Photodetachment of negative ion in an electric field near a moving surface

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Photo-detached electron dynamics of the negative ion in the electric field near a moving-surface has been investigated for the first time. This system is interesting because it provides a rudimentary model for simulating cosmic rays' collisions with planets by looking at the detached electron's movement in the electric field near a moving surface. In contrast to the photodetachment of negative ion in the electric field near a static surface, the detached electron's trajectory gets much more complicated due to the influence of the moving surface. As a correspondence, the photodetachment cross section exhibits an irregular oscillatory structure compared with the stair-case structure for the same but the surface is static. Our results suggest that the photodetachment cross section of this system depends on the electric field strength, the initial position and the speed of the moving surface sensitively. The method used in this work is universal and can be applied to study the photodetachment of non-hydrogen negative ion. Our work provides some insights into the moving surface effect on the photodetachment dynamics of negative ion in the electric field and may guide the future experimental researches in the ion trap.

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1. Introduction

Photodetachment of negative ion is an important example of fundamental processes in the field of light and matter interacts. Such process occurs in stellar and planetary atmosphere, astrophysics, plasmas, etc. Since H^- is the simplest ion and is an important prototype in atomic physics [1], it has been studied by many researchers both experimentally and theoretically. The theoretical work on the photodetachment of H^- ion in the presence of external fields has attracted much attention since the early 1980s [2-3]. It has been shown that the photodetachment cross section of the H^- ion in the electric field displays a "ripple" structure, which consists of a smooth background term plus a sinusoidal oscillation term. Fabrikant used classical and semiclassical method to interpret the "ripple" structure in the photodetachment cross section [2]. The experimental observation for the "ripple" structure in the photodetachment cross section of H^- ion in the electric field was firstly observed by Bryant et al. [4]. Rau and Wong [5] and Green and Rouze [6] applied the "Frame transformation theory" to explain these oscillations. They demonstrated that the oscillations in the cross section was induced by the quantum interference between the detached-electron waves emanating outward from the source and those reflected from the electric potential barrier. At the same time, Du and Delos [7] put forward a simple analytical formula for calculating the photodetachment cross section of ion in the static electric field. They used the quantum approach by solving time-independent Schrodinger equation in momentum representation combined with the stationary phase approximation. Furthermore, a new semi-classical approach called closed orbit theory (COT) developed by Du and Delos [8-10] was used to analyze the field-induced oscillations in the photodetachment cross section of ion. They thought that the "ripple" structure in the cross section was caused by the interference between the detached electron wave emitting out from the nucleus and the wave returning back to the nucleus traveling along the closed orbit [11]. Their closed orbit theory result agreed well with the quantum method [7], which suggests the correctness of the closed orbit theory. Since closed orbit theory provided a clear physical description for the photodetachment dynamics of the negative ions in the external fields, many researcher have used this method to study the photodetachment of negative ion in other external fields, such as in crossed electric and magnetic fields [12-16], in parallel electric and magnetic fields [17-21], and in a gradient electric field [22] etc.

In fact, besides the external electric and magnetic fields, other external environments such as surface, quantum well or cavity can also affect the photodetachment of negative ions significantly. In 2006, Yang et al have studied the photodetachment of ion near an elastic surface [23]. They found that the surface-induced oscillation in the cross section was quite similar to the case of a static electric field. Subsequently, they further studied the electric field effect on the photodetachment of ion near an elastic surface using both the semiclassical method and the quantum method [24].For an elastic wall perpendicular to the electric field, the photodetachment of ion displays a stair-case structure in contrast to the smooth sinusoidal oscillatory pattern when only the electric field or a single surface exists. Subsequently, the photodetachment of H^- ion in a quantum well [25,26] or in a microcavity [27-31] have been reported by different researchers. In these previous studies, the external surface or the surfaces in the quantum well or in the cavity are static. As to the moving surface effect on the photodetachment of negative ion, the reports are relatively few. Recently, our group have studied the photodetachment of negative ion near a moving surface or in a quantum well with a moving wall [32-33]. As to the photodetachment of negative ion in the coexistence of the electric field and the moving surface, no one has given the report to the best of our knowledge. For a moving surface perpendicular to the electric field, after collision with the moving surface, the detached electron will lose some energy, thus the returning kinetic energy of the detached electron is unequal to its initial value. As a consequence, due to the influence of the moving surface, only a portion of the electronic wave was bounced back by the moving surface to the nucleus. Therefore, the interference effect between the returning electron wave with the initial outgoing electron wave gets weakened, and the photodetachment cross section displays an irregular structure, contrasting to the photodetachment of negative ion in the presence of an electric field near a static surface [24].

