Resonant four-body interaction in cold Rydberg atoms

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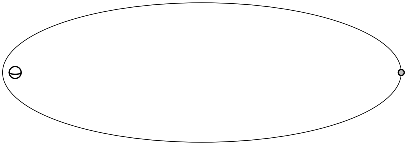
Outline

What's a Rydberg Atom?

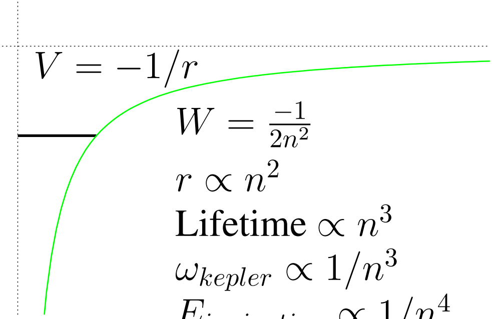


Any atom with one or more electrons of large principal quantum number n, where $n > 10$.

This Talk: $n \approx 23$

Introduction to Rydberg Atoms

Properties of Rydberg Atoms



$V = -1/r$

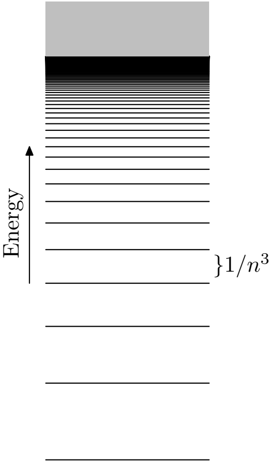
$W = \frac{-1}{2n^2}$

$r \propto n^2$

Lifetime $\propto n^3$

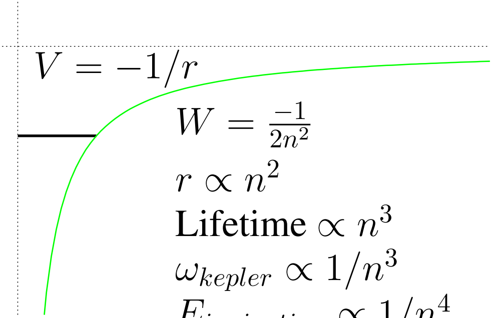
$\omega_{kepler} \propto 1/n^3$

$E_{ionization} \propto 1/n^4$



Introduction to Rydberg Atoms

Properties of Rydberg Atoms



$W = \frac{-1}{2n^2}$

$r \propto n^2$

Lifetime $\propto n^3$

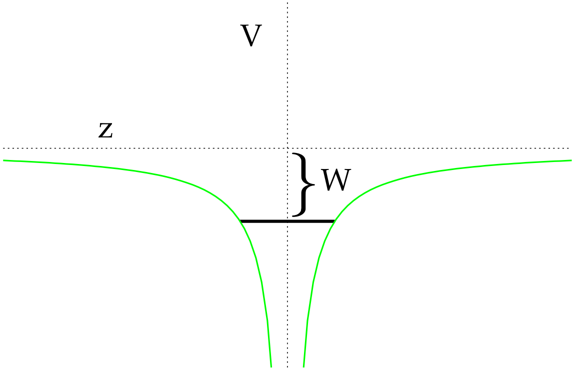
$\omega_{kepler} \propto 1/n^3$

$E_{ionization} \propto 1/n^4$

For n=100:

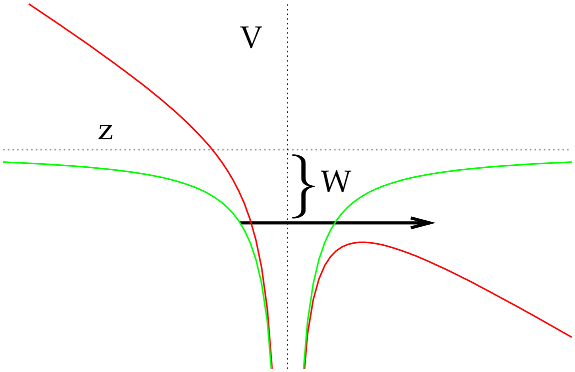
- $W = -1.4$ meV
- $< r >= 0.5\,\mu$m
- $\tau = 1$ ms
- $\omega_{kepler} = 2\pi \times 6.5$ GHz
- $E_{ionization} = 5.7$ V/cm

Field Ionization



$$V(z) = \frac{-1}{|z|}$$

Field Ionization



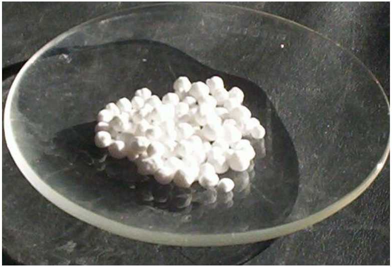
$$V(z) = \frac{-1}{|z|} - Ez$$

$$E = \frac{W^2}{4}$$

Huge Dipole Moments

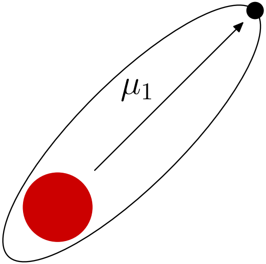
KBr

Dipole Moment: 10.41 D



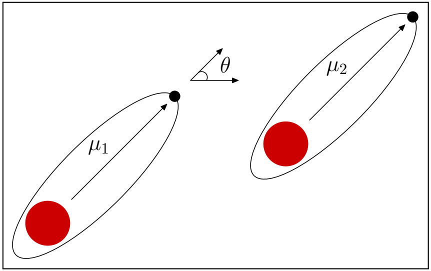
Rydberg Atoms

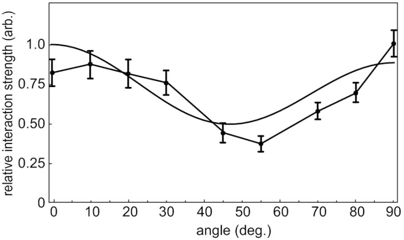
Dipole Moment: $2.54n^2$ D



Dipole-Dipole Interaction

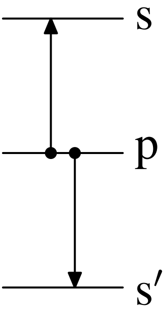
Anisotropic Interaction: $V_{12} = \frac{\vec{\mu_1}\cdot\vec{\mu_2} - 3(\vec{\mu_1}\cdot\hat{R})(\vec{\mu_2}\cdot\hat{R})}{R^3}$

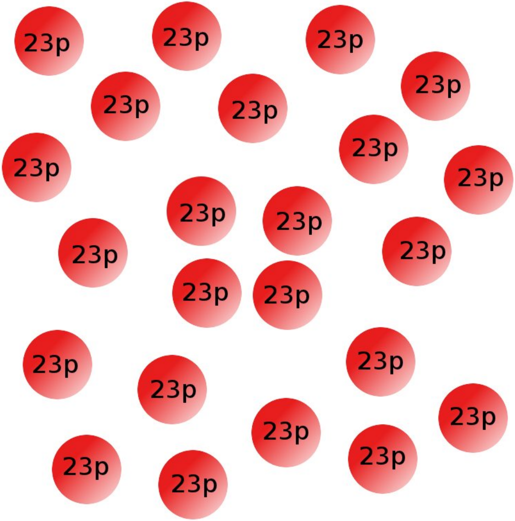




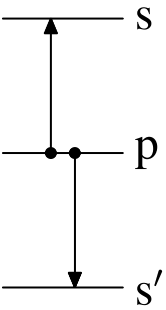
T.J. Carroll *et al.* PRL (2004).

