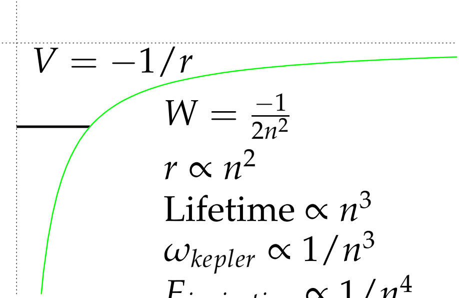
From One to Many Photons: Connecting field ionization to photoionization via GHz microwave ionization of Rydberg atoms

Joshua Gurian
T.F. Gallagher

9 December 2010

Introduction to Rydberg Atoms

Properties of Rydberg Atoms



$V = -1/r$

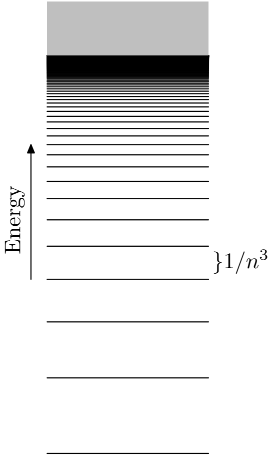
$W = \frac{-1}{2n^2}$

$r \propto n^2$

Lifetime $\propto n^3$

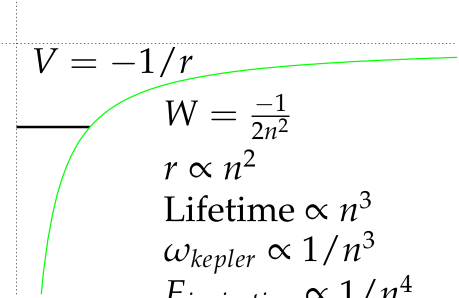
$\omega_{kepler} \propto 1/n^3$

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



Introduction to Rydberg Atoms

Properties of Rydberg Atoms



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$r \propto n^2$

Lifetime $\propto n^3$

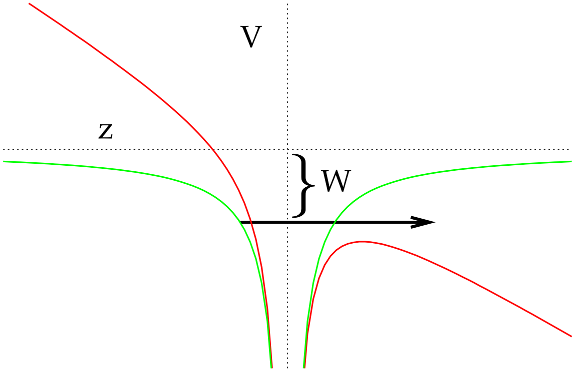
$\omega_{kepler} \propto 1/n^3$

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

For n=100:

- $W = -1.4\,\mathrm{meV}$
- $< r >= 0.5\,\mu\mathrm{m}$
- $\tau = 1\,\mathrm{ms}$
- $\omega_{kepler} = 2\pi \times 6.5\,\mathrm{GHz}$
- $E_{ionization} = 5.7\,\mathrm{V/cm}$

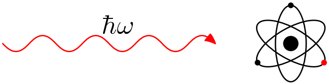
Field Ionization



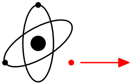
$$V(z) = \frac{-1}{|z|} - Ez$$

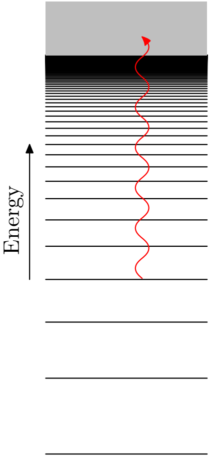
$$E = \frac{W^2}{4}$$

Photoionization

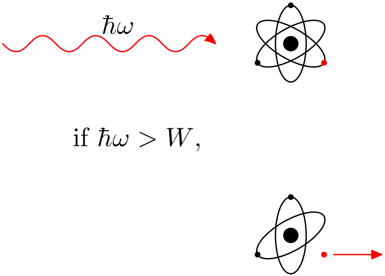


if $\hbar\omega > W$,



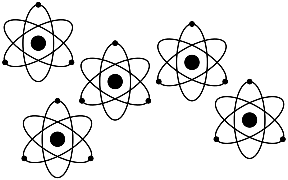


Photoionization



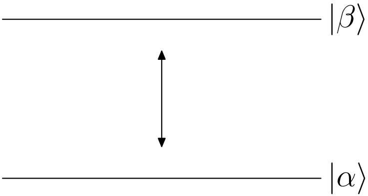
if $\hbar\omega > W$,

If we have some collection of atoms,



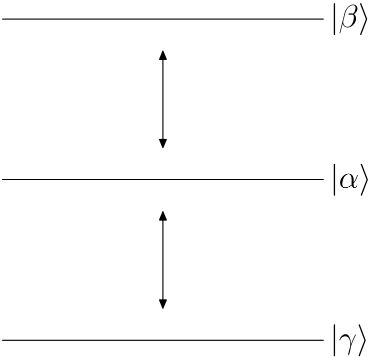
how do we calculate the ionization rate?

Fermi's Golden Rule



Fermi's Golden Rule:
$\Gamma_1 = 2\pi|\langle\alpha|\mu E|\beta\rangle|^2\rho_f$

Fermi's Golden Rule

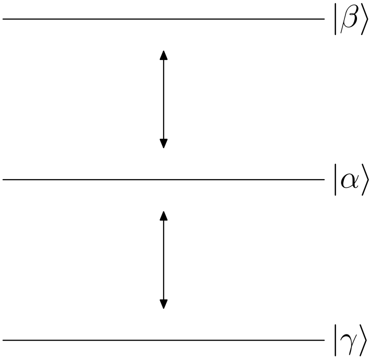


Fermi's Golden Rule:

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

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

Fermi's Golden Rule



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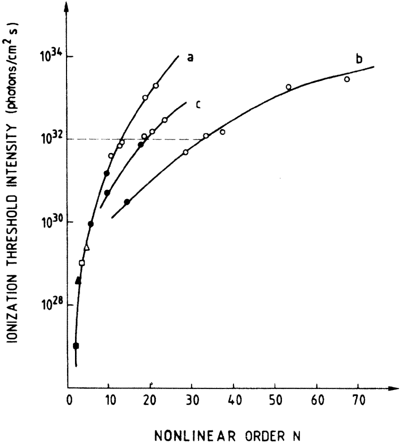
$$\Gamma_N \propto E^{2N}$$

Fermi's Golden Rule



l'Huillier *et al.*, *PRA* 27 (1983).

