Precision Laser Spectroscopy of Lithium

a) Li^+ 1s2s ^3S – 1s2p ^3P Transition

b) Li D Lines

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Why study Li^+/Li?

1. **Test QED**
   Effects scale to lowest order as $Z^4\alpha^3$ times Rydberg energy. QED effects order of magnitude greater than in H or He [1,2].

2. **Theoretical Advances**
   Two & maybe 3 electron systems now "well understood" using Hylleraas Variational calculations [2,3].

3. **Nuclear Probe**
   Measurements of isotope shifts plus theory yields relative nuclear charge radii with accuracies < 1 x 10^{-17} meter, more accurate than electron scattering. Ideal for studying halo neutrons ^{6,7,8,9,11}Li [4], particularly relevant in light of discrepancies determining proton radius [5].

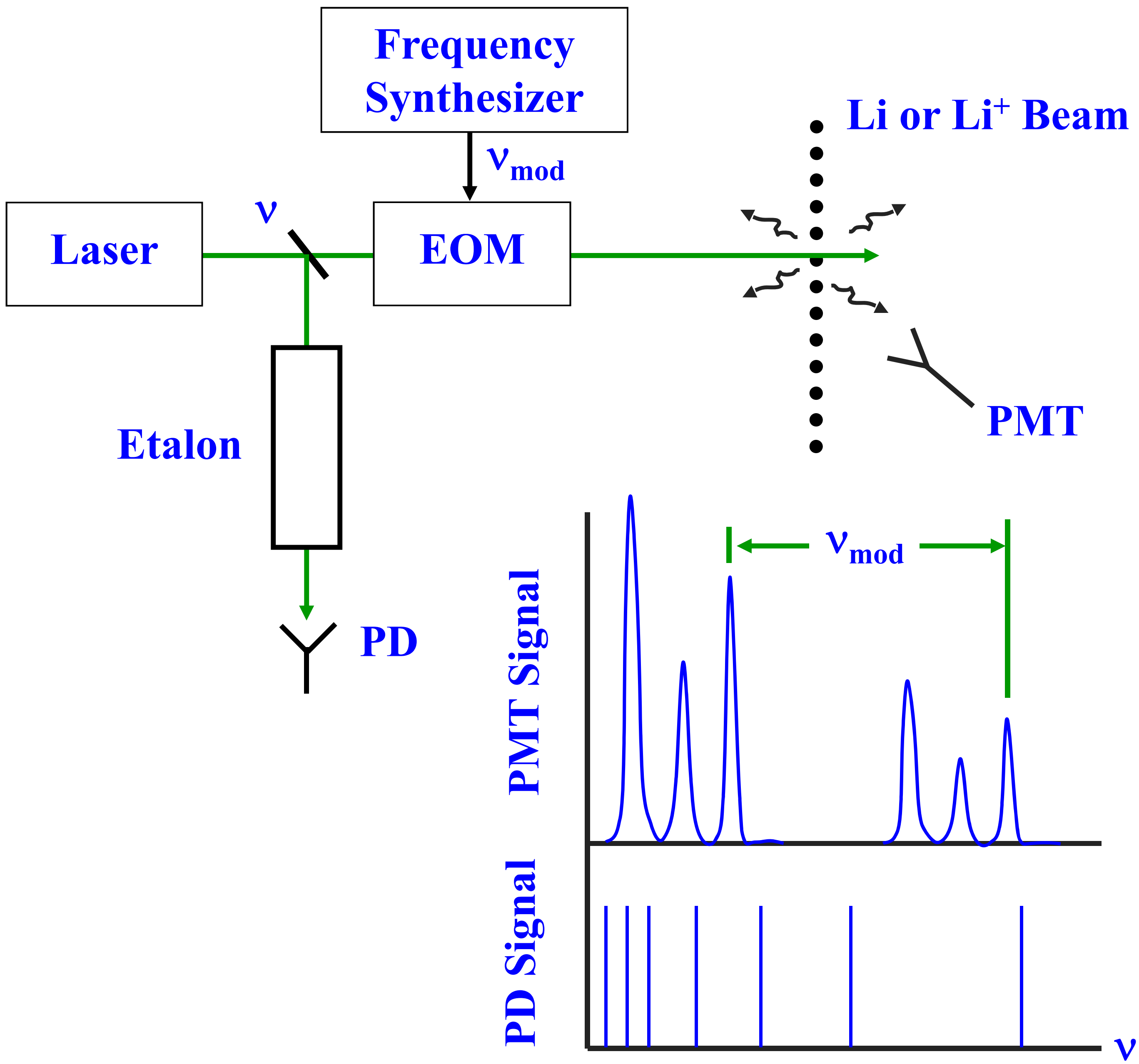
4. **Experimental Discrepancies**
   a) **Li^+ 1s2p $^3P_{1,2}$ Fine Structure:** Two measurements with 1σ uncertainty ~0.65 MHz disagree by 11 MHz.

   b) **Neutral Li D Lines:** Fabry Perot calibration problems.

1. G. Noble & W. A. van Wijngaarden, Can. J. Phys. **87**, 807 (2009)
2. Z. C. Yan et al, PRL **100**, 243002 (2008)
3. M. Puchalski et al, PRA **79**, 032510 (2009)
4. W. Nörterhauser et al, PRA, **83**, 012516 (2011)
5. A. Antognini et al, J. Phys. **312,** 032002 (2011)

