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

E.A. Pronin∗1, M.V. Frolov†, N.L. Manakov†, Anthony F. Starace∗∗2

∗Dept. of Physics & Astronomy, The University of Nebraska, Lincoln, NE 68588-0111, USA
†Department of Physics, Voronezh State University, Voronezh 394006, Russia

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 \( I_0 \sim 10^{15} - 10^{16} \text{ W/cm}^2 \) [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:

\[
d^2W/d(Ed\Omega) = p[A_1^2 + 2\text{Re}(A_1^*A_2)].
\]

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 \( 2\text{Re}(A_1^*A_2) \) 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:

\[
d^2W/d(Ed\Omega) = \alpha_0 I_0 \cos^2 \theta \\
+ \frac{I_0^{3/2}}{4} \text{Re}\{[\alpha_1 \cos \theta + \alpha_2 \cos^3 \theta] \exp(i\phi)\},
\]

where \( \theta \) is the angle between the polarization axis and electron momentum \( p \), and \( \alpha_0, \alpha_1, \alpha_2 \) are atom-specific dynamical parameters dependent on both pulse shape and energy. The interference term changes sign when \( \theta \rightarrow \pi - \theta \), 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 \( \xi \) of an attopulse.

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References


1E-mail: pronin@unlserve.unl.edu
2E-mail: astarace1@unl.edu