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Laser parameter influence on quantum path selection in a bichromatic field

Shaoyi Wang¹, Weiyi Hong¹, Pengfei Lan¹, Qingbin Zhang¹ and Peixiang Lu¹,²

¹ Wuhan National Laboratory for Optoelectronics, Huazhong University of Science and Technology, Wuhan 430074, People’s Republic of China
² State Key Laboratory of Precision Spectroscopy, East China Normal University, Shanghai 200000, People’s Republic of China

E-mail: lupeixiang@mail.hust.edu.cn

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Abstract

We theoretically investigate the laser parameter influence on quantum path selection in a two-colour laser pulse, of which both fundamental field and its controlling field are linearly polarized. The laser’s parameters, namely, the relative intensity of the controlling field and its relative phase with respect to the fundamental field, determine the quantum path selection by affecting their ionization probabilities. In both cases of the $\omega + 3\omega$ and $\omega + 2\omega$ laser fields, it is shown that the quantum path selection in the multi-cycle pulse is more dependent on the parameters than that in the few-cycle pulse, and the selection of the quantum path in the multi-cycle $\omega + 3\omega$ pulse shows stability to the phase and intensity variation. Our results are very beneficial to choosing appropriate parameters for quantum path selection in experiments.

1. Introduction

Driven by an intense femtosecond laser pulse, atomic and molecular systems can emit lights at frequencies multiple of that of the laser field. This nonlinear process, known as high harmonic generation (HHG), attracts great interest owning to its potential applications for the coherent extreme ultraviolet source and the generation of attosecond pulses [1]. A typical HHG spectrum shows that the signal intensity decreases drastically for the few low orders, then it remains almost constant for many orders to form a plateau and finally it drops sharply for the high orders called the cutoff [2]. The mechanism of HHG can be well explained by the three-step model [3]. The electron first tunnels through the barrier formed by the Coulomb potential and the laser field, then it oscillates in the laser field and, finally, it may return to the ground state by recombining with the parent ion and emit a harmonic photon with energy up to $I_p + 3.17U_p$, where $U_p = E_0^2/(4\omega^2)$ is the ponderomotive potential and $I_p$ is the ionization potential. During the process of HHG, the two most important orbits contributing to each harmonic are the so-called short and long trajectories, characterized by electron travel times in the continuum of approximately one-half and one optical cycles, respectively [4, 5]. The coexistence of the two trajectories leads to an irregular pulse train. A clear and regular attosecond pulse train or a single attosecond pulse can be obtained when an individual quantum path is well selected, and the harmonics are synchronous, i.e., phase-locked. Then, the selection of a single quantum path has valuable applications, which attract much attention. The quantum path selection has been achieved macroscopically and in the single-atom response. Macroscopically, the short path can be selected by carefully adjusting the phase-matching condition [6], or spatial filtering [7]. In the single-atom response, the quantum path selection can be realized by using a two-colour field [8–14] or an attosecond pulse train [15]. It is demonstrated that it is an effective method for the quantum path selection to use a two-colour field. In a two-colour linear-polarized laser field, the laser’s parameters, namely, the relative intensity of the second field and its relative phase with respect to the first field, determine the quantum path selection by affecting their ionization probabilities. The impact of those parameter fluctuation is important in experiment, which has seldom been investigated [9, 13, 16, 17]. In this paper, we focus on the laser parameter influence on quantum path selection in a two-colour laser pulse. In the multi-cycle $\omega + 3\omega$ case, the selection of the quantum path shows stability to the phase and intensity variation. In both cases of the $\omega + 3\omega$ and $\omega + 2\omega$ laser fields, it
In order to clearly understand the physics picture of the HHG process by the semiclassical three-step pulse. We will theoretically investigate the laser parameter influence on quantum path selection in a two-colour laser pulse.

For convenience, we consider the interaction between a He atom and the combination of the laser field and the controlling field by numerically solving the one-dimensional time-dependent Schrödinger equation. In our simulation, we use the soft-core potential: \( V = -1 / \sqrt{\alpha + x^2} \), where \( \alpha = 0.484 \) is the smoothing parameter for helium. The electric field with profile is described by \( \beta (\beta = E_{i}^2/E_{0}^2) \) is the ratio between the peak intensities of the fundamental and controlling laser field. In our simulation, for the \( \omega + 3\omega \) laser field, the driving field is \( 6 \times 10^{14} \text{ W cm}^{-2} \), 10 optical cycles, 800 nm fundamental filed in combination with a 267 nm controlling field. A trapezoidal profile is adopted with 3 cycle linear ramps [20], which is considered as an approximation of the long pulse.

