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Coulomb potential effects in strong-field photoelectron holography with a midinfrared laser pulse

G L Shi¹, J W Xu¹, H T Zhang¹, C Lin¹, X H Song¹, J Chen^{2,3} and W F Yang¹

¹Department of Physics, College of Science, Shantou University, Shantou, Guangdong 515063, China

²Center for Applied Physics and Technology, Peking University, Beijing 100084, China

³ Institute of Applied Physics and Computational Mathematics, P. O. Box 8009, Beijing 100088, China

E-mail: wfyang@stu.edu.cn

Abstract. A profound ringlike pattern coming from the interplay between the intra- and the intercycle interference of electron trajectories can be observed in the deep tunneling ionization regime, and an appropriate experimental condition for the observation of the photoelectron holography was provided.

1. Introduction

Coulomb potential effects in photoelectron holography (PH) with midinfrared wavelength laser pulses are investigated by solving numerically the time-dependent Schrödinger equation (TDSE) and using a generalized quantum-trajectory Monte Carlo (GQTMC) method. It is found that the Coulomb potential plays a key role in the interference of PH, especially in the parameter region $\gamma \sim 1$ ($\gamma = \sqrt{\frac{I_p}{2U_p}}$ is the Keldysh parameter, U_p is the ponderomotive energy or the averaged quiver energy of a free electron in the laser field, $U_p = \frac{I}{4\omega^2}$, where I is the laser intensity and ω is the angular frequency, and I_p is the ionization potential) in which the potential barrier combining with the laser and Coulomb field changes drastically. The interference structure of PH can be observed in the photoelectron momentum distribution (PMD) in the tunneling regime, where $\gamma < 1$ either with or without considering the long-range Coulomb potential. The interference structure of PH cannot be observed without the long-range Coulomb potential in the parameter region, where $\gamma \sim 1$. With the help of the GQTMC simulation, we show that the wavepacket dynamics of rescattered electrons can be influenced strongly by the Coulomb field. The rescattered electrons miss the first return to the parent ion without the long-range Coulomb potential. Therefore, the interference between the direct and rescattered electron wavepackets can hardly occur without the driving of the Coulomb force, which agrees well with the TDSE simulation. Moreover, the interference structures in PMD for different laser parameters provide the information of electron dynamics with sub-optical-cycle resolution.



2. Discussion and Results

Atomic photoionization under intense laser irradiation is a fundamental process in strong-field light-matter interactions. Since above-threshold ionization (ATI) was firstly observed more than thirty years ago [1], a series of experimental discoveries together with subsequent theoretical efforts have greatly advanced our understanding of the underlying physics of the interaction between atoms and intense laser fields [2, 3]. Recently, holographic *fork* structures have been observed in the photoelectron momentum distribution of ionized metastable xenon atoms [4]. This photoelectron holography, which records underlying electron dynamics on a sub-cycle time scale, offers opportunities to extract information of core and electron dynamics encoded in the interference patterns in the PMD [5–11].

Calculations based on numerical solution of the time-dependent Schrödinger equation can quantitatively reproduce well the experimental observations of PH [4–11]. However, it is difficult to explore the underlying physics. Very recently, a quantum-trajectory Monte Carlo (QTMC) method was developed from the classical-trajectory Monte Carlo method [12–14] by including quantum interference effect after the tunneling [15]. However, the QTMC method, which treats ionization rate with the quasistatic approximation, is only rigorously valid in the limit $\gamma \ll 1$ [16]. Here we develop a generalized QTMC (GQTMC) method [17, 18] which could be applied to relatively large region of the Keldysh parameter γ . This method provides an efficient way to probe the nonadiabatic effects, Coulomb potential effect, and unravel the underlying ultrafast electron dynamics encoded in the interference structures in the PMDs.

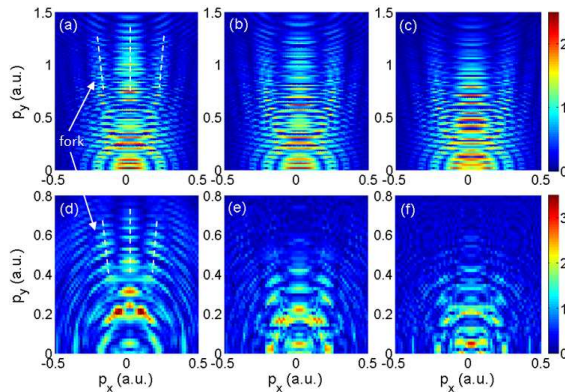


Figure 1. Photoelectron momentum distribution for ionization of Xe by a laser pulse with 1700 nm, (a), (b), and (c) 7.0×10^{13} W/cm², and $\gamma = 0.55$, and (d), (e) and (f) 1.2×10^{13} W/cm², and $\gamma = 1.33$, calculated by the TDSE with (a) and (d) the full long-range Coulomb potential, (b) and (e) the modified potential with $r_c = 5$ a.u. and (c) and (f) the modified potential with $r_c = 2$ a.u.

We have carried on the numerical calculation by solving the TDSE [19–21]. Firstly, we compare the 2D PMDs in two different parameter regions by solving the TDSE with different Coulomb potential models: figures 1 (a) and (d) using the long-range Coulomb potential of Xe atom; (b) and (e) using the modified potential with cutoff radius $r_c = 5$ a.u. and (c) and (f) $r_c = 2$ a.u. For the calculation in the upper panel of figure (1), the laser pulse has a wavelength of 1700 nm, and peak intensity of 7.0×10^{13} W/cm² with Keldysh parameter of 0.55, which would be considered to be in the tunneling ionization regime. For the calculation in the lower panel of figure (1), the laser has same wavelength and a large peak intensity of 1.2×10^{13} W/cm². The Keldysh parameter is 1.33 which is slightly larger than 1.

