Direct observation of a resonant 4-body interaction in cold Rydberg atoms

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23 November 2011

The Cold Rydberg Team

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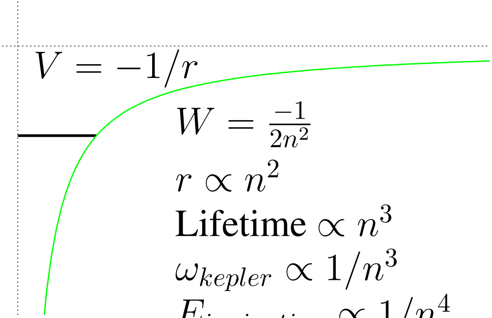
Introduction to Rydberg Atoms

Properties of Rydberg Atoms



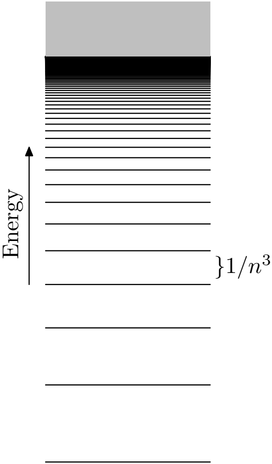
$$W = \frac{-1}{2n^2}$$

$$r \propto n^2$$

$$\text{Lifetime} \propto n^3$$

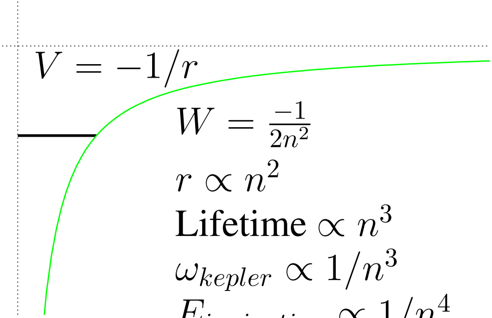
$$\omega_{kepler} \propto 1/n^3$$

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



Introduction to Rydberg Atoms

Properties of Rydberg Atoms



$V = -1/r$

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

$r \propto n^2$

Lifetime $\propto n^3$

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

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

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

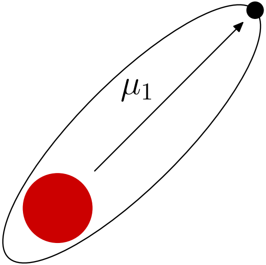
Huge Dipole Moments

KBr

Dipole Moment: 10.41 D

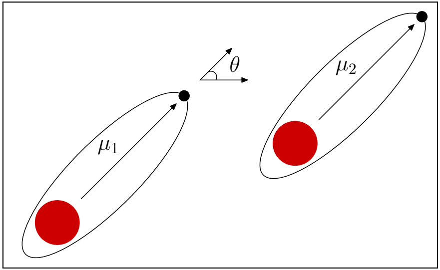
Rydberg Atoms

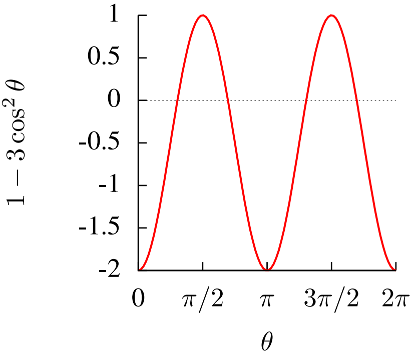
Dipole Moment: $2.54n^2$ D



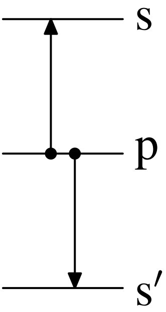
Dipole-Dipole Interaction

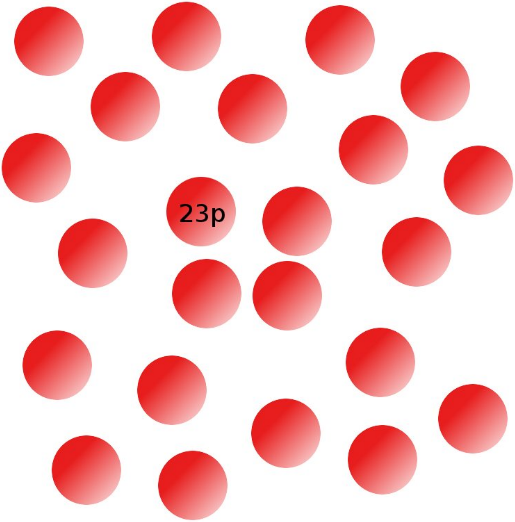
$$V_{12} = \frac{\mu_1 \mu_2}{4\pi\epsilon_0 R^3}(1 - 3\cos^2\theta)$$