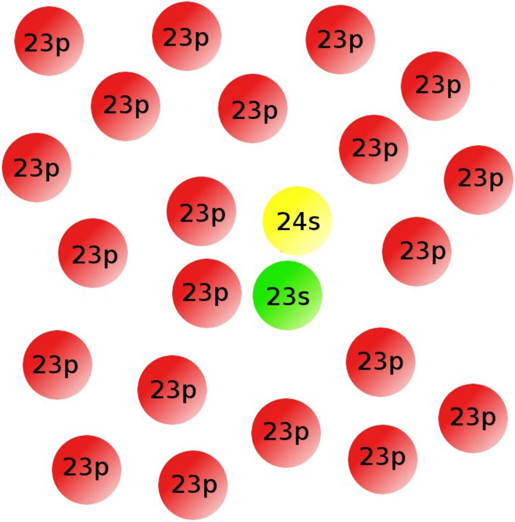
Dipole-Dipole Energy Transfer





Dipole-Dipole Energy Transfer





Dipole Energy Transfer

VOLUME 47, NUMBER 6 PHYSICAL REVIEW LETTERS 10 AUGUST 1981

Resonant Rydberg-Atom–Rydberg-Atom Collisions

K. A. Safinya,[a] J. F. Delpech,[b] F. Gounand,[c] W. Sandner,[d] and T. F. Gallagher
Molecular Physics Laboratory, SRI International, Menlo Park, California 94025
(Received 22 June 1981)

VOLUME 80, NUMBER 2 PHYSICAL REVIEW LETTERS 12 JANUARY 1998

Resonant Dipole-Dipole Energy Transfer in a Nearly Frozen Rydberg Gas

W. R. Anderson,* J. R. Veale, and T. F. Gallagher
Department of Physics, University of Virginia, Charlottesville, Virginia 22901
(Received 4 August 1997)

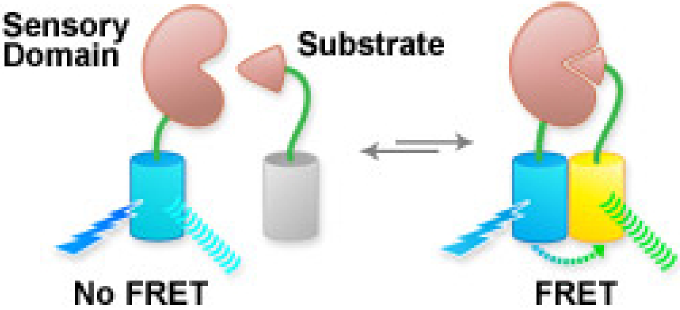
VOLUME 80, NUMBER 2 PHYSICAL REVIEW LETTERS 12 JANUARY 1998

Many-Body Effects in a Frozen Rydberg Gas

I. Mourachko, D. Comparat, F. de Tomasi, A. Fioretti, P. Nosbaum,* V. M. Akulin,† and P. Pillet
Laboratoire Aimé Cotton, CNRS II, Bât. 505, Campus d'Orsay, 91405 Orsay Cedex, France
(Received 4 August 1997)

Förster Resonance Energy Transfer

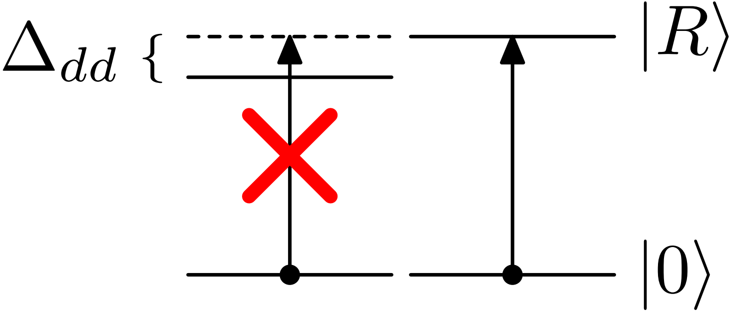
Analogous to FRET in biochemistry



D. W. Piston, M. E. Dickinson, & M. W. Davidson, *FRET Microscopy with Spectral Imaging*

Dipole Blockade

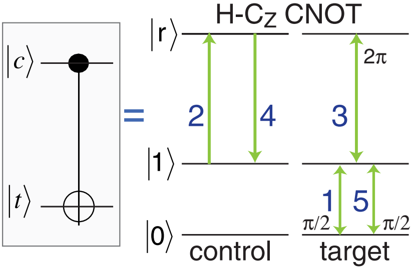
Dipole interaction prevents excitation of multiple Rydberg atoms



K. Singer *et al.*, PRL (2004). D. Tong *et al.*, PRL (2004).
T. Vogt *et al.*, PRL (2006). D. Comparat & P. Pillet JOSA B (2010).

Rydberg CNOT Gates

Two Rydberg atoms, $|c\rangle$ and $|t\rangle$, entangled via dipole-dipole interaction



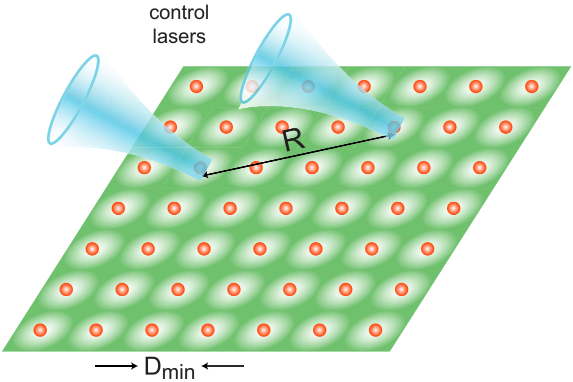
IN		OUT	
$\lvert c\rangle$	$\lvert t\rangle$	$\lvert c\rangle$	$\lvert t\rangle$
0	0	0	0
0	1	0	1
1	0	1	1
1	1	1	0

Many CNOT gates with low gate error → A Quantum Computer

L. Isenhower *et al.* PRL 104 (2010), T. Wilk *et al.* PRL 104 (2010).

Collective Ensemble

For $n = 100$ atoms in a 2D array:



Saffman & Co. estimate possible entanglement of up to 470 qubits.

M. Saffman & K. Mølmer, PRA (2008).
M. Saffman, T.G. Walker & K. Mølmer, RMP (2010).

Many-body influence

Mizel & Lidar: Many-body effects can cause errors beyond 15%

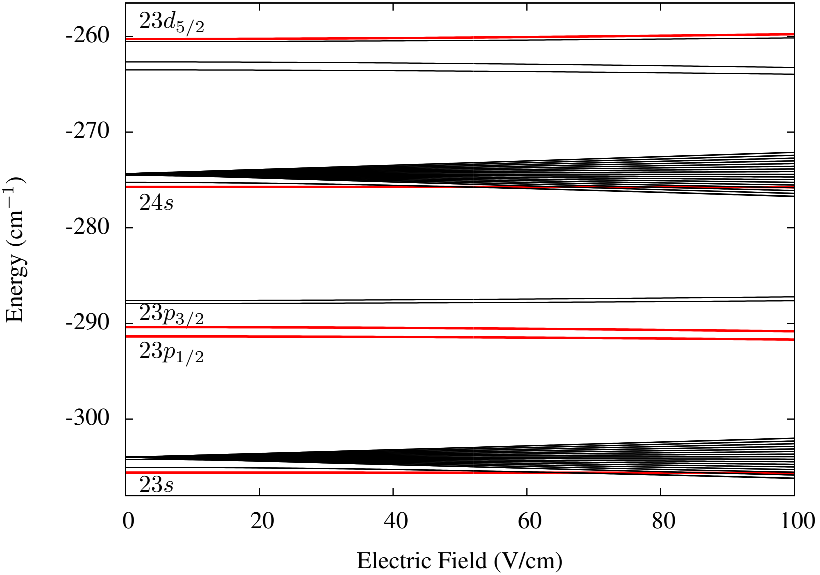
Noel Group:
$31d + 31d \rightarrow 33p + 29k$
Require up nine atoms to explain their 2-body results