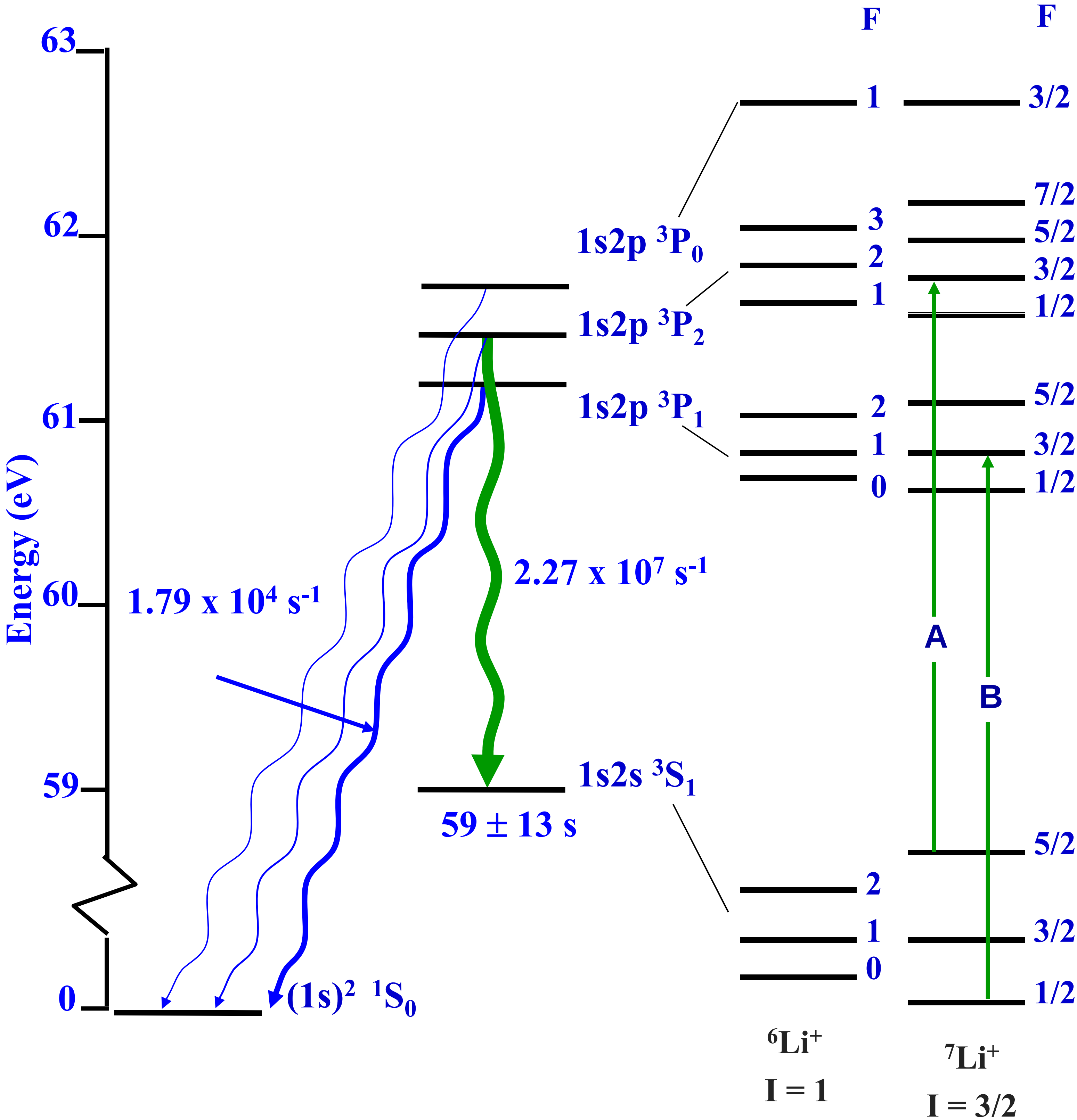
a) Measurement Technique

W. van Wijngaarden, Adv. At. Mol. Opt. Phys. **36**, 141 (1996)



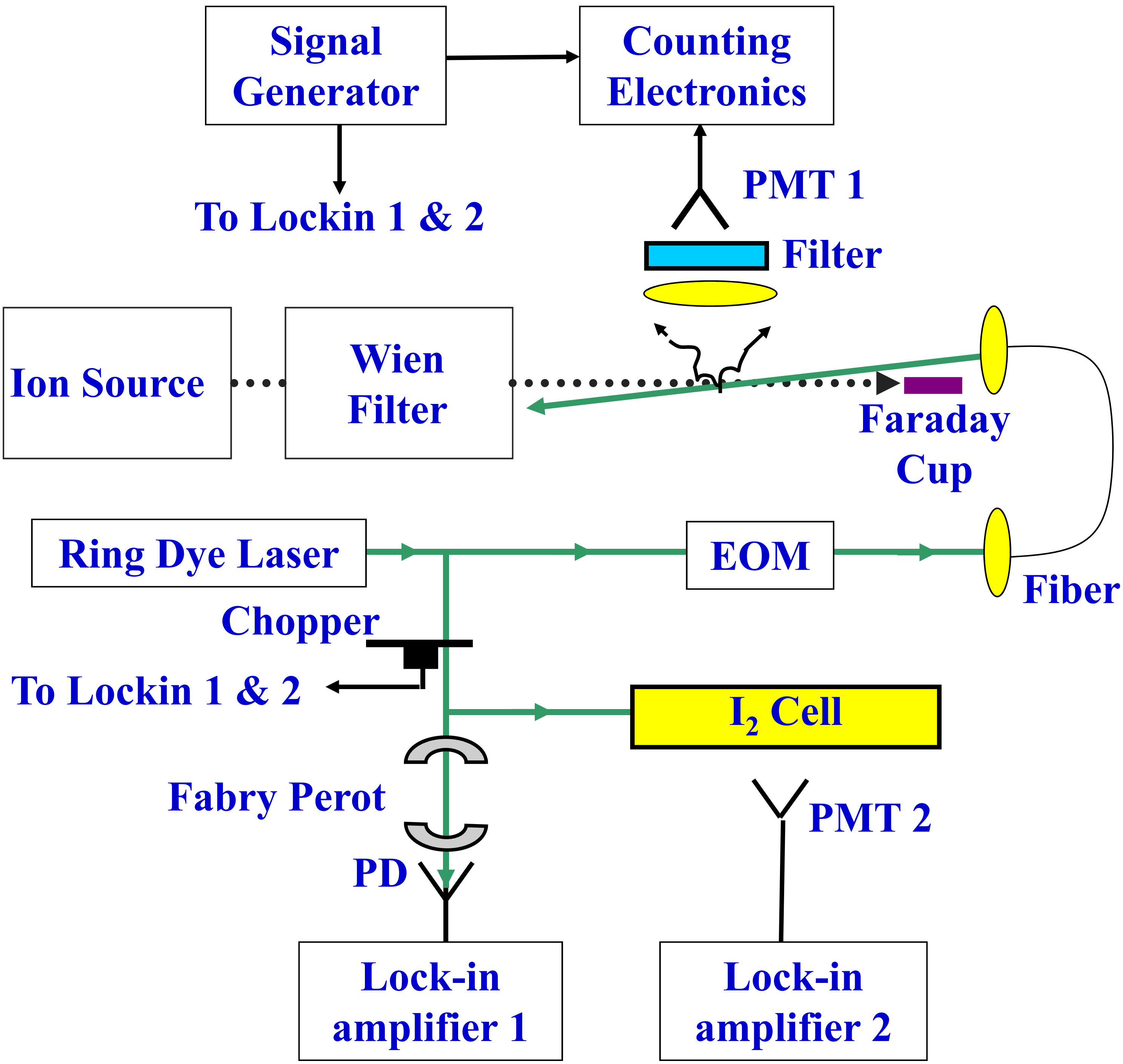
- Etalon peaks account for nonlinearity of laser scan
- Free spectral range found using EOM modulation frequency

