Strontium Rydberg gases (and ultra-cold plasmas)

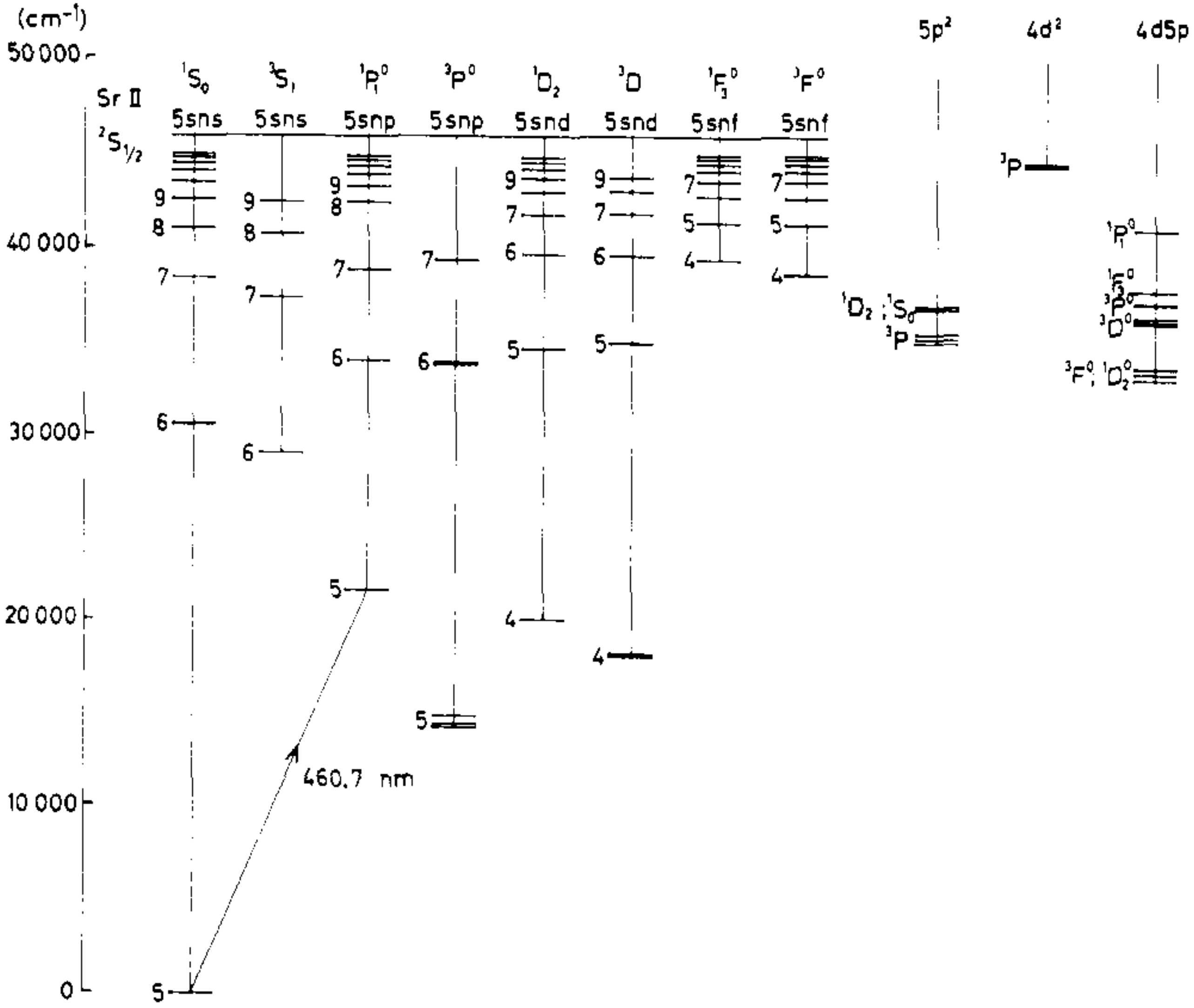
Matt Jones

Durham University

Outline

1. Rydberg spectrum of two-electron atoms
2. Autoionization and MQDT
3. Future directions

Rydberg spectrum of two electron atoms



From J. R. Rubbmark and S. A. Borgstrom, Physica Scripta **18**, 196-208 (1978)

Rydberg spectrum of two electron atoms

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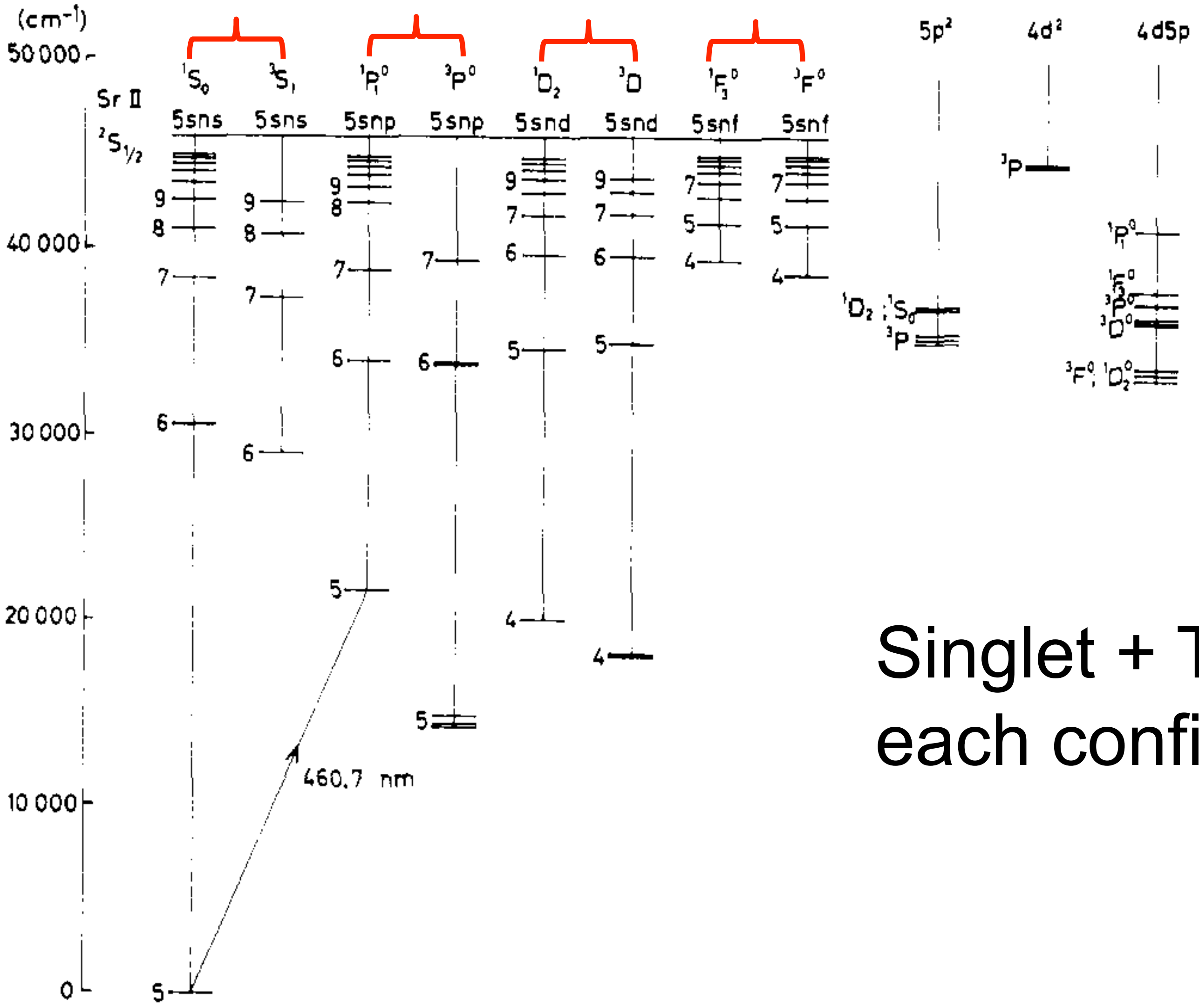

Singlet + Triplet for each configuration

From J. R. Rubbmark and S. A. Borgstrom, Physica Scripta **18**, 196-208 (1978)

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Rydberg spectrum of two electron atoms

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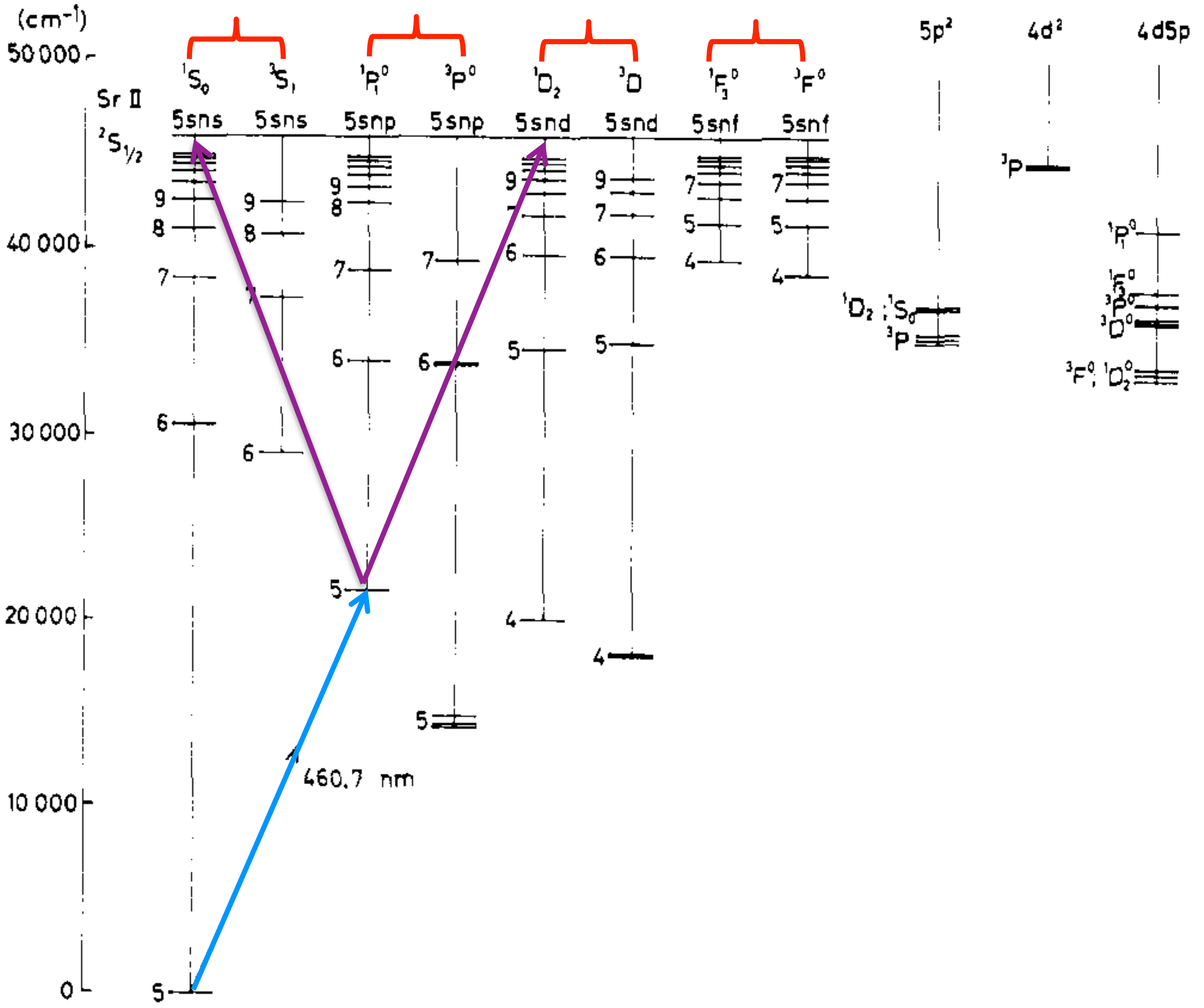
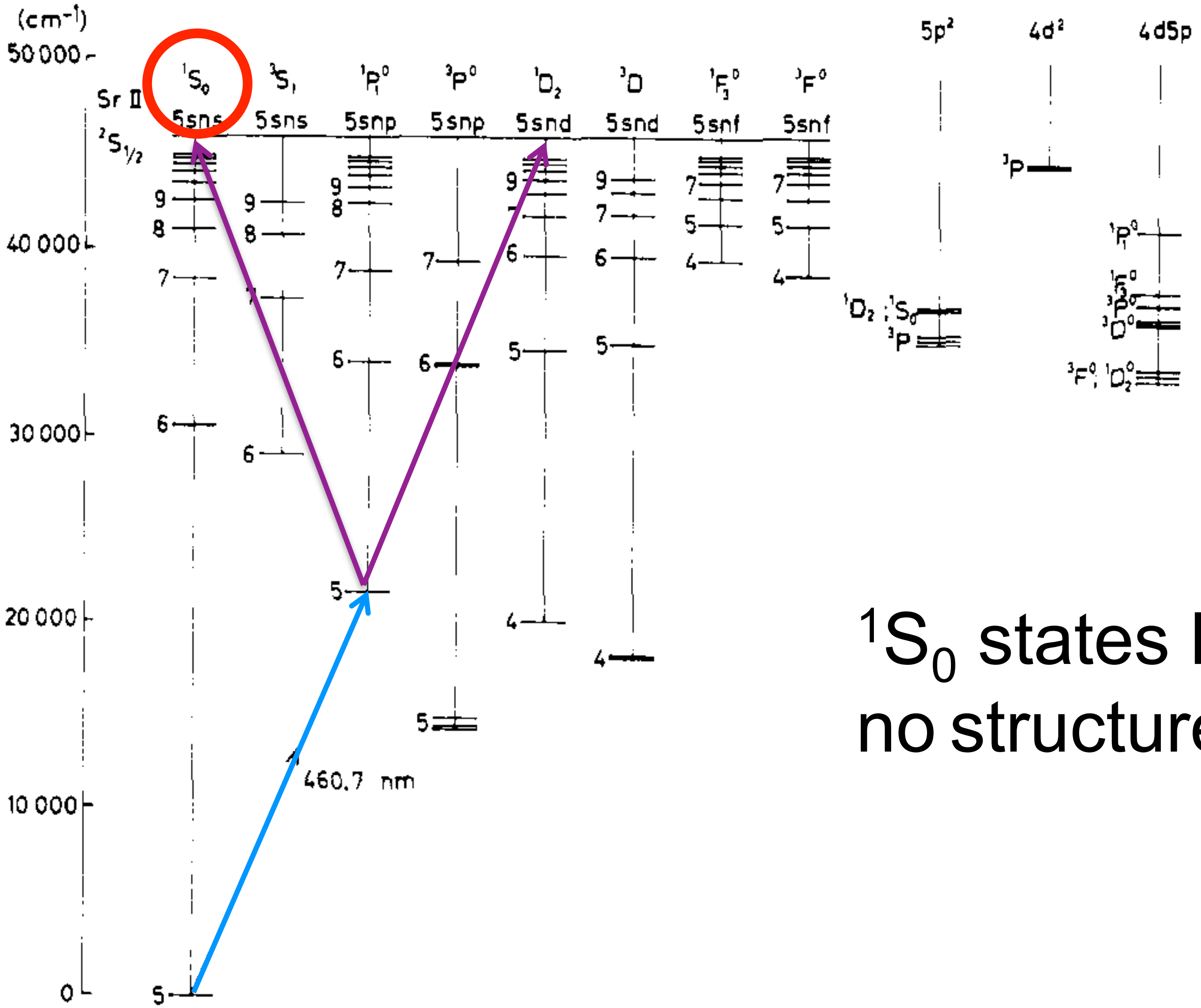


From J. R. Rubbmark and S. A. Borgstrom, Physica Scripta **18**, 196-208 (1978)

Rydberg spectrum of two electron atoms



$^1S_0$ states have no structure

From J. R. Rubbmark and S. A. Borgstrom, Physica Scripta **18**, 196-208 (1978)

