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Coulomb effect on the left–right asymmetry in photoelectron emission with few-cycle laser pulses

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ABSTRACT

We theoretically study the strong-field ionization of hydrogen atom in few-cycle laser pulses with the Coulomb–Volkov distorted-wave approximation (CVA) theory and focus on the role of the Coulomb potential in the left–right asymmetry of the photoelectron yields along the laser polarization direction, by comparing the CVA results with strong-field approximation (SFA) simulations. Our simulations show that the carrier-envelope phase (CEP) dependent asymmetry in CVA deviates from the SFA simulation and more interestingly, there is a phase shift of the asymmetry curve as a function of CEP when the laser intensity increases, contrary to what is expected in the SFA simulations. In terms of the simple man's model, the deviation of the asymmetry curves in CVA from the SFA simulations is attributed to the significant influence of the Coulomb potential on the forward rescattering electron which will get close to the core again after tunneling ionization. Furthermore, the laser-intensity dependence of the phase shift of the asymmetry curves in CVA is elucidated.

1. Introduction

Advances in ultrafast laser technology have opened the door to the new region of the intense laser-matter interaction. For example, the generation of the few-cycle femtosecond laser pulses provides a powerful tool to understand and control the electron dynamics in atom and molecule on its natural timescale of attosecond [1]. For the few-cycle laser pulses, the temporal shape of the laser electric field depends on the so-called carrier-envelope phase (CEP) [2,3]. By varying the CEP of the field, it allows one to control the electric field of the few-cycle laser pulses and thus, to steer the emission direction of photoelectrons. The primary phenomena related to the CEP effect were observed in the emission of photoelectrons with few-cycle laser pulses [4]. Later, the few-cycle laser pulses were used in the investigations of high harmonic generation (HHG) [5–7], above-threshold ionization (ATI) [8–11], and nonsequential double ionization (NSDI) [12,13]. Recently, the few-cycle laser pulses have been used to control electron localization in the dissociative ionization of molecules [14–16].

Due to the significant CEP dependence of the strong-field ionization processes, the precise measurement of the CEP becomes a crucial point for the application of the few-cycle laser pulses. The first measurement of the CEP of the few-cycle pulses was performed in a "stereo-ATI" experiment [8] by detecting the left–right asymmetry of photoelectron yields with two opposing detectors placed along the laser polarization direction. The asymmetry of the photoelectron yields emitted along the opposite directions origins from the spatially asymmetric electric fields of the few-cycle laser pulses. In the measurement of the absolute phase of the few-cycle laser pulses, the high-energy photoelectrons are usually used to analyze the left–right asymmetry of photoelectron yields. One reason is that the asymmetry of the high-energy electrons is more sensitive to the CEP than that of the low-energy electrons. For example, Paulus et al. [8] experimentally showed that the maximal ratio of the left–right asymmetry of photoelectron yields along the polarization direction can reach 5 for the high-energy electrons, but it is only about 1.1 for the low-energy electrons. Another reason is that the influence of the residual Coulomb potential on the high-energy electron is relatively weak in comparison with the low-energy electron. Several works [17,18] have shown that the left–right asymmetry of photoelectron yields can be well described with strong-field approximation (SFA) theory which completely neglects the Coulomb potential effect on the ionized electron. On the contrary, recent experiments show that for the low-energy electron, the influence of the Coulomb potential will cause lots of unusual strong-field phenomena, e.g., the low-energy structure (LES) in the photoelectron energy spectra [19,20],

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the double-hump structures in the low-energy part of the momentum distributions [21], the cusp in the transverse electron momentum distribution [22], and the asymmetry in momentum distributions with elliptical laser fields [23]. Therefore, due to the significant Coulomb potential effect on the low-energy electrons, the high-energy photoelectrons are usually used to measure the CEP of the few-cycle laser pulses for simplicity.

On the other hand, how the residual Coulomb potential affects the left–right asymmetry of the photoelectron yields, especially for the low-energy electrons, has not been well investigated. Chelkowski et al. [24] studied the left–right asymmetry of the total photoelectron yields by solving the time-dependent Schrödinger equation (TDSE) nonperturbatively. They found that the CEP dependent left–right asymmetry clearly deviates from the SFA simulation and moreover, there is a phase shift of the asymmetry curve as the laser intensity increases in the tunneling regime (Keldysh parameter $\gamma < 1$ [25]), contrary to what is expected in the SFA simulations. Similar results about the intensity-dependent asymmetry curves in few-cycle laser pulses have also been observed in the TDSE simulations in Ref. [26]. The deviation of the CEP dependent left–right asymmetry in the TDSE from the SFA simulations is attributed to that the SFA theory neglects the Coulomb attraction on the ionized electron [24,26,27]. However, it is still unknown how the Coulomb potential leads to the change of the left–right asymmetry of the photoelectron yields.

Recently, a modified SFA theory, i.e., Coulomb–Volkov distorted-wave approximation (CVA) theory [28], in which the Volkov state used in SFA is replaced by a Coulomb–Volkov state, provides an efficient way to explore the Coulomb potential effect in photoionized electron dynamics. For example, Arbó et al. [29] showed that the CVA simulation of a bouquet-shape structure near threshold region of the doubly differential electron momentum distribution is well consistent with the exact TDSE calculations [30], pointing out the importance of the Coulomb correction in CVA related to the emission angle of the photoelectron. Moreover, a cusp structure in the transverse electron momentum spectra [22] is well reproduce in the CVA simulation [29], which is attributed to the attraction of the Coulomb potential, also called Coulomb focusing. Note that the CVA theory has also been employed to simulate the Coulomb effect on the asymmetry in photoelectron emission by the few-cycle laser pulses [29]. The phase of the asymmetry curve exhibits relatively stable when the laser intensity increases since the laser intensity is in the regime with $\gamma > 1$ [24]. To understand the phase shift of the asymmetry curve shown in the TDSE calculations, the higher laser intensity is needed in the CVA simulations [24].