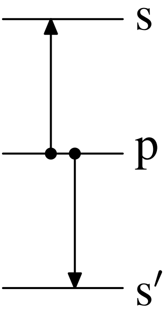


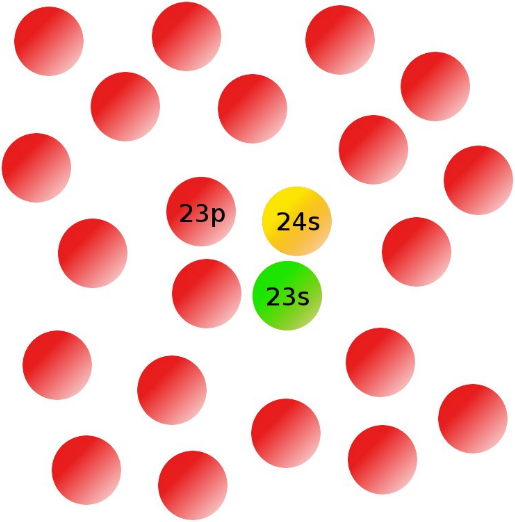
Dipole-Dipole Energy Transfer



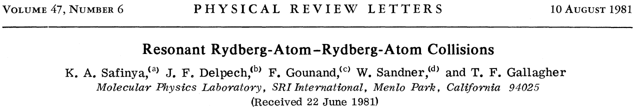


Dipole-Dipole Energy Transfer





Dipole Energy Transfer

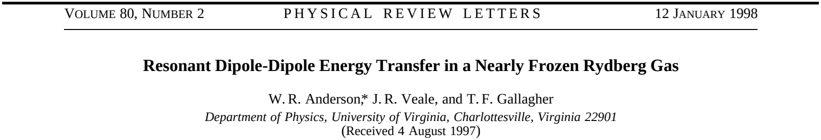


VOLUME 47, NUMBER 6 PHYSICAL REVIEW LETTERS 10 AUGUST 1981

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)

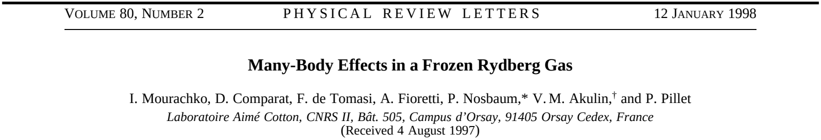


VOLUME 80, NUMBER 2 PHYSICAL REVIEW LETTERS 12 JANUARY 1998

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

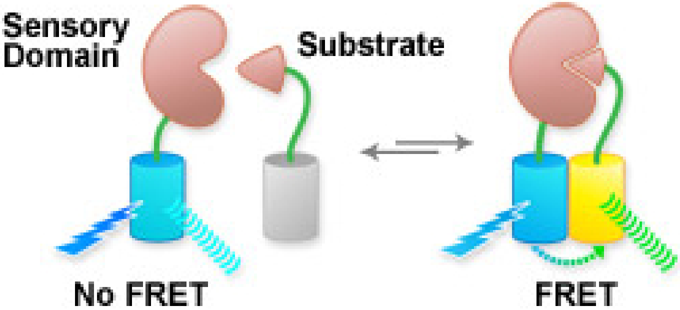
Many-Body Effects in a Frozen Rydberg Gas

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

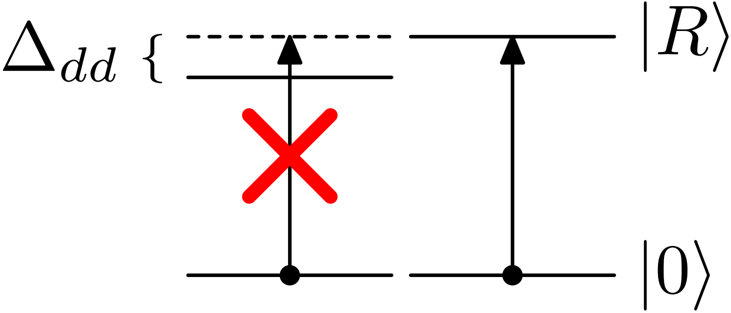
Analogous to FRET in biochemistry



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

Dipole Blockade

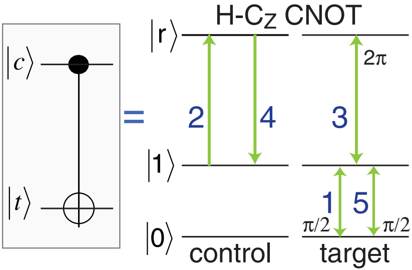
Dipole interaction prevents excitation of multiple Rydberg atoms



K. Singer *et al.*, PRL (2004).
D. Tong *et al.*, PRL (2004).
T. Vogt *et al.*, PRL (2006).

Rydberg CNOT Gates

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



IN		OUT	
$\|c\rangle$	$\|t\rangle$	$\|c\rangle$	$\|t\rangle$
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).