Relevant Li^+ States & Hyperfine Levels

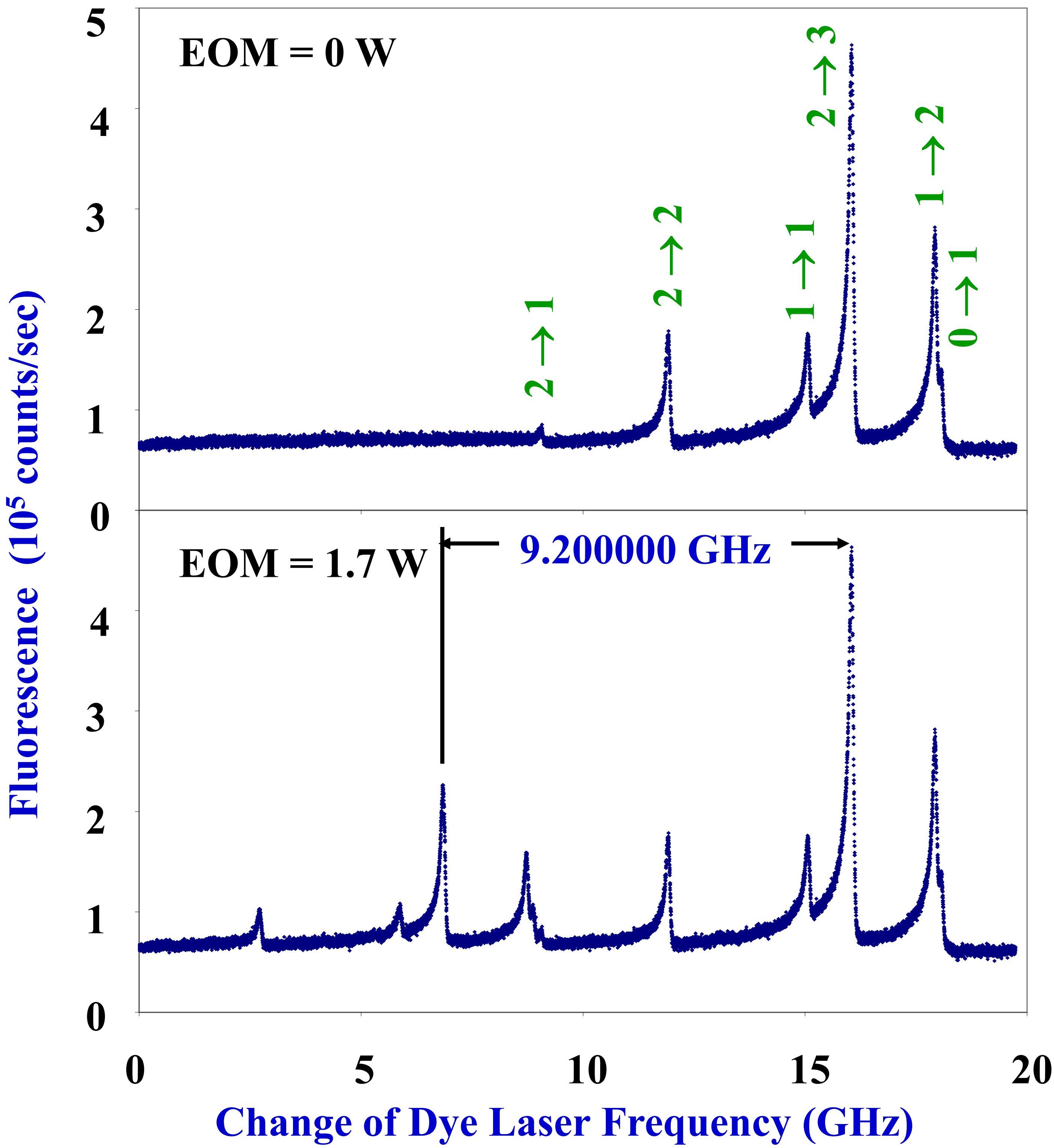


Apparatus for studying Li^+

J. Clarke & W. van Wijngaarden, PRA **67**, 012506 (2003)

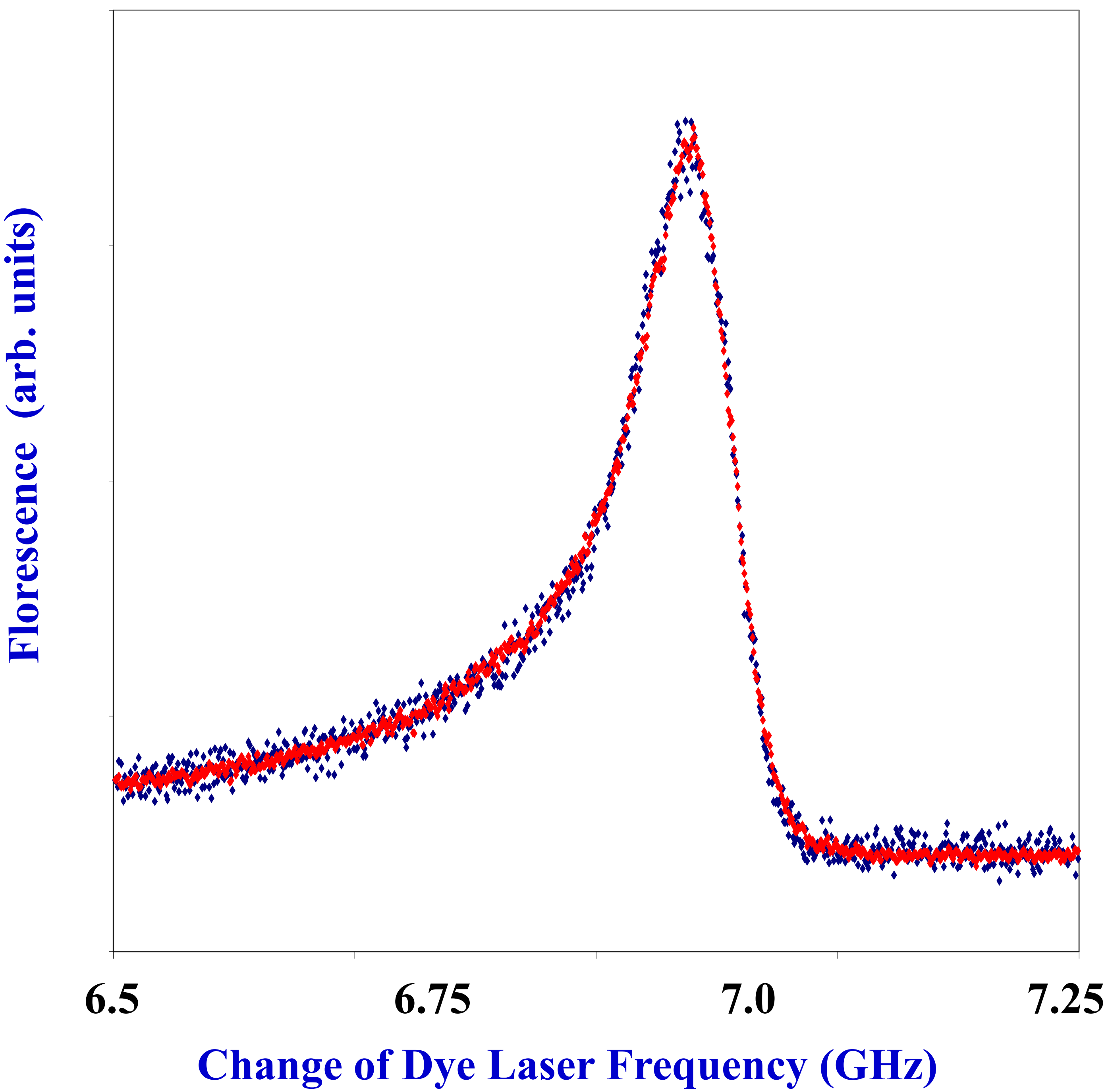


$^{6}Li^{+}$ 1s2s $^{3}S_{1}(F) \rightarrow$ 1s2p $^{3}P_{2}(F')$
with 9.2 GHz EOM



Determination of Frequency Intervals

Red peak excited by unshifted laser beam scaled & shifted to overlap **blue** peak produced by 9.2 GHz shifted laser beam.



$^{6}Li^{+}$ Hyperfine Intervals

State	Interval F → F'	Interval (MHz)	Technique
1s2s $^{3}S_{1}$	2 → 1	6,003.600 ± 0.050	Microwave[1]
		6,003.66 ± 0.51	Our Expt[2]
