Microwave Transitions Between Pair States Composed of Two Rb Rydberg Atoms

Jeonghun Lee
Advisor: Tom F. Gallagher
Overview

• Investigating a microwave transition

\[ nd_{5/2}nd_{5/2} \rightarrow (n+1)d_j(n-2)f \]
Outline

• Rydberg Atoms
• Experiment (Theory)
• Experimental Setup
• Experiment
• Results
Rydberg Atoms
Rydberg Atoms

• A Rydberg atom is a highly excited atom

• They have exaggerated characteristics such as:
  - large size
  - low binding energy
  - large dipole moment
  - and so on

which make them an interesting object to study
Properties of Rydberg Atoms

Bohr model of H atom

Binding Energy \( \propto n^{-2} \)
Radius \( \propto n^2 \)
Dipole Moment \( \propto n^2 \)
The experiment
(Theory)
Background

- $nd_{5/2}nd_{5/2} \rightarrow (n+1)d_j(n-2)f$ was recently observed

- The transition is allowed because dipole-dipole induced configuration interaction between $nd_{5/2}nd_{5/2}$ and $(n+2)p_{3/2}(n-2)f$ states admixes some of the latter state into the former
• With configuration interaction, $nd_{5/2}nd_{5/2}$ state for $R<\infty$ can be written as

$$\left| nd_{5/2}nd_{5/2} \right> = \left| nd_{5/2}nd_{5/2} \right> + \varepsilon \left| (n+2)p_{3/2}(n-2)f \right>$$

where

$$\varepsilon = \frac{\left< nd_{5/2}nd_{5/2} \right| \frac{\mu_1\mu_2}{R^3} \left| (n+2)p_{3/2}(n-2)f \right>}{\Delta}$$

$$\Delta = W_{nd_{5/2}nd_{5/2}} - W_{(n+2)p_{3/2}(n-2)f}$$
• The coupling between $nd_{5/2}nd_{5/2}$ and $(n+1)d_j(n-2)f$ states in lowest order is:

$$V = \varepsilon \langle (n+2)p_{3/2}(n-2)f | \mu E | (n+1)d_j(n-2)f \rangle$$

• Since $\frac{1}{R^3} \propto \rho_{Ryd}$ and the dipole matrix elements are proportional to $n^2$,

$$V \approx \frac{\rho En^6}{\Delta}$$
• Our primary experimental interest is to verify the expression:

\[ V \approx \frac{\rho E n^6}{\Delta} \]

• As \( n \) is changed from 42 to 35

\[ \left( \frac{n^6}{\Delta} \right)_{n=42} \div \left( \frac{n^6}{\Delta} \right)_{n=35} \approx 47 \]

• Is it possible to compensate this by adjusting the microwave field strength?
Previous Result

\[ 42d_{5/2} \rightarrow 43d_{j} 40f_{7/2} \]

Yinan Yu, Hyunwook Park, and T. F. Gallagher
Previous Result

$42d_{5/2} \rightarrow 43d_{j} 40f_{7/2}$

Yinan Yu, Hyunwook Park, and T. F. Gallagher

Experimental Setup
Experiment Overview

• We use magneto-optical trap and optical excitation to make a cold sample of Rb Rydberg atoms
• We use microwave to excite Rydberg atoms to different states
• We use Field ionization to ionize the Rydberg atoms and MCP detector to collect data
Experimental Setup

• Magneto-Optical Trap (MOT)
• Optical Excitation Laser
• Microwave Setup & Field Ionization
• Data Acquisition
MOT Basics

MOT uses laser cooling with magneto-optical trapping to produce Samples of cold, trapped, neutral atoms

Lauren Levac, Observation of the Dipole-Dipole Interaction in Dressed State Rydberg Atoms by Microwave Spectroscopy, MS thesis, University of Virginia, 2013
Magneto Optical Trapping

Typical Parameters for Our MOT

• # of trapped atoms: $10^5 \sim 10^6$
• Diameter: $\sim 1\text{mm}$
• Density: $10^9/\text{cm}^3$

• # of Rydberg atoms: $10^4$
• Density of Rydberg atoms (max): $10^8/\text{cm}^3$
Optical Excitation Laser

Excites Rb atoms to Rydberg state

Lauren Levac, Observation of the Dipole-Dipole Interaction in Dressed State Rydberg Atoms by Microwave Spectroscopy, MS thesis, University of Virginia, 2013
Field Ionization

(a) An electric field applied to the atoms tips the potential well such that loosely bound electrons are able to escape.

