

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

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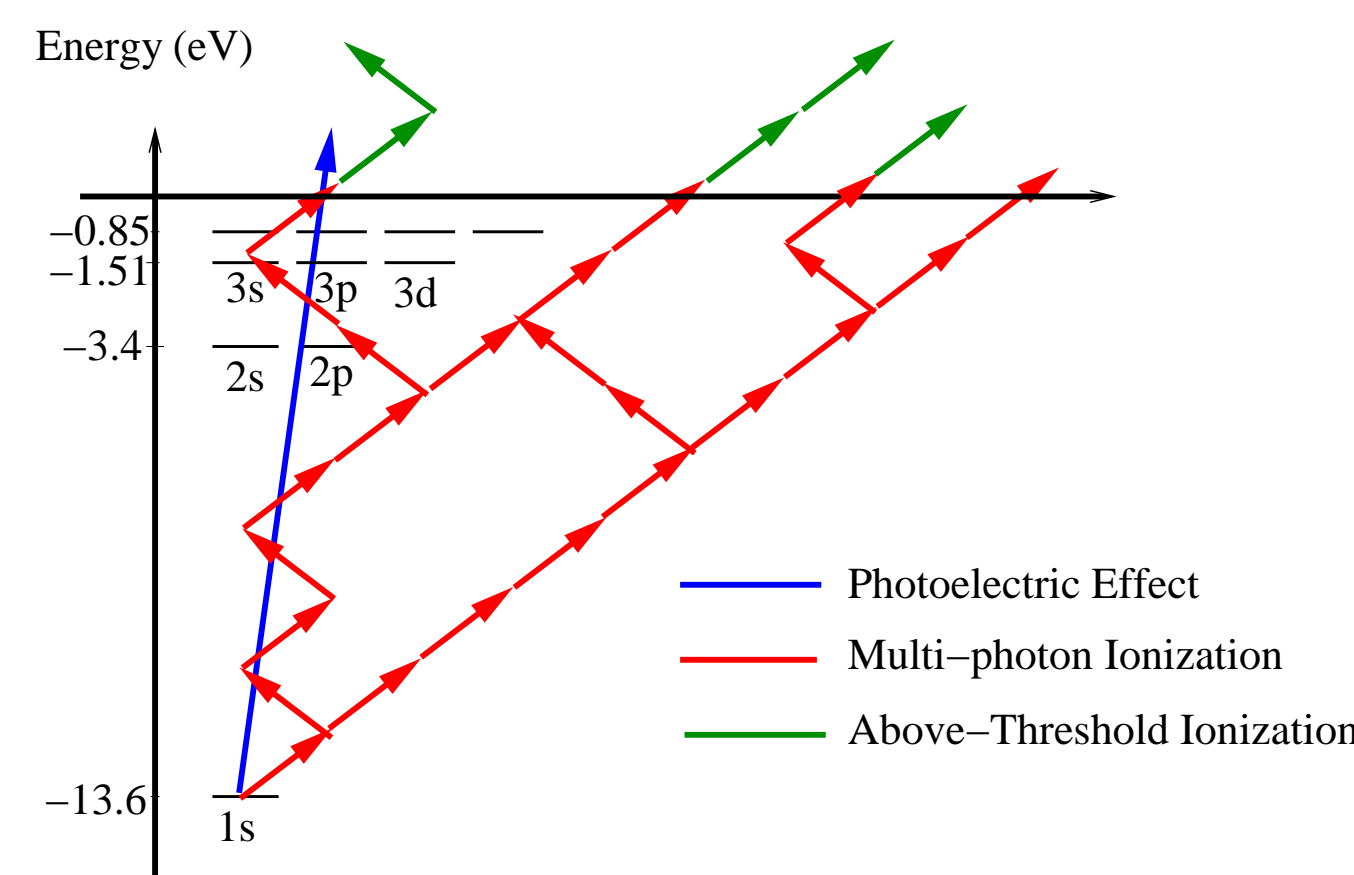
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## Abstract

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  $10^{12}$  to  $10^{15}$  W/cm<sup>2</sup>.
- $10^{14}$  W/cm<sup>2</sup> 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:
  - Multi-photon ionization
  - Above-threshold ionization
  - Field (tunnel) ionization



## The Stark Effect

$$|nlm\rangle = \begin{cases} |200\rangle \\ |210\rangle \\ |211\rangle \\ |21-1\rangle \end{cases} \begin{cases} m=0 \\ m=\pm 1 \\ m=0 \end{cases} \begin{cases} \frac{1}{\sqrt{2}}[|200\rangle - |210\rangle] \\ |211\rangle, |21-1\rangle \text{ 2 degenerate states} \\ \frac{1}{\sqrt{2}}[|200\rangle + |210\rangle] \end{cases}$$

- The **Stark effect** splits up 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  $1s \rightarrow 2s, 2p$  resonance transition as as stepping stone.
- Also, we vary the splitting by ramping on/off the pulse.
- **Notation:** S (L) =  $\sin^2$  (linear) 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**