Many-body influence

Many-body effects can cause computation errors beyond 15%

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

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

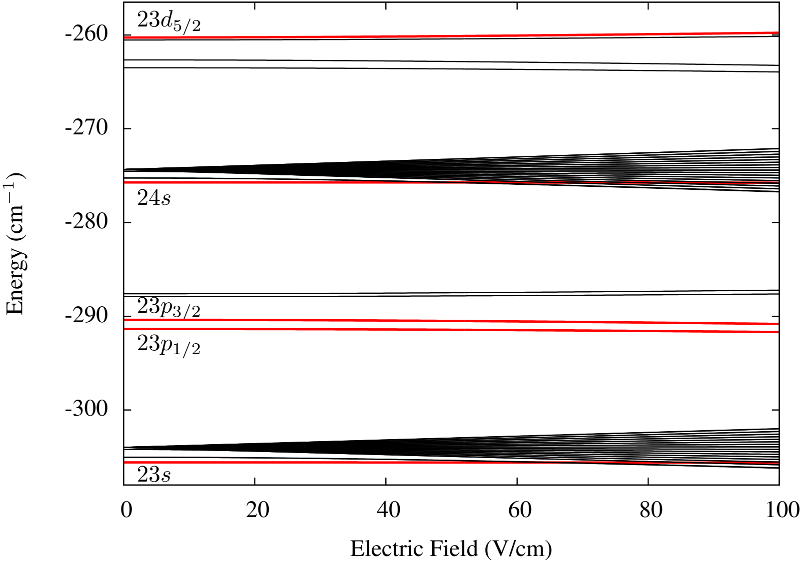
Can we directly observe a many-body Rydberg energy transfer?

A. Mizal & D. Lidar, PRL 92 (2004).

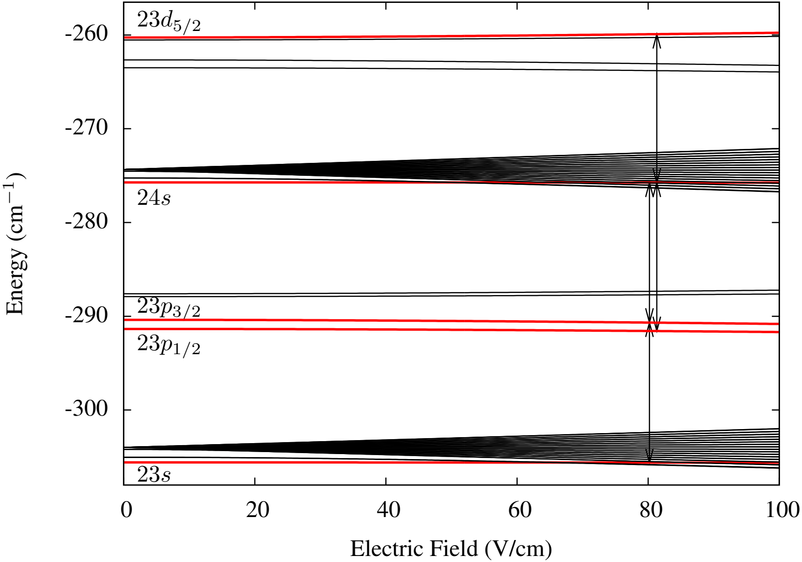
T. J. Carroll, S. Sunder, & M. W. Noel, PRA 73 (2006).

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


$23d_{5/2}$
$24s$
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-260
-270
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-290
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Energy (cm^{-1})
0
20
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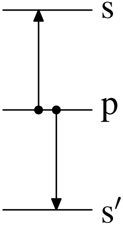
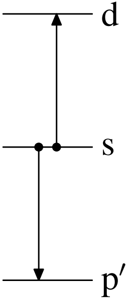
Energy Difference