In the following, we consider the parameter \( \beta \) influence on the quantum path selection in the \( \omega + 3\omega \) laser field. \( \varphi_3 \) is set to 1\( \pi \) and we only adjust the parameter \( \beta \). Figure 2 shows the time–frequency properties [21, 22] of HHG with different \( \beta \) increased from 0.03 to 0.15. It can be seen that the fluctuation of the relative intensity ratio does not affect the similarity of the time–frequency characteristics in figure 2. In figure 2(a), there is only one dominant arm contributing to the long trajectory in each half optical cycle, and the intensity of the right arm corresponding to the long trajectory is nearly equal to that of the short one. Thus the long trajectory selection can be achieved only once in every full cycle [19]. Moreover, for the \( \omega + 2\omega \) case, the electrons corresponding to the second return have also high ionization rates, and the maximal energy of those electrons is not negligible while the ionization rates of the second return in the \( \omega + 3\omega \) case are low. Thus, the second return in the \( \omega + 2\omega \) case has a non-negligible influence on the quantum path selection. When the laser parameters are chosen properly, the quantum path selection can be achieved. However, in fact, the performance of the experimental instrument fluctuates in the certain range. Thus the impact of the parameter fluctuation on the quantum path selection is important in experiment.

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2. Result and discussion

In order to clearly understand the physics picture of the quantum path selection in the two-colour field, we first investigate the HHG process by the semiclassical three-step model, then the classical dynamics of the electrons in a continuous-wave (cw) field is considered for convenience. The electron motion in the \( \omega + 3\omega \) field \((j = 3)\) and in the \( \omega + 2\omega \) field \((j = 2)\) with profile is described by the equation:

\[
\ddot{x}(t) = -\left[E_0 \cos(\omega_0 t) + E_j \cos(j\omega_0 t + \varphi_j)\right], \quad j = 2, 3,
\]

where \( E_0 \) and \( E_j \) are the amplitude of the driving and the controlling fields, respectively. \( \varphi_j \) is the relative phase. \( E_0, E_2 \) and \( E_3 \) are set to 0.1305 au \((6 \times 10^{14} \text{ W cm}^{-2})\), 0.0369 au \((4.8 \times 10^{13} \text{ W cm}^{-2})\) and 0.0369 au, respectively. \( \omega_0 \) is set to 0.057 au, corresponding to the wavelength of 800 nm. \( \varphi_2 \) and \( \varphi_3 \) are set to 1.8\( \pi \) and 1\( \pi \). One optical cycle is \( T_0 = 2\pi/\omega_0 \). Figure 1 shows the classical electron trajectories as well as the electric field and the time dependence of the ionization rate of the electrons in the two-colour field. Figures 1(a) and 1(b) show the dependence of the kinetic energy \( E_i \) on the ionization (green crosses for the first return and blue circles for the second return) and recombination times (red diamonds for the first return and purple dots for the second return) in the \( \omega + 3\omega \) field and the \( \omega + 2\omega \) field, respectively. Figures 1(c) and 1(d) show the electric field of the two-colour pulse (red line) and the tunnel ionization rate (grey filled curve) calculated by the Ammosov–Delone–Krainov (ADK) model in the two-colour field [18]. In the \( \omega + 3\omega \) field (see figures 1(a) and 1(c)), it is shown that there are two classes of trajectories (for the first return) corresponding to the same energies, which are called short and long trajectories. The electrons corresponding to the short trajectories have high ionization rates, while the ionization rates of the long trajectories are very low. Then the long trajectories vanish. This is why the short trajectories can be selected. For the \( \omega + 2\omega \) field (see figures 1(b) and 1(d)), in the half optical cycle marked by R1, the ionization rate of the long trajectory is higher than that of the short trajectory, and the long one is selected. However, in the adjacent half optical cycle marked by R2, the ionization rate corresponding to the long trajectory is nearly equal to that of the short one. Thus the long trajectory selection can be achieved only once in every full cycle [19]. Moreover, for the \( \omega + 2\omega \) case, the electrons corresponding to the second return have also high ionization rates, and the maximal energy of those electrons is not negligible while the ionization rates of the second return in the \( \omega + 3\omega \) case are low. Thus, the second return in the \( \omega + 2\omega \) case has a non-negligible influence on the quantum path selection. When the laser parameters are chosen properly, the quantum path selection can be achieved. However, in fact, the performance of the experimental instrument fluctuates in the certain range. Thus the impact of the parameter fluctuation on the quantum path selection is important in experiment.

