Photodetachment dynamics of H^- ion in a harmonic potential plus a time-dependent oscillating electric field*

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The photodetachment dynamics of H^- ion in a harmonic potential plus an oscillating electric field is studied using the time-dependent closed orbit theory. An analytical formula for calculating the photodetachment cross section of this system is put forward. It is found that the photodetachment cross section of this system is nearly unaffected for the weak oscillating electric field strength, but oscillates complicatedly when the oscillating electric field strength turns strong. In addition, the frequency of the harmonic potential and the oscillating electric field (the frequency of the harmonic potential and the frequency of the oscillating electric field are the same in the paper, unless otherwise stated.) can also affect the photodetachment dynamics of this system. With the increase of the frequency in the harmonic potential and the oscillating electric field, the number of the closed orbits for the detached electrons increased, which makes the oscillatory structure in the photodetachment cross section much more complex. Our study presents an intuitive understanding of the photodetachment dynamics driven by a harmonic potential plus an oscillating electric field from a space and time dependent viewpoint. This study is very useful in guiding the future experimental research for the photodetachment dynamics in the electric field both changing with space and time.

Keywords: harmonic potential, oscillating electric field, time-dependent closed orbit theory, photodetachment dynamics

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1. Introduction

Photodetachment process plays an important role in investigating the structure of negative ions in atomic or molecular physics. As is well known the external field or environment can modulate the photodetachment process of negative ion. It has been observed that the photodetachment cross section of H^- ion in a strong static electric field displayed a ripple structure.[1] In order to explain this phenomenon, many theoretical studies have been carried out using both the quantum mechanical method and the semiclassical method.[2–7] For example, in 1988, Rau and Wong used the "Frame transformation theory" to calculate the photodetachment cross section in the coordinate representation.[2] The effect of the electric field appeared as a modulating factor given by a derivative of an Airy function. At the same time, Du and Delos adopted a quantum method involving a momentum space wave function and stationary phase approximation and derived a simple formula for calculating the photodetachment cross section of this system.[3] Later, Du and Delos used the semiclassical closed orbit theory to explain the oscillatory structure in the photodetachment cross section and found their result accords very well with the quantum mechanical result.[4–7] Since the closed orbit theory provides a clear physical picture description for the photodetachment of H^- ion in the electric field, many researchers have developed this theory to study the photodetachment of H^- ion in other external fields or different environments, such as in parallel or crossed electric and magnetic fields, near an elastic or metal surface, in different microcavities, etc.[8–22] In these previous studies, the external fields or environment remain unchanged. As to the photodetachment of H^- ion in the changing external field or environment, the researches are relatively few. In 1999, Yang *et al.* studied the photodtachment of H^- ion in a space-dependent gradient electric field.[23] Later, Zhao *et al.* calculated the photodetachment cross section of H^- ion in a harmonic potential.[24] Recently, Yang and Robicheaux have developed the closed orbit theory from the static electric field into the time-dependent electric field. They studied the photodetachment of H^- and F^- ion in a time-dependent electric field.[25,26] On this basis,we have studied the photodetachment of H^- ion in a time-dependent gradient electric field and oscillating electric field.[27,28] However, it is unknown what will happen for the photodetachment of H^- ion in an electric field varying with both space and time.

In the present work, the photodetachment dynamics of the H^- ion in a harmonic potential plus an oscillating time-dependent electric field is studied. We put forward an analytical formula for calculating the photodetachment cross section of this system. It is found that the photodetachment cross sec-

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tion depends sensitively on the strength of the oscillating electric field and the frequency in the harmonic potential and the oscillating electric field (the frequency of the harmonic potential and the frequency of the oscillating electric field are the same in the paper, unless otherwise stated.). Since the harmonic potential corresponds to a space-dependent electric field, thus our study presents an intuitive understanding of the photodetachment dynamics of negative ions in the electric field from a space and time dependent viewpoint.

In the following section, we give the Hamiltonian and obtain the classical motion equations for the detached electrons in the harmonic potential plus the oscillating electric field. Then we search out the closed orbits for the detached electrons. In Section 3, we put forward an analytical formula for calculating the photodetachment cross section of this system. The influences of the oscillating electric field strength and the variation of the frequency in the harmonic potential and the oscillating electric field on the photodetachment cross section are calculated and discussed in Section 4. In Section 5 a short summary of this paper is presented. Atomic units (a.u.) are used unless indicated otherwise.

