NTHU AMO seminar, 3/19/2012

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National Tsing Hua University

Precision Measurement of Lithium Hyperfine Structure

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Outline

- Historical review: spectroscopy of simple atoms
- Examples (H, He, Li)
- What physics to study?
- Experiment in NTHU
- Our results and outlook

Precision spectroscopy of simple atoms

- To the extent atomic structure is calculable, precision measurement test fundamental physics
- Electromagnetic interaction well known
- Advances in atomic theory
- Simple atoms, e.g.: H, He, Li, etc…
- What fundamental physics to study

Hydrogen

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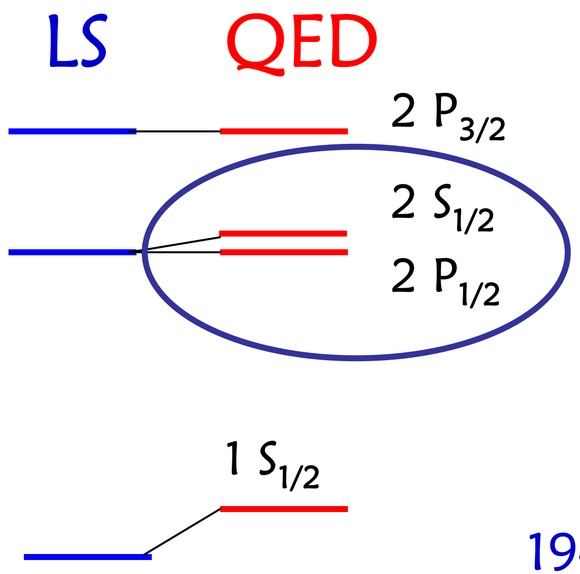
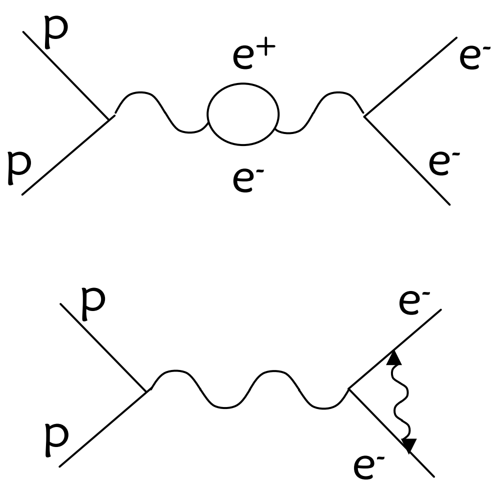
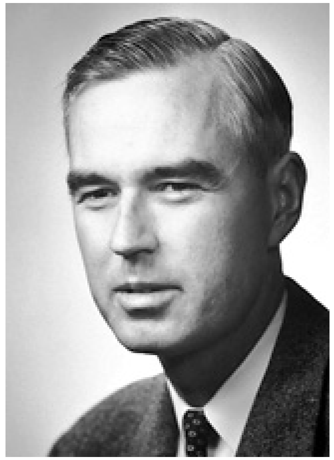
- non-relativistic $$E_n = -\alpha^2 mc^2 \left(\frac{1}{2n^2}\right) = \frac{-13.6eV}{n^2}$$
- relativistic correction $$-\alpha^4 mc^2 \frac{1}{4n^2}\left[\frac{2n}{(l+1/2)} - \frac{3}{2}\right]$$
- spin-orbit interaction (L·S, fine structure) $$-\alpha^4 mc^2 \frac{1}{4n^2}\left[\frac{2n}{(j+1/2)} - \frac{3}{2}\right]$$
- 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 magnetic moment (hyperfine structure) $$\left(\frac{m}{m_p}\right)\alpha^4 mc^2 \frac{4\gamma_p}{3n^2}[f(f+1)-3/2]$$
- nuclear size effect $$\frac{2\pi}{3} Ze^2 |\psi(0)|^2 \langle r^2 \rangle_{proton}$$

- $E = E_{Bohr} + E_{rel} + E_{ls} + E_{Darwin} + E_{HF} + E_{QED} + E_{nuclear}$

The Lamb Shift

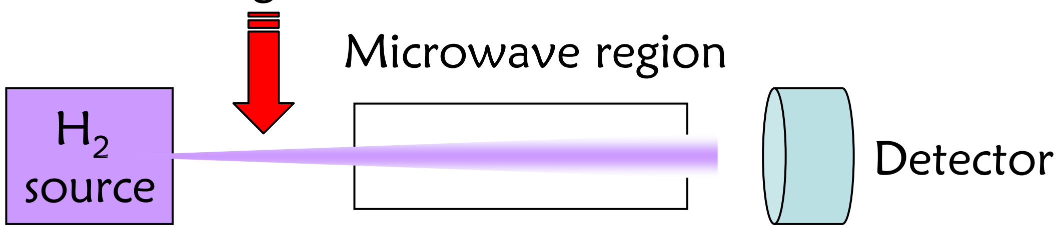






1947 by Lamb ~1060 MHz
now: 1057.846(4) MHz

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



g-2 experiment of electron and muon:

g_e (exp) = 2.0023193043617(15), g_e (th) to determine fundamental constant

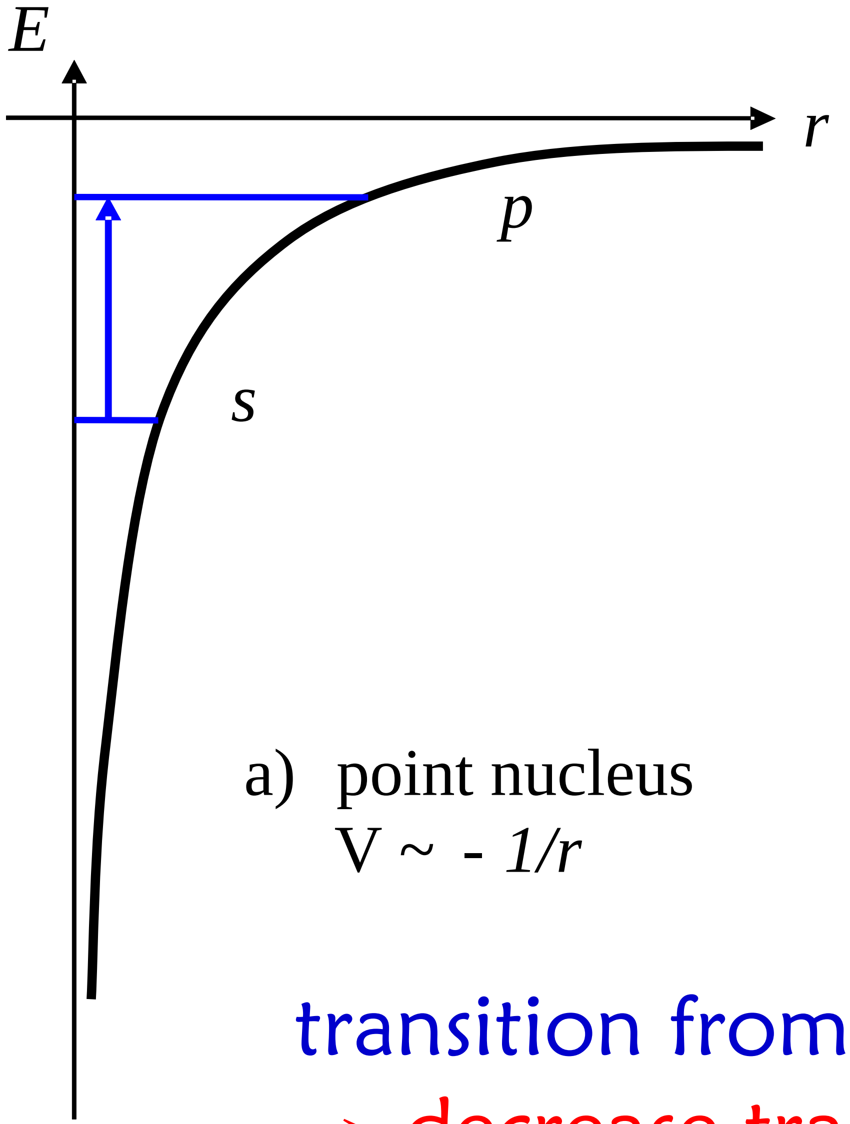
g_μ (exp) = 2.0023318416(12)

g_μ (th) = 2.0023318367(13)

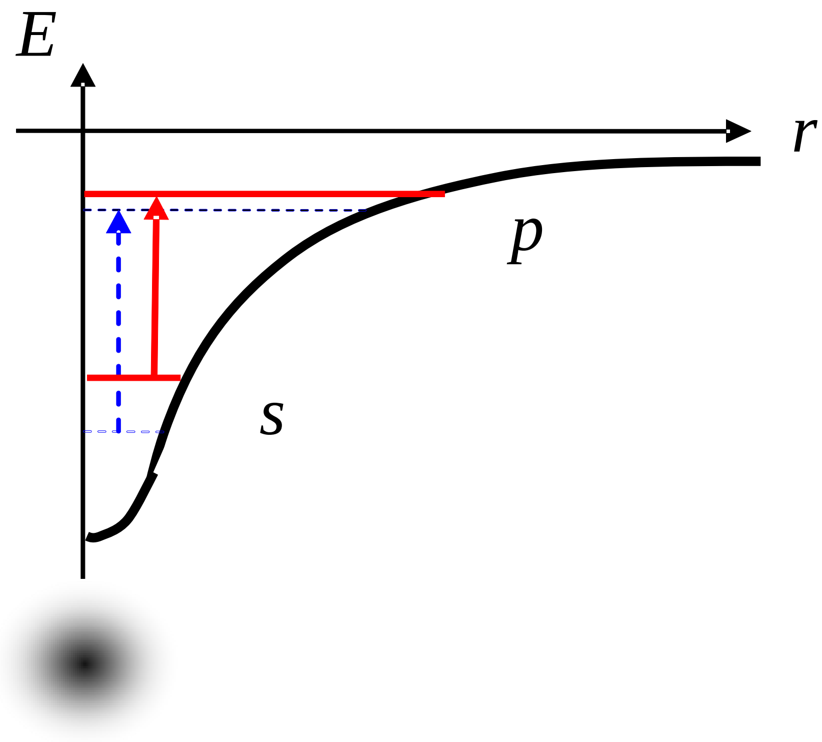
G.W. Bennett et al., *Phys Rev Lett.* **92**, 161802 (2004)