		6,003.614 ± 0.024	Theory[3]
	1 → 0	3,001.780 ± 0.050	Microwave[1]
		3,001.827 ± 0.47	Our Expt[2]
		3,001.765 ± 0.038	Theory[3]
1s2p $^{3}P_{1}$	2 → 1	2,888.98 ± 0.63	Our Expt[2]
		2,888.327 ± 0.029	Theory[3]
	1 → 0	1.316.06 ± 0.59	Our Expt[2]
		1,317.649 ± 0.046	Theory[3]
1s2p $^{3}P_{2}$	3 → 2	4,127.16 ± 0.76	Our Expt[2]
		4,127.882 ± 0.043	Theory[3]
	2 → 1	2,857.00 ± 0.72	Our Expt[2]
		2,858.002 ± 0.060	Theory[3]

1. J. Kowalski et al, Hyp Int **15** 159 (1983)
2. J. Clarke et al, PRA **67**, 12506 (2003)
3. E. Riis et al, PRA **49** 207 (1994)

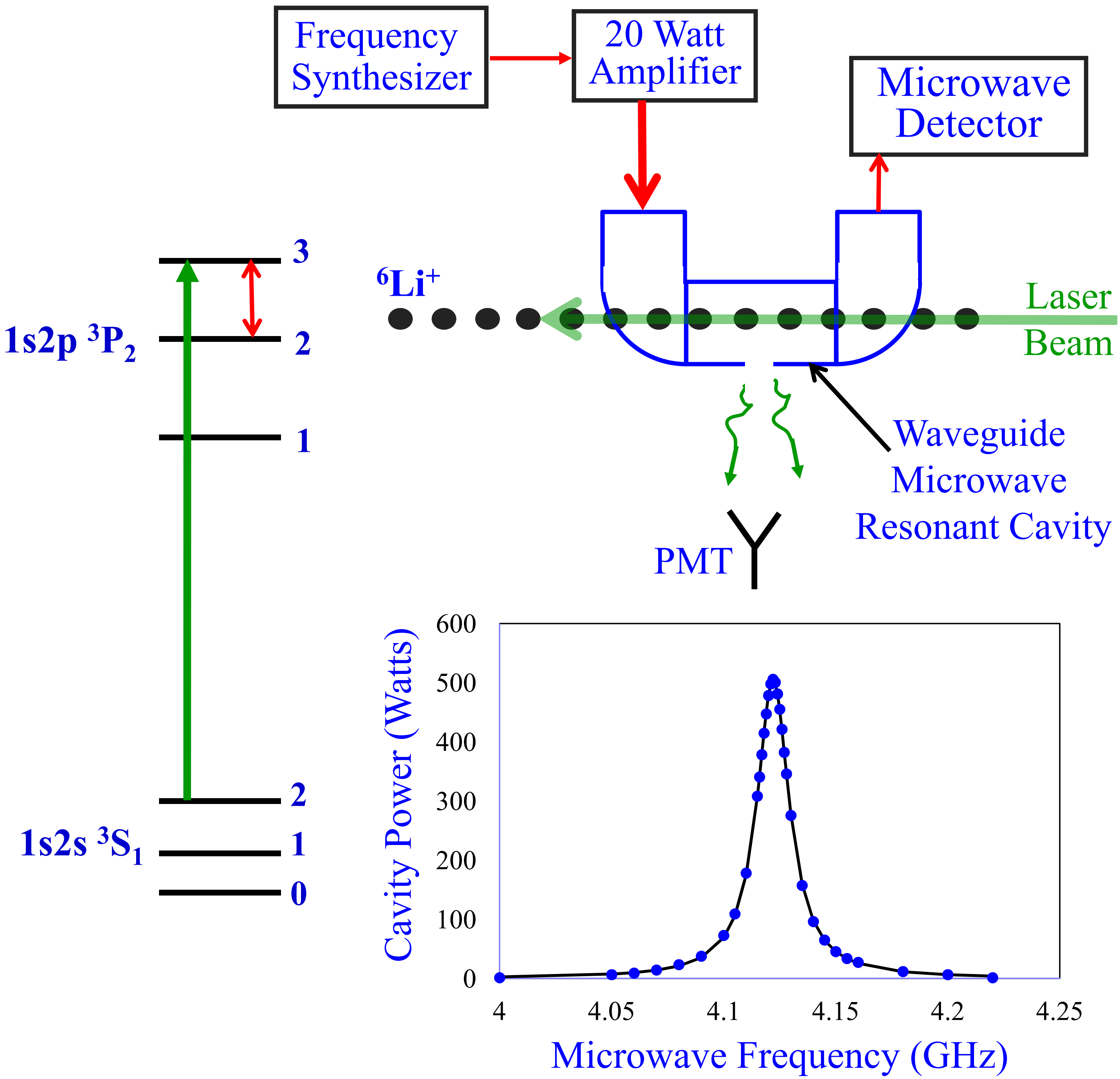
$^7Li^+$ 1s2p $^3P_{1-2}$ Fine Structure

