Precision Measurement of Li Hyperfine & Fine Structure

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Why study Li^+/Li?

1. **Test QED**
   Effects scale 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 & 3 electron systems now "well understood" using Hylleraas Variational calculations [2,3].

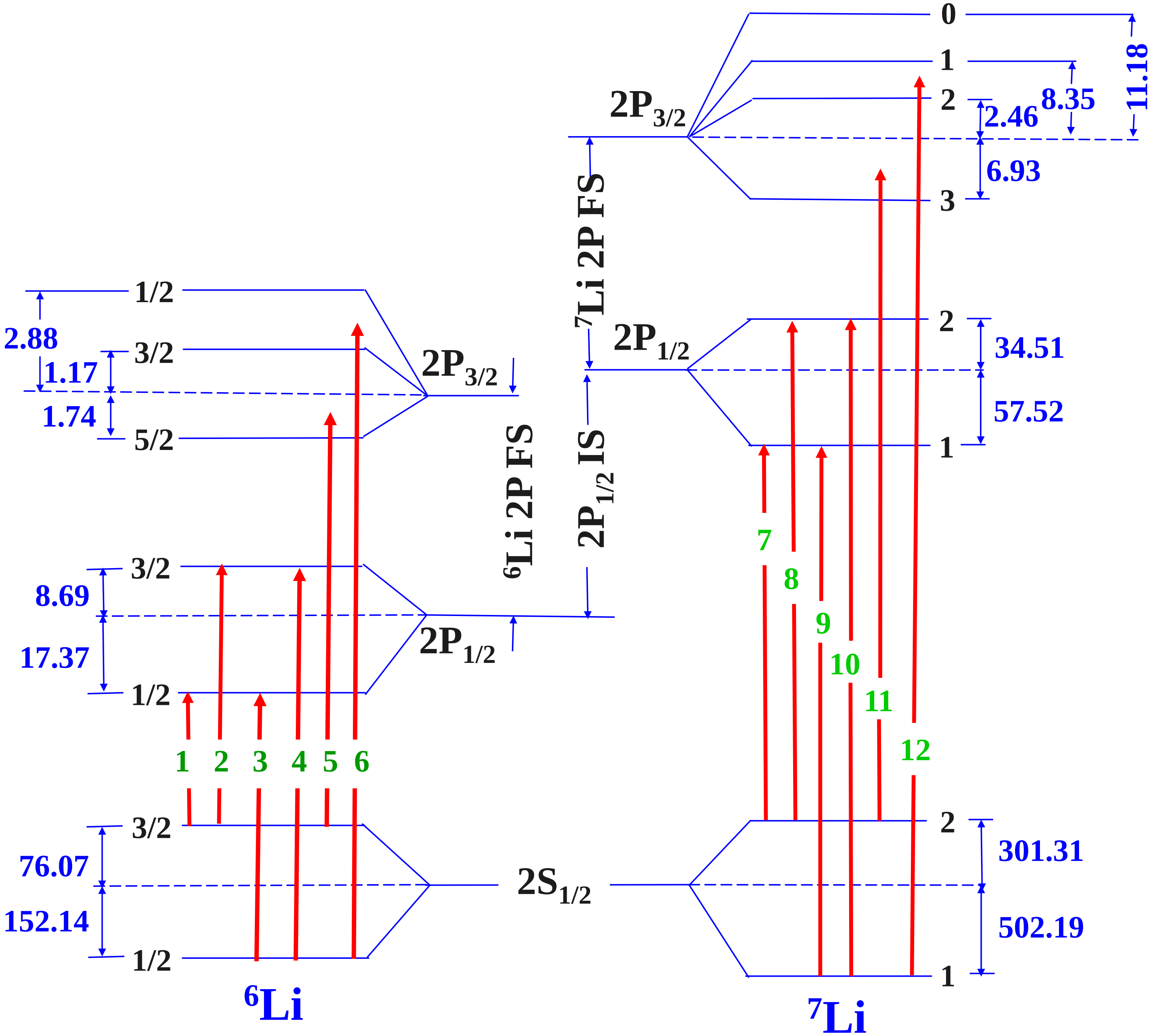
3. **Nuclear Probe**
   Measured isotope shifts + theory yield relative nuclear charge radii r_c with accuracies $< 1 \times 10^{-17}$ meter, more accurate than electron scattering.

