Multiphoton Microwave Ionization of Rydberg Atoms

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11 March 2010
Rydberg Atoms and How They Ionize

- Rydberg Atoms
- Field Ionization
- Photoionization
- MW Ionization

Experimental Setup

- Experimental Apparatus
- kHz Laser

Experimental Results

- Multiphoton MW Ionization
- Single Photon Ionization Rates
- Above-Threshold Bound States
Introduction to Rydberg Atoms

Properties of Rydberg Atoms

\[ V = -\frac{1}{r} \]

\[ W = -\frac{1}{2n^2} \]

\[ r \propto n^2 \]

\[ \text{Lifetime} \propto n^3 \]

\[ \omega_{\text{kepler}} \propto \frac{1}{n^3} \]

\[ E_{\text{ionization}} \propto \frac{1}{n^4} \]
Introduction to Rydberg Atoms

Properties of Rydberg Atoms

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For \( n=100 \):
- \( W = -1.4 \text{ meV} \)
- \( <r> = 0.5 \mu\text{m} \)
- \( \tau = 1 \text{ ms} \)
- \( \omega_{\text{kepler}} = 2\pi \times 6.5 \text{ GHz} \)
- \( E_{\text{ionization}} = 5.7 \text{ V/cm} \)
Field Ionization

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

\[ E = \frac{W^2}{4} \]
Photoionization

\[ h\omega \]

if \( h\omega > W \),
If we have some collection of atoms,

how do we calculate the ionization rate?
Fermi’s Golden Rule

\[ \Gamma_1 = 2\pi |\langle \alpha | \mu E | \beta \rangle|^2 \rho_f \]
Fermi’s Golden Rule

\[ \Gamma_1 = 2\pi |\langle \alpha | \mu E | \beta \rangle|^2 \rho_f \]

\[ \Gamma_2 = 2\pi \left| \frac{\langle \gamma | \mu E | \alpha \rangle \langle \alpha | \mu E | \beta \rangle}{\Delta W} \right|^2 \]
Fermi’s Golden Rule

\[
\Gamma_1 = 2\pi |\langle \alpha | \mu E | \beta \rangle|^2 \rho_f
\]

\[
\Gamma_2 = 2\pi \left| \frac{\langle \gamma | \mu E | \alpha \rangle \langle \alpha | \mu E | \beta \rangle}{\Delta W} \right|^2
\]

\[
\Gamma_N \propto E^{2N}
\]
Fermi’s Golden Rule

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\[ \Gamma_N \propto E^{2N} \]

l’Huillier et al., PRA 27 (1983).
Where does Microwave Ionization fit?

Scaled Microwave Units:

\[ \Omega = \frac{\omega}{\omega_{\text{Kepler}}} = \omega n^3 \]

\[ E_0 = \frac{E}{E_{\text{Coulomb}}} = E n^4 \]
Hydrogenic Microwave Ionization

First experiments by Bayfield and Koch:

Non-constant \( \frac{dW}{dE} \) projects \((n, k)\) state onto Stark manifold

\[ E = \frac{1}{9n^4} \]
Non-Hydrogenic Microwave Ionization

Ladder-climbing mechanism for ionization:

$$E = \frac{1}{3n^5}$$

Where Does Microwave Ionization Fit?

Scaled Microwave Units:

\[ \Omega = \frac{\omega}{\omega_{\text{Kepler}}} = \omega n^3 \]

\[ E_0 = \frac{E}{E_{\text{Coulomb}}} = En^4 \]

Experimentally, what happens as we approach the photoionization limit?
Outline

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   MW Ionization

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   kHz Laser

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   Single Photon Ionization Rates
   Above-Threshold Bound States
Experimental Setup

Introduction

Experimental Setup

Experimental Results

Experimental Apparatus

kHz Laser

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**2s**

| 671 nm |
| 2p    |
| 813 nm |
| 3s    |
| ~614 nm |

---

0 200 400 600 800 1000 1200

time (ns)