Interval (MHz)		Technique
62,658	± 28	Laser Scan/Etalon[1]
62,678	± 14	Wavemeter[2]
62,682	± 6	Fast Beam[3]
62,667.4	± 2.0	Laser Heterodyne[4]
62,678.41	± 0.65	Fast Beam[5]
62,679.46	± 0.98	Our Expt[6]
62,679.4	± 0.5	Theory[7]

1. R. Bayer et al, Z. Phys. A **292**, 329 (1979)
2. R. Schwarzwald, Diplome Thesis, U. of Heidelberg (1982)
3. E. Riis et al, PRA **33**, 3023 (1986)
4. H. Rong et al, Z. Phys D **25**, 337 (1993)
5. E. Riis et al, PRA **49**, 207 (1994)
6. J. Clarke & WvW, PRA **67**, 12506 (2003)
7. T. Zhang et al, PRL, **77**, 1715 (1996)

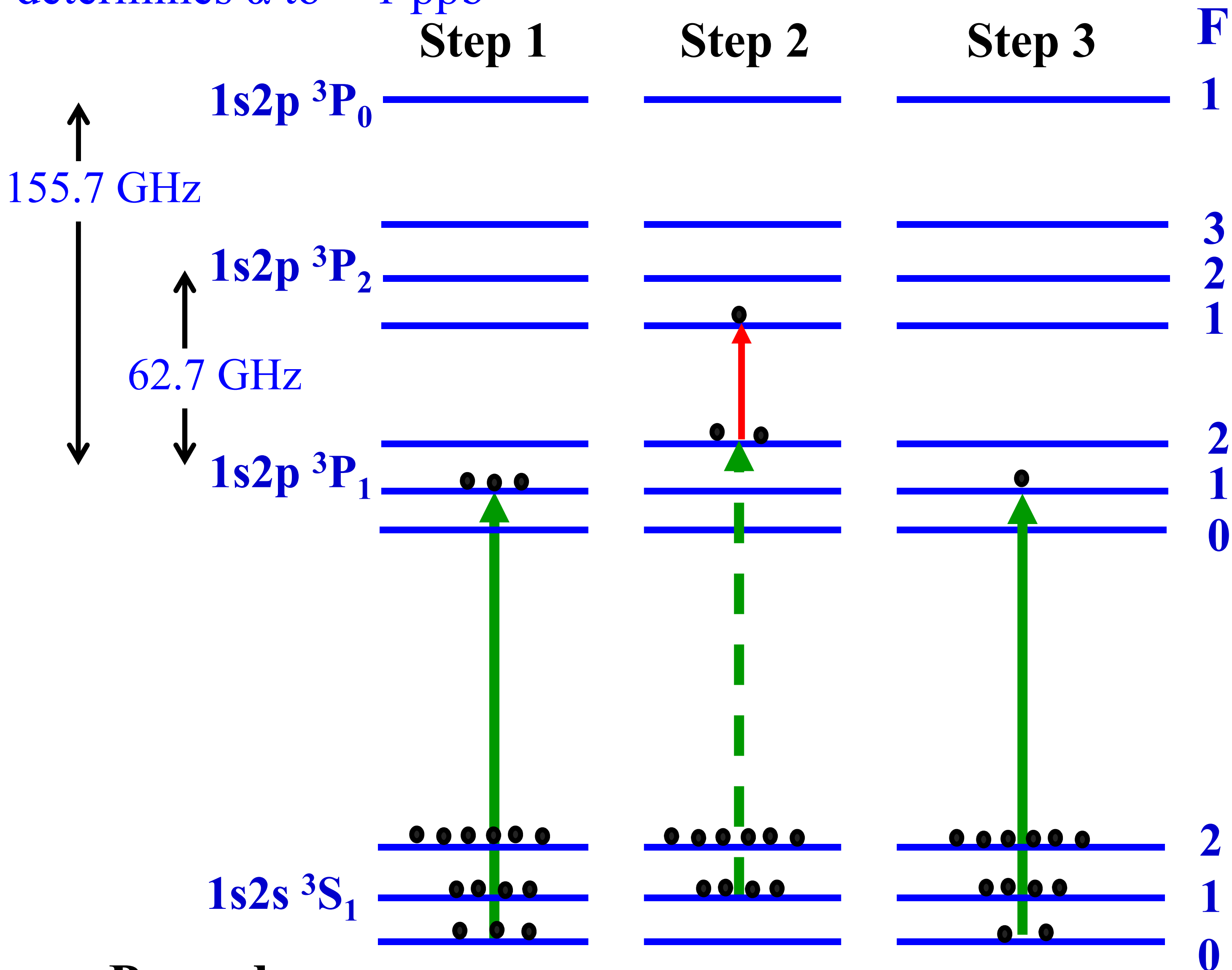
Ongoing Work: Optical Double Res. Expt.

Measure $^6Li^+$ 1s2p ^3P Hyperfine Interval



Proposal: Measure 1s2p ^3P Fine Structure

Measuring line center to 0.1% of transition natural linewidth determines α to ~ 1 ppb



Procedure

1) Optical Pumping depletes 1s2s $^3S_1$ (F=0) level.

2) AO shifted laser excites 1s2s $^3S_1$ (F=1) → 1s2p $^3P_1$ (F=2) & microwaves excite 1s2p $^3P_1$ (F=2)→ $^3P_2$ (F=1) transition.

3) Excite 1s2s $^3S_1$ (F=0) level & detect fluorescence to measure # transitions induced by microwaves

Determination of α

Motivation

Test QED and check possible time evolution of α predicted by cosmology & field theory. [1]

g-2 Experiment

Precise measurement of electron trapped in Penning trap determines g-2 to less than 1 part in 10^{12} [2]. QED then determines α with relative uncertainty of 4×10^{-10} [3]. This disagreed sharply with Quantum Hall, AC Josephson experiments etc. [4].