2. Hamiltonian and the closed orbit of the detached electron

Considering that an H^- ion is placed in a harmonic potential $V_z = (1/2)\omega^2 z^2$ plus a time-dependent oscillating electric field $F(t) = F_0 \sin(\omega t)$, where ω is the frequency of the harmonic potential and the oscillating electric field, F_0 is the electric field strength. The laser field for the photodetachment of the H^- ion has the following form[25]

$$f_{\rm L}(t) = \frac{1}{2}\left[\tanh\left(\frac{t-t_{\rm u}}{t_{\rm L}}\right) - \tanh\left(\frac{t-t_{\rm d}}{t_{\rm L}}\right)\right], \tag{1}$$

where $t_{\rm u}$, $t_{\rm d}$, and $t_{\rm L}$ are the laser field parameters, with $t_{\rm u}$, and $t_{\rm d}$ indicating the time when the laser light is turned on and off, respectively,and $t_{\rm L}$ controlling how fast the laser field is turned on and off.[27] In this work, we choose $t_{\rm d} = -t_{\rm u} = 3.14$ ps, and $t_{\rm L} = 0.23$ ps.

Assuming that the laser field and the oscillating electric field both point along the z axis. Then the Hamiltonian governing the motion of the detached electron in the harmonic potential plus the oscillating electric field has the following form:

$$\begin{aligned} &H(\rho, z, t, p_\rho, p_z, p_t) \\ &= \frac{1}{2}p_\rho^2 + \frac{1}{2}p_z^2 + \frac{1}{2}\omega^2 z^2 + F_0 \sin(\omega t) z + p_t + V_{\rm b}(r). \end{aligned} \tag{2}$$

Here p_t is a conjugate momentum relating to the classical dynamical variable t, $V_{\rm b}(r)$ is the binding potential and can be neglected after the electron has been far from the hydrogen atom.

Since the Hamiltonian is related to time t, we introduce an additional evolution time τ to describe the electron movement in the harmonic potential plus the oscillating electric field, $\tau = t - t_{\rm i}$. Here $t_{\rm i}$ denotes the initial outgoing time of the electron trajectory and t is the real time. By solving the time-dependent Hamiltonian canonical equations with the initial conditions: $\rho(t_{\rm i}) = 0$, $z(t_{\rm i}) = 0$, $p_\rho(t_{\rm i}) = k_0 \sin\theta_{\rm i}$, $p_z(t_{\rm i}) = k_0 \cos\theta_{\rm i}$, we obtain the motion equations of detached electron as follows:

$$\begin{cases} \rho(t) = k_0 \sin\theta_{\rm i}(t - t_{\rm i}), \\ z(t) = A\cos(\omega t + \varphi_0) + \dfrac{F_0}{2\omega} t\cos(\omega t), \end{cases} \tag{3}$$

where $k_0 = \sqrt{2E}$ is the initial momentum of detached electron, $\theta_{\rm i}$ denotes the outgoing angle between the initial momentum with the $+z$ axis, A and φ_0 are the integration constants, which can be determined by the initial conditions of the detached electron:

$$A = \frac{1}{\omega}\sqrt{\left[-\frac{F_0}{2}t_{\rm i}\cos(\omega t_{\rm i})\right]^2 + \left[\frac{F_0}{2\omega}\cos(\omega t_{\rm i}) - \frac{F_0}{2}t_{\rm i}\sin(\omega t_{\rm i}) - k_0\cos\theta_{\rm i}\right]^2}, \tag{4}$$

$$\varphi_0 = \begin{cases} \cos^{-1}\left[-\dfrac{F_0}{2A\omega}t_{\rm i}\cos(\omega t_{\rm i})\right] - \omega t_{\rm i}, & \text{if } \cos\theta_{\rm i} > 0, \\ 2\pi - \cos^{-1}\left[-\dfrac{F_0}{2A\omega}t_{\rm i}\cos(\omega t_{\rm i})\right] - \omega t_{\rm i}, & \text{if } \cos\theta_{\rm i} < 0. \end{cases} \tag{5}$$

From Eq. (3), we find that the electron motion along the z axis is a cyclotron one, and the motion perpendicular to the z axis is a linear motion. Then only the electron emitted along the z axis can be drawn back to the origin to form a closed orbit. Therefore, the initial outgoing angle of the closed orbit of electron in the harmonic potential plus the oscillating electric field is $\theta_{\rm i} = 0$ or $\theta_{\rm i} = \pi$.

Let $z(t) = 0$, then we will obtain

$$A\cos(\omega t + \varphi_0) + \frac{F_0}{2\omega} t\cos(\omega t) = 0. \tag{6}$$

By solving the above equation, we can obtain the initial time $t_{\rm i}$ and the returning time t of each closed orbit. Some

typical closed orbits are shown in Fig. 1. Figure 1(a) shows the electron emitted along the $+z$ direction, due to the influences of the harmonic potential and the electric field force, after a period of time it will return back to the origin. We call this kind of closed orbit the up orbit. Figure 1(b) shows the electron emitted along the $-z$ axis with the outgoing angle $\theta_i = \pi$, after some time, it reaches the lowest point, and then pulls back to the origin by the harmonic potential and the electric field force. This kind of closed orbit is called the down orbit. Figure 1(c) can be considered as a combination of the up and down closed orbit, which is called the up–down orbit. Figure 1(d) shows an orbit similar to the up–down orbit, but in reverse order. We call it the down–up orbit. The other two closed orbits can be analyzed in the same manner. Figures 1(e) and 1(f) are called the up–down–up orbit, and down–up–down orbit, respectively.