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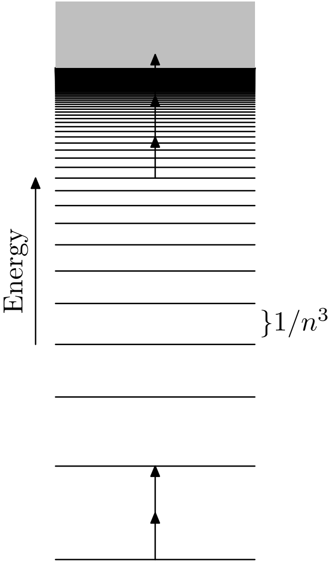
Where does Microwave Ionization fit?



Scaled Microwave Units:

$$\Omega = \frac{\omega}{\omega_{Kepler}} = \omega n^3$$

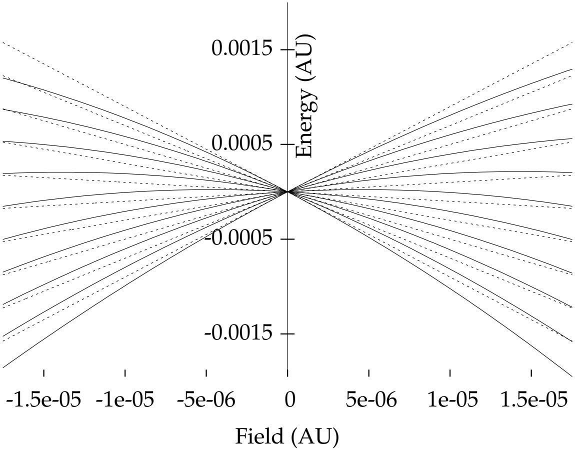
$$E_0 = \frac{E}{E_{Coulomb}} = En^4$$

Hydrogenic Microwave Ionization

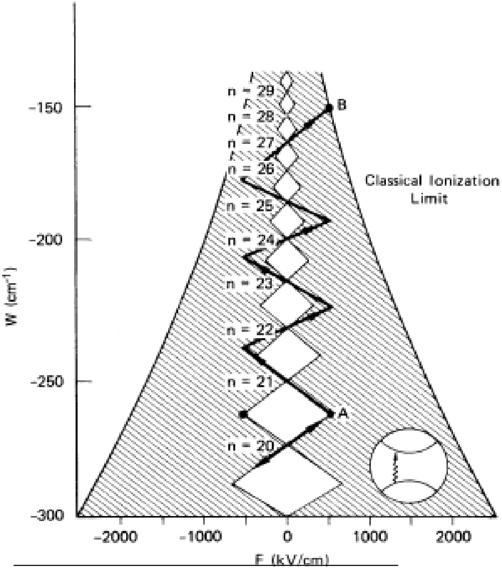
First experiments by Bayfield and Koch:

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

$$E = \frac{1}{9n^4}$$



Non-Hydrogenic Microwave Ionization

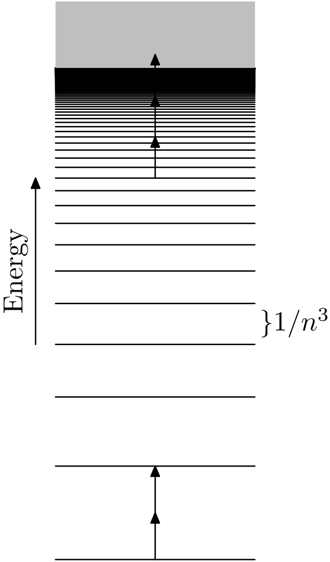


Pillet *et al.*, *Phys. Rev. Lett.* 50, 1983.

Ladder-climbing mechanism for ionization:

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

Where does Microwave Ionization fit?



Scaled Microwave Units:

$$\Omega = \frac{\omega}{\omega_{Kepler}} = \omega n^3$$

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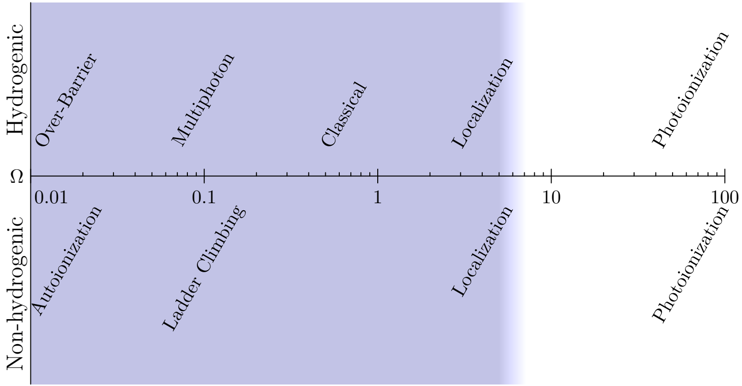
Experimentally, what happens as we approach the photoionization limit?

Microwave Ionization

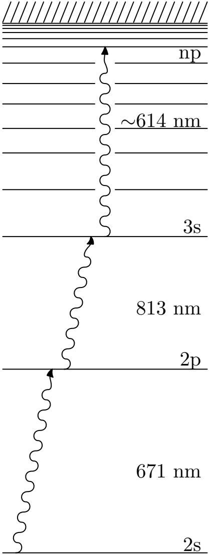
$$\Omega = \frac{\omega}{\omega_{Kepler}} = \omega n^3 \qquad E_0 = \frac{E}{E_{Coulomb}} = E n^4$$

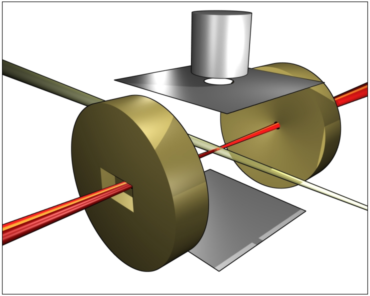


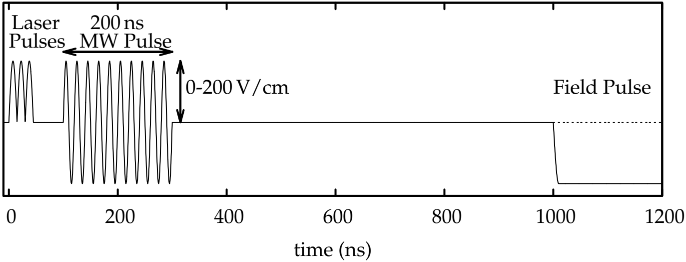
What happens as we approach the photoionization limit?