Weidemüller Group:
$32p_{3/2} + 32p_{3/2} \rightarrow 32s + 33s$
Require 4-10 atoms to explain their 2-body results

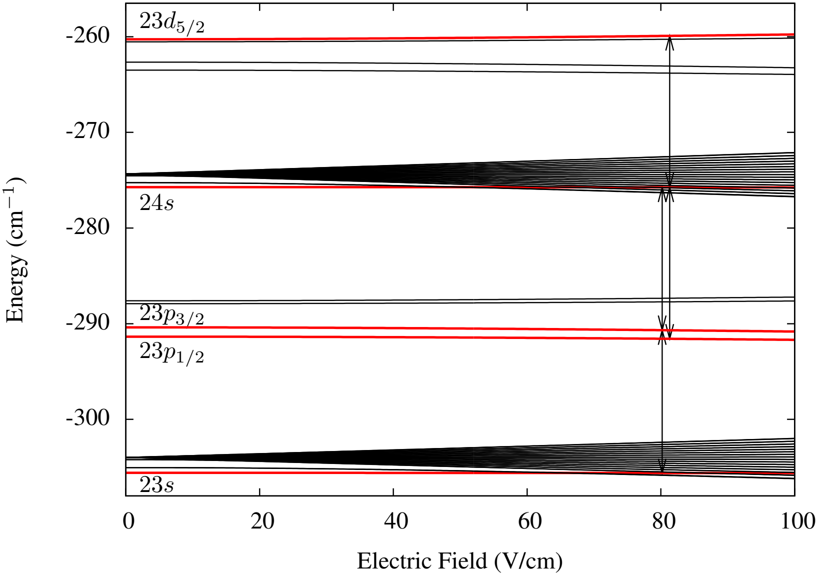
Can we directly observe a many-body Rydberg energy transfer?

A. Mizel & D. A. Lidar, PRL 92 (2004).
T. J. Carroll, S. Sunder, & M. W. Noel, PRA 73 (2006).
S. Westermann *et al.* Eur. Phys. J. D 40 (2006).

Cs Stark Map


$23d_{5/2}$
$24s$
$23p_{3/2}$
$23p_{1/2}$
$23s$
-260
-270
-280
-290
-300
Energy (cm^{-1})
0
20
40
60
80
100
Electric Field (V/cm)

Cs Stark Map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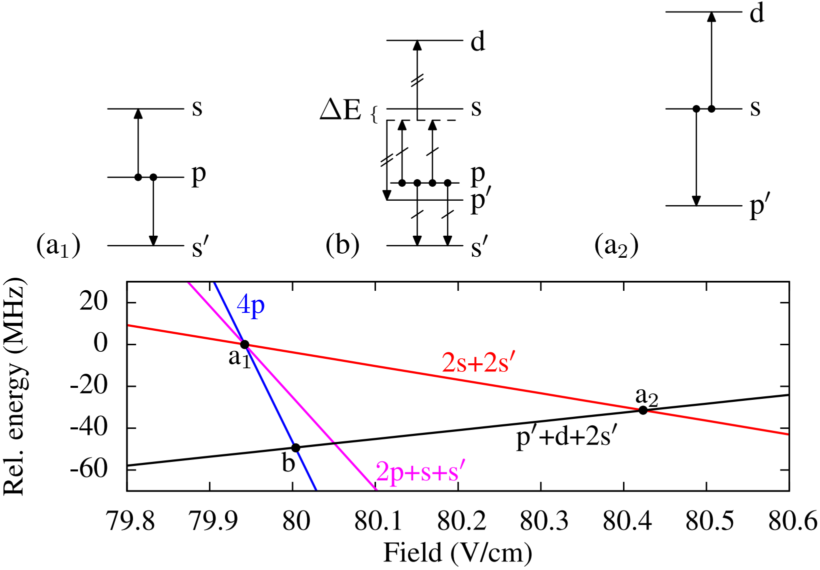
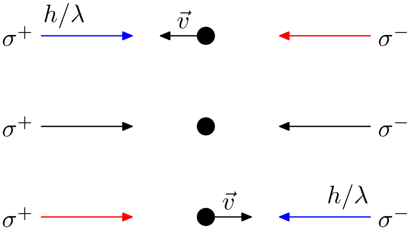
$23p_{1/2}$
$23s$
Energy (cm^{-1})
0
20
40
60
80
100
Electric Field (V/cm)

