

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

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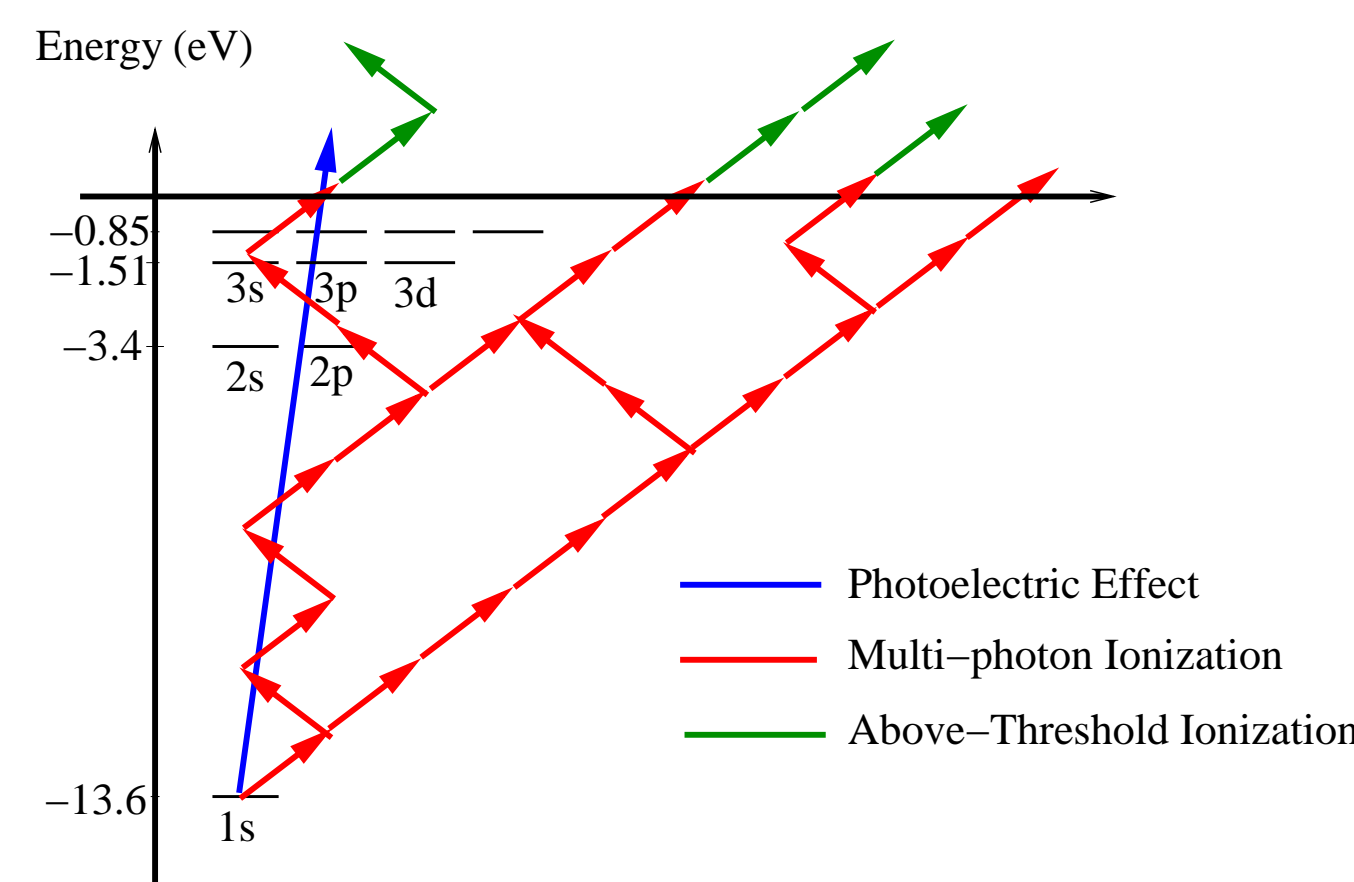
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Abstract

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/cm².
- 10^{14} W/cm² 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 (T) = \sin^2 (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**

