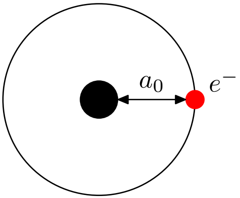
From One to Many Photons: Microwave Ionization of Rydberg Atoms

Josh Gurian, '04
T.F. Gallagher

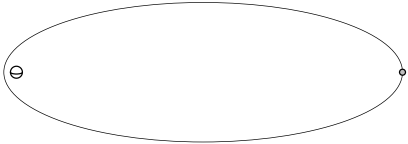
December 10, 2009

Atomic Units



Mass	m_e	9.1×10^{-31} kg	= 1
Action	$\hbar$	1.05×10^{-34} J·sec	= 1
Charge	e	1.6×10^{-19} C	= 1
Length	a_0	5.29×10^{-11} m	= 1
Energy	W	2×13.6 eV	= 1
Frequency	$\omega/2\pi$	6.5761×10^{6} GHz	= 1
Electric Field	E	5.137×10^{9} V/cm	= 1

What's a Rydberg Atom?



Any atom with one or more electrons of large principal quantum number n, where $n > 10$.

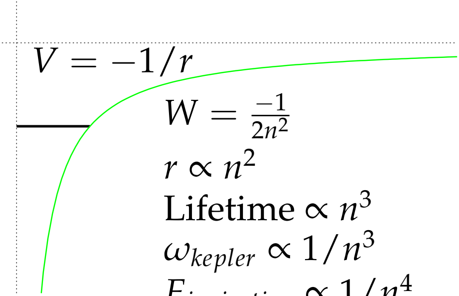
Morgan Lab: $15 < n < 30$

Gallagher Lab: $20 < n < 45$

This Talk: $70 < n < 600$

Introduction to Rydberg Atoms

Properties of Rydberg Atoms



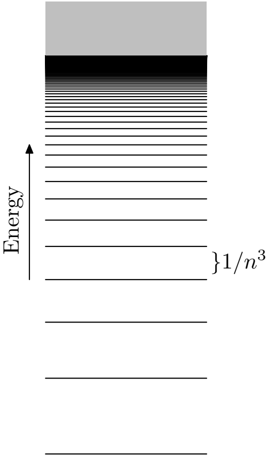
$W = \frac{-1}{2n^2}$

$r \propto n^2$

Lifetime $\propto n^3$

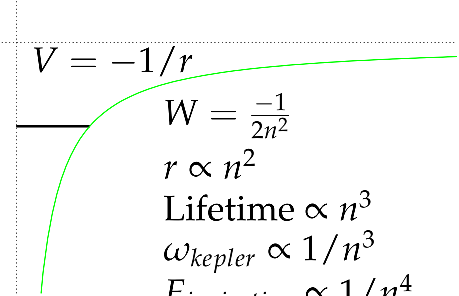
$\omega_{kepler} \propto 1/n^3$

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



Introduction to Rydberg Atoms

Properties of Rydberg Atoms



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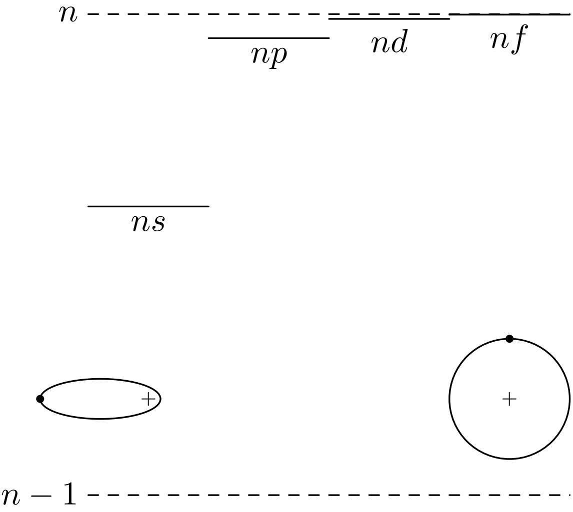
For n=100:

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

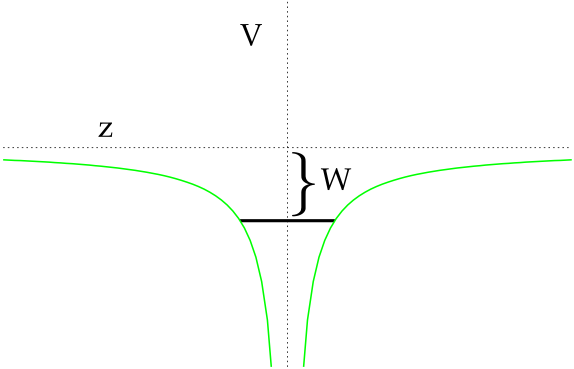
Non-hydrogenic Atoms

Ion core interactions shift energy levels

$$W = \frac{-1}{2(n - \delta_\ell)^2}$$

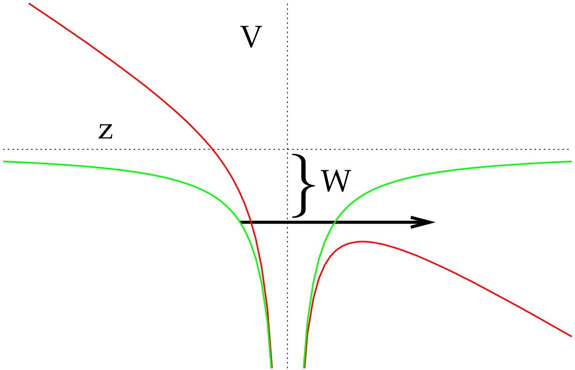


Field Ionization



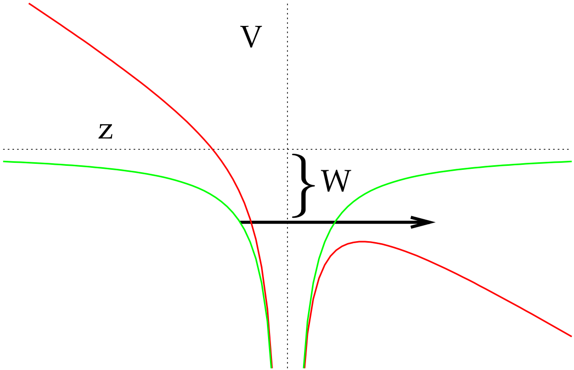
$$V(z) = \frac{-1}{|z|}$$

Field Ionization



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

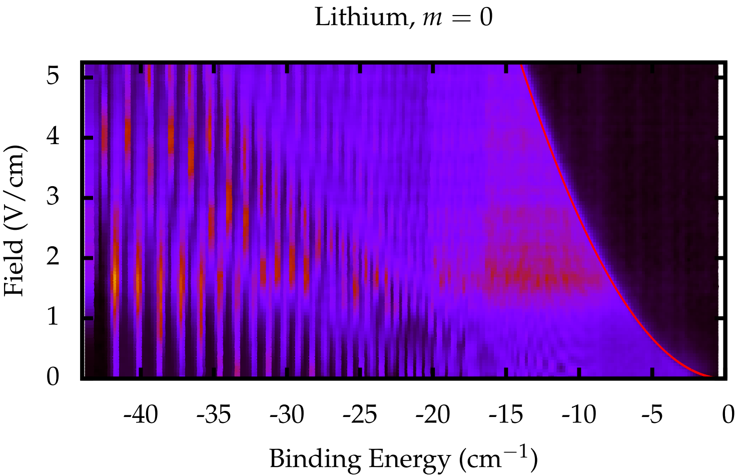
Field Ionization



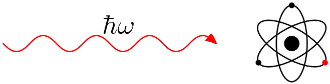
$$V(z) = \frac{-1}{|z|} - Ez$$

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

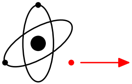
Field Ionization

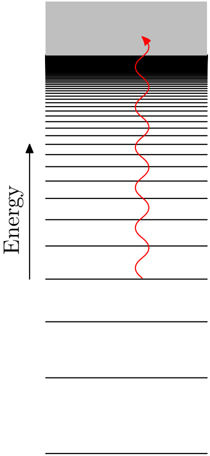


Photoionization



if $\hbar\omega > W$,





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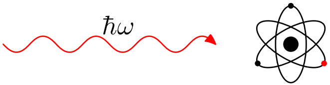

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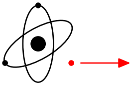
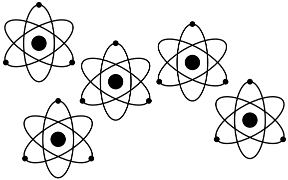
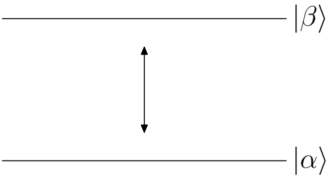


If we have some collection of atoms,



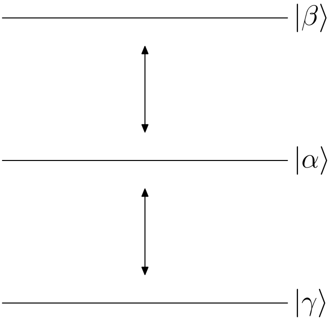
how do we calculate the ionization rate?

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

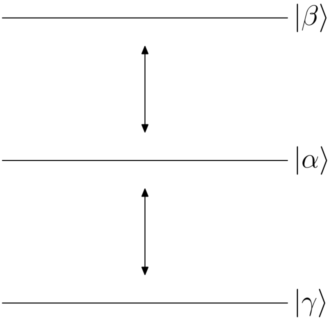


Fermi's Golden Rule:

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

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

Fermi's Golden Rule



Fermi's Golden Rule:

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

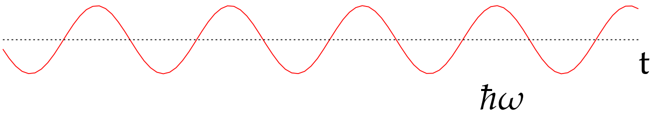
$$\Gamma_2 = 2\pi \left| \frac{\langle\gamma|\mu E|\alpha\rangle\langle\alpha|\mu E|\beta\rangle}{\Delta W} \right|^2$$

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

What about microwaves?

If microwaves are just oscillating electric fields...

$$F_0(t)\cos(\omega t)$$

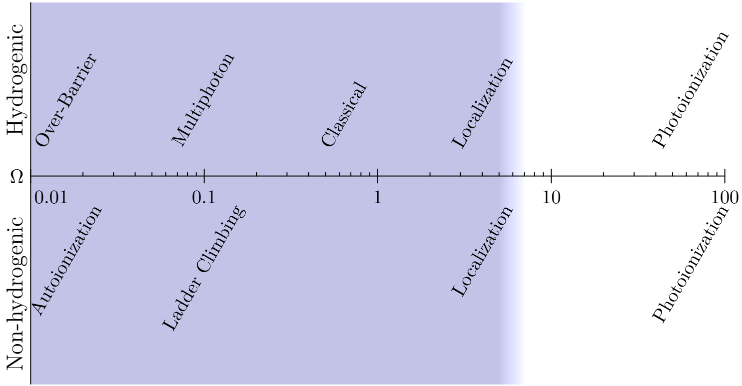


and if microwaves are just photons...

Can we connect field ionization to photoionization using microwave ionization of Rydberg atoms?

Microwave Ionization

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



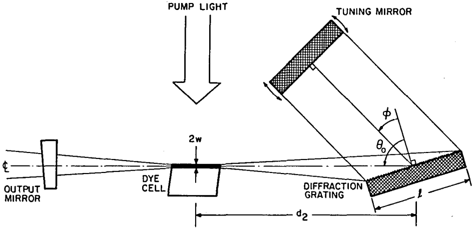
What happens as we approach the photoionization limit?

Outline

How Do We Make Rydberg Atoms?

Nd:YAG laser

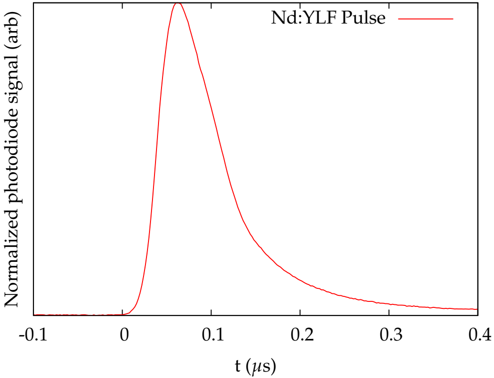
- 1064 nm → 532 nm
- 10-30 Hz pulse repetition frequency
- 5-8 ns pulsewidths
- Pump a system of Littman dye lasers



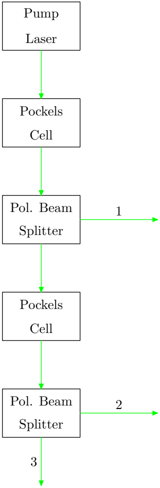
Littman and Metcalf, *Appl. Opt.* 17, 1978.

