Final state distributions of Li Rydberg atoms at high scaled microwave frequency

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Introduction

We present experimental results of final state distributions of non-ionized Rydberg atoms in the presence of a microwave field of frequency ω, where the scaled frequency, or ratio of ω to the classical Kepler frequency, $1/n^3$, is much greater than one. Recent microwave ionization experiments of Rydberg atoms at high scaled frequency have exhibited a strong periodicity in the ionization rate as a function of binding energy, where the period is determined by the energy of the microwave photon[2]. However, the distribution of final states for the remaining bound atoms does not exhibit a similar periodicity, and is markedly different at ten, five, or one photon to the ionization limit. Notably, we observe population trapped in high lying n states one microwave photon below the ionization limit when the initial state is an integer number of microwave photons below the limit. These high lying states remain bound even in microwave fields two orders of magnitude higher than the field required for classical ionization, in agreement with results seen at lower n[4]. This population trapping suggests that the coupling of this last bound state to the continuum is what mediates multiphoton microwave ionization.

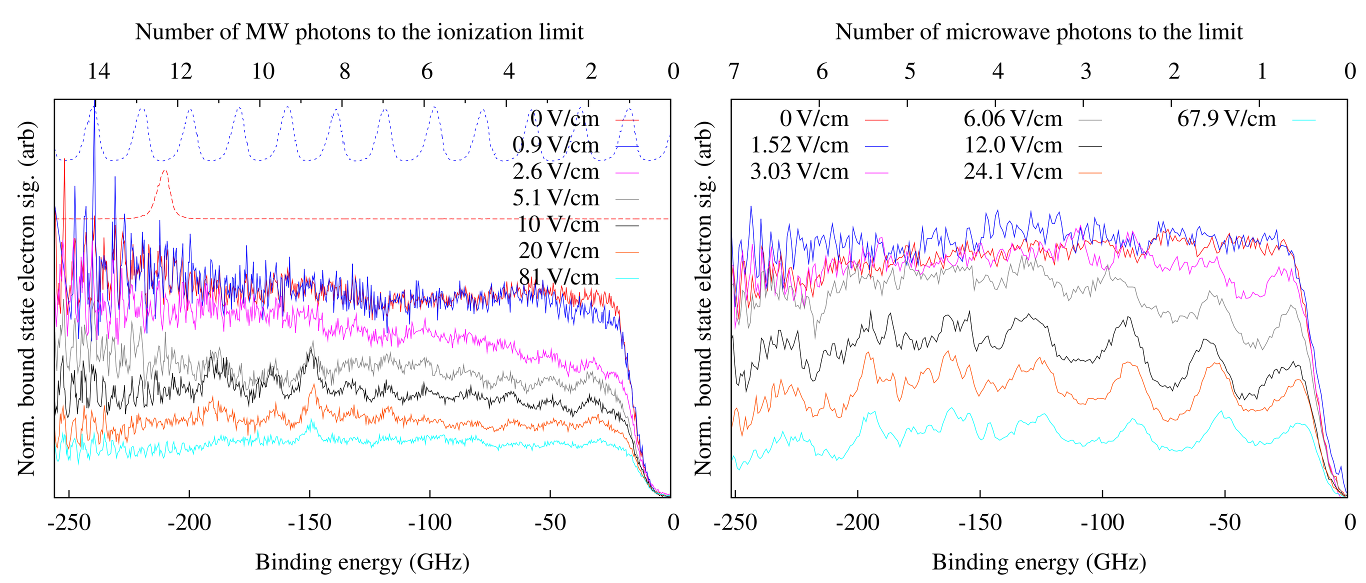
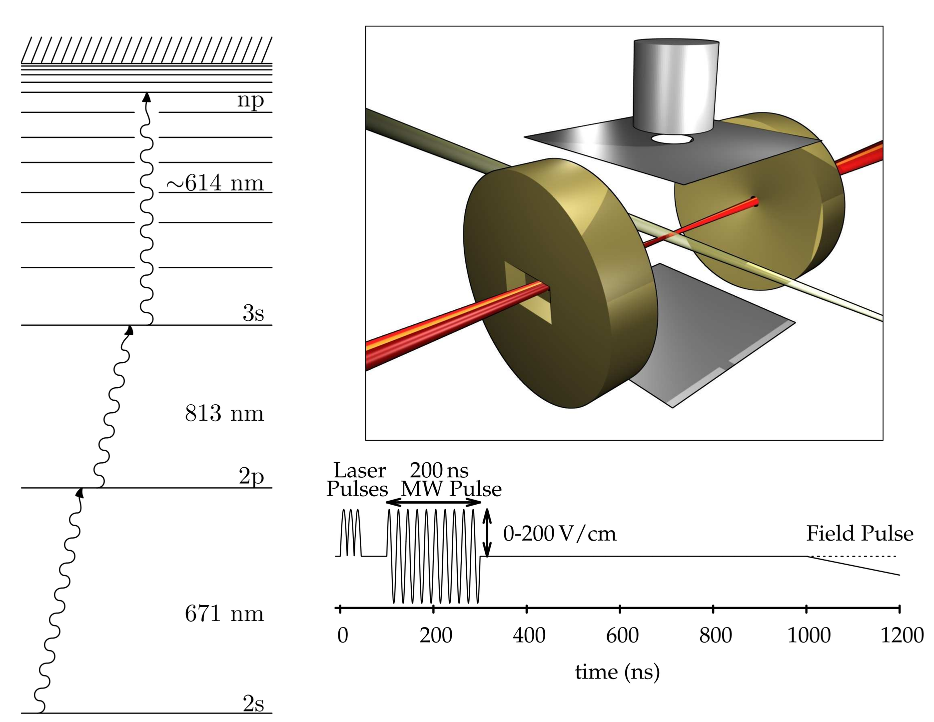