In the present work, we investigated the moving surface effect on the photodetachment dynamics of H^- ion in the electric field. Firstly, we find out all the closed orbits of the detached electron and obtain the period, action for each closed orbit using the iterative method. Then we put forward an analytical formula for calculating the photodetachment cross section of this system. The calculation results suggest that the moving speed of the surface is an important factor to modulate the photodetachment cross section. In addition, the electric field strength and the initial distance between the ion and the surface can also affect the photodetachment cross section of this system. Therefore, we can control the photodetachment of negative ion in the external field using a moving surface. The method used in this work is universal and can be applied to study the photodetachment of non-hydrogen negative ion (such as F^-, S^-, Cl^-, etc) in the external field near a moving surface. Therefore, our work provides some insights into the moving surface effect on the photodetachment dynamics of negative ion in the electric field and may guide the future experimental researches toward this field.

This paper is summarized as follows: Section 2 shows a theoretical model for the photodetachment process of H^- ion in the electric field near a moving surface. In particular, the closed orbit of the detached electron is examined in great detail. Sec.3 briefly gives the formula for calculating the photodetachment cross section of this system. In section 4, we calculate the photodetachment cross section of this system, and discuss the influence of the electric field strength, the moving speed and the initial position of the surface on the photodetachment cross section. Some conclusions of this paper are presented in section 5. Atomic units are used in this work unless indicated otherwise.

2. Theoretical model and the closed orbit of the detached electron

A schematic description of the photodetachment process of H^- ion in an electric field near a moving surface is shown in Fig. 1. The solid dark point at the origin denotes the H^- ion source. The electric field is pointing along the +z axis. An elastic surface is located perpendicular to the –z axis and is moving along the –z axis with a speed *v*. The initial distance between the ion and the surface is d_0. After a period of time *t*, the distance between the ion and the surface is *d*: $d=d_0+vt$.

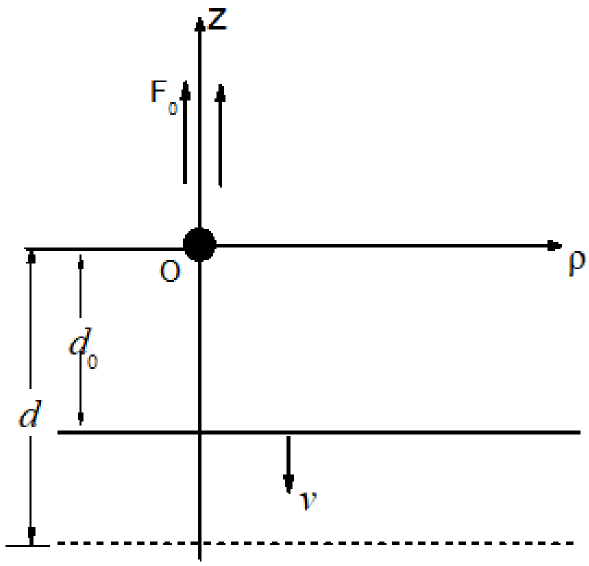

Fig. 1. Schematic description of the photodetachment process of H^- ion in an electric field near a moving surface

When a laser light irradiates H^- ion in an electric field, the bound electron may absorb a photon. As the photon energy is larger than the binding energy of the H^- ion, the bound electron will be photo-detached. The electron wave propagates away from the hydrogen atom in all directions according to the semiclassical mechanics, and it is correlated with classical trajectories. Due to the influence of the electric field and the moving surface, some of the electron wave will be returned back to the origin to form a closed orbit. The interference effect between the returning electron waves traveling along the closed orbits with the initial outgoing electron waves induces the oscillatory structures in the photodetachment cross section. After photodetachment, the Hamiltonian governing the electron motion in the electric field near a moving surface is:

$$H = \frac{1}{2}(p_\rho^2 + p_z^2) + F_0 z + V_b(r) \quad (1)$$

Here the cylindrical coordinates (ρ, z, φ) have been used. Due to the cylindrical symmetry of this system, the φ motion has been separated. Since the z component of the angular momentum is a constant of motion, we choose $l_z = 0$ in this work. When the electron is far away from the nucleus, the short-ranged potential $V_b(r)$ between the neutral atom and the bound electron can be neglected. Suppose the electron is emitted from the origin with the initial momentum k, the initial outgoing angle relative to the +z-axis is θ. By solving the Hamiltonian canonical equations with the initial condition $\rho(t=0)=0$, $z(t=0)=0$, $p_\rho(t=0) = k\sin\theta$, $p_z(t=0) = k\cos\theta$, we can obtain the detached electron's motion equation

$$\rho(t) = k\sin\theta\, t \quad (2)$$

$$z(t) = k\cos\theta\, t - F_0 t^2/2 \quad (-d < z < +\infty) \quad (3)$$

It is noted that the ρ motion is a uniformly linear one and the z motion above the surface is a uniformly accelerated motion. Some trajectories of the detached electron in the electric field near a moving surface are shown in Fig. 2.

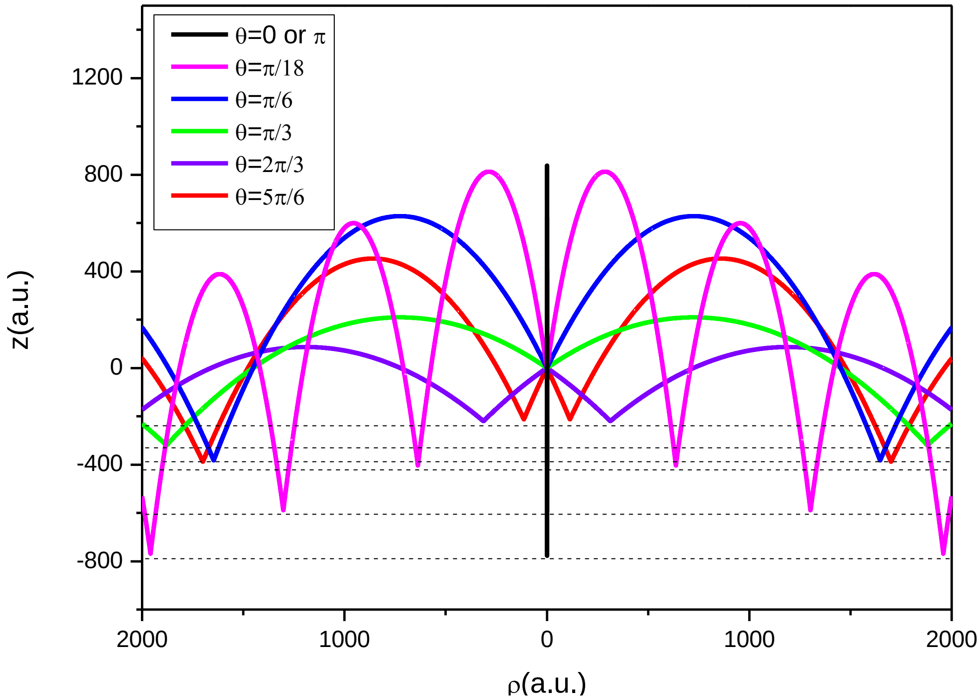

Fig. 2. Some classical trajectories of the detached electron in the electric field near a moving surface. The electric field strength F_0=200kV/cm, the photon energy E_p=1.0eV. The initial distance from the ion to the moving surface is d_0=200a.u., the moving speed of the surface is v=0.0001a.u. Different lines denote different trajectories emitted from the origin. The initial outgoing angle of the electron trajectory is given in the plot (color online)

From the above figures, we can obviously find that only the detached electron emitted up ($\theta = 0$) or down ($\theta = \pi$) along the z axis can be returned back by the electric field or the surface to the origin to form a closed orbit. Among all the orbits closed at the nucleus, the following four types are fundamental. (i) The electron goes up along the +z direction, reaches its maximum, and then is pulled back by the electric field and returns to the origin. We call this orbit the up orbit. (ii)The electron goes down in the −z direction, after a period of time, it hits the moving surface and then bounces back to the origin. This orbit is called the down orbit. (iii) The electron completes the up orbit first and then passes through the origin, and continues to complete the down orbit, which is called the up-down orbit. (iv) The electron completes the down orbit first and then the up orbit, which is called the down-up orbit. These four types of closed orbits described above are called basic closed orbits. The other closed orbits are the combination of these four types of orbits. We use two indices (j,n) to distinguish different closed orbit, where j=1,2,3,4 and n=0,1,2,3,… Here n=0 means that the orbit is a fundamental closed orbit (j=1,2,3 and 4 for the above four closed orbits). When , the orbit (j,n) has two parts. The first part is always the j-th fundamental closed orbit. The second part consists of n repetitions of the j=3 or j=4 orbit. Some closed orbits are given in Fig.3. Fig.3(a-d) shows the four fundamental closed orbits. Fig.3(e) shows the (j=1,n=1) orbit, which can be considered as a combination of the (j=1,n=0) orbit and the (j=4,n=0) orbit. Fig.3(f) is the (j=2,n=1) orbit, which is the combination of orbits (j=2,n=0) and (j=3,n=0).