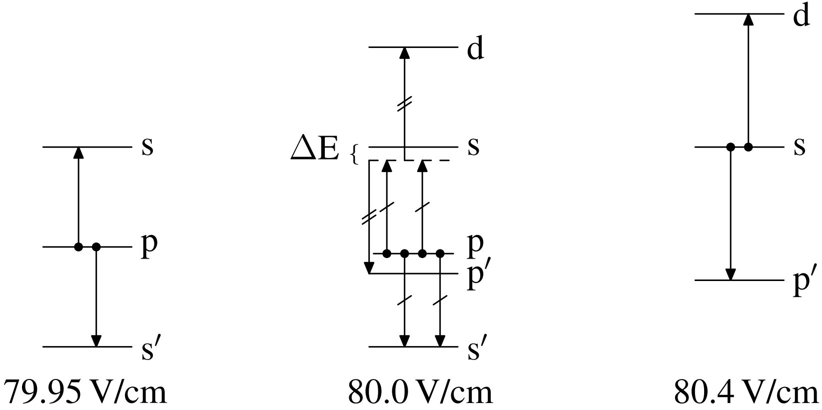


79.95 V/cm



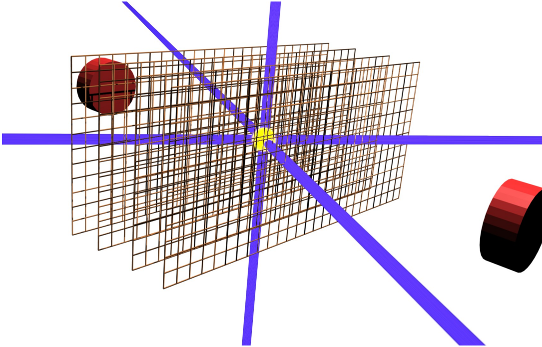
80.4 V/cm

Energy Difference



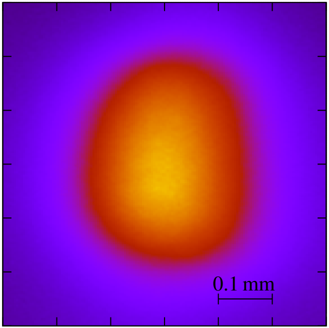
Apparatus

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

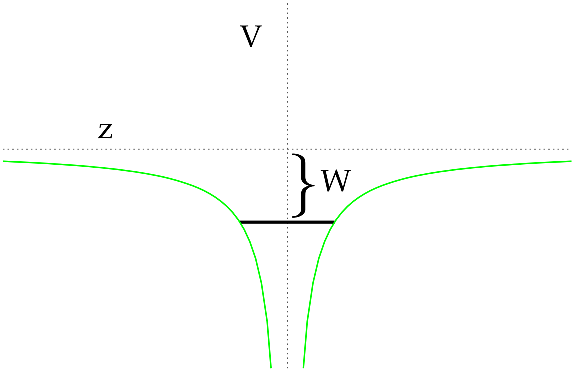


Rydberg Excitation

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

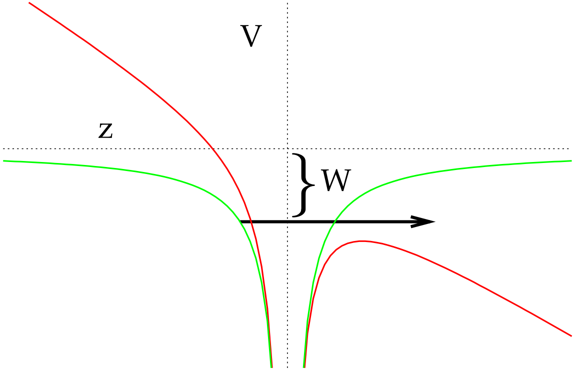


Field Ionization



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

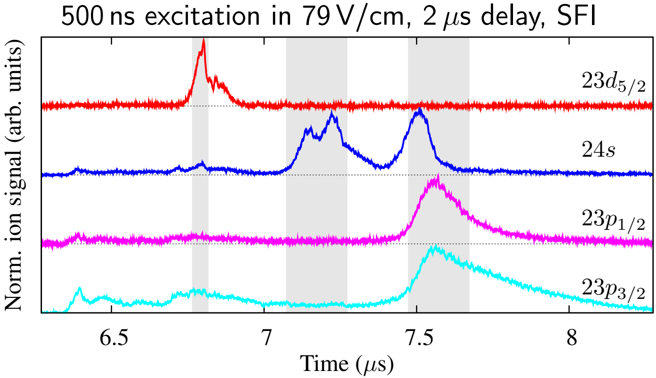
Field Ionization



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

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

Oscilloscope Traces

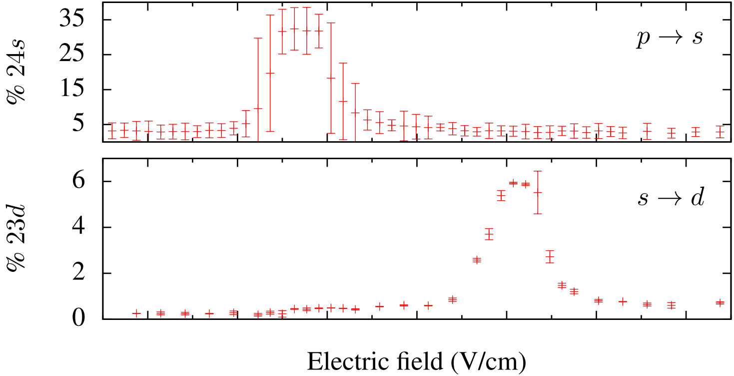


$$\begin{pmatrix} d_{out} \\ s_{out} \\ p_{out} \end{pmatrix} = \begin{pmatrix} 1.0494 & -0.1911 & -0.1223 \\ -0.039 & 2.559 & -0.3257 \\ -0.0104 & -1.3685 & 1.448 \end{pmatrix} \begin{pmatrix} d_{in} \\ s_{in} \\ p_{in} \end{pmatrix}$$