Figure 1: Field ionization signals as a function of laser tuning, given in terms of the binding energy, for 200-ns-long, 17-GHz (a) and 36-GHz (b) microwave (MW) pulses. Etalon signal and optogalvanic signal are also shown in (a). For both 17 and 36 GHz the signals are normalized to the signals obtained with no MW field. Figure from Ref.[2].

Experimental Setup

A thermal beam of Li atoms pass through a 17.564 GHz Fabry-Pérot microwave cavity. The atoms are excited at the center of the cavity by three 5 ns laser pulses to np states of $70 \leq n$ to the ionization limit via the route $2s \rightarrow 2p \rightarrow 3s \rightarrow np$[1]. Subsequent to the laser excitation the atoms are exposed to a 200 ns 17 GHz microwave pulse, as shown below. Finally, remaining atoms are field ionized by a ramped field ionization pulse (FPI), rising to 400 V in 1 μs, ionizing Rydberg atoms as n^{-4}. The resultant ions are detected by a microchannel plate (MCP) detector and the time-of-flight oscilloscope trace is recorded by a computer. A calibration scan with no applied microwave field is shown in Fig. 3.



Experimental Results

Notably, for atoms bound by less than 100 GHz, population is clearly transferred out of the initial state to n states one photon below the ionization limit, as shown below. These high n results illustrate that population is "trapped" one microwave photon below the limit, with population easily moving to n states centered about $n = 430$, but not ionizing. This implies that the coupling between the final bound state and the continuum is what mediates microwave ionization.

