Ejected-Electron Angular Distribution in Multi-Photon Ionization of Atomic Hydrogen by Ultrashort High-Intensity Laser Pulses*

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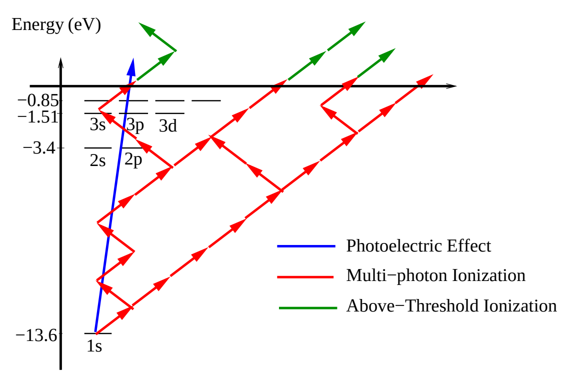
Attosecond Physics

- **1 attosecond** is defined as one-millionth of one millionth of one millionth (10^{-18}) of a second.
- There are **twice as many attoseconds in one second than there are seconds in the age of the universe (15 billion years)!**
  - Atomic unit of time:
    $$\frac{0.529\times10^{-10}\,\mathrm{m}}{3\times10^{8}\,\frac{\mathrm{m}}{\mathrm{s}}/137}\approx 24\ \text{attoseconds}$$
  - period for the $n = 1$ orbit in atomic hydrogen: ≈ 150 attoseconds
- **Attosecond laser pulses provide a window to study the details of (valence) electron interactions in atoms and molecules.**
- These capabilities promise a **revolution in our microscopic understanding of matter.**
- A major role for **theory** in attosecond science is to **elucidate novel ways to investigate and to control electronic processes in matter on such ultra-short time scales.**
- If we could **control the behavior of valence electrons**, this may open up new avenues to:
  - **manipulate the outcome of chemical reactions**
  - **make novel materials**
  - **do many other fancy things we aren't even thinking of yet**

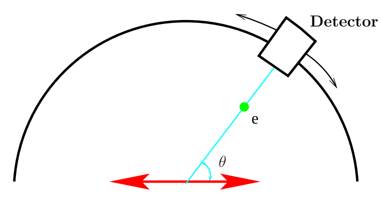
Our Project

- We study the hydrogen atom under the influence of an **intense attosecond laser pulse**.
- The intensities range from $10^{12} - 10^{15}\,\mathrm{W/cm^2}$ concentrated on a tiny area (less than $1\,\mathrm{mm}^2$).
- **$10^{14}\,\mathrm{W/cm^2}$ 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 (taught in Physics 12 and Modern Physics).
- Even if one photon does not have enough energy, several photons can collaborate in a **multi-photon ionization process**.
- **Above-threshold ionization** can give additional energy to the ejected electron.
- In **our project** we concentrate on:
  - the **angular distribution** of the ejected electrons
  - **visualization of the results**