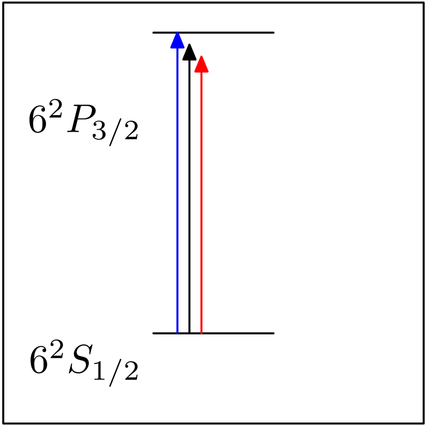
Energy Difference



Outline

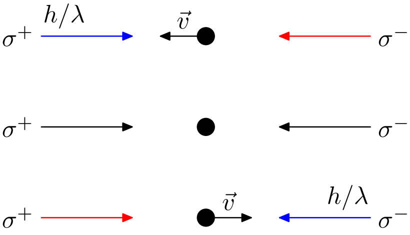
Cs Levels

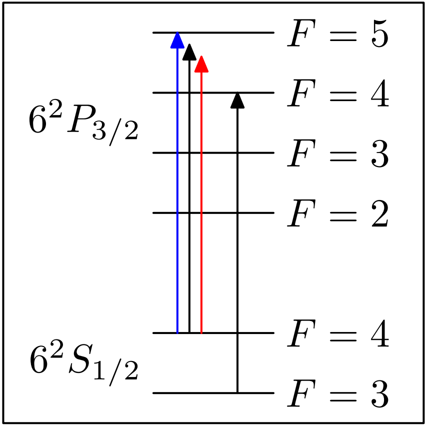




D. A. Steck, "Cesium D Line Data"

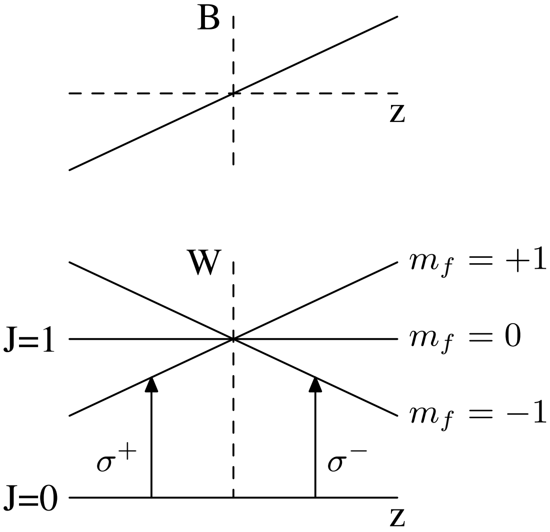
Cs Levels



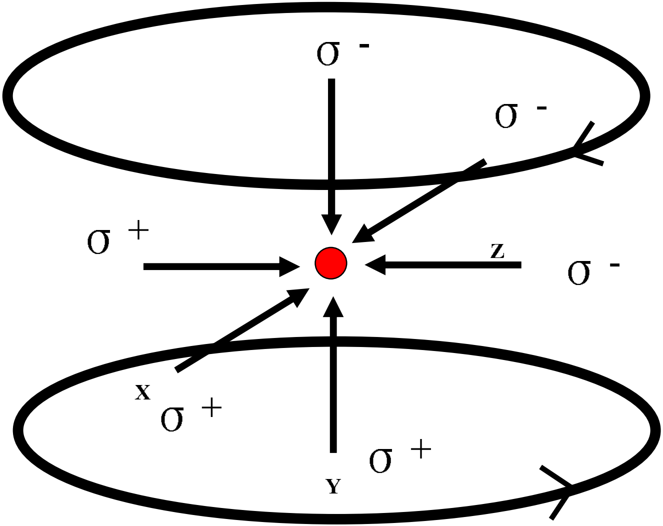


D. A. Steck, "Cesium D Line Data"

Magentic Trapping

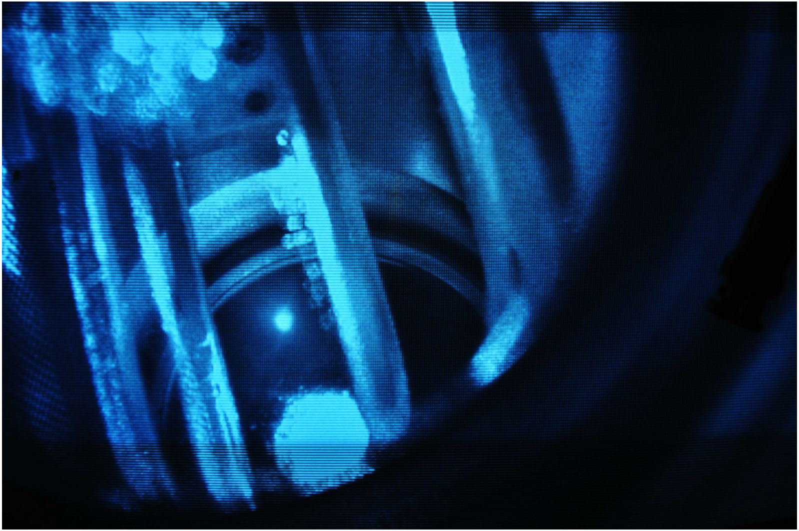


MOT Diagram



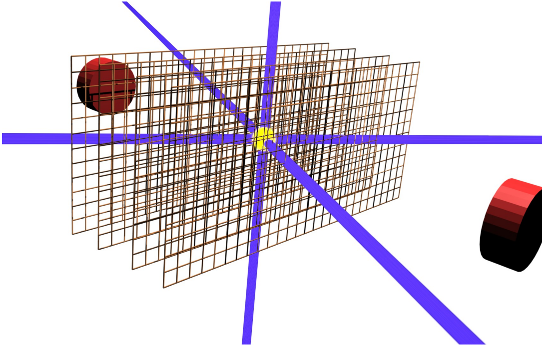
from J. Han, *Dipole effects in a cold Rydberg gas.* (2009).

Exp. MOT



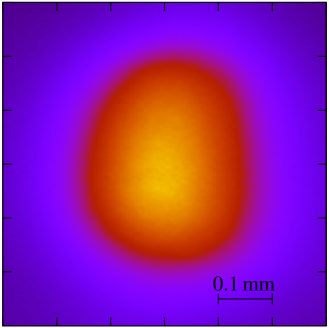
Apparatus

- Background loaded Cs MOT
- Four parallel wire grids
- Two MCP detectors for ion and electron detection
- TOF and charged particle imaging

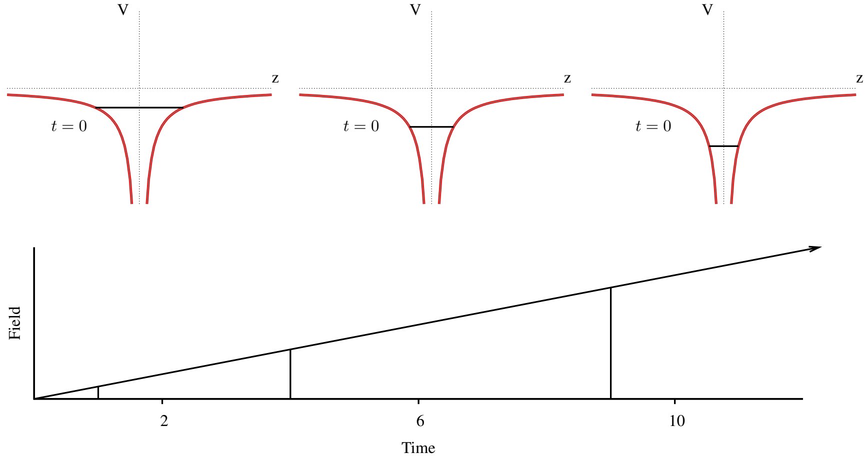


Rydberg Excitation

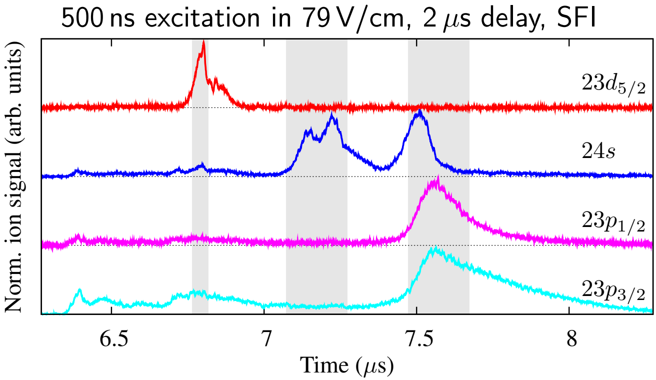
- $6s \rightarrow 6p \rightarrow 7s \rightarrow np$
- Excite 2×10^5 $23p$ atoms
- $260\,\mu$m diameter gaussian cloud
- Peak density $9 \times 10^9\,\text{cm}^{-3}$



SFI Analysis



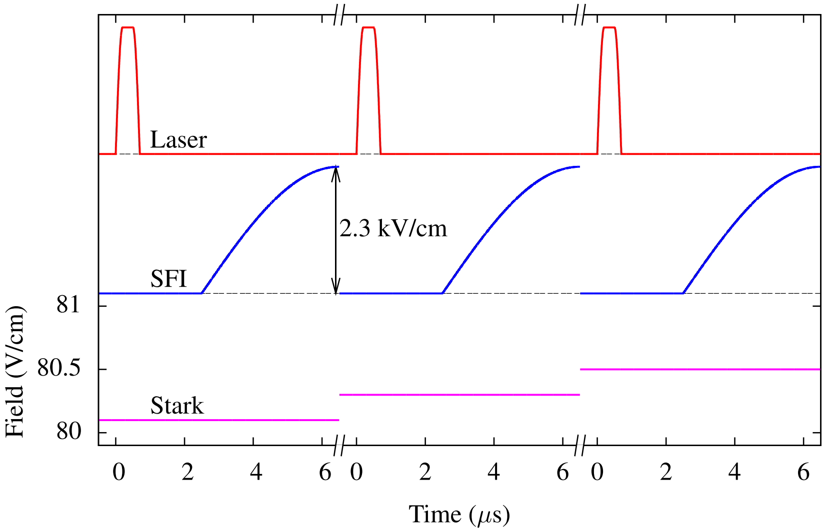
Oscilloscope Traces



$$\begin{pmatrix} d_{actual} \\ s_{actual} \\ p_{actual} \end{pmatrix} = \begin{pmatrix} 1.0494 & -0.1911 & -0.1223 \\ -0.039 & 2.559 & -0.3257 \\ -0.0104 & -1.3685 & 1.448 \end{pmatrix} \begin{pmatrix} d_{detected} \\ s_{detected} \\ p_{detected} \end{pmatrix}$$