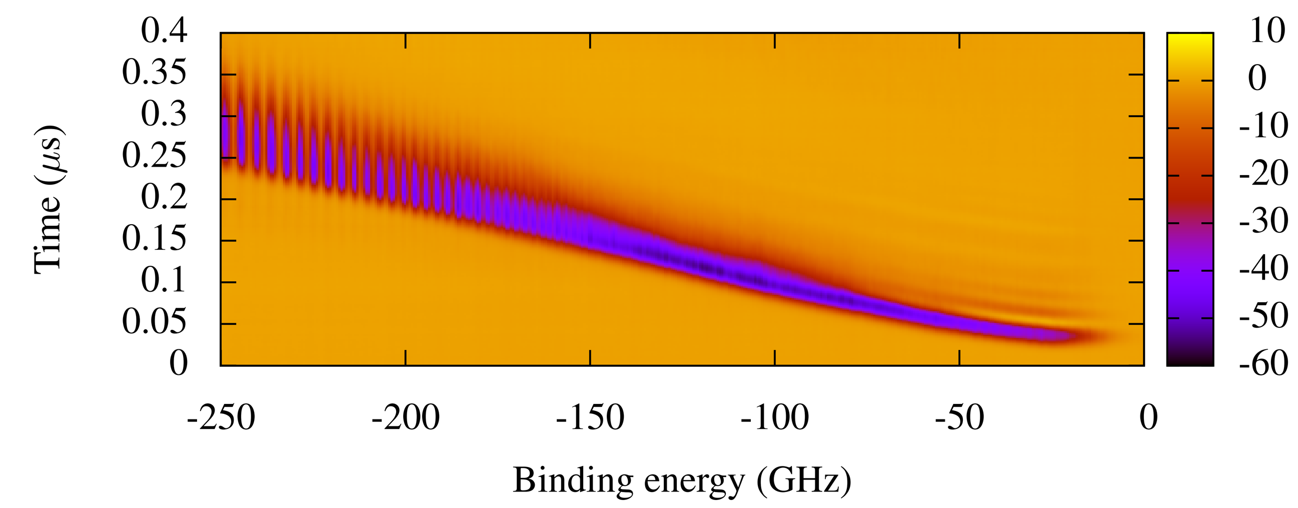


Figure 3: Final state distribution for zero microwave field.

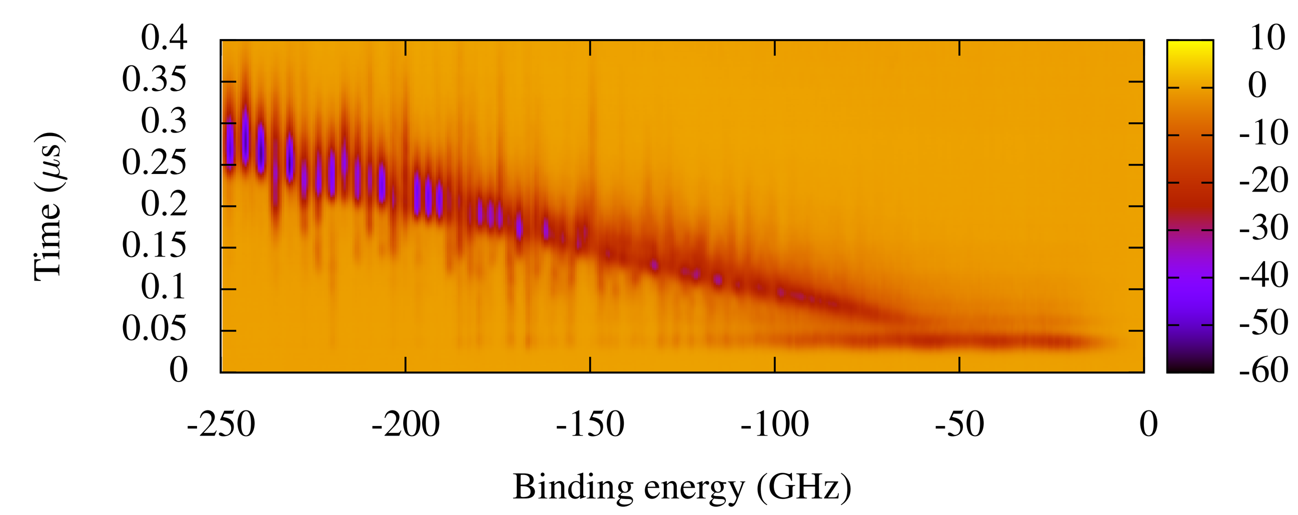


Figure 4: Final state distribution for 200 ns, 17.850 GHz, 3 V/cm microwave pulse.