B. Odom et al., *Phys. Rev. Lett.* **97**, 030801 (2006)

Nuclear size effect



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



b) finite size nucleus

transition from s to p state
→ decrease transition frequency

Result for hydrogen

- Measure total transition frequency:

uncertainty: theory ~10 kHz, experiment ~20 kHz

→ charge radius of proton

R_p = 0.883(14) fm [1, 2]

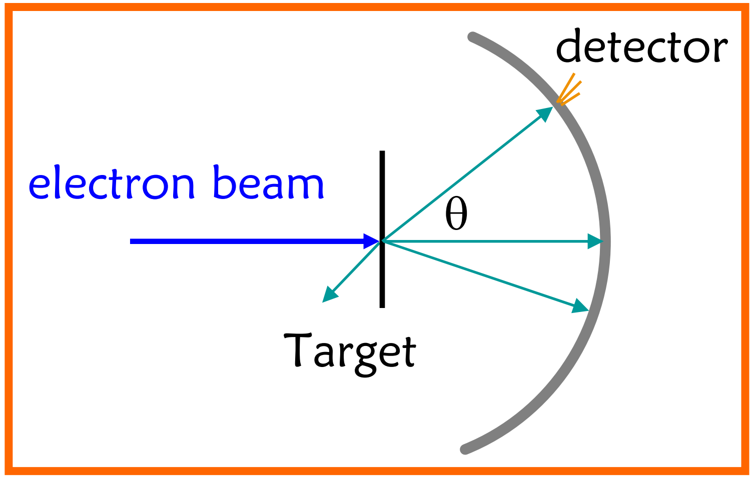
= 0.890(14) fm [3]

Reference:
[1] C. Schwob et al., Phys. Rev. Lett. **82**, 4960 (1999).
[2] Kirill Melnikov and Timo van Ritbergen, Phys. Rev. Lett., **84**, 1673(2000).
[3] T. Udem et al. Phys. Rev. Lett. **79**, 2646, (1997).

Electron scattering

- Electron beam on nucleus

$$\left(\frac{d\sigma}{d\Omega}\right)_{Rutherford} = \frac{Z^2\alpha^2(\hbar c)^2}{4E^2\sin^4\frac{\theta}{2}}$$



Nuclei with finite size:

$$\left(\frac{d\sigma}{d\Omega}\right)_{\exp} = \left(\frac{d\sigma}{d\Omega}\right)_{Rutherford} * \cos^2\frac{\theta}{2} * \left|G_E(q^2)\right|^2$$

$$< r^2 >= -6\hbar^2 \frac{dG_E(q^2)}{dq^2}\bigg|_{q^2=0}$$

Note: not the shape to fit, but the slope at $q^2=0$

Discrepancy

2σ deviation

R_p = 0.862(12) fm ⟷ R_p = 0.883(14) fm [1, 2]
= 0.890(14) fm [3]

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)

Muonic hydrogen

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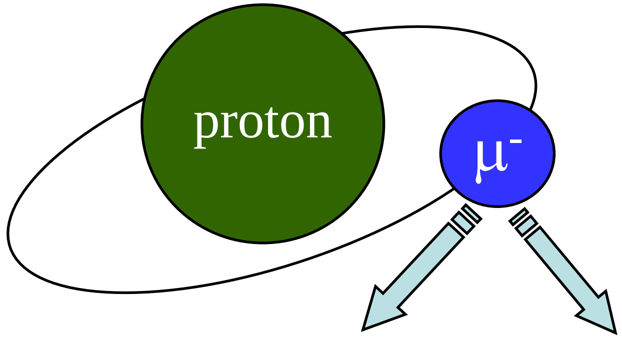


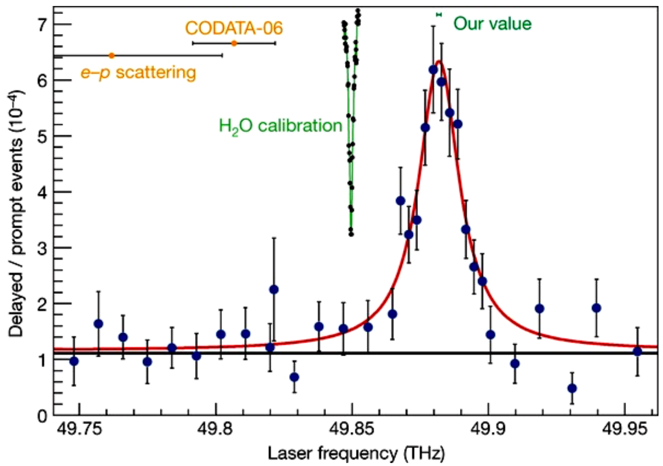
muon decay $\mu^- \rightarrow e^- \nu \bar{\nu}$

- $m_\mu / m_e \sim 200$
- 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~ $|\Psi(0)|^2 \langle r^2 \rangle$
- Sensitivity ~ $(m_\mu / m_e)^2$

at PSI, reaching 0.1 % precision

R_{rms} = 0.84184(67) fm

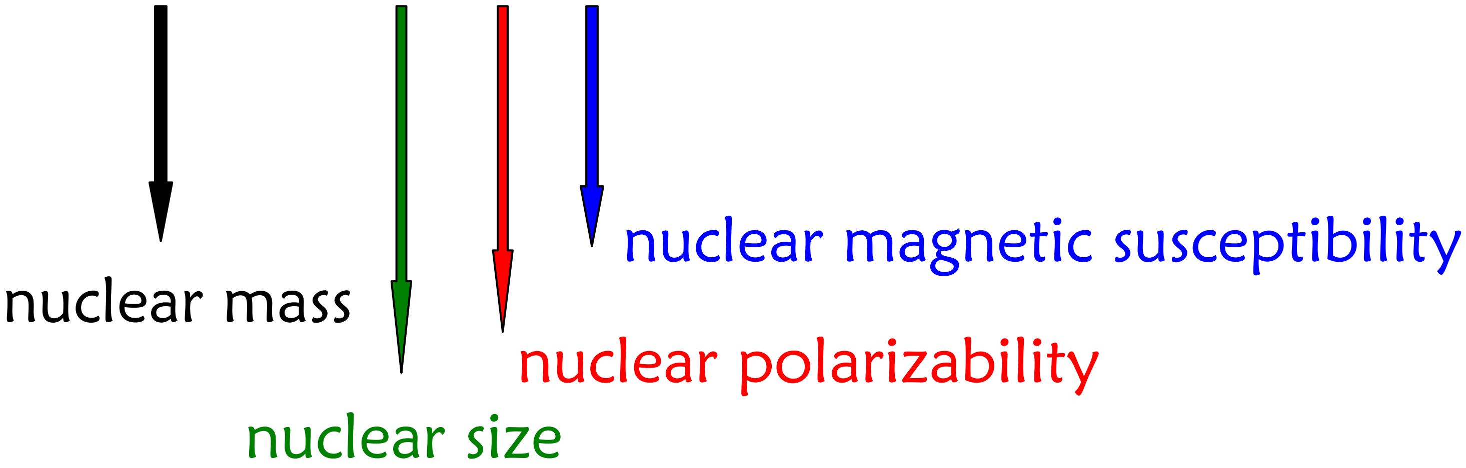
Nature **466**, 213–216, 2010



Isotope shift

- Measure isotope shift, 1s →2s at 121 nm

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



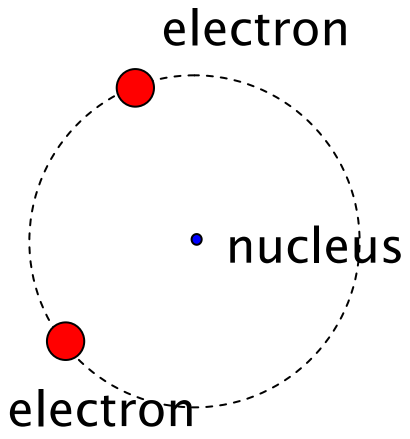
A. Huber et al., Phys. Rev. Lett. **80**, 468 (1998)

Summary of QED uncertainty

- H: 10 kHz, He: 1 MHz, Li: > 10 MHz
- Typical nuclear effect: several MHz
- G. Drake: QED uncertainty largely cancel in isotope shift (IS) and fine structure (FS) splitting measurement
- Uncertainty in isotope shift:
  H: <1 kHz, He: <10 kHz, Li: 100 kHz
- Total transition frequency: test QED calculation
- Isotope shift: nuclear property
- FS and HFS: nuclear moment and many-body calculation