Atom Interferometry

$$\alpha^2 = 2R/c \;\; M/m \;\; h/M$$

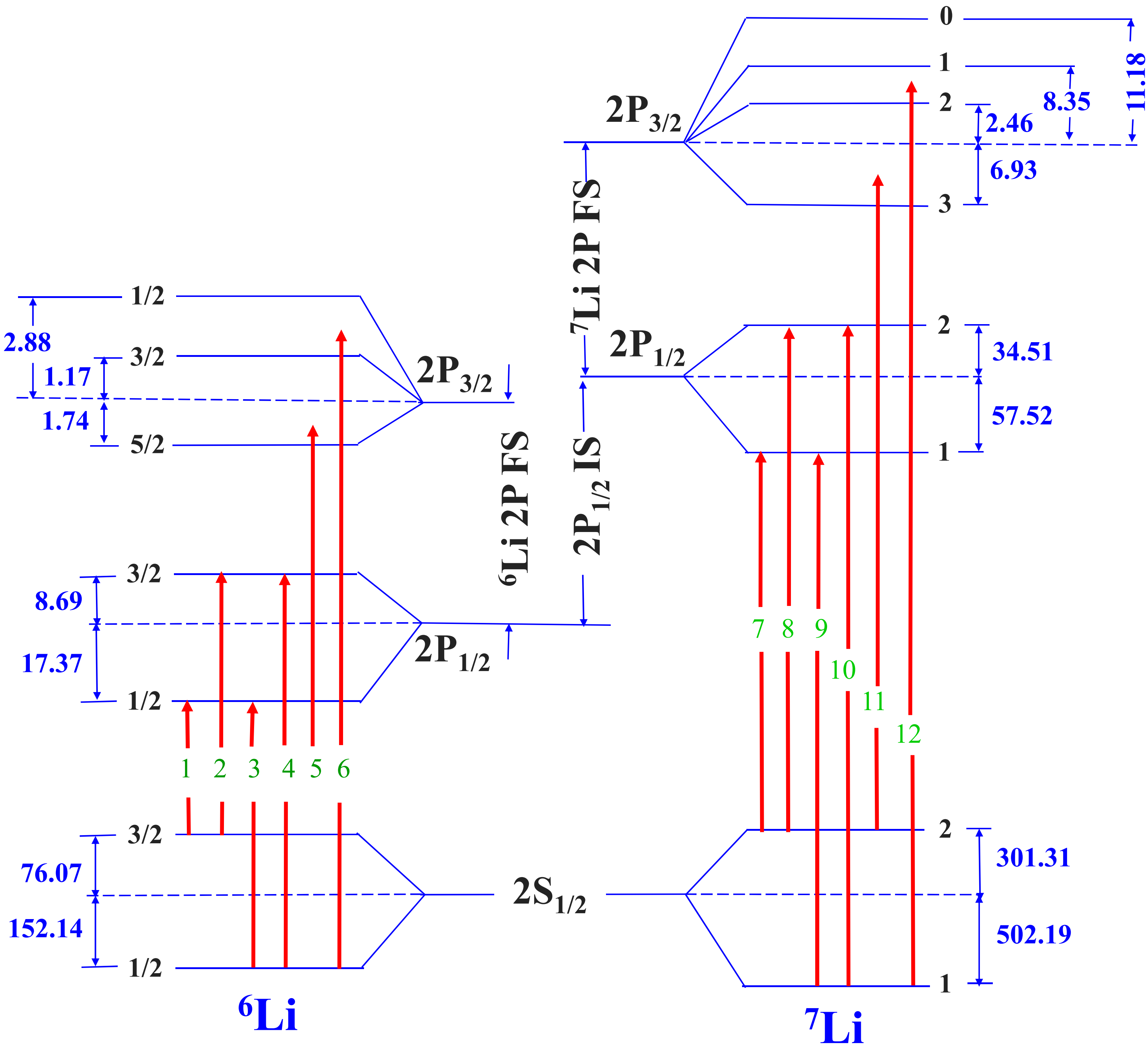
3 experiments measure:

1. Rydberg constant R with relative uncertainty of 7×10^{-12} [5]
2. Ratio of Atomic Mass M to electron mass m with relative uncertainty of 5×10^{-10} [6]
3. h/M found from recoil velocity $v_{rec} = \hbar k / M$ using an atom interferometer when atom absorbs photon. This has been done using ultracold Cs [4] & ^{87}Rb [7]. Value of 137.03599904(9) agrees with g-2 experiment.

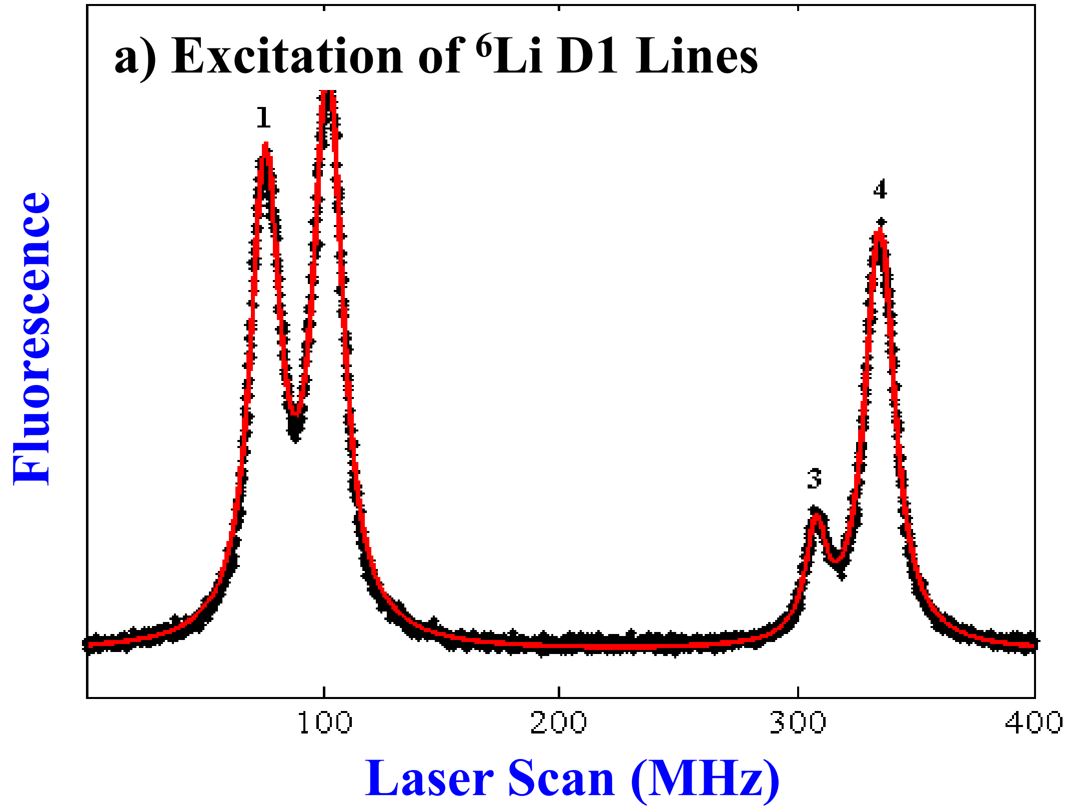
1. M. Murphy et al, PRL **99**, 239001 (2007)
2. D. Hanneke et al, PRL **100**, 120801 (2008)
3. T. Aoyama et al, PRL **99**, 110406 (2007)
4. A. Wicht et al, Phys. Scr. **T102**, 82 (2002)
5. P. Mohr et al, Rev. Mod. Phys. **80**, 633 (2008)
6. T. Udem et al, PRL **79**, 2646 (1997)
7. R. Boucendira et al, PRL **106**, 080801 (2011)

