \sqrt{\frac{m}{2\pi kT}} \times Exp\left[-\frac{mc^2(\nu-\nu_0)^2}{2kT{\nu_0}^2}\right] \times \frac{c}{\nu_0} \times F(\nu-\nu_0)$$

Amplitude Modulation Transfer Signal

$$S_{AMT} = A_0\left(Exp[-\kappa' \times z] - Exp[-\kappa \times z]\right)$$

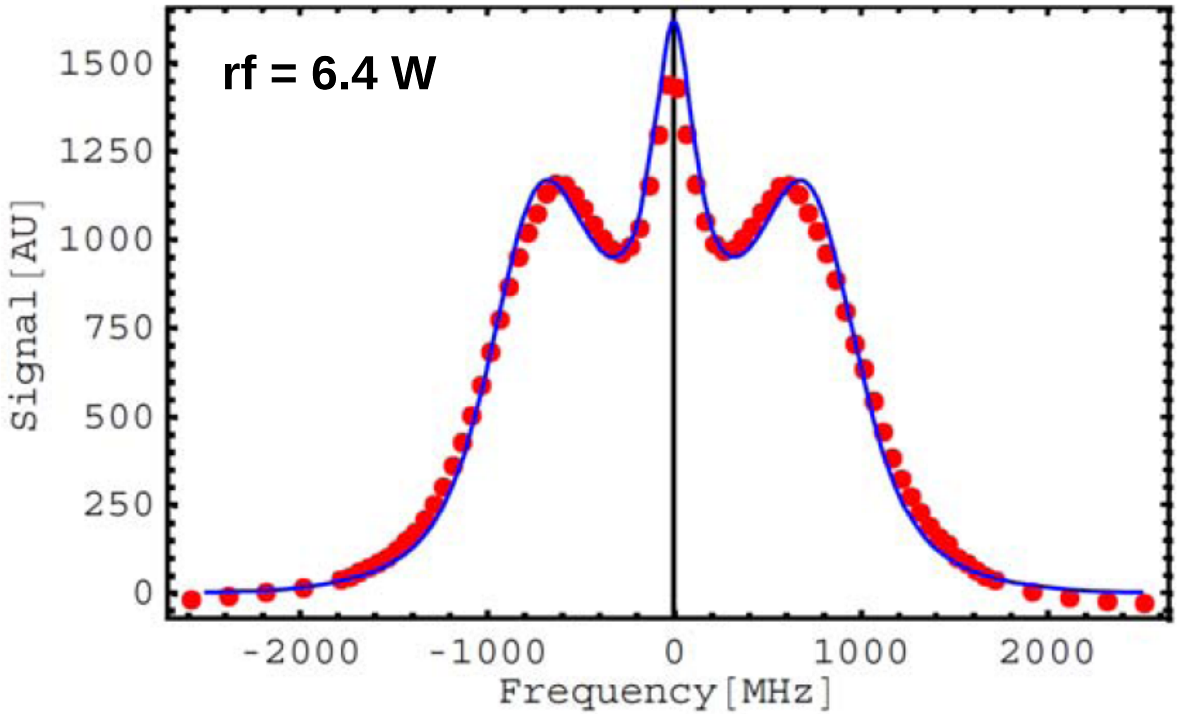
Simulation


rf = 2 W
rf = 2.5 W
rf = 3.2 W
rf = 6.4 W
Signal [AU]
Frequency [MHz]
1750
1500
1250
1000
750
500
250
0
-2000
-1000
0
1000
2000
8000
6000
5000
4000
3000
2000

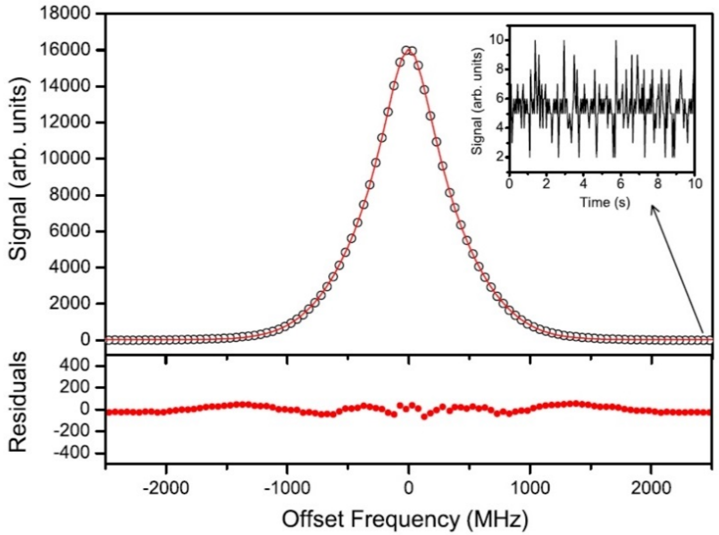
Simulation of Saturated Absorption Spectra