A New Laser System

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



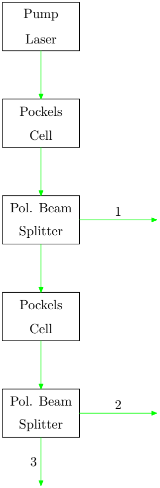
External Pockels Cells

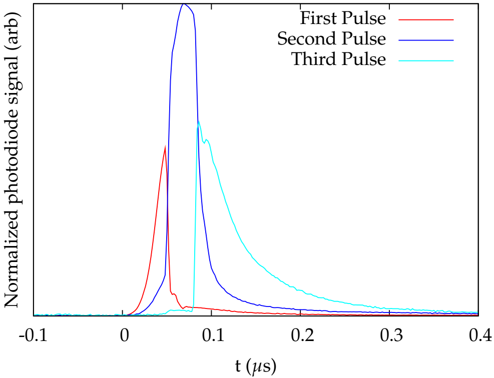


Voltage controlled wave plate

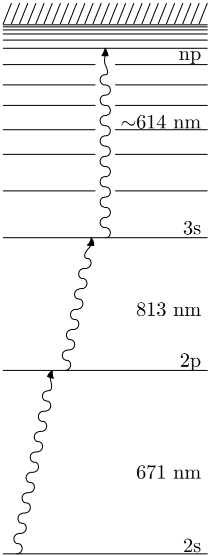
$$\Delta\varphi = \frac{2\pi n_0^3 r_{63} V}{\lambda_0}$$

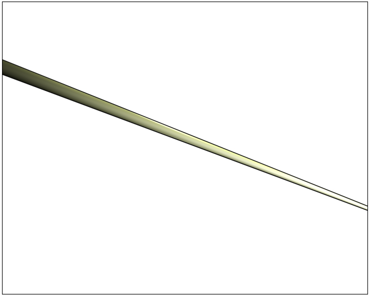
External Pulse Splitting

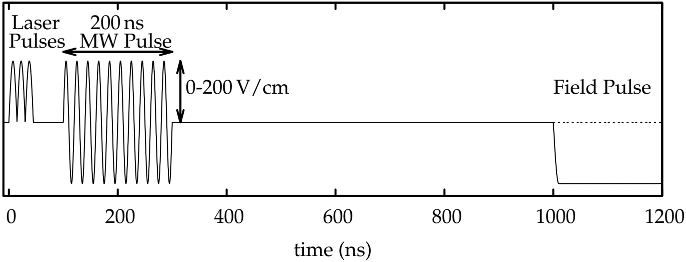




Experimental Setup







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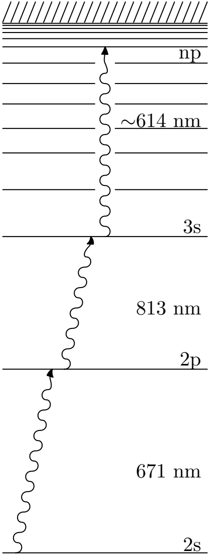

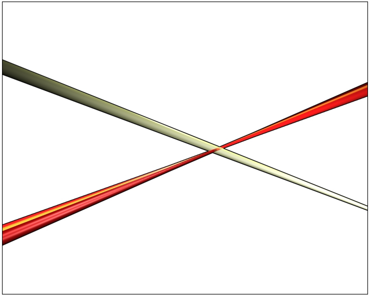

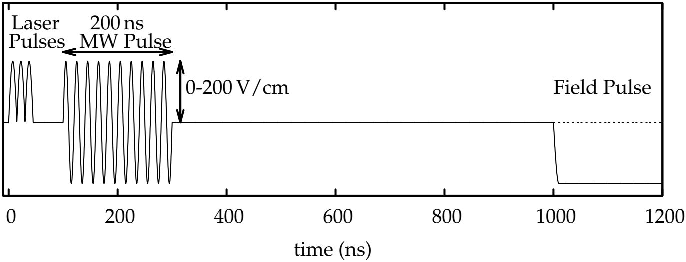

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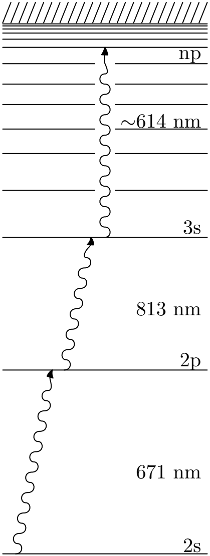

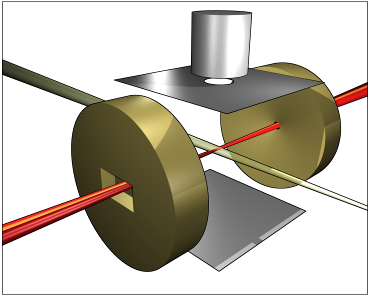

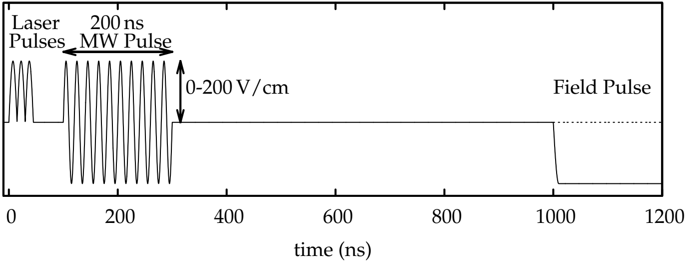

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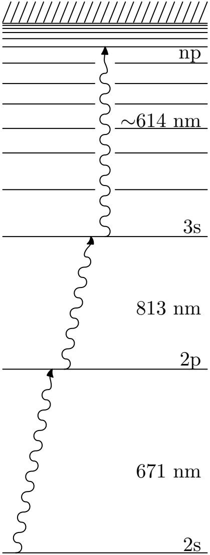
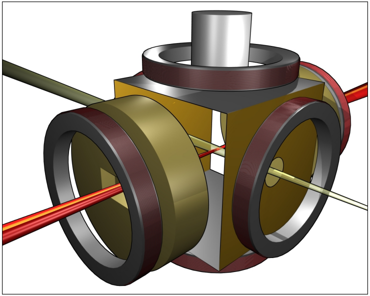
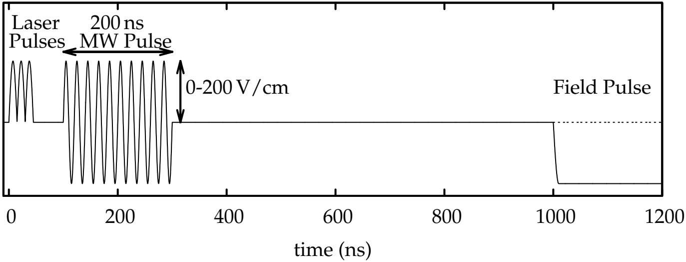
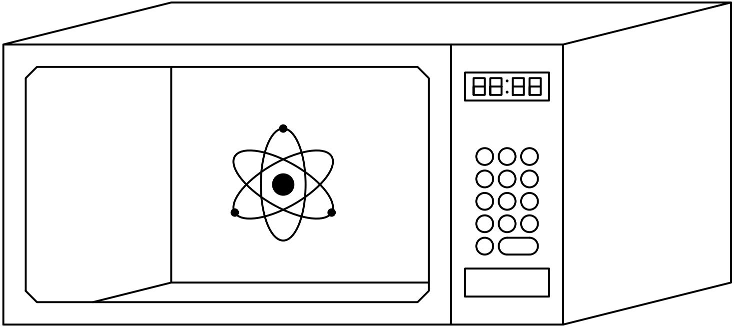