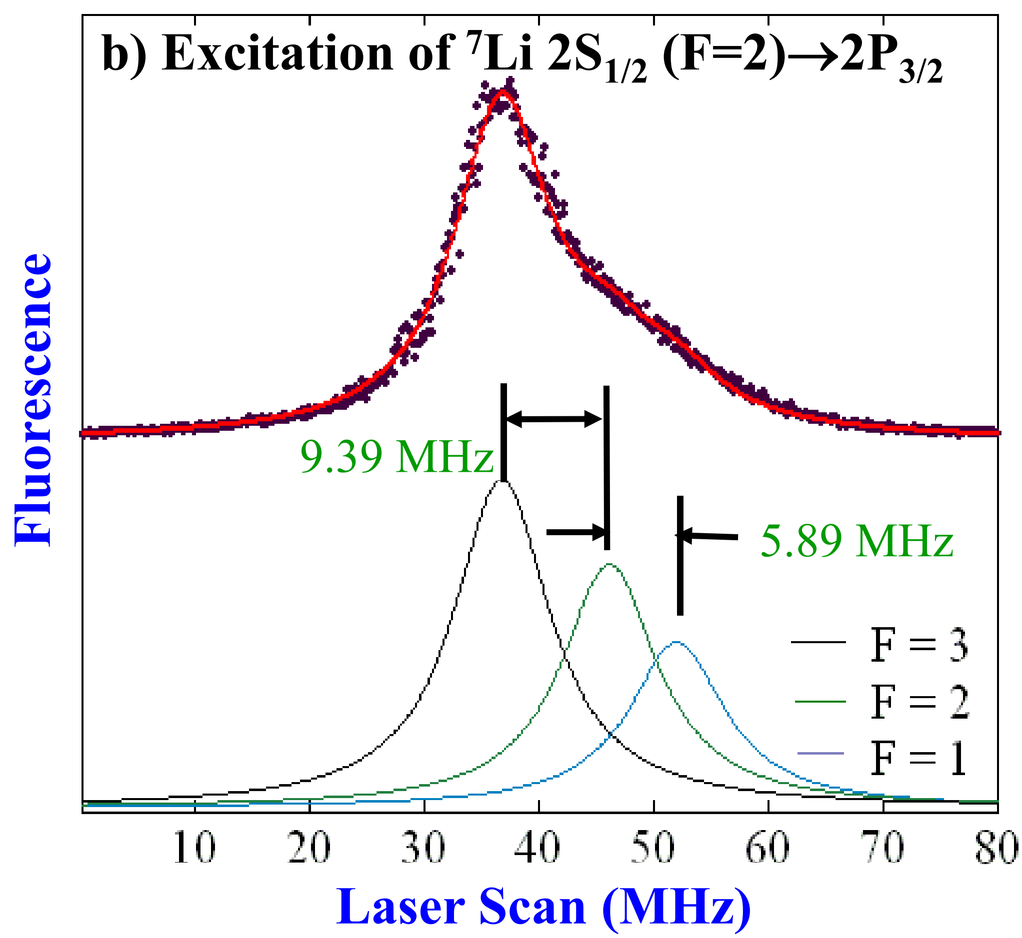
b) Relevant Li Energy Levels

(units in MHz)

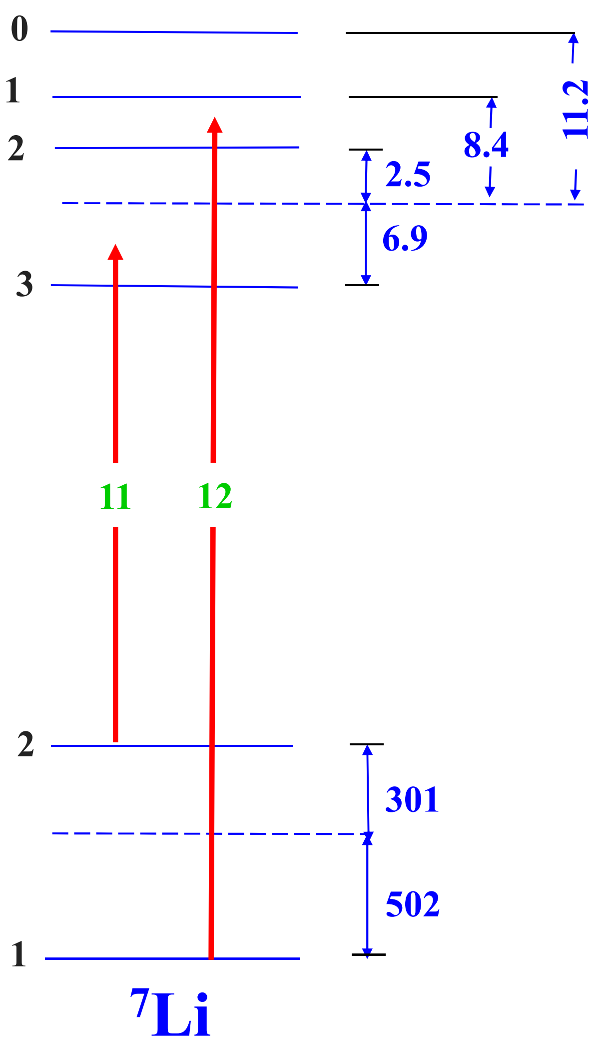


Study of Li D Lines



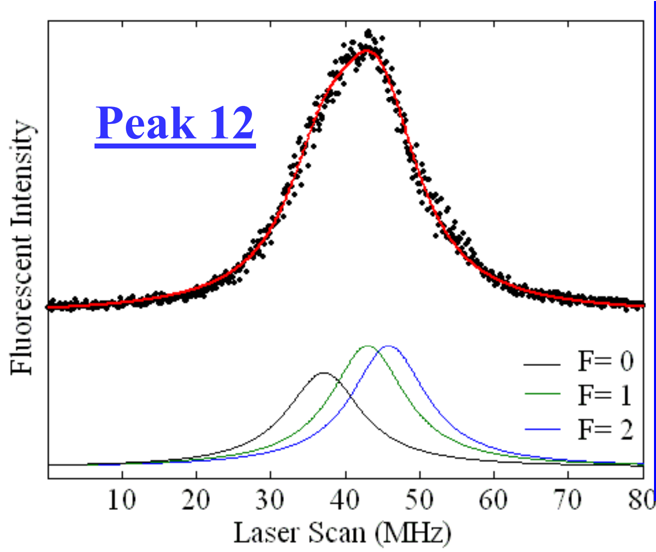


Determining Line Center to better than Natural Linewidth



$2P_{3/2}$ Hyperfine Spacing $\leq$ Natural Linewidth

- Optical pumping changes population of $2S_{1/2}$ m_F levels as atom passes through laser affecting contributions of $2P_{3/2}$ F = 0, 1, 2 levels to peak 12
- Fluoresence fraction due to various excited state hyperfine levels can be predicted and compared to observations.