$$E_{nuc} = 2\pi/3\, Z\, e^2\, r_c^2 < \Sigma_i\, \delta\, (r_i) >$$

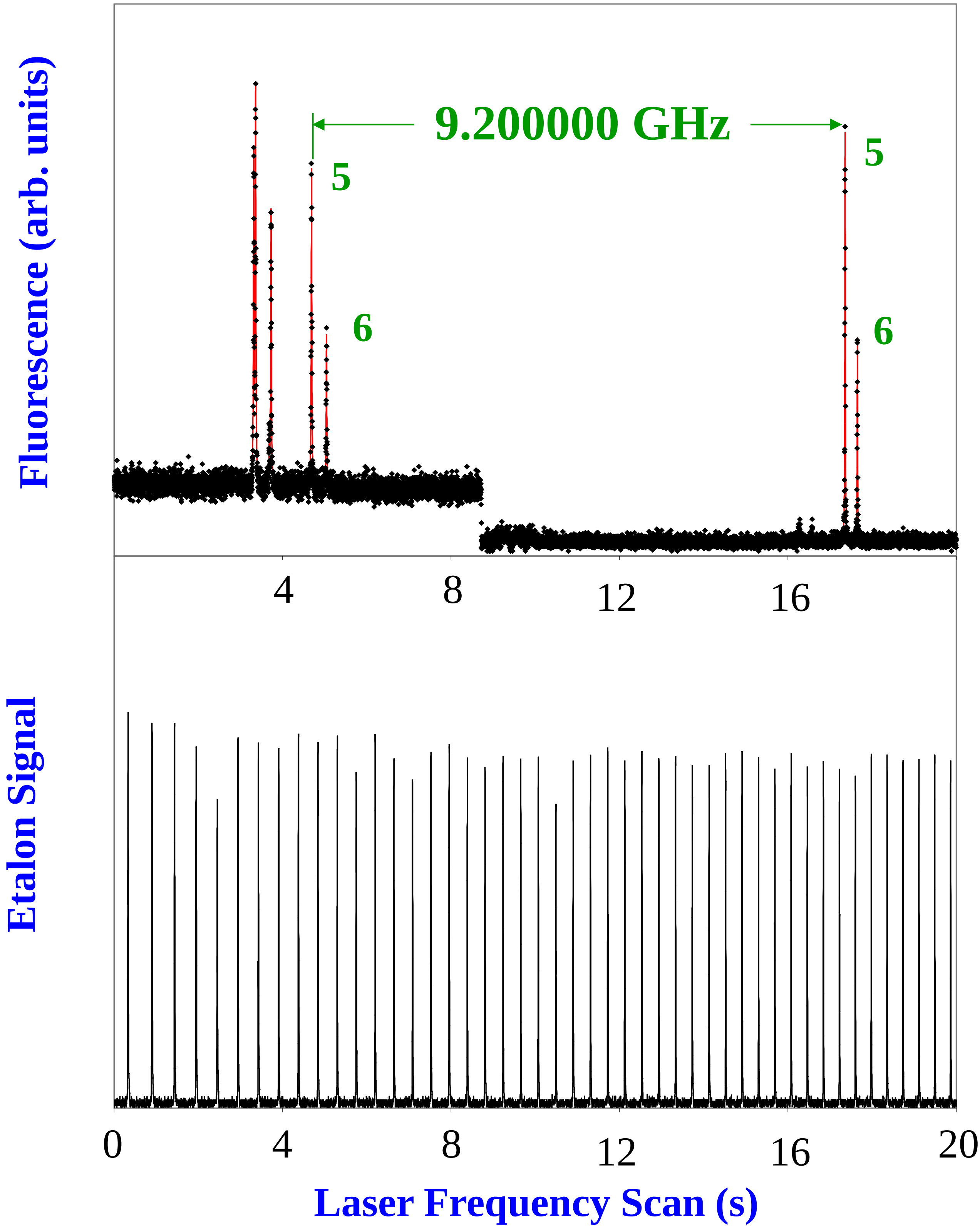
   Ideal for studying halo neutrons $^{6,7,8,9,11}Li$ [4], relevant in light of discrepancies determining proton radius [5].