- 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

Experimental Setup







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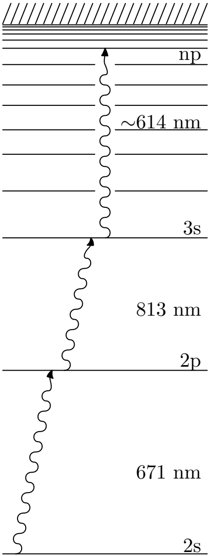
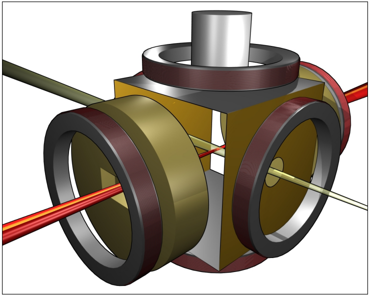
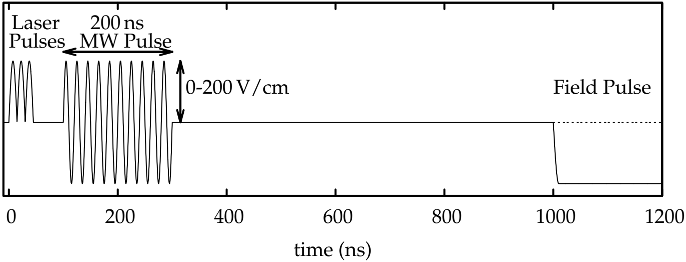
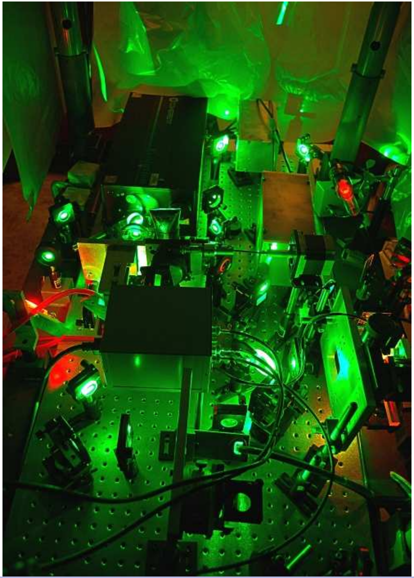
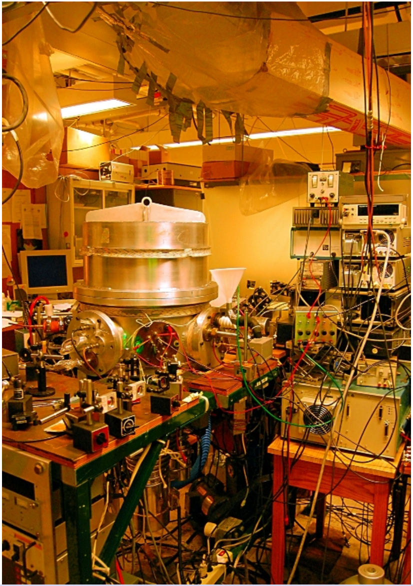






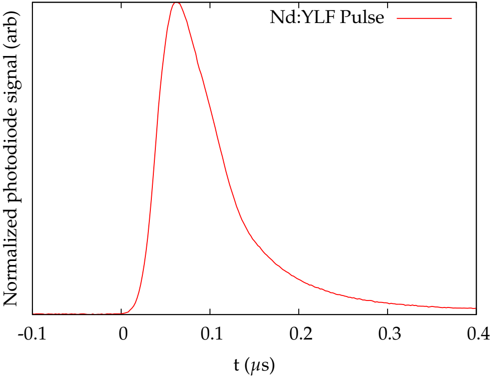
Pictures



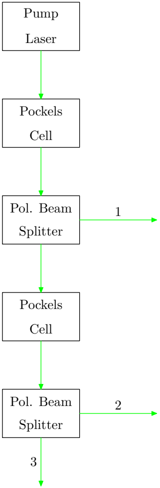


A New Laser System

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



External Pulse Splitting



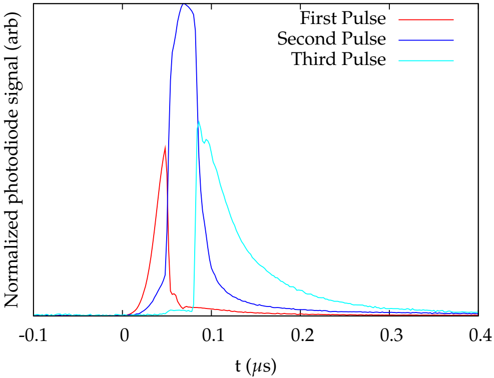
Pump Laser

Pockels Cell

Pol. Beam Splitter

Pockels Cell

Pol. Beam Splitter



Dye Laser Output: $\approx 20\mu$J/pulse

JHG, HM, and TFG, Rev. Sci. Instrum. 81 073111 (2010).

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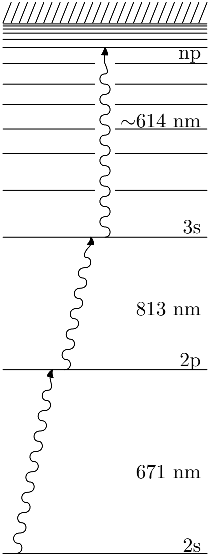
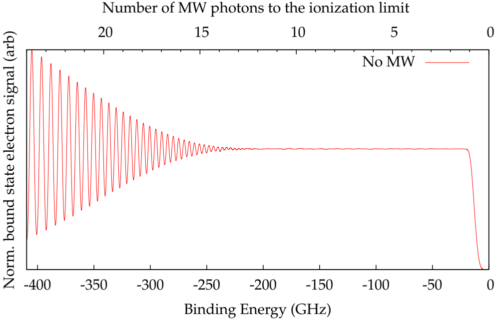
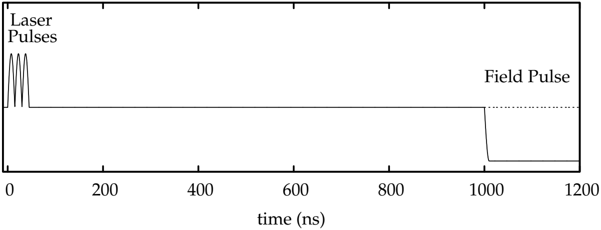
Expected Results