Pictures



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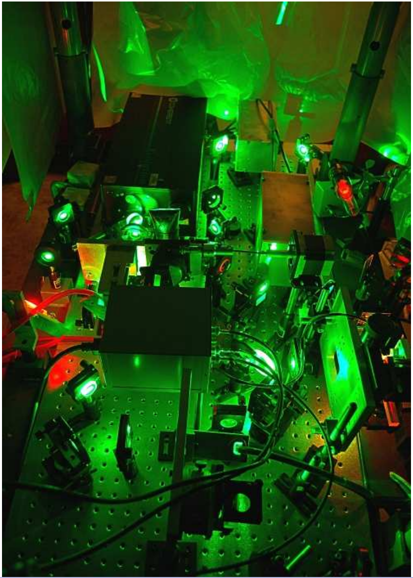
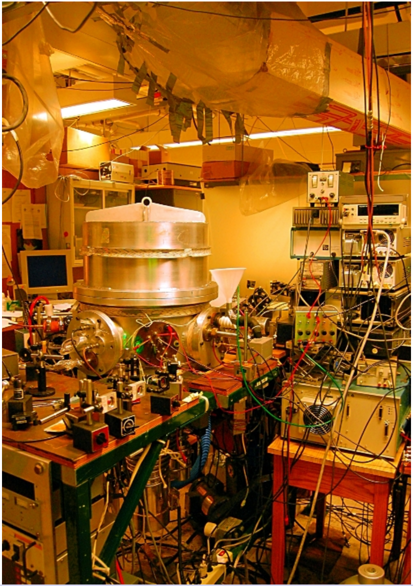
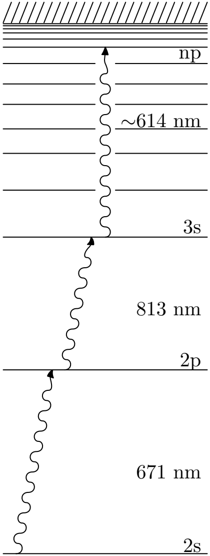
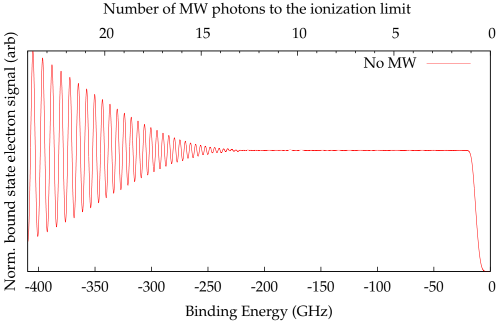


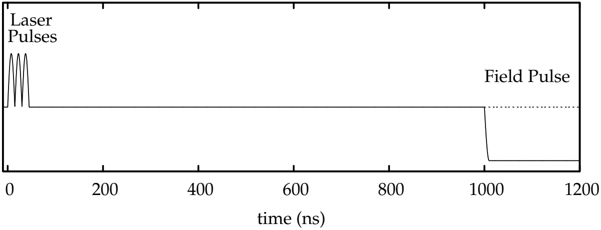


Outline

Expected Results







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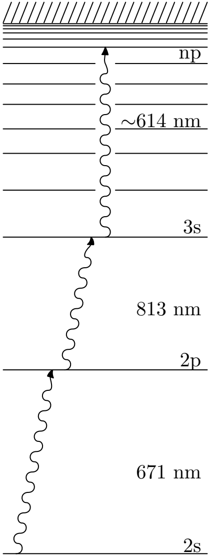
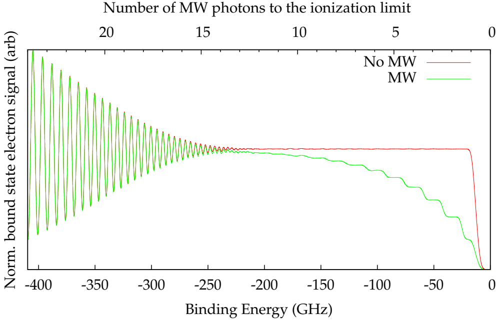
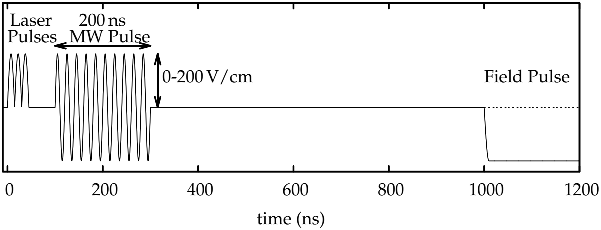
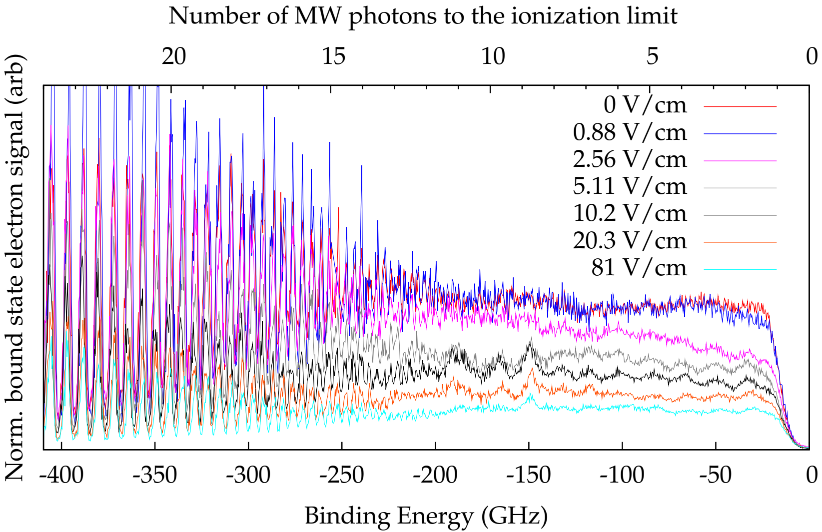