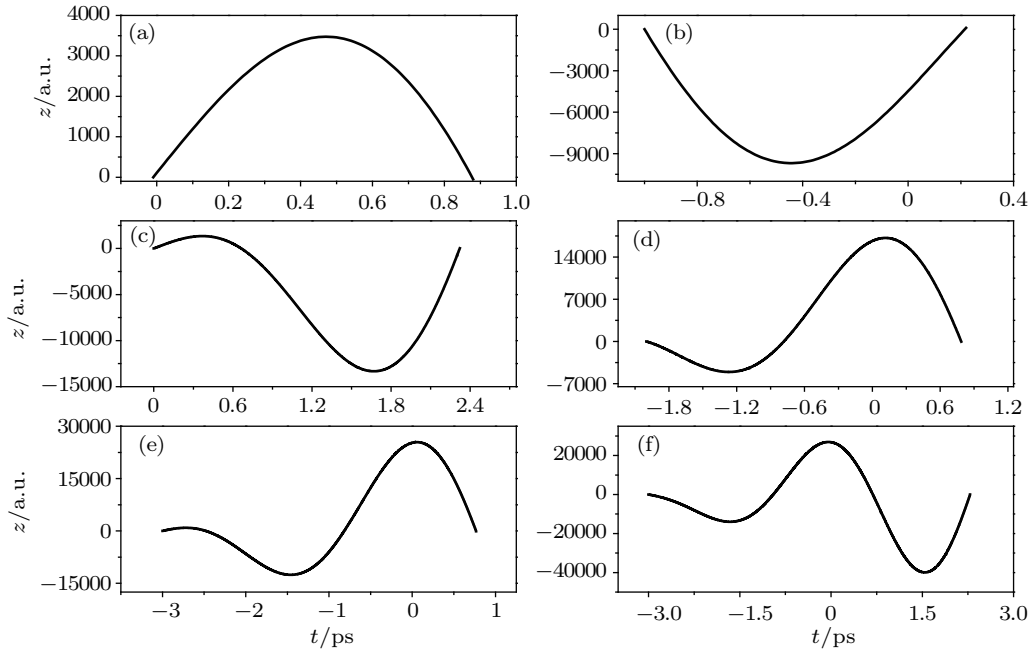


Fig. 1. Graphic demonstrations of some closed orbits for the detached electron in the harmonic potential plus the oscillating electric field: (a) up closed orbit, (b) down closed orbit, (c) up–down closed orbit, (d) down–up closed orbit, (e) up–down–up closed orbit; and (d) down–up–down closed orbit.

3. Derivation of the time-dependent photodetachment cross section

According to the closed orbit theory,[7] the external field can modulate the photodetachment process of the H^- ion by returning back an outgoing wave to the source region, where the initial bound state of H^- ion is localized. If the harmonic potential and the oscillating electric field are strong enough that the electron can be driven back to the origin, oscillatory structures may appear in the photodetachment cross section. Each closed orbit of the detached electron contributes a sinusoidal term in the total photodetachment cross section. In contrast to the photodetachment of the H^- ion in the static electric field, where the photodetachment cross section is time- independent. However, in the time-dependent oscillating electric field, the returning electron orbit oscillates with time, which makes the photodetachment cross section change with time t. It has been shown that the time-dependent photodetachment cross section can be divided into two parts[27]

$$\sigma(E,t) = \sigma_0(E,t) + \sigma_{\rm osc}(E,t), \tag{7}$$

where $\sigma_0(E,t)$ is a smooth background term, which is only related to the laser field, $\sigma_0(E,t) = \sigma_0(E) f_{\rm L}^2(t)$, where $\sigma_0(E) = 16\sqrt{2}B^2\pi^2E^{3/2}/3cE_{\rm p}$ is the photodetachment cross section of H^- ion in the free space.[7] Here c is the speed of light; $B = 0.31552$; $E_{\rm p} = E + E_{\rm b}$ is the photon energy, with E being the energy of detached electron and $E_{\rm b}$ being the binding energy of the H^- ion and $E_{\rm b} = 0.754$ eV; $\sigma_{\rm osc}(E,t)$ denotes the oscillating cross section, corresponding to the contribution of the returning electron wave:

$$\sigma_{\rm osc}(E,t) = -\frac{4\pi E_{\rm p}}{c}\,{\rm Im}\langle f_{\rm L}(t)\,{\rm e}^{-{\rm i}Et} D\varphi_{\rm i}|\psi_{\rm ret}(\boldsymbol{r},t)\rangle. \tag{8}$$