Removes signal overlap and BB transfer

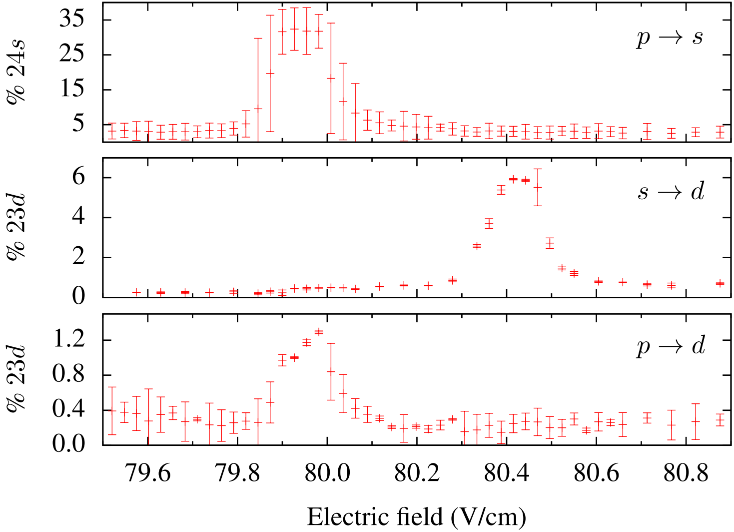
Two Body Resonances

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

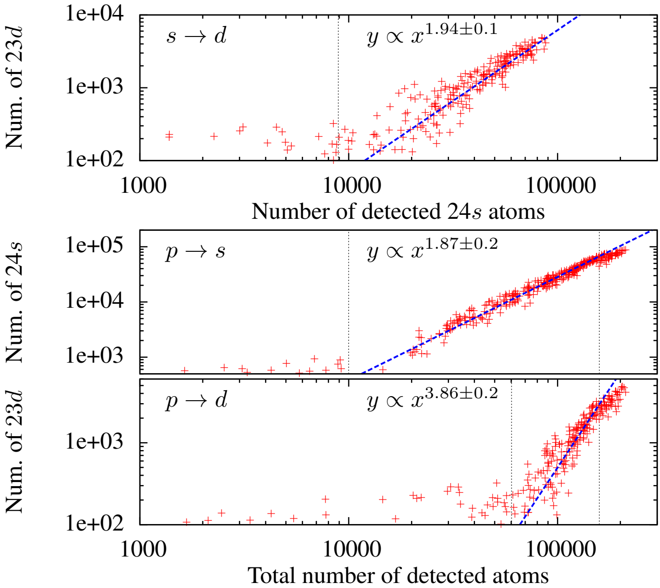


$$24s + 24s \rightarrow 23p_{1/2} + 23d_{5/2}$$

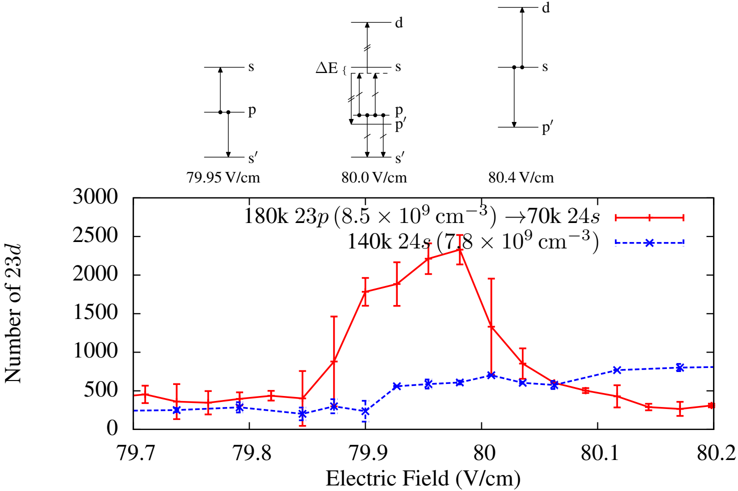
$4 \times 23p_{3/2} \rightarrow 2 \times 23s + 23p_{1/2} + 23d_{5/2}$



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?