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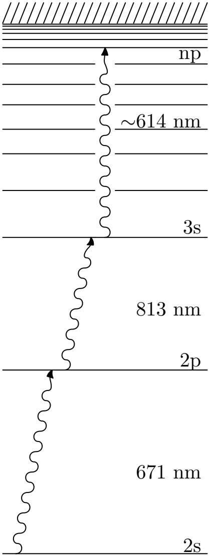
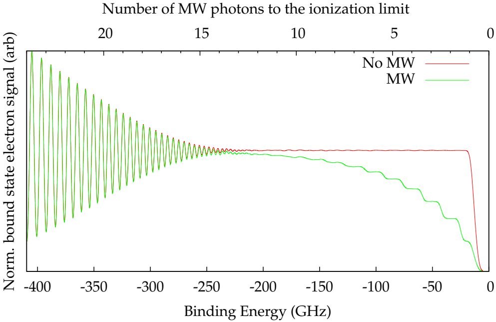
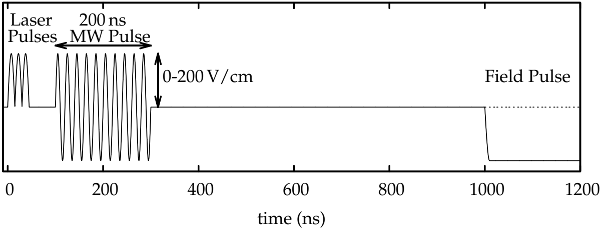
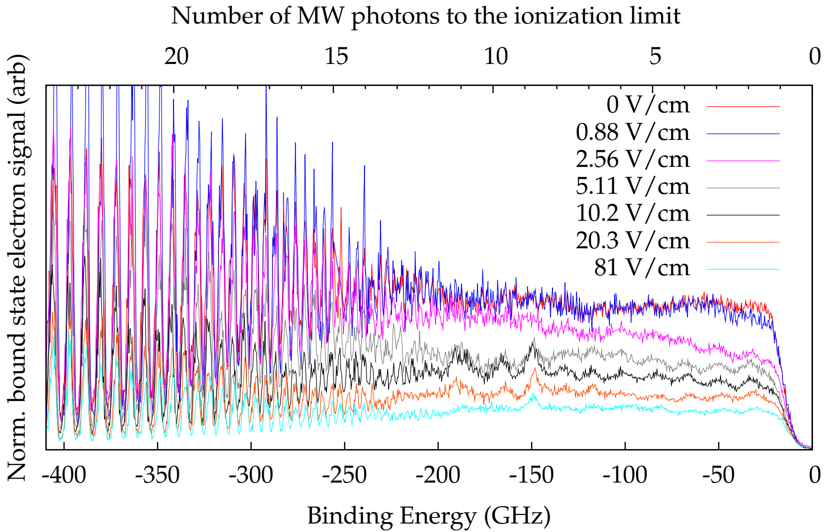


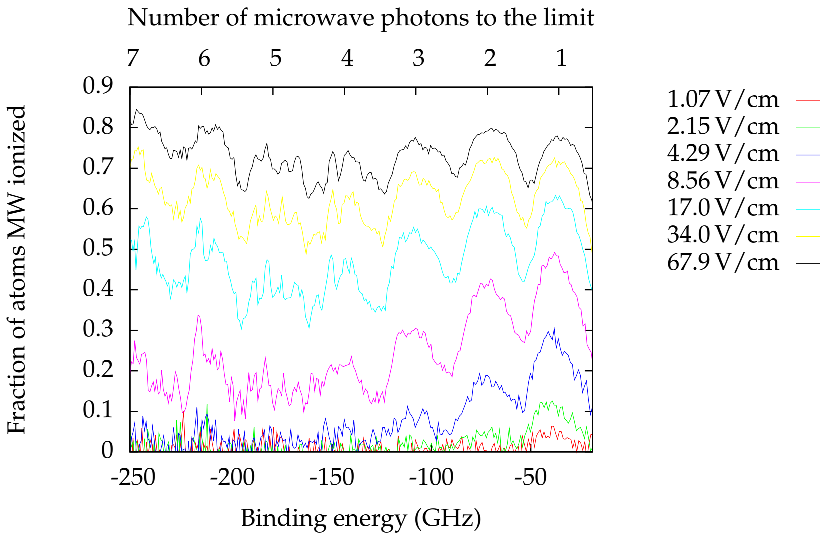




Microwave Ionization Steps - 17 GHz

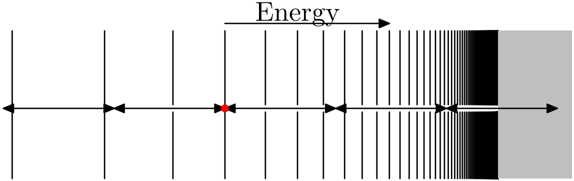


Microwave Ionization Steps - 36 GHz



Dynamical Anderson Localization

First work by Casati *et al.*



Anderson Localization - Destructive interference between many multiphoton paths localizes the electronic wave function, and ionization occurs when electron transport diffuses over the limit.
Schelle *et al.* - Anderson Localization crossing over to Fermi's Golden Rule

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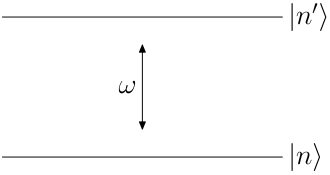
Schelle, Delande, and Buchleitner, *PRL* 102 (2009).
Casati *et al.*, *Phys. Rep.* 154 (1987).

Jensen *et al.* Model



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

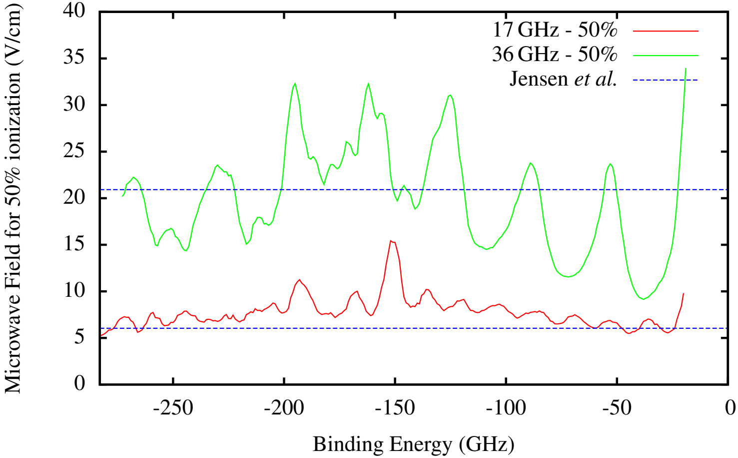
State spacing = $\frac{1}{n^3}$

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

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

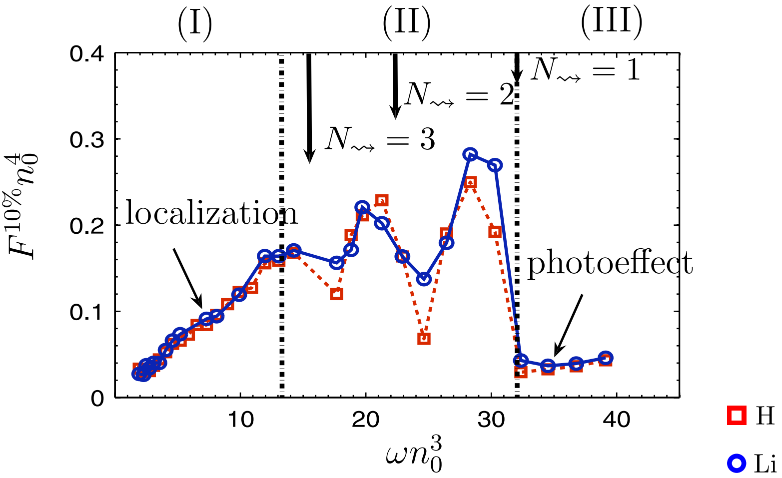
Jensen *et al.*, *Phys. Rev. Lett.* 62, (1989).

