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ARTICLE

Asymmetry in the Strong-field Photodetachment of H^- by Linearly Polarized Few-cycle Pulses

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Photodetachment of H^- irradiated by linearly polarized few-cycle laser field is investigated by time-dependent Schrödinger equation numerically. The photo-electron left-right asymmetry parameter as a function of carrier-envelop (CE) phase of few-cycle pulses is attained. We confirm the asymmetry of photoelectron distribution in H^- photodetachment and find that the maximal asymmetry parameter of H^- is equal to that of H atom under the same conditions but the corresponding CE phases are quite different. Thus a CE phase shift appears. Compared to that of H atom and field free electron, the zero asymmetry CE phase shift is sensitively affected by Coulomb field. The Coulomb effect on the asymmetry of H^- photodetachment mainly behaves in the CE phase shift of H^- instead of the amplitude of asymmetry parameter curve.

Key words: Asymmetry parameter, Photodetachment, Carrier-envelop phase, Few-cycle pulse, H^-

I. INTRODUCTION

Few-cycle even isolated single-cycle pulses with stable carrier-envelop (CE) phase have been achievable by recent laser technology [1]. The CE phase describes the offset of the peak laser field with respect to the peak position of the envelope. Asymmetry phenomenon in laser-matter interactions is unique in few-cycle region. For multi-cycle laser pulses, the distribution of electric filed is even, leading to symmetric photoelectrons spectra when interacting with atomic and molecular targets. Thus no measurable effect can be induced by the CE phase of multi-cycle pulses [2]. But for few-cycle pulses, electric field distribution depends greatly on CE phase, so does the physical processes it induce [3, 4].

The photoelectron distributions in photodetachment of negative ions have attracted much attention [5−7]. Recently, using analytical S-matrix method, Peng *et al.* has shown that the angular-resolved spatial distribution of the photodetachment electrons of H^- is very sensitive to the CE phase and the duration of the short laser pulse [5]. They found the energy distribution of the detached electron in forward direction φ is the same as that in backward direction $2\pi-\varphi$. We confirm this in instantaneous photodetachment probability by numerically solving TDSE. In addition, we further present how the asymmetry parameter varying with CE phase of pulse. Our study focus on the asymmetric photoelectron distribution, assuming the photoelectrons eject strictly along laser polarized direction in the one-dimensional (1D) approximation, which only has left and right direction. Asymmetry parameter can be attained by comparing left and right partial probabilities.

In this work, we investigate the photodetachment asymmetry of negative ion H^- subjected to linearly polarized intense few-cycle laser pulses. By numerically solving 1D time-dependent Schrödinger equation (TDSE) we calculate the asymmetry parameter of H^-, obtain the probabilities of ejected photoelectrons emitted to opposite directions at special CE phases. We find that the maximal asymmetry parameter of H^- is equal to that of H atom under the same conditions. However, CE phases corresponding to the same asymmetry parameters are quite different. CE phases corresponding to zero asymmetry parameter are 0.95π for H^- and 0.7π for H in a period. CE phases corresponding to maximal asymmetry parameter are 0.45π for H^- and 0.25π for H in a period, which appears a CE phase shift. Impacts of Coulomb potential and pulse intensities on asymmetry parameter are also discussed. H^- is the simplest multi-electron system with a weak binding energy of 754.2 meV [8]. Owing to the fact that the outmost electron of H^- is loosely bound and easily detached, we choose single-active-electron approximation in our calculation, where the physical model in this problem is treated as an effective single electron problem interacting with a neutral core [9]. In this work, atomic units ($\hbar=e=m_e=1$) are used.

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II. COMPUTATION METHOD

In the length gauge we numerically solve 1D TDSE:

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

which describes the interaction of H^- with linearly polarized few-cycle laser field $E(t)$ of single-active-electron approximation [10]. $\Psi(x,t)$ is the time-dependent wave function of electron, $V(x)$ is Coulomb potential, $xE(t)$ is the time-dependent dipole interaction. In this 1D treatment, we consider the electrons eject along the direction of laser polarized vector. To avoid singularity in this 1D calculation, we choose a smoothed model potential. The Coulomb potential between active electron and neutral core can be written as:

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

In calculation, we choose α=1, β=7.8. The model H^- has the binding energy of 0.754 eV. Our integration grid was defined by $0<x<x_{\max}$, with $x_{\max}$=256 Bohr, spatial steps Δx=0.1 a.u., integration step in time is 0.055 a.u. Using Crank-Nicolson method we give 1D direct numerical solution of TDSE. We consider detachment from H^- is subjected to sine-square envelope pulse, so the electric field can be written as [11]:

$$E=E_0\sin^2\left(\frac{\omega_p t}{2}\right)\cos(\omega t+\varphi) \qquad (3)$$

$$\omega_p=\frac{\omega}{n_p} \qquad (4)$$

where ω is frequency, E_0 is peak electric-field strength, and φ is the CE phase. n_p is the optical cycle number of laser pulse. Pulse duration $\tau=n_pT$, where $T=2\pi/\omega$. The asymmetry phenomena in the photodetachment of H^- by few-cycle laser pulses can be characterized by asymmetry parameter [12]:

$$a=\frac{P_+-P_-}{P_++P_-} \qquad (5)$$

where P_+ and P_- are left and right partial ionization probabilities calculated along the negative and positive x-axis, respectively. Whereas in experiment, P_+ and P_- are photoelectron ejection signals recorded with two opposite detectors in a plane perpendicular to the laser beam. a=0 means symmetric electron signals, such as in the case long pulse-matter interaction, while $a=\pm1$ means fully asymmetric electron ejection to one side. a=1 means only left electron signal P_+; a=−1 means only right electron signal P_-.

III. RESULTS AND DISCUSSION

The asymmetry parameter of H^- as a function of the CE phase is presented in Fig.1. We find that the asymmetry parameter curves of H^- are sine-like, varying from its positive maximum to zero then negative maximum to zero with periodicity of 2π. Peng *et al.* also get the result in analytical way [5]. We notice that CE phases corresponding to the maximal asymmetry parameter are nearly at 0.45π and 1.45π in a period, while the CE phases corresponding to zero asymmetry parameter are nearly at 0.95π and 1.95π in a period. For CE phase $\varphi=0.45\pi$, most photoelectrons are ejected to the leftside while for CE phase $\varphi=1.45\pi$ most photoelectrons are ejected to the rightside.

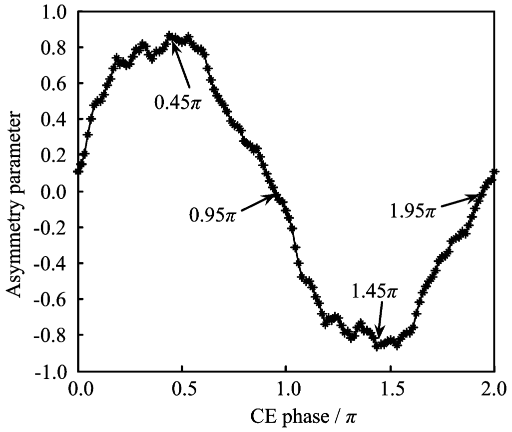

FIG. 1 Asymmetry parameter of H^- varying with CE phase at laser intensity I=1.4 PW/cm^2 (E_0=0.2 a.u.), wavelength λ=812 nm (ω=0.056 a.u.), and n_p=4.

Figure 2 gives a direct asymmetric image of H^- irradiated by linearly polarized four-cycle laser pulses at these special asymmetry points. The calculated instantaneous photodetachment probabilities varying with pulse propagation at four special CE phases are presented. In Fig.2(a) for CE phase $\varphi=0.95\pi$ we clearly find that the left detachment probability P_+ is almost equal to the right detachment probability P_-, which means a symmetric instantaneous photodetachment. While in Fig.2(b) for CE phase $\varphi=0.45\pi$ the left instantaneous probability P_+ is significantly stronger than P_-, reaching a maximal asymmetry, which corresponds to a=1. Figure 2(c) for CE phase $\varphi=1.95\pi$ is another zero asymmetry point in a period. In Fig.2(d) the right instantaneous detachment probability P_- reaches its maximum, while the left instantaneous detachment probability P_+ reaches its minimum, which corresponds to a=1.

The special CE phases corresponding to maximal asymmetry parameter and zero asymmetry parameter are useful in measuring the CE phase experimentally [3]. According to Milošević *et al.*, CE phases corresponding to zero asymmetry parameter for H atom is -0.3π mod π [3, 11]. Our calculations of H are in good agreement with those of Milošević *et al.* since π minus 0.3π is 0.7π. Obviously atomic and molecular targets with different Coulomb potential lead to different asymmetry curve. Asymmetry of H atom ionization by few