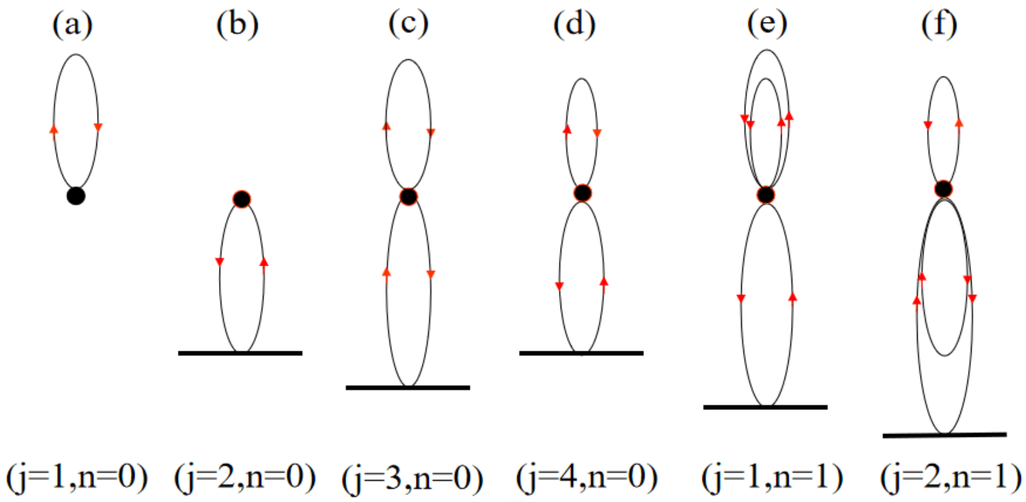

Fig. 3. Some typical closed orbits for the detached electron in the electric field near a moving surface

The period of the detached electron's closed orbit can be calculated as follows. For the four fundamental close orbits(n=0, j=1,2,3,4), the period can be easily obtained from the motion equations of the detached electron. For the (j=1,n=0) orbit , its period can be deduced from Eq.(3):

$$T_{1,0} = \frac{2k}{F_0} \tag{4}$$

For the (j=2,n=0) orbit, its period can be divided into two parts. In the first part, the electron propagates along the –z axis with the initial momentum k , after a period of time t_l , it hits the surface. This period of time is: $t_l = \frac{-(k-v)+\sqrt{(k-v)^2+2F_0d_0}}{F_0}$. After collision with the moving surface, the speed of the detached electron will reduce 2v. Its returning momentum becomes: $k_{ret} = -v + \sqrt{(k-v)^2 + 2F_0d_0}$. Meanwhile, the distance from the surface to the origin now becomes $d=d_0+vt_l$. In the second part, the electron is bounced back by the surface and propagates along the +z axis with the returning momentum k_{ret} . After a period of time t_r , $t_r = \frac{k_{ret} - \sqrt{(k_{ret})^2 - 2F_0d}}{F_0}$, the electron returns back to the origin. We found that Therefore, the period of the (j=2,n=0) orbit can be written as:

$$T_{2,0} = t_l + t_r \tag{5}$$

The period of the (j=3,n=0) orbit can be considered as a combination of (j=1,n=0) orbit and (j=2,n=0) orbit:

$$T_{3,0} = T_{1,0} + t_l + t_r \tag{6}$$

The period of the (j=4,n=0) orbit is equal to the period of the (j=2,n=0) orbit plus the (j=1,n=0) orbit:

$$T_{4,0} = T_{2,0} + \frac{k + F_0(t_l - t_r) - 2v}{F_0} \tag{7}$$

For the other close orbit ($n \neq 0$, j=1,2,3,4), its period $T_{j,n}$ can be calculated using the iterative method.