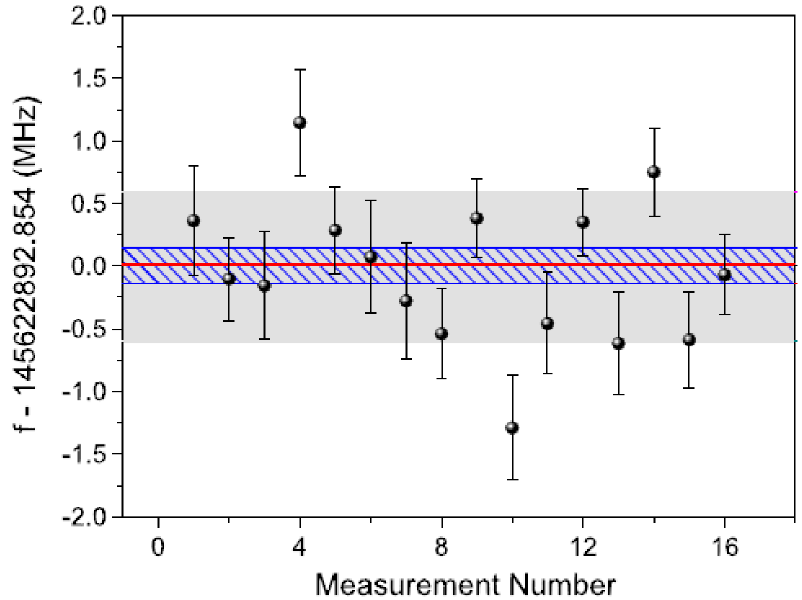
$$S'_{AMT} = A_0\left(Exp[-\kappa' \times z] - Exp[-\kappa \times z]\right) + B_0\left(Exp[4\ln 2\frac{(\nu-\nu_0)^2}{\delta_G{}^2}]\right)$$

Velocity-Changing Collision

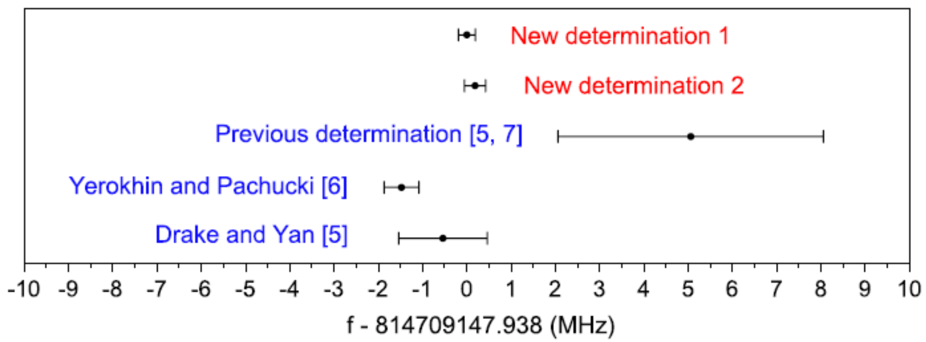


Spectroscopic results





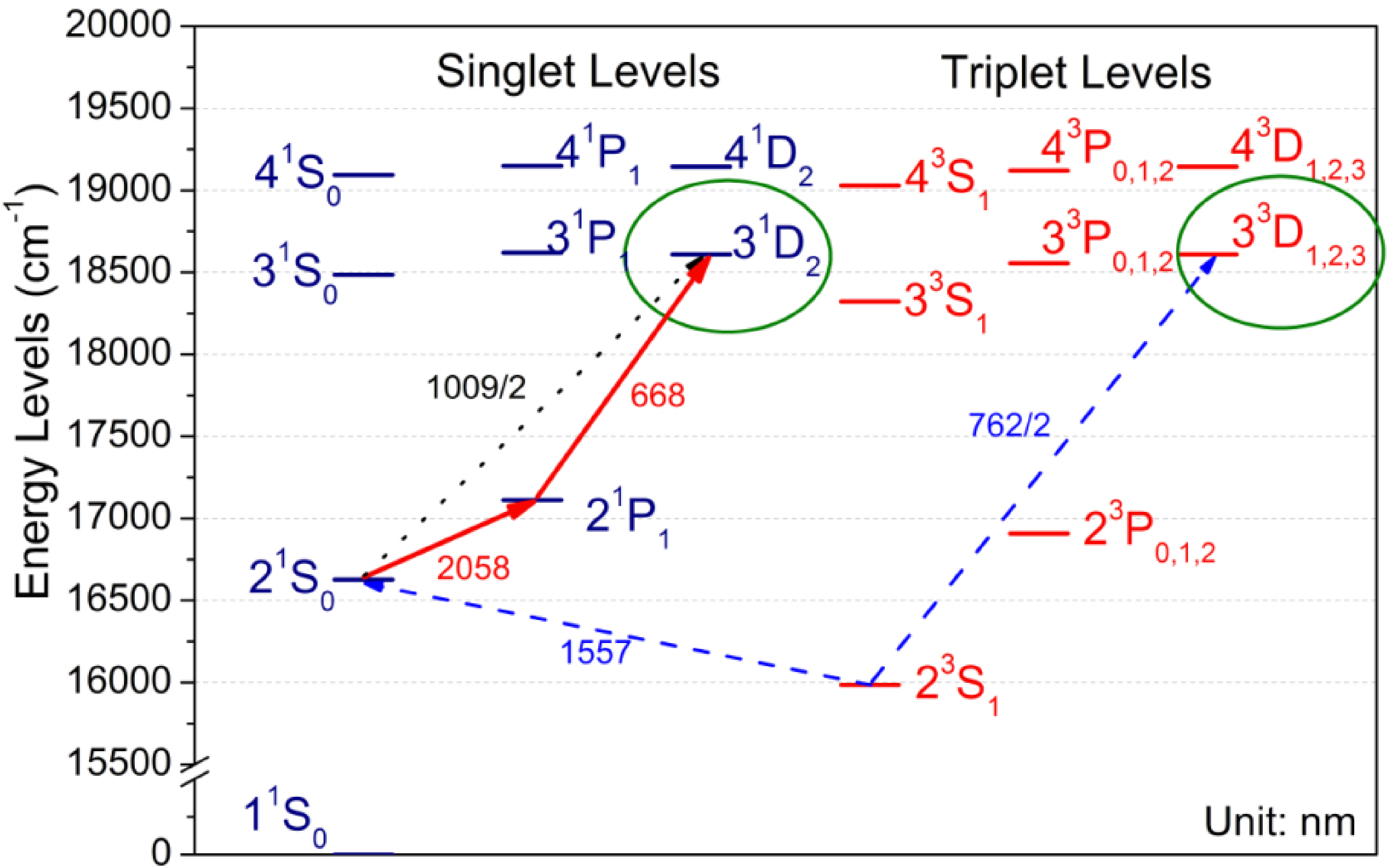
Source	kHz
Statistical error	141
OFC accuracy	<5
Frequency locking stability of laser 1 and OFC	<5
Frequency offset locking stability of two lasers	<2
Pressure shift	9.3
Light intensity	66
rf discharge power	82
Zeeman effect	<7
Overall uncertainty	183



