Theory of atomic response in nonlinear photoconductive sampling

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Nonlinear photoconductive sampling is an experimental technique that uses strong-field ionization in atoms as a temporal gate for petahertz-bandwidth measurements of optical fields. In our attempt to create a rigorous *ab initio* theory for it, we also found that the coulombic electron-ion interaction plays a vital role in these measurements.

During nonlinear strong field ionization, an electron is set free from its parent atom due to a strong pump field via tunneling and/or multiphoton ionization process [1]. Assuming that, once freed by the pump pulse (polarized along the z axis), this electron behaves like a classical particle, a very intuitive mechanism behind NPS would involve considering its classical acceleration due the probe's electric field $a_x(t) = -eE_x(t)/m_e$.m. If the Coulomb force of the parent ion is too weak to change the electron's trajectory, the total macroscopic current [2] accounting for electrons starting their classical motion at times t_b is:

$$I_\Gamma(\tau) = \frac{e^2}{m_\mathrm{e}} \int_{-\infty}^{\infty} \Gamma(E_z(t_\mathrm{b} - \tau)) A_x(t_\mathrm{b})\, dt_\mathrm{b}, \qquad (1)$$

where $\Gamma(E_z(t_b))$ is the ionization rate [3] and $)A_x(t_b)$ the vector potential of the probe field defined by $E(t) = -A'(t)$. Naturally, the measured current changes with the delay τ of the pump's arrival with respect to the probe, giving a delay-dependent current that is proportional to the probe's vector potential.
However NPS is not limited to the mechanism described above. Successful resolution of the probe pulse only requires that the drift current responds linearly with respect to any changes in the probe field, i.e.

$$I(\tau) = \frac{-e}{m_\mathrm{e}} \langle \mathbf{p} \cdot \mathbf{e}_x \rangle = \frac{e^2}{m_\mathrm{e}} \int_{-\infty}^{\infty} G(t_\mathrm{b} - \tau) A_x(t_\mathrm{b})\, dt_\mathrm{b}. \quad (2)$$

Equation (2) encapsulates all quantum-mechanical interactions that may result in any electron motion along the x axis. While the gating function $G(t)$ is the counterpart of the ionization rate in Eq.(1), it may account for effects other than ionization. The gating function is determined entirely by the pump pulse, which ensures the linearity of the expression with respect to the probe field. We used Eq. (2) as the starting point to obtain an analytical model based on the strong-field approximation (SFA), where we were able to derive an expression for ionization rate without using the saddle-point approximation. We then compared the predictions of the SFA model to the outcomes of a numerical solution of the Time-Dependent Schrödinger Equation (TDSE), for which we used tRecX [4] As shown in Fig. 1, there are small but notable discrepancies between the delay-dependent drift currents evaluated by these two models.

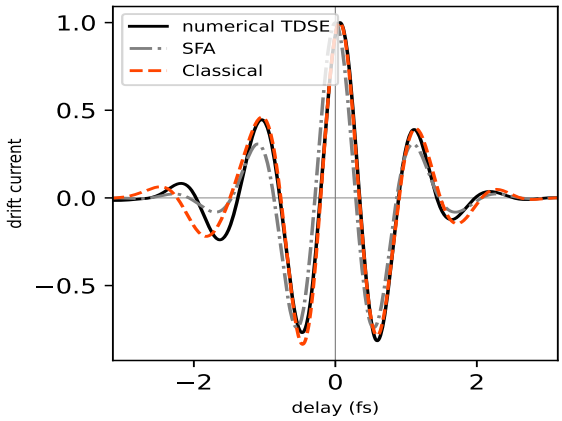

FIG. 1. delay-dependent drift current in hydrogen atom computed using SFA(blue) and numerical TDSE(black). The probe's vector potential(grey) and the pump's electric field(shaded) are provided for context.

Here, we considered atomic hydrogen. Our analysis shows that the discrepancies stems from the modification of the free electron's trajectory due to the parent ion's Coulomb potential—an effect that is entirely absent in SFA.

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