Ionization of Atomic Hydrogen in Strong Infrared Laser Fields

Presented by: Brant Abeln [1]
Collaborators: Alexei Grum-Grzhimailo [2], Dan Weflen [3], Klaus Bartschat [1], Timothy Urness [1]

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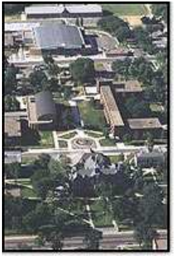
[3]University of Colorado at Boulder

May 27, 2010

DAMOP 2010

Where is Drake University?



Outline

1. Introduction
   - Ultrafast Physics
   - Laser Pulse
2. Analysis
   - Observables
   - Numerical Methods
   - Matrix Iteration
3. New Results
   - Comparisons
   - New Calculations
4. Conclusions and Outlook

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Attosecond/Femtosecond Physics

Definition

1 Attosecond is one-millionth of one millionth of one millionth (10^{-18}) of a second.

- There are twice as many attoseconds in 1 second than seconds in the **age of the universe** (15 billion years)!
- The period for the $n = 1$ orbit in atomic hydrogen is ≈ 150 attoseconds
- Attosecond laser pulses provide a window to study the details of (valence) electron interactions in atoms and molecules.
- A major role for **theory** in attosecond science is to **explain novel ways to investigate and to control electronic processes** in matter on such ultra-short time scales.

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Hydrogen Atom in Strong Infrared Laser Pulse

- Intensity range from $10^{12} - 10^{15}$ W/cm^2
- **10^{14} W/cm^2 is a million billion times stronger than the radiation that the Earth gets from the Sun directly above us on a clear day.**
- Such intensities can rip electrons away from atoms in a very different way from the standard photoeffect:
  - Multi-photon ionization
  - Above-threshold ionization
  - Field (tunnel) ionization
- Keldysh Parameter (for atomic hydrogen):

$$\gamma \approx \frac{850}{\lambda[\mathrm{nm}]\sqrt{I[10^{14}\mathrm{W/cm^2}]}}$$

$\gamma \gg 1 \rightarrow$ multi-photon ionization; $\gamma < 0.5 \rightarrow$ tunnel ionization

$\gamma \approx 1 \rightarrow$ no clear picture and treatment becomes very difficult

$\gamma = 1.06$ for $\lambda = 800\,$nm and $I = 10^{14}$ W/cm^2!!!

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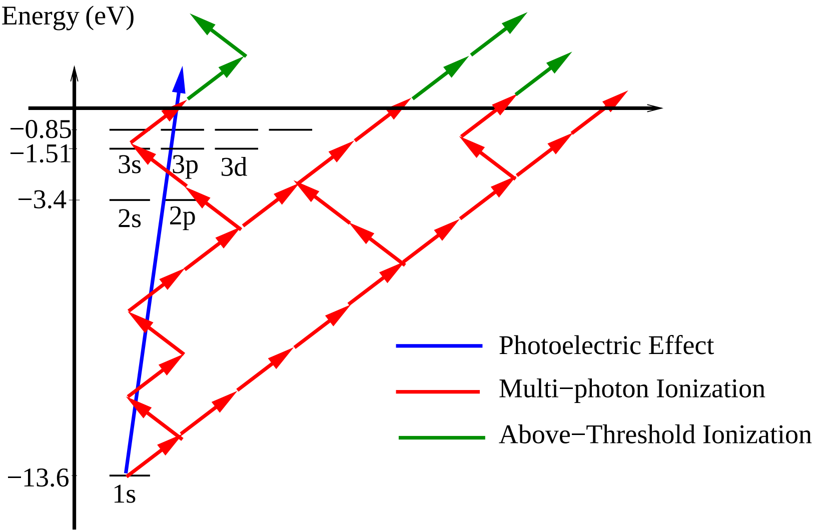
Single vs. Multi−Photon Ionization in Atomic Hydrogen



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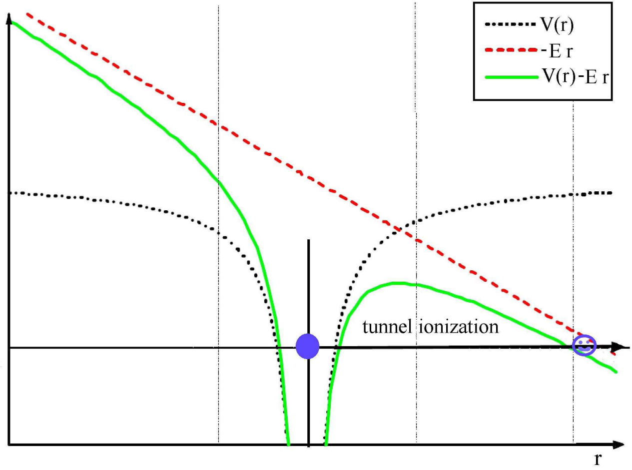
Field (Tunnel) Ionization