P.-L. Luo et al., *Phys. Rev. Lett.* **111**, 013002 (2013)

- First absolute frequency measurement on this transition
- 10 time more precise in isotope shift

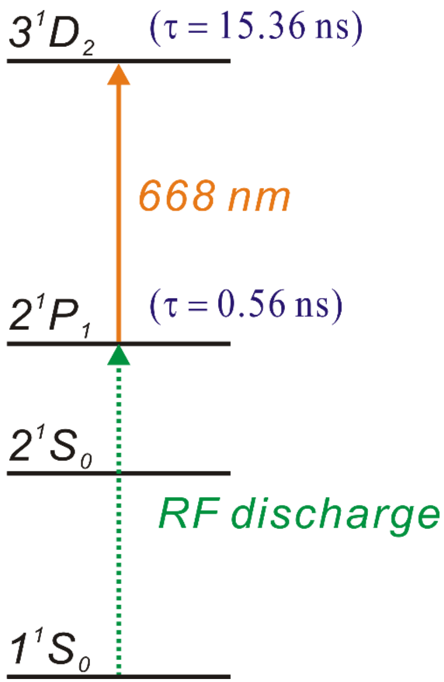
Helium spectroscopy

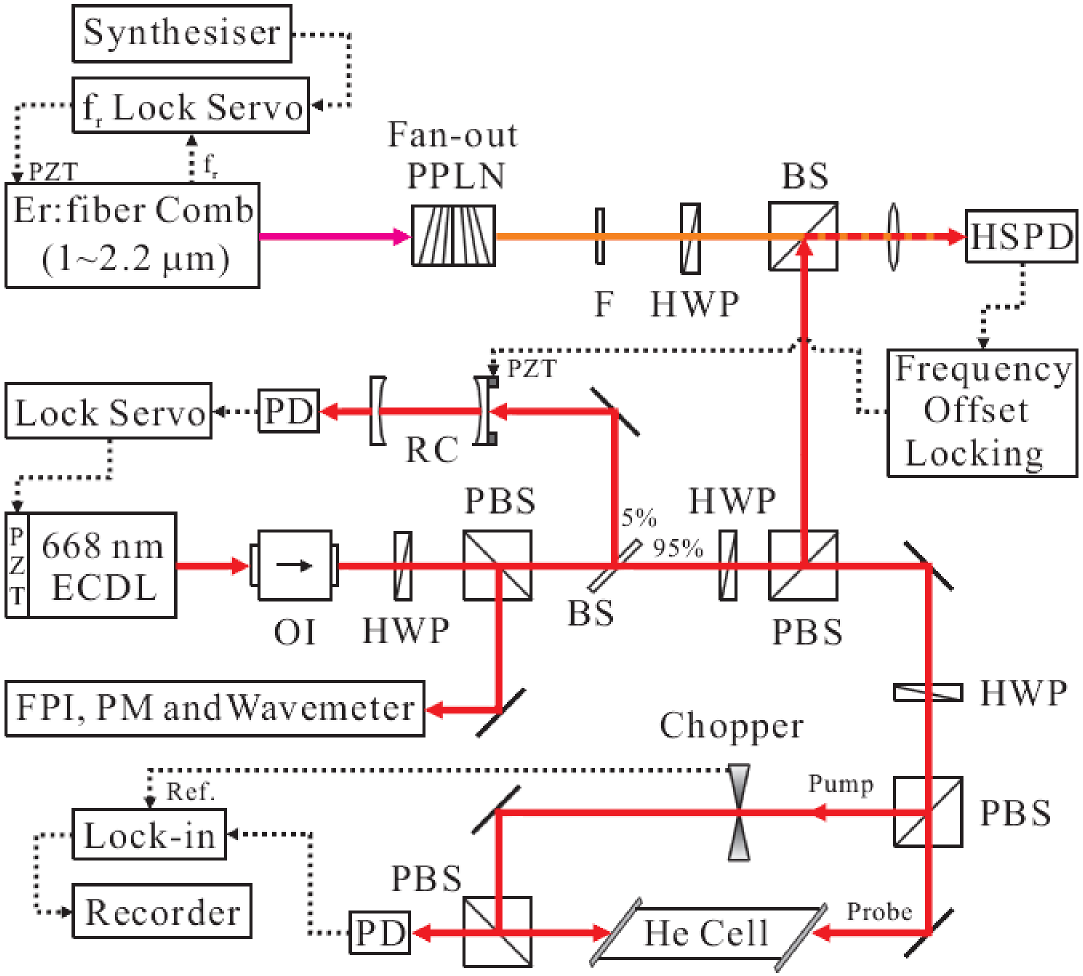


668 nm transition

Department of Physics
National Tsing Hua University

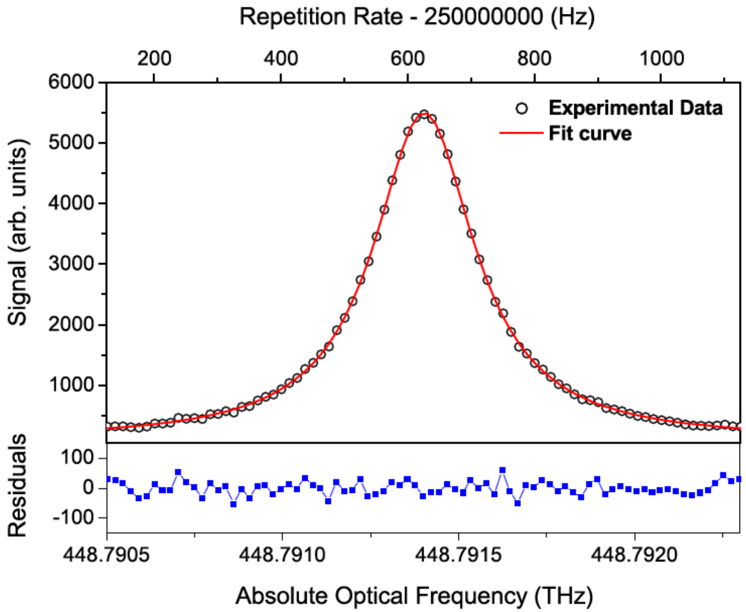
- ECDL at 668 nm locked to frequency comb
- Comb → PPLN, change rep rate

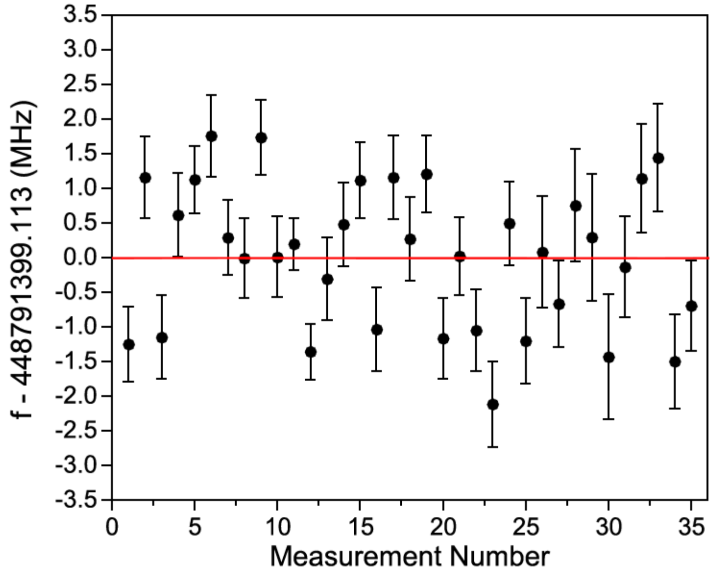




$$f_L = n \times f_r + 2 \times f_o \pm f_b$$

Results





Source	shift	uncertainty
Statistical error	0	177
OFC accuracy	0	<5
Frequency locking of ECDL and OFC	0	<5
Pressure shift	0	192
Zeeman effect	0	<7
Overall	0	268