Jensen *et al.* Comparison



Jensen *et al.*, *Phys. Rev. Lett.* 62, (1989).

Schelle, Delande, and Buchleitner Model



Schelle, Delande, and Buchleitner, *Phys. Rev. Lett.* 102, (2009).

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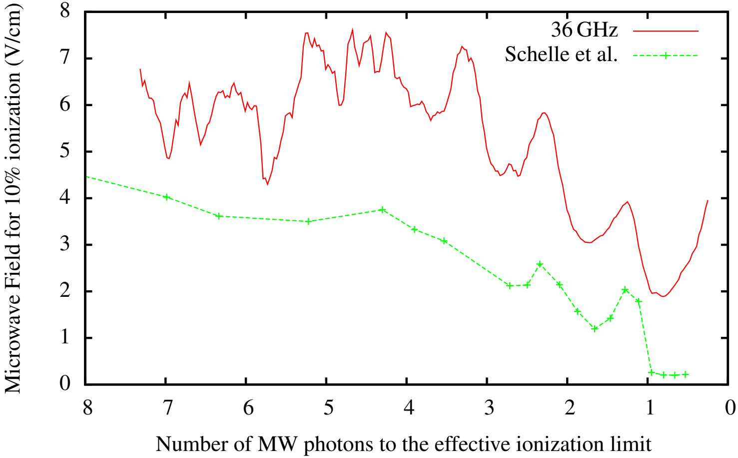
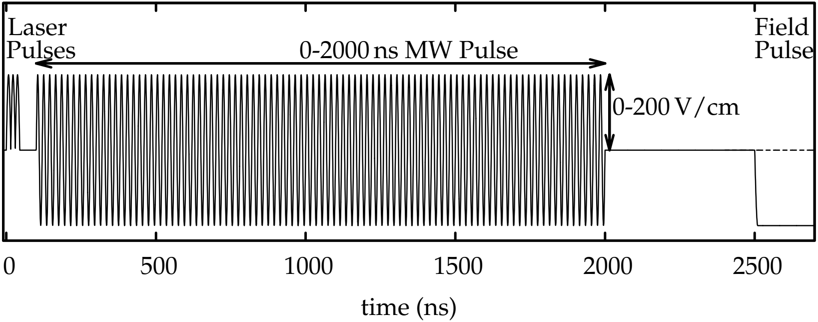
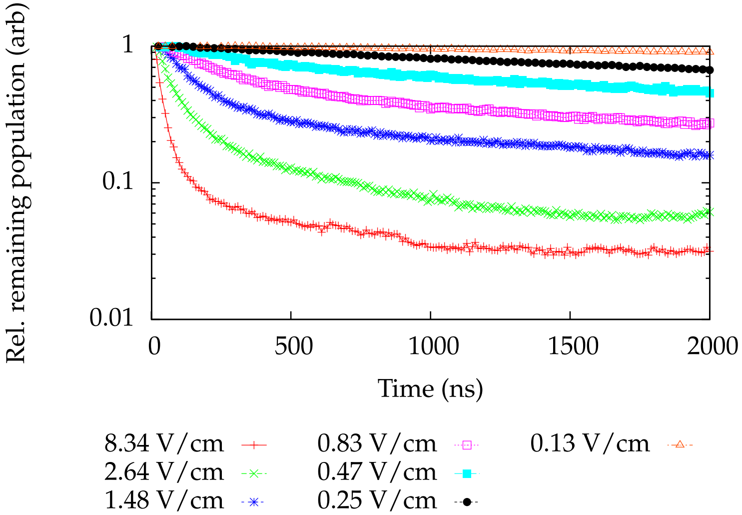


Schelle, Delande, and Buchleitner, *Phys. Rev. Lett.* 102, (2009).

Photoionization - Timing



Single Photon Ionization



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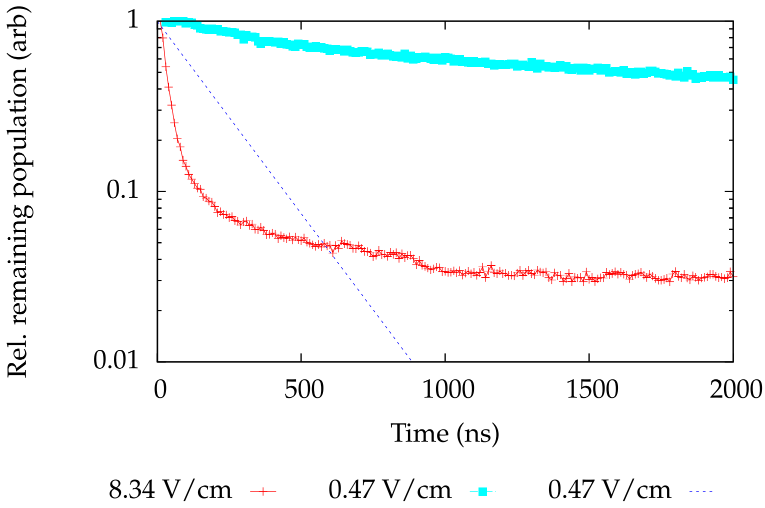
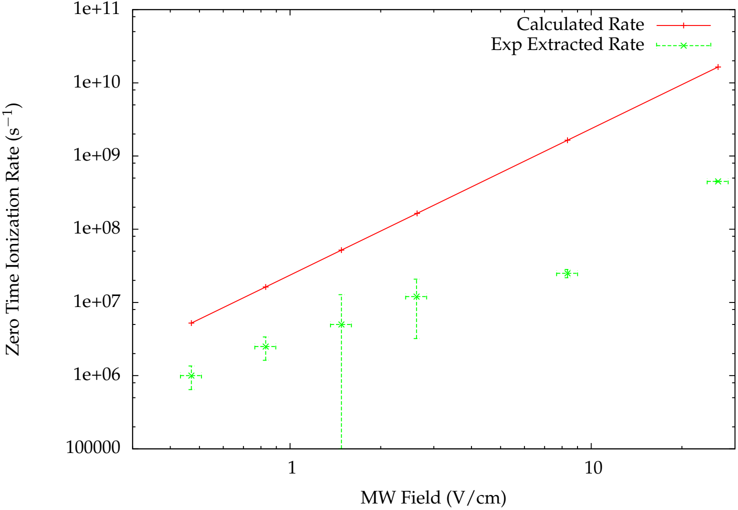


