The Tip Experiment:
Imaging of Blockade Effects in a
Rydberg Gas

Andy Schwarzkopf
Raithel Lab
1/20/2010
Rydberg Atoms

- Highly-excited atoms with large “n”
- “n” scaling dependencies:
  - Orbital radius $\sim n^2$
  - Dipole moment between nearby levels $\sim n^2$
  - Polarizability $\sim n^7$
  - Radiative lifetime $\sim n^3$ ($\sim n^5$ for circular states)
- Due to these large scalings, can have strong interactions
- Long lifetimes and strong interactions make them attractive for use in quantum information
  
  e.g. M.D. Lukin et al., PRL 87, 037901 (2001).
Interactions

- Interaction Hamiltonian $V \sim \mu_A \mu_B / R^3$
  \[ \mu \sim n^2 \text{ (dipole between nearby levels)} \]
- In resonant case, energy perturbation $\Delta E \sim V \\
  \sim n^4 / R^3$
- In off-resonant case, perturbation $\Delta E \sim V^2 / \Delta \\
  \sim n^{11} / R^6$
Excitation Blockade

- Interactions detune system from resonance with laser
- Suppresses Rydberg excitations beyond the first

Figure from: A. Reinhard et al., Phys. Rev. A 75, 032712 (2007)
“Bubbles”

- Cannot excite two atoms next to each other
- Minimum distance is roughly given by setting interaction strength equal to laser linewidth * hbar
- “bubbles” can be used to give a hand-wavy interpretation for many experiments
The experiments I'll talk about all happen to use cold Rb

Excite Rydberg atoms with one (or several) laser beams, generally pulsed.

Detect Rydberg atoms by ionizing them, and counting electrons / ions.

These steps must be done quickly.
A Few Previous Experiments

- Looked at various characteristics of the blockade
  - Saturation of Rydberg excitation
  - Narrowing of excitation-number statistics
  - Spectroscopy of level shifts
  - Blockade between atoms in adjacent dipole traps
Saturation Curves

- Interactions suppress further excitations
- Interactions are stronger for larger “n”

D. Tong et al., PRL 93, 063001 (2004).
Counting Statistics

- Cubel et al. measured counting statistics
- Showed statistics to be sub-poissonian

T. Cubel Liebisch et al., PRL 95, 253002 (2005).
Spectroscopy

- Reinhard et al measured level-shifts spectroscopically.
- Two pairs of pulses, one pair for each step of the ladder. Second one has freq varied, for spectroscopy.
Blockade Between Adjacent Dipole Traps

- Implemented a phase gate

The state of the target atom, after a $2\pi$ pulse, depends on the state of the control atom.

Prediction of Pair-Correlation Function

- Hasn't been measured yet – this is my project's goal.

- Robicheaux calculated Ryd-Ryd correlation assuming van der Waals interactions and various pulse characteristics.

F. Robicheaux et al., PRA 72, 63403 (2005).
Prediction of Pair-Correlation Function

- Hasn't been measured yet – this is my project's goal.

F. Robicheaux et al., PRA 72, 63403 (2005).
Tip experiment
Field Ionization
How my experiment works
Project Milestones

- See ions
- Set up experimental control systems
- Check that I have magnification
  Calibrate the magnification
- Minimize E-field (especially inhomogeneities)
- Check if I have a blockade
- Search for structures in correlation function
Experimental Systems

Computer → Timing

Images

Camera

Fast switches

AOMs

MCP

Laser pulses

HV switch

MOT

Tip

Electric field control

Noise filter
Movie

- Ions move across MCP when I move the excitation beam
- Demonstrates spatial resolution
  (play video in external player)
Magnification / Resolution

- Rough prediction: 100x
  MOT sits ~1mm from tip
  MCP is 20cm from tip
  This would give ~1μm resolution, due to MCP's resolution (good enough to see blockade)

- Rough measurement: 50x
  Assuming 10μm beam width, and measuring approximate width in image

- Parameters to play with:
  Distance from tip to excitation volume
  Ionization voltage on tip
  MCP front plane voltage
Experimental Systems (2)

- To minimize the E-field, took Stark maps using this system
- Count number of ions with electronics, rather than camera

![Diagram showing the experimental setup with labels: Computer, Counts, Photon counter (Counts # of ions), MCP, Laser wavelength, Electric field control, MOT, Tip.]
Electrode Wiring Diagram
Stark Maps, 44D

- Shows good electric field control, low inhomogeneity
- Method: set freq, scan voltage, new freq, scan voltage...
- Can minimize field by finding symmetry point of Stark map, iterating over X, Y, Z
- Reasons for 44D: oscr strength, E-field sensitivity, strong interactions
E-field Zeroing with the Tip

- Find minimum E-field by symmetry point of Stark map
- To save time, don't take a full Stark map each day

Only take 4 frequency scans (blue, at left)
Saturation Curve

- Establishes that the blockade is effective in my experiment.