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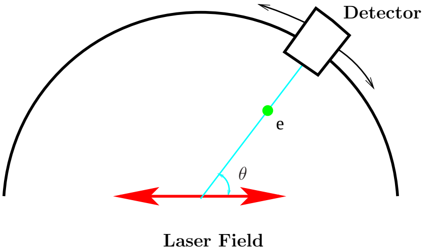
Observables

- Energy spectrum
- Angular distribution
- Time-resolved visualization

Scheme of an Angular-Distribution Experiment



Gauge

Time-Dependent Schrödinger Equation

$$\hat{H}\Psi = i\frac{\partial}{\partial t}\Psi \qquad (1)$$

Length form of electric dipole operator

$$\hat{H} = -\frac{1}{2}\nabla^2 + \frac{\ell(\ell+1)}{2r^2} - \frac{1}{r} + r\cos(\vartheta)E(t) \qquad (2)$$

Velocity form of electric dipole operator

$$\hat{H} = -\frac{1}{2}\nabla^2 + \frac{\ell(\ell+1)}{2r^2} - \frac{1}{r} - \frac{i\mathbf{A}(t)}{c}\cdot\nabla \qquad (3)$$

Propagation

- Finite difference
  - Crank-Nicholson
  - Matrix Iteration
  - Leap-Frog
- Finite elements

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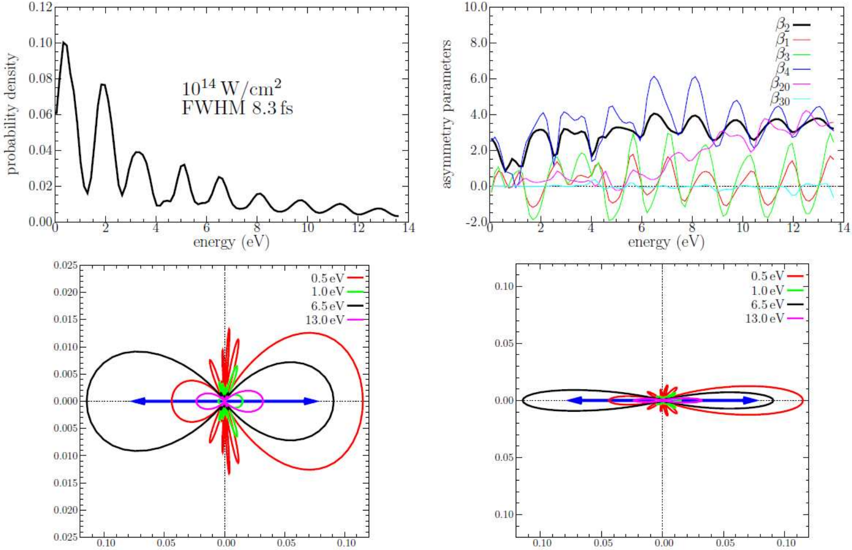

probability density
energy (eV)
10^{14} W/cm^2
FWHM 8.3 fs
asymmetry parameters
β_2
β_1
β_3
β_4
β_{20}
β_{30}
0.5 eV
1.0 eV
6.5 eV
13.0 eV

Matrix Iteration (MIM)

Crank-Nicholson Approximation

$$\Psi(\mathbf{r}, t + \Delta t) \approx \frac{1 - i\hat{H}\Delta t/2}{1 + i\hat{H}\Delta t/2}\Psi(\mathbf{r}, t) \tag{4}$$

- $1 + i\hat{H}\Delta t/2 = \hat{O}_D + \hat{O}_{ND}$
- $[1 + i\hat{H}\Delta t/2]^{-1} \approx (1 - \hat{O}_D^{-1}\hat{O}_{ND} + \hat{O}_D^{-1}\hat{O}_{ND}\hat{O}_D^{-1}\hat{O}_{ND} + \ldots)\hat{O}_D^{-1}$
- M. Nurhuda and F.H.M. Faisal (PRA **60** 4, 1999)