Next, we will theoretically investigate the laser parameter influence on quantum path selection in a two-colour laser pulse.
Figure 2. The time–frequency properties of HHG in the $\omega + 3\omega$ laser field with different relative intensities. The driving field is $6 \times 10^{14}$ W cm$^{-2}$, 10 optical cycles, 800 nm fundamental filed in combination with 10 optical cycles, 267 nm controlling field and $\varphi$ is $1\pi$. $T_0$ is the optical cycle. The relative intensities are 0.03, 0.07, 0.11 and 0.15 corresponding to (a)–(d), respectively.

and (d), the time–frequency properties are similar to those in figure 2(a). Therefore, the short trajectory selection can be achieved when the relative intensity fluctuates from 0.03 to 0.15, which leads to a clear and regular attosecond pulse train. Figure 3 shows the attosecond pulse trains produced by superposing harmonics from 60th to 85th driven by the $\omega + 3\omega$ laser field. The parameters are the same as those in figure 2, and the attosecond pulses in the half optical cycle are chosen to show in figure 3. Comparing the four curves in figure 3, the launch time and the relative intensities of the attosecond pulses change slightly. The four attosecond pulses corresponding to four different $\beta$ are very clear and regular, the durations (FWHM) of the attosecond pulses are approximately 104 as. Therefore, regular attosecond pulses can be obtained with the four different relative intensities. From the results in figures 2 and 3, we can see that the short trajectories selection in the $\omega + 3\omega$ laser field is weakly dependent on $\beta$.

Next, we investigate the relative phase influence on the short trajectory selection in the $\omega + 3\omega$ laser field. The time–frequency properties of HHG at different relative phases $\varphi$ increased from $0.91\pi$ to $1.09\pi$ are shown in figure 4. The parameters except for the relative phase and $\beta$ are the same as those in figure 3. $\beta$ is set to 0.04. It can be seen that four time–frequency properties with different relative phases have the similar characteristics. From figure 4, we find that the short trajectory selection can be achieved when the relative phase fluctuates from $0.91\pi$ to $1.09\pi$, and the attosecond pulse trains produced by superposing 25 harmonics are shown in figure 5. The parameters correspond to those of figures 4(a)–(d). Four attosecond pulse trains corresponding to four different phases $\varphi$ are regular, and the pulse durations are all approximately 104 as. But the intensities of the attosecond pulse trains change a lot.

To systematically investigate the laser parameter influence on quantum path selection in the $\omega + 3\omega$ field, we introduce the parameter $\eta$ to measure the degree of phase locking which is defined by [23–25]

$$\eta = \frac{\int_{\tau_N}^{T_0/2} d\tau I_{\text{XUV}}(\tau)}{\int_{\tau_N/2}^{T_0/2} d\tau I_{\text{XUV}}(\tau)},$$

(1)

where $I_{\text{XUV}}(\tau)$ is the intensity of the attosecond pulse, $\tau_N = T_0/(2N), N$ is the number of harmonics superposed to generate the attosecond pulse and $T_0$ is the optical cycle. We then normalize $\eta$ to $\tilde{\eta} = (\eta - 2\tau_N/T_0)/(0.775 - 2\tau_N/T_0)$, where
Figure 4. The time–frequency properties of HHG in the $\omega + 3\omega$ laser field with different phases. The parameters except for the relative phase and $\beta$ are the same in figure 2(a). $\beta$ is 0.04. The relative phases are $0.91\pi$, $0.96\pi$, $1.05\pi$ and $1.09\pi$ corresponding to (a)–(d), respectively.

Figure 5. The temporal profile of the attosecond pulse generated in the middle region of the spectrum ($60–85\omega_0$) by the $\omega + 3\omega$ laser field with different relative phases. The parameters are corresponding to those in figure 4. The black curves: $\varphi = 0.91\pi$. The carmine curve: $\varphi = 0.96\pi$. The green and blue curves: $\varphi = 1.05\pi$ and $\varphi = 1.09\pi$, respectively.

0.775 is the ratio one would get from a Fourier transform-limited pulse. This means that if the quantum paths are best selected $\tilde{\eta}$ equals one, and $\tilde{\eta}$ is zero if $I_{XUV}(t)$ is a constant. When $\tilde{\eta}$ is above 0.6, we consider that the quantum selection can be achieved.