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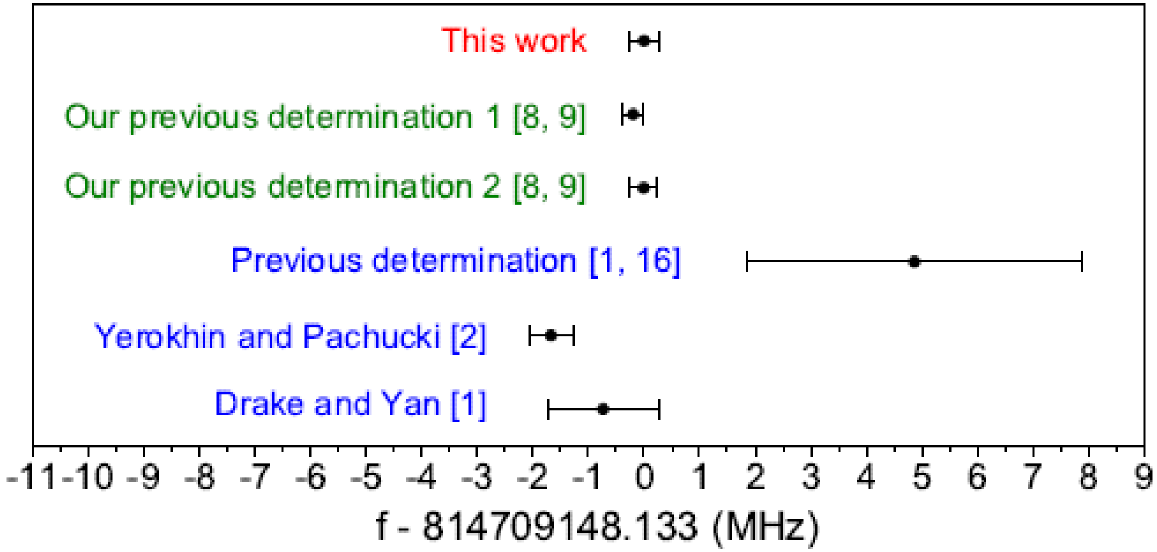
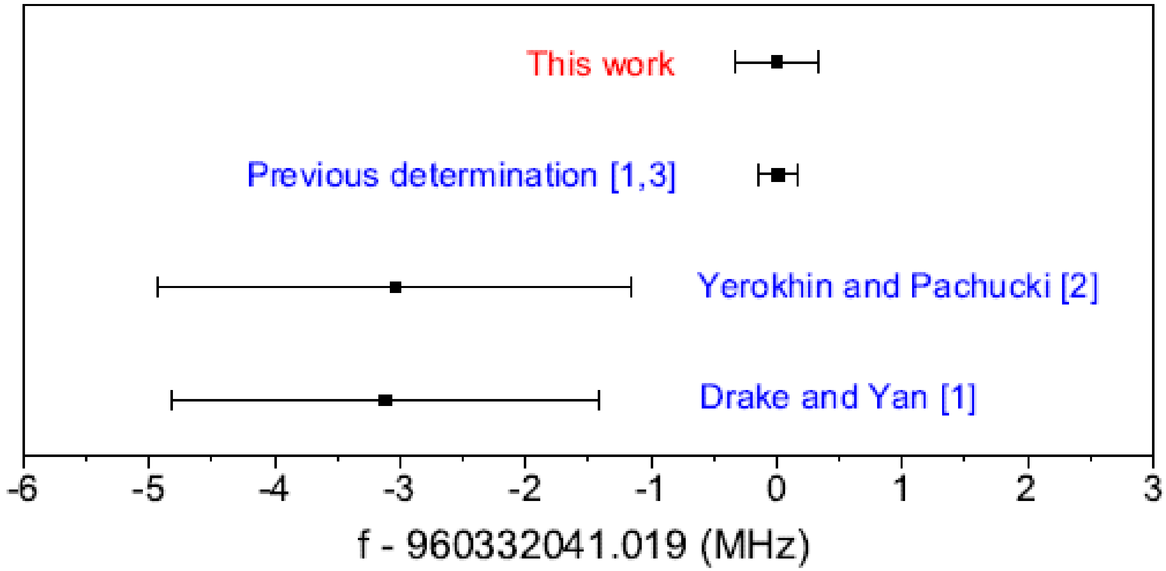
10 time more precise than previous measurement

Ionization energy



2P



2S

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PHYSICS FOCUS

Precision Laser Spectroscopy of Helium Testing QED Atomic Calculations

Helium is the simplest multi-electron atom and has been the best testing ground for many-body QED atomic calculations. Unlike the hydrogen atom, for which analytical solutions exists, similar studies of helium requires extensive numerical calculations in order to determine its electronic structures. Precision laser spectroscopy of He can improve the theoretical value of Lamb shift and be used to determine the nuclear charge radii of helium.

Recently, researchers from a multi- had to control precisely many experimental parameters, e.g., laser power stability, magnetic field shielding, discharge condition, and helium gas pressure. Otherwise, any systematic error will limit the final precision of the measurement. A typical spectrum is shown in Fig. 2. This represents the first Doppler-free measurement of the $2^1S_0 \rightarrow 2^1P_1$ transition.

For the ionization energy of the 2^1P_1 state, a discrepancy of 3.5 σ with the most precise theoretical value is found. This is shown in Fig. 3. This