3. Photodetachment cross section

On the basis of the closed orbit theory, the photodetachment cross section of the H^- ion in the external environment can be written as:

$$\sigma(E) = \sigma_0(E) + \sigma_{ret}(E) \tag{8}$$

The first part $\sigma_0(E)$ is the smooth background term, which is the photodetachment cross section without the electric field or the surface:

$$\sigma_0(E) = \frac{16\sqrt{2}\pi^2 B^2 E^{3/2}}{3c(E + E_b)^3}. \tag{9}$$

Here, B =0.31552 is a normalization constant. E_b is the binding energy of the H^- ion: E_b = 0.754 eV.

The second part is the oscillating term, which corresponds to the contribution of the returning wave interfering with the ion source wave:

$$\sigma_{ret}(E) = -\frac{4\pi E_p}{c} \operatorname{Im}\langle D\psi_i | \psi_{ret} \rangle. \tag{10}$$

where E_p is the photon energy: $E_p = E + E_b$, D is the dipole operator. For z-polarized laser light, D=Z. ψ_i is the initial bound state wave function of the H^- ion: $\psi_i = Be^{-k_b r}/r$, $k_b = \sqrt{2E_b}$. $D\psi_i$ is the ion source wave function. ψ_{ret} is the returning electron wave function, which can be got using the semiclassical method. Firstly, we draw a small spherical surface centered at the origin with radius R, the initial outgoing wave on this sphere surface is

$$\psi_{out}(R,\theta,\phi) = C(k_{j,n}) Y_{lm}(\theta,\phi) \frac{e^{ik_{j,n}R}}{R} \tag{11}$$

$C(k_{j,n})$ is an energy-dependent factor, which depends upon the laser polarization. For the photodetachment of H^- ion, $C(k_{j,n})$ can be written as:

$$C(k_{j,n}) = \frac{4Bk_{j,n}i}{\left(k_b^2 + k_{j,n}{}^2\right)^2} \sqrt{\frac{4\pi}{3}} \tag{12}$$

$Y_{lm}(\theta,\phi)$ is the spherical harmonic function. Since the detached electron wave source is a p wave corresponds to H^- ion, then $l = 1$, m=0.

As the outgoing wave propagates out from the spherical surface, due to the influence of the electric field and the moving surface, its amplitude and phase will be changed. According to the semiclassical approximation, the electron wave function in the outside of the spherical surface can be written as:

$$\psi_{sc}(r,\theta,\phi) = \sum_{j,n} \psi_{out}(R,\theta,\phi) A_{j,n} e^{i[S_{j,n} - \mu_{j,n} \cdot \pi/2]} \tag{13}$$

The sum includes all the closed orbit of the detached electron. A_{jn} is the amplitude of the wave function:

$$A_{j,n} = \left| \frac{\det J_{j,n}^{(2)}(\rho,z,0)}{\det J_{j,n}^{(2)}(\rho,z,T_{j,n})} \right|^{1/2} \left| \frac{\rho(0)}{\rho(T_{j,n})} \right|^{1/2} \tag{14}$$

Here, $J_{j,n}(\rho,z,t)$ is the Jacobian: $J_{j,n}(\rho,z,t) = \rho(t) \frac{\partial(\rho,z)}{\partial(t,\theta)}$. Using the classical motion equation of the electron in the electric field near a moving surface (Eq.(3)), we get:

$$A_{j,n} = \left| \frac{1}{T_{j,n}^2 (k_{j,n}{}^2 + (-1)^j F_0 k_{ret}^{j,n} T_{j,n})} \right|^{\frac{1}{2}}. \qquad 15)$$

Here $k_{ret}^{j,n}$ is the returning momentum along the j,n-th closed orbit.

$S_{j,n}$ in Eq.(13) is the action along the *j,n*-th closed orbit: $S_{j,n}=\int_0^{T_{j,n}}\vec{p}\cdot d\vec{q}$. $\mu_{j,n}$ is the Maslov index corresponding to the *j,n*-th closed orbit, which can be written as: $\mu_{j,n}=\mu_{j,0}+3n$. Here $\mu_{j,0}$ denotes the Maslov index of the four fundamental closed orbit, $\mu_{1,0}=1$, $\mu_{2,0}=2$, $\mu_{3,0}=3$, $\mu_{4,0}=3$.