1. WvW & B. Jian Eur. Phys. J. **222**, 2057 (2013)
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)

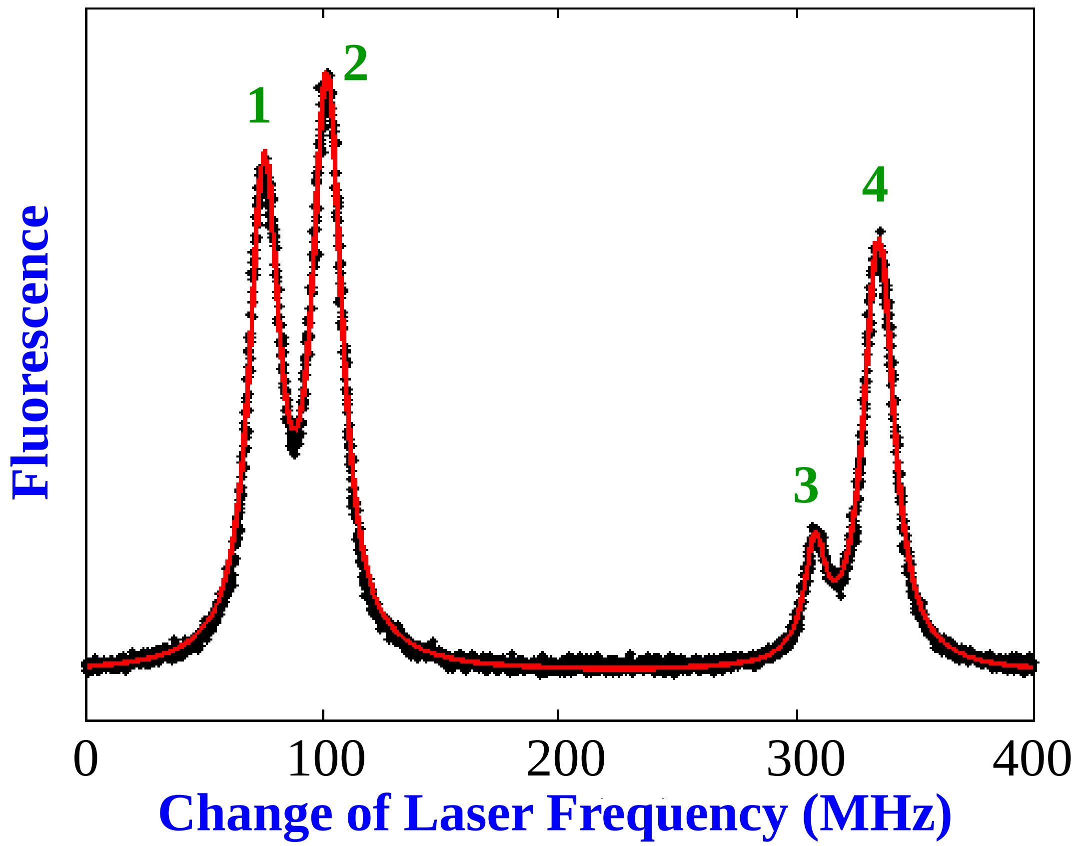
I: Neutral Lithium
Fine/Hyperfine Levels of Li D Lines
(units of MHz)