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

- In the **Length Form** of the electric dipole operator,

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

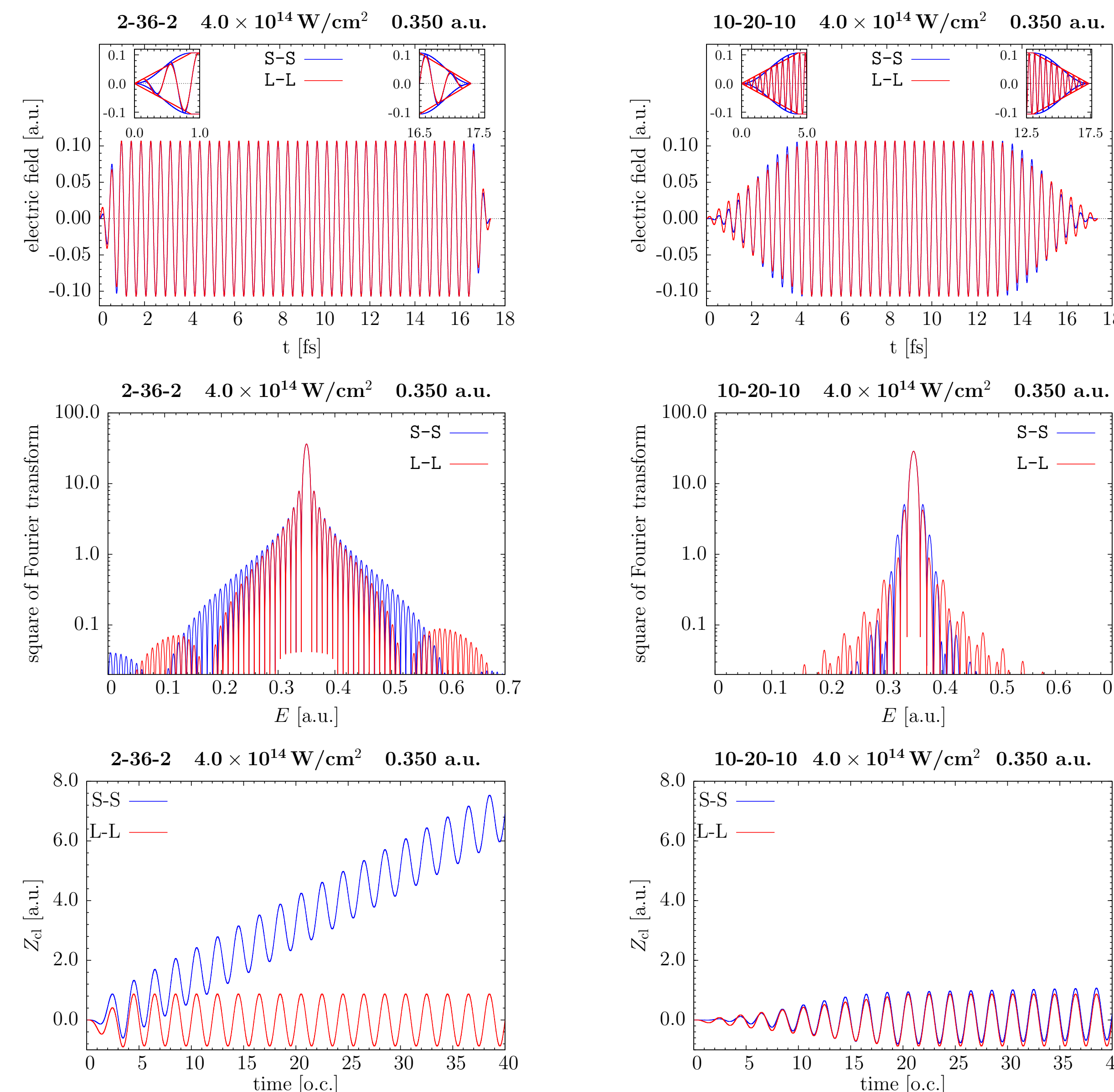
- We propagate the initial wavefunction  $\Psi(\mathbf{r}, t=0)$  in time using **Finite Differences**.

- We use the **Crank-Nicolson Approximation**

$$\Psi(\mathbf{r}, t + \Delta t) \approx \frac{1 - i\hat{H}\Delta t/2}{1 + i\hat{H}\Delta t/2}\Psi(\mathbf{r}, t) \quad (3)$$

- This is an **implicit** method that allows for large timesteps.

## Field and Displacement



## Conclusions

- The pulse-shape effect only occurs at the **highest intensity studied** ( $4.0 \times 10^{14}$  W/cm<sup>2</sup>).
- It also only occurs **if the pulse is ramped on/off very rapidly**.
- The effect is **much stronger than in the one-photon case**; see Phys. Rev. A **90** (2014) 043401.
- **A significant displacement seems to be the key factor.**
- **Further work is needed to explain the details.**

## Results