When the electron wave is bounced by the electric field or the moving surface to the negative ion source along the closed orbit, the returning wave can be approximated as a sum of plane waves traveling along the z axis:

$$\psi_{ret}=\sum_{j,n}N_{j,n}Y_{lm}(\theta,\varphi)\exp(\pm ik_{ret}^{j,n}\cdot z) \qquad (16)$$

where $N_{j,n}$ is a factor, which can be written as:

$$N_{j,n}=(-1)^{\mu_{j,n-1}}C(k_{j,n})A_{j,n}e^{i[S_{j,n}-\mu_{j,n}\cdot\pi/2]} \qquad (17)$$

By substituting the above equation into Eq.(16) and carry out the overlap integration in Eq.(10), we obtain the oscillating term in the photodetachment cross section:

$$\sigma_{ret}=\sum_{j,n}M_{j,n}\sin(S_{j,n}-\mu_{j,n}\frac{\pi}{2}), \qquad (18)$$

In which

$$M_{j,n}=(-1)^{\mu_{j,n-1}}\frac{\pi^2}{c}\frac{1}{T_{j,n}\sqrt{|k_{j,n}{}^2+(-1)^jF_0k_{ret}^{j,n}T_{j,n}|}}\frac{8BE}{(E_b+E)^3} \qquad (19)$$

Finally, the total photodetachment cross section of H^- ion in the electric field near a moving surface can be written as:

$$\sigma=\sigma_0+\sigma_{ret}=\frac{16\sqrt{2}\pi^2B^2E^{3/2}}{3c\left(E+E_b\right)^3}+\sum_{j,n}M_{j,n}\sin(S_{j,n}-\mu_{j,n}\frac{\pi}{2}) \qquad (20)$$

4. Calculations and discussions

From Eq. (20), we find that the photodetachment cross section of this system is related to the moving speed of the surface, the initial distance from the surface to the ion and the electric field strength. Firstly, we choose the electric field strength F_0=200kv/cm, and show the variation of the photodetachment cross section with the moving speed of the surface *v* and the initial distance from the surface to the ion d_0. Fig. 4 shows the influence of the initial position of the moving surface on the photodetachment cross section. Suppose the speed of the moving surface is *v*=0.001a.u. Fig. 4(a) shows the photodetachment cross section with the initial distance from the moving surface to the origin is relatively small, d_0=100a.u. Under this condition, we find that the oscillating amplitude in the cross section is relatively large. With the increase of the initial distance from the moving surface to the origin, the oscillating amplitude in the cross section becomes decreased. If the initial distance from the moving surface to the origin is very large, d_0=5000a.u.., the oscillatory structure caused by the moving surface nearly disappears, and the photodetachment cross section approaches to the case in the electric field, as we can see from Fig. 4(f). The reason can be interpreted as follows: when the moving surface is close to the ion, the number of the closed orbit for the detached electron is very large. The four fundamental closed orbits and their repetitions as described in Sec.2 all contribute to the photodetachment cross section, which makes the interference between the returning electron wave with the initial outgoing wave get strong. Therefore, the oscillating amplitude in the cross section is very large. As we move the surface far away from the ion, only the up closed orbit induced by the electric field has some influence on the photodetachment cross section, the effect of other closed orbits is very small and can be neglected. Thus the interference between the returning electron wave with the initial outgoing wave get weakened, which decreases the oscillating amplitude in the photodetachment cross section.