Removes signal overlap and BB transfer

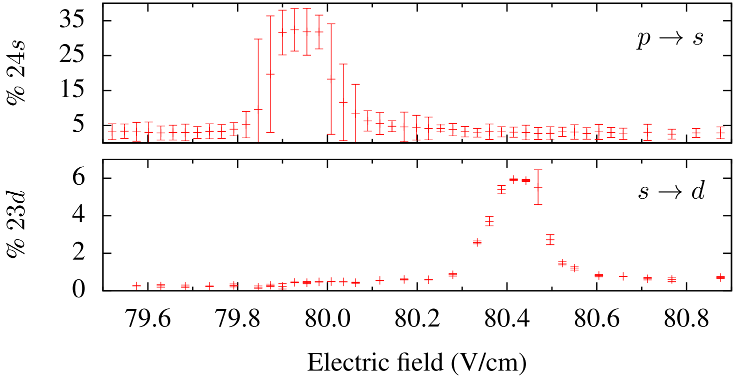
Experimental Timing



Outline

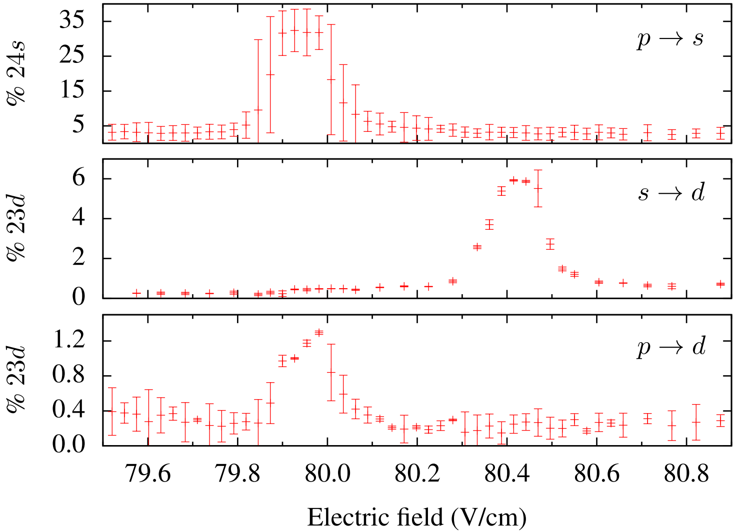
Two Body Resonances

$$23p_{3/2} + 23p_{3/2} \rightarrow 23s + 24s$$

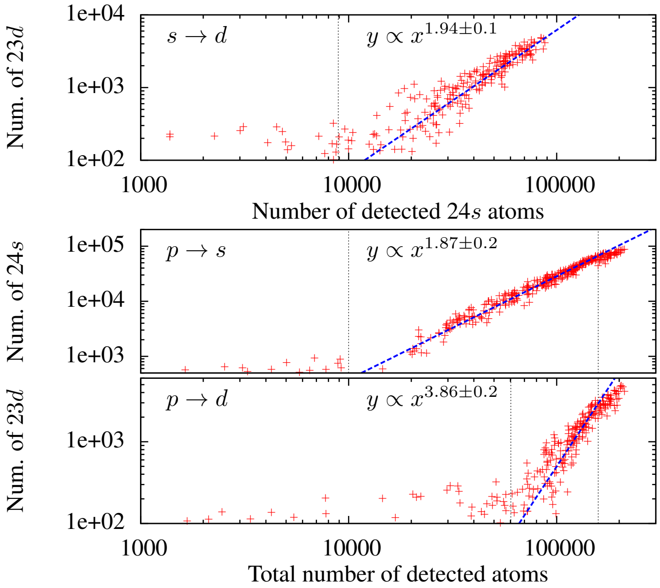


$$24s + 24s \rightarrow 23p_{1/2} + 23d_{5/2}$$

$4 \times 23p_{3/2} \rightarrow 2 \times 23s + 23p_{1/2} + 23d_{5/2}$

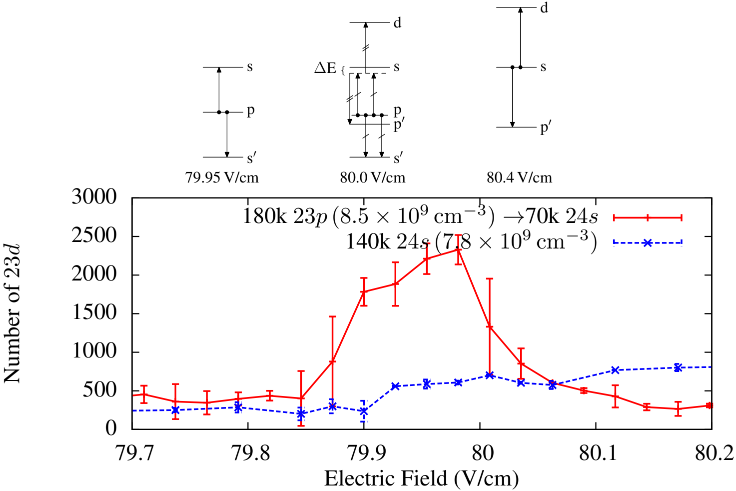


Intensity



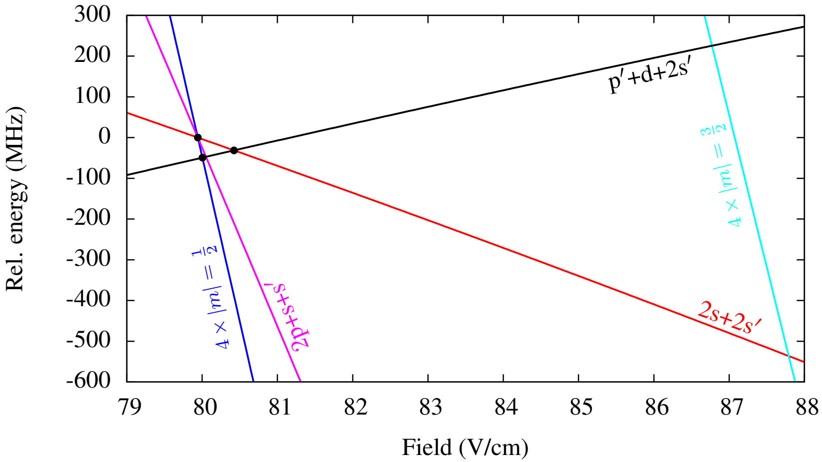
Num. of 23d
1e+04
1e+03
1e+02
$s \to d$
$y \propto x^{1.94\pm0.1}$
1000
10000
100000
Number of detected 24s atoms
Num. of 24s
1e+05
1e+04
1e+03
$p \to s$
$y \propto x^{1.87\pm0.2}$
Num. of 23d
1e+03
1e+02
$p \to d$
$y \propto x^{3.86\pm0.2}$
1000
10000
100000
Total number of detected atoms

True 4-body process?



On-resonant 4-body process creates more $23d$ atoms than off-resonant two-body $s \to d$ process!