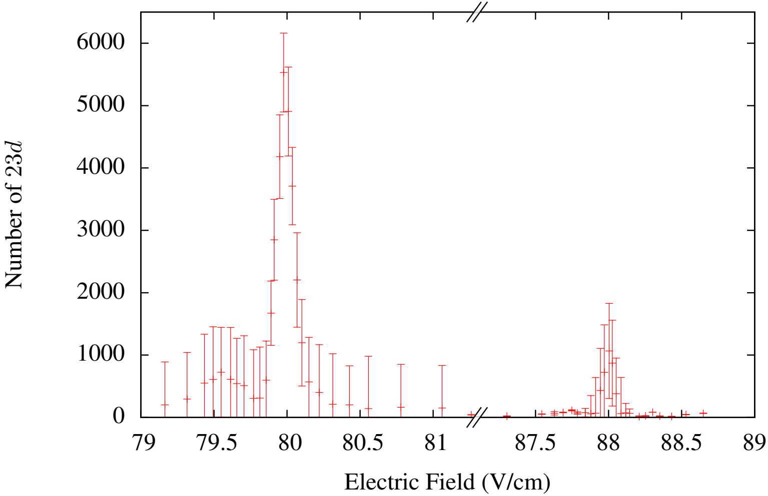


On-resonant 4-body process creates more $23d$ atoms than off-resonant two-body $s \to d$ process!

$|m_f| = 3/2$ Comparison

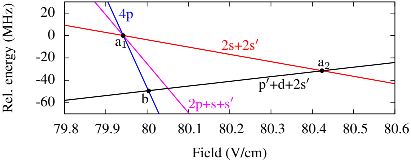
$2 \times 23p_{\frac{3}{2}|m|=\frac{1}{2}} \rightarrow 23s + 24s$: 80 V/cm

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



Toy Model

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



$$p \rightarrow s$$

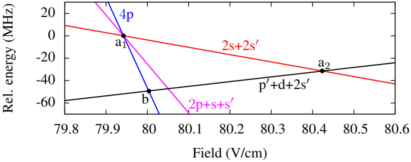
$$H = \begin{pmatrix} \frac{E_0}{2} & V_{01} \\ V_{01} & \frac{E_1}{2} \end{pmatrix}$$

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

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

Toy Model

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



$$s \rightarrow d$$

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

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

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

Toy Model

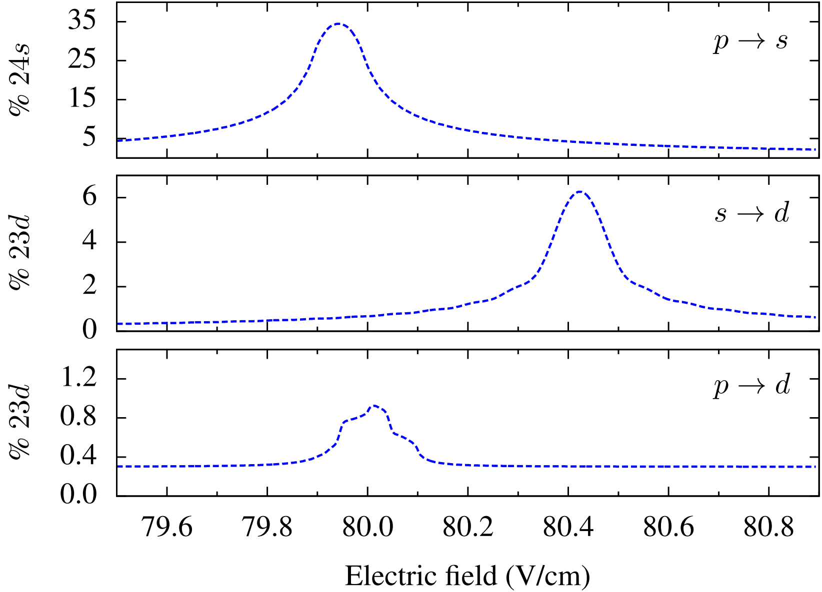
$$|0\rangle = |pppp\rangle \quad |1\rangle = |ss'pp\rangle \quad |2\rangle = |ss'ss'\rangle \quad |3\rangle = |p'ds's'\rangle$$