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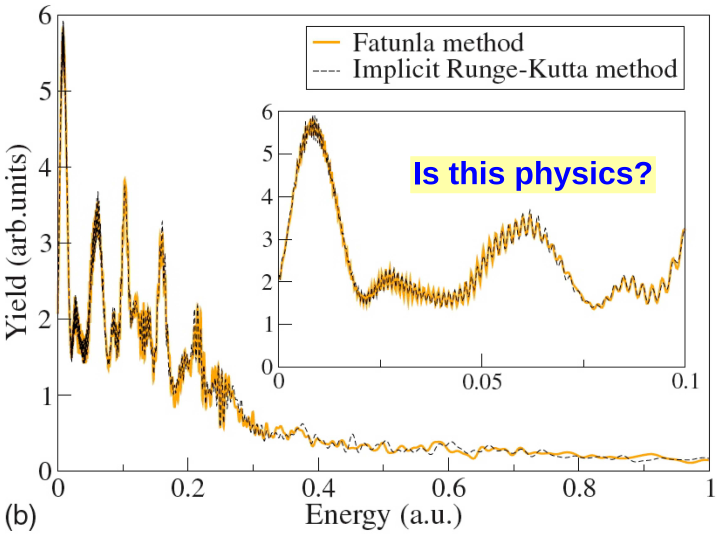
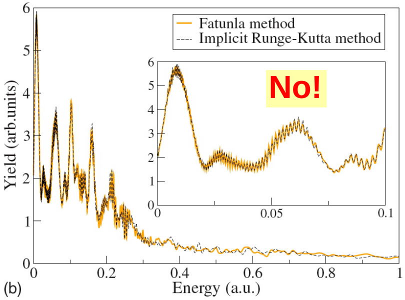
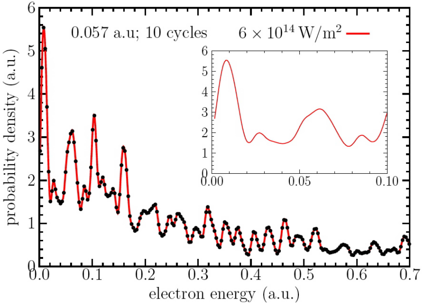
Madronero and Piraux



Comparisons

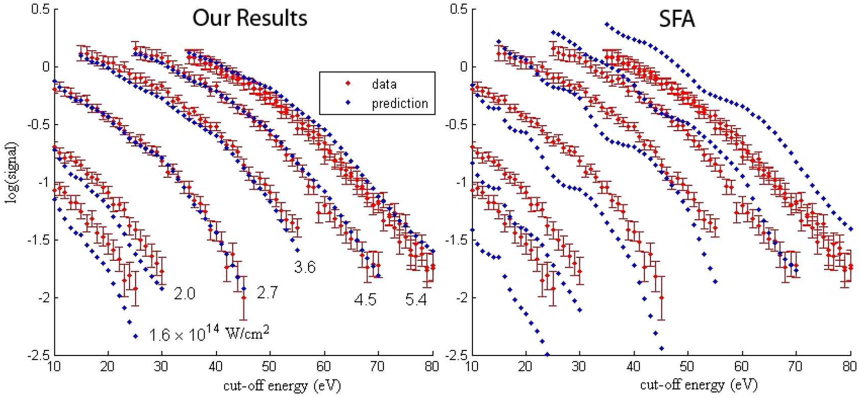
Our results show no numerical wiggles but more physics at high energies.





Comparison with Experiments

strong-field approximation is not sufficient!



Conclusions

- IR laser fields calculations are **computationally expensive**.
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- Parallelize computer code (each run takes several days on single CPU)
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More?

PHYSICAL REVIEW A **81**, 043408 (2010)

Ionization of atomic hydrogen in strong infrared laser fields

Alexei N. Grum-Grzhimailo,* Brant Abeln,† Klaus Bartschat,‡ and Daniel Weflen§
Department of Physics and Astronomy, Drake University, Des Moines, Iowa 50311, USA

Timothy Urness‖
Department of Mathematics and Computer Science, Drake University, Des Moines, Iowa 50311, USA
(Received 27 January 2010; published 14 April 2010)

We have used the matrix iteration method of Nurhuda and Faisal [Phys. Rev. A **60**, 3125 (1999)] to treat ionization of atomic hydrogen by a strong laser pulse. After testing our predictions against a variety of previous calculations, we present ejected-electron spectra as well as angular distributions for few-cycle infrared laser pulses with peak intensities of up to 10^{15} W/cm^2. It is shown that the convergence of the results with the number of partial waves is a serious issue, which can be managed in a satisfactory way by using the velocity form of the electric dipole operator in connection with an efficient time-propagation scheme.

DOI: 10.1103/PhysRevA.81.043408 PACS number(s): 32.80.Rm

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Thank You!