Rydberg spectrum of two electron atoms

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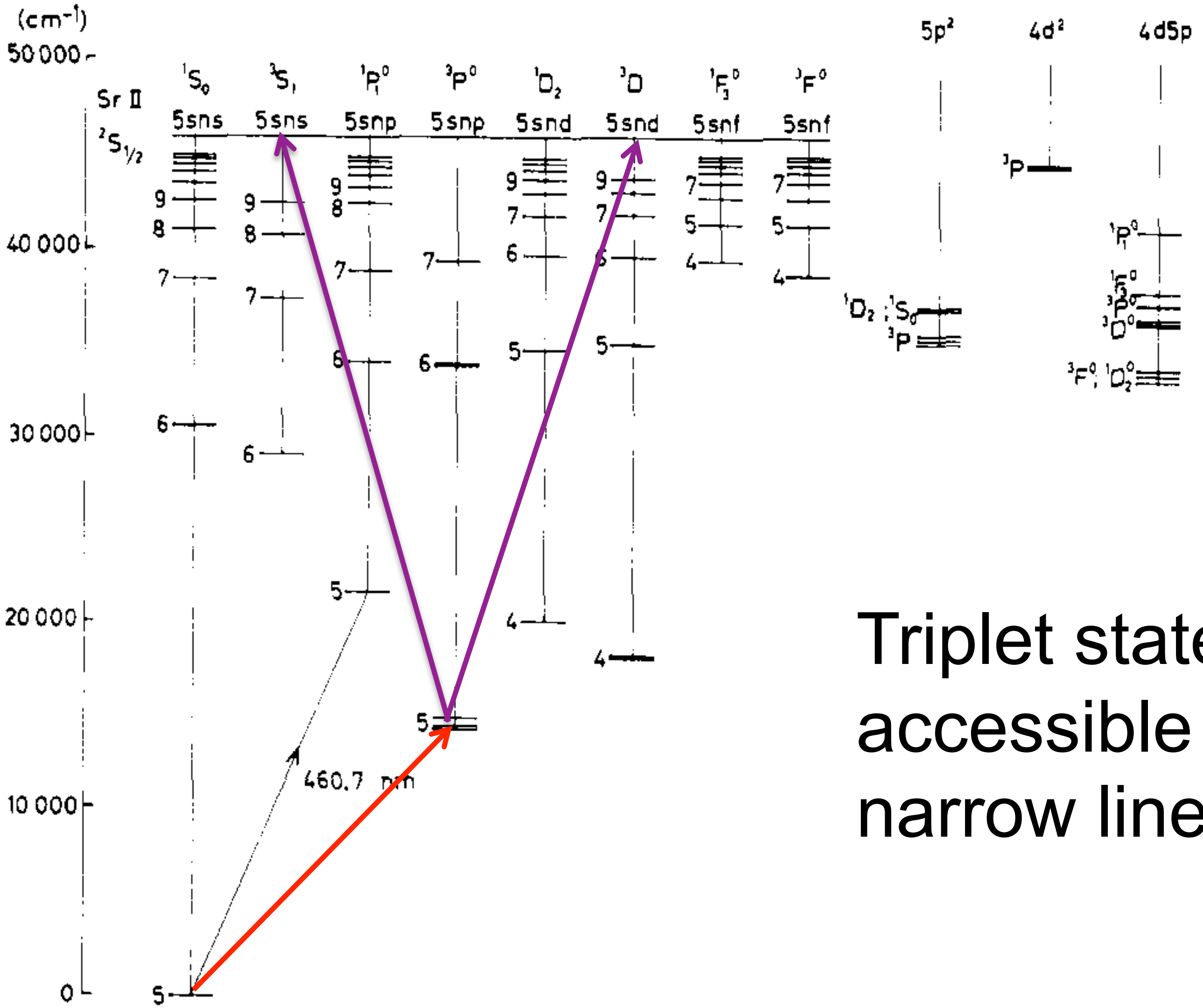

Triplet states accessible via narrow line

From J. R. Rubbmark and S. A. Borgstrom, Physica Scripta **18**, 196-208 (1978)

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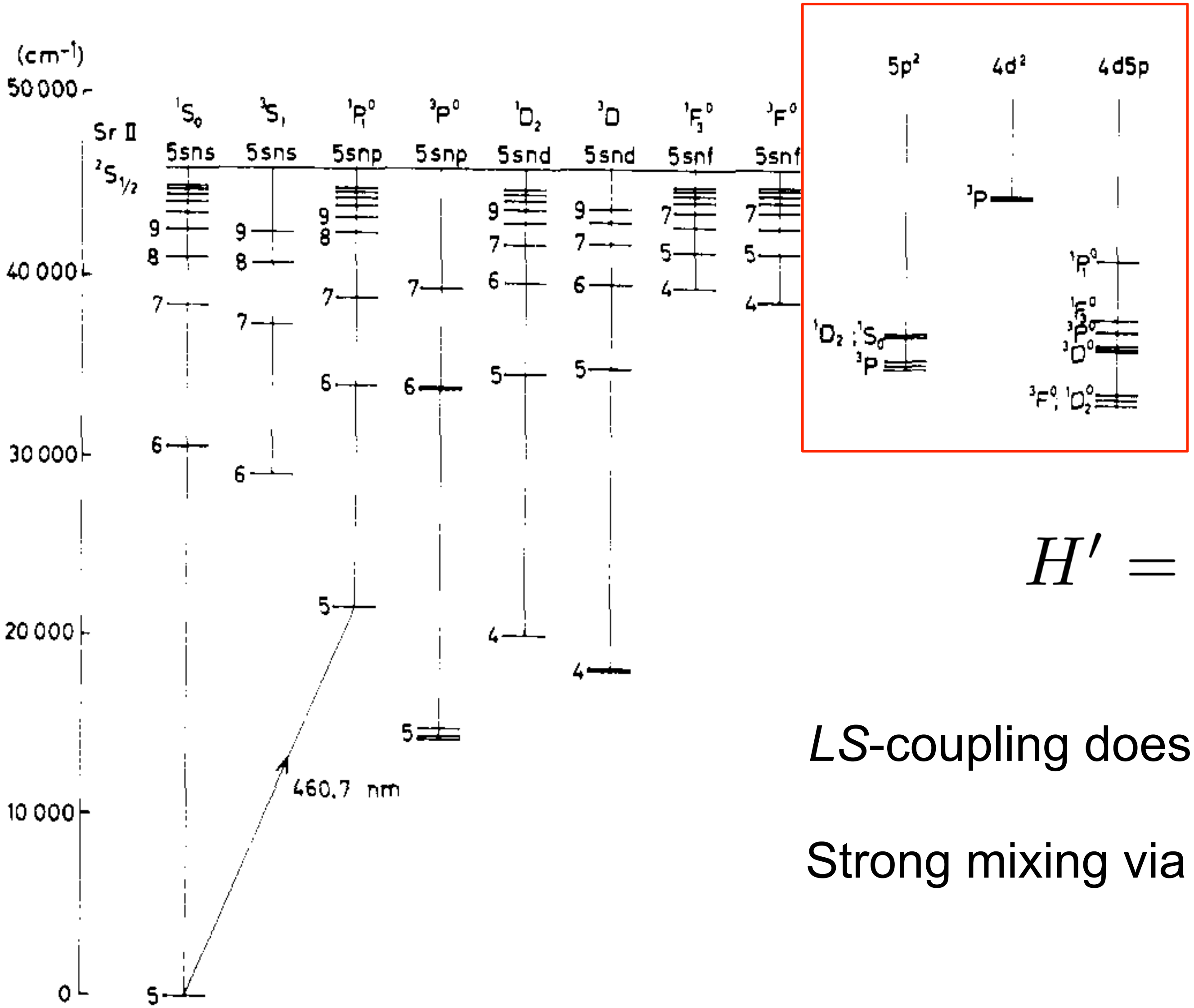
Singlet-triplet mixing



$$H' = \frac{1}{r_{12}}$$

LS-coupling does not hold

Strong mixing via perturbers

From J. R. Rubbmark and S. A. Borgstrom, Physica Scripta **18**, 196-208 (1978)

Singlet-triplet mixing

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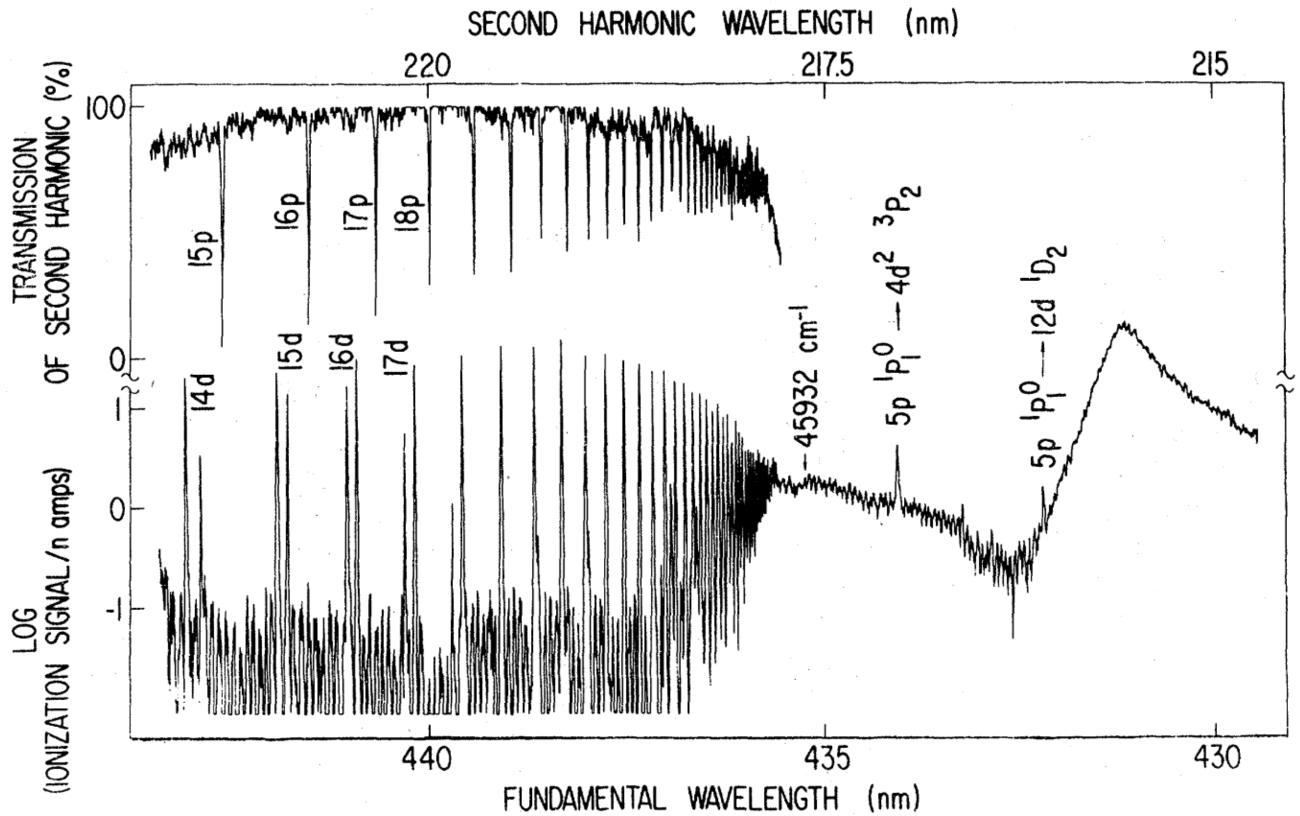

- Two 5snd series observed
- Exchange of amplitude at n=15

P. Escherick, PRA **15**, 1920 (1977)

Analysis of the energies

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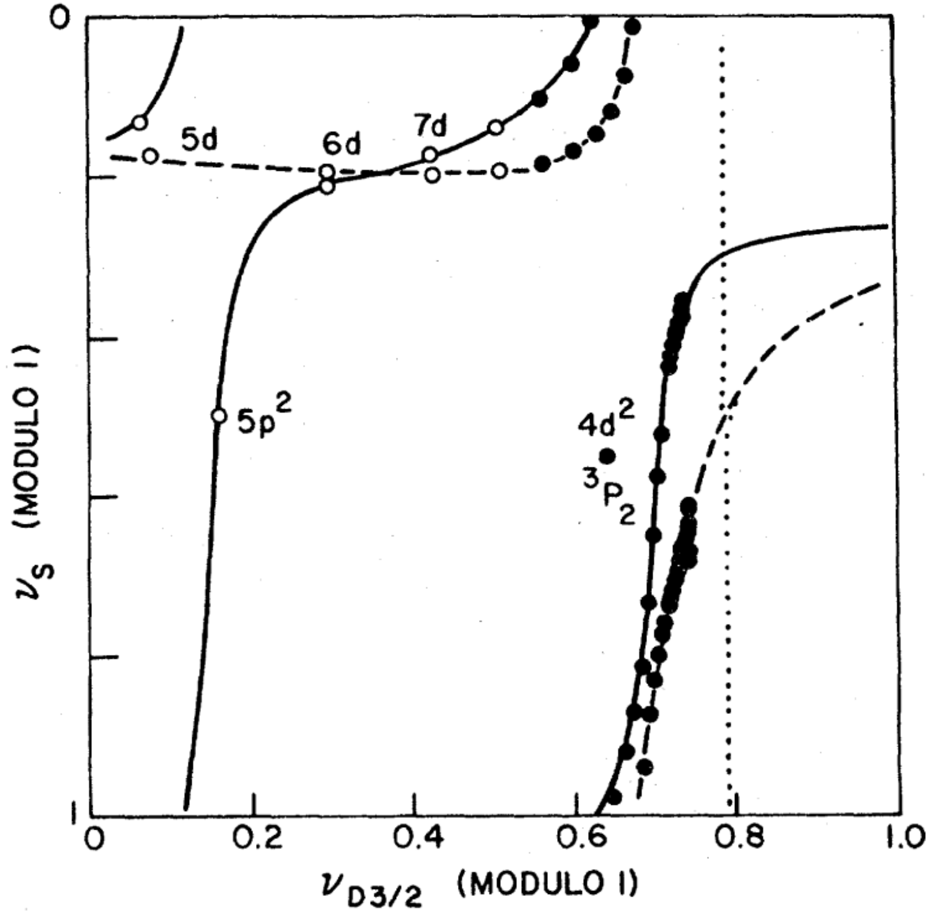
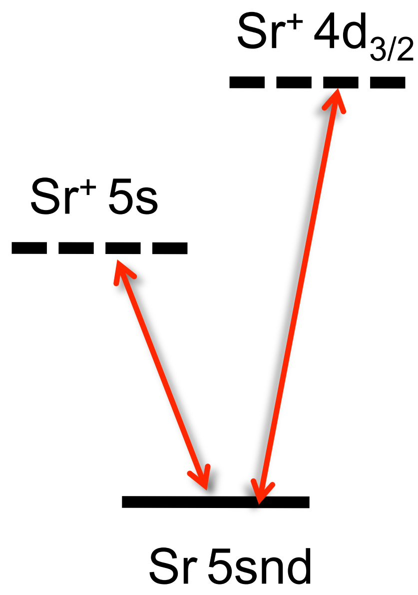
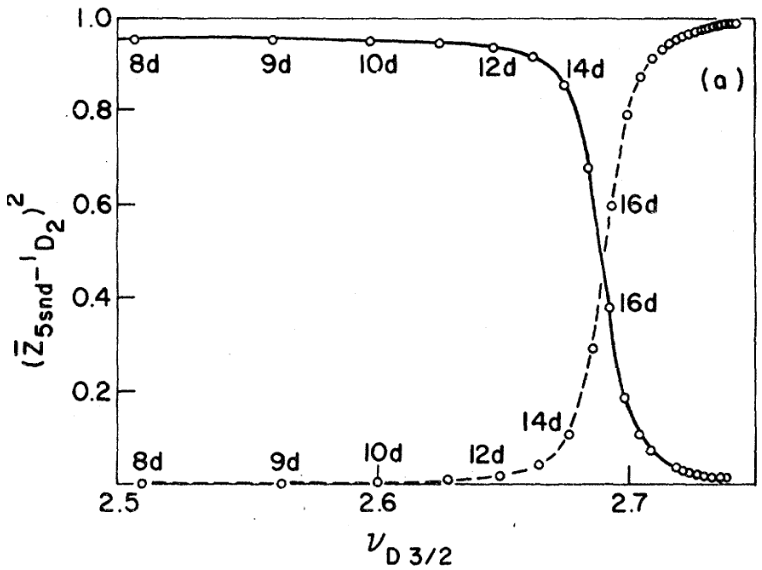


Lu – Fano plot

P. Escherick, PRA **15**, 1920 (1977)

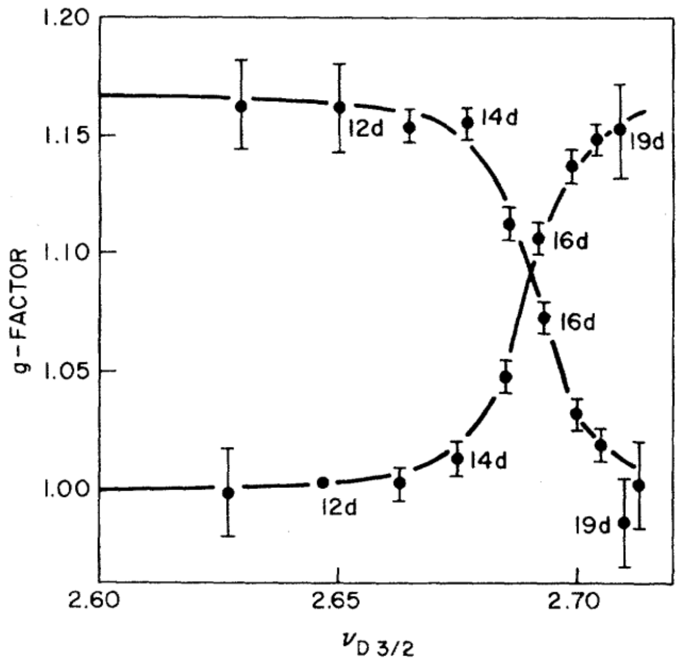


Singlet-triplet mixing



P. Escherick, PRA **15**, 1920 (1977)

$^1D_2$ character in each observed series from energies



J. J. Wynne et al., PRL **39**, 1520 (1985)

Measured g_J

To what extent does this modify e.g. interactions?