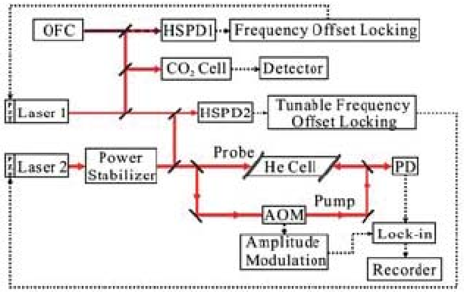
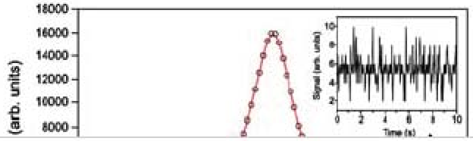
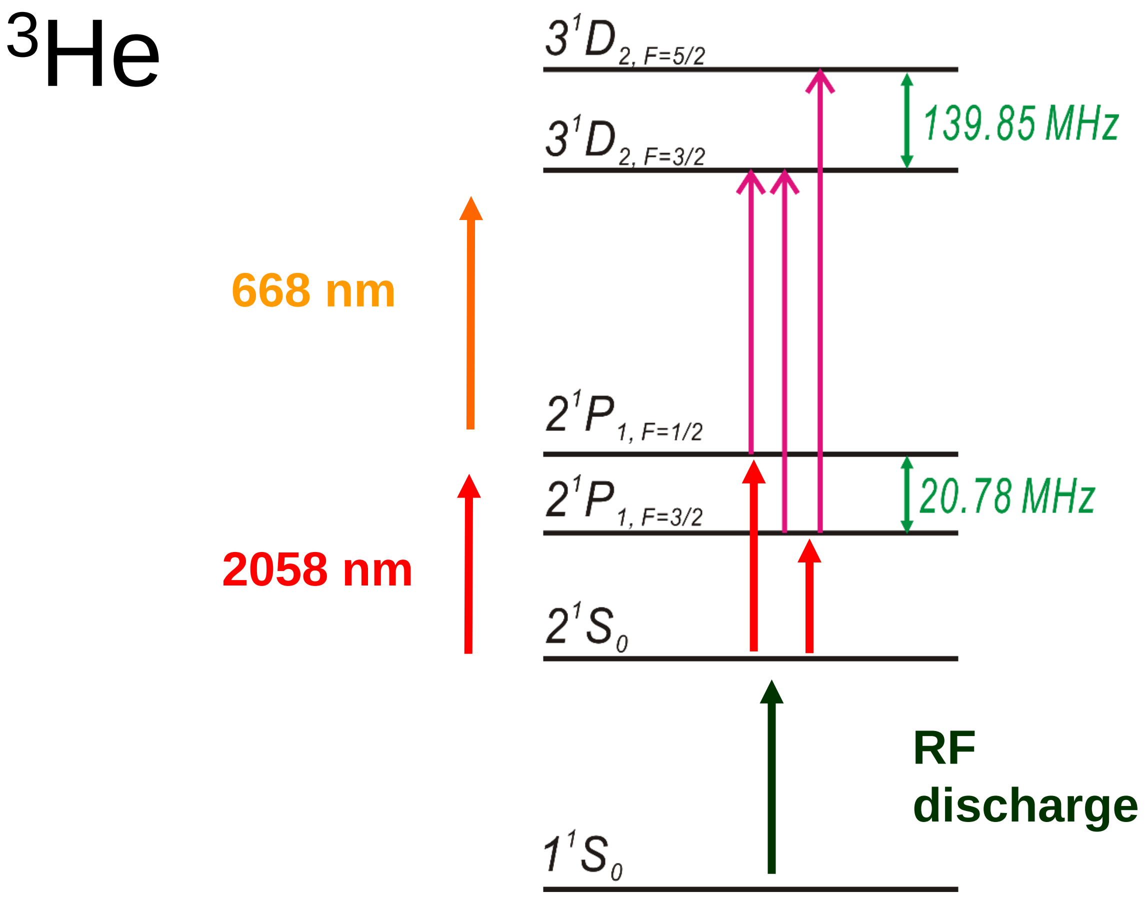