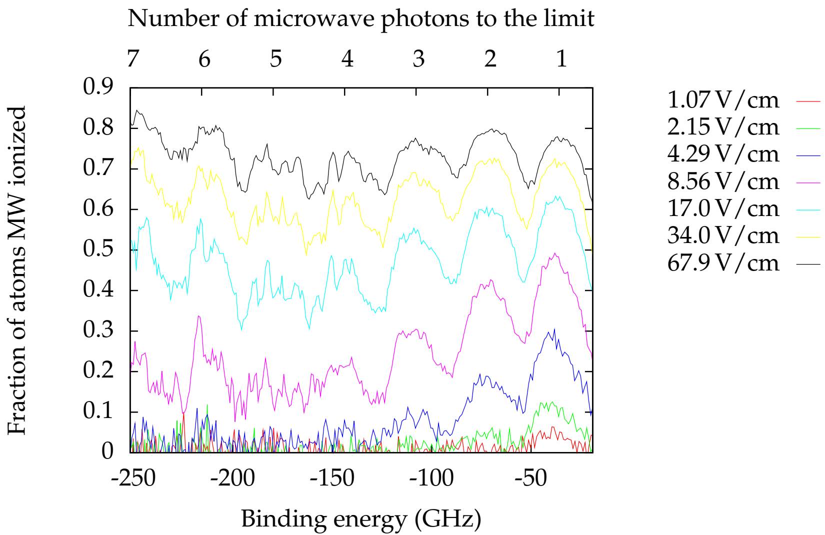




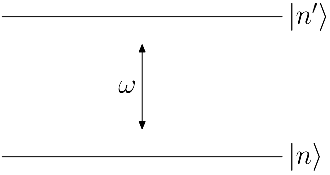
Microwave Ionization Steps - 17 GHz



Microwave Ionization Steps - 36 GHz



Jensen *et al.* Model



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

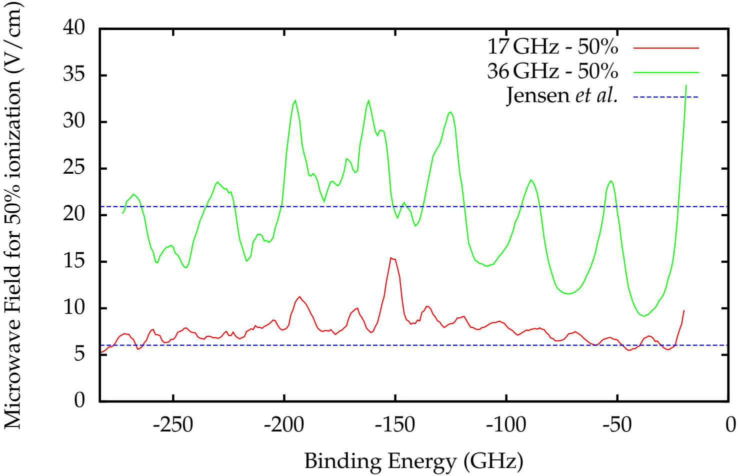
State spacing = $\dfrac{1}{n^3}$

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

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

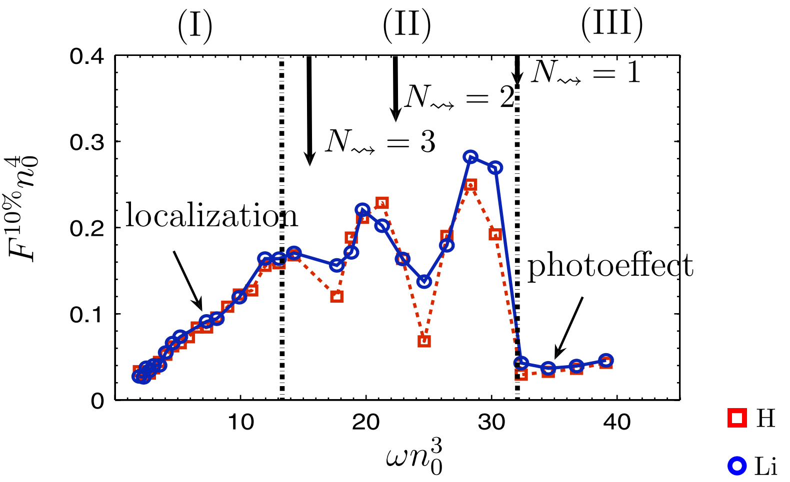
Jensen *et al.*, *Phys. Rev. Lett.* 62, (1989).

Jensen *et al.* Comparison



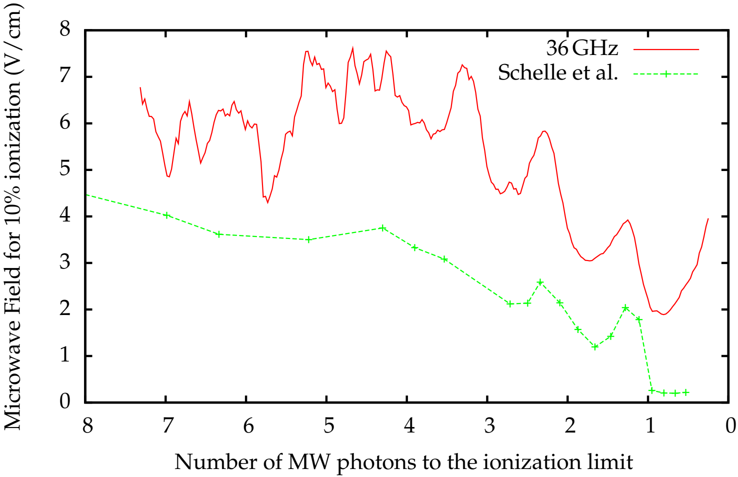
Jensen *et al.*, *Phys. Rev. Lett.* 62, (1989).