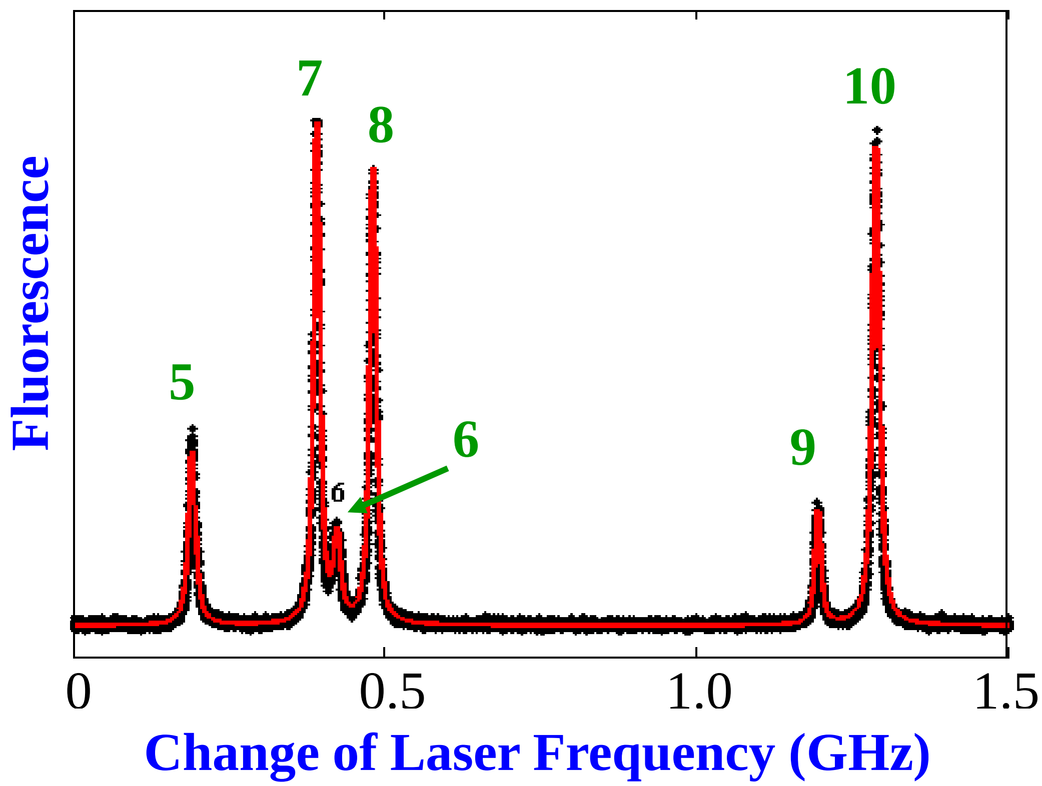


Excitation of ^{6}Li D Lines

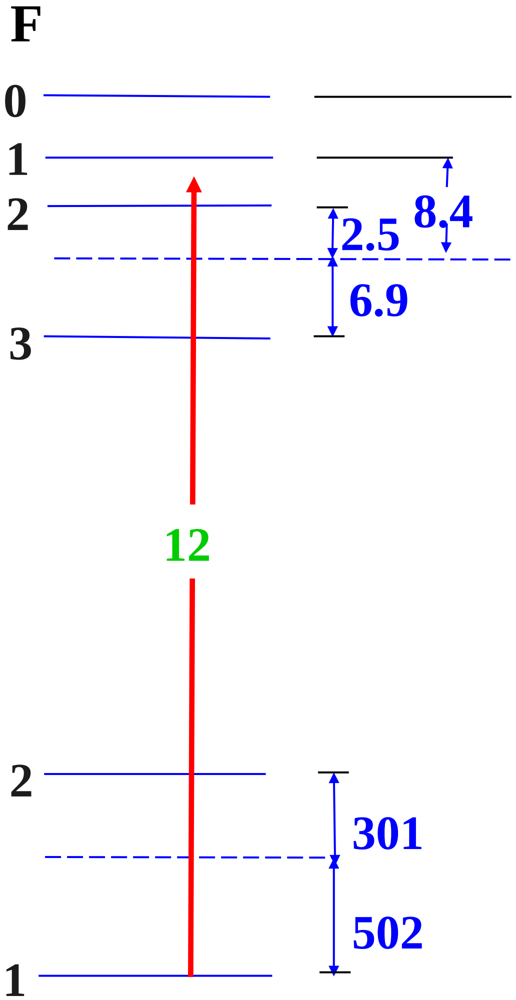


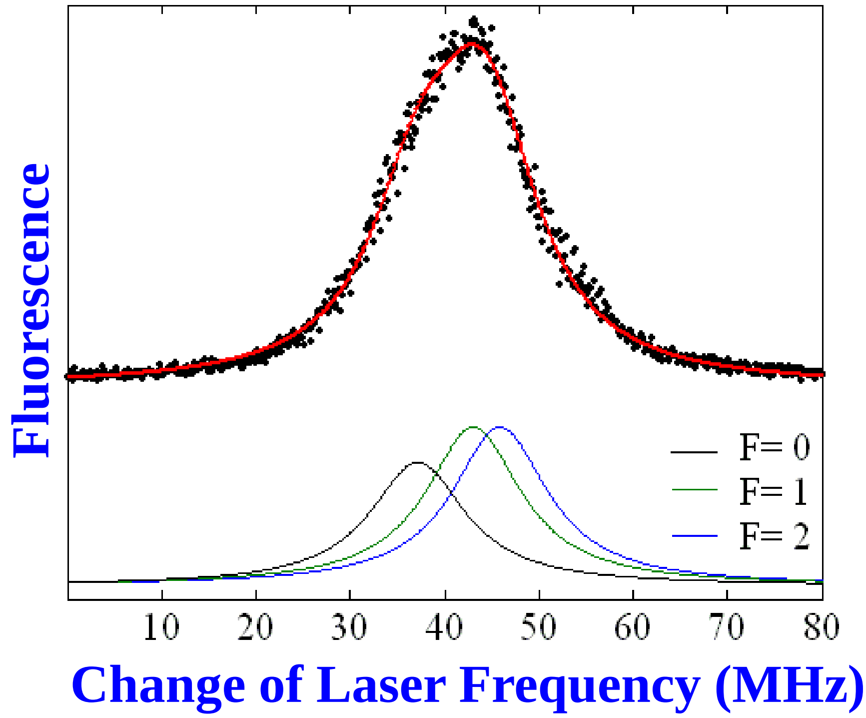
Excitation of ^{6,7}Li D Lines





Determining Line Center of ^{7}Li D2 Line Peak 12





- Optical pumping changes population of $2S_{1/2}$ m_F levels as atom passes through laser beam affecting contributions of $2P_{3/2}$ F = 0, 1, 2 levels to peak 12

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

2P Fine Structure Splitting

	Interval (MHz)	Technique
^{6}Li	10052.964 ± 0.050	Our Work [1]
	10053.435 ± 0.021	Frequency Comb [2]
	10052.779 ± 0.017	Frequency Comb [3]
	10052.477 ± 0.008	Theory [5]
	10052.72 ± 0.06	Theory [6]
^{7}Li	10053.184 ± 0.058	Optical Double Resonance [4]
	10053.119 ± 0.058	Our Work [1]
	10052.837 ± 0.022	Frequency Comb [2]
	10053.310 ± 0.017	Frequency Comb [3]
	10050.932 ± 0.008	Theory [5]
	10053.25 ± 0.06	Theory [6]

1. G. Noble et al, PRA **74** 012502 (2006)
2. C. Sansonetti et al, PRL **107**, 023001 (2011)
3. R. Brown et al, PRA 87, 032504 (2013)
4. H. Orth et al, Z. Phys. A **273**, 221 (1975)
5. M. Puchalski et al, PRA **79**, 032510 (2009)
6. M. Puchalski et al, PRL **113**, 073004 (2014)