Independent electron model:

Core potential:

$$V = -\frac{1}{r} - \frac{(Z-1)e^{-ar}}{r} + be^{-cr} - 1$$

(Klapisch)

1. Series extrapolated using simulated annealing

2. Core potential fitted to measured quantum defects

3. Radial wavefunctions from Numerov method

4.. Radial dipole matrix elements

Stark maps

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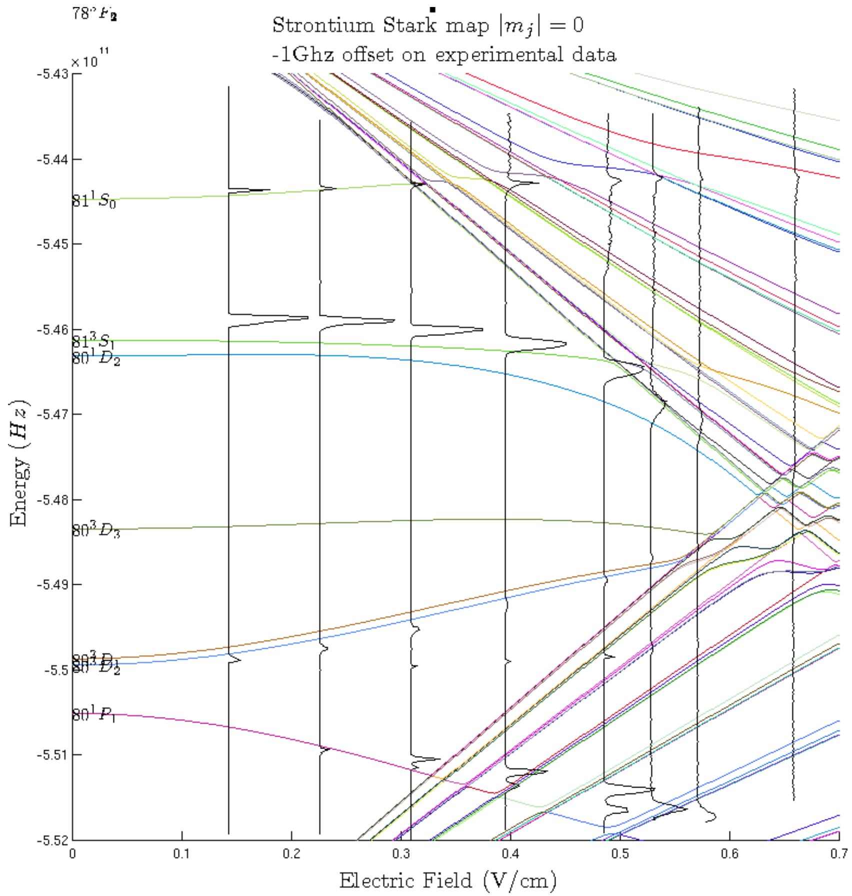
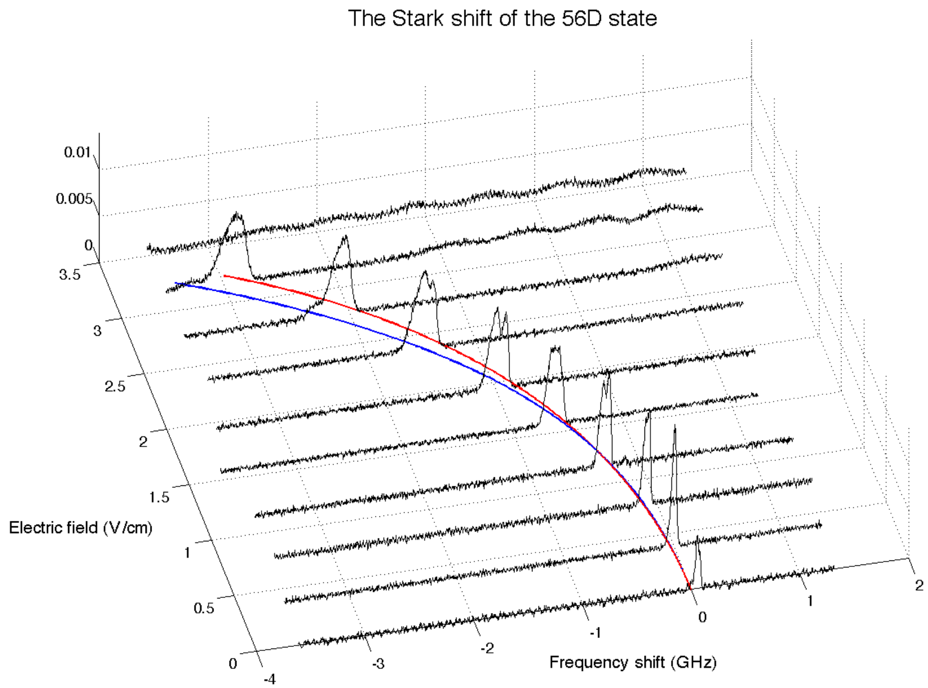
n=80



n=56



Other observables

Good agreement for e.g. Stark map

Should be OK for interactions

Lifetimes *are* dramatically modified

Valence states

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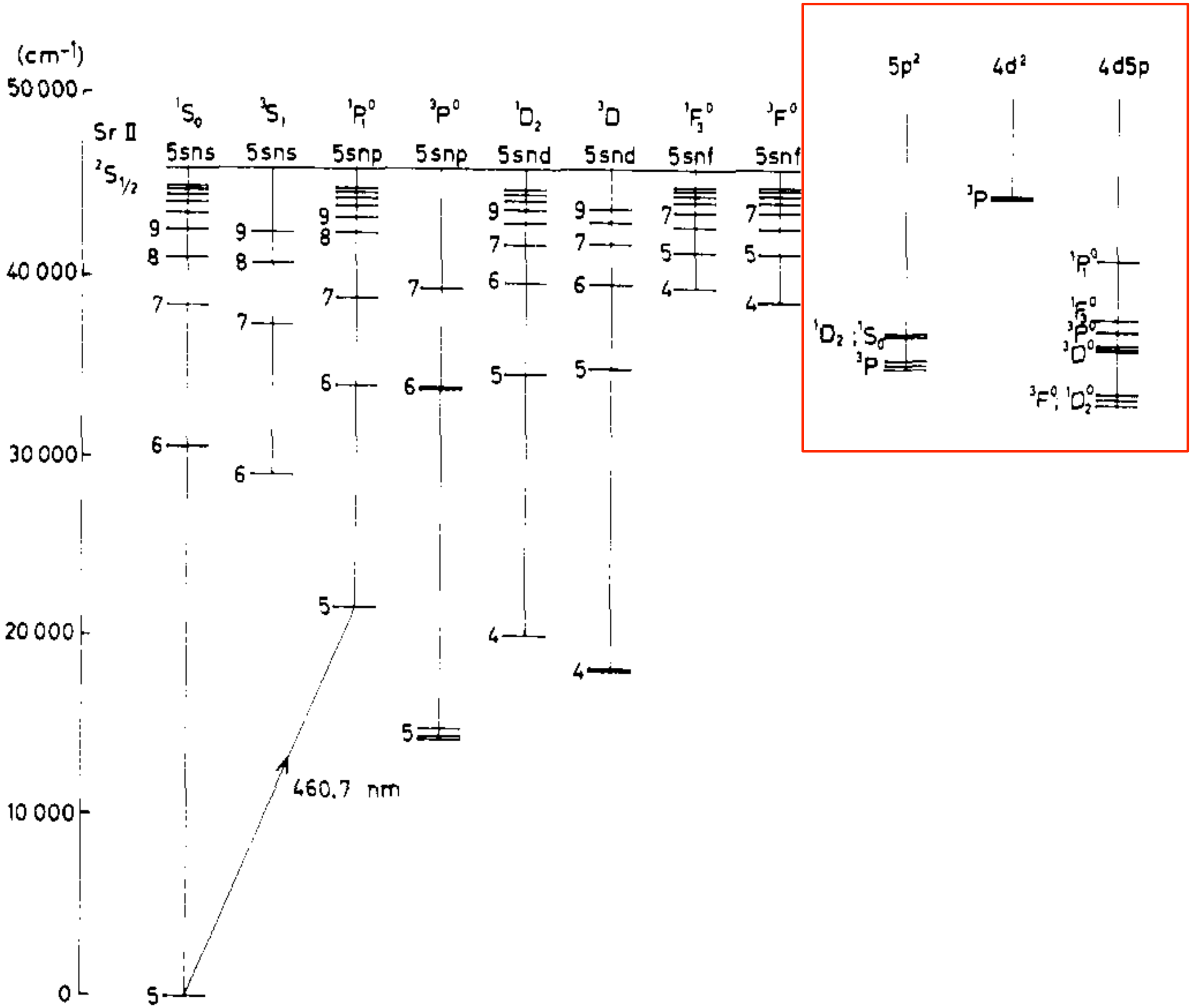


From J. R. Rubbmark and S. A. Borgstrom, Physica Scripta **18**, 196-208 (1978)

MQDT and autoionization

Basic notions

2-channel case

Fitting our data

Can describe bound and autoionizing spectra

Can be semi-empirical, or *ab inito*

Power is the ability to reduce complex spectra to very small number of parametrs

Follows Cooke and Cromer, PRA **32,** 2725
Also Gallagher's book:

$$\Psi = \sum_i A_i \phi_i$$

Channels:

$$\phi_i = \underbrace{\left[s\left(W_i, r\right)\cos\left(\pi\nu_i\right) + c\left(W_i, r\right)\sin\left(\pi\nu_i\right)\right]}_{\text{radial wavefunction}} \; \underbrace{\chi_i}_{\text{angular, spin, core}}$$

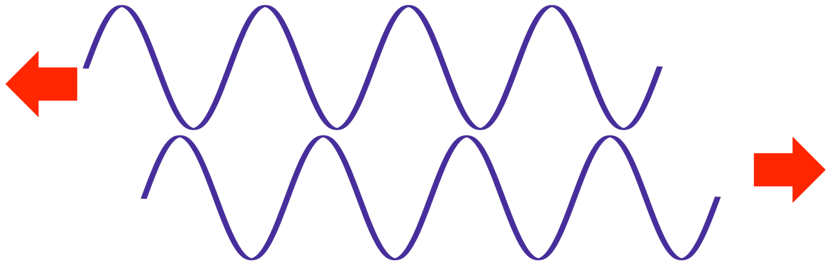
radial wavefunction

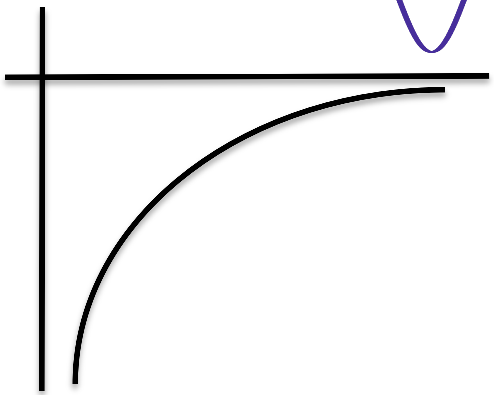
- angular
- spin
- core

$$W_i = -\frac{1}{2\nu_i^2} \qquad E_i = I_i + W_i$$

Boundary conditions

$r \to 0$





$r \to \infty$

Bound states $\quad \Psi \to 0$

The R-matrix equation

$$\Psi = \sum_i A_i \phi_i$$

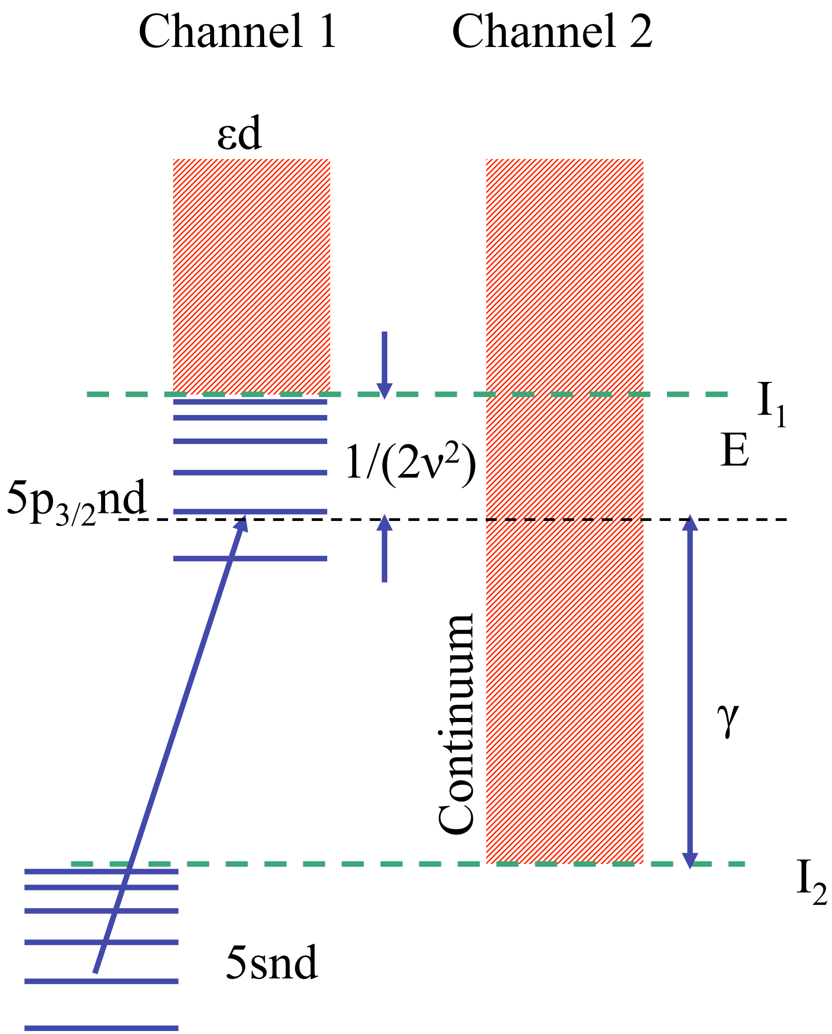
$$a_i = A_i \cos\left(\pi \nu'_i\right)$$

$$\nu'_i = \nu_i + \delta_i$$

$$\mathbf{R} + \tan\left(\pi \nu'\right) \mathbf{a} = 0$$

$$\left|\mathbf{R} + \tan\left(\pi \nu'\right)\right| = 0$$

Example: two channels



Example: two channels

$$\begin{pmatrix} 0 & R_{12} \\ R_{12} & 0 \end{pmatrix} + \begin{pmatrix} \tan(\pi\nu_1') & 0 \\ 0 & \epsilon_c \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} = 0$$