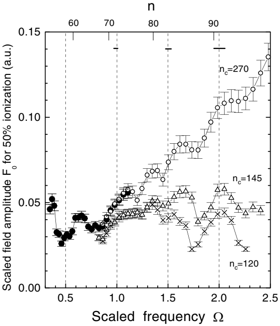
Fermi's Golden Rule Comparison



Influence of Stray Field

Stray fields limit the maximum *n* we can validly investigate

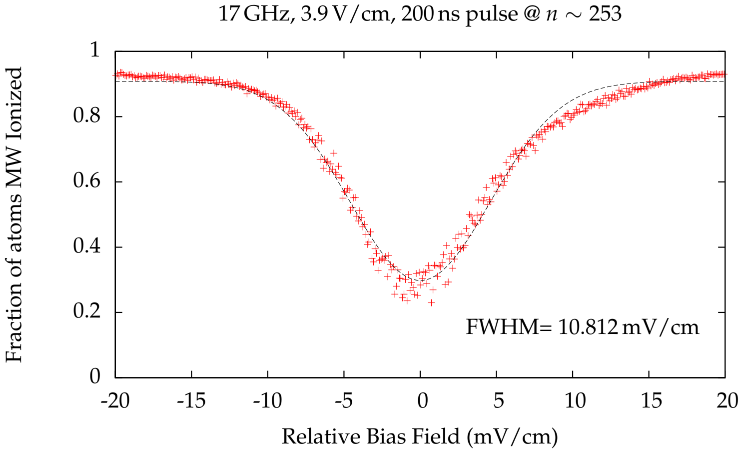
If we artificially depress n_c, we see that stray fields depress the microwave ionization threshold



New cut-off *n* has been increased from $n_c = 270$ to $n_c = 575$

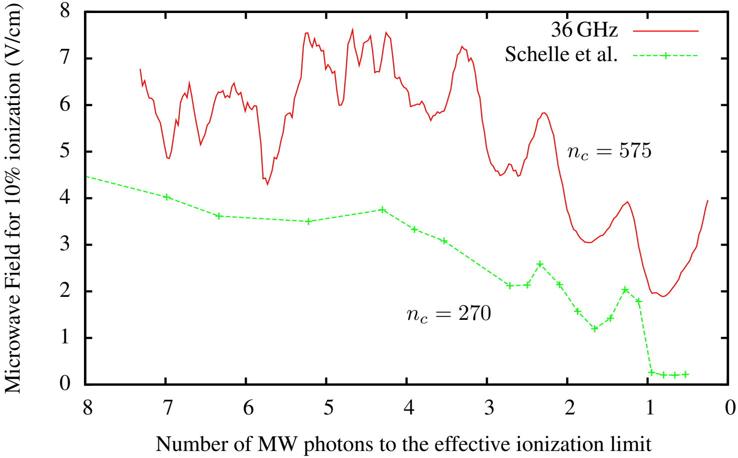
Maeda and Gallagher, *Phys. Rev. Lett.* 93, 2004.

Applied Bias Field



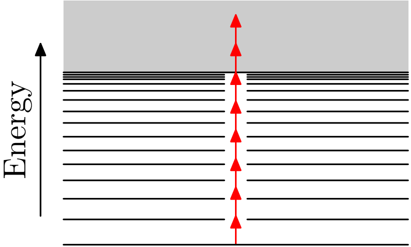
We can reduce stray field to below 3 mV/cm

Schelle, Delande, and Buchleitner Comparison



Schelle, Delande, and Buchleitner, *Phys. Rev. Lett.* 102, (2009).

Dressed Atom Picture



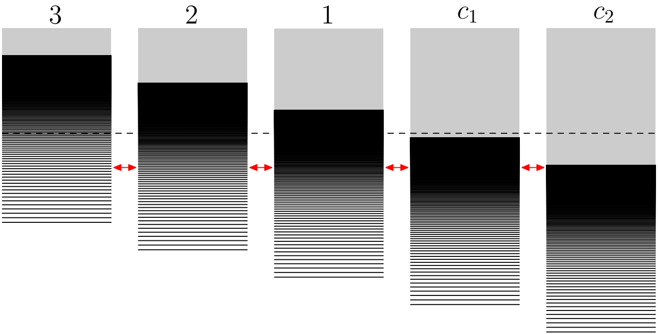
Can we simply use a Floquet picture to describe system?

How do we choose the correct levels to include?

How do we include the above-threshold continuum states?

MQDT-Floquet Model

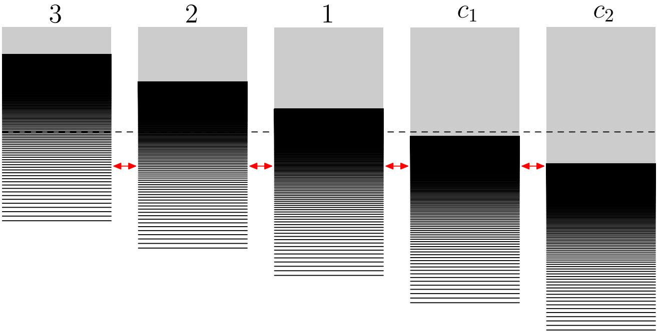
Giusti-Suzor and Zoller proposed a Floquet-MQDT model for Rydberg atoms in laser fields where the couplings between channels are radiative dipole couplings. The Rydberg electron is in a Coulomb potential, and can only scatter to other states near the core.



Giusti-Suzor and Zoller, *Phys. Rev. A* 36, (1987).

MQDT-Floquet Model

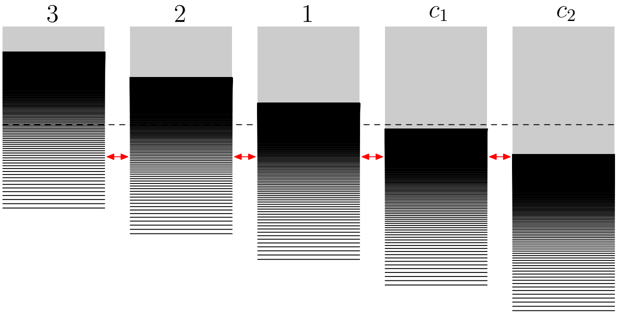
We can define a series of channels, each separated by one microwave photon.