Here D is the dipole operator and $D = Z$ for the z-polarized laser light; $\varphi_{\rm i}(r) = B\,{\rm e}^{-k_{\rm b}r}/r$ is the initial bound state wave function of the H^- ion, $k_{\rm b} = \sqrt{2E_{\rm b}}$, $\psi_{\rm ret}(\boldsymbol{r},t)$ denotes the returning electron wave function:

$$\psi_{\rm ret}(\boldsymbol{r},t) = \sum_v \psi_{\rm ret}^v(\boldsymbol{r},t). \tag{9}$$

Hear, $\psi_{\rm ret}^v(\boldsymbol{r},t)$ is the returning wave corresponding to the v-th closed orbit of the detached electron, and the sum includes all the closed orbits of electron:

$$\begin{aligned}\psi_{\rm ret}^v(\boldsymbol{r},t) \;=\; & f_{\rm L}(t_{\rm i})C(k_0){\rm Y}_{lm}(\theta_{\rm i},\varphi_{\rm i})\frac{{\rm e}^{{\rm i}k_0R}}{R}A_v \\ & \times \exp[{\rm i}(S_v - Et_{\rm i} - \lambda_v\pi/2)].\end{aligned} \tag{10}$$

Here, $C(k_0)$ is a coefficient:

$$C(k_0) = \mathrm{i}\sqrt{\frac{4\pi}{3}}\frac{4Bk_0}{(k_\mathrm{b}^2+k_0^2)^2};$$

$\mathrm{Y}_{lm}(\theta_\mathrm{i},\varphi_\mathrm{i})$ is the harmonic function, in this work, we choose $l=1$, $m=0$; R is the radius of a small spherical surface around the negative ion, $R\approx 10$ a.u; A_v and S_v are the amplitude and action along the $v-$th trajectory; λ_v is the Maslov index characterizing the geometrical properties of the v-th trajectory, which can be calculated by counting the number of the singular points, including returning points, caustics, and foci, etc.[27]

The amplitude A_v is the ratio of the square root of Jacobian at time $\tau = t-t_\mathrm{i}$ to that at $\tau=0$, i.e.,

$$A_v = \left|\frac{J_v(\tau=0)}{J_v(\tau=t-t_\mathrm{i})}\right|^{1/2}.$$

In the cylindrical coordinates, $J(\tau)$ is defined as[24]

$$J(\tau) = \rho\det\left(\frac{\partial(\rho,z,t)}{\partial(t_\mathrm{i},\theta_\mathrm{i},\tau)}\right). \tag{11}$$

Using the classical motion equation for the detached electron in the harmonic potential plus the oscillating electric field (Eq. (3)), we obtain

$$A_v = \frac{R}{(t-t_\mathrm{i})}\left|\frac{k_0}{\cos\theta_\mathrm{i}k_0\left[A\omega\sin(\omega t+\varphi_0)\dfrac{\partial\varphi_0}{\partial t_\mathrm{i}}-\cos(\omega t+\varphi_0)\dfrac{\partial A}{\partial t_\mathrm{i}}\right]}\right|^{1/2}. \tag{12}$$

The classical action S_v along the v-th closed orbit can be calculated from

$$S_v = \oint_v p\,\mathrm{d}q = \int_{t_\mathrm{i}}^{t} p_\rho\,\mathrm{d}\rho + \int_{t_\mathrm{i}}^{t} p_z\,\mathrm{d}z + \int_{t_\mathrm{i}}^{t} p_t\,\mathrm{d}t. \tag{13}$$

Due to the influences of the harmonic potential and the electric field force, the electron will return back to the source region after a period of time. Around the source region (usually a few atomic units in size, $r<10a_0$), we find that the influences of the electric field potential and the harmonic potential $F_0\sin(\omega t)z+(1/2)\omega^2z^2$ on the detached electron are small. Therefore, the returning wave function behaves like a plane wave:

$$\psi_\mathrm{ret}^v(\mathrm{r},t) = f_\mathrm{L}(t_\mathrm{i})\,\mathrm{e}^{-\mathrm{i}Et}C(k_0)\mathrm{Y}_{lm}(\theta_\mathrm{i},\varphi_\mathrm{i})N_\mathrm{co}^v\,\mathrm{e}^{\pm\mathrm{i}k_\mathrm{ret}z}, \tag{14}$$

where N_co^v is a matching factor, which is given by

$$N_\mathrm{co}^v = \frac{A_v}{R}\exp\left[\mathrm{i}\left(\tilde{S}_v-\lambda_v\frac{\pi}{2}\right)\right], \tag{15}$$

with $\tilde{S}_v$ being a redefined action function[24] $\tilde{S}_v = S_v + E(t-t_\mathrm{i})$.

The symbol "$\pm$" in the exponent in Eq. (14) is determined by the direction of the returning wave: if the electron wave returns along the $-z$ axis, we choose "$-$" in the phase factor; however, for the electron wave returns along the $+z$ axis, we use symbol "$+$". The k_ret in Eq. (14) is the returning electron momentum.