^{6,7}Li Relative Nuclear Charge Radius

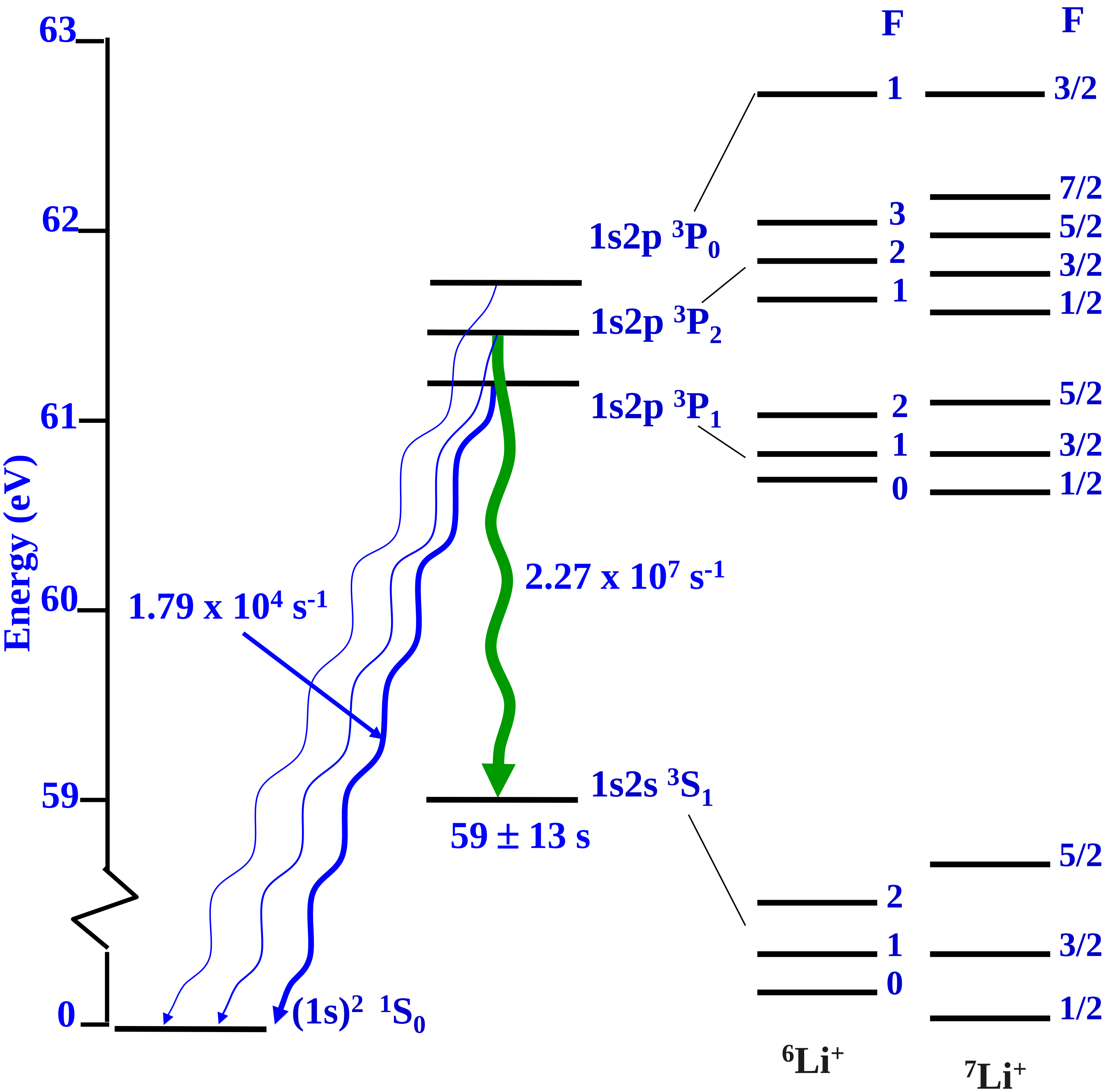
$$\Delta r_c^2 = r^2_c(^6\text{Li}) - r^2_c(^7\text{Li}) = (ISO_{meas} - E_{mass\ shift}) / C_{theory} \quad [1]$$