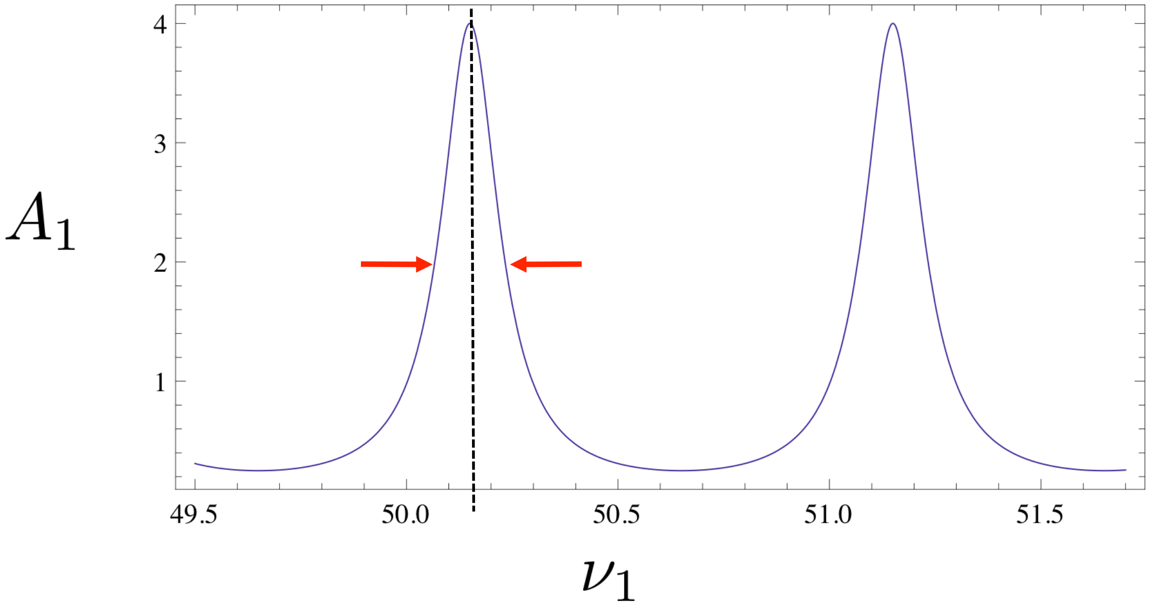
$$|\mathbf{R} + \tan\left(\pi\nu'\right)| = 0 \qquad\qquad \epsilon_c = \sqrt{\frac{R_{12}^2}{\tan(\pi\nu_1')}}$$

$$a_1^2 = R_{12}^2 \frac{1}{(\tan\pi\nu_1)^2 + R_{12}^4}$$

Example: two channels

$$a_i = A_i \cos\left(\pi \nu_i'\right)$$

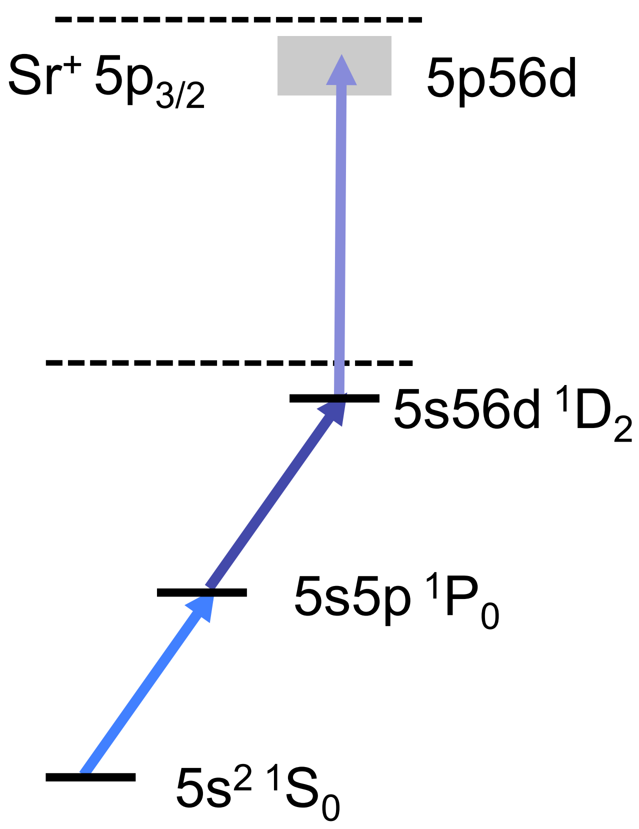
$$A_1^2 = R_{12}^2 \left[\frac{1+\tan^2(\pi\nu_1')}{\tan^2\left(\pi\nu_1'\right) + R_{12}^4}\right]$$



$$\nu_i' = \nu_i + \delta_i$$

$$\Gamma = \frac{2R_{12}^2}{\pi}$$

The isolated core excitation cross-section



$$\sigma = \frac{4\pi^2\omega}{c} \left|\langle b\,|\mu|\,\Psi\rangle\right|^2$$

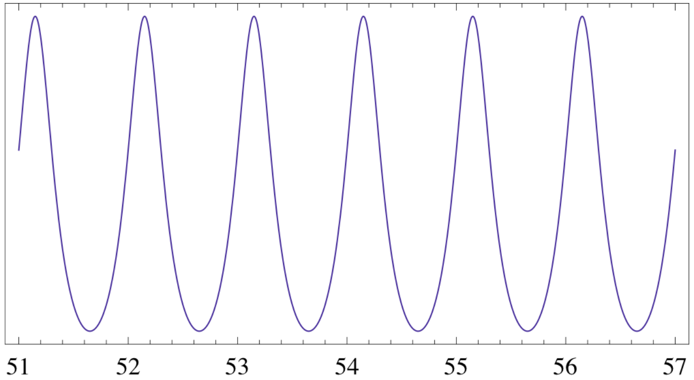
$$\Psi = \sum_i A_i \phi_i$$

$$|\phi\rangle = |5p\rangle|\Omega_1\rangle|\nu_1, l\rangle$$

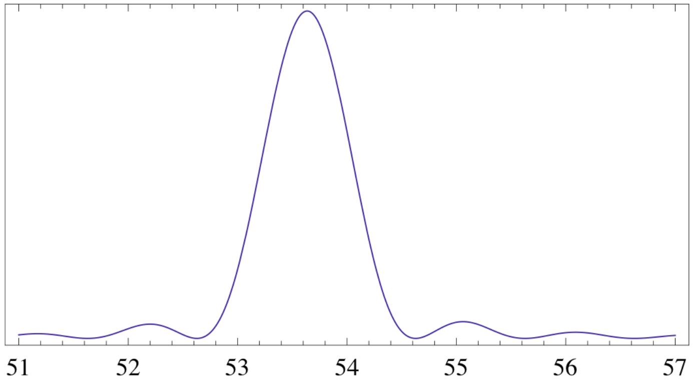
$$\langle b| = \langle 5s|\langle\Omega_b|\langle\nu_b, l_n|$$

$$\left|\langle\Psi\,|\mu|\,b\rangle\right|^2 = \left|\langle 5s|\mu|5p\rangle\right|^2 \delta_{l,l_b} A_1^2 \left|\langle\nu_b, l_b|\nu_1, l\rangle\right|^2$$

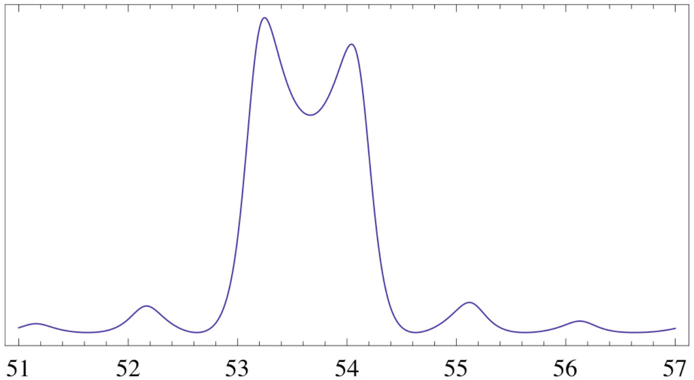
The isolated core excitation cross-section



$$A_1^2 = R_{12}^2 \left[\frac{1 + \tan^2(\pi\nu_1')}{\tan^2(\pi\nu_1') + R_{12}^4} \right]$$



$$|\langle \nu_b, l_b | \nu_1, l \rangle|^2 = \left[\frac{2\nu_b^2 \nu_1^2}{\pi(\nu_1^2 - \nu_b^2)} \sin\left[\pi(\nu_1 - \nu_v)\right] \right]^2$$



$$\sigma^2$$

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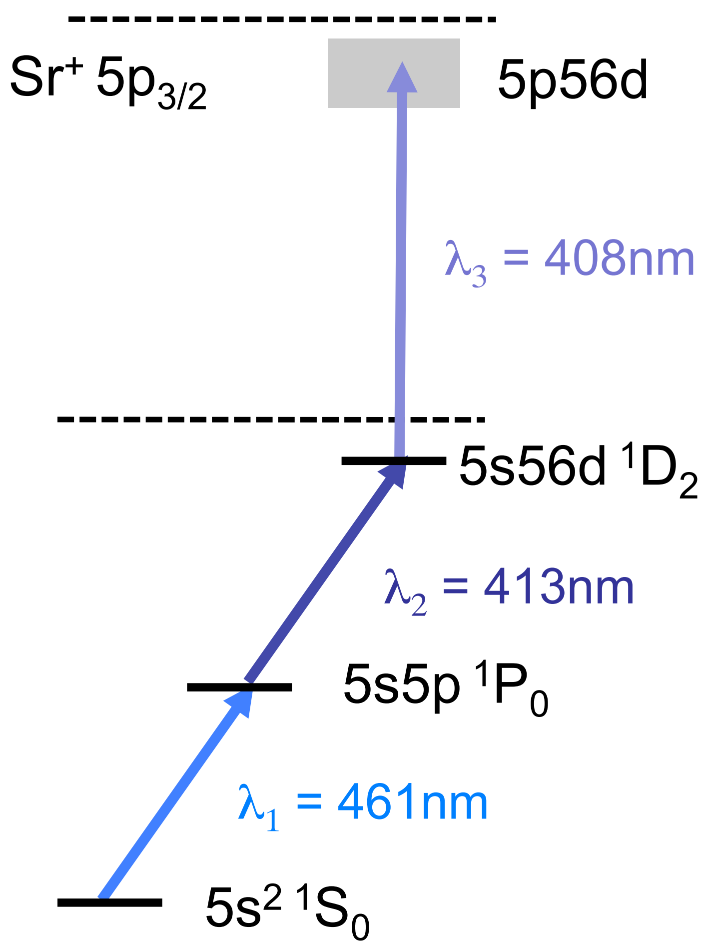
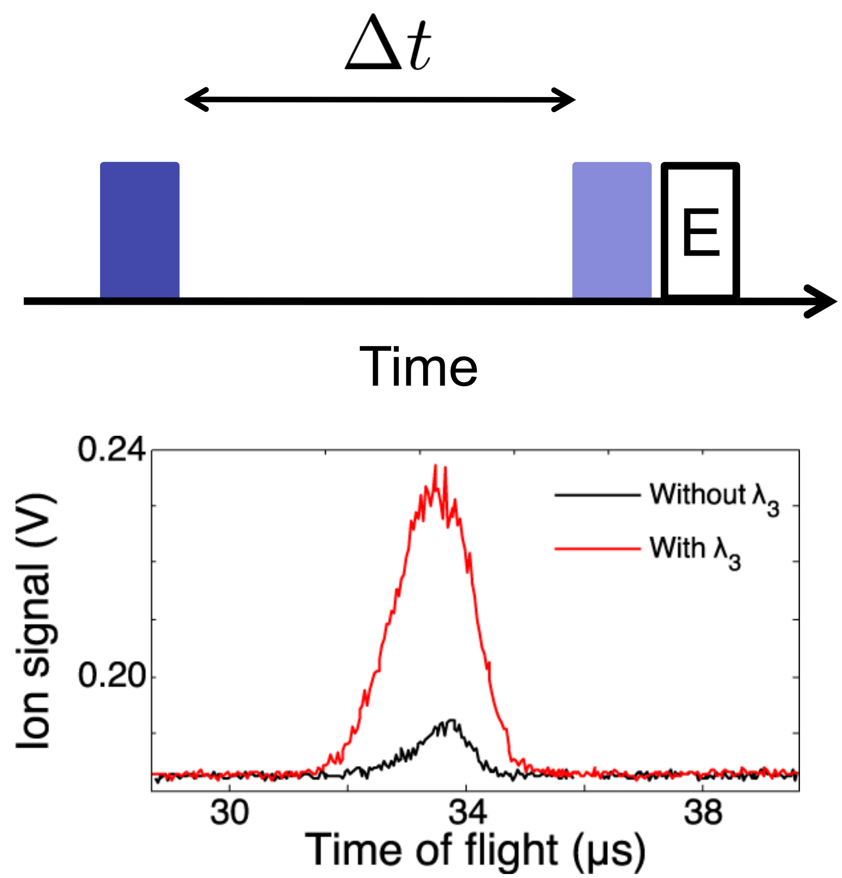
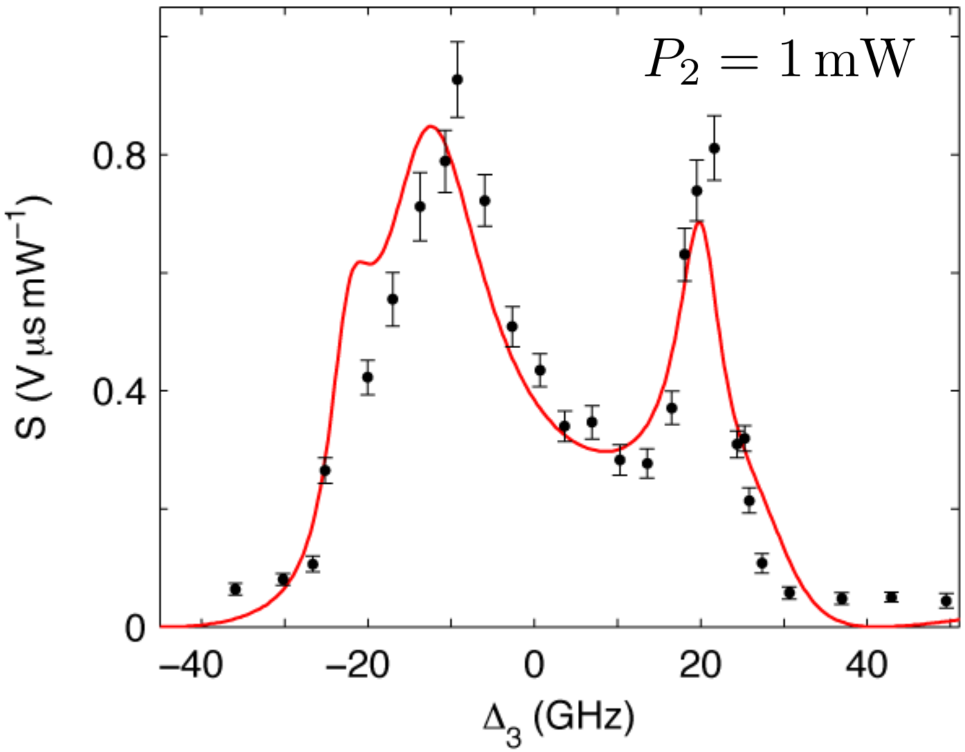




Vary λ_3 and Δt

Fitting our data

$$\Delta t = 0.5\,\mu\mathrm{s}$$

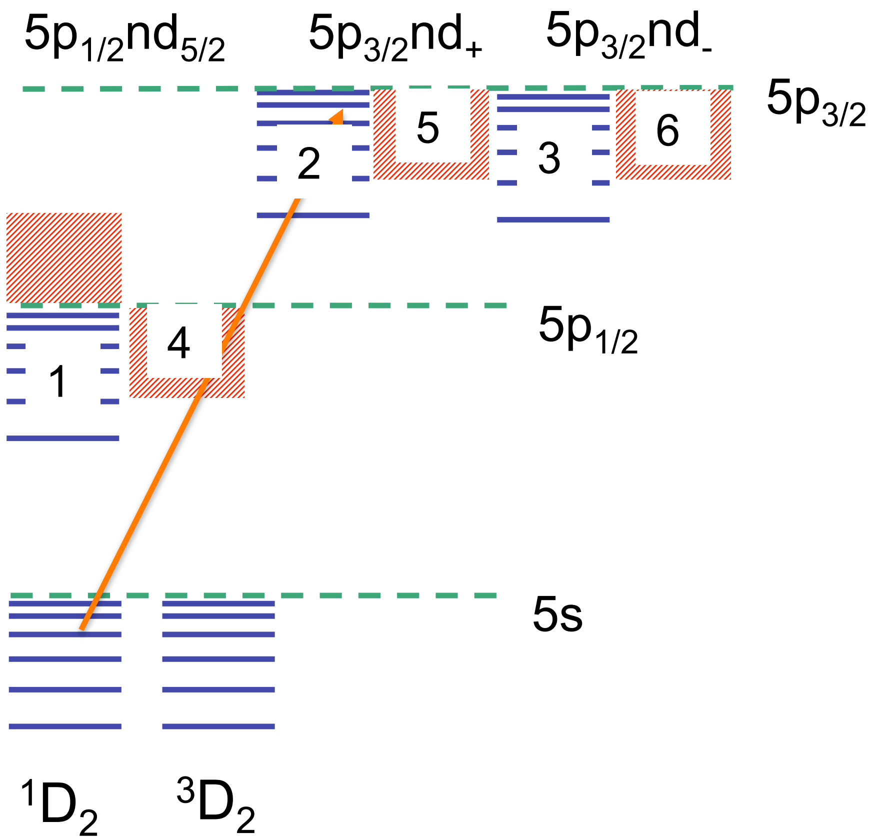


$$\Delta_3 = \lambda_3 - \lambda_{\mathrm{ion}}$$

Fit is 6-channel MQDT for 5snd states

(Xu et al., PRA **35**, 1138 (1987))