The coupling between channels are radial dipole couplings - the same as the level coupling used by Jensen *et al.*

MQDT-Floquet Model

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

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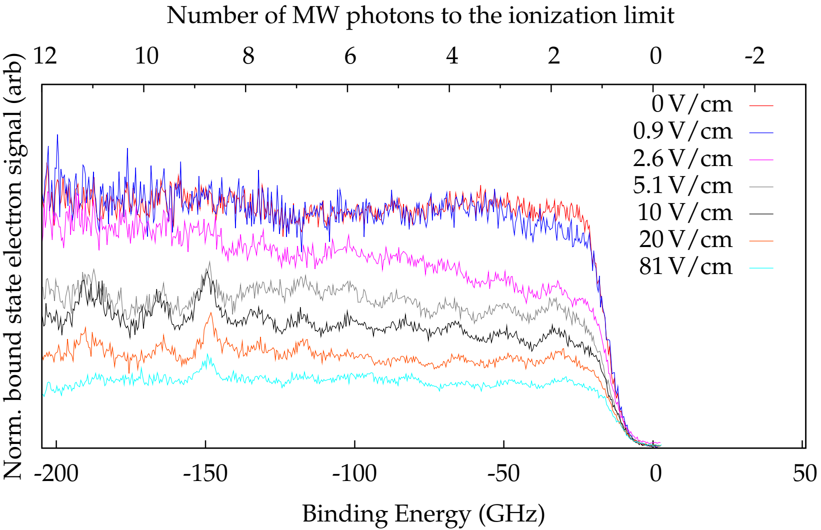
Cooke and Cromer, *Phys. Rev. A* 32, (1985).

Model Comparison



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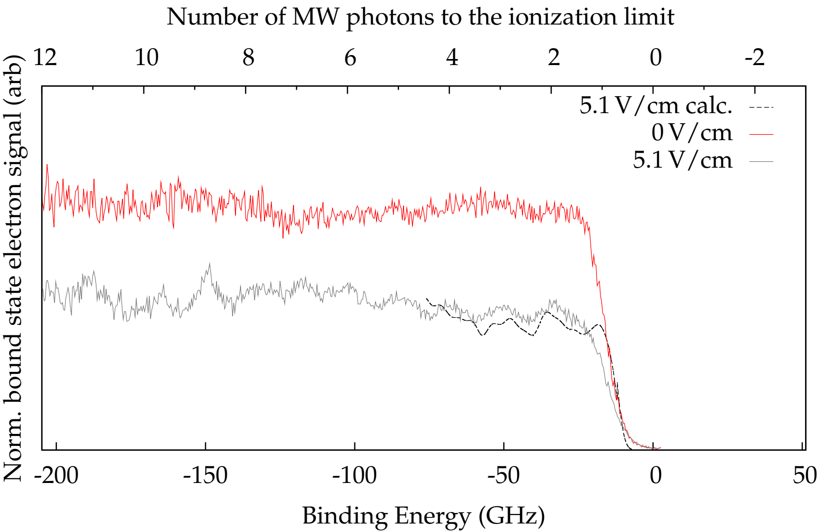

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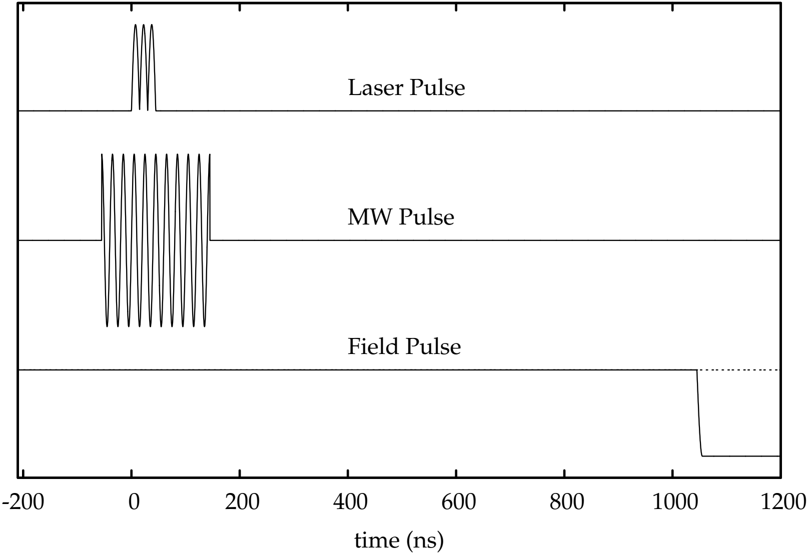
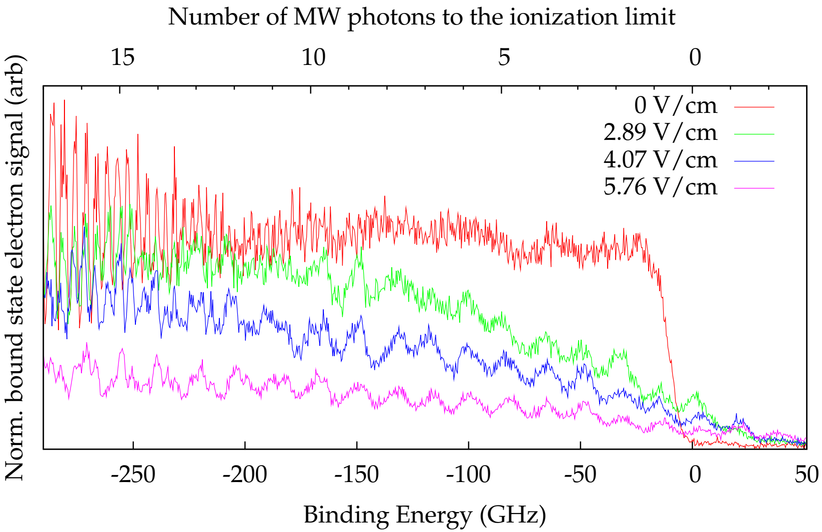
- Above-Threshold Bound States