Two-electron system

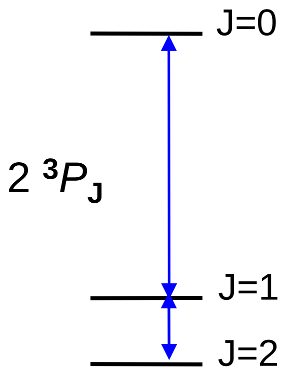
- non-relativistic ($\sim 1/n^2$)
- relativistic correction
- spin-orbit interaction
- nuclear magnetic moment
- QED effect
- nuclear size effect (e- inside the nucleus)
- nuclear polarizibility
- many-body (e^2/r_{12})
- recoil correction ($p_1 p_2$)



Previous attempt for helium

Fine structure of helium-4

- Interval 29 GHz and 2.3 GHz
- Use one for constraining fine structure constant α; another one for checking theory calculation



Previous attempt for helium

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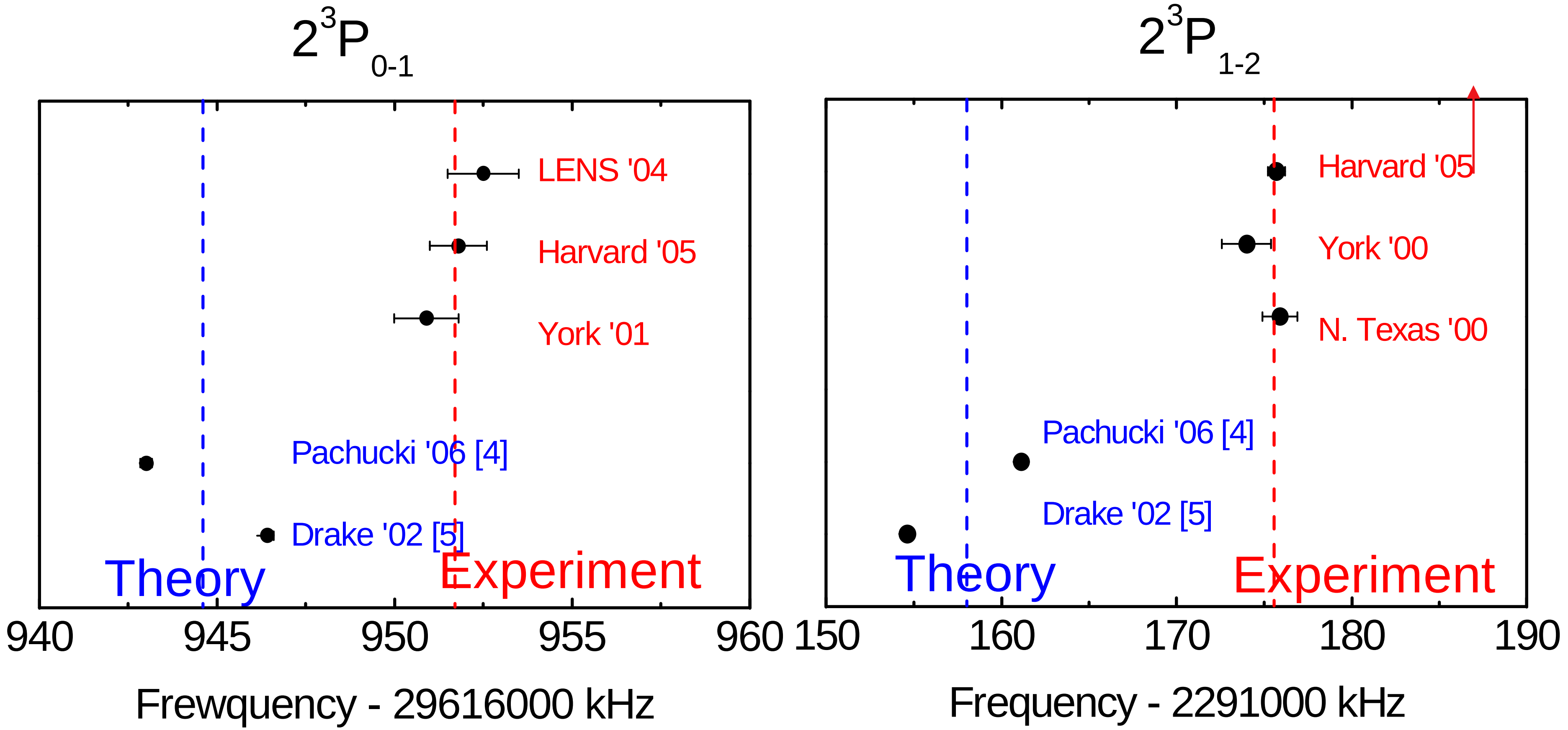
- uncertainty of theory and exp < 1 kHz
- difference = 10 kHz and 20 kHz

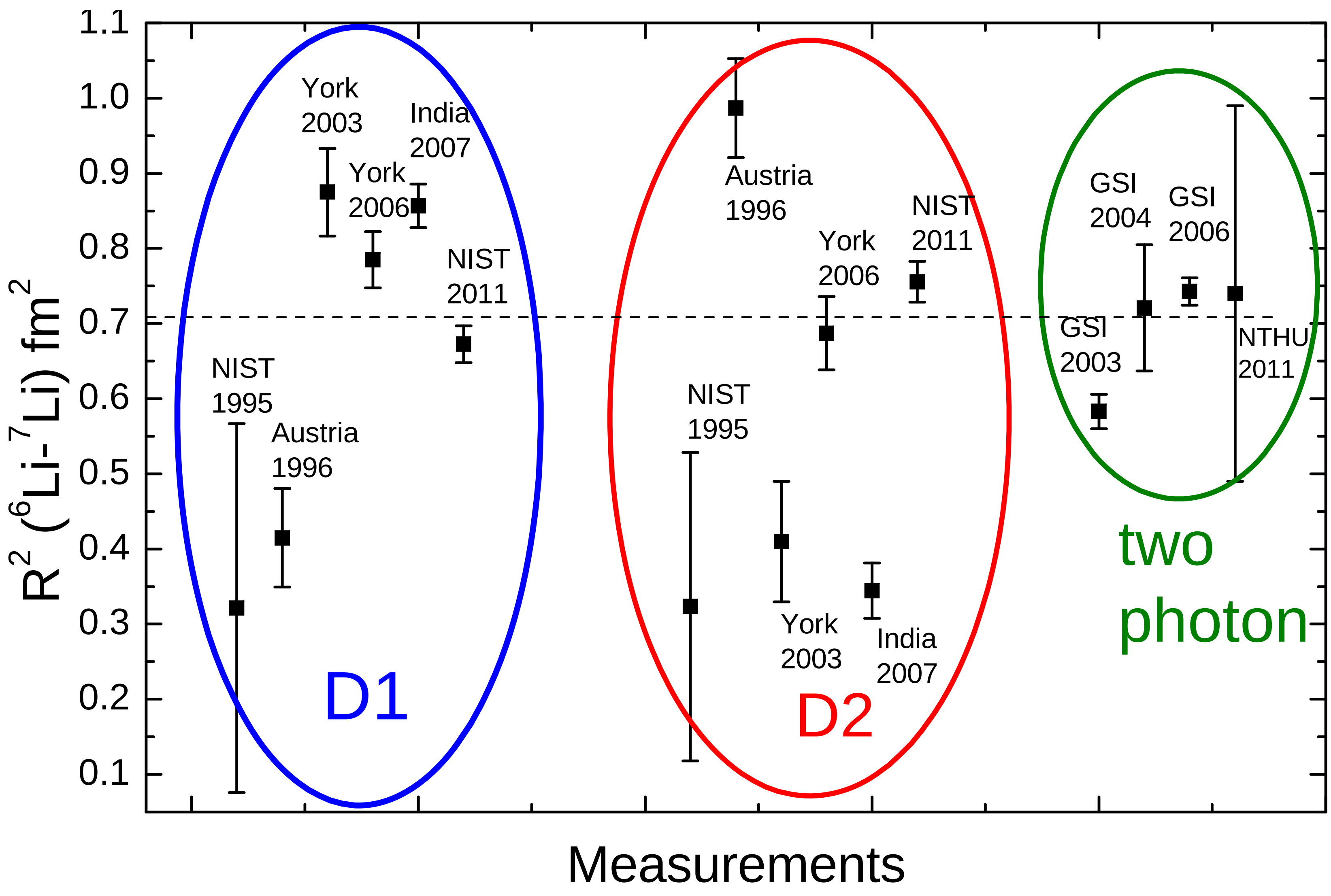


Lithium

- Lithium, more complicated
- Experimental discrepancy between York and Austria measurement