Six channels

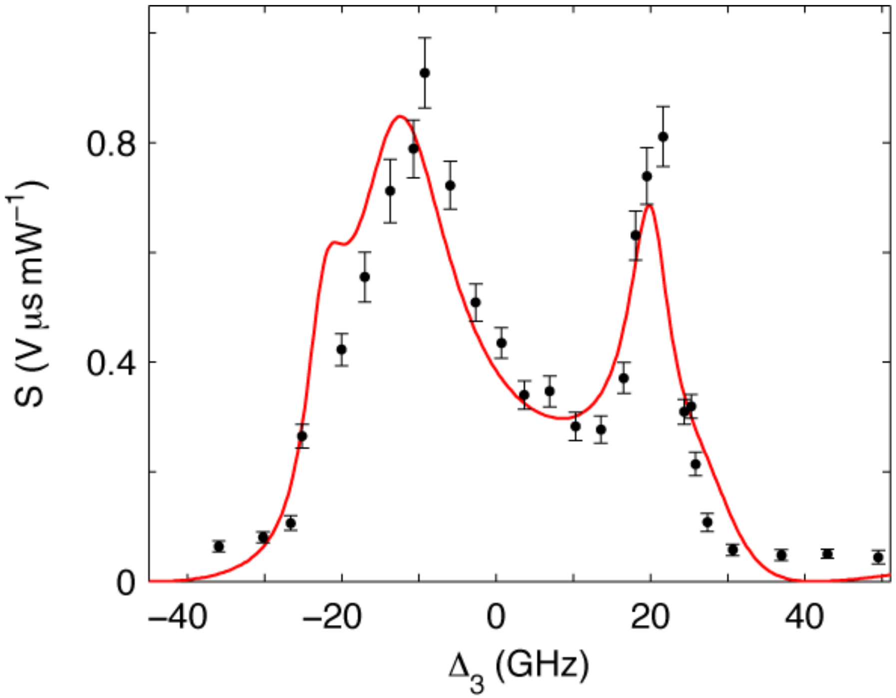


Consider states with J=3

$$|nd\rangle_+ = |(\cos\phi)nd_{3/2} + (\sin\phi)nd_{5/2}\rangle$$

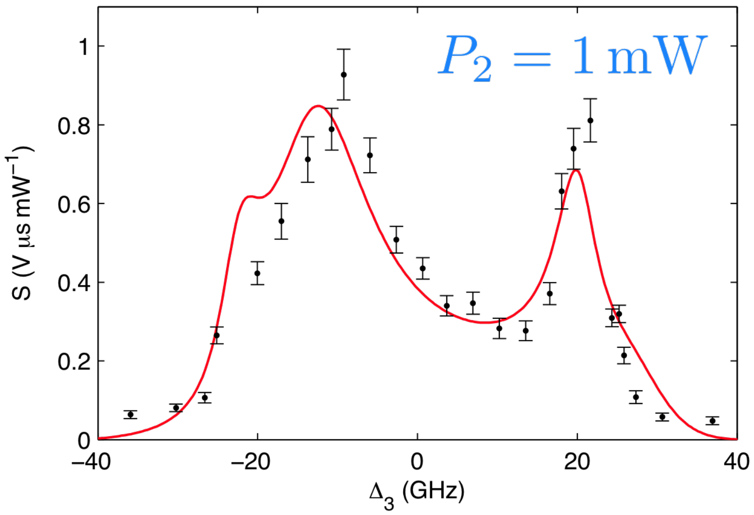
$$|nd\rangle_- = |(-\sin\phi)nd_{3/2} + (\cos\phi)nd_{5/2}\rangle$$

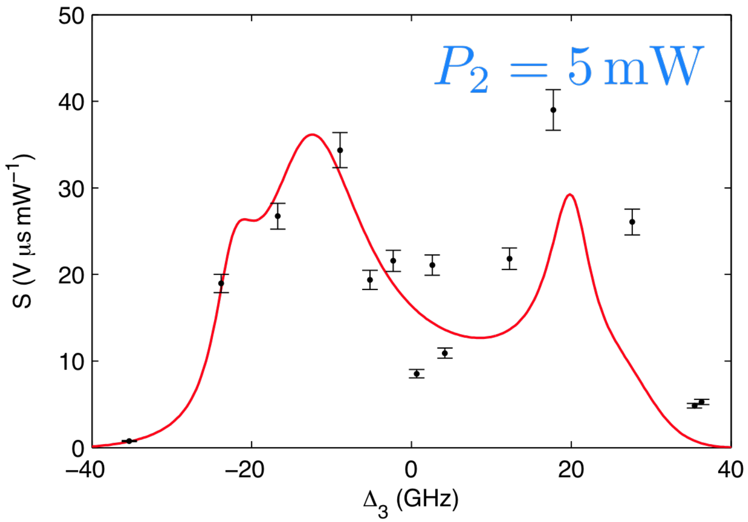
Fitting our data

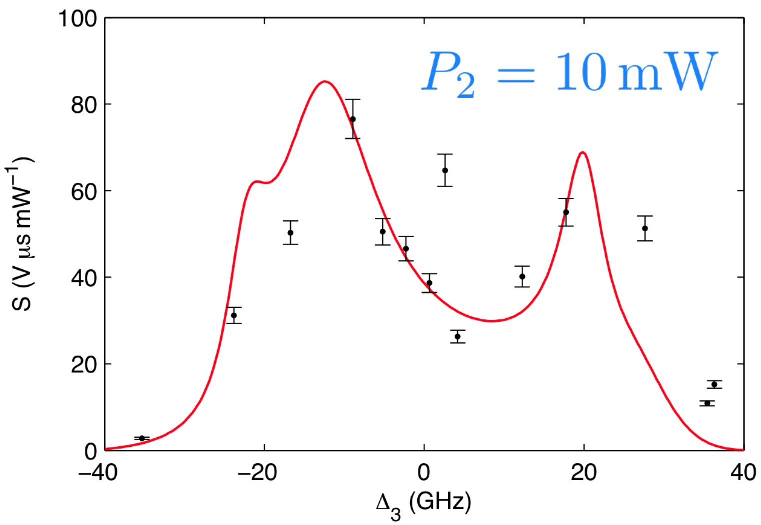


Parameter	Gallagher	Us
μ_1	2.79±0.02	
μ_2	2.78±0.02	2.68
μ_2	2.81±0.02	2.89
R_{12}	0.40	
R_{13}	0.05	
R_{14}	0.45	
R_{25}	0.61	
R_{36}	0.46	
φ	0.69	1.24

Increasing the Rydberg density







$$\Delta t = 0.5\,\mu\mathrm{s}$$

Increasing the delay

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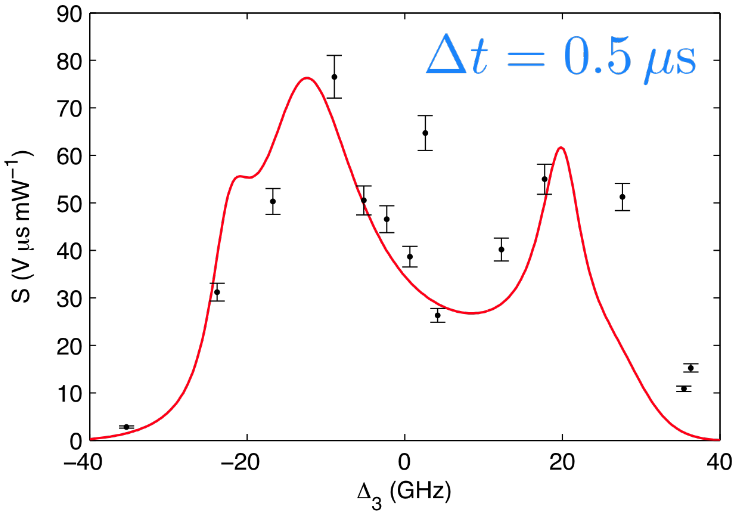
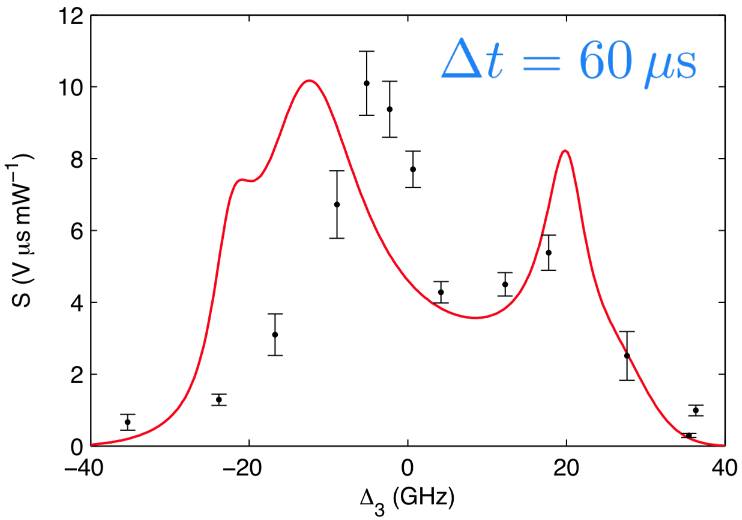
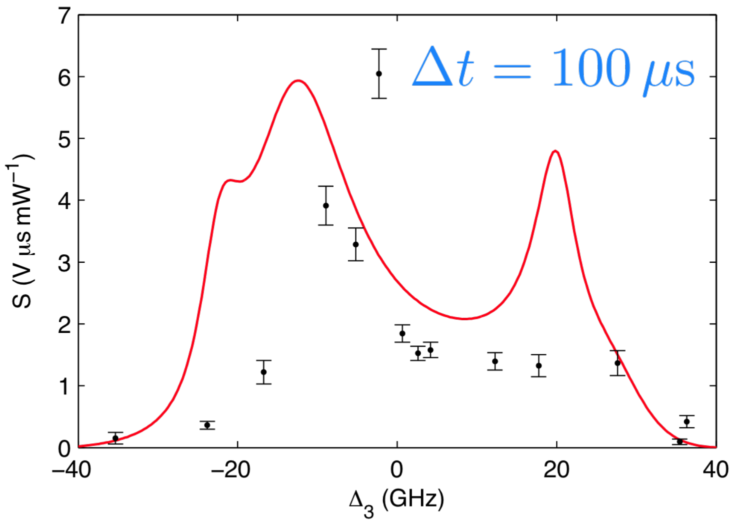
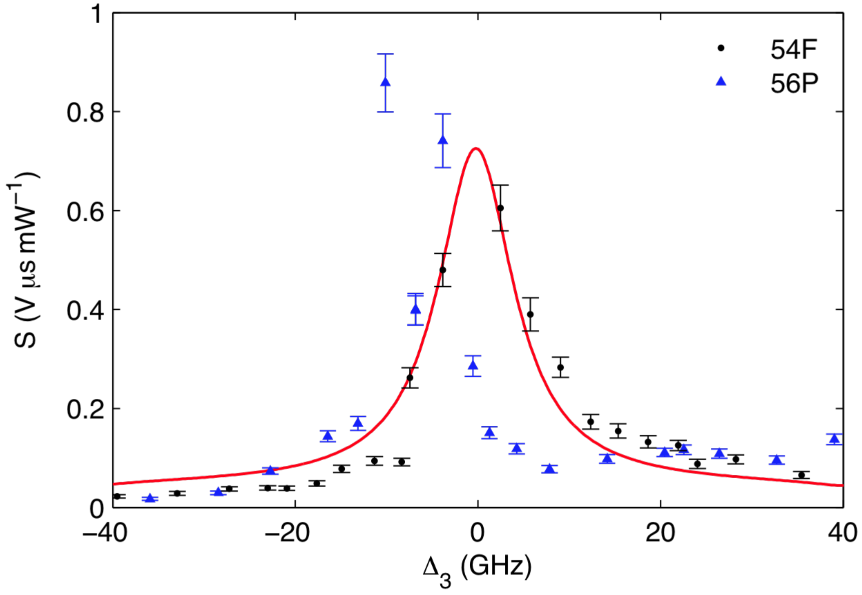






Narrow peak ≠ 5s56d

2-channel fit to the F state



2-channel MQDT fit

$$\nu_F^B = 0.0895$$

Cooke & Gallagher Opt. Lett. **6**, 173 (1979)

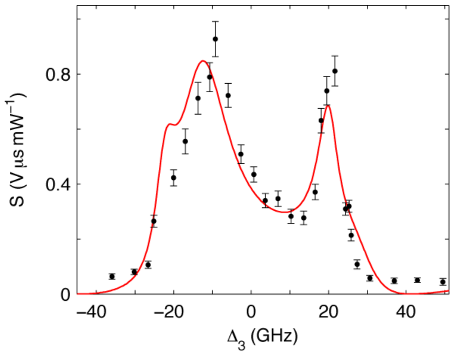
We obtain

$$\nu_F = 0.37$$

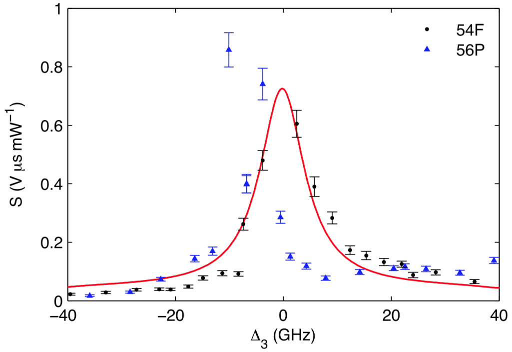
$$R_F = 0.5$$

$$A_1^2 = R_{12}^2 \left[\frac{1 + \tan^2(\pi\nu_1')}{\tan^2(\pi\nu_1') + R_{12}^4} \right]$$

Combined fits



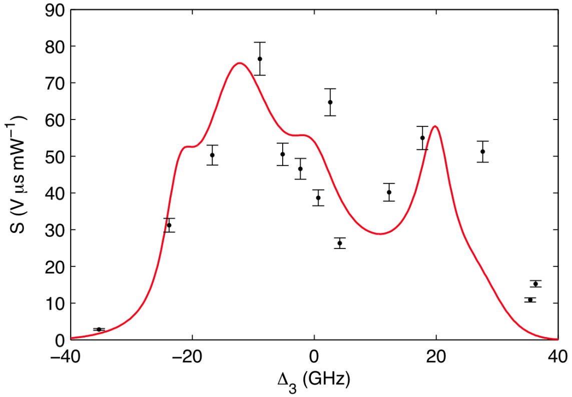
56D 6-channel MQDT



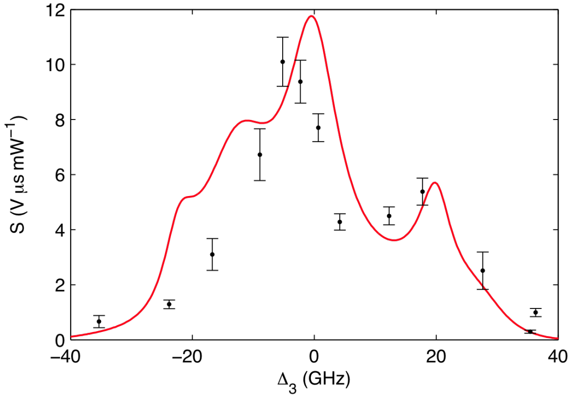
54F 2-channel MQDT

$\tau_{56\mathrm{D}}, \tau_{54\mathrm{F}}$

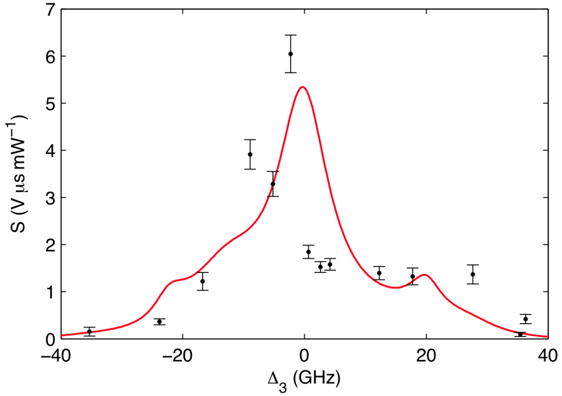
Measured lifetimes



$\Delta t = 0.5\,\mu s$



$\Delta t = 60\,\mu s$



$\Delta t = 100\,\mu s$

$$\frac{N_F}{N_D} = \frac{\sigma_D}{\sigma_F}(\lambda_3)\,\frac{S_F}{S_D}(\lambda_3)$$

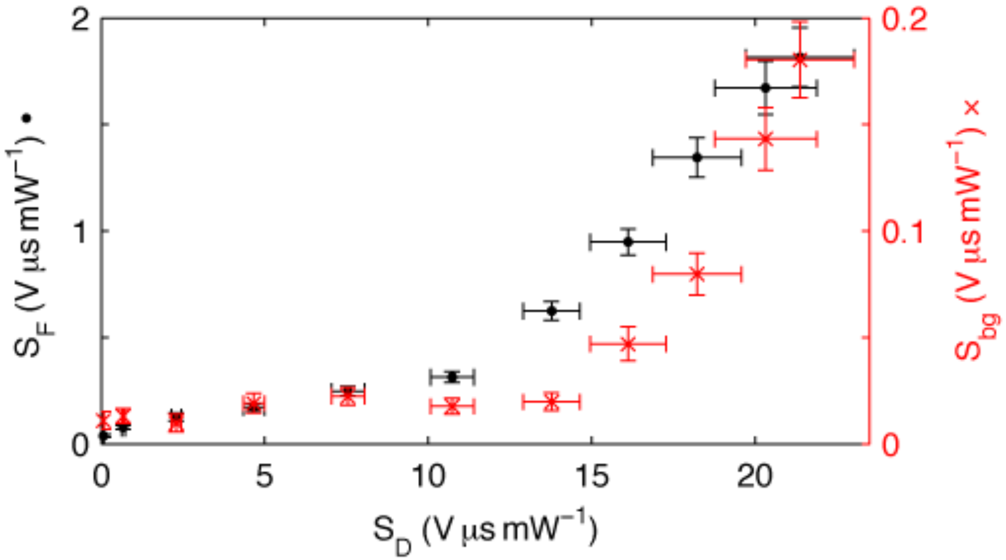
Two –channel treatment:

$$\frac{\sigma_D}{\sigma_F} = \frac{A_{1,D}(\nu_D, R_D)}{A_{1,F}(\nu_F, R_F)}\,\frac{O(\nu_D, \nu_D^B)}{O(\nu_F, \nu_F^B)}$$