Reference	**Transition**	$\Delta r_c^2(\text{fm}^2)$	**Average** $\Delta r_c^2(\text{fm}^2)$
Riis [2]	$Li^+\ 2\ ^3S_1 - 2\ ^3P_0$	0.78 ± 0.06	0.733 ± 0.036
	$Li^+\ 2\ ^3S_1 - 2\ ^3P_1$	0.78 ± 0.07	
	$Li^+\ 2\ ^3S_1 - 2\ ^3P_2$	0.64 ± 0.06	
GSI/ TRIUMF[3]	$Li\ 2\ ^2S_{1/2} - 3\ ^2S_{1/2}$	0.72 ± 0.08	0.731 ± 0.022
		0.73 ± 0.02	
Our Work [4]	Li D1 line	0.79 ± 0.03	0.736 ± 0.024
	Li D2 line	0.69 ± 0.04	
NIST [5]	Li D1 line	0.67 ± 0.01	0.700 ± 0.003
	Li D2 line	0.70 ± 0.01	
		Unweighted Average	**0.725 ± 0.017**
		e- Scattering [6]	**0.79 ± 0.25**

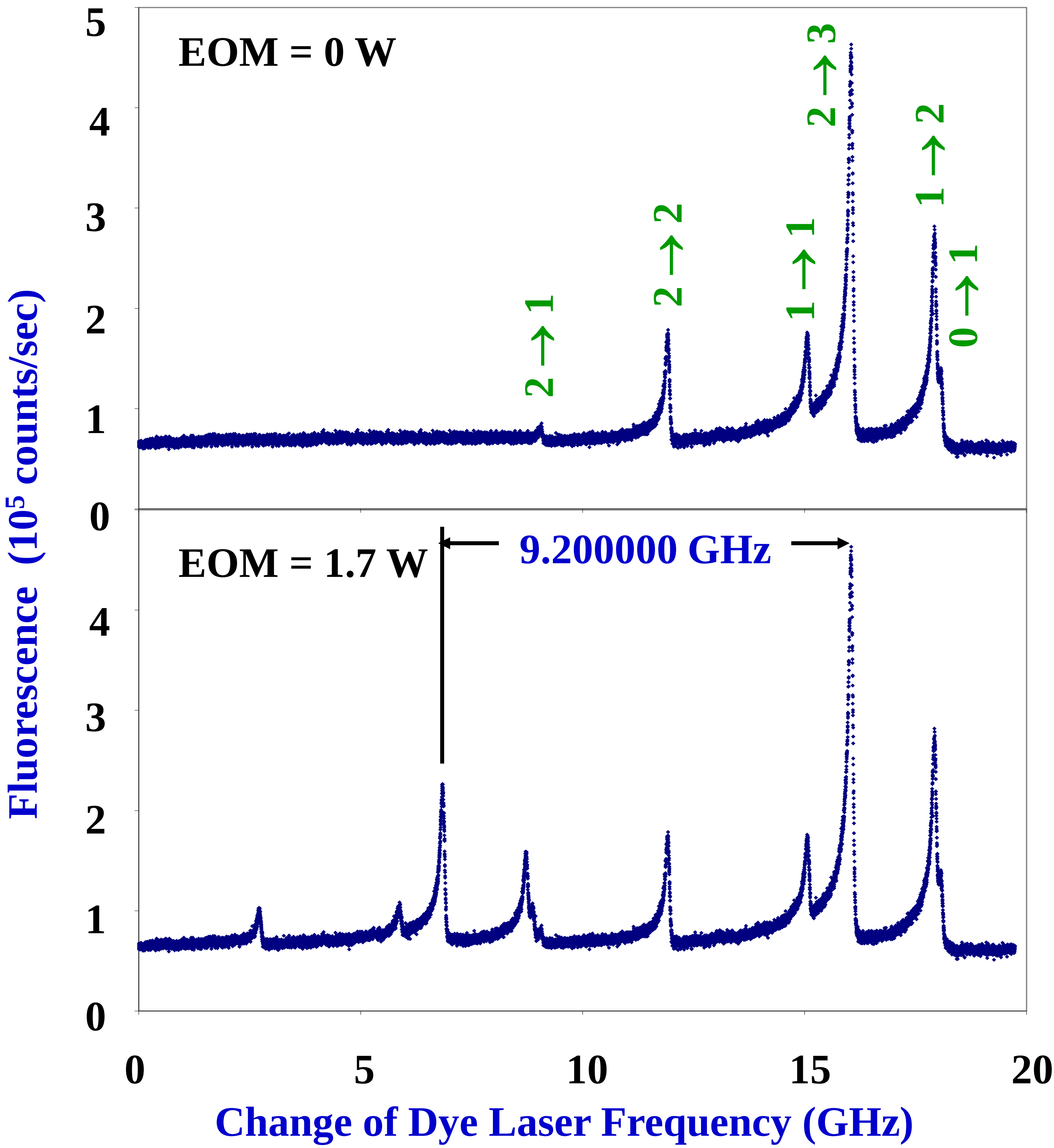
Using r_c (^{6}Li) = 2.53 ± 0.03 fm $\Rightarrow \Delta r_c = 0.150 \pm 0.003$ fm

1. W. Nörterhauser et al, PRA, 83, 012516 (2011)
2. E. Riis et al, PRA **49**, 207 (1994)
3. B. Bushaw et al, PRL **91**, 043004 (2003)
4. G. Noble et al, PRA **74** 012502 (2006)
5. R. Brown et al, PRA , 87, 032504 (2013)
6. H. de Vries et al, At. Nucl. Tables 36, 495 (1987)

