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The above-threshold detachment of negative ions in half-cycle laser field

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ABSTRACT

We study partial detachment rate and photodetachment asymmetry of F^- detached by half-cycle linearly polarized laser field using numerical simulation. Similar to photodetachment for negative ions in few-cycle laser fields, we find that partial detachment rates of a couple opposite directions in the above-threshold detachment of F^- are not equal, the detachment is asymmetric. Furthermore, the photodetachment asymmetry degree increases with carrier-envelop phase (CEP) as the peak laser intensity becoming stronger or the pulse width becoming shorter. The maximal asymmetry degree is stronger with higher laser intensity. We confirm the effect of the CEP, laser intensity and pulse width on the above-threshold detachment of F^- in half-cycle laser fields. It provides a possible way to determine the CEP of half-cycle laser fields by measuring detached photoelectrons.

1. Introduction

Recent years, the generation of half-cycle pulse (HCP) has been achieved [1–4]. The HCP is a unidirectional electromagnetic field pulse and consists only half optical cycle. The HCP has become a powerful tool to research the interaction between strong field and material, operating in the microphysics process directly. Many achievements have been made in the ionization of atoms and ions by short HCPs [5–8], especially in the Rydberg atom ionization by half-cycle laser pulses [9–13].

An important parameter describing HCP is the carrier-envelop phase (CEP). CEP is the relative phase between pulse envelope peak value and the nearest carrier peak value. For HCPs the distribution of the laser field is decided by the CEP directly. So CEP has immediately impact on the interaction of strong field and material. Recent years, studies about CEP have become an important content for few-cycle laser pulses [14,15]. Study of HCPs has drawn much attention. Many studies about the influence of CEP on ionization by HCP are reported [16–18].

In this paper we investigate the above-threshold detachment (ATD) of F^- by solving time-dependent Schrödinger equation numerically. The partial detachment rates of ATD for F^- by strong laser field are obtained. The partial detachment rates of two opposite directions are not equal. The detachment is asymmetric. Moreover, we learn that the asymmetry degree increases along CEP under decreasing pulse width and increasing peak laser intensity. The maximal asymmetry degree which varies under different central wavelength increases as peak laser intensity increases.

2. Theoretical approach

Respect to the interaction of linear polarization laser pulses and the material, the interaction process and the direction of emitted electron will occur mainly in the laser pulse's polarization orientation. In this case, we use one-dimensional time-dependent Schröndinger equation (TDSE) to reflect the main physical process. Under the length standard and dipole approximation, the one-dimensional TDSE can be written as the following form: (unless special illustration atomic units are used throughout the whole content)

$$i\frac{\partial}{\partial t}\Psi(x,t) = \left[-\frac{1}{2}\frac{\partial^2}{\partial x^2} + xE(t) + V(x)\right]\Psi(x,t), \tag{1}$$

where $\Psi(x,t)$ is electron wave function which is time-dependent. In the right square brackets of the equation the first term is the kinetic energy of the electron, the second term stands for the time-dependent dipole interaction, the third term represents the Coulomb potential of F^-.

$E(t)$ is electrical field of the laser pulse which is denoted as:

$$E(t) = E_0 \sin^2 \omega t \cos(\omega t + \phi), \tag{2}$$

Here the electric field $E(t)$ has a sin-square envelope and its peak electric field strength is E_0 with the central frequency ω. We use ϕ indicate the CEP. In our calculation, we define $E(t)$ in the range $0 \le t \le T$ with the above expression, otherwise it is zero.

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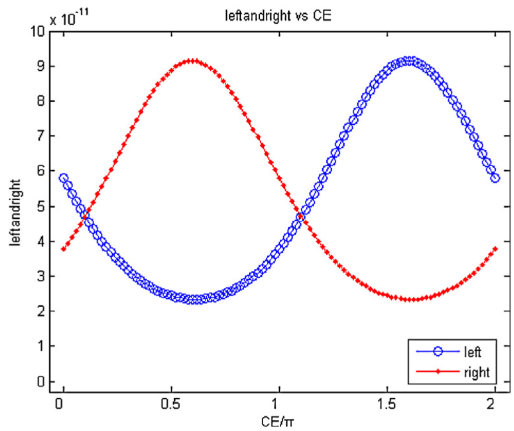

Fig. 1. The partial detachment rates P_L and P_R with different CEPs for F^- interacting with half-cycle laser pulses. The laser intensity is 3.5×10^{10} W/cm^2, laser wavelength is 1400 nm, and laser cycle is 0.5.

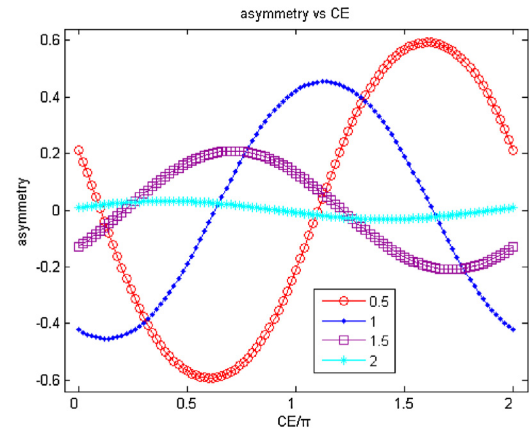

Fig. 2. Asymmetry parameters varying with CEP for four different pulse widths (corresponding pulse widths in cycle numbers are 0.5, 1, 1.5 and 2, respectively). The laser intensity is 3.5×10^{10} W/cm^2, and the central laser wavelength is 1400 nm.

