Analytic Theory of Few-Cycle XUV Attosecond Pulse Photoionization of Atoms

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Synopsis The doubly differential probability (DDP) for ionization of an atom by a few-cycle attosecond XUV pulse is analyzed using first and second orders of time-dependent perturbation theory (PT). We factorize the carrier-envelope phase (CEP) and angular dependence of the DDP for an initial bound S-state and analyze the general properties of CEP-induced asymmetries in photoelectron angular distributions (PADs) for an XUV pulse with *arbitrary* polarization and shape.

The importance of carrier-envelope phase (CEP) effects for few-cycle pulses has been demonstrated for IR pulses both experimentally and theoretically [1], and several theoretical works on CEP effects for XUV attopulses have appeared, e.g. [2, 3]. For few-cycle IR pulses, typical intensities lie in the non-perturbative regime, thus requiring appropriate analytical methods (e.g., SFA) or direct numerical solution of the TDSE. These methods have also been applied to the case of few-cycle XUV pulses. However, the clearest physical insight is provided by perturbation theory (PT), which is highly accurate for describing the interaction of atomic systems with XUV pulses up to $I_0 \sim 10^{15} - 10^{16}$ W/cm^2 [4].

In this work the doubly differential probability for ionization of an atom by a few-cycle attosecond XUV pulse is analyzed using first and second orders of time-dependent PT:

$$d^2W/(dEd\Omega) = p\big[|A_1|^2 + 2\mathrm{Re}(A_1^* A_2)\big]. \quad (1)$$

Here A_1 and A_2 are the first and second order amplitudes for ionization from a bound state of energy E_0 to a final state with energy $E = p^2/2$. The term $2\mathrm{Re}(A_1^* A_2)$ is non-zero only in the case of ionization by a short pulse, as it describes interference of the first and second orders of PT leading to the same final state. We factorize the CEP and angular dependence of $d^2W/(dEd\Omega)$ for an initial bound S-state and analyze the general properties of CEP-induced asymmetries in photoelectron angular distributions (PADs) for an XUV pulse with *arbitrary* polarization and shape. For the case of a linear polarization, our general parametrization gives:

$$d^2W/(dEd\Omega) = \alpha_0 I_0 \cos^2\theta + I_0^{3/2}\mathrm{Re}\{[\alpha_1 \cos\theta + \alpha_2 \cos^3\theta]\exp(i\phi)\}, \quad (2)$$

where θ is the angle between the polarization axis and electron momentum $\mathbf{p}$, and α_0, α_1, α_2 are atom-specific dynamical parameters dependent on both pulse shape and energy. The interference term changes sign when $\theta \to \pi - \theta$, leading to an asymmetry in the PAD and providing a means to determine the CEP of the pulse by measuring the PAD. Comparisons of PT results with numerical solutions of the TDSE [3] for the hydrogen atom show excellent agreement, including the $I_0^{3/2}$ dependence of CEP effects in (2) found numerically in Ref. [3]. Note also that the CEP dependence in (2) is in agreement with the general parametrization of CEP effects presented in Ref. [5]. The interference term in (1) also leads to dichroism in the PAD, i.e. dependence on the sign of the degree of circular polarization ξ of an attopulse.

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