II. Relevant Li^+ States
Fine & Hyperfine Levels



$^6Li^+$ 1s2s $^3S_1(F) \rightarrow$ 1s2p $^3P_2(F')$ with 9.2 GHz EOM



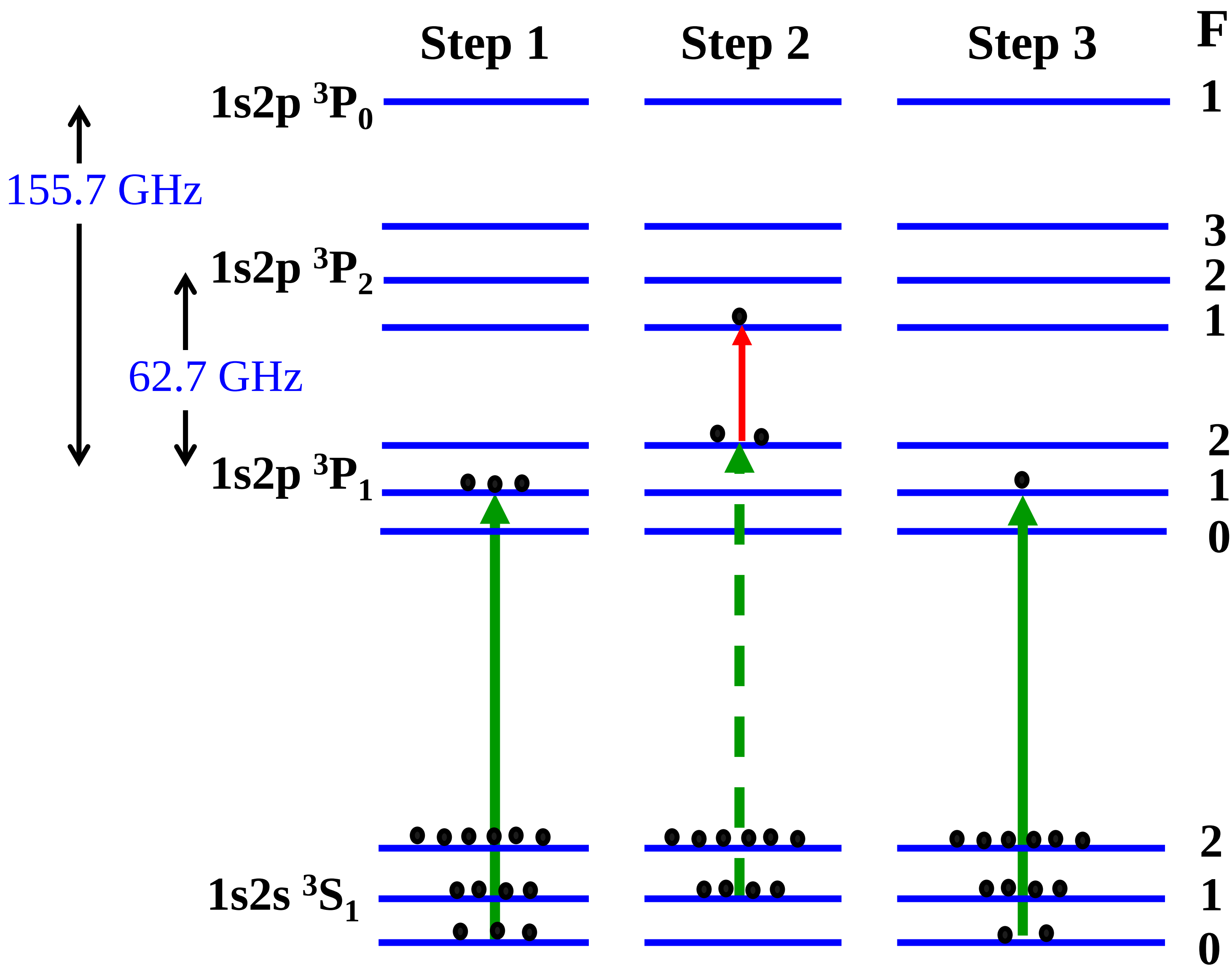
$^{6}Li^{+}$ Hyperfine Intervals

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

Proposed Fine Structure Measurement

Measure fine structure to < 0.1% of transition natural linewidth determines α to ~ 1 ppb

