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

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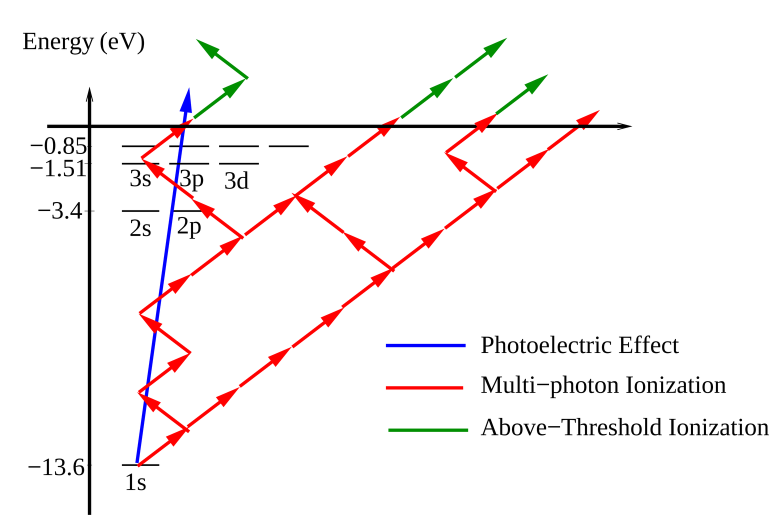
Abstract

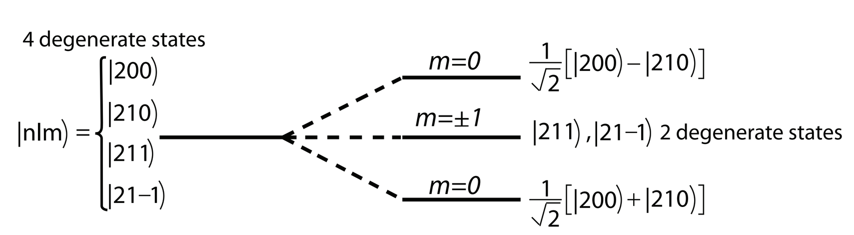
We have applied a newly developed parallelized computer code to treat the ionization of atomic hydrogen by a strong laser pulse. In particular, we studied the effect of the pulse shape, as well as the peak intensity and the central wavelength, on the theoretical results for the so-called Autler-Townes 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^{12} to 10^{15} W/cm^2.
- **10^{14} 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:
  - **Multi-photon ionization**
  - **Above-threshold ionization**
  - **Field (tunnel) ionization**



The Stark Effect



- 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 → 2s, 2p resonance transition as as stepping stone.
- Also, **we vary the splitting by ramping on/off the pulse.**

Numerical Method

- We start with the **Time-Dependent Schrödinger Equation**

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

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

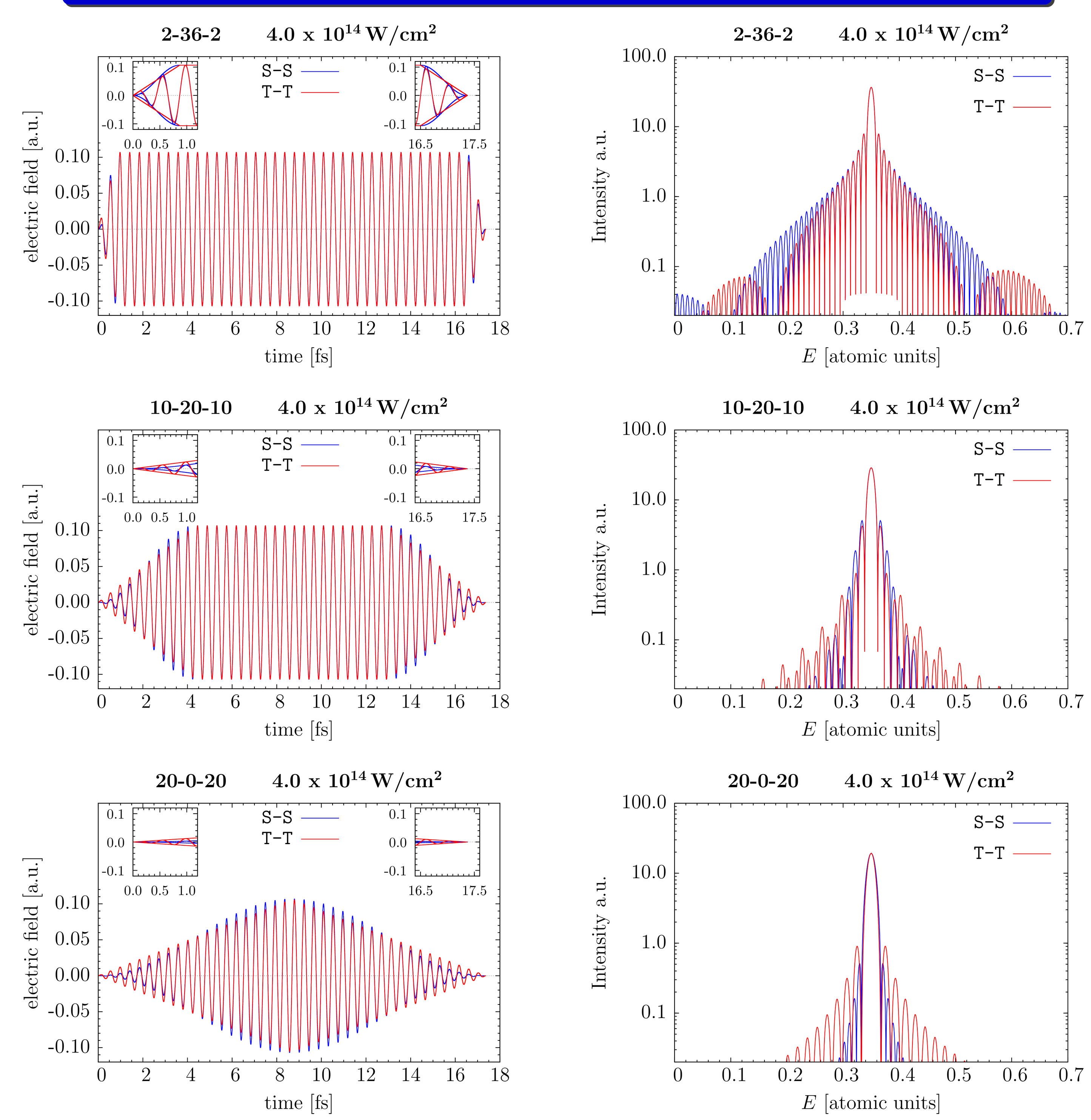
$$\hat{\boldsymbol{H}} = -\frac{1}{2}\boldsymbol{\nabla}^2 - \frac{1}{r} + r\cos(\vartheta)E(t) \qquad (2)$$

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

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

- 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/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.**

Results