Substituting N_co^v into Eq. (14), and carrying out the overlap integral in Eq. (8), we obtain the oscillating term in the photodetachment cross section as follows:

$$\sigma_\mathrm{osc}(E,t) = \sigma_0\cdot\sum_v 3g_v f_\mathrm{L}(t)f_\mathrm{L}(t_\mathrm{i})\frac{C(k_\mathrm{ret})}{C(k_0)}\times\frac{A_v}{k_0R}\sin\left[\left(\tilde{S}_v-\lambda_v\frac{\pi}{2}\right)\right], \tag{16}$$

where g_v is a factor. If the outgoing and returning directions for the electron orbit are the same, $g_v=-1$; otherwise $g_v=1$.[26]

By combining Eq. (16) and Eq. (7), we o the total time-dependent photodetachment cross section of H^- ion in the harmonic potential plus the oscillating electric filed:

$$\begin{aligned}\sigma(E,t) &= \frac{16\sqrt{2}B^2\pi^2E^{3/2}}{3cE_\mathrm{p}^3}f_\mathrm{L}^2(t)\\ &+\frac{16\sqrt{2}B^2\pi^2E^{3/2}}{cE_\mathrm{p}^3}\sum_v g_v f_\mathrm{L}(t)f_\mathrm{L}(t_\mathrm{i})\\ &\times\frac{C(k_\mathrm{ret})}{C(k_0)}\frac{A_v}{k_0R}\sin\left[\left(\tilde{S}_v-\lambda_v\frac{\pi}{2}\right)\right].\end{aligned} \tag{17}$$

4. Results and discussion

Using Eq. (17), we calculate the time-dependent photodetachment cross section of an H^- ion in the harmonic potential plus the oscillating electric field. In this work, we choose the photon energy $E_\mathrm{p}=1.0$ eV, the initial outgoing time t_i and the returning time t which are localized in the region $[-3.14$ ps, $+3.14$ ps$]$. Firstly, we keep the frequency in the harmonic potential and the oscillating electric field unchanged, $\omega_0 = 1.21\times10^{-5}$ a.u., then we study the influence of the oscillating electric field strength on the photodetachment cross section.

In Fig. 2, we discuss the photodetachment of this system with a relatively weak electric field strength, $F_0=10$ kV/cm. Through numerical calculation, we find only two closed orbits of the detached electron existing: one is the down closed orbit and the other is the down–up closed orbit as shown in Fig. 1.

The t–t_i curves for these two orbits are shown in Fig. 2(a). From this figure, we can obtain the initial outgoing time t_i and the returning time t for the down and down–up closed orbits. Figure 2(b) shows the photodetachment cross section under this condition. Oscillatory structure appears in the cross section due to the effect of interference between the returning electron wave and the initial outgoing wave. However, the oscillating amplitude is relatively small and the oscillatory structure is restricted only in a small interval. The reason can be explained as follows. If the oscillating electric field strength F_0 is very weak, the electric field force acting on the detached electron is very small compared with the effect of the harmonic potential. If the electron is emitted along the $+z$ axis, the electric field force cannot return it back to the origin. Thus the up closed orbit does not exist. In addition, the variation of the photodetachment cross section with time is not obvious and the time-dependent effect on the cross section can be neglected.

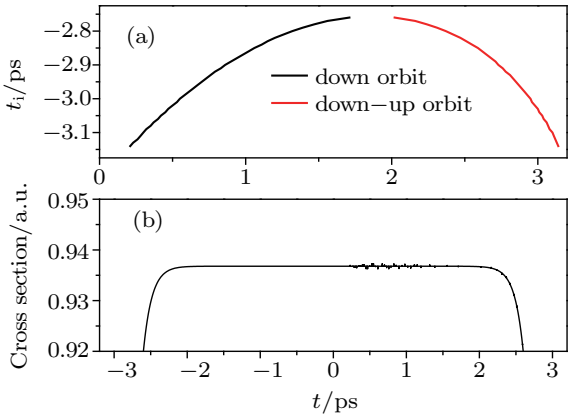


Fig. 2. (color online) (a) Plot t_i–t for the detached electron in the harmonic potential plus the oscillating electric field, with frequency in the harmonic potential and the electric field being $\omega = 1.21 \times 10^{-5}$ a.u., the electric field strength $F_0 = 10$ kV/cm, and the photon energy $E_p = 1.0$ eV, and (b) corresponding time-dependent photodetachment cross section in the harmonic potential plus the oscillating electric field.

