Above-threshold ionization of hydrogen atoms in a two-color laser field

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Abstract. By using the method of electron wave packet interference, we investigate the above-threshold ionization (ATI) of hydrogen atoms in a linearly polarized two-color laser pulse ($\lambda_1=800$ nm and $\lambda_2=400$ nm). Firstly, using the strong field approximation (SFA) with the time window function, we obtain the intracycle interference and intercycle interference patterns of hydrogen atoms in a 10 fs laser pulse, and it is found that the general characteristics of two-dimensional photoelectron momentum spectrum are formed by the interplay of the intracycle interference and intercycle interference, and the side rings in two-dimensional photoelectron momentum spectra originate from intercycle interference. Subsequently, we calculate the two-dimensional photoelectron momentum spectra of hydrogen atoms by SFA in full pulse. When the relative phase $\phi=0$, the intracycle interference and intercycle interference fringes in two-dimensional momentum spectrum are symmetrical, and when the relative phase is $\phi=0.5\pi$, the intracycle interference fringes in the two-dimensional momentum spectrum are obviously asymmetrical. The results show that ionization is vitally dependent on relative phase of two laser pulses in two-color laser filed.

1. Introduction
Above-threshold ionization (ATI) is a fundamental process in laser-matter interaction and has been extensively investigated during the past three decades [1]. The photoelectron energy spectra show that ATI occurs either in the form of multiphoton ionization and tunnelling ionization. According to the classical three-step model theory, photoelectrons can be classified into direct and rescattered electrons in the tunnelling ionization regime [2].

The interference between two electron wave packages is a very important concept in intense laser field ionization. The interference will occur in the electron wave packages with the same final momentum, and the interference theory can be used to analyze many phenomena in intense field ionization [3-5]. According to the time interval of releasing the electron wave packet, the interference can be classified into intercycle interference (the time interval is exactly one optical cycle) and intracycle interference (the time interval within one optical cycle). The interplay of intracycle interference and intercycle interference forms the typical characteristics of ATI photoelectron energy spectra and two-dimensional momentum spectra. In recent years, many interference phenomena in intense laser fields have been studied by saddle point approximation, classical orbital Monte Carlo method and quantum orbital Monte Carlo method [6-8].

In this paper, we use SFA model with a time window function [9] to obtain electron wave packets in a two-color laser pulse. By using this method, we demonstrate how the electron wave packet
interference patterns of two-dimensional photoelectron momentum spectra are formed. In this paper, atomic units are used.

2. Theoretical methods

We consider the interaction of a target atom with a two-color laser pulse with frequencies $\omega$ and $2\omega$. The linearly polarized electric field $F(t)$ of the laser pulse along the $z$ axis is given by

$$F(t) = a(t)F_0 \left[ \cos \omega t + \alpha \cos(2\omega t + \phi) \right] \hat{z}$$

where $\omega$ is fundamental laser frequency, $\phi$ is the relative phase, $\alpha$ is the ratio of the second harmonic field, and $F_0$ is the amplitude of the fundamental field. The envelope function $a(t)$ is chosen to be

$$a(t) = \cos^2 \left( \frac{\pi t}{\tau} \right)$$

where $\tau$ is the full duration of the laser pulse which is 2.75 times of the full width at half maximum (FWHM). In this paper, the pulse duration is defined as the FWHM.

In the SFA model the momentum-dependent ionization amplitude is given by [10]

$$f(p) = f_i(p) + f_s(p)$$

where $p$ is the momentum of the detected photoelectron. In Equation (3), the first term

$$f_i(p) = -i \int_{-\infty}^{\infty} dt \langle \chi_s(t) | H_i(t) | \psi_o(t) \rangle$$

is SFA1, where $H_i(t)$ is the atom-field interaction, $|\chi_s(t)\rangle$ and $|\psi_o(t)\rangle$ are scattering state (the Volkov states) and the ground state, respectively. The second term is the SFA2,

$$f_s(p) = -\int_{-\infty}^{\infty} dt \int_{-\infty}^{\infty} dt' \langle \chi_s(t') | V | \chi_s(t) \rangle$$

$$\times \int |dk| \langle \chi_s(t') | H_i(t) | \psi_o(t) \rangle$$

where $k$ is the momentum of intermediate state and $V$ is the atomic potential.

For a linearly polarized laser field, we can define the 2DMD as

$$\frac{d^2 P}{dp_x dp_y} = 2\pi |f(p)|^2$$

where $p_x$ and $p_y$ are momentum components along the $y$ axis (or $x$ axis) and polarization axis, respectively. We can obtain the energy spectra

$$\frac{dP}{dE} = 2\pi \sqrt{2E} \int |f(p)|^2 d(\cos \theta)$$

where $\theta$ is the angle between the $z$ axis and the direction of photoelectron momentum.