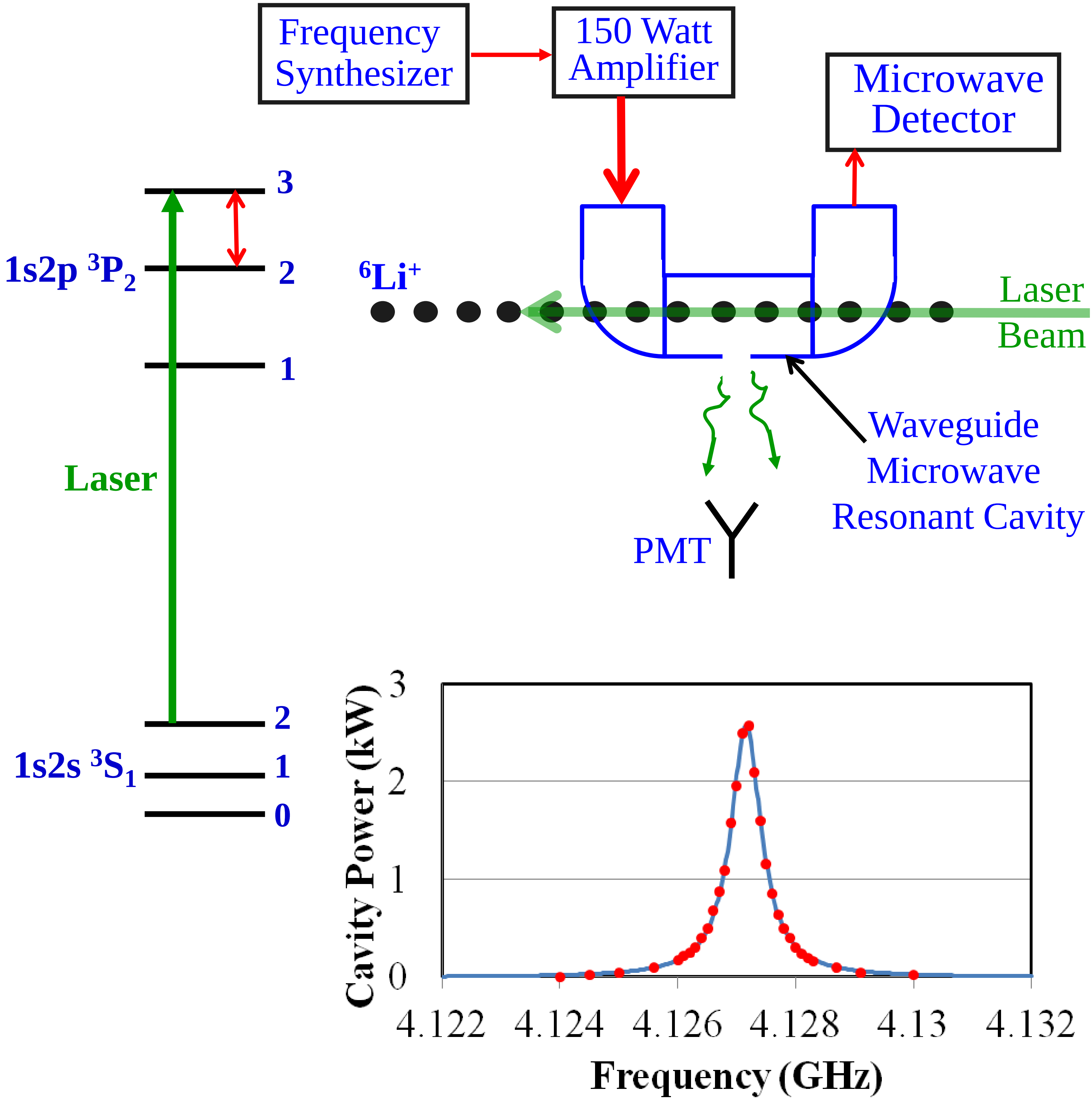


1) Optical Pumping depletes 1s2s $^3S_1$ (F=0) level

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

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



Conclusions

Neutral Li

- 2P fine structure theory now agrees with experiment
- Halo neutrons in ^{11}Li - different mass/charge nuclear radius
- Optically measured isotope shifts & theory yield relative nuclear charge radii to parts times 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.

Lithium Ion

- Hyperfine intervals of $^{6}Li^{+}$ 1s2p ^{3}P state order of magnitude more accurate than previous work
- Discrepancy of 1s2p Li^{+} fine structure resolved
- Excellent agreement between theory & experiment

Ongoing Work

- Improve 1s2p ^{3}P Li^{+} fine/hyperfine structure by order of magnitude to test QED & develop independent measurement of α to ppb.

Fine Structure Constant α

Motivation

Test QED & 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 gives α with relative uncertainty of 4 x 10^{-10} [3]. This disagrees with Quantum Hall, AC Josephson experiments etc. [4].

Atom Interferometry

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

1. Rydberg constant R with relative uncertainty of 7 x 10^{-12} [5]
2. Ratio of Atomic Mass M to electron mass m with relative uncertainty of 5 x 10^{-10} [6]
3. h/M found from recoil velocity $v_{rec} = \hbar k/M$ using atom interferometer when ultracold Cs or ^{87}Rb absorbs photon [4,7].

1/α =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)