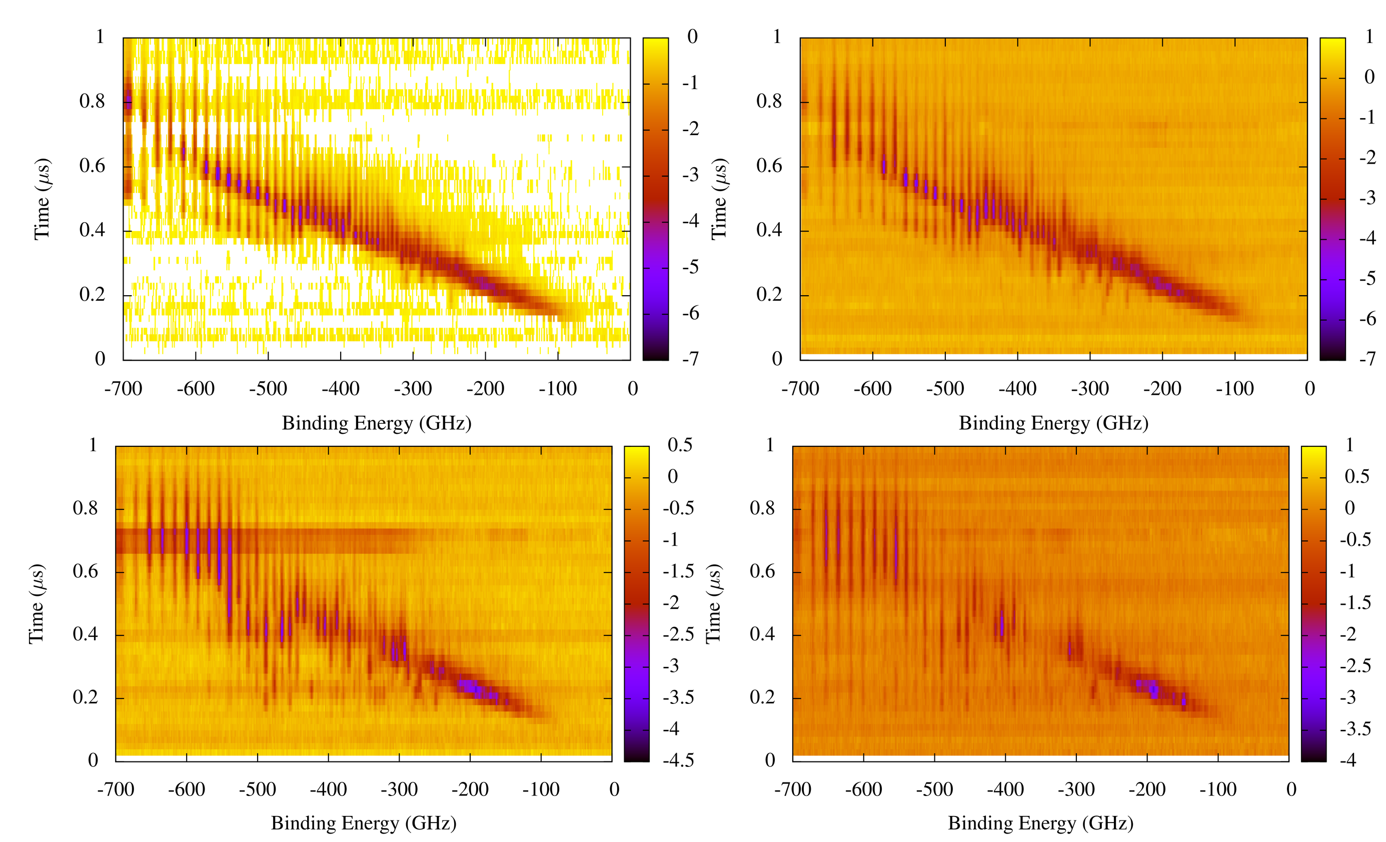


Figure 5: Final state distributions for 200 ns 17.1105 GHz microwave pulses for a set of field amplitudes. Figures (a)-(d) are for field amplitudes of 0.6 V/cm, 0.9 V/cm, 1.2 V/cm, and 1.8 V/cm, respectively.