In this paper, we theoretically investigate the strong-field ionization of hydrogen atom in few-cycle laser pulses with CVA theory in the tunneling regime ($\gamma < 1$) and the focus of the paper is, by comparing the CVA results with the SFA simulations, to elucidate the role of the Coulomb potential in the left–right asymmetry of the photoelectron yields along the laser polarization direction. Our results exhibit that the left–right asymmetry in CVA as a function of CEP shows a clear sin-like curve and more interestingly, the CEP dependent asymmetry curve deviates from the SFA simulation and a phase shift is found when the laser intensity increases. In terms of the simple man's model [31,32], the deviation of the asymmetry curves in CVA from the SFA simulations origins from the significant influence of the Coulomb potential on the forward rescattering electron which will return to the core after the tunneling and furthermore, the laser-intensity dependence of the phase shift of the asymmetry curves in CVA is elucidated.

This paper is organized as follows. In Sec. 2, we briefly recall the SFA and CVA theories. Subsequently, we present the SFA and CVA simulations of the asymmetry coefficient as a function of CEP at two different laser intensities and furthermore, discuss how the Coulomb potential leads to the change of the left–right asymmetry. Finally, in Sec. 4 our conclusions are given. Atomic units (a.u.) are used throughout unless otherwise indicated.

2. Theoretical methods

In our numerical simulations, the electric-field vector of the few-cycle laser pulse is given by

$$\mathbf{E}(t) = E_0 \sin^2\left(\frac{\omega t}{2N_C}\right)\cos(\omega t + \varphi)\hat{\mathbf{e}}_z, \tag{1}$$

where ω and E_0 are the laser frequency and peak electric field amplitude, respectively, φ is the CEP of the few-cycle laser pulse, and N_C is the number of the optical cycles in one laser pulse from the time $t = 0$ to T with $T = (2\pi/\omega)N_C$.

2.1. SFA theory

In the SFA theory, the transition amplitude of the bound electron from the initial state $|\psi_0(t)\rangle$ to the Volkov state $|\psi_{\mathbf{p}}^{(\mathrm{V})}(t)\rangle$ with the momentum $\mathbf{p}$ is given by [33–35]

$$M_{\mathbf{p}}^{\mathrm{SFA}} = -i\int_{-\infty}^{\infty} dt\,\langle\psi_{\mathbf{p}}^{(\mathrm{V})}(t)\mid \mathbf{r}\cdot\mathbf{E}(t)\mid\psi_0(t)\rangle, \tag{2}$$

where $\mathbf{r}\cdot\mathbf{E}(t)$ is the laser-field-electron interaction in length gauge and dipole approximation. The Volkov state $|\psi_{\mathbf{p}}^{(\mathrm{V})}(t)\rangle$ describes a free electron in the time-dependent electric field,

$$\psi_{\mathbf{p}}^{(\mathrm{V})}(t) = \frac{\exp\left[i(\mathbf{p}+\mathbf{A}(t))\cdot\mathbf{r}\right]}{(2\pi)^{3/2}} \times \exp\left[-i\int^{t} dt'\,\frac{[\mathbf{p}+\mathbf{A}(t')]^2}{2}\right] \tag{3}$$

where $\mathbf{A}(t) = -\int_{-\infty}^{t}\mathbf{E}(\tau)d\tau$ is the vector potential of the laser field. Inserting Eq. (3) into Eq. (2), the transition amplitude can be written as

$$M_{\mathbf{p}}^{\mathrm{SFA}} = -i\int_{0}^{T} dt\,\exp\left[iS(\mathbf{p},t)\right]\langle\mathbf{p}+\mathbf{A}(t)\,|\mathbf{r}\cdot\mathbf{E}(t)|\,\psi_0(r)\rangle \tag{4}$$

where

$$S(\mathbf{p},t) = -\frac{1}{2}\int^{t} d\tau\,[\mathbf{p}+\mathbf{A}(\tau)]^2 + I_p t \tag{5}$$

is the semiclassical action and I_p denotes the ionization potential. In this work, we study the strong-field ionization of hydrogen atom in the few-cycle laser pulses with the ground state $\psi_0(r) = e^{-r}/\sqrt{\pi}$ and the ionization potential $I_p = 0.5$ a.u.

2.2. CVA theory

Instead of the Volkov state used in the SFA theory, a Coulomb–Volkov state is used to describe the ionized electron in the combination of the laser field and the Coulomb potential in the CVA theory,

$$\psi_{\mathbf{p}}^{(\mathrm{CV})}(t) = \psi_{\mathbf{p}}^{(\mathrm{V})}(t)\kappa_C(Z_T,\mathbf{p},\mathbf{r}), \tag{6}$$

which is firstly proposed by Jain and Tzoar [28] and later extensively used in the strong-field ionization [36]. In comparison with the Volkov state, there is an additional Coulomb factor $\kappa_C(Z_T,\mathbf{p},\mathbf{r})$ in the Coulomb–Volkov state. Here, $\kappa_C(Z_T,\mathbf{p},\mathbf{r}) =$