The Coulomb potential of F^- is written in the following form [19]

$$V(x) = -\frac{\alpha e^{-\beta x}}{\sqrt{1+x^2}}, \tag{3}$$

α is a non-vanishing softened parameter here, it describes the bound strength between Coulomb field and electron. β is short range bound parameter. When β is nonzero, it is usually the representative of negative ions potential. According to Refs [20,21], the ground state energy of F^- is -0.125 a.u. (5.4488×10^{-19} J), so we choose $\alpha = 0.5$ and $\beta = 1.009$.

We use the Crank-Niclson central difference method to solve the one-dimensional TDSE numerically. In the calculation, a $\cos^{1/8}$-like absorbing mask function is used to avoid the reflections from the boundaries. The integration steps in time and in space are 0.2 a.u. and 0.1 a.u.

In this paper, we define the asymmetry coefficient to show the asymmetry degree [22]:

$$a = \frac{P_L - P_R}{P_L + P_R}, \tag{4}$$

we regard the partial detachment probabilities along the negative and positive directions respectively as P_L and P_R in one-dimensional coordinate, that is in the experiment we record the signals of photoelectrons by the left and the right detectors respectively. When $a = \pm 1$ we see the photoelectrons eject all to one side, and $a = 0$ means isotropy of the photoelectrons emission.

3. Results and discussion

3.1. The effect of CEPs on ATD

With $E_0 = 0.001$ a.u. (corresponding to a peak intensity of 3.5×10^{10} W/cm^2) and the carrier frequency $\omega = 0.0326$ a.u. (corresponding to wavelength of 1400 nm), we calculate the partial detachment rates P_L and P_R of different CEPs for F^- interacting with HCPs, as shown in Fig. 1.

It is obvious that, for most CEPs, P_L is not equal to P_R, i.e., the photodetachment shows asymmetric characteristic. However, for some special CEPs, P_L is same to P_R (we call these CEPs symmetric phase), the symmetric phases are 0.1π and 1.1π in Fig. 1. The left and right detachment rates vary with the CEP as a sinusoidal function with a periodicity of 2π. The recent experimental observations and theoretical study have presented the asymmetric pattern [23–27]. Moreover, Fig. 1 also shows that when the detachment rate of right (or left) side arrives at its maximum, detachment rate of the opposite side is at its minimum, and the asymmetry degree is maximal. For example, in one period the maximum P_R is 9.143×10^{-11} and the minimum P_L is 2.343×10^{-11} for CEP at 0.6π. CEPs corresponding to maximal asymmetry degree are 0.6π and 1.6π in one period. Detachment is decided by electric field. Moreover, the electric field of half-cycle laser has asymmetry and the distribution of electric field is decided by the CEP. So the asymmetry of photodetachment is caused by the asymmetry of electric field, then the photodetachment asymmetry is decided by the CEP.

3.2. The effect of laser field on the ATD

The effect of CEPs on photodetachment can be reflected through the photodetachment asymmetry parameter. The asymmetry degree depends on the pulse width, the laser intensity and the laser wavelength. Then effects of the above factors are discussed in the following.

3.2.1. The effect of pulse width on the ATD

With the same laser parameters as those of Fig. 1, we study the effect of pulse width on photodetachment. We calculate the asymmetry parameter varying with CEP for four different pulse widths (see Fig. 2, corresponding the pulse cycle numbers 0.5, 1, 1.5 and 2 the pulse durations are 2.33 fs, 4.66 fs, 6.99 fs and 9.33 fs, respectively). The variation of asymmetry parameter with the CEP is inconspicuous when cycle number is large, just as when cycle number is 2. As the pulse width decreases, the vibration of asymmetry parameter becomes severe. By comparing the four curves, three points are distinct. Firstly, these four curves are sin-like patterns and the asymmetry parameter curves vibrate with a periodicity of 2π. Secondly, with the decrease of pulse width, vibration of asymmetry parameter curve increases, photodetachment asymmetry degree becomes more distinct. The maximal asymmetry parameters are 0.0321, 0.2091, 0.4532 and 0.5920 respectively to the corresponding cycle numbers 2, 1.5, 1 and 0.5. With same peak laser intensity, when the laser pulse width is larger, the kinetic energy of photoelectrons is lower, the number of transition channels in photodetachment process is smaller, a transition channel means a possible combination of absorbed-photon numbers in the photodetachement process. Then the detachment asymmetry is inconspicuous. For laser pulses with shorter pulse width, the number of transition channels is larger, interference among different transition channels is more distinct, so the asymmetry degree is much larger for HCPs. Similar phenomenon is common in atom range [28]. Lastly, asymmetry parameter curve under different cycle numbers shows different maximal asymmetry phases and