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

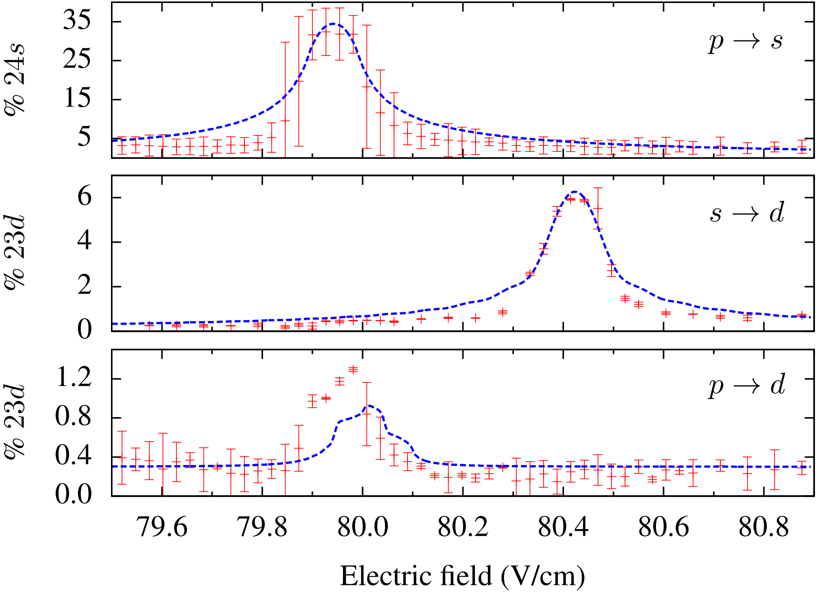
$$\rho(t) = e^{-iHt}\rho_0 e^{iHt} \qquad \rho_0 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

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

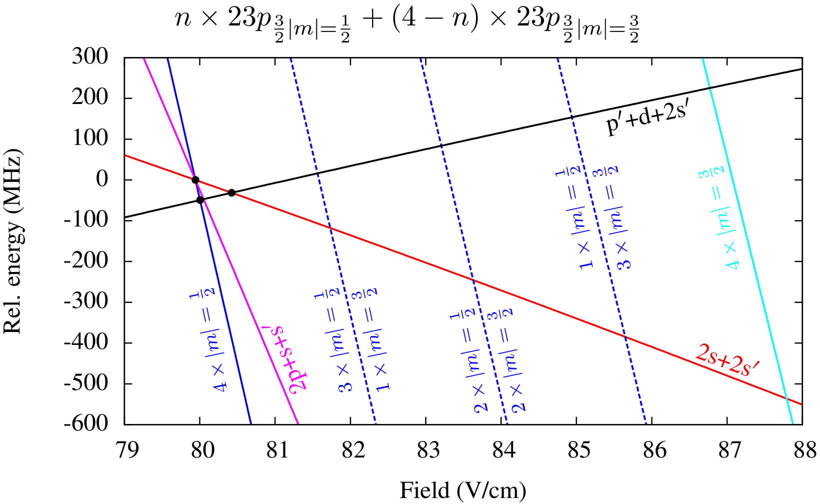
Toy Model Results



Toy Model Comparison



Next Steps



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

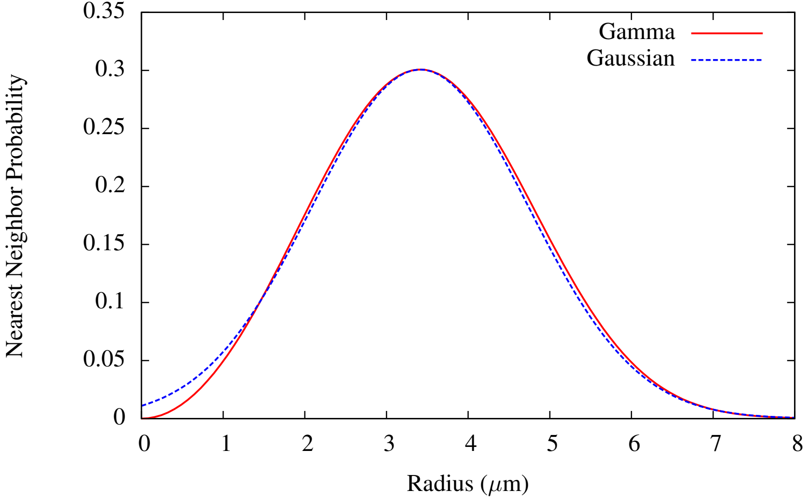
Conclusions

- 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.