Discrepancy in lithium

- Test QED calculation, but discrepancy also exist



Energy level of Li-6,7

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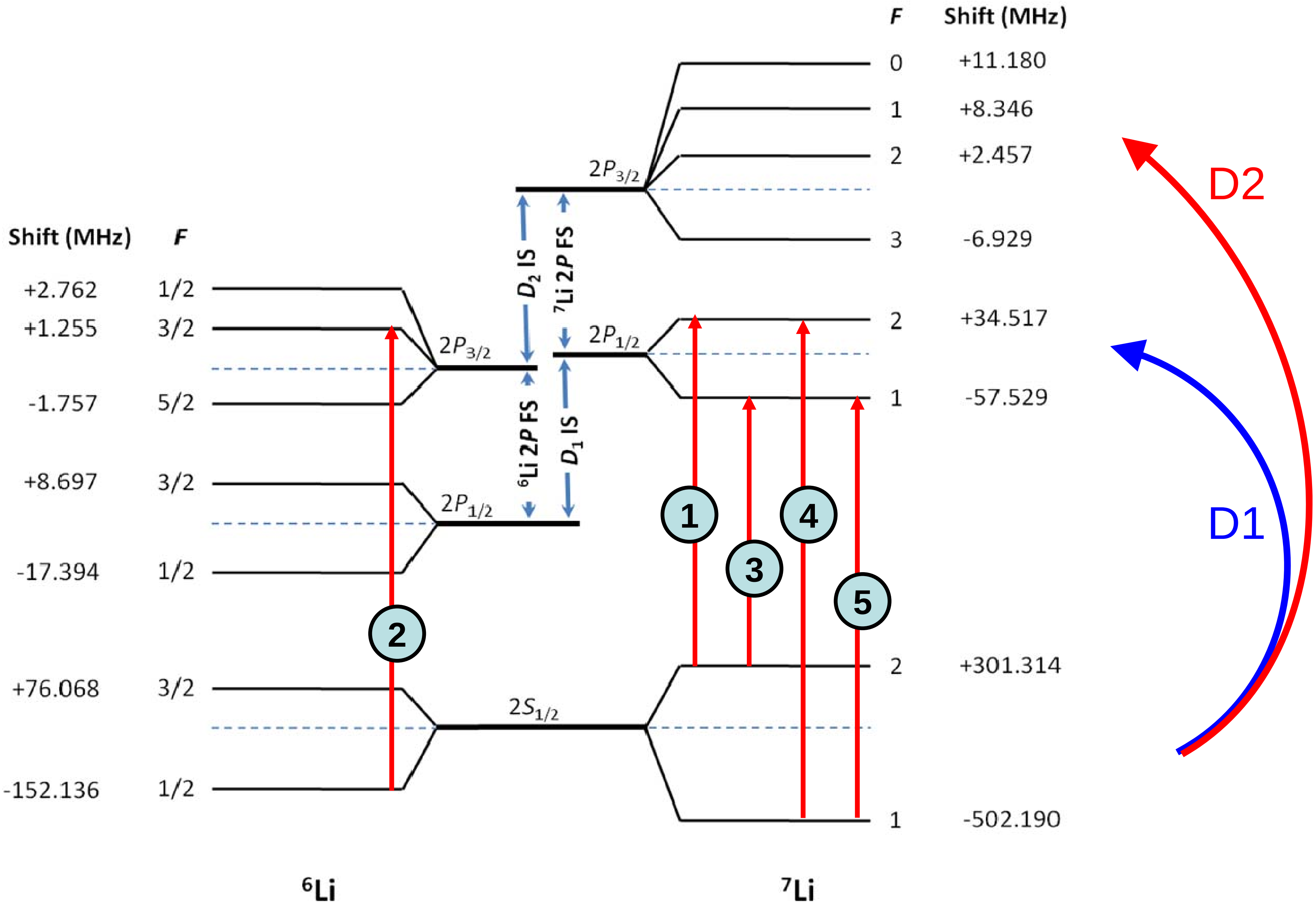
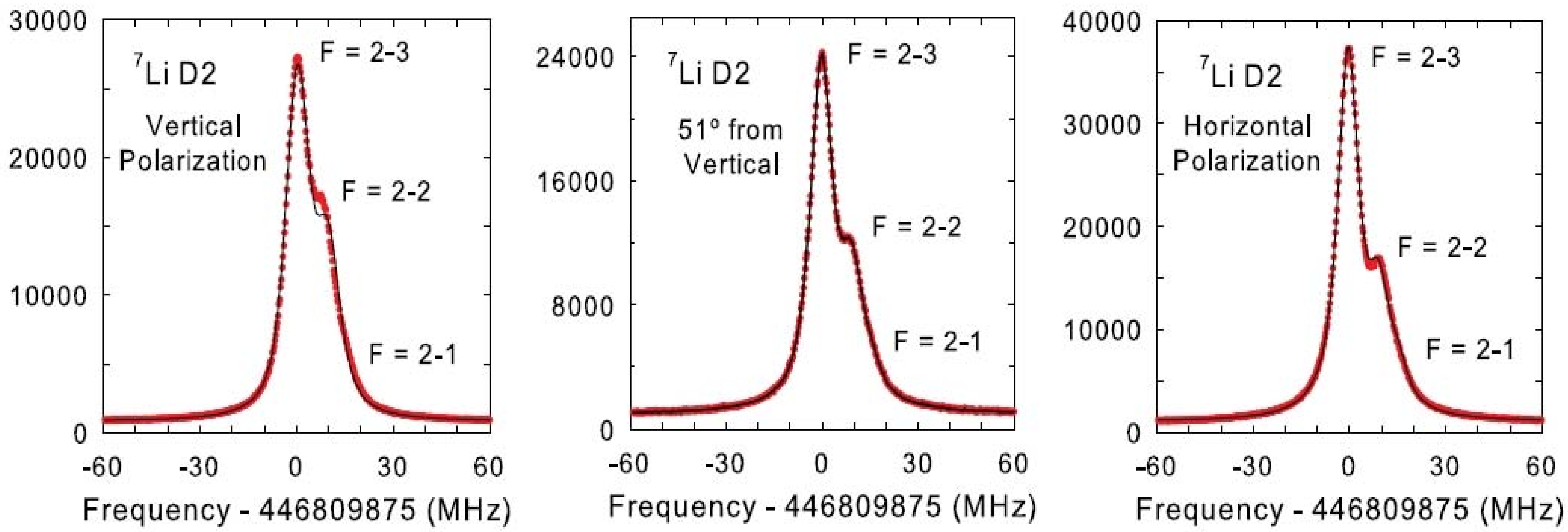


Explanation for D2 by NIST 2011

- D2 line not well resolved
- Exhibit quantum interference
- Large polarization dependence



D1 line

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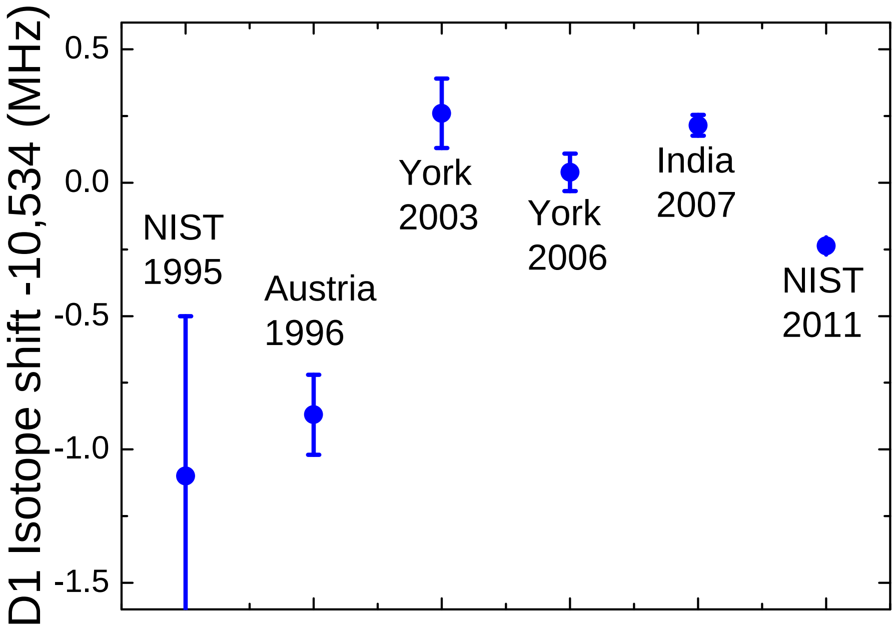

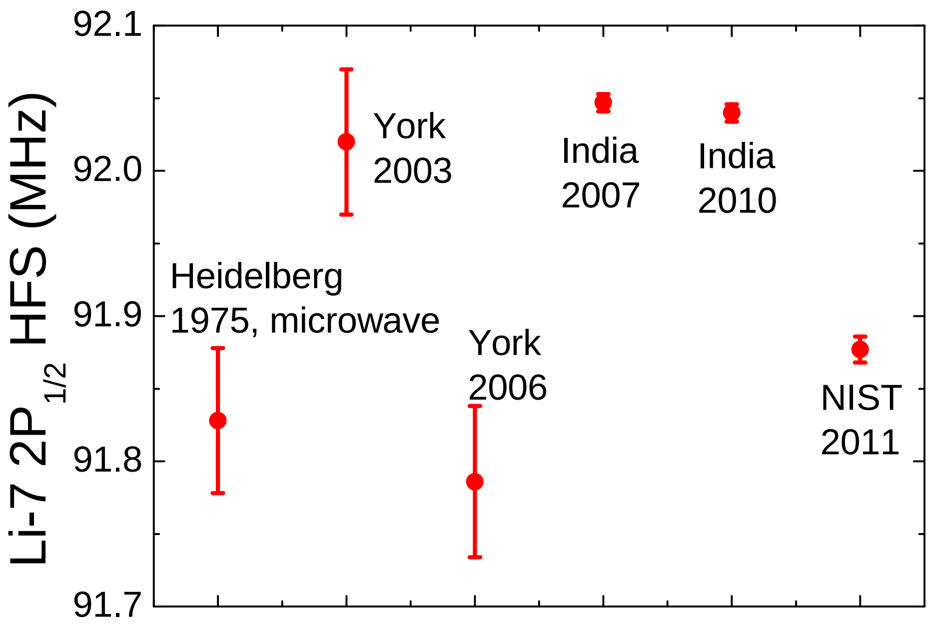

- Isotope shift: different velocity may cause systematic effect
- FS and HFS in one isotope: almost immune to beam alignment