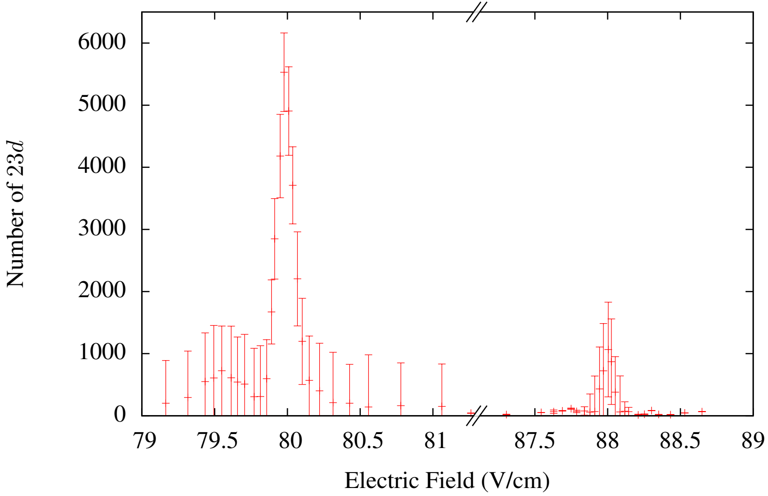
$23p_{\frac{3}{2}}|m| = \frac{3}{2}$ 4-Body Resonance



$|m_f| = 3/2$ Comparison

$2 \times 23p_{\frac{3}{2}|m|=\frac{1}{2}} \rightarrow 23s + 24s$: 80 V/cm

$2 \times 23p_{\frac{3}{2}|m|=\frac{3}{2}} \rightarrow 23s + 24s$: 88 V/cm



Outline

Introduction to Rydberg Physics
- Rydberg Atoms
- Dipole Interaction
- Motivation

Experiment
- How to cool atoms in a MOT
- Our Experimental Setup

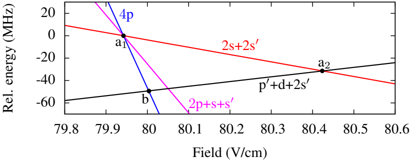
Results
- $|m| = 1/2$
- $|m| = 3/2$

Model
- Introduction
- Results
- Comparison with Experimental Results

Conclusions

Toy Model

$$|0\rangle = |pppp\rangle \quad |1\rangle = |ss'pp\rangle \quad |2\rangle = |ss'ss'\rangle \quad |3\rangle = |p'ds's'\rangle$$



$$p \to s$$

$$H = \begin{pmatrix} \frac{E_0}{2} & V_{01} \\ V_{01} & \frac{E_1}{2} \end{pmatrix}$$

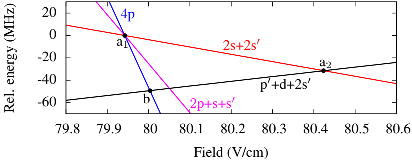
TDSE: $\rho(t) = e^{-iHt}\rho_0 e^{iHt}$

$$\rho_0 = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$$

Assume dipole couplings V_{ij}, average over Gamma distribution.

Toy Model

$$|0\rangle = |pppp\rangle \quad |1\rangle = |ss'pp\rangle \quad |2\rangle = |ss'ss'\rangle \quad |3\rangle = |p'ds's'\rangle$$



$$s \to d$$

$$H = \begin{pmatrix} \frac{E_2}{2} & V_{23} \\ V_{23} & \frac{E_3}{2} \end{pmatrix}$$

TDSE: $\rho(t) = e^{-iHt}\rho_0 e^{iHt}$

$$\rho_0 = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$$

Assume dipole couplings V_{ij}, average over Gamma distribution.

Toy Model

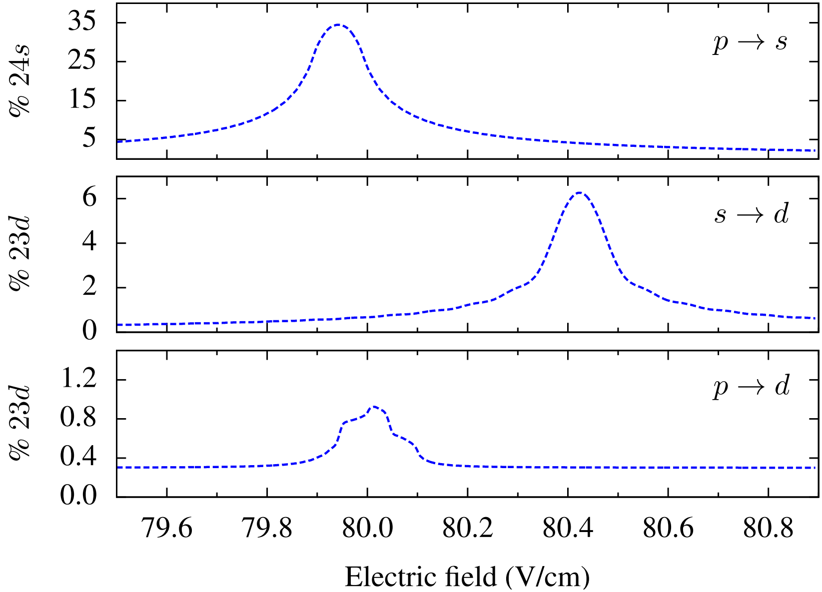
$$|0\rangle = |pppp\rangle \quad |1\rangle = |ss'pp\rangle \quad |2\rangle = |ss'ss'\rangle \quad |3\rangle = |p'ds's'\rangle$$

$$H = \begin{pmatrix} \frac{E_0}{2} & V_{01} & 0 & 0 \\ V_{01} & \frac{E_1}{2} & V_{12} & 0 \\ 0 & V_{12} & \frac{E_2}{2} & V_{23} \\ 0 & 0 & V_{23} & \frac{E_3}{2} \end{pmatrix}$$

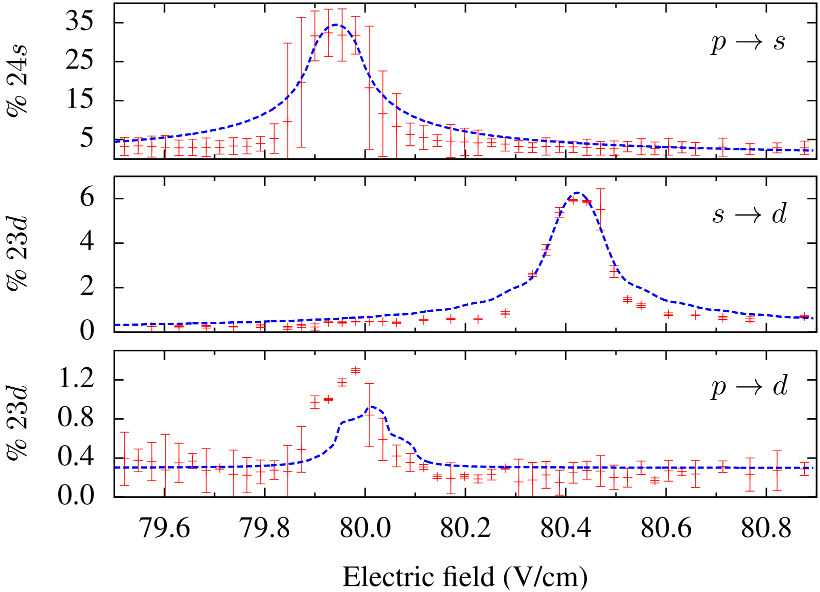
TDSE: $\rho(t) = e^{-iHt}\rho_0 e^{iHt}$ $\qquad \rho_0 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$

Assume dipole couplings V_{ij}, average over cubic Gamma distribution.

Toy Model Results



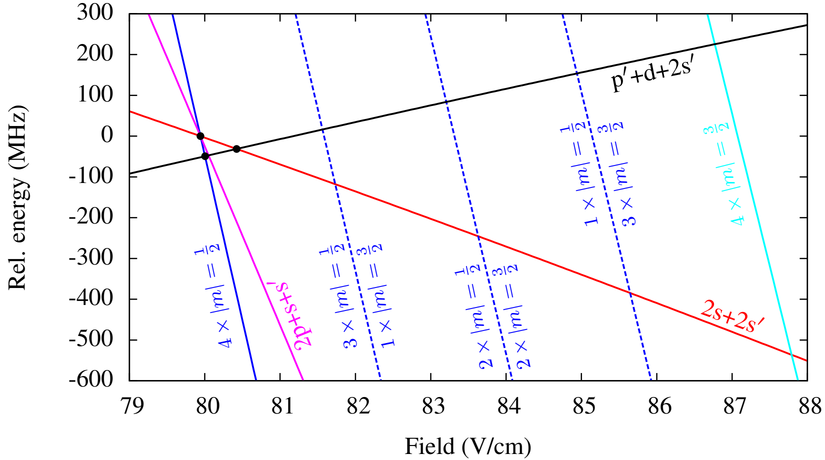
Toy Model Comparison



Outline

Next Steps

$$n \times 23p_{\frac{3}{2}|m|=\frac{1}{2}} + (4-n) \times 23p_{\frac{3}{2}|m|=\frac{3}{2}}$$