(b) Timing diagram for Field Ionization pulse.

\[ V = \frac{1}{r} - E_z \]
Timing diagram

- **B Field off**
- **480nm LASER Pulse (~10ns)**
- **Microwave Pulse**
  - Duration: 500ns to 2us
- **Field Ionization Pulse**

- Time: 4ms
The Experiment
(experimental technique)
Data Acquisition

Ions or Electrons are produced → MCP Detector → Gated Integrator → DAQ Card → PC

MCP: Micro-channel Plate
Measuring resonance frequency & Measuring power shift

Gate is placed on the \((n+1)\)d peak

The population of atoms in \((n+1)\)d state is monitored as microwave frequency is scanned across the calculated resonance frequency

\[ 40d_{5/2} \rightarrow 41d_{5/2} \]

\[ 38f \]
$40d_{5/2} \rightarrow 41d_{5/2}$
Measuring Fractional Population Transfer (FPT)

Gate is placed on the nd peak

The population of atoms in nd state is monitored as microwave at resonance frequency is turned on and off

\[ 40d_{5/2} \quad 40d_{5/2} \rightarrow 41d_{5/2} \quad 38f \]
\[ FPT = \left( 1 - \frac{\text{baseline} - V_{\text{MW \_on}}}{\text{baseline} - V_{\text{MW \_off}}} \right) \times 100 \]
Results
Resonance frequency & Power shift of the resonance frequency

Extrapolating the points back to zero microwave power allows us to determine resonance frequency of the transition.

42d_{5/2} 42d_{5/2} \rightarrow 43d_{5/2} 40f_{7/2}
Transition frequency for
\[ nd_{5/2} nd_{5/2} \rightarrow (n+1)d_{5/2} (n-2) f \]

<table>
<thead>
<tr>
<th>n</th>
<th>Calculated (GHz)</th>
<th>Measured (GHz)</th>
<th>Percent Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>34</td>
<td>49.898</td>
<td>49.898</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>35</td>
<td>45.916</td>
<td>45.915</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>36</td>
<td>42.344</td>
<td>42.341</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>37</td>
<td>39.131</td>
<td>39.129</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>38</td>
<td>36.233</td>
<td>36.231</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>39</td>
<td>33.613</td>
<td>33.612</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>40</td>
<td>31.239</td>
<td>31.236</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>41</td>
<td>29.082</td>
<td>29.079</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>42</td>
<td>27.118</td>
<td>27.113</td>
<td>0.017</td>
</tr>
</tbody>
</table>
Transition frequency for
\[ nd_{5/2}nd_{5/2} \rightarrow (n+1)d_{3/2}(n-2)f \]

<table>
<thead>
<tr>
<th>n</th>
<th>Calculated (GHz)</th>
<th>Measured (GHz)</th>
<th>Percent Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>34</td>
<td>49.618</td>
<td>49.617</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>35</td>
<td>45.660</td>
<td>45.660</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>36</td>
<td>42.109</td>
<td>42.106</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>37</td>
<td>38.914</td>
<td>38.912</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>38</td>
<td>36.033</td>
<td>36.031</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>39</td>
<td>33.429</td>
<td>33.428</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>40</td>
<td>31.068</td>
<td>31.066</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>41</td>
<td>28.923</td>
<td>28.921</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>42</td>
<td>26.970</td>
<td>26.968</td>
<td>&lt;0.01</td>
</tr>
</tbody>
</table>
FPT data

FPT vs. $\rho E n^6/\Delta$

42d data from 1/13/15
Normalizing MW power using Stark Shift

• MW power output changes
→ Need to normalize MW power

• Use the fact that the Stark shift

\[
\Delta \omega \propto \frac{|\langle \phi | \mu | \psi \rangle E|^2}{\Delta} \approx \frac{n^4 E^2}{\Delta}
\]
FPT vs. $\rho E n^6/\Delta$

![Graph showing FPT vs. $\rho E n^6/\Delta$ with data points for 35, 1/28/15 and 36, 10/3/14.](image-url)
FPT vs. \( \rho E n^6/\Delta \)
FPT vs. $\rho E n^6/\Delta$

![Graph showing a scatter plot with data points and labels indicating dates.]

35, 1/28/15
36, 10/3/14
37, 1/23/15
38, 12/9/14
FPT vs. $\rho E n^6/\Delta$
FPT vs. $\rho E n^6/\Delta$

![Graph showing FPT vs. $\rho E n^6/\Delta$ with various data points and markers for different dates and years.](image-url)
FPT vs. $\rho*E*n^6/\Delta$
FPT vs. $\rho*E*n^6/\Delta$
Conclusion

• The resonance frequencies of the ndnd-(n+1)d(n-2)f transitions for n=35 to 42 have been measured

• power shifts of the resonance frequencies have been measured for n=35 to 42.

• The dependence of the fractional population transfer from the ndnd to (n+1)d(n-2)f states on the microwave field strength and atomic density has been measured and can be compared to a simple theoretical model.
Acknowledgement

• My lab mates: Vincent, Alexandr, Eric, Safra, Kapila, Jirakan

• Dr. Gallagher

• This research is supported by Air Force Office of Scientific Research