As the strength of the oscillating electric field increases, its influence on the detached electron becomes strong. Except the down and down–up closed orbits, the up closed orbit also appears. Figure 3(a) shows the t_i–t curves for these three orbits with the electric field strength $F_0 = 20$ kV/cm. From this plot, we find for the down and down–up closed orbits, the initial outgoing time t_i for the detached electron is negative; however, for the up closed orbit, t_i can be negative or positive. In addition, the returning time for the up closed orbit is only localized in a small interval: $2.97 < t < 3.14$ ps. The corresponding photodetachment cross section with the electric field strength $F_0 = 20$ kV/cm is shown in Fig. 3(b). It is found that the oscillatory structure in the photodetachment cross section turns complex and the time-dependent effect on the cross section becomes obvious compared with the scenario in Fig. 2(b). However, the oscillation in the cross section is mainly caused by the down and down–up closed orbit, the contribution of the up closed orbit to the photodetachment cross section is very small and can be neglected.

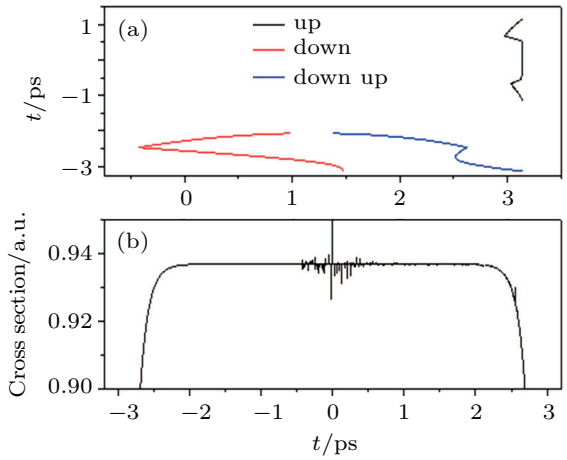


Fig. 3. (color online) (a) Plot t_i–t for the detached electron in the harmonic potential plus the oscillating electric field, with frequency in the harmonic potential and the electric field being $\omega = 1.21 \times 10^{-5}$ a.u., the electric field strength $F_0 = 20$ kV/cm, and photon energy $E_p = 1.0$ eV, (b) corresponding time-dependent photodetachment cross section with the electric field strength $F_0 = 20$ kV/cm.

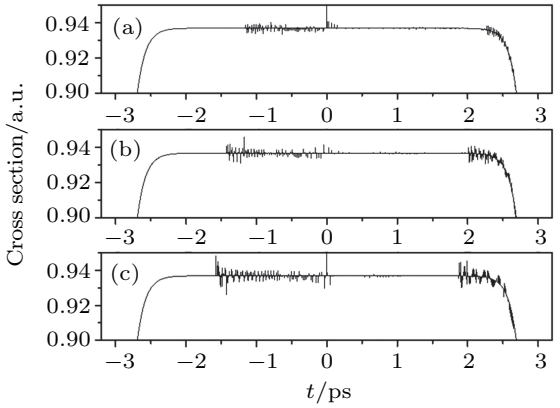


Fig. 4. Influences of the oscillating electric field strength on the photodetachment cross section of H^- ion in the harmonic potential plus the oscillating electric field, with frequency in the harmonic potential and the electric field $\omega = 1.21 \times 10^{-5}$ a.u., photon energy $E_p = 1.0$ eV, and electric field strength $F_0 = 50$ kV/cm (a), 100 kV/cm (b), and 200 kV/cm (c).

As the oscillating electric field strength further increases, there are still three different types of closed orbits as shown in Fig. 3(a). But the contribution of the up closed orbit to the cross section turns apparent and the oscillatory structure in the photodetachment cross section becomes much more complicated. Both the oscillating region and the oscillating amplitude are enlarged. For example, in Fig. 4(a), the electric field strength $F_0 = 50$ kV/cm. We find that the oscillating structure in the photodetachment cross section is localized in the region $-1.14 < t < 3.14$ ps; however, when the electric field strength increases to $F_0 = 200$ kV/cm as shown in Fig. 4(c), the oscillating region increases $-1.58 < t < 3.14$ ps. The reason can be analyzed as follows: with the increase of electric field strength,

the electric field force acting on the detached electron becomes stronger, which makes the period of the closed orbit shorter. From Eq. (12), we find that the amplitude for each closed orbit becomes increased. According to the closed orbit theory, the oscillation in the photodetachment cross section is caused by the interference between the returning electron wave and the initial outgoing electron wave. After the electron is emitted from the origin, the strong electric field force will return the electron back in a small period of time, which causes the interference effect in the photodetachment cross section to become stronger. Therefore, the oscillatory structure in the time-dependent cross section goes complicated with the increase of electric field strength.