Gamma Distribution

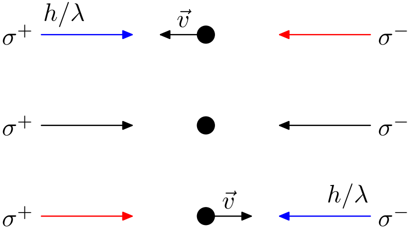
$n = 10^9\ \mathrm{cm}^{-3}$ $4\pi n R^2 e^{-(4/3)n\pi R^3}$

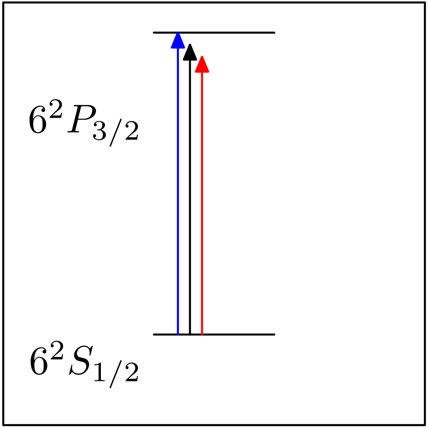
◂ Return to Talk



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

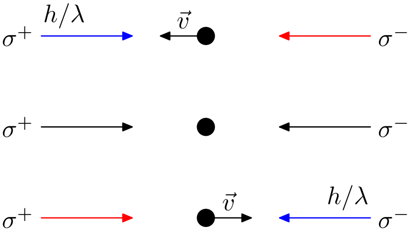
Cs Levels

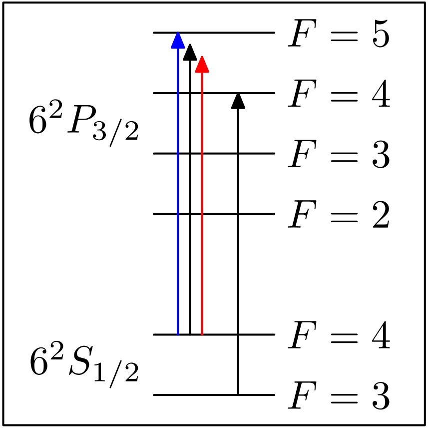




D. A. Steck, "Cesium D Line Data"

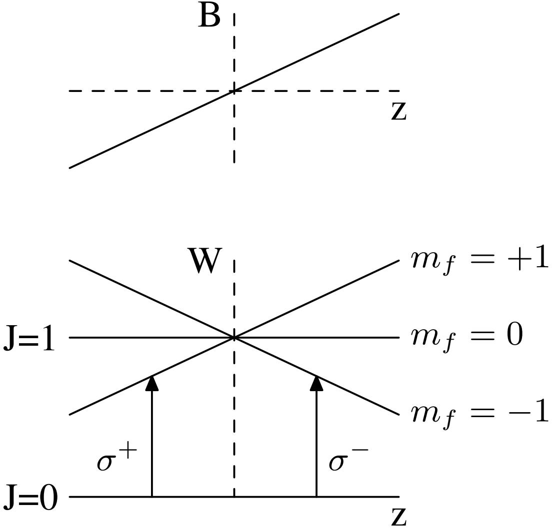
Cs Levels



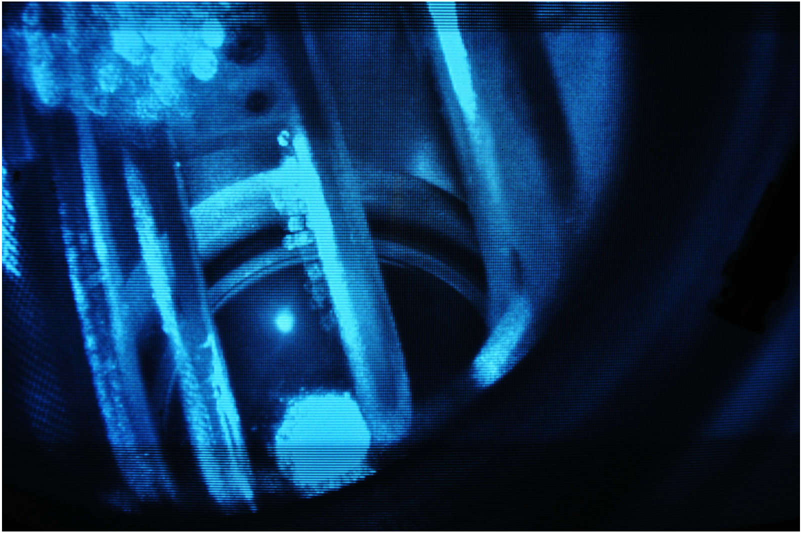


D. A. Steck, "Cesium D Line Data"

Magentic Trapping



Exp. MOT



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$|r|n\ell\rangle \propto n^{-3/2}$

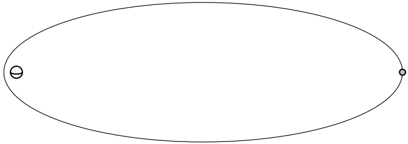
$$\tau_{n\ell} = \left[\sum_{n'\ell'} A_{n'\ell',n\ell}\right]^{-1}$$

$$\tau \propto n^3$$

This ignores blackbody radiation and ℓ scaling!

◂ Return to Talk

What's a Rydberg Atom?



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

This Talk: $23 \leq n \leq 306$