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

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

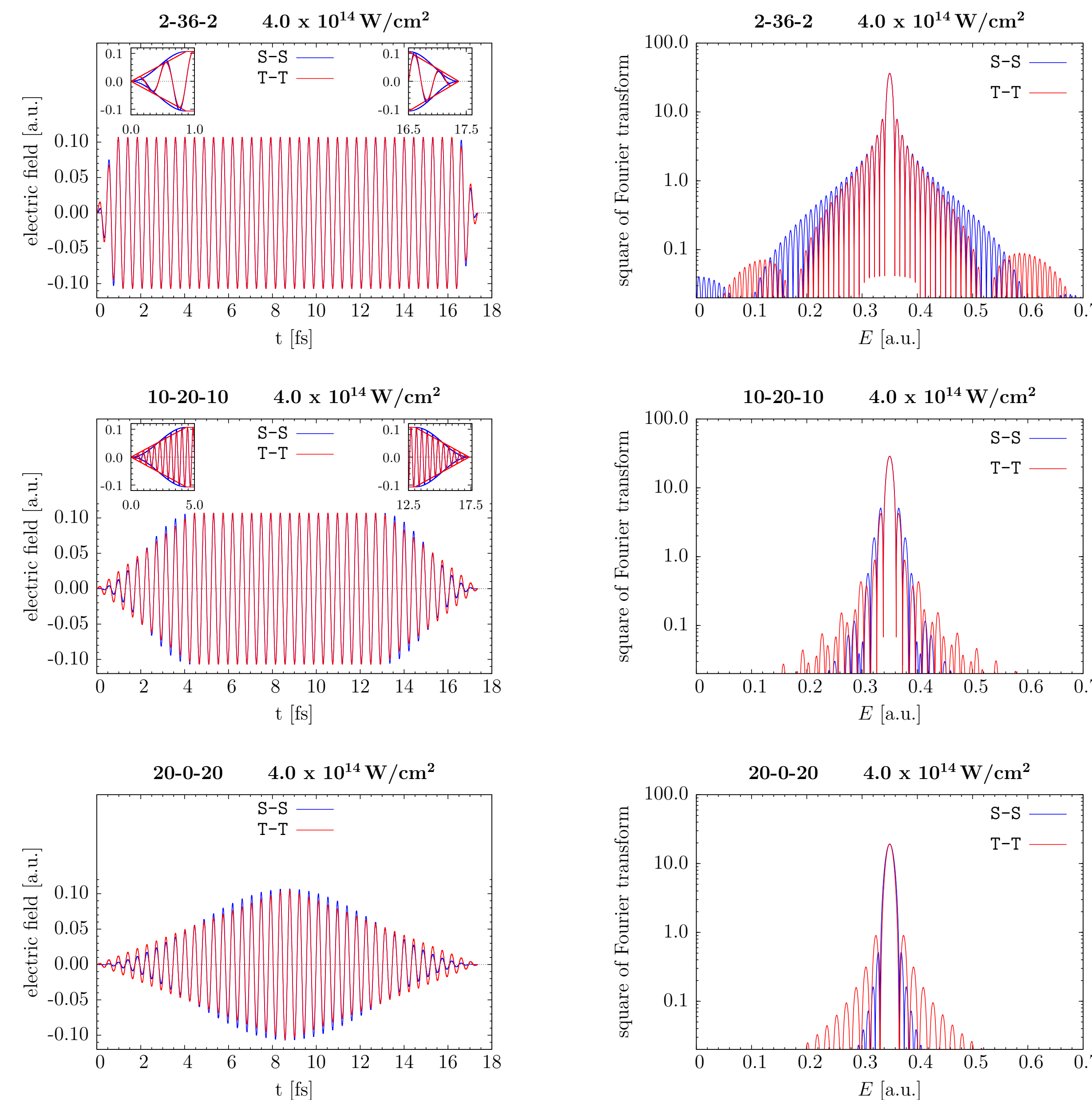
$$\hat{H} = -\frac{1}{2}\nabla^2 - \frac{1}{r} + r\cos(\vartheta)E(t) \quad (2)$$

- 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.

The Field



Conclusions

- The pulse-shape effect only occurs at the **highest intensity studied** (4.0×10^{14} W/cm²).
- 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.**

Results