0-200 V/cm

Laser Pulses

200 ns

MW Pulse

Field Pulse

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MW Ionization of Rydberg Atoms

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Experimental Setup

Experiment on Rydberg Atoms

- Experimental Apparatus
  - kHz Laser

- Experimental Setup
  - 2s
  - 671 nm
  - 2p
  - 813 nm
  - 3s
  - ∼614 nm
  - np

- Laser Pulses
  - 200 ns

- MW Pulse

- Field Pulse
  - 0-200 V/cm

- time (ns)
  - 0 200 400 600 800 1000 1200
Pictures
A New Laser System

- Coherent Evolution-30
- Nd:YLF @ 527 nm
- 20 mJ/pulse w/ 1 kHz Pulse Repetition Frequency

![Nd:YLF Pulse](chart)
External Pulse Splitting

Dye Laser Output: \( \approx 20 \mu \text{J/pulse} \)
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Expected Results

- Multiphoton MW Ionization Rates

Expected Results

- 2s
- 671 nm
- 2p
- 813 nm
- 3s
- ∼614 nm
- np

Graphs showing:

- Number of MW photons to the ionization limit
- Binding Energy (GHz)
- Norm. bound state electron signal (arb)

Graphs illustrating the response of bound state electron signals with respect to binding energy and number of MW photons.
Expected Results

The figure illustrates the expected results of multiphoton microwaves (MW) ionization of Rydberg atoms. The diagram shows the transitions between energy levels: 2s, 2p, 3s, and np levels. The expected results include the number of MW photons to the ionization limit, normalized bound state electron signal, and the binding energy in GHz.

The graph on the right shows the influence of MW pulses on the ionization process, with a laser pulse and a field pulse applied at different times. The data is presented in terms of time (ns) and binding energy (GHz) for the cases with and without MW pulses.
Microwave Ionization Steps - 17 GHz

Number of MW photons to the ionization limit

Binding Energy (GHz)

Norm. bound state electron signal (arb)

0 V/cm
0.88 V/cm
2.56 V/cm
5.11 V/cm
10.2 V/cm
20.3 V/cm
81 V/cm
Microwave Ionization Steps - 36 GHz

Number of microwave photons to the limit

Fraction of atoms MW ionized

Binding energy (GHz)

1.07 V/cm
2.15 V/cm
4.29 V/cm
8.56 V/cm
17.0 V/cm
34.0 V/cm
67.9 V/cm
Photoionization - Timing

![Diagram of timing setup for photoionization experiment]

- Laser Pulses
- 0-2000 ns MW Pulse
- Field Pulse

0-200 V/cm

0 500 1000 1500 2000 2500

Time (ns)
Single Photon Ionization

![Graph showing single photon ionization rates with different electric field strengths.](image)

- **8.34 V/cm**
- **2.64 V/cm**
- **1.48 V/cm**
- **0.83 V/cm**
- **0.47 V/cm**
- **0.25 V/cm**
- **0.13 V/cm**
Single Photon Ionization

![Graph showing relaxation rates for different electric field strengths.](image-url)

- **Relative remaining population (arb)** vs **Time (ns)**
- **Electric Field Strengths**:
  - 8.34 V/cm
  - 0.47 V/cm

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MW Ionization of Rydberg Atoms
Fermi’s Golden Rule Comparison

![Graph showing Fermi’s Golden Rule Comparison](image)

- **Calculated Rate**
  - Red line
- **Exp Extracted Rate**
  - Green markers

**Axes:**
- **Y-axis:** Zero Time Ionization Rate (s\(^{-1}\))
- **X-axis:** MW Field (V/cm)

**Data Points:**
- **Calculated Rate:** Linear increase with MW Field
- **Exp Extracted Rate:** Dispersed markers indicating experimental data points.
Dynamical Anderson Localization

First work by Casati et al.

Destructive interference between many multiphoton paths localizes the electronic wave function, and ionization occurs when electron transport diffuses over the limit.

