Pulse-Shape Effects on the Autler-Townes Doublet in Strong-Field Ionization of Atomic Hydrogen

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Abstract

We have applied a newly developed parallelized computer code to treat the ionization of atomic hydrogen by a strong laser pulse. In particular, we studied the effect of the pulse shape, as well as the peak intensity and the central wavelength, on the theoretical results for the so-called Autler-Townes doublet. While the splitting is well known for the quasi-static case, the dynamic (time-dependent) Stark effect studied here is much less understood. The strong dependence on the laser pulse found in this work is not only surprising, but may also be a limiting factor for calibrating absolute laser intensities.

Introduction and Motivation

- Very short and intense laser pulses can be used to study the details of (valence) electron interactions in atoms and molecules.
- Typical laser intensities in this field range from $10^{15}$ to $10^{17}$ W/cm$^2$.
- $10^{17}$ W/cm$^2$ is a million billion times stronger than the radiation that the Earth receives from the Sun directly above us on a clear day.
- Such intensities can rip electrons away from atoms in several ways:
  - Two-photon ionization
  - One-photon ionization
  - Field (tunnel) ionization

The Stark Effect

- The Stark effect splits the energetically degenerate (for fixed $n$) energy levels in atomic hydrogen by the interaction with a strong external electric field.
- The energy splitting is proportional to the electric field strength.
- For linearly polarized light, we can "see" only the two $m = 0$ levels.
- These levels form the Autler-Townes doublet in the energy spectrum of the ejected electron.
- We investigate this doublet in two-photon ionization, where the central frequency of the laser is tuned in such a way that it either hits (0.375 a.u. = 10.2 eV) or just misses (0.350 a.u. = 9.5 eV) the 1s $\rightarrow$ 2p resonance transition as it is ramped up.
- Also, we vary the splitting by ramping on/off the pulse.
- Notation: $S(T) = \sin^2(\text{trapezoidal envelope at ramp-on/off})$.
- $n_1 - n_2 - n_3$: number of cycles for ramp-on-plateau-ramp-off.

Numerical Method

- We start with the Time-Dependent Schrödinger Equation
  \[ i\hbar \frac{\partial \Psi}{\partial t} = -\frac{1}{2} \nabla^2 \Psi + U(r) \Psi \]
- In the Length Form of the electric dipole operator,
  \[ H = -\frac{1}{2} \nabla^2 - \frac{1}{2} r \cos(\theta) \Omega(t) \]
- We propagate the initial wavefunction $\Psi(r, t = 0)$ in time using Finite Differences.
- We use the Crank-Nicholson Approximation
  \[ \Psi(r, t + \Delta t) = \frac{1}{2} \frac{H \Delta t/2}{1 + i H \Delta t/2} \Psi(r, t) \]
- This is an implicit method that allows for large timesteps.

Results

- The pulse shape effect only occurs at the highest intensity studied ($4.0 \times 10^{14}$ W/cm$^2$).
- It also only occurs if the pulse is ramped on/off very rapidly.
- The ramp-off is far more important than the ramp-on.

Conclusions

- The pulse shape effect only occurs at the highest intensity studied ($4.0 \times 10^{14}$ W/cm$^2$).
- It also only occurs if the pulse is ramped on/off very rapidly.
- The ramp-off is far more important than the ramp-on.
- This suggests possible interference effects between electrons ejected at different times.
- Further work is needed to explain the details.