Schelle *et al.* Comparison



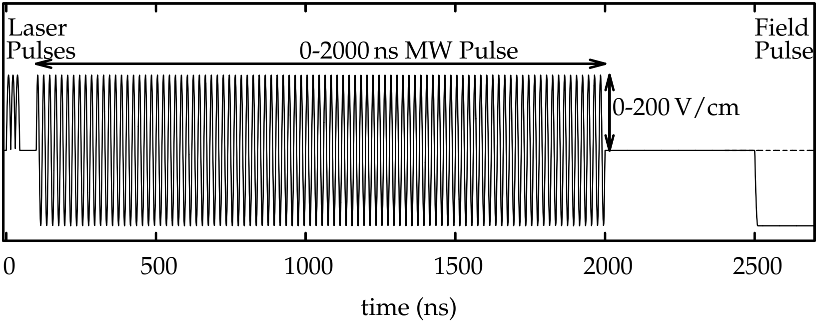
Schelle *et al.*, *Phys. Rev. Lett.* 102, (2009).

Schelle *et al.* Comparison

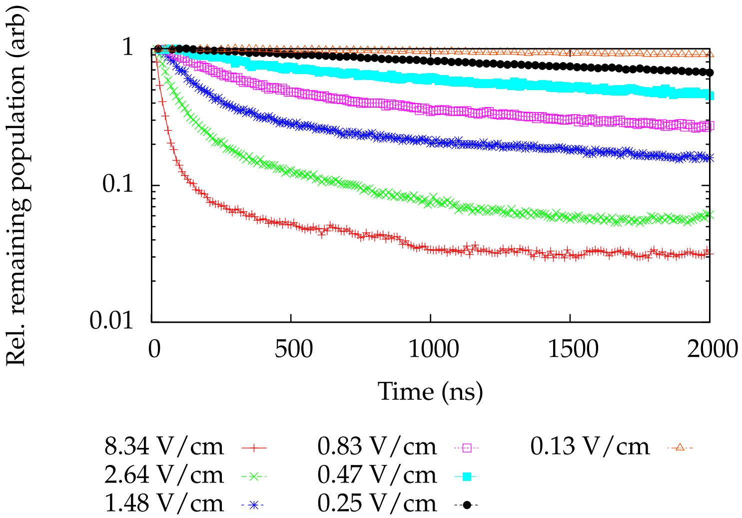


Schelle *et al.*, *Phys. Rev. Lett.* 102, (2009).

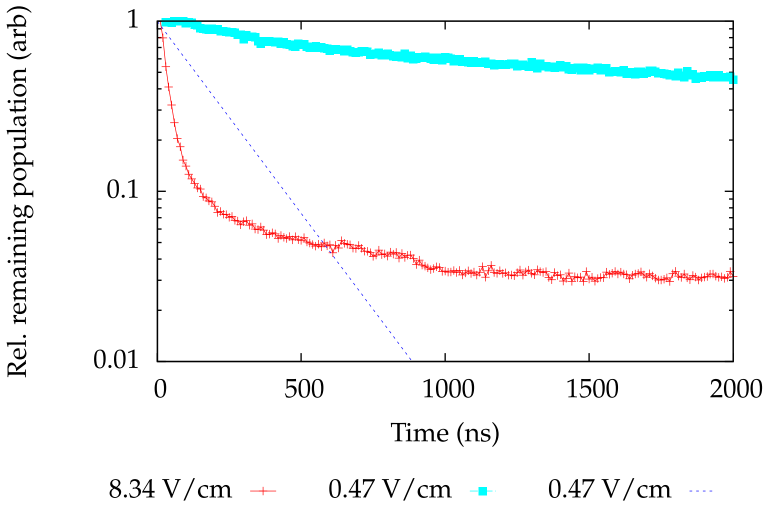
Photoionization - Timing



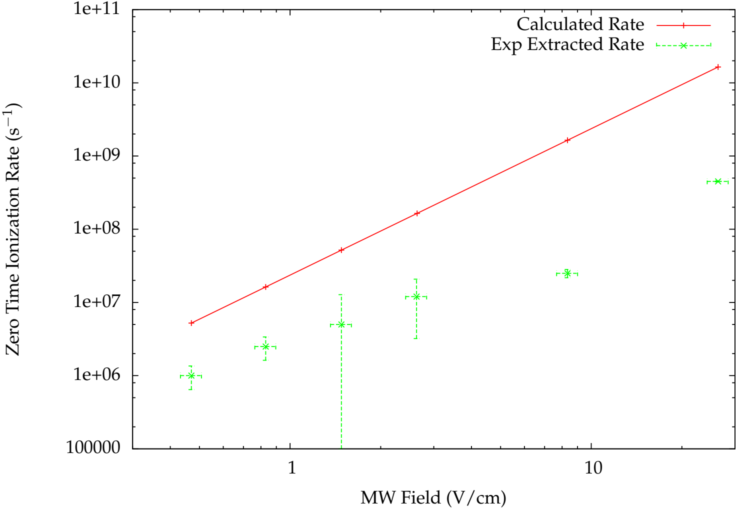
Single Photon Ionization



Single Photon Ionization



Fermi's Golden Rule Comparison

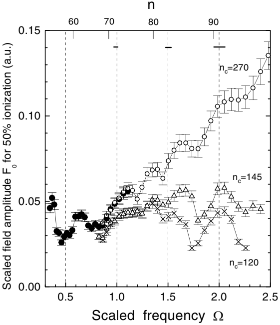


Outline

Why hasn't this been done before?

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

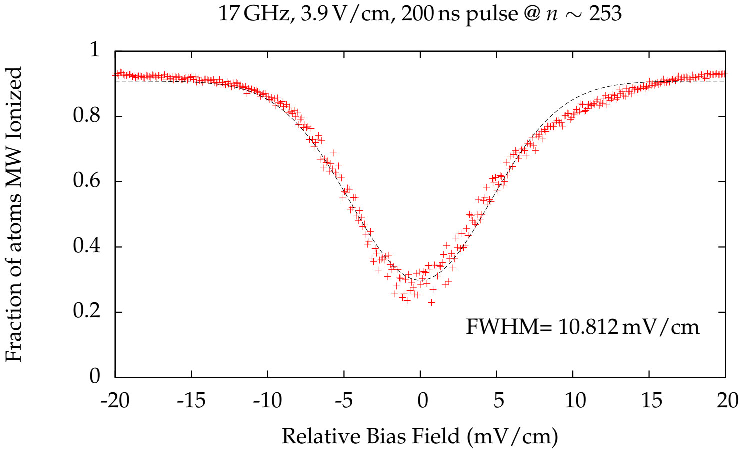
If we artificially depress n_c, we see that stray fields depress the microwave ionization threshold