$2P_{3/2}$ Hyperfine Level	**Predicted Contribution to Peak 12**	**Observed Contribution to Peak 12**
F = 0	28%	29%
F = 1	36%	34%
F = 2	36%	37%

2P Fine Structure Splitting

	Interval (MHz)	Technique
^{6}Li	10052.76 ± 0.22	Level Crossing[1]
	10051.62 ± 0.20	Laser Atomic Beam[2]
	10052.964 ± 0.050	Our Expt[3]
	10053.435 ± 0.021	Frequency Comb[4]
	10050.846 ± 0.012	Theory[6]
	10051.477 ± 0.008	Theory[7]
^{7}Li	10053.24 ± 0.22	Level Crossing[1]
	10053.184 ± 0.058	Optical Double Resonance[5]
	10053.4 ± 0.2	Laser Atomic Beam[2]
	10053.119 ± 0.058	Our Expt[3]
	10052.837 ± 0.022	Frequency Comb[4]
	10051.214 ± 0.012	Theory[6]
	10050.932 ± 0.008	Theory[7]

1. K. Brog et al, Phys. Rev. **153**, 91 (1966)
2. W. Scherf et al, Z. Phys. D **36**, 31 (1996)
3. G. Noble et al, PRA **74** 012502 (2006)
4. C. Sansonetti et al, PRL **107**, 023001 (2011)
5. H. Orth et al, Z. Phys. A **273**, 221 (1975)
6. Z. Yan et al, PRA **66**, 042504 (2002)
7. M. Puchalski et al, PRA **79**, 032510 (2009)

Relative Nuclear Charge Radius

$\Delta r_c^2 = r^2_c(^6Li) - r^2_c(^7Li) = (ISO_{meas} - E_{mass\ shift}) / C$ [1]

Reference	**Transition**	**ISO_{meas} (MHz)**	**$\Delta r_c^2 (fm^2)$**
Riis et al	$Li^+\ 2\ ^3S_1 - 2\ ^3P_0$	34747.73 ± 0.55	0.78 ± 0.06
	$Li^+\ 2\ ^3S_1 - 2\ ^3P_1$	34747.46 ± 0.67	0.78 ± 0.07
	$Li^+\ 2\ ^3S_1 - 2\ ^3P_2$	34748.91 ± 0.62	0.64 ± 0.06
Scherf et al	Li D1 line	10533.13 ± 0.15	0.42 ± 0.06
	Li D2 line	10534.93 ± 0.15	0.99 ± 0.06
GSI/TRIUMF Group	Li D1 line	10533.160 ± 0.068	0.43 ± 0.03
	$Li\ 2\ ^2S_{1/2} - 3\ ^2S_{1/2}$	11453.734 ± 0.030	0.58 ± 0.02
		11453.95 ± 0.13	0.72 ± 0.08
		11453.970 ± 0.034	0.73 ± 0.02
D. Das et al	Li D1 line	10534.215 ± 0.039	0.86 ± 0.02
	Li D2 line	10533.352 ± 0.068	0.34 ± 0.03
Our Work	Li D1 line	10534.039 ± 0.070	0.79 ± 0.03
	Li D2 line	10534.194 ± 0.104	0.69 ± 0.04
Sansonetti et al	Li D1 line	10533.763 ± 0.009	0.67 ± 0.01
	Li D2 line	10534.362 ± 0.029	0.76 ± 0.01

1. W. Nörterhauser et al, PRA, 83, 012516 (2011)

Comparison to Nuclear Theory & Electron Scattering

Transition	Δr_c^2 (fm^2)
Li^+ 2 ^3S – 2 ^3P	0.73 ± 0.04
Li 2 $^2S_{1/2}$ – 3 $^2S_{1/2}$	0.73 ± 0.02
Li D1 line	0.79 ± 0.03
Li D2 line	0.69 ± 0.04
Average	**0.74 ± 0.01**
Nuclear Theory [1]	0.74 ± 0.15
e^- Scattering [2]	0.79 ± 0.25

Using r_c (^{6}Li) = 2.53 ± 0.03 fm ⇒ Δr_c = 0.150 ± 0.003 fm

1. S. Pieper et al, Phys. Rev. C **64**, 014001 (2001)
2. C. W. de Jager et al, At. Nucl. Data Tables **36**, 495 (1987)

Observation of Halo Neutrons

Isotope	Δr_c^2 (fm)^2	Charge Radius fm	Mass Radius[2] fm
^{6}Li		2.53 ± 0.03	2.35 ± 0.03
^{7}Li	0.74 ± 0.01	2.38 ± 0.03	2.35 ± 0.03
^{8}Li	1.23 ± 0.03[1]	2.27 ± 0.03	2.38 ± 0.02
^{9}Li	1.66 ± 0.03[1]	2.18 ± 0.04	2.32 ± 0.02
^{11}Li	0.54 ± 0.07[1]	2.42 ± 0.04	3.10 ± 0.17

Mass radii determined by scattering incoming accelerated beam of Li^+ from target nuclei & measuring interaction cross section.

$$\sigma = \pi (R_I^2 + R_T^2)$$

Various targets (Be, C Al) used to separately determine radii of incoming R_I & target R_T nuclei.

1. W. Nörterhauser et al, PRA **83**, 012516 (2011)
2. I. Tanihata et al, Phys. Lett. B **206**, 592 (1988)

Conclusions

Li^+ 1s2s ^3S - 1s2p ^3P Transition

- Hyperfine intervals of $^6Li^+$ 1s2p ^3P state order of magnitude more accurate than previous work
- Discrepancy of 1s2p Li^+ fine structure resolved
- Excellent agreement between theory & experiment for Li^+, a 2 electron system

Ongoing Work

- Improve 1s2p ^3P Li^+ fine/hyperfine structure by order of magnitude to test QED & determine α.

Neutral Li

- 2P Fine Structure
  a) Discrepancies between values found by 2 theory groups
  b) Theoretical values are several MHz lower than results of several experiments using different techniques
- Optically measured isotope shifts & theory yield relative nuclear charge radii to ~ 1 x 10^{-18} meter.

We understand how Li electrons interact with nucleus better than how macroscopic electron beam scatters from a nucleus – an impressive achievement of atomic theory & experiment.