The dependence of the degree of phase locking $\tilde{\eta}$ on the parameters in the $\omega + 3\omega$ laser field with the 10 cycle trapezoidal profile (red diamonds) is shown in figure 6. $N$ corresponds to the combination of the harmonics from 60th to 85th. For comparison, the dependence of $\tilde{\eta}$ on the parameters in the 5 cycle pulse with $\sin^2$ profile (blue circles) and 10 cycle $\sin^2$ profile (green circles) profiles, respectively, are also present. As shown in figure 6(a), the parameters except for $\beta$ are the same as those in figure 2. For the 10 cycle trapezoidal profile, it can be clearly seen that the degree of phase locking $\tilde{\eta}$ is approximately 0.3 when $\beta = 0.01$. $\tilde{\eta}$ increases rapidly to
more than 0.6 as $\beta$ is 0.04. The degree of phase locking $\eta$ is highest when $\beta$ is about 0.1. Approximately in the region for $\beta$ from 0.03 to 0.21, $\eta$ is above 0.6. The result indicates that the short quantum path selection corresponding to the parameter $\beta$ in this region can be achieved. In figure 6(b), the parameters except for $\psi_3$ are the same as those in figure 4. The short trajectory selection can be resolved from 0.91$\pi$ to 1.13$\pi$ and the degree of phase locking $\eta$ is highest when $\psi = 1\pi$. For the 5 cycle and 10 cycle sin$^2$ profiles, other parameters are the same as those in the trapezoidal pulse. In the 5 cycle pulse, the selection of the quantum path is weakly dependent on the parameters. As the pulse duration increases the quantum path selection is more dependent on the parameters, which indicates that the pulse duration has a non-negligible influence on the results. As shown in figure 6, in the multi-cycle case, the selection of the quantum path shows stability to the phase and intensity variation. Moreover, the quantum path selection in the multi-cycle pulse is more dependent on the parameters than that in the few-cycle pulse.

The quantum path selection in the $\omega + 2\omega$ field has also been of great interest. As shown in figure 1, the long trajectories can be selected when the laser parameters are chosen properly. In the following, we systematically investigate laser parameter influence on the long trajectory selection in the $\omega + 2\omega$ field. In our simulation, the driving field is $6 \times 10^{14}$ W cm$^{-2}$, 800 nm fundamental filed with a 400 nm controlling field. The relative phase is set to 1.71$\pi$. Figure 7 shows that the dependence of the maximal kinetic energy $E_k$ of the second return on the relative intensity in the $\omega + 2\omega$ field with 5 cycle (blue circles), 10 cycle sin$^2$ (green circles) and 10 cycle trapezoidal (red circles) profiles. When the relative intensity is 0.43, the maximal kinetic energy in the 5 cycle pulse can reach 2.88$U_p$ corresponding to the 82nd-order harmonic. Thus, the harmonics from 83th to 103th are chosen to avoid the interference between the trajectories of the first and the second returns.

The dependence of the degree of phase locking $\eta$ on the parameters in the $\omega + 2\omega$ laser field with 5 cycle sin$^2$ (blue circles), 10 cycle sin$^2$ (green circles) and 10 cycle trapezoidal (red circles) profiles is present in figures 8(a) and (b). $N$ is 20, which corresponds to the harmonics from 83th to 103th. In figure 8(a), $\beta$ is set to 0.08. For the trapezoidal pulse, it is shown that the long trajectory selection can be achieved approximately from 1.68$\pi$ to 1.81$\pi$, and the degree of phase locking can reach the highest point as $\psi = 1.71\pi$. In figure 8(b), $\psi$ is set to 1.71$\pi$, the selection of the quantum paths in only the region of $\beta$ approximately from 0.07 to 0.11 is achieved. The degree of phase locking $\eta$ is highest when $\beta$ is about 0.08. For the cases with 5 cycle and 10 cycle sin$^2$ profiles, the other parameters except for the duration are the same as those in the case with the trapezoidal profile. Comparing with the three pulses, we find that the quantum paths selection in the 10 cycle sin$^2$ and trapezoidal pulses is more dependent on the parameters than that in the few-cycle pulse. From figure 8, in the multi-cycle case, the selection of the quantum path shows instability to the phase and intensity variation.

3. Conclusion

In conclusion, we investigate the laser parameter influence on quantum path selection in a two-colour laser pulse. The laser’s parameters, including the relative intensity of the controlling field and its relative phase with respect to the fundamental field, determine the quantum path selection by affecting their ionization probabilities. It is shown that the selection of the quantum path in the multi-cycle $\omega + 2\omega$ pulse shows the instability to the phase and intensity variation comparing with that in the multi-cycle $\omega + 3\omega$ laser fields. Moreover, in the two cases, the quantum path selection in the multi-cycle pulse is more dependent on the parameters than that in the few-cycle pulse.
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