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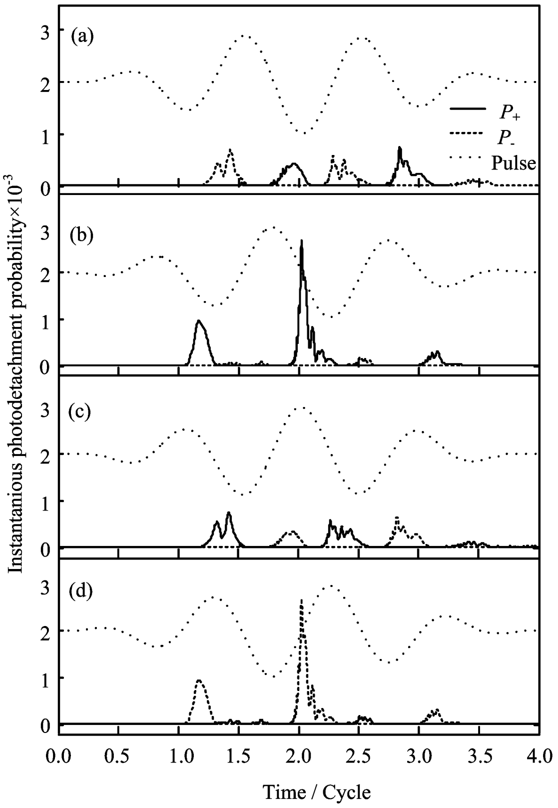

FIG. 2 The time-resolved instantaneous photodetachment probability for zero asymmetry with CE phases: (a) φ=0.95π, (c) φ=1.95π, and for maximal asymmetry for CE phases: (b) φ=0.45π, (d) φ=1.45π.

cycle laser pulse has been explicitly studied by Zhang *et al.* [13−15]. The asymmetry parameter of H in this work calculated agrees well with Zhang *et al.*'s result [16]. Figure 3 depicts the influence of Coulomb potentials on the asymmetry. Comparison among asymmetry parameters of H, H$^-$ and field-free electron as a function of CE phase is presented. We find the asymmetry of field-free electron is a sinusoidal curve, with its zero asymmetry point at φ=0, π, 2π, which agrees well with the strong field approximation prediction in assuming the binding energy can be neglected once electron emits [4]. While in Coulomb field affected case, asymmetry parameter has an obvious zero point shift for both H$^-$ and H atom. For H$^-$, CE phases corresponding to zero asymmetry are 0.95π and 1.95π, respectively. For H, CE phases corresponding to zero asymmetry are 0.7π and 1.7π, respectively. It's obvious that this zero asymmetry shift is sensitive to Coulomb field. We find that the zero asymmetry point of H$^-$, with a weak binding energy of 0.0277 a.u., is close to the zero asymmetry point of field free situation, with a small shift of 0.05π. But for H atom, with binding energy of 0.5 a.u., zero asymmetry point shifts 0.3π. However, the maximal asymmetry isn't affected prominently by Coulomb effect. Both H and H$^-$ have the maximal asymmetry

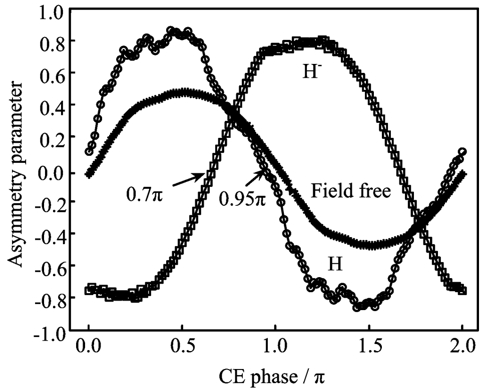

FIG. 3 Asymmetry parameter varying with the CE phase for different targets. The circle line represents H$^-$, square line represents H and star line represents field free electron. Parameters of laser pulses are the same as that in Fig.1.

parameter 0.8.

Thus the asymmetry parameter is not only sensitive to pulse duration, but also very sensitive to Coulomb field. This finding agrees with the study of Zhang *et al.* [17], who employ the standard Coulomb-Volkov theory to study the Coulomb effects on the photoionization processes of H atom.

IV. CONCLUSION

We have studied the asymmetry varying with the CE phase of photodetachment of H$^-$ by few-cycle laser pulses. Within a periodicity of 2π, CE phase corresponding to the maximal asymmetry phase are 0.45π and 1.45π, zero asymmetry CE phase is 0.95π and 1.95π. The instantaneous probabilities at these special phases are presented. Compare with field free electron, zero asymmetry CE phase of H$^-$ shifts 0.05π, while the corresponding phase of H shifts 0.3π. Coulomb field sensitively affects the zero asymmetry CE phases, causing a shift. At the same time the difference of Coulomb effect between H and H$^-$ doesn't show much impact on the maximal asymmetry. The Coulomb field mainly affects the asymmetry of H$^-$ photodetachment in the CE phase shift instead of the asymmetry parameter curve amplitude.

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