- Note that, assuming 10μm focus width, 100μW $\rightarrow$ $\sim$100W/cm$^2$
Autocorrelation Method

- Take ~1000 images of blips on MCP
- Calculate autocorrelation of each image
  
  Each will be noisy; only ~10-20 blips
- Average these autocorrelations
  
  To reduce noise
- Primary differences from Robicheaux:
  
  *Auto*-correlation (not pair correlation) → central feature
  
  Geometry of excitation volume is evident in autocorrelation (rather than having isotropic space)
Correlation Function Measurement

Vertical integration of the autocorrelation

Vertical integration of a 5px-high central horizontal slice of the autocorrelation, rescaled and with "background" subtracted.

"Background" is the autocorrelation of the average of images (as opposed to the average of the autocorrelation).
Correlation Function Measurement

Vertical integration of the autocorrelation

Vertical integration of a 5px-high central horizontal slice of the autocorrelation, rescaled and with "background" subtracted.

"Background" is the autocorrelation of the average of images (as opposed to the average of the autocorrelation)
Project Milestones, Revisited

- See ions
- Set up experimental control systems
- Check that I have magnification
  - Calibrate the magnification
- Minimize E-field (especially inhomogeneities)
- Check if I have a blockade
- Search for structures in correlation function
Measurement Plan

- How the blockade radius depends on the Rydberg atom quantum number “n”.
- How the blockade effect depends on the density of ground state atoms.
- How the blockade effect depends on the excitation light intensity.
- How the dimensionality of the sample (linear vs planar) affects the results.
Acknowledgements

My Committee
Georg Raithel
Paul Berman
Aaron Leanhardt

The Raithel Group
- Rachel Sapiro
- Brenton Knuffman
- Everyone who helps daily in lab, and especially those who helped at my practice
Calculation of Interactions

- 2\textsuperscript{nd} order perturbation theory

\[ \Delta W^{(2)} = - \sum_{n', \ell', j', m_j'} |\langle n'', \ell'', j'', m_{j''} | \otimes \langle n', \ell', j', m_j' | V_{dd} | n, \ell, j, m_j \rangle \otimes | n, \ell, j, m_j \rangle|^2 \]

- If no resonant interactions, this is a van der Waals interaction

\[ \Delta W^{(2)} = - \sum_{\lambda', m_j', \lambda'', m_{j''}, \Delta \neq 0} |\langle \lambda'', m_{j''} | \otimes \langle \lambda', m_j' | V_{dd} | \lambda, m_j \rangle \otimes | \lambda, m_j \rangle|^2 \]

- With resonant interactions, (tuned by E-field) re-diagonalize and use first-order perturbation to calculate dipole-dipole interaction

\[ \Delta W^{(1)} = \pm |\langle \lambda', m_j' | \otimes \langle \lambda'', m_{j''} | V_{dd} | \lambda, m_j \rangle \otimes | \lambda, m_j \rangle| \]
Interactions and resonance

- Note that the $n^{11}$ scaling has been normalized out.
Magnification variables

Average of images, HV switch: 100V
Magnification variables

Average of images, HV switch: 200V
Magnification variables

Average of images, HV switch: 300V
Magnification variables

Average of images, HV switch: 400V
Effect of a slow slew-rate FI ramp

Direct ionization (tip at constant HV)

Rydberg excitation (tip with HV ramp)
Tip systems

For imaging

For scans / Stark maps

1. **Computer** → Timing → Fast switches → Camera → Images
2. **Camera** → AOMs → Laser pulses → MCP → (MOT) → Tip
3. **Electric field control** → Noise filter → (MOT) → Tip

For scans / Stark maps

1. **Computer** → Counts → Photon counter (Counts # of ions) → MCP
2. **MCP** → Laser wavelength → Electric field control → (MOT) → Tip
Computer

Counts

Photon counter (Counts # of ions)

MCP

Laser wavelength

Electric field control

MOT

Tip
Tip systems

For imaging

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(MOT)
Tip experiment