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

Dunning Does Better

Dunning's Stark effect method

- $< 0.05\,\text{mV/cm}$
- sub-MHz laser resolution required
- 2-3 hours/day

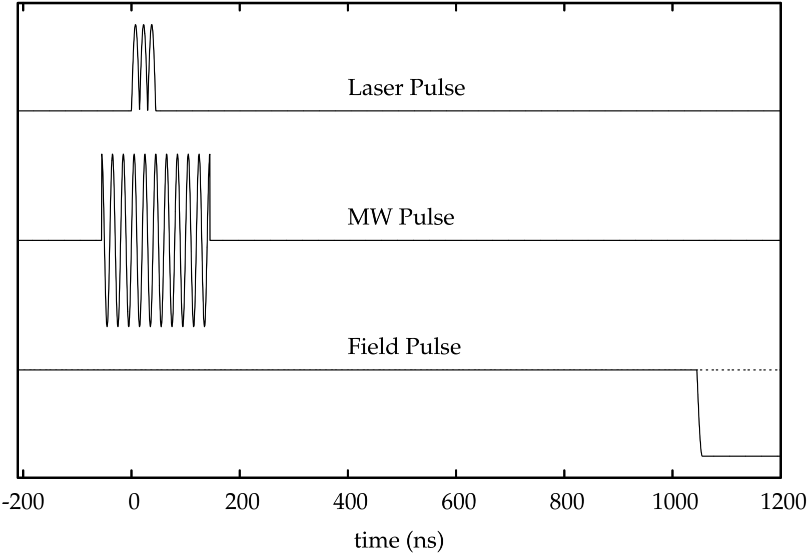
Microwave Ionization

- $< 3\,\text{mV/cm}$
- No laser linewidth requirements
- No scaled microwave frequency requirements
- 10 min/day

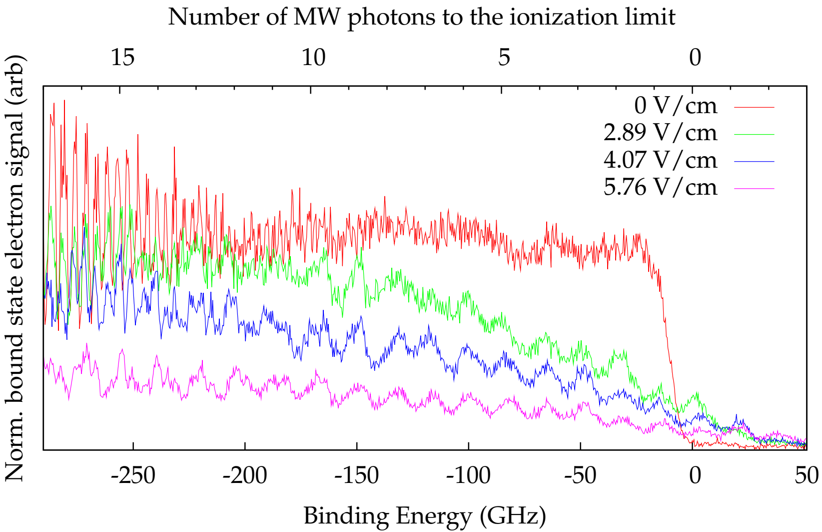
Frey *et al.*, *Rev. Sci. Instrum.* 64, 1993.