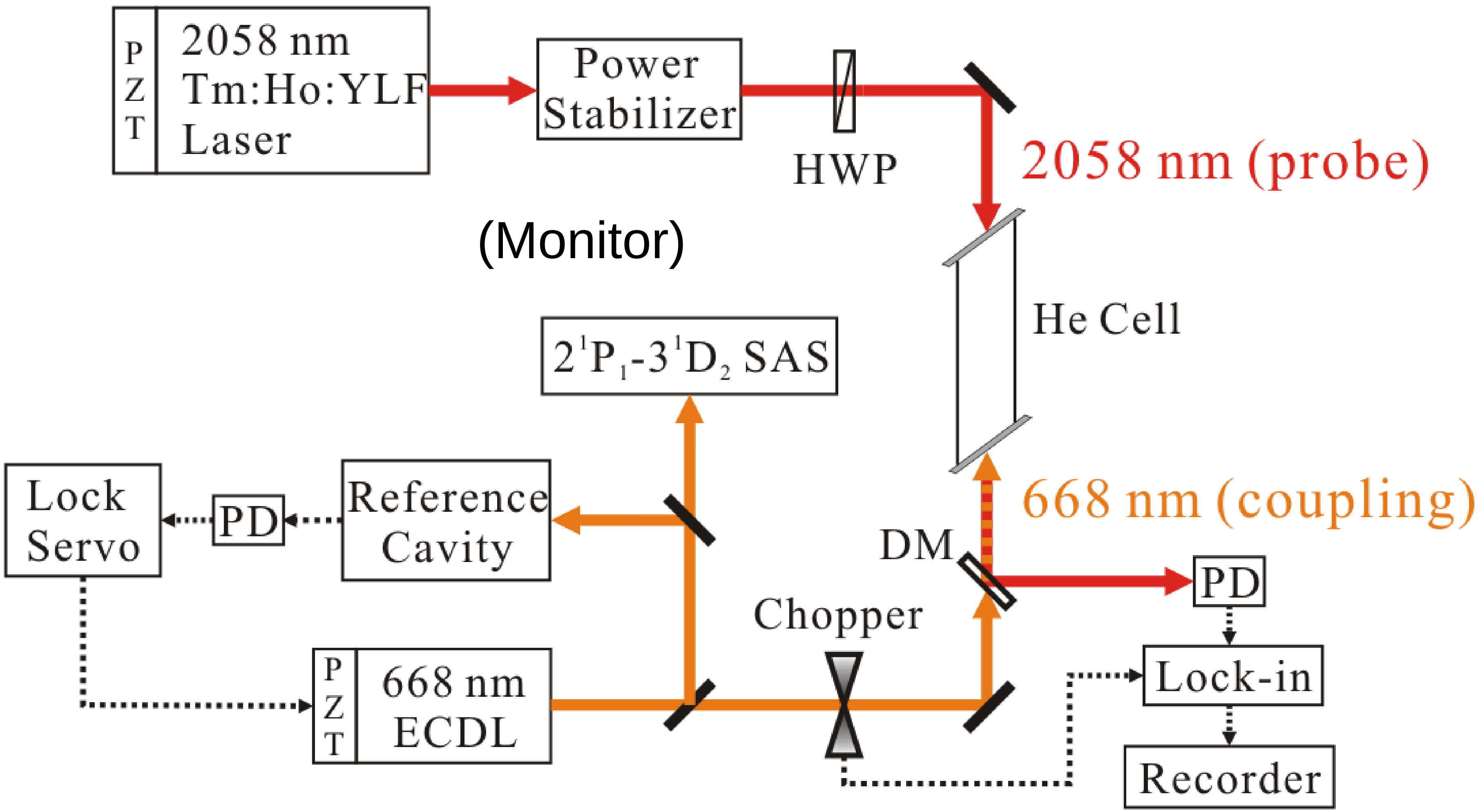
Fig. 1: Schematic of the experimental setup. OFC: optical frequency comb; PD: photodetector; HSPD: high-speed photodetector; AOM: acousto-optical modulator.



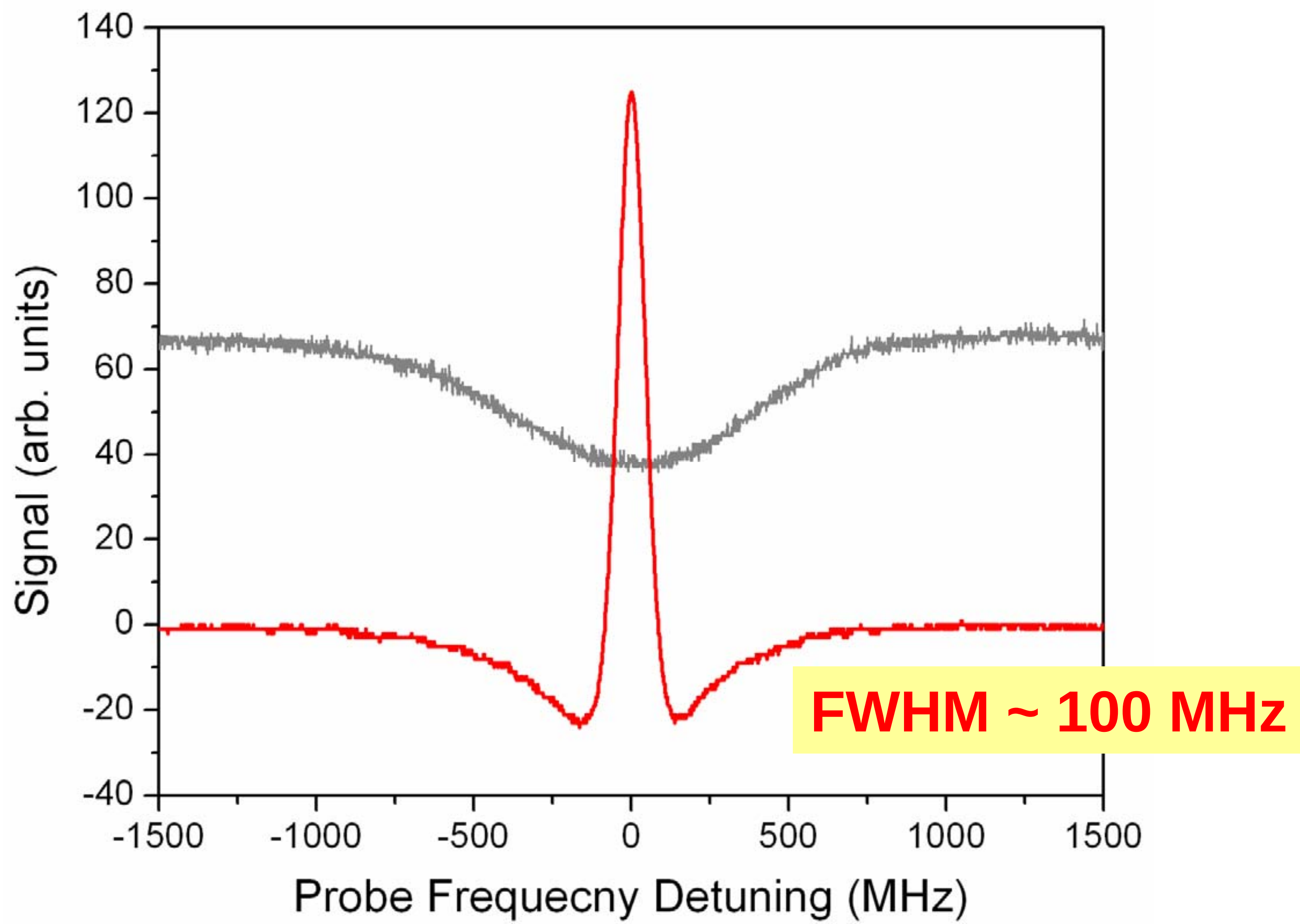
EIT in the He 2^1S_0-2^1P_1-3^1D_2 Transition