Next, we keep the electric field strength $F_0 = 100$ kV/cm unchanged, then we discuss the variation of the photodetachment cross section with frequency ω in the harmonic potential and the oscillating electric field. The result is shown in Fig. 5. Figure 5(a) shows the photodetachment cross section with frequency $\omega = 0.605 \times 10^{-5}$ a.u. Under this condition, the influences of the harmonic potential and the oscillating electric field on the detached electron are small, only the down and the down–up closed orbits exist. The oscillating amplitude in the photodetachment cross section is relatively small. With the increase of the frequency in the harmonic potential and the oscillating electric field, the number of the closed orbits increases. Figure 5(b) shows the photodetachment cross section with frequency $\omega = 1.0 \times 10^{-5}$ a.u. There are three different types of closed orbits of detached electron, namely, the up orbit, down orbit, and the down–up orbit, which makes the oscillatory structure in the photodetachment cross section complex. As the frequency increases to $\omega = 3.5 \times 10^{-5}$ a.u., the number of the closed orbits of detached electron increases to 4. Except the up, down, and the down–up orbit, the up–down orbit can also exist. The total photodetachment cross section is shown in Fig. 5(c). The oscillatory structure in the photodetachment cross section goes further complex. Figure 5(d) shows the photodetachment cross section with frequency $\omega = 4.84 \times 10^{-5}$ a.u. Under this condition, the fast oscillation in the harmonic potential and the oscillating electric field makes the number of the closed orbits increased to 7. We can clearly see that the oscillatory structures become much more complicated, and the oscillating amplitude in the cross section increases greatly. The reason is as follows. With the increase of the frequency in the harmonic potential and the oscillating electric field, the number of the closed orbits of the detached electron increases. As we stated above, the interference between the returning electron wave and the initial outgoing electron wave leads to the oscillatory structure in the photodetachment cross section: the more the number of the closed orbits, the more the returning waves that return back to the atom; therefore, their interference effect will become strong, which makes the oscillation in the cross section complicated.

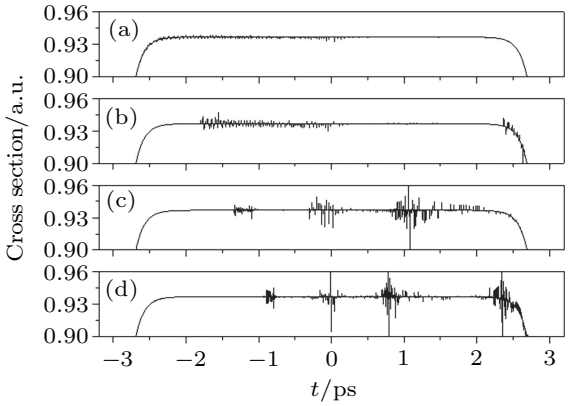


Fig. 5. Variations of the photodetachment cross section with time t at electric field strength $F_0 = 100$ kV/cm and the photon energy $E_p = 1.0$ eV for frequency in the harmonic potential and the oscillating electric field $\omega = 0.605 \times 10^{-5}$ a.u. (a), 1.0×10^{-5} a.u. (b), 3.5×10^{-5} a.u. (c), and 4.84×10^{-5} a.u. (d)

Finally, in order to see the relation of each closed orbit to the photodetachment cross section, we remove the background term in Eq. (17) and only calculate the oscillating part $\sigma_{\rm osc}(E,t)$ in the photodetachment cross section. The electric field strength and the frequency in the harmonic potential and the oscillating electric field are the same as those given in Fig. 5(d). Under this circumstance, there are 7 closed orbits of the detached electron: the up orbit, down orbit, up–down orbit, down–up orbit, up–down–up orbit, down–up–down orbit, and up–down–up–down orbit. Figure 6(a) shows the total oscillating cross section caused by these 7 closed orbits of the detached electron. Figures 6(b)–6(h) show the oscillating cross sections caused by the corresponding type of closed orbit respectively. By comparing the above figures, we can see that the oscillations in the cross section, caused by the up and down closed orbits play the significant roles, followed by the contribution of the up–down and down–up orbits. The oscillations in the cross section, caused by the other three closed orbits, are relatively small. The reason is as follows. Because the periods of the up orbit and down orbit are relatively shorter than the periods of the other orbits, from Eq. (12) we can see that the values of amplitude factor A for these two orbits are large, thus their contributions to the cross section are significant. However, for the other closed orbits, their periods are longer, which makes the amplitude factor become smaller, as a consequence, the oscillating amplitudes caused by these orbits are negligible compared with those by the up and down orbits.