13±3% of the Rydberg atoms are transferred

l-transfer associated with cold plasma formation

S. K. Dutta et al., PRL **86**, 3993 (2001)
A. Walz-Flannigan et al., **69**, 063405 (2004)



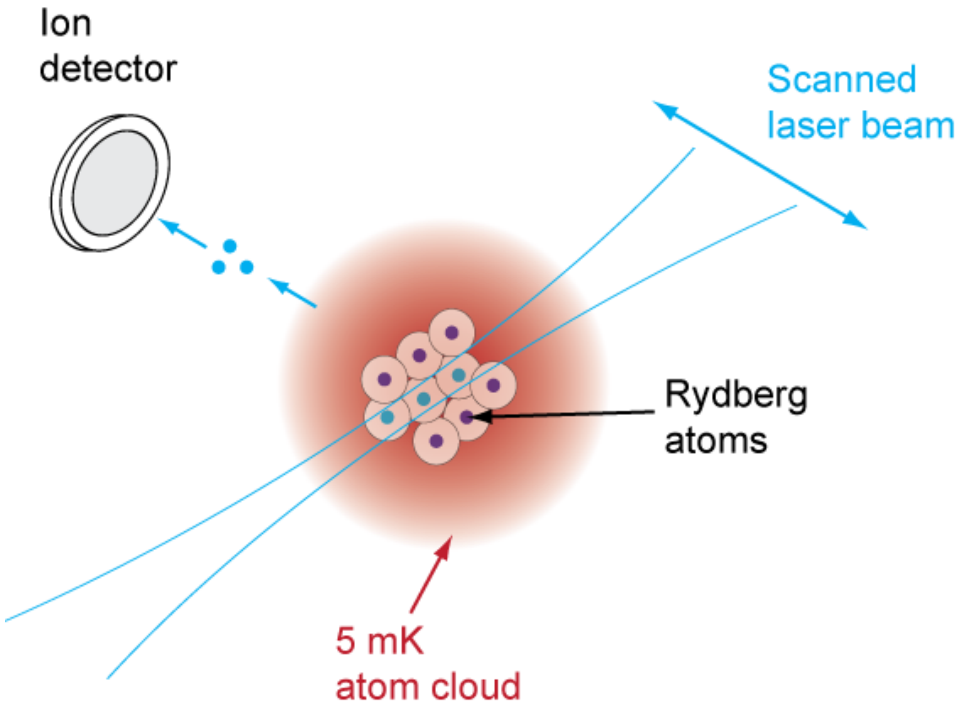
~1000 ions required for plasma to form

Future directions

Spatial resolution

Optical traps for Rydberg atoms

Rydberg quantum metrology


Ion
detector
Scanned
laser beam
Rydberg
atoms
5 mK
atom cloud

A scanning microscope for Rydberg gases

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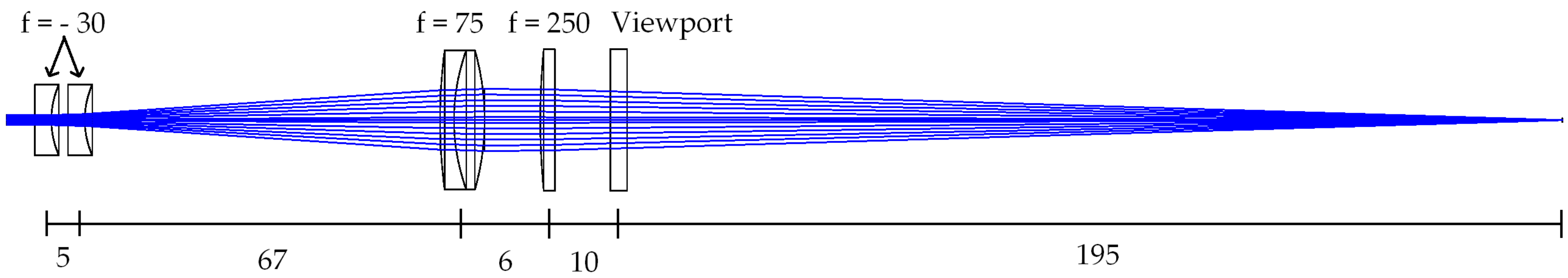
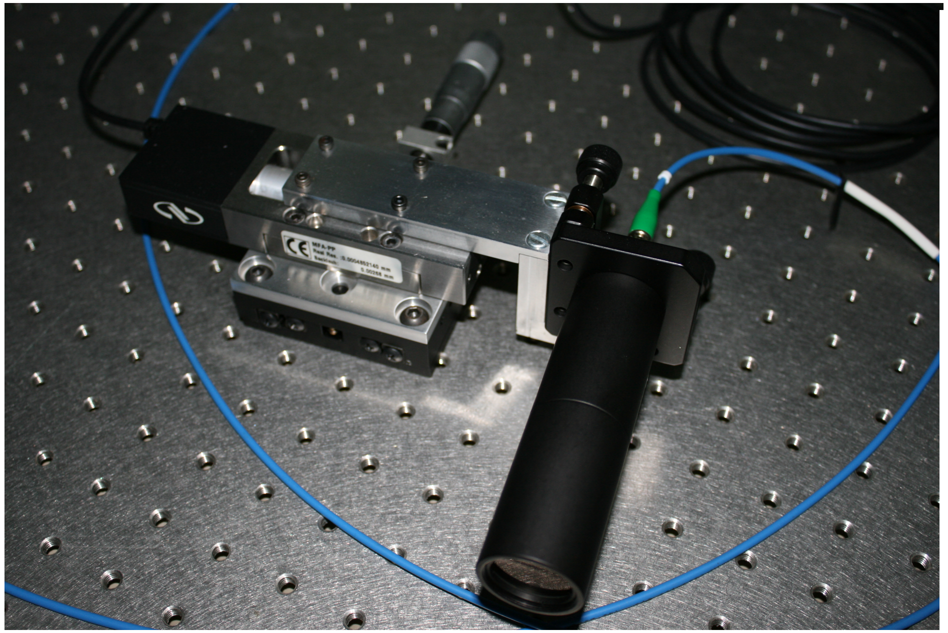
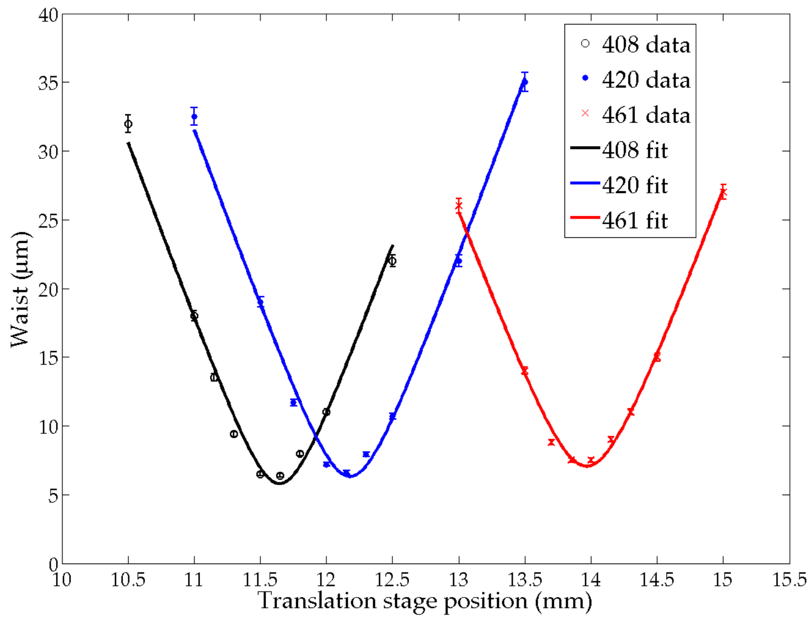
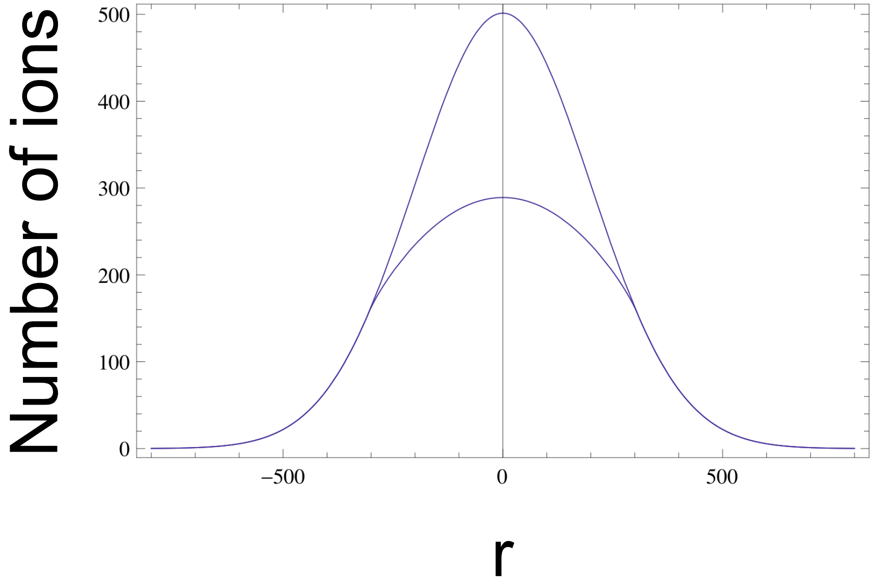




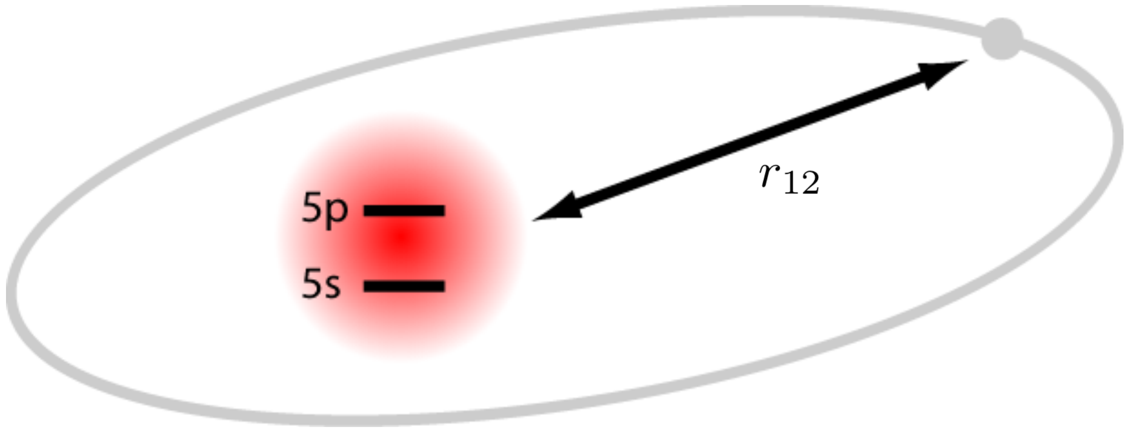


Effect of blockade on spatial distribution

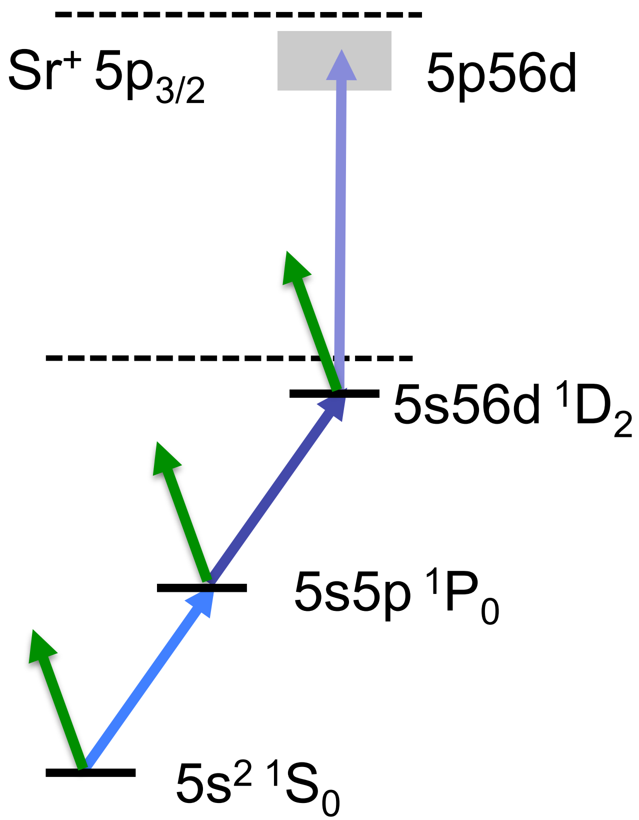


Also correlations?