Our approach

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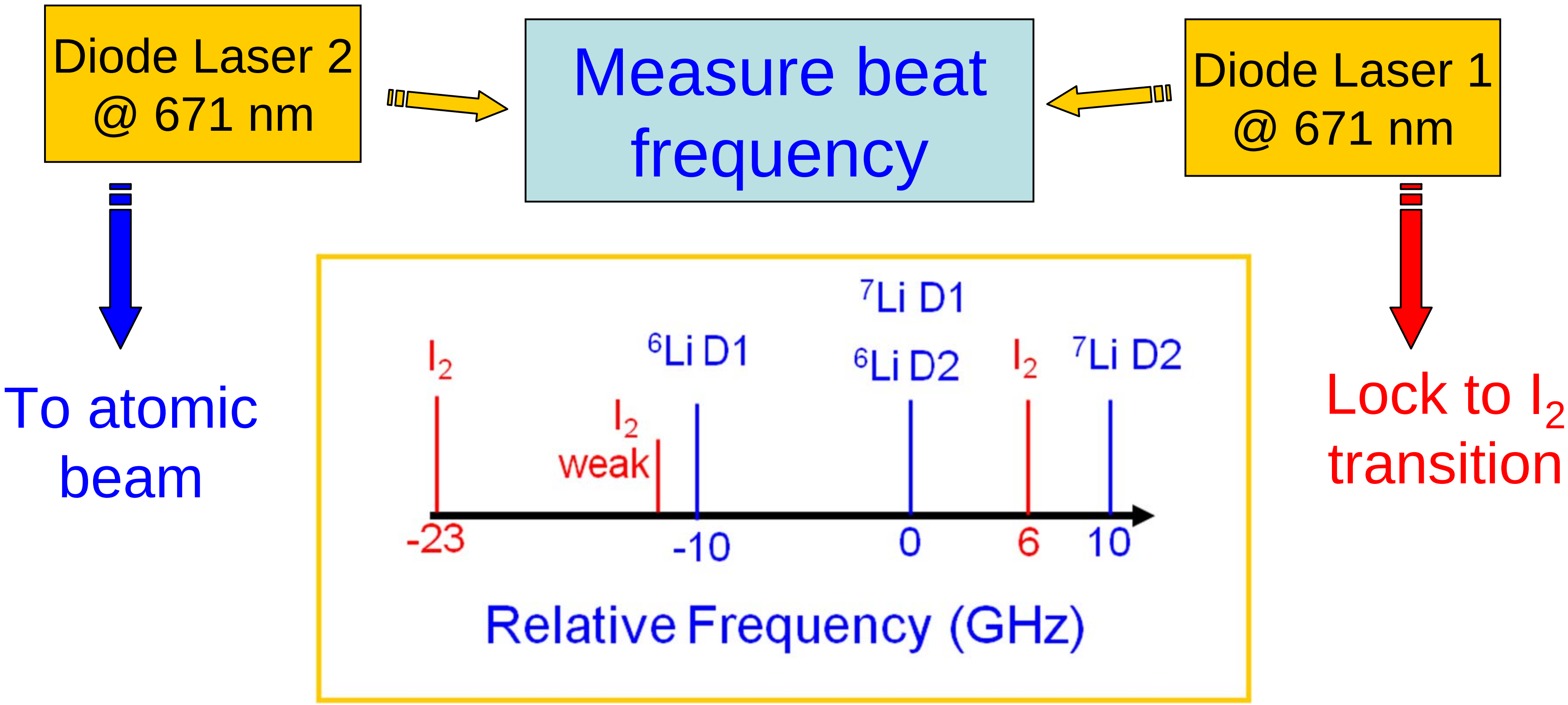
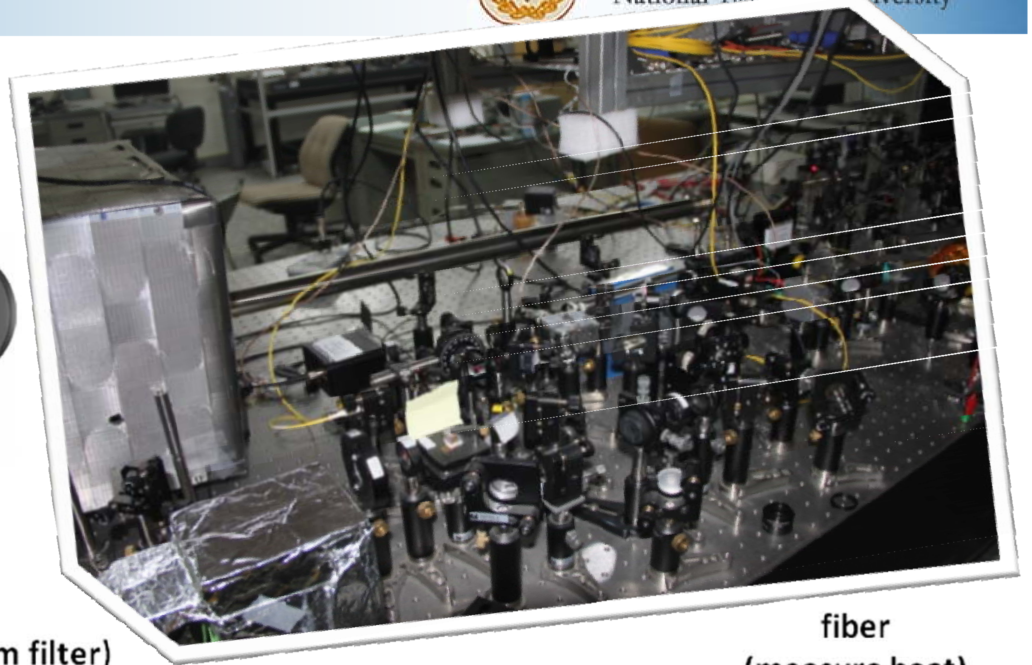
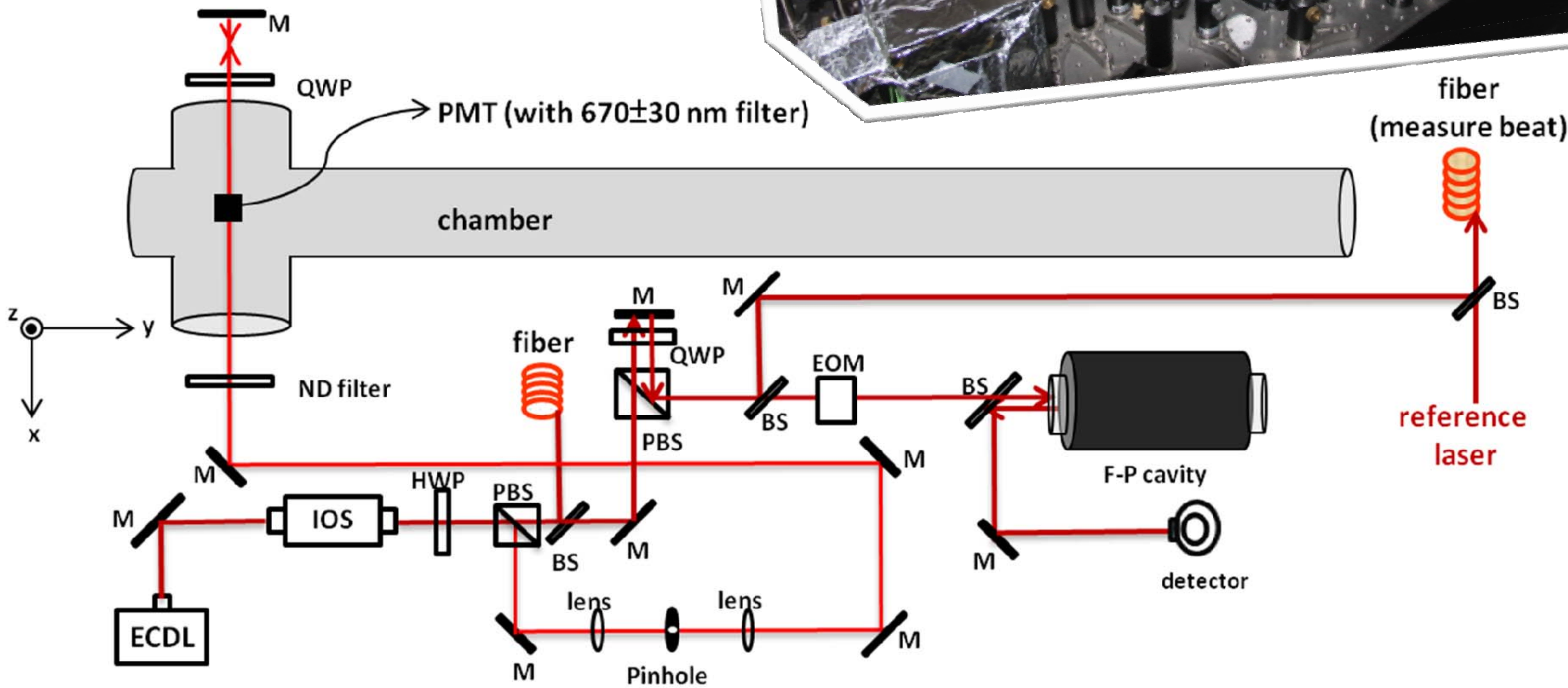