Jensen et al. Model

Rabi width = $\mu \cdot E = \frac{0.4108E}{\omega^{5/3}n^3}$

State spacing = $\frac{1}{n^3}$

MW ionization occurs when the Rabi width $\geq$ state spacing

$E = 2.4\omega^{5/3}$

Jensen et al. Comparison

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure.png}
\caption{Comparison of Microwave Field for 50% ionization (V/cm) with Binding Energy (GHz).}
\end{figure}

Schelle, Delande, and Buchleitner Model

\[ F^{10\%}n_0^4 \]

\[ \omega n_0^3 \]

\( N_{\sim} = 2 \)

\( N_{\sim} = 1 \)

\( N_{\sim} = 3 \)

localization

photoeffect

Can we simply use a Floquet picture to describe system?

How do we choose the correct levels to include?

How do we include the above-threshold continuum states?
Giusti-Suzor and Zoller proposed a Floquet-MQDT model for Rydberg atoms in laser fields where the couplings between channels are radiative dipole couplings. The Rydberg electron is in a Coulomb potential, and can only scatter to other states near the core.

MQDT-Floquet Model

We can define a series of channels, each separated by one microwave photon.

The coupling between channels are radial dipole couplings - the same as the level coupling used by Jensen *et al.*
Following the method of Cooke and Cromer, we can easily calculate the time-dependent transfer of the bound channel populations to the continuum along the dashed line.

By iterating the binding energy (the dashed line) we can compute the ionization spectrum

Model Comparison

Number of MW photons to the ionization limit

-200 -150 -100 -50 0 50
-2 0 2 4 6 8 10 12

Norm. bound state electron signal (arb)

Binding Energy (GHz)

0 V/cm
0.9 V/cm
2.6 V/cm
5.1 V/cm
10 V/cm
20 V/cm
81 V/cm
Model Comparison

![Graph showing the number of MW photons to the ionization limit vs. binding energy.](image)

- Graph labels:
  - Y-axis: Norm. bound state electron signal (arb)
  - X-axis: Binding Energy (GHz)
  - Legend:
    - 5.1 V/cm calc.
    - 0 V/cm
    - 5.1 V/cm

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Above-Threshold Bound States - Timing

- Laser Pulse
- MW Pulse
- Field Pulse

Time (ns): -200 0 200 400 600 800 1000 1200
Above-Threshold Bound States

Number of MW photons to the ionization limit

-250 -200 -150 -100 -50 0 50
0 5 10 15
Norm. bound state electron signal (arb)
Binding Energy (GHz)
Number of MW photons to the ionization limit
0 V/cm
2.89 V/cm
4.07 V/cm
5.76 V/cm
Above-Threshold Bound States

Number of MW photons to the ionization limit

Binding Energy (GHz)

Norm. bound state electron signal (arb)

2.89 V/cm
4.07 V/cm
5.76 V/cm

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MW Ionization of Rydberg Atoms
Above-Threshold Bound States

Number of 36 GHz MW photons above the limit

Percent surviving pop., offset by MW Field

Energy (GHz)

12.6 V/cm
17.8 V/cm
25.1 V/cm
35.5 V/cm
50.1 V/cm
70.8 V/cm
SM Model
Simpleman’s Model

\[ F_0(t) \cos(\omega t) \]

\[ W = - \int_0^{t_f} \vec{F}(t) \cdot \vec{v}(t) \, dt \]

\[ \Delta E = 2U_{pond} = \frac{F^2}{2\omega^2} \]
New Classical Model

\[ F_0(t) \cos(\omega t) \]

Above-Threshold Bound States

Number of 36 GHz MW photons above the limit

Percent surviving pop., offset by MW Field by MW Field

Energy (GHz)

12.6 V/cm
17.8 V/cm
25.1 V/cm
35.5 V/cm
50.1 V/cm
70.8 V/cm
Shuman Model
Pond. shift
Conclusions

- An Anderson Localization model crossing over to Fermi’s Golden Rule does not match experimental results.
- The coherent coupling of levels both above and below the ionization limit describes high scaled frequency microwave ionization.
- A simple classical model illustrates population transfer from above the limit to bound states.