Optical traps for Rydberg atoms

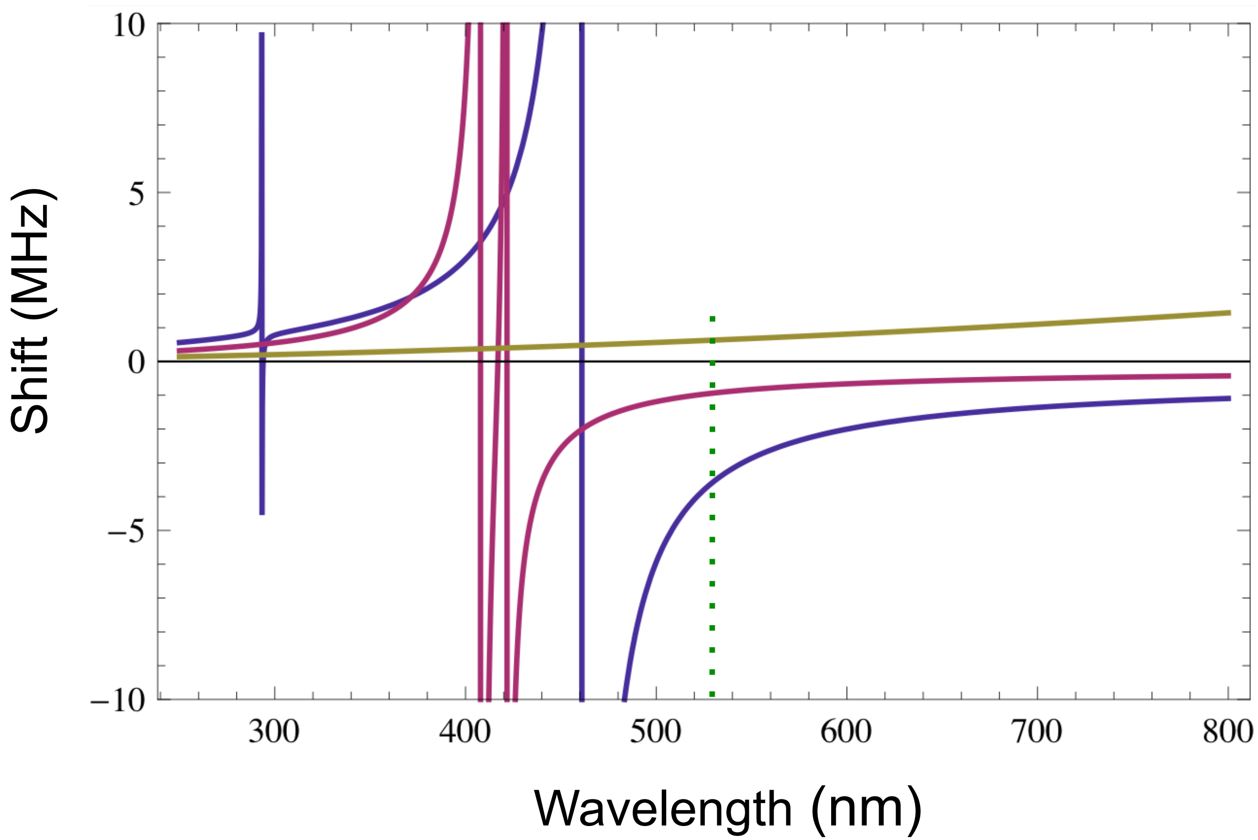


$$H' = \frac{1}{r_{12}}$$

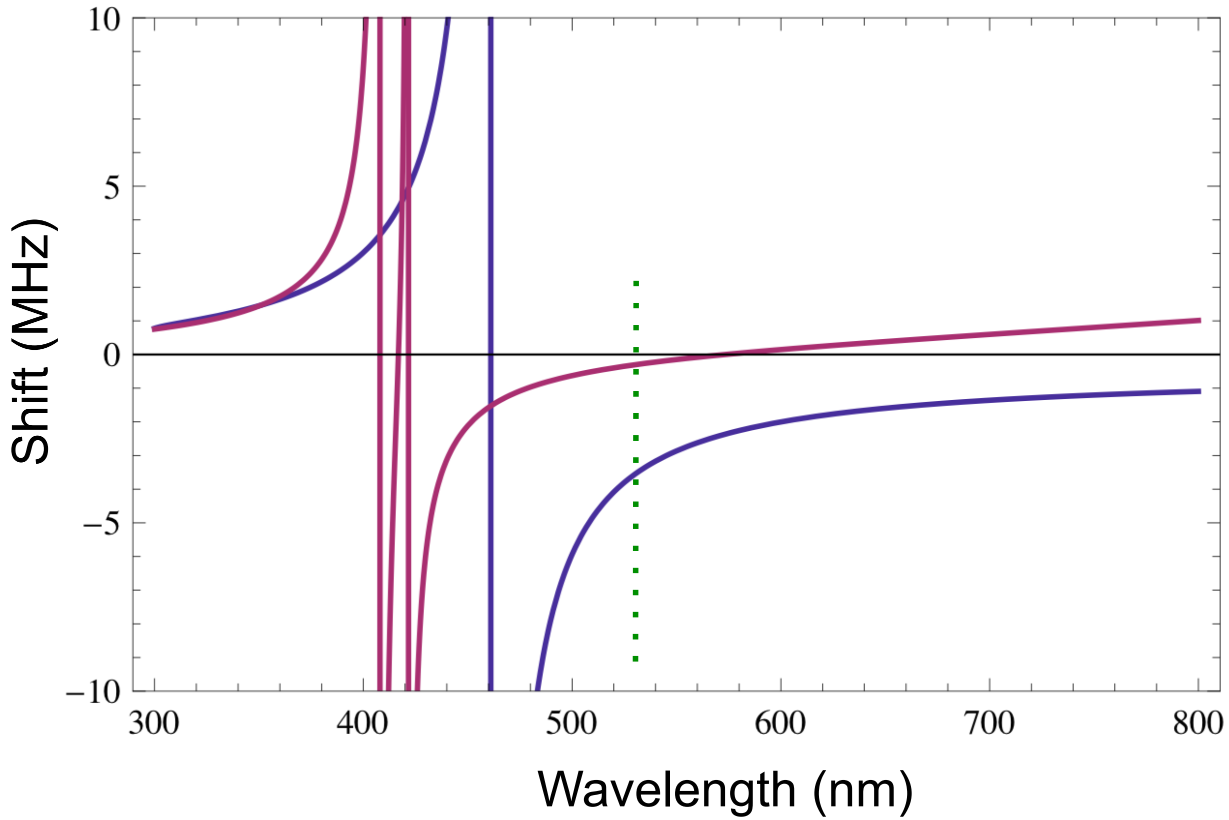


Also ponderomotive shift

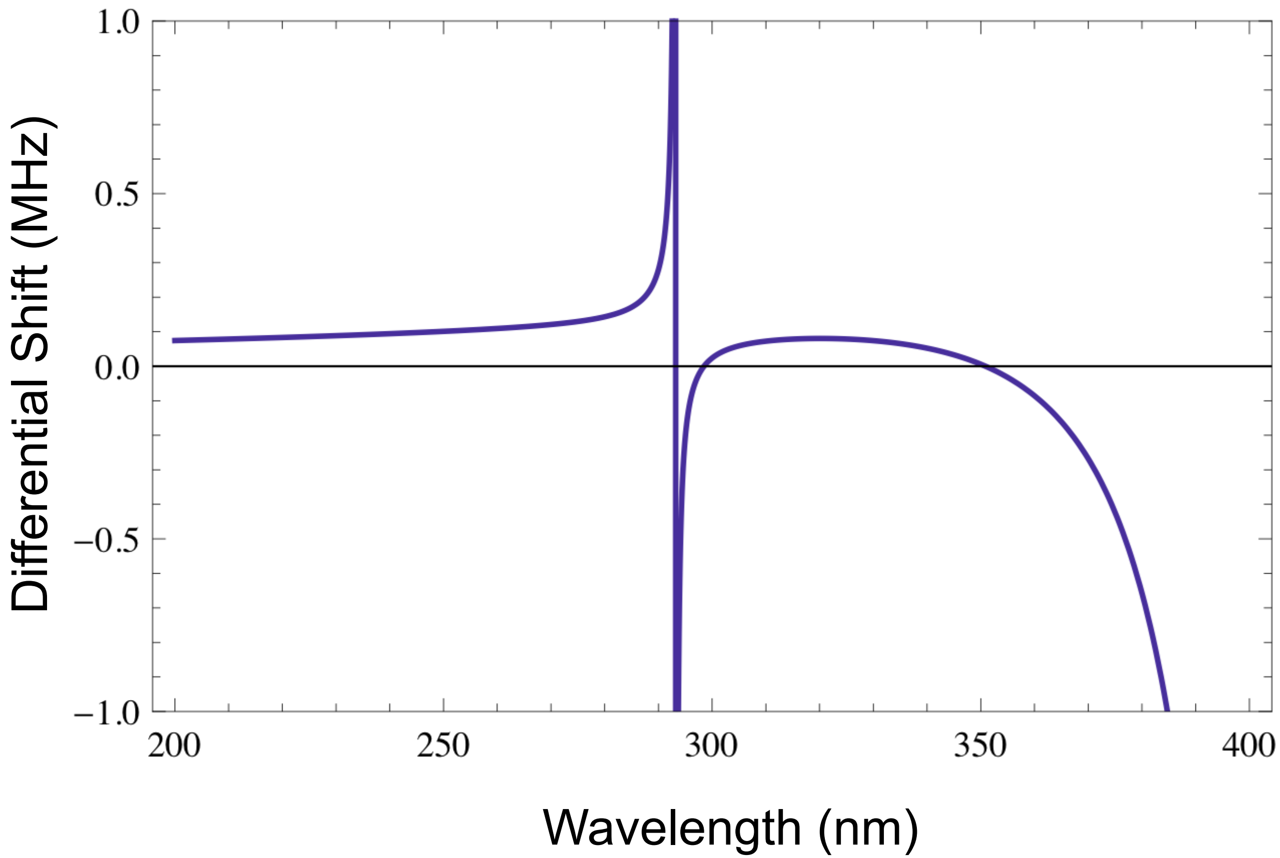
AC Stark shifts



AC Stark shifts

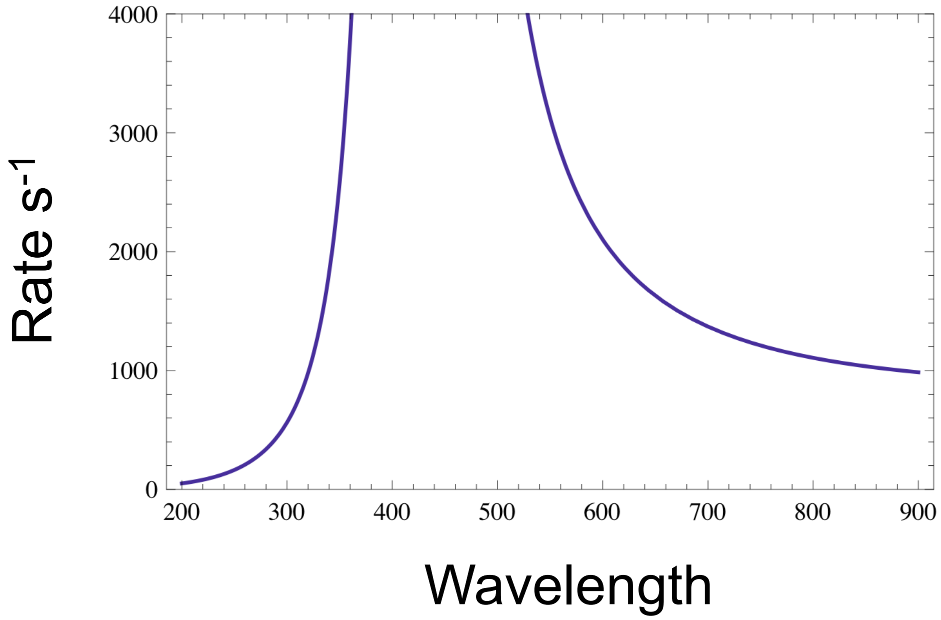


AC Stark shifts



Nd:YAG 3rd harmonic=355 nm

Assumes Γ=50GHz (n=56)



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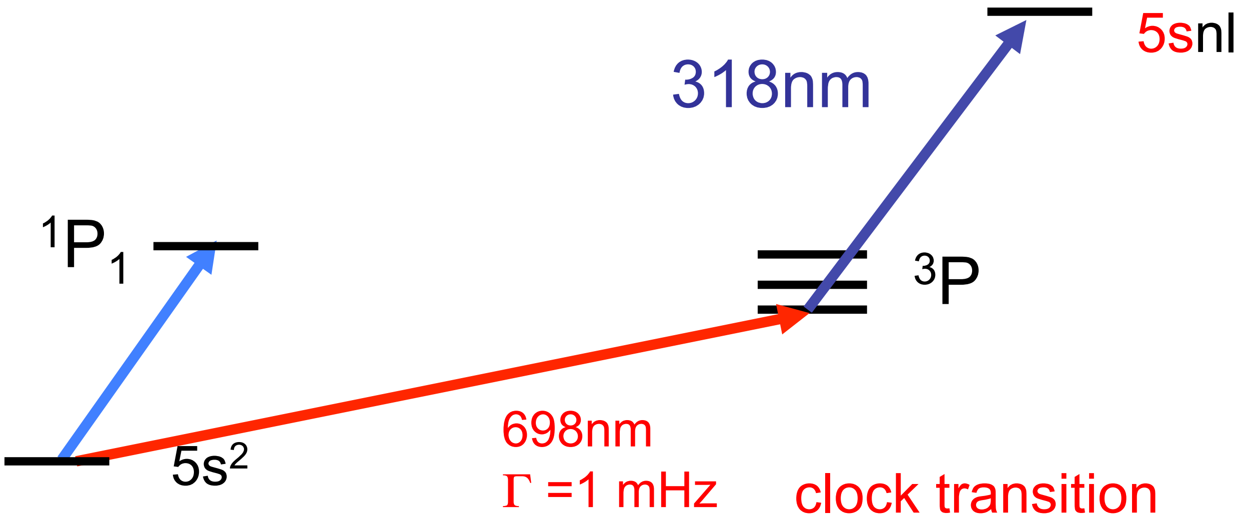
Quantum metrology


5snl
318nm
$^1P_1$
^3P
$5s^2$
698nm
Γ =1 mHz
clock transition

Quantum frequency metrology

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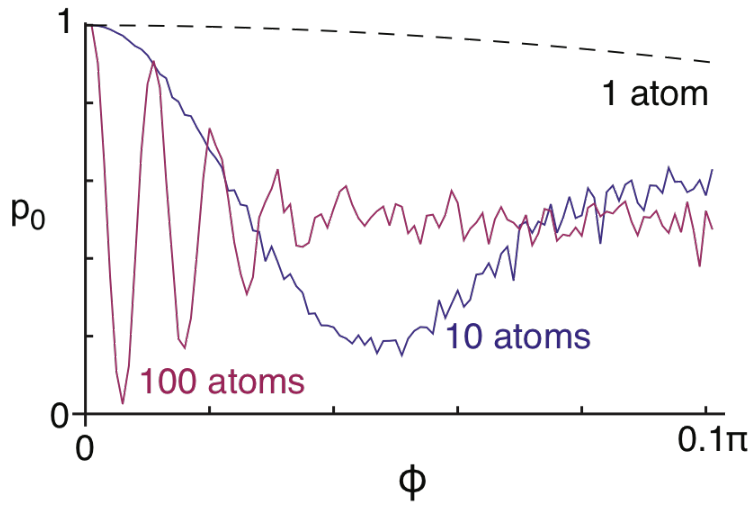


independent $\Psi = \left(|0\rangle + e^{i\theta}|1\rangle\right)^N$ $\qquad \dfrac{\Delta f}{f} \propto \dfrac{1}{\sqrt{N}}$

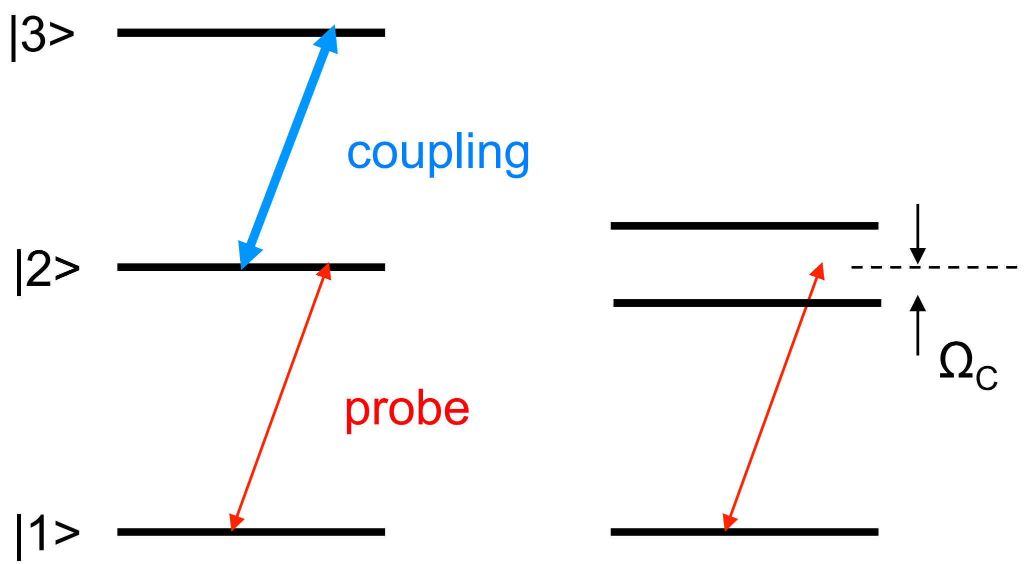
entangled $\Psi_E = \left(|0_N\rangle + e^{i\theta_E}|1_N\rangle\right)$ $\qquad \dfrac{\Delta f}{f} \propto \dfrac{1}{N}$

Detecting strontium Rydberg states using electromagnetically induced transparency (EIT)

S. Mauger et al. J. Phys B **40**, F319 (2007)

Rydberg EIT

Optical detection of Rydbergs using a strong ground-state transition.

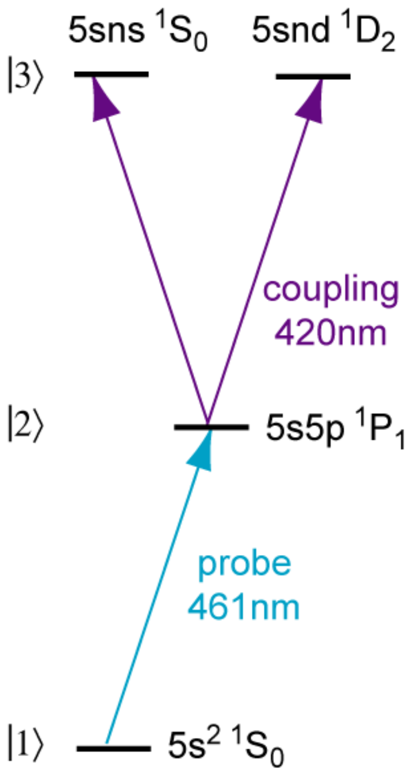


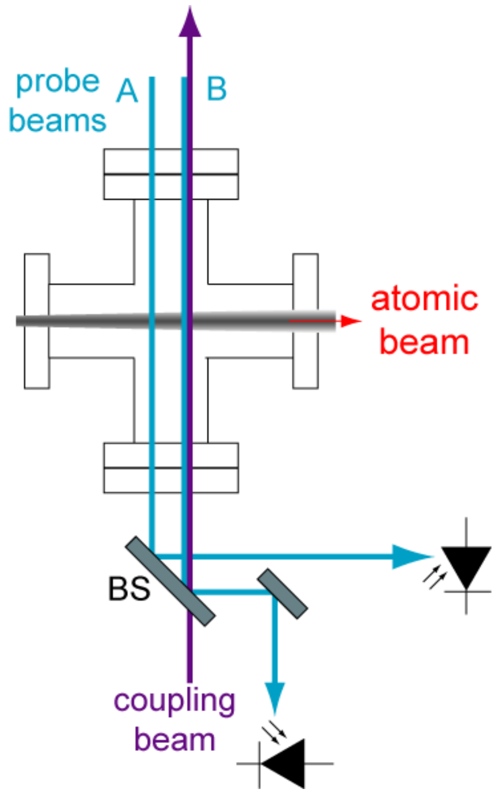
Strong coupling laser "dresses' the system

Transitions have equal amplitudes but opposite phases.