3. Results and discussions

In this paper, we use SFA and time window function to analyze the electron wave packet interference patterns in ATI by two-color field. We choose the laser parameters of two-color field as follows: $\lambda_1 = 800$ nm and $\lambda_2 = 400$ nm, and peak intensity $I_1 = I_2 = 1 \times 10^{13}$ W/cm$^2$ (set the ratio $\alpha = 1$). The electric field and vector potential are plotted in figure 1 with relative phase $\phi = 0$ and $\phi = 0.5\pi$. According to the classical theory, the electron wave packet with the same drift momentum will interfere, and the drift momentum is directly related to the vector potential of the electron ionization time. In figures 1(a) and 1(b), we set the time windows A, B and C (they have same vector potential), when windows A and C are opened, we can get the intracycle interference pattern; when windows B and C are opened, we can get the intercycle interference pattern.
The electron wave packet interference patterns are shown in Figure 2. In Figures 2(a) and 2(b), we present the two-dimensional momentum spectra of intracycle interference and intercycle interference, respectively. From Figure 2(a), we can see that the intracycle interference patterns are concentric circles (the side rings), and the circles centered at $p_z = 1.2$ and $p_y = 0$. From Figure 2(b), we can see that the intracycle interference patterns are ATI rings centered at origin. The photoelectron energy spectra of electron wave packet interference as shown in Figures 2(c) and 2(d), for intracycle interference energy spectrum, the interval between peaks increases with the increase of photoelectron energy, but for intercycle interference energy spectrum, the interval between peaks is equal, which is a typical ATI peak.
In Figure 3, we show the two-dimensional momentum spectra for single ionization of hydrogen calculated by SFA in full laser pulses with different pulse durations and relative phases. Figures 3 (a) and 3 (b) present the two-dimensional momentum spectra by a 10 fs pulse with $\phi = 0$ and $\phi = 0.5\pi$, and we can see intercycle and intracycle interference fringes clearly both in Figures 3 (a) and 3 (b). However, the interference fringes on the left and right sides of the Figure 3 (b) are obviously asymmetrical. On the left side of the figure, there are obvious interference fringes in the period, but the interference fringes in the period can hardly be seen on the right side of the figure. Compare Figures 3 (a) and 3 (b), it is obvious that the relative phase of two laser pulses has a significant effect on ionization in two-color field. The two-dimensional momentum spectra for 5 fs pulses as shown in Figures 3 (c) and 3 (d), on the whole, the results are consistent with those of 10 fs, but the intracycyle interference fringes are more obvious.

![Figure 3. Two-dimensional momentum spectra of hydrogen calculated by SFA in full laser pulses in two-color laser pulses and the laser parameters same as Figure 1. Upper panel: 10 fs, lower panel: 5 fs. (a) and (c) $\phi = 0$, (b) and (d) $\phi = 0.5\pi$.]

4. Conclusions

In conclusion, we investigate the two-dimensional photoelectron momentum spectrum of hydrogen atoms in above-threshold ionization (ATI) by a linearly polarized two-color laser pulse by using SFA model. It is found the general character of two-dimensional photoelectron momentum spectra can be attributed to the interplay of intercycle and intracycle interferences, in addition, the side rings in two-dimensional photoelectron momentum spectra originate from the intercycle interference. Moreover, we found that two-dimensional photoelectron momentum spectra are vitally dependent on relative phase of two laser pulses in two-color laser filed.

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References

[1] C. D. Lin, A.T. Le, Z. Chen, J. Phys. B 43, 122001 (2010)
[2] F. Lindner, M. G. Schatzel, Phys. Rev. Lett. 95, 040401 (2005)
[3] X. Bian, Y. Huismans, O. Smirnova, et al., Phys. Rev. A 84, 043420 (2011)
[4] J. Chen, X. Zheng, Z. Zhang, et al., Acta Phy. Sin. 65, 083202 (2016)
[5] X. Xiao, M. Wang, L. M, et al., Acta Phys. Sin. 65, 220203 (2016)
[6] D. G. Arbó, K. L. Ishikawa, et al., Phys. Rev. A 82, 043426 (2010)
[7] X. Song, J. Xu, C. Lin, et al., Phys. Rev. A 95, 033426 (2017)
[8] W. Yang, H. Zhang, C. Lin, et al., Phys. Rev. A 94, 043419 (2016)
[9] Z. Guo, Z. Chen, X. Zhou, Chin. Phys. B 23, 043201 (2014)
[10] Z. Chen, T. Morishita, et al., Phys. Rev. A 76, 043402 (2007)