Experimental Setup



Observation of EIT Signal in ^{4}He



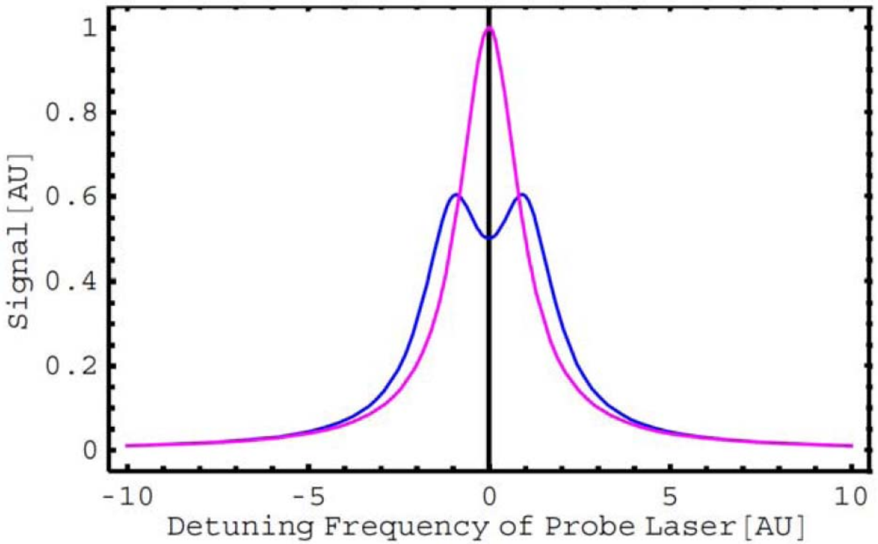
Ladder-Type EIT in an RF Discharge

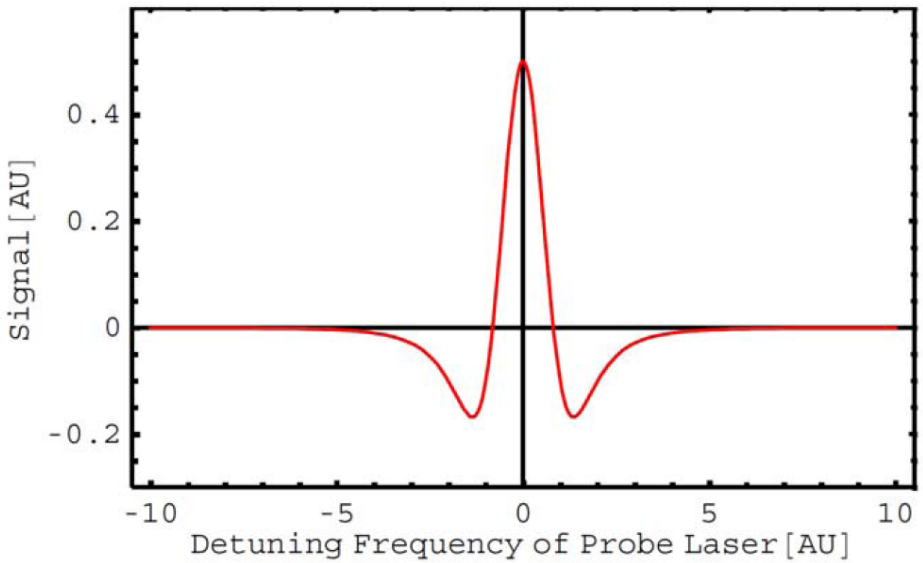
Department of Physics
National Tsing Hua University

$$\chi_P = N \times \frac{\delta_P + \delta_C - i\Gamma_{bc}}{(\delta_P - i\Gamma_{ab}) \times (\delta_P + \delta_C - i\Gamma_{bc}) - (K \times \Gamma_{ab}\Gamma_{bc})}$$

$$\chi_{P0} = N \times \frac{\delta_P}{(\delta_P - i\Gamma_{ab}) \times \delta_P}$$

$$N = -\frac{n_c |D_{ab}|^2}{\hbar}$$





Summary

Work completed

- Lithium HFS, IS in D1 line
- Helium singlet 2S-2P, 2P-3D states
- Either resolve discrepancy or test theories

Work in progress and future work

- Lithium 2S-3P measurement at 323 nm
- EIT study of helium 2S-2P and 2P-3D transition
- Helium 2S-3D two photon transition at 1009 nm
- Lithium ion spectroscopy

People involved

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工研院量測中心:彭錦龍博士

成功大學光電所:崔祥辰老師

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