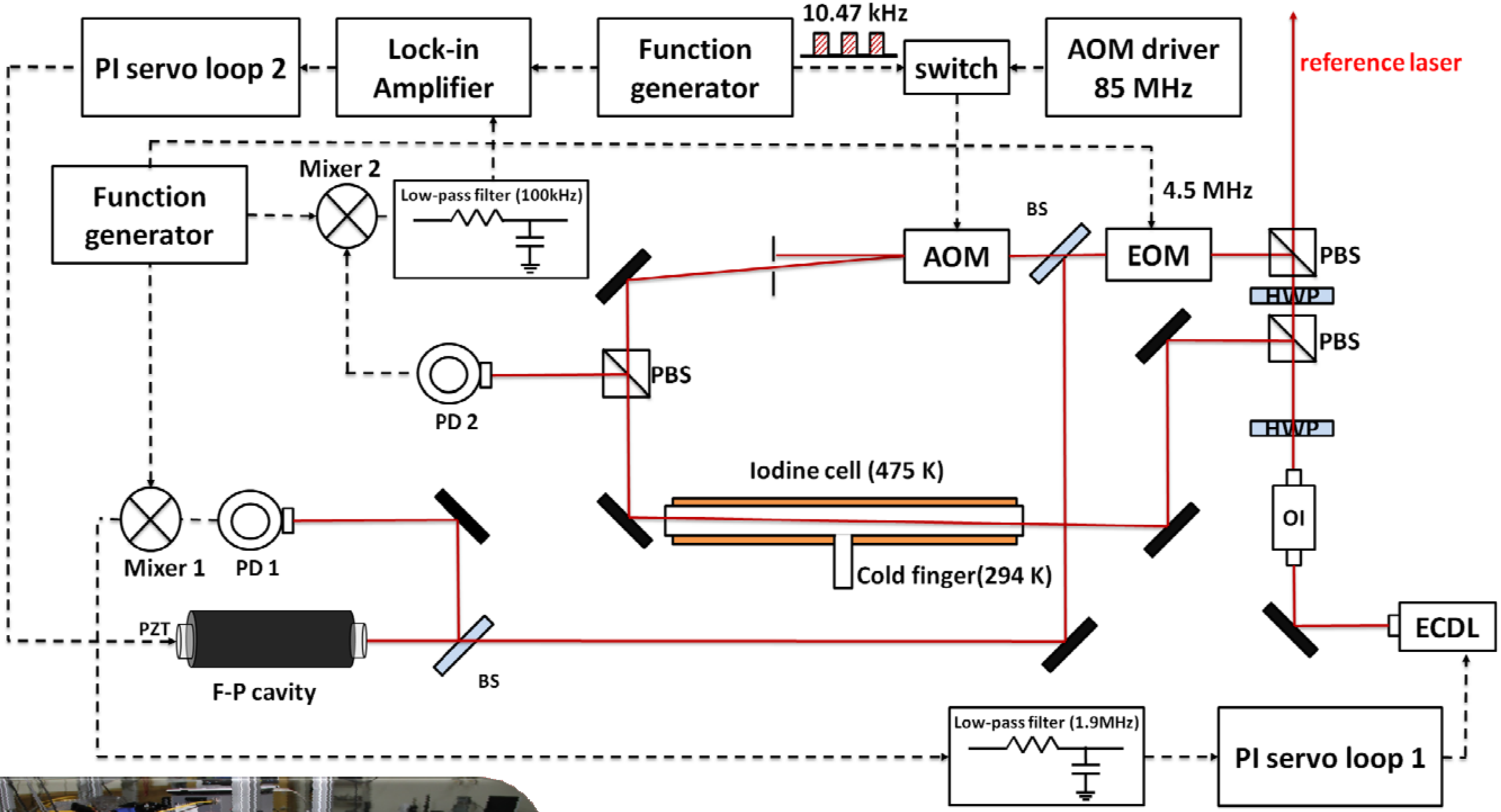
No.	Transition energy level	Center(MHz)	Width(MHz)
1	^{7}Li $2S_{1/2}$ F=2 → $2P_{1/2}$ F=2	6285.173(23)	11.060(75)
2	^{6}Li $2S_{1/2}$ F=1/2 → $2P_{3/2}$ F=1/2,3/2	6345.231(34)	15.103(1.053)
3	^{7}Li $2S_{1/2}$ F=2 → $2P_{1/2}$ F=1	6377.143(18)	10.003(55)
4	^{7}Li $2S_{1/2}$ F=1 → $2P_{1/2}$ F=2	5481.770(15)	11.322(48)
5	^{7}Li $2S_{1/2}$ F=1 → $2P_{1/2}$ F=1	5573.584(45)	9.247(147)

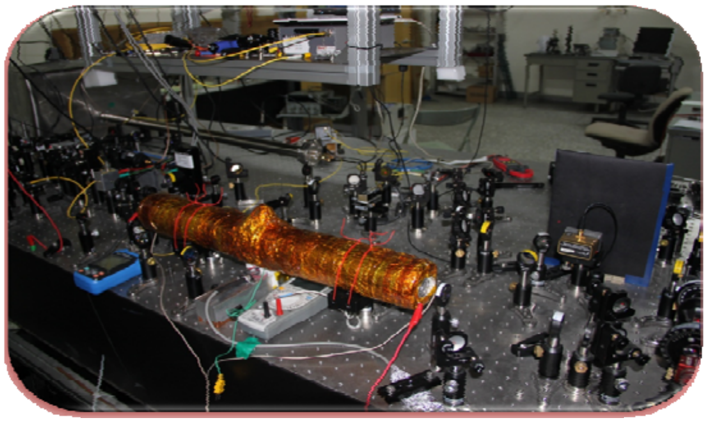
Spectroscopy laser





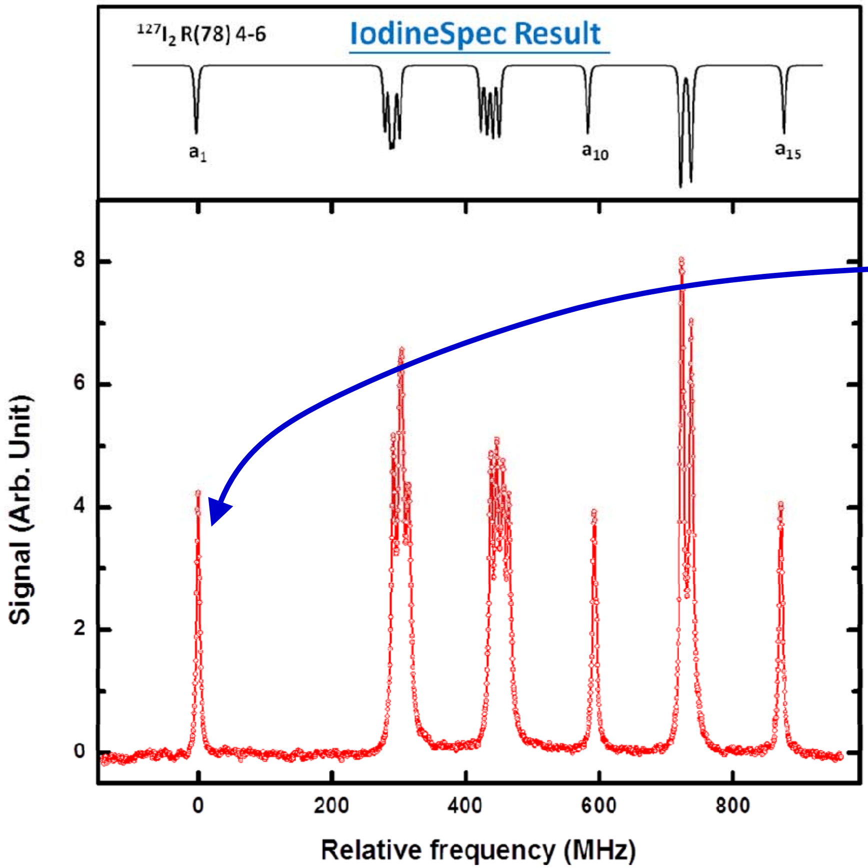
Reference laser



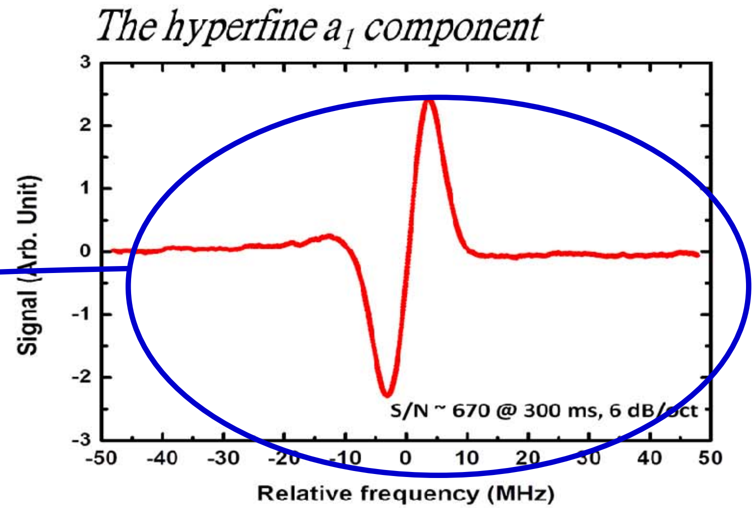


Iodine spectrometer

The transitions and derivative signal of $^{127}I_2$ at 671 nm:



The hyperfine a_1 component



Parameters

Pump Power = 2.8 mW

Probe Power = < 1 mW

Signal slope: 695 mV/MHz

Signal-to-noise ratio: ~ 670 @ 300 ms

Iodine measurement

- Frequency-comb measurement of the iodine transition
- Pressure shift, pump power shift, etc.