There are no strong correlations between population transfer and scaled microwave frequency or microwave pulse length. Instead, the population transfer to other final states is dominated by whether the microwave frequency is resonant with the states lying one microwave photon above or below the initial state.

Floquet Analysis

Transitions from an initial np state to a distribution of final states are describable using a Floquet diagram, with the initial np state making transitions to other $n\ell$ states via a series of avoided crossings[3, 5]. Floquet energy levels are plotted relative to the initial state energy modulo the microwave photon energy. The analysis is illustrated for two adjacent n states, $n = 91$ and $n = 92$, but has been completed and is similar for all n states between $90 \leq n \leq 100$.

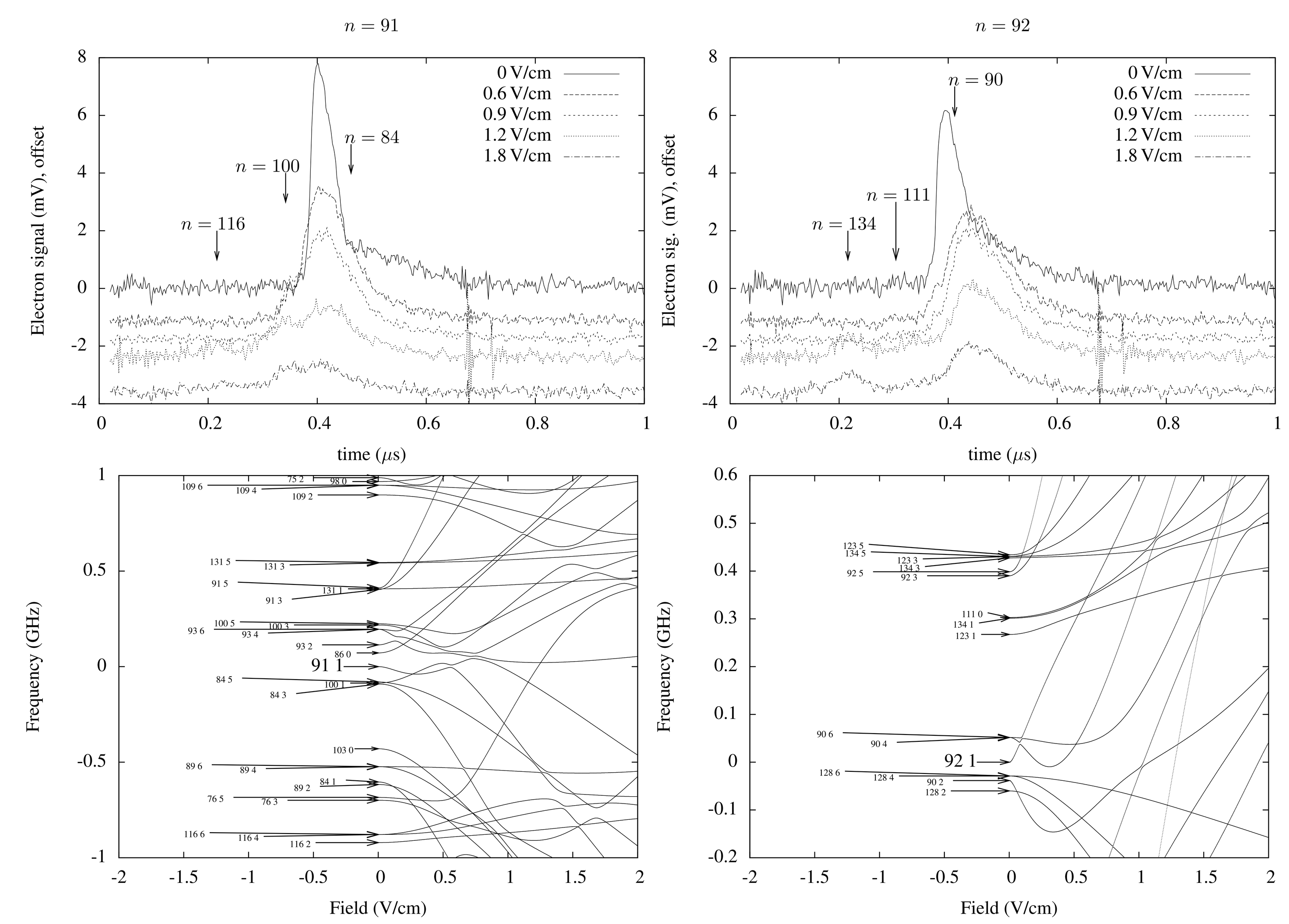


Figure 6: Final state distribution for $n = 91$ and $n = 92$ and the equivalent Floquet maps. Zero field states are labeled by $n\ell$. The initial np state is at 0 GHz in the Floquet map.

The final state distributions for the initial $91p$ state for a set of 17.1015 GHz microwave fields from zero to 1.8 V/cm are shown above left. For even small field amplitudes there is coupling to the $n = 84$ ($t = 462$ ns) state and the $n = 100$ ($t = 342$ ns) state. For fields above 1.2 V/cm the initial $91p$ state is transferred to the $n = 116$ ($t = 286$ ns) state. The Floquet map is congruent with these results, showing coupling with the $n = 116$ manifold at 1.3 V/cm.