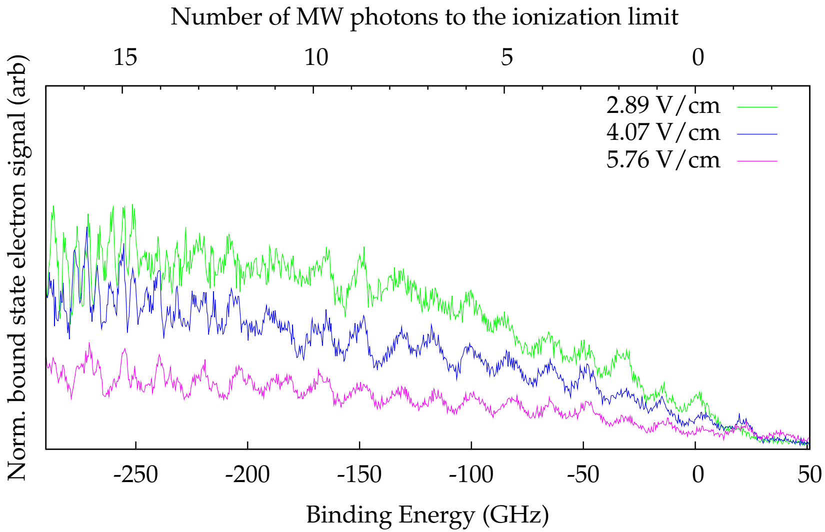
Above-Threshold Bound States - Timing



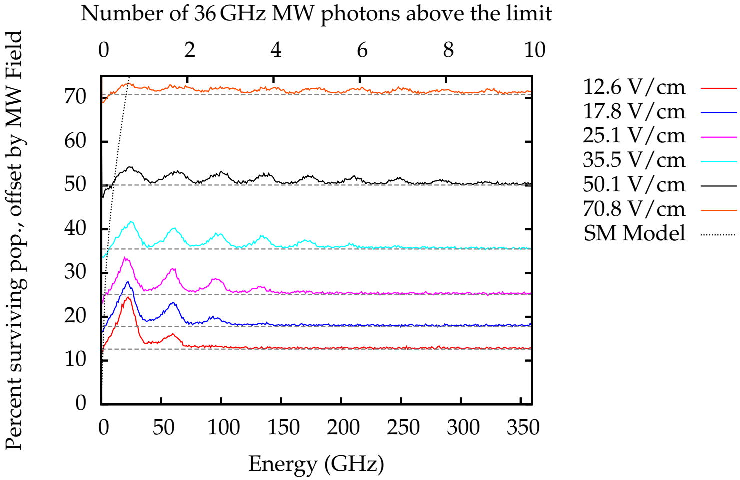
Above-Threshold Bound States



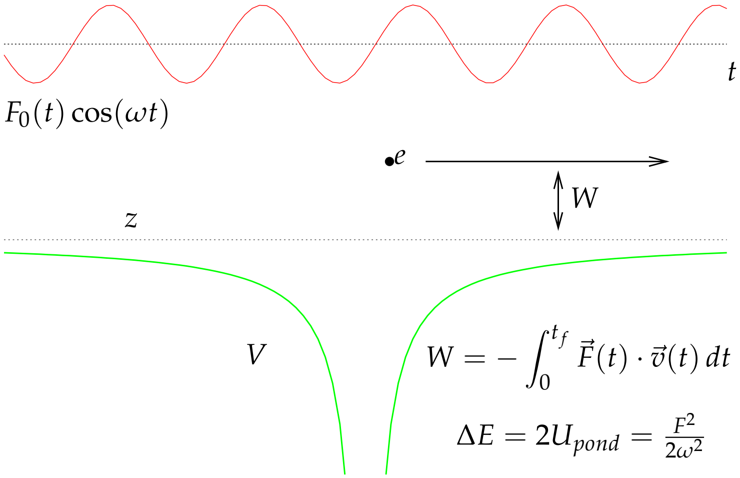
Above-Threshold Bound States



Above-Threshold Bound States



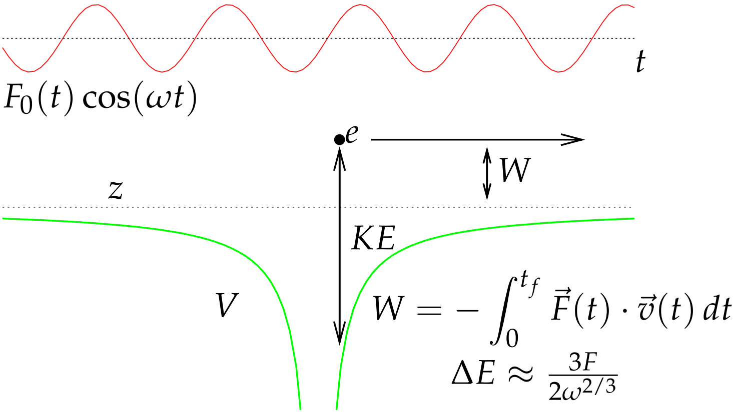
Simpleman's Model



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

$$\Delta E = 2U_{pond} = \frac{F^2}{2\omega^2}$$

New Classical Model

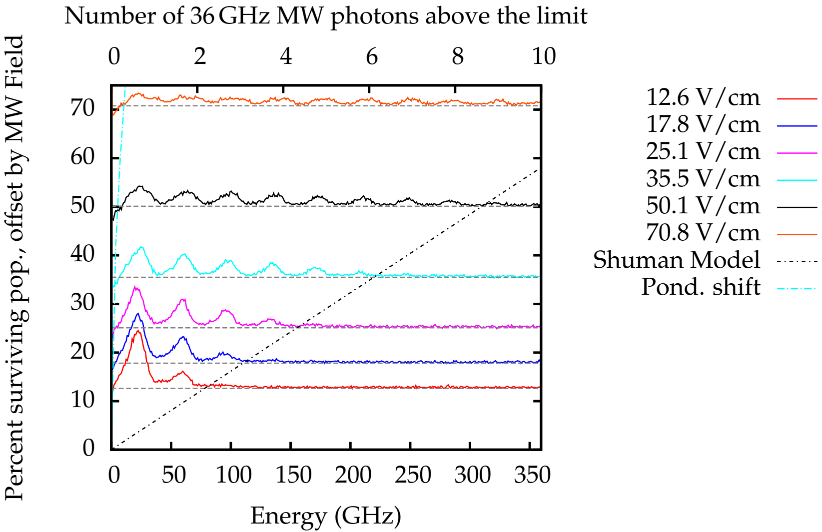


$$W = -\int_0^{t_f} \vec{F}(t)\cdot\vec{v}(t)\,dt$$

$$\Delta E \approx \frac{3F}{2\omega^{2/3}}$$

Shuman et al., *Phys. Rev. Lett.* 101, (2009).

Above-Threshold Bound States



Conclusions

- Anderson Localization model fits experimental results
- There is no experimentally accesible regime where Fermi's Golden Rule applies
- 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