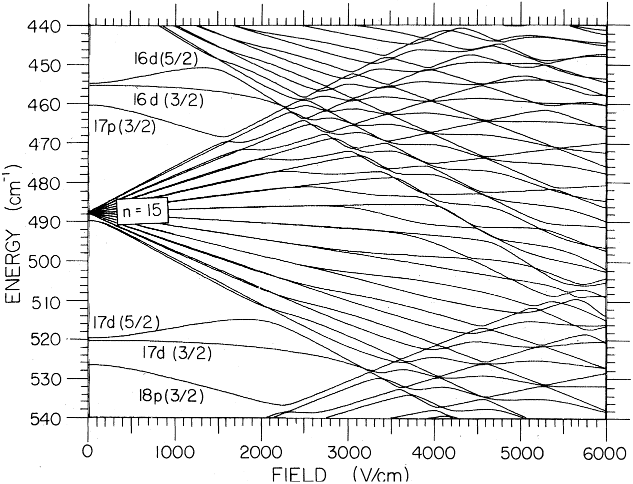


Requires two excitation lasers to excite both $|m| = \frac{1}{2}$ and $|m| = \frac{3}{2}$

Conclusions

- Observation of direct product of Stark-tuned 4-body Rydberg interaction
  - Density scaling approaching n^4
  - On-res. 4-body process $>$ Off-res. 2-body process
  - J.H. Gurian *et al.* PRL (arxiv:1111.2488)
- Next: Two color 4-body resonance
- Future: Further control multibody Rydberg interaction via RF or B-field.

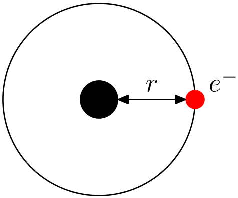
Cs Stark Map



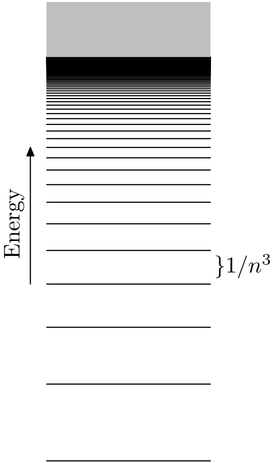
M. L. Zimmerman *et al.* PRA (1979).

Outline

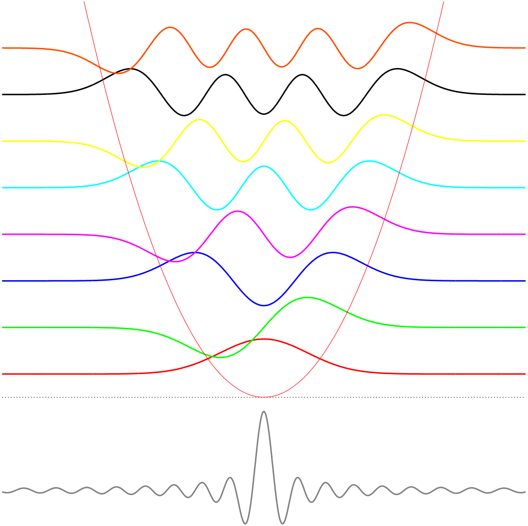
Bohr Model

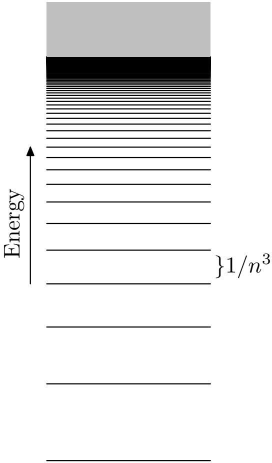


- $$\frac{mv^2}{r} = \frac{Zk_e e^2}{r^2}$$
- $L = mvr = n\hbar$
- $$W = KE + U = \frac{1}{2}mv^2 - \frac{Zk_e e^2}{r}$$
- $$r = \frac{n^2\hbar^2}{mZk_e e^2}$$
- $$\boxed{W = \frac{-mZ^2k_e^2e^4}{2\hbar^2n^2}}$$



Creating A Wavepacket

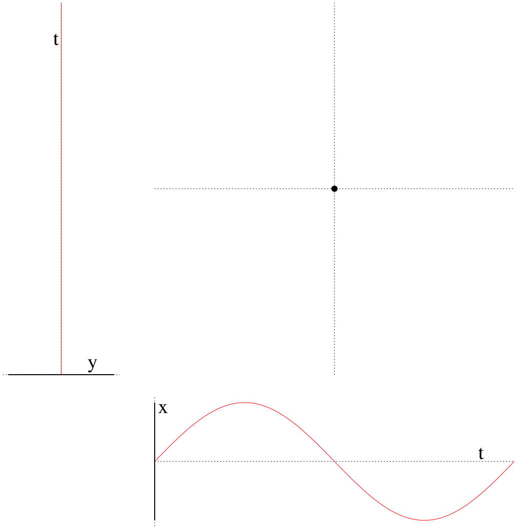




A. Buchleitner & D. Delande, PRL (1995).
Bialynicki-Birula, Kalinsky, & Eberly, PRL (1994).

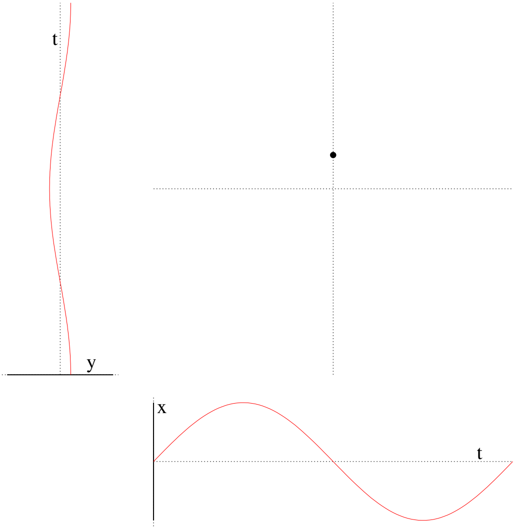
MW Phase Locking

- MW phase lock electron



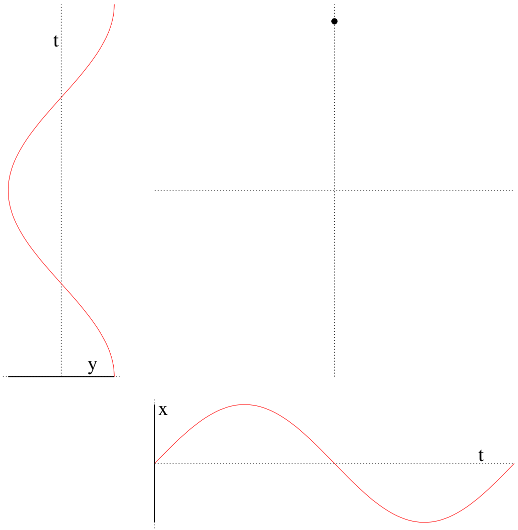
MW Phase Locking

- MW phase lock electron
- Slowly increase 2nd MW field



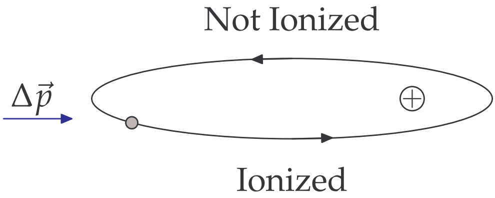
MW Phase Locking

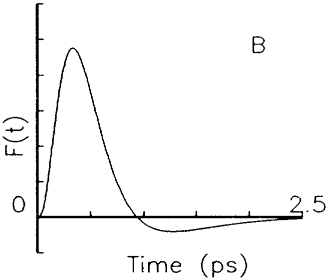
- MW phase lock electron
- Slowly increase 2nd MW field
- Long-lived circular Bohr orbit