Final state distributions for the initial $92p$ state are shown above right. For microwave field amplitudes from 0.6 to 1.8 V/cm there is strong coupling to lower lying states. At zero microwave field the $92p$ state is near-resonant with $n = 90$ transitions, lying between the $90d$ state and the rest of the $n = 90$ manifold. From the experimental spectra, transitions are most likely multiphoton transitions to $n = 90\ell$ states where $\ell \geq 4$. The $90p$ state ionize at $t = 412$ ns, and higher angular momentum states ionize later. The $n = 92$ Floquet map suggests an avoided crossing between the $n = 92p$ state and the $n = 90$ ($t = 412$ ns) manifold in fields as small as 0.1 V/cm. However, dipole selection rules prevent direct transitions from $91p$ to states other than $90s$ and $90d$. Therefore, the transitions must be mediated by other off-resonant s and d states to reach higher angular momentum states. Experimentally, if the microwave field amplitude is increased to 1.2 V/cm there is population transfer to $n = 134$ ($t = 216$ ns), which is also in agreement with the calculated Floquet map, as well as coupling to the $n = 111$ manifold.

References

[1] J. H. Gurian, H. Maeda, and T. F. Gallagher. Kilohertz dye laser system for high resolution laser spectroscopy. *Rev. Sci. Instrum.*, 81(7):073111, 2010.

[2] J. H. Gurian, K. R. Overstreet, H. Maeda, and T. F. Gallagher. Connecting field ionization to photoionization via 17- and 36-ghz microwave fields. *Phys. Rev. A*, 82(4):043415, Oct 2010.

[3] H. Maeda and T. F. Gallagher. Nondispersing wave packets. *Phys. Rev. Lett.*, 92:133004, 2004.

[4] M. W. Noel, W. M. Griffith, and T. F. Gallagher. Population trapping in extremely highly excited states in microwave ionization. *Phys. Rev. Lett.*, 83:1747–1750, 1999.

[5] J. H. Shirley. Solution of the schrödinger equation with a hamiltonian periodic in time. *Phys. Rev.*, 138:B979—-B987, 1965.