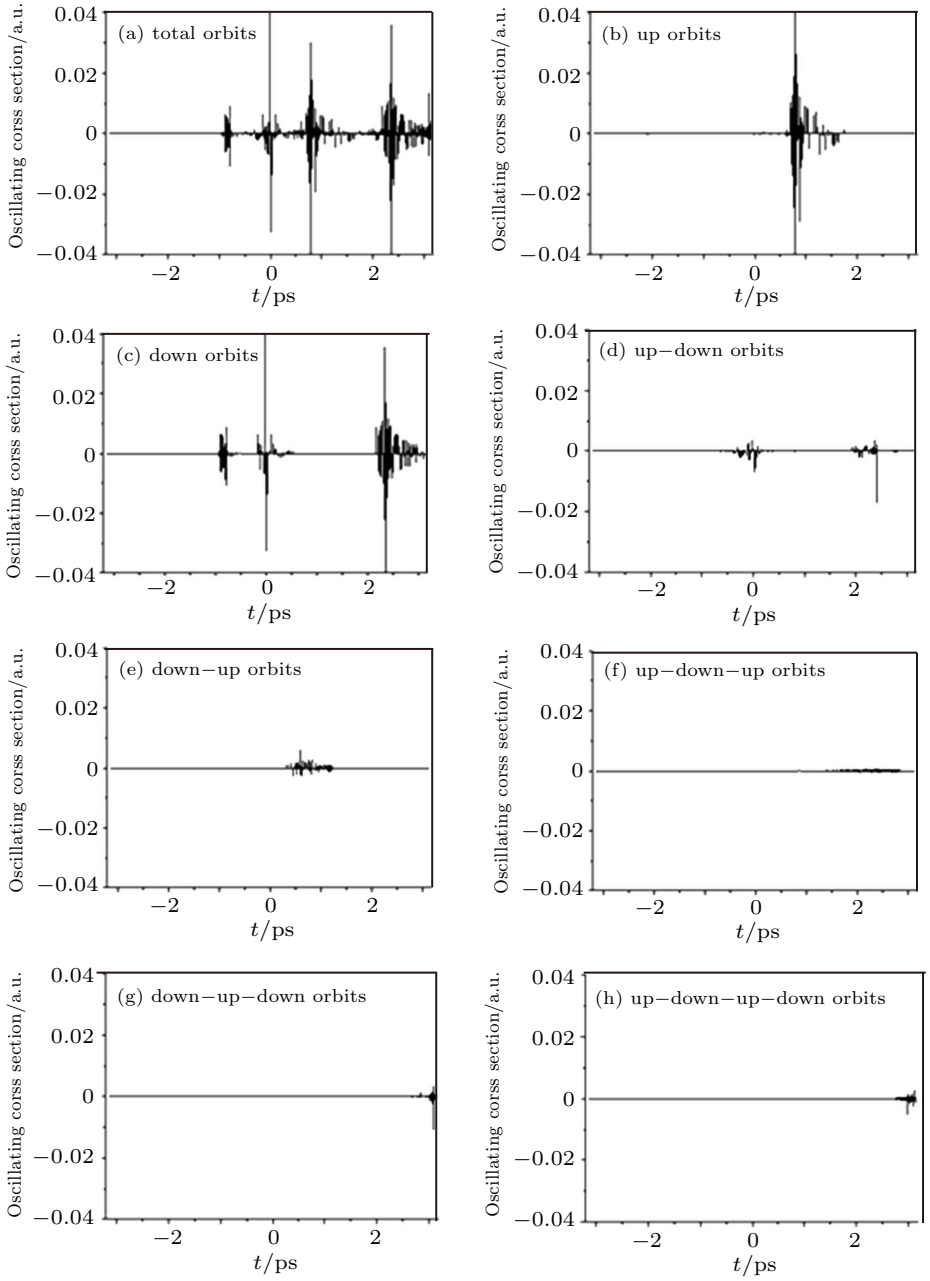


Fig. 6. (a) Total oscillating cross section of H^- ion in the harmonic potential plus the oscillating electric field, at electric field strength $F_0 = 100$ kV/cm, the photon energy $E_p = 1.0$ eV, and frequency in the harmonic potential and the oscillating electric field $\omega = 4.84 \times 10^{-5}$ a.u. (b)–(h) Oscillating cross sections caused by the up orbit, down orbit, up–down orbit, down–up orbit, up–down–up orbit, down–up–down orbit, and the up–down–up–down orbit, respectively.

5. Conclusions

According to the time-dependent closed orbit theory, we study the influences of the harmonic potential and the oscillating electric field on the photodetachment cross section of the H^- ion. An analytical formula for calculating the photodetachment cross section of this system is put forward. It is found that when the oscillating electric field strength is very weak, the oscillatory structure in the photodetachment cross section is nearly invisible. However, if the electric field is strong, the photodetachment cross section oscillation turns complicated. On the other hand, we notice that when the frequency in the harmonic potential and the oscillating electric field is small, only two closed orbits of detached electron exist, which makes the interference effect in the photodetachment cross section less complex. With the increase of the frequency in the harmonic potential and the oscillating electric field, the number of closed orbits of detached electron increases, and the oscillatory structure in the photodetachment cross section goes much more complex. In addition, the relation of each closed orbit to oscillating photodetachment cross section is analyzed qualitatively. In this work, we only consider the case that the frequencies of the oscillating electric field and the harmonic potential are equal. When the frequency in the oscillating electric field is unequal to the frequency in the harmonic po-

tential, the motion equations of the detached electron and the photodetachment cross section will be changed. However, the method we used in this paper is still suitable. Our study provides a clear and intuitive picture for the photodetachment dynamics of H^- ion driven by a harmonic potential plus a time-dependent oscillating electric field. We hope that our work can guide the future experimental research of the photodetachment dynamics in the space and time varying electric field.

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