Unit: MHz

line	Result	IodineSpec	Difference
a1	446806191.649(23)	446806194.57	2.92
a10	446806778.709(33)	446806781.53	2.82
a15	446807072.397(33)	446807075.27	2.87

Typical signal for lithium-7

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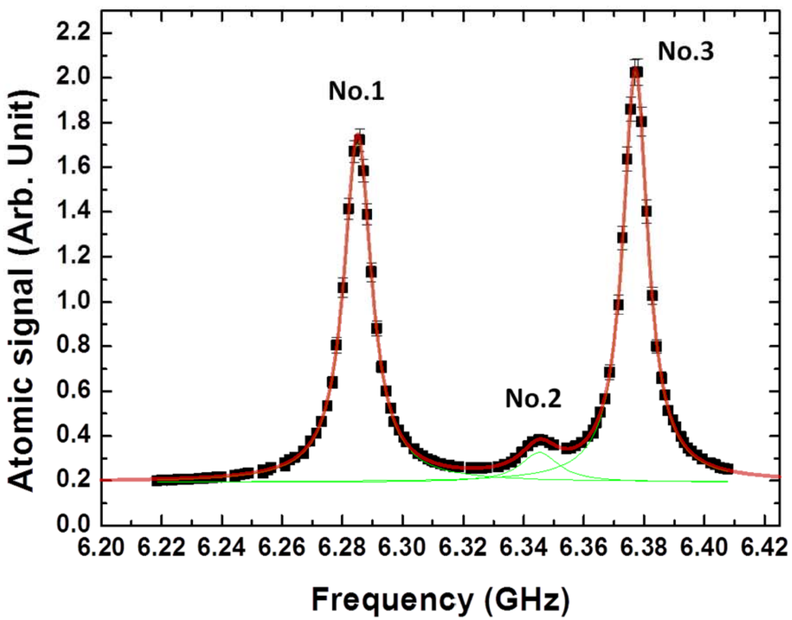
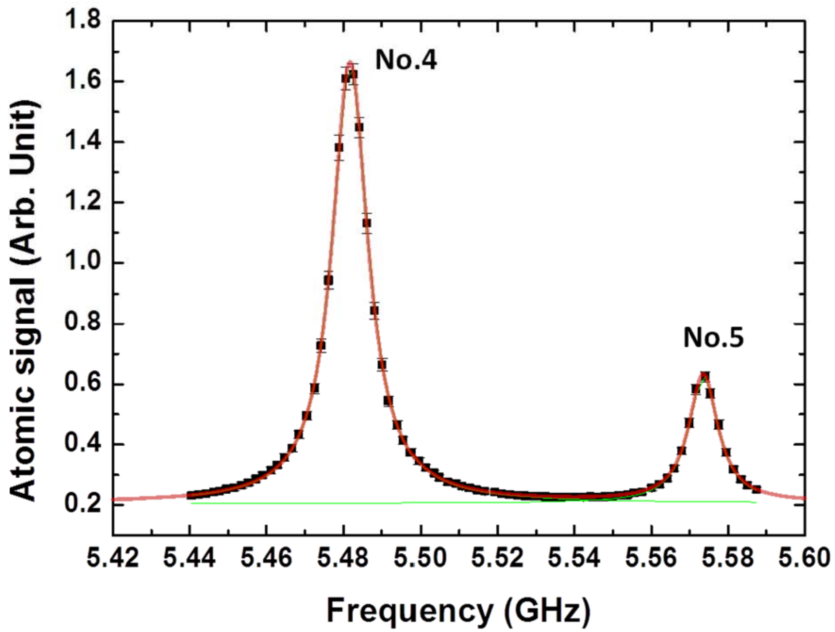
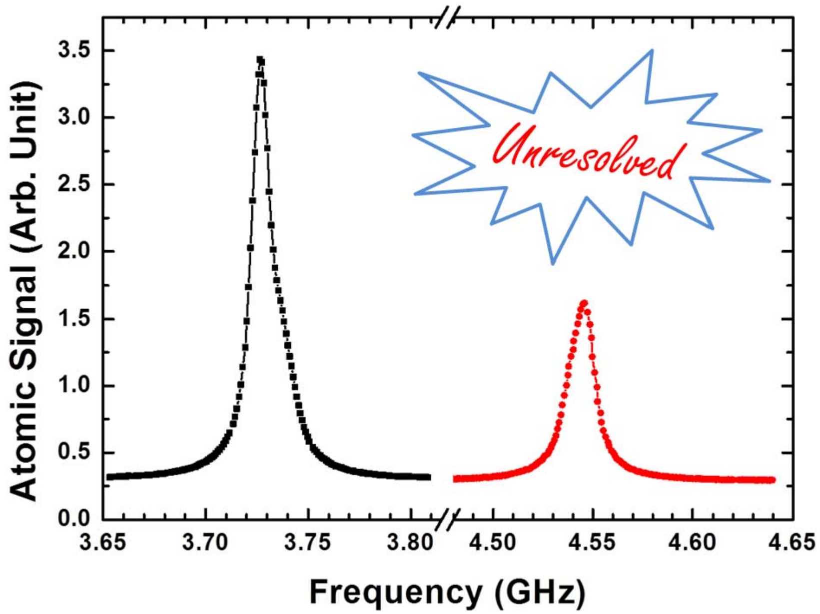