It can be clearly seen that the influence of the Coulomb potential on the PMDs is different in different parameter regions. In the tunneling regime ($\gamma = 0.55$), the *fork* structure which has been identified as the typical interference structure of the PH in previous theoretical and experimental results [22, 23] can be clearly observed both in the long-range Coulomb potential and the short-range potential results. The interference between the rescattered and direct electron wavepackets in the tunneling regime cannot be erased by reducing the cutoff radius

of the potential, which suggests that: (a) when the electron appears in the continuum it is under the strong influence of the laser electric field, (b) the electron has a large kinetic energy when it is driven back to the nucleus by the strong laser field, and (c) the atomic potential force can be neglected comparing with the force of the laser electric field. These agree with the physical mechanism of the tunneling ionization and recollision processes in strong laser fields [24]. For the parameter region where $\gamma \sim 1$, the *fork* interference structure can be identified in PMD with the full long-range Coulomb potential (see figure 1(d)). However, the cutoff energy of the *fork* interference structure becomes smaller with decreasing cutoff radius of the Coulomb potential in figures 1(e) and (f). When the cutoff radius is reduced to $r_c = 2$ a.u., the PH interference structure can hardly be observed (see figure 1(f)). As a result, we see a substantial change of the interference structure in PMDs by modifying the Coulomb potential, which indicates that the Coulomb potential plays an essential role in the electron dynamics in the parameter region where $\gamma \sim 1$. In order to understand this critical effect of Coulomb potential on the interference

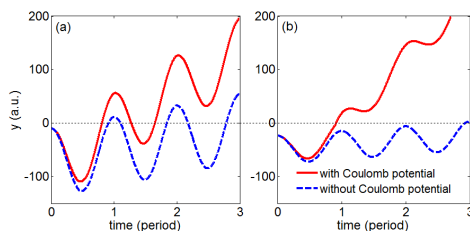


Figure 2. Typical trajectories of electrons along the laser polarization direction calculated by the semiclassical model with the same laser parameters (a) in figure 2(a); and (b) in figure 2(d).

of rescattered and direct electron wavepackets, we plot in figures 2(a) and (b) typical electron trajectories calculated by the GQTMC with and without considering the Coulomb potential for $\gamma = 0.55$ and 1.33 . In the case of tunneling ionization regime $\gamma = 0.55$, the electron has a large excursion amplitude, and when it goes far away from the parent ion, the Coulomb force becomes much smaller than the force of laser electric field. Thus, the force of laser electric field dominates the motion of electron in this case. The electron is ionized near the peak of the laser field and can be driven past their parent ion more than once. It can be seen in figure 2(a) that the two electron trajectories with and without considering the Coulomb potential have similar trends. The first and subsequent revisits of the ionized electron to the core take place in both of the electron trajectories. These typical recollision trajectories combining with similar statistic distributions of rescattered electrons result in the similar interference structure in the momentum spectra in tunneling ionization regime (see figures 1(a)-(c)). However, the situation is quite different in the parameter region where $\gamma \sim 1$. The electron driven by the force of electric field and the Coulomb force will revisit the core after one optical period (the red line in figure 2(b)). The ionized electron has a relatively small excursion amplitude comparing with that in tunneling ionization regime and is affected strongly by the Coulomb potential in this small region around the parent ion. When the effect of Coulomb potential is not considered (the blue dashed line in figure 2(b)), the electron will miss the important first revisit to the parent ion. Therefore, GQTMC results are consistent with those of TDSE, and both of them demonstrated that the effect of the Coulomb potential is essential to generate the interference between the direct and rescattered electron wavepackets in the parameter region where $\gamma \sim 1$, and the force of the laser electric field dominates the rescattering dynamics when $\gamma < 1$. From figure 1, one can see that the interference structures are also different in different parameter regions. In conclusion, we have investigated 2D PMDs with midinfrared wavelength laser pulses by solving the TDSE for different laser intensities and wavelengths. By comparing the PMDs for the long-range and short-range Coulomb potentials, the dynamic mechanism of the PH interference, viz., the interference between the direct electron and rescattered electron wavepackets was clearly

revealed. This interference can always occur in the long-range Coulomb interaction for different laser parameter regions. In tunneling regime where $\gamma < 1$, this interference and the interference structure which originates from the interference between the two electron wave packets appear on the opposite sides of the ion but have the same drift momentum, can be observed in high energy region of PMD both for the long-range and short-range Coulomb potentials. In the parameter region where $\gamma \sim 1$, the interference structures of PH and ATI can be observed in PMDs for the long-range Coulomb potential. However, only the interference structure of ATI can be distinguished in PMDs for the short-range Coulomb potential.

To explore the physical reason behind the interference structures, we have also used the GQTMC to calculate typical electron trajectories and the distributions of the rescattered electrons with and without considering the Coulomb potential. The results obtained are consistent with the TDSE simulations. It is shown that in the tunneling regime where $\gamma < 1$, the force of the laser electric field plays a dominant role in the rescattering dynamics, which leads to similar interference structures in PMDs for the long-range and short-range Coulomb potentials. When the tunneling picture is not valid ($\gamma \sim 1$), the Coulomb force is relatively strong and the Coulomb potential has significant effects on the motion of electrons and the rescattering processes.

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