Outline

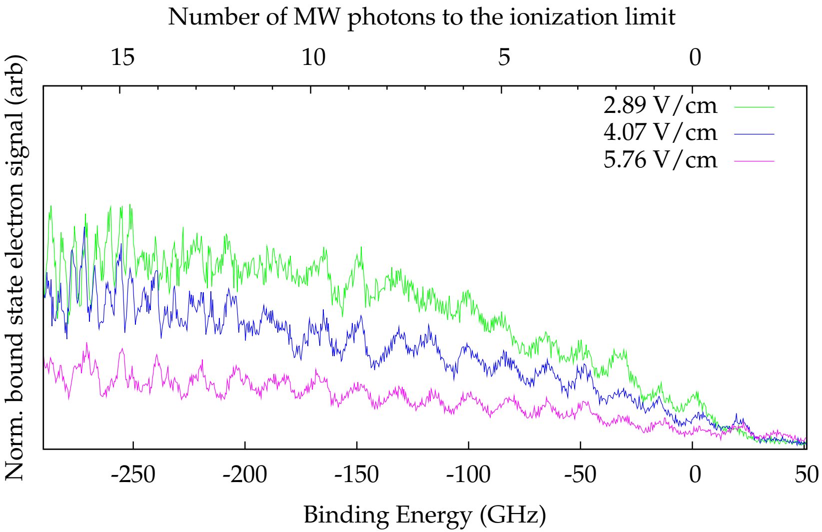
Above-Threshold Bound States - Timing



Above-Threshold Bound States

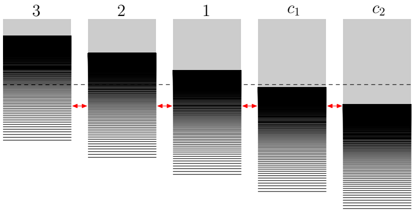


Above-Threshold Bound States

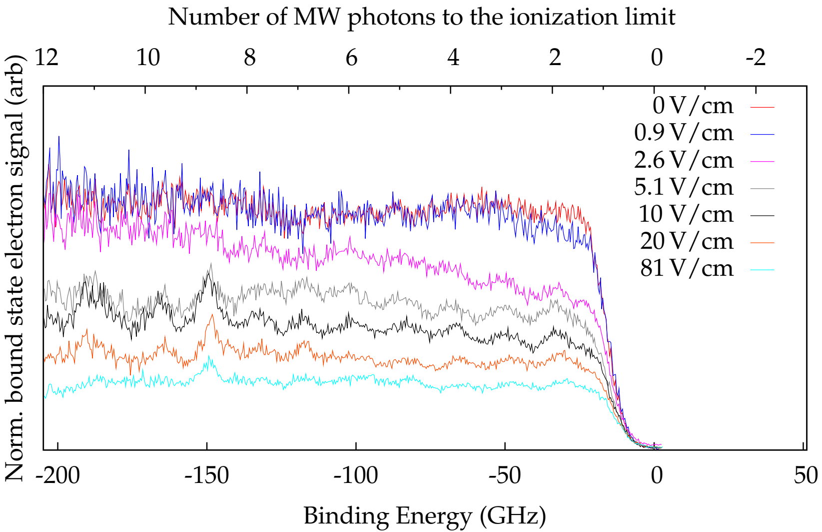


MQDT-Floquet Model

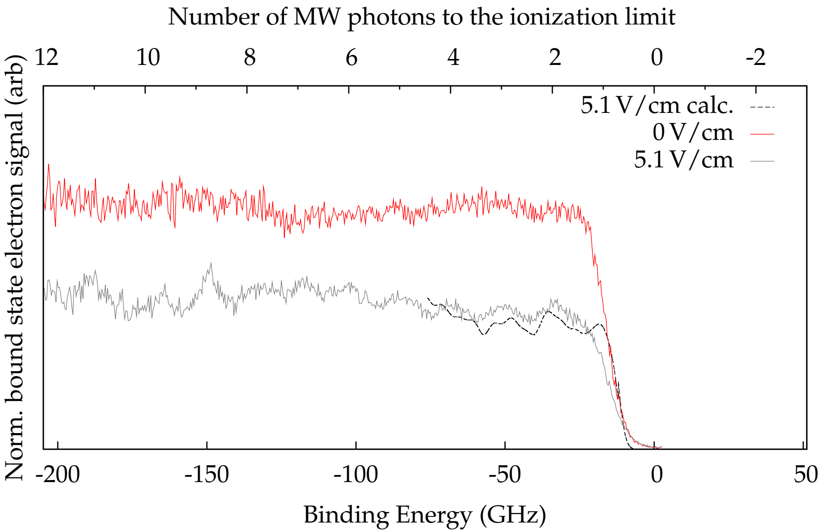
- Coherent coupling of states above and below ionization limit suggests a Multichannel Quantum Defect Theory - Floquet Model
- Floquet Theorem - Periodic perturbations yield periodic solutions



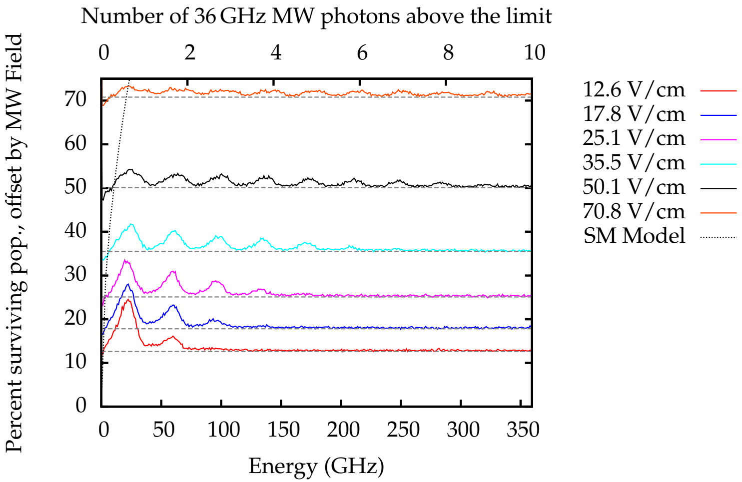
Model Comparison



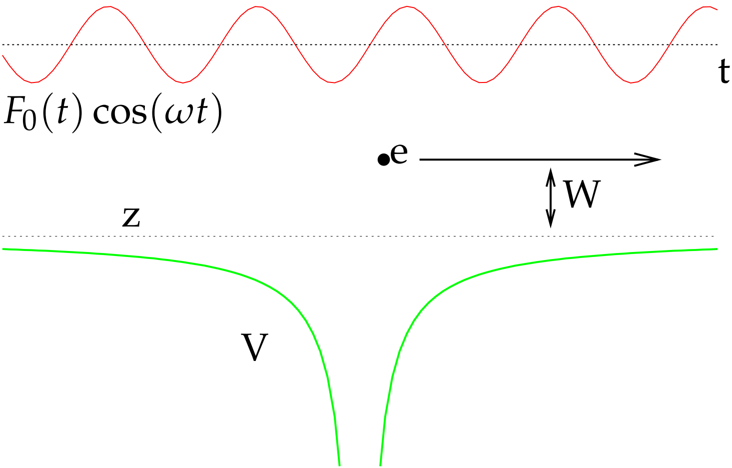
Model Comparison



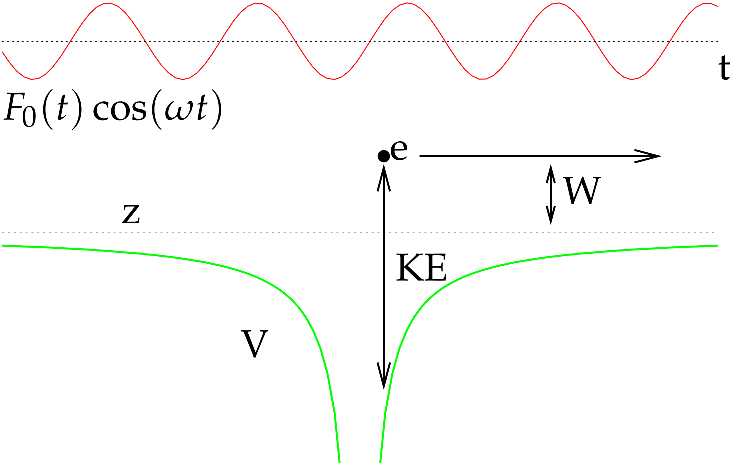
Above-Threshold Bound States



Simpleman's Model

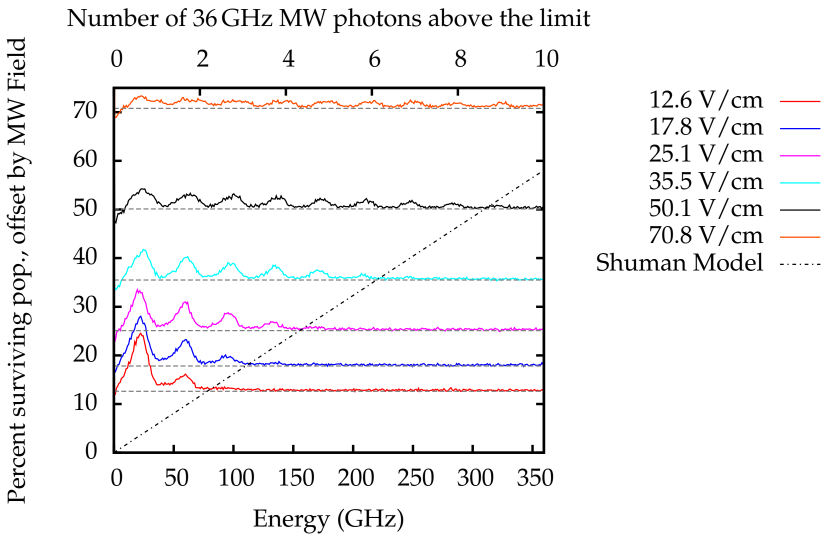


New Classical Model



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

Above-Threshold Bound States



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