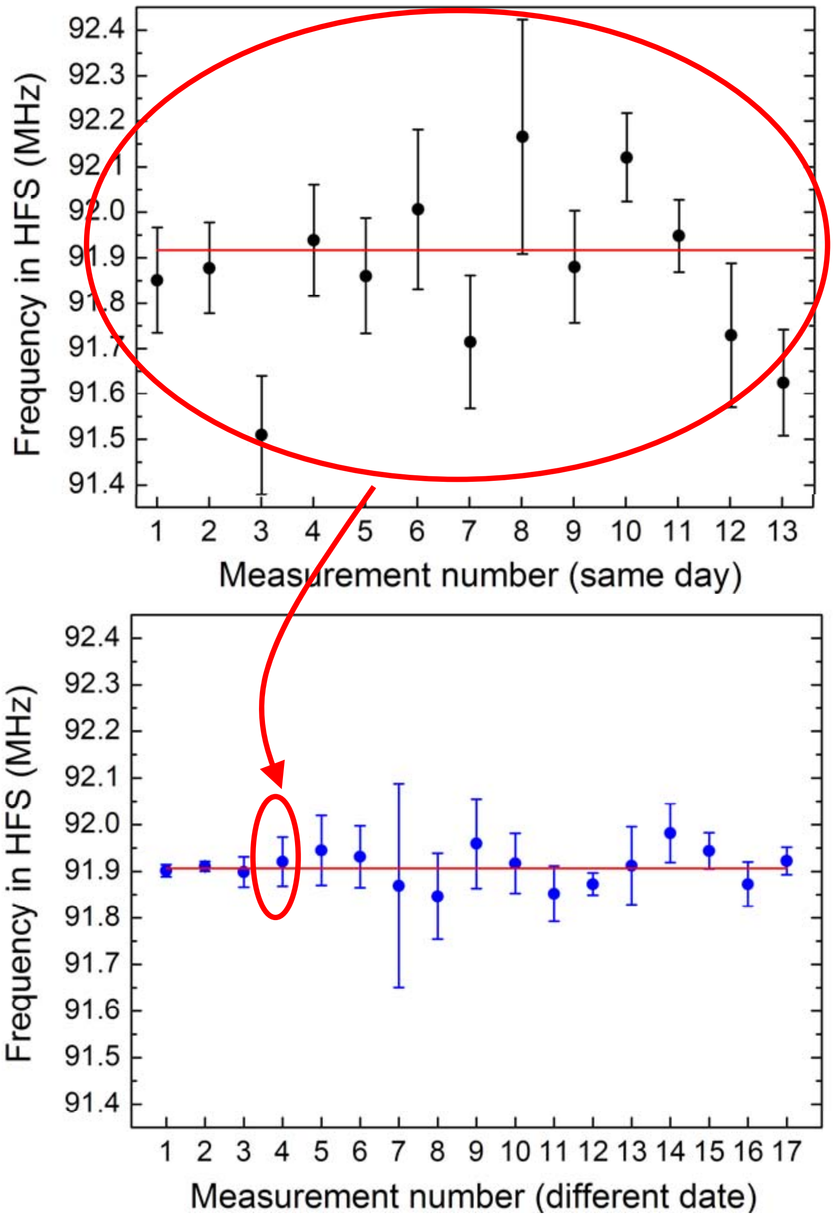




D1 line: hyperfine structure well resolved

D2 line: only the ground state hyperfine structure resolved

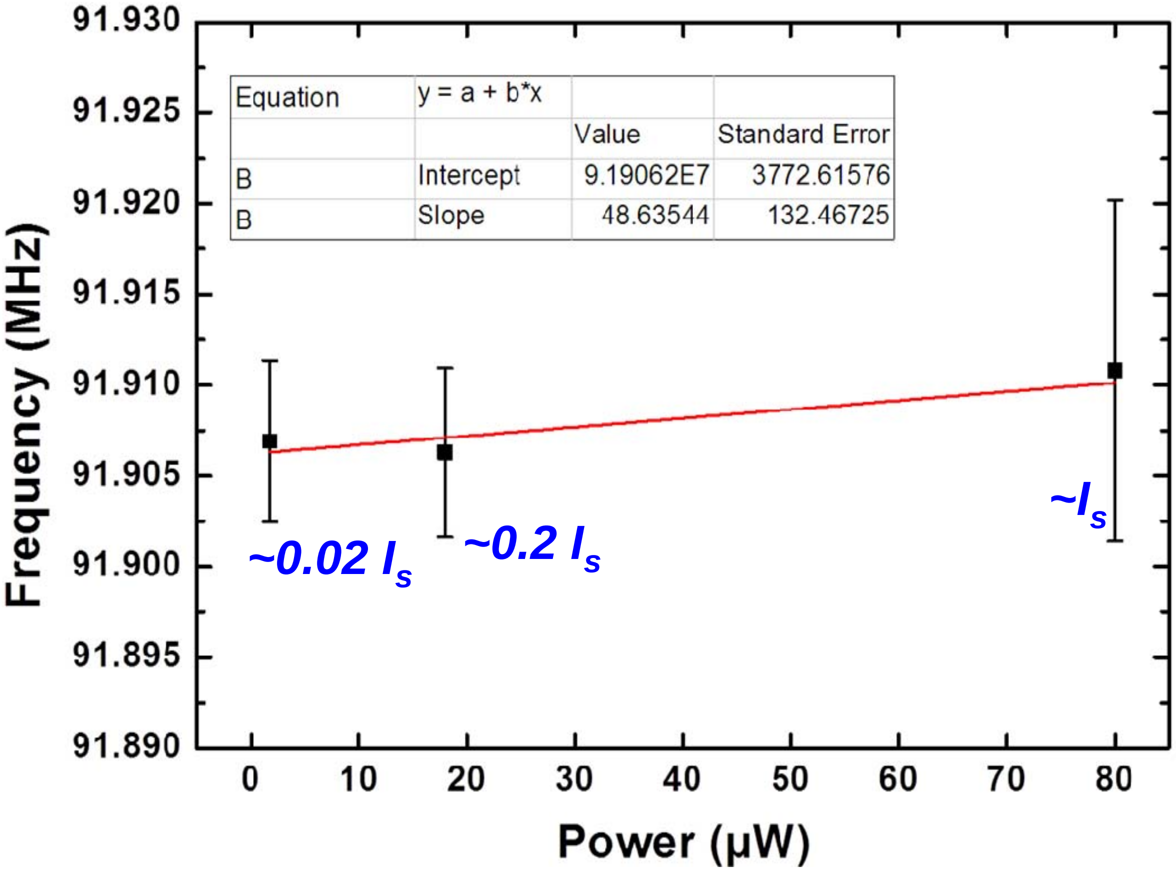
Data analysis



- Difference between two peaks
- Scan up and down
- Quick scan, ~1 point/sec
- I_2 instability → $\chi^2 > 1$

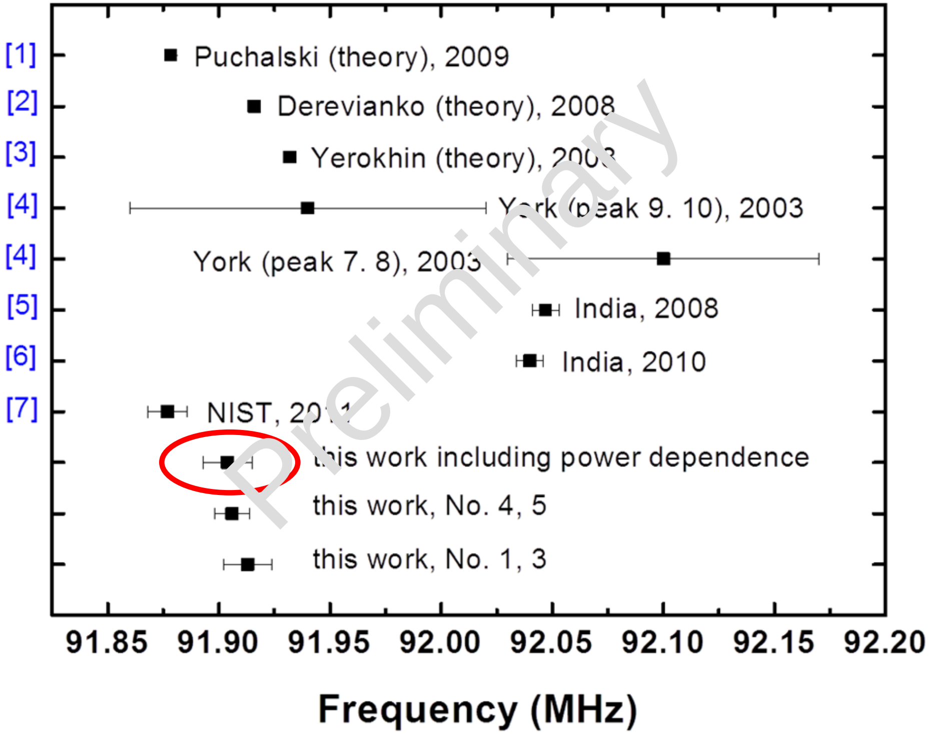
- Consistent in different dates
- I_2 drift and cavity drift

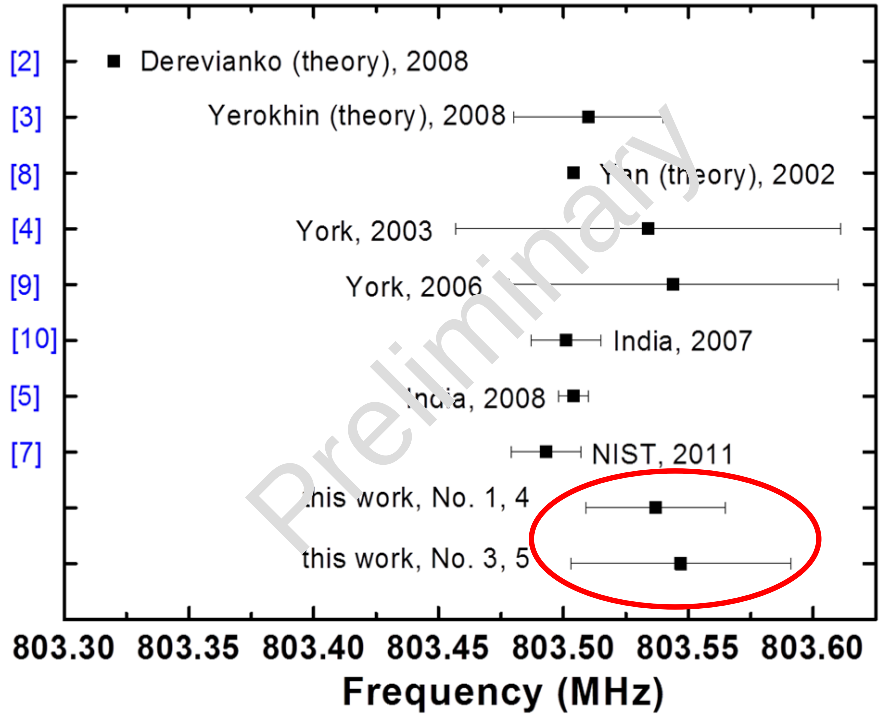
Laser power dependence



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

Results





[1] M. Puchalski and K. Pachucki, Phys. Rev. A **79**, 032510 (2009).
[2] A. Derevianko, S.G. Porsev, and K. Beloy, Phys. Rev. A **78**, 010503 (2008).
[3] V. A. Yerokhin, Phys. Rev. A **78**, 012513 (2008).
[4] J. Walls, R. Ashby, J. J Clarke, B.Lu, and W. A. van Wijngaarden, Eur. Phys. J. D **22**, 159 (2003).
[5] D. Das, and V. Natarajan, Phys. B. **41**, 035001 (2008).
[6] A. K. Singh, L. Muanzuala, and V. Natarajan, Phys. Rev. A **82**, 042504 (2010).
[7] C. J. Sansonetti, C. E. Simien, J. D. Gillaspy, J. N. Tan, S. M. Brewer, R. C. Brown, S. Wu, and J. V. Porto, Phys. Rev. Lett. **107**,023001 (2011).
[8] Z. C. Yan, and G. W. F. Drake, Phys. Rev. A **66**, 042504 (2002).
[9] G. A. Noble, B. E. Schultz, H. Ming, and W. A. van Wijngaarden, Phys. Rev. A **74**, 012502 (2006).
[10] D. Das, and V. Natarajan, Phys. B. **75**, 052508 (2007).

Error Budgets

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Sources	Magnitude (kHz))
Statistical error	5
Laser power effect	5
Beam misalignment	< 1
B field effect	< 3
Total	**8**

Iodine instability included in statistical error

Note: the hyperfine splitting does not simply relate to A and B coefficients as:

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

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

$$\frac{HFS}{2} + 27\ kHz = A$$

$$HFS = 2A$$

2nd order effect from state mixing

K. Beloy and A. Derevianko, Phys. Rev. A **78**, 032519 (2008).

Summary

- For H, better theory desired

  also muonic hydrogen problem
- For He, discrepancy in fine structure

Li spectroscopy: (with optical frequency comb)

- measure Li-6,7 isotope shift and HFS in atomic beam, vapor cell and MOT
- Li^+ spectroscopy in discharge, ion beam, and trap

People involved Lithium D line: 駱瑋駿, 黃耀欽, 郭彥廷
Iodine spectroscopy: 蕭仔真 Li^+: 高政揚
Former member: 王宥人, 曾安廷, 陳柏安
Supported by NSC and MOE 5y50b fund