Half-Cycle Pulses

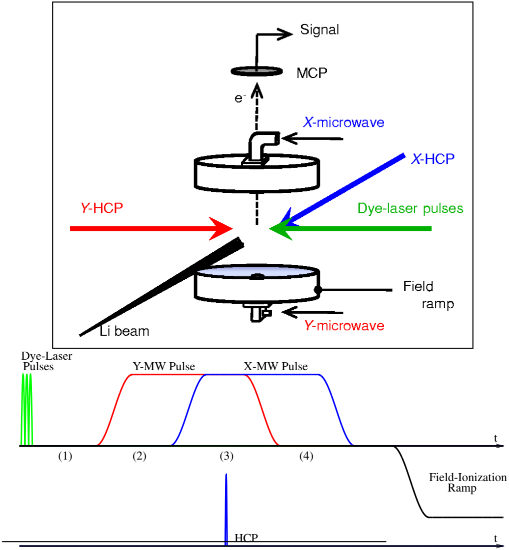
$$\Delta\vec{p} = -\int_{-\infty}^{\infty} \vec{F(t)}\,dt$$

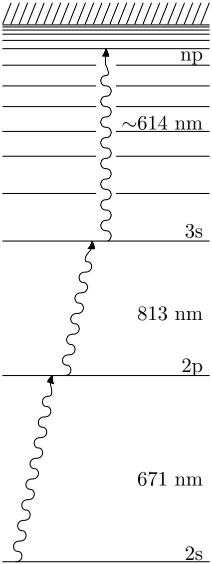




R. R. Jones, D. You, & P. H. Bucksbaum, PRL 70 (1993).

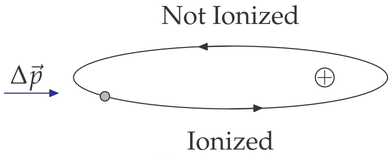
Experimental Setup

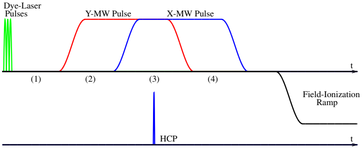


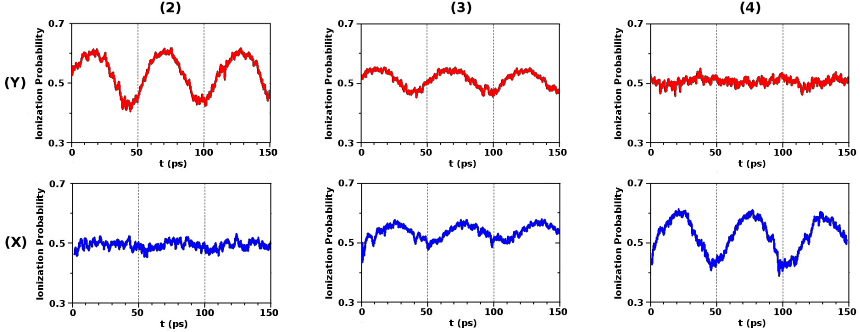


J. H. Gurian, H. Maeda, & T. F. Gallagher, Rev. Sci. Instrum. 81 (2010).

Half-cycle Pulse Detection

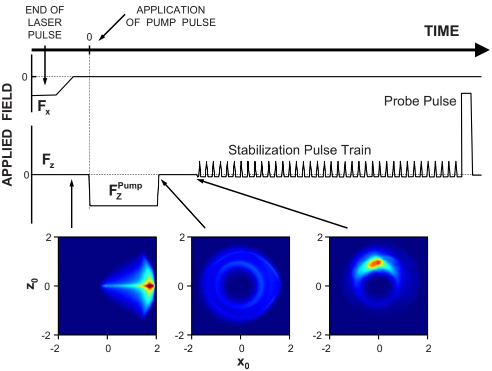


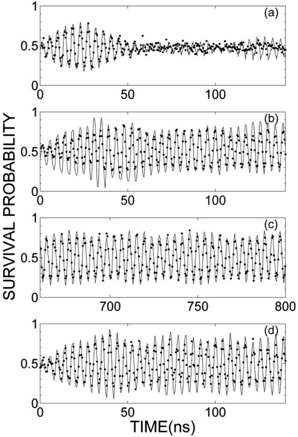




H. Maeda, J. H. Gurian, & T. F. Gallagher, PRL 102 (2009).

Dunning's Bohr Atoms





Train of HCP kicking $n = 306$ K atom

J. J. Mestayer *et al.*, PRA 79, (2009).

Rydberg Lifetime

Einstein's A coefficient: $A_{n'\ell',n\ell} = \frac{4}{3}\omega^3_{n\ell,n'\ell'}\frac{\ell_{max}}{2\ell+1}|\langle n'\ell'|r|n\ell\rangle|^2$

As $n \to \infty$, $\omega \to$ constant.
$\langle$ground state$|r|n\ell\rangle \propto n^{-3/2}$
$\tau_{n\ell} = \left[\sum_{n'\ell'} A_{n'\ell',n\ell}\right]^{-1}$

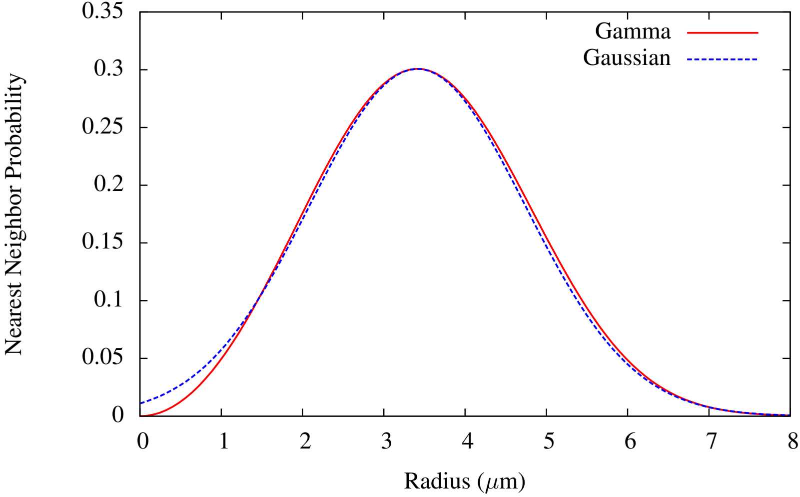
$\tau \propto n^3$

This ignores blackbody radiation and ℓ scaling!

Gamma Distribution

$n = 10^9$ cm^{-3} $4\pi n R^2 e^{-(4/3)n\pi R^3}$

Return to Talk

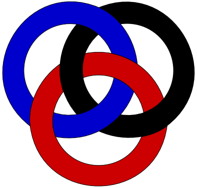


S. Torquato, B. Lu, & J. Rubenstein, PRA (1990).

Efimov States

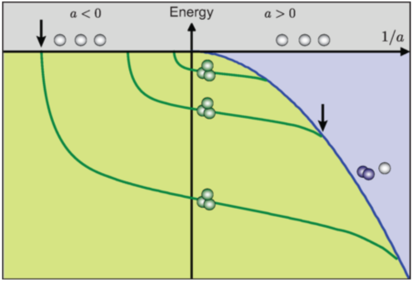
Infinite series of excited three-body energy levels at the two-body dissociation threshold.

First predicted by Efimov in 1970...
...experimentally confirmed by Grimm *et al.* in 2005.



Tune the scattering parameter, a, via an applied B-field

Tetramers observed in 2009!



F. Ferlaino & R. Grimm, Physics 3, 9 (2010)