Applied to Rydberg spectroscopy in Rb in Mohatpatra et. al. PRL **98**, 113003 (2007)

Experimental setup

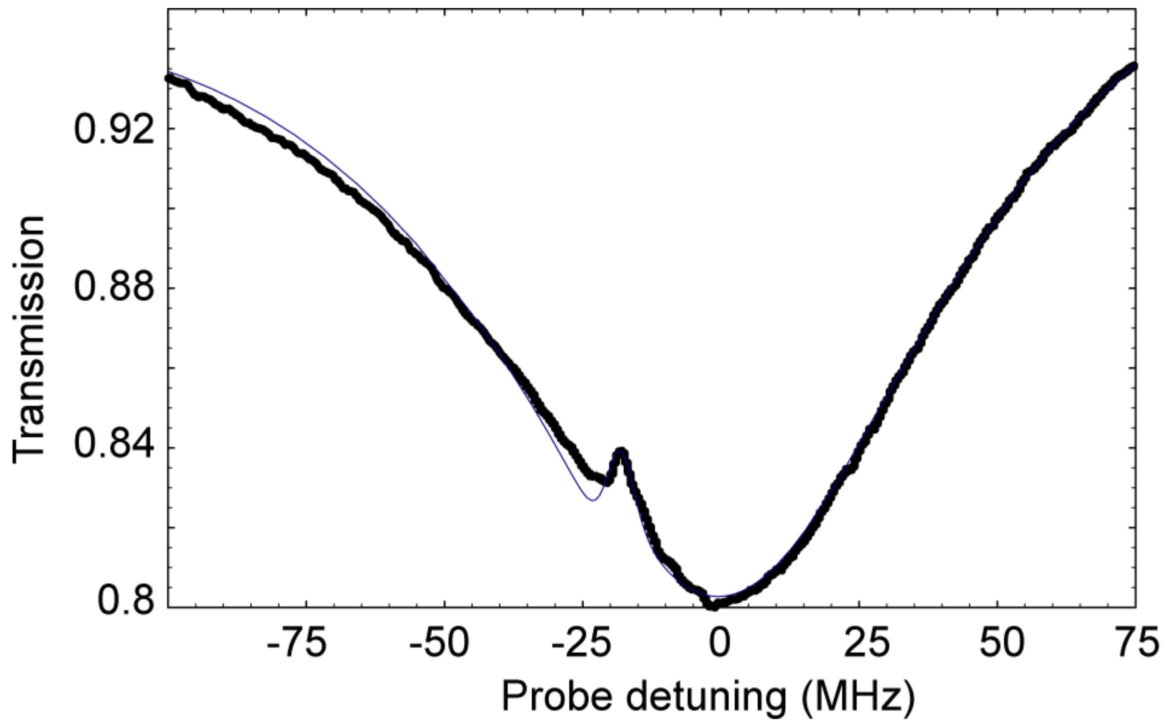




Lasers are both commercial frequency doubled diode laser systems (Toptica)

Results

Coupling laser is tuned close to the 5s18d $^1D_2$ state

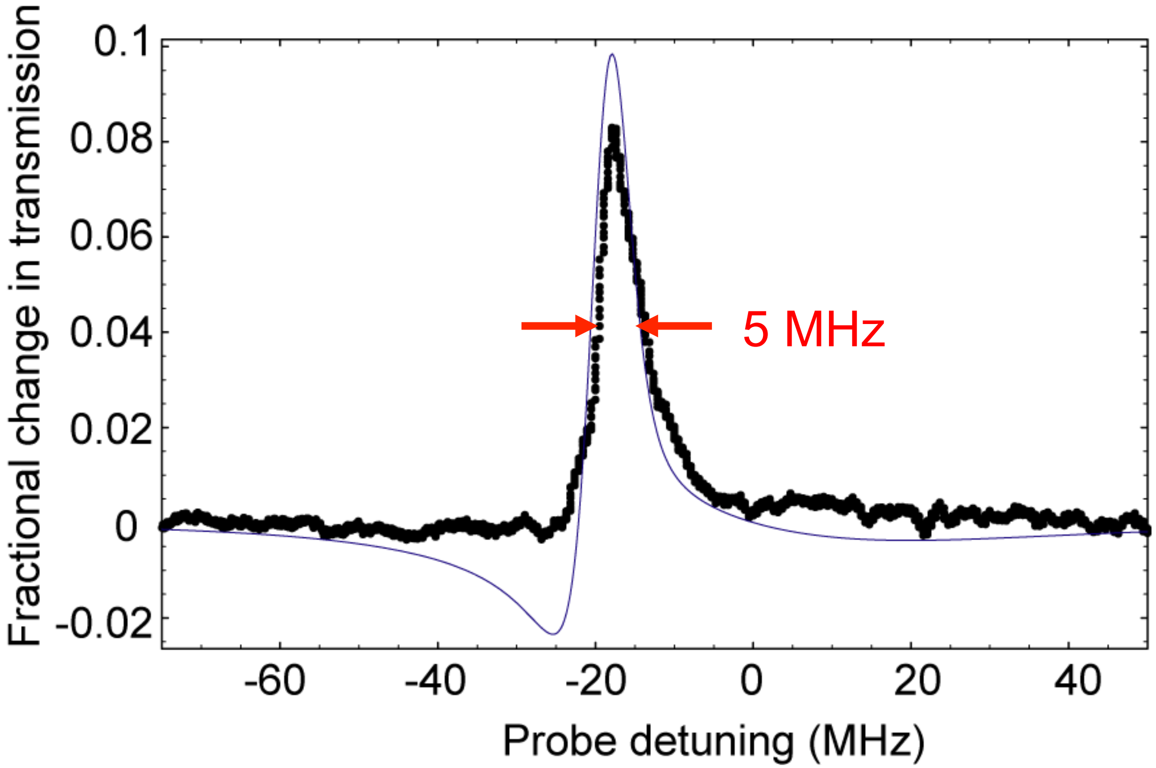


$$(\gamma_3 = 2\pi \times 3.5\,\text{MHz},\ \Omega_c = 2\pi \times 7.5\,\text{MHz}, \Delta_c = 2\pi \times 20\,\text{MHz}, \Delta v = 16.5\,\text{ms}^{-1})$$

Probe power: 150μW
Coupling power: 12mW

Probe linear
Pump circular

Results

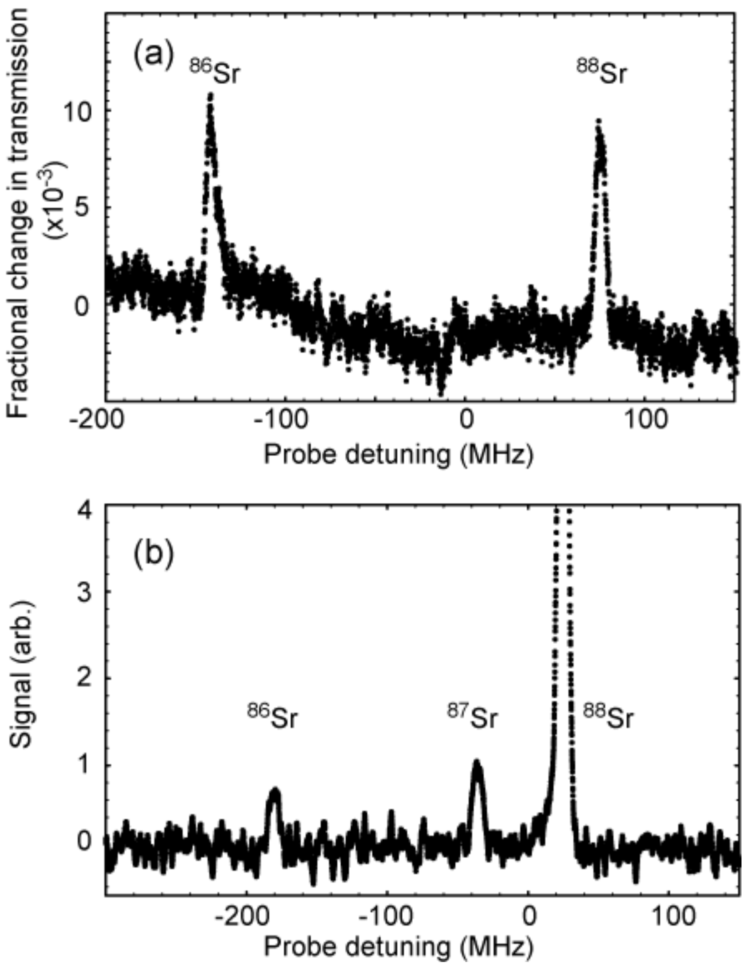


Resonance is much narrower than 32 MHz natural linewidth

Isotope shifts

5s18d $^1D_2$

5s19s $^1S_0$



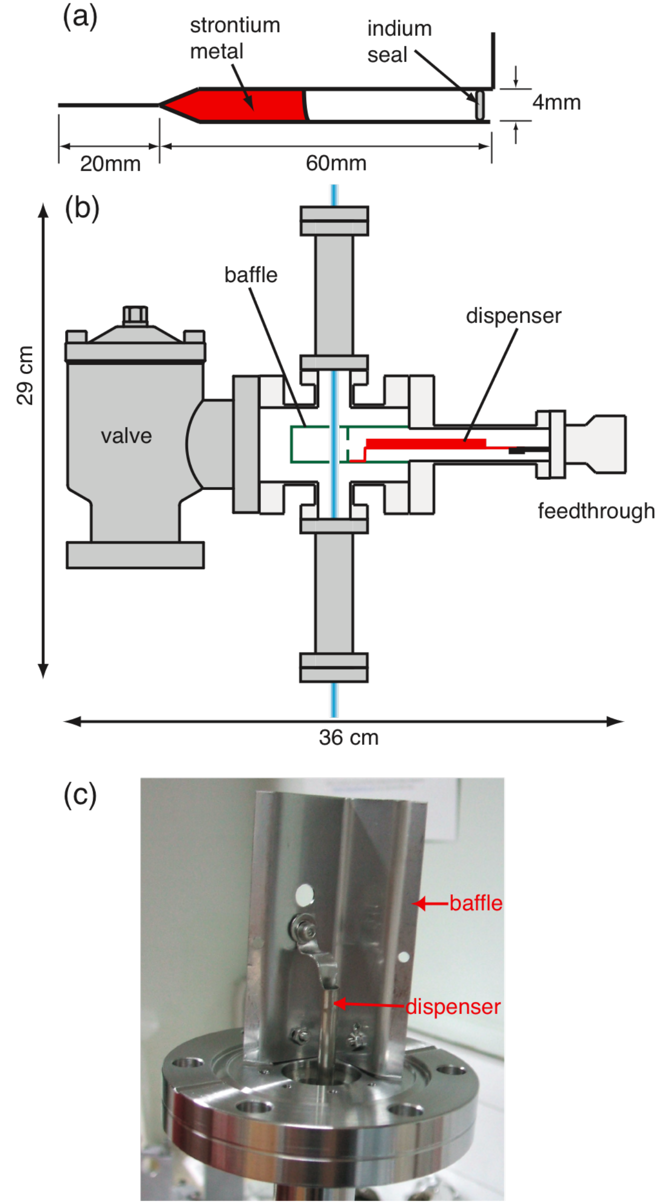
(with lock-in detection)

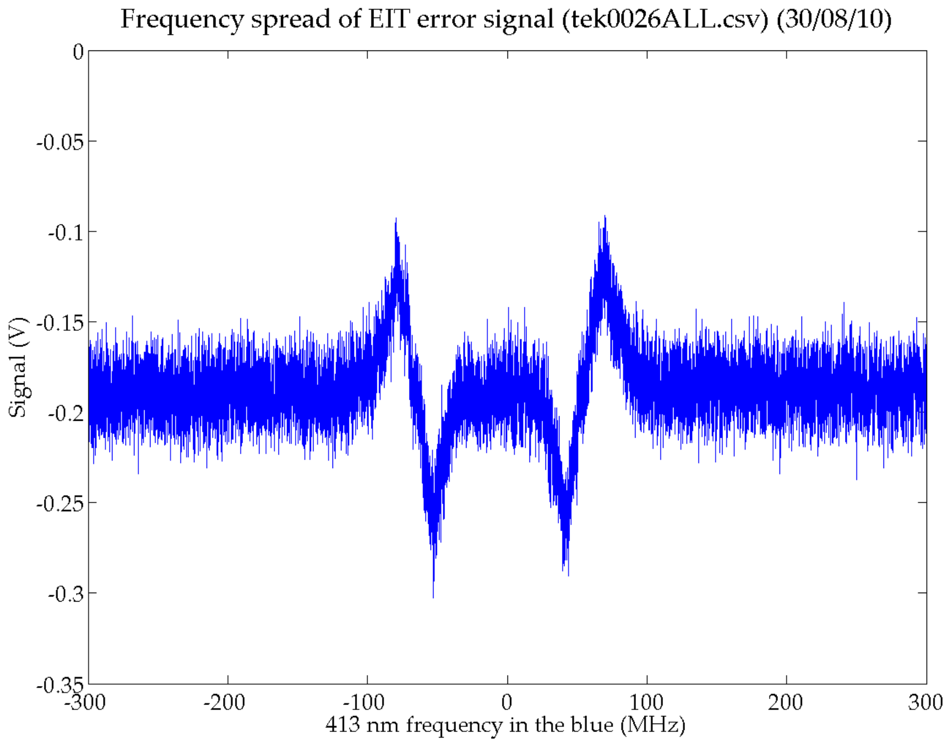
By changing the coupling laser detuning we can see EIT signals from the other isotopes.

Using known isotope shifts of the $^1P_1$ state we obtain the isotope shift of the Rydberg states

Rydberg state	^{88}Sr - ^{86}Sr (MHz)	^{88}Sr - ^{87}Sr (MHz)
5s18d $^1D_2$	226 ± 7	-
5s19s $^1S_0$	213 ± 7	62 ± 8

Rydberg EIT in a cell

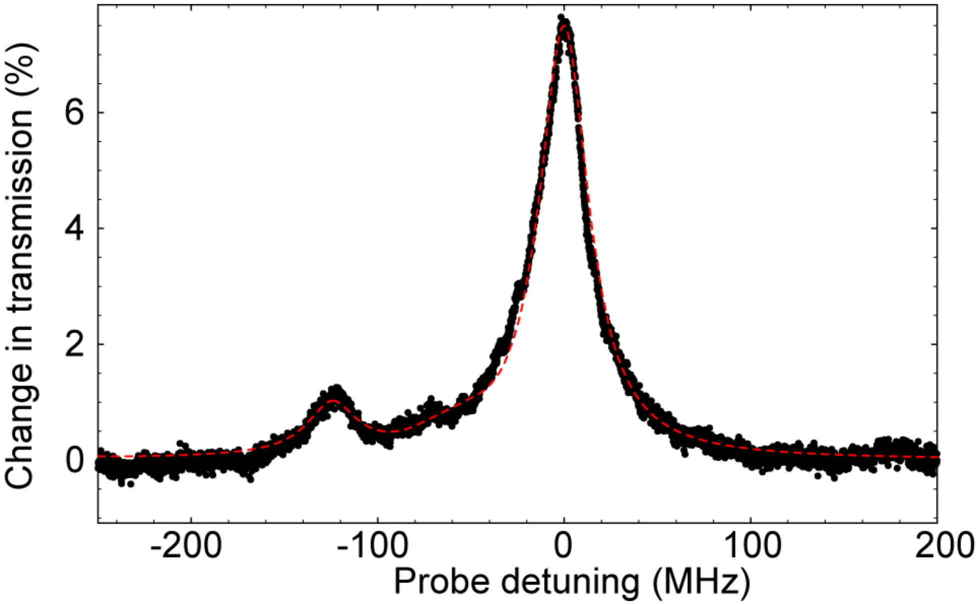




Scan calibration

Scan calibrated using saturated absorption spectroscopy on the $^1S_0$ to $^1P_1$ line.

Isotope		Detuning (MHz)	Abundance (%)
84		-270.8	0.56
86		-124.8	9.86
87	7/2	-9.7	4/15 * 7
	9/2	-68.9	1/3 * 7
	11/2	-51.9	2/5 * 7
88		0	82.58



Lorentzian lineshape with width equal to natural linewidth.

Frequency intervals accurate to 3%

Frozen Rydberg gas

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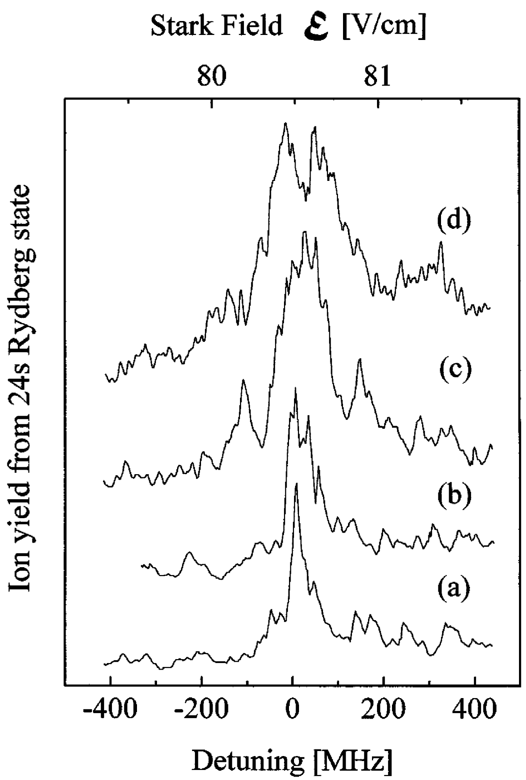
Start with a cloud of cold atoms released from a MOT

Ball of 10^7 atoms at ~100μK, separated by ~10μm

Excite to a Rydberg state

Interactions completely dominate kinetic energy

Frozen Rydgerg gas, with many-body interactions



Mourachko et al. PRL 80, 253 (1998)