Single vs. Multi−Photon Ionization in Atomic Hydrogen



Scheme of an Angular-Distribution Experiment



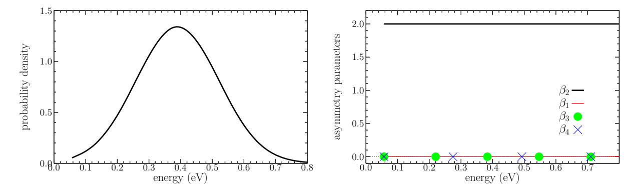
Numerical Method

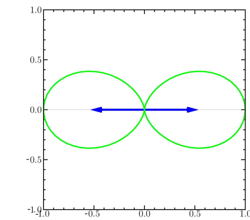
- We solve the **time-dependent Schrödinger equation**
$$i\frac{\partial\Psi(\mathbf r,t)}{\partial t} = H(\mathbf r,t)\Psi(\mathbf r,t)$$
with the atomic Hamiltonian and a **linearly polarized laser field**:
$$H(\mathbf r,t) = -\frac{\Delta}{2} + V(\mathbf r) + r\cos\vartheta\,E(t)$$
by the time-dependent close-coupling method:
$$\Psi(\mathbf r,t) = \frac{1}{r}\sum_{\ell=0}^{\infty} a_\ell(r,t)\sqrt{\frac{2\ell+1}{4\pi}}P_\ell(\cos\vartheta).$$
- The coefficients $a_\ell(r,t)$ satisfy the set of close-coupling equations:
$$i\frac{\partial a_\ell(r,t)}{\partial t} = \left[-\frac{1}{2}\frac{\partial^2}{\partial r^2} + \frac{\ell(\ell+1)}{2r^2} + V(r)\right]a_\ell(r,t) + rE(t)\sum_{\ell'=\ell\pm1}\nu_{\ell\ell',1}\,a_{\ell'}(r,t);$$
$$\ell = 0, 1, \ldots, \ell_{max}.$$
- This is a **coupled system of partial differential equations**; we sometimes have up to **100 functions**, each of which is defined on up **200,000 points** in space.
- We typically propagate the initial solution for **20,000 - 100,000 time steps**.

Observables of Interest

- **Photoelectron spectrum:**
$$\sigma(E) = \sum_\ell |Z_{E\ell}|^2,$$
where
$$Z_{E\ell} = \lim_{t\to\infty}\int_0^\infty P_{E\ell}(r)\,a_\ell(r,t)dr$$
- **Angular distribution of photoelectrons:**
$$\frac{d^2\sigma}{dE d\Omega_{\mathbf k}} = \left|\langle\,\Phi^-_{\mathbf k}(\mathbf r)|\Psi(\mathbf r,t)\,\rangle\right|^2_{t\to\infty} = \frac{\sigma(E)}{4\pi}\left[1+\sum_L \beta_L(E)\,P_L(\cos\theta)\right],$$
with the photoelectron wavefunctions of the atomic Hamiltonian:
$$\Phi^-_{\mathbf k}(\mathbf r) = 4\pi r^{-1}\sum_{\ell m} i^\ell e^{-i\delta_{E\ell}}P_{E\ell}(r)Y^*_{\ell m}(\hat{\mathbf r})Y_{\ell m}(\hat{\mathbf k}).$$
- **Anisotropy parameters:**
$$\beta_L(E) = (2L+1)\sum_{\ell\ell'} i^{\ell'-\ell}e^{i(\delta_{E\ell}-\delta_{E\ell'})}\nu_{\ell\ell',L}\,Z_{E\ell}\,Z^*_{E\ell'}\Big/\sum_\ell |Z_{E\ell}|^2,$$
where $\nu_{\ell\ell',L} = \nu_{\ell'\ell,L} = \sqrt{(2\ell+1)/(2\ell'+1)}\,(\ell 0, L0\,|\,\ell' 0)^2$.

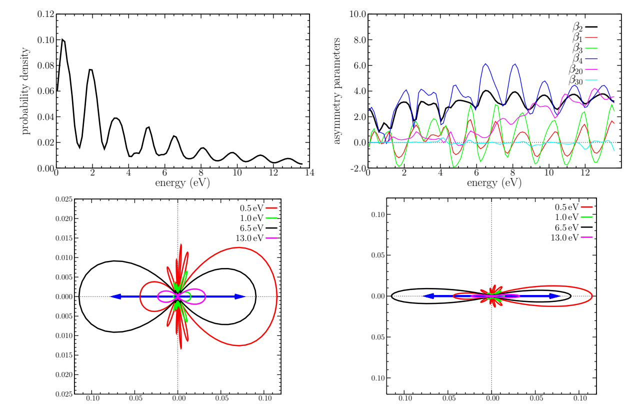
Single-Photon Ionization by Long Pulse with Energy 14.0





nice, but kind of boring

Multi-Photon Ionization by Short Pulse with Energy ≈ 1.5



Summary and Outlook

- We have learned to solve the **time-dependent Schrödinger equation** for intense-field laser-atom interactions on a numerical space-time grid.
- We can **visualize the results** as electron spectra, angular distributions, and **real-time movies**.
- **The calculations require a large amount of computational resources.**
- To check and hopefully **improve the efficiency**, we are looking at
  - different time-propagation schemes
  - parallelization of the code