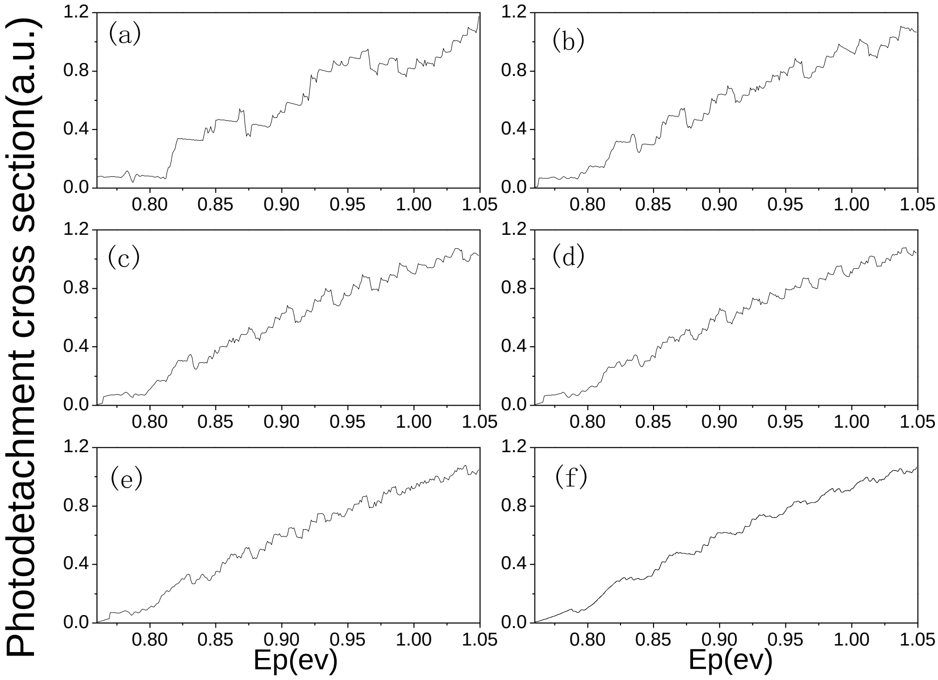

Fig.4. Variation of the photodetachment cross section of H^- ion in the electric field with the initial distance of the moving surface. Suppose the speed of moving surface is v=0.001a.u. The electric field strength is F_0=200kV/cm. The initial distance between the negative ion source and the moving surface is as follows: (a) d_0=100a.u , (b) d_0=300a.u, (c) d_0=500a.u, (d) d_0=700a.u ,(e) d_0=1000a.u , (f) d_0=5000 a.u.

Fig. 5 shows the dependence of the photodetachment cross section with the moving speed of the surface. Suppose the initial distance between H^- ion and the surface is fixed to be d_0=200a.u.

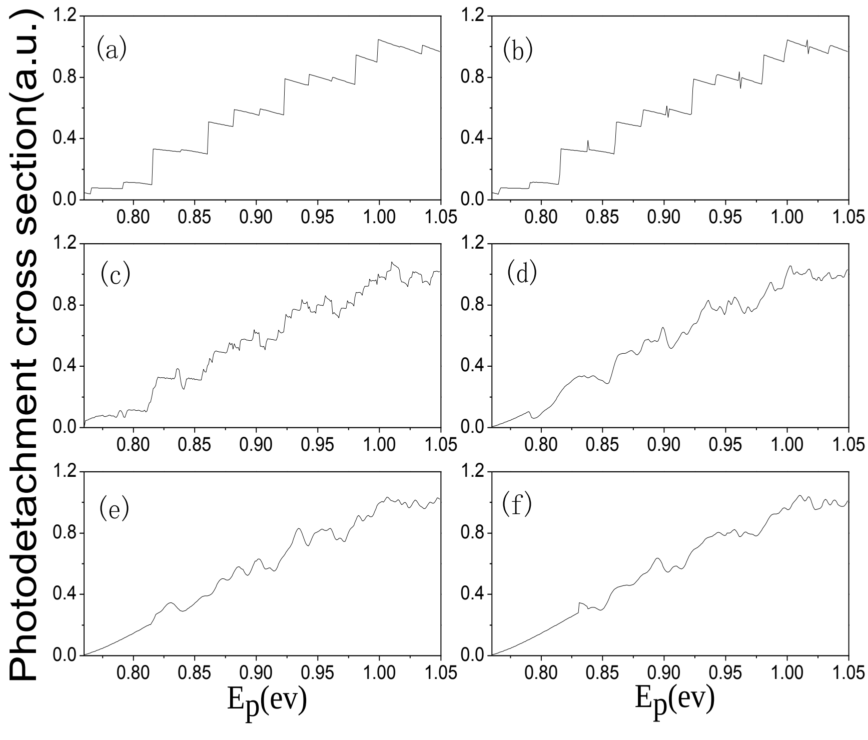

Fig. 5. Dependence of the photodetachment cross section on the speed of the moving surface. The initial distance between H^- ion and the surface is fixed to be d_0=200a.u., the electric field strength is F_0=200kV/cm. The speed of the moving surface is as follows: (a) v=0.0a.u, (b) v=0.0001a.u, (c) v=0.001a.u, (d) v=0.005a.u, (e) v=0.008a.u, (f) v=0.01a.u.

Fig. 5(a) is the photodetachment cross section of H^- ion in the electric field near a static surface, which is a regular stair-case structure as shown in Ref.[24]. As the surface is moving along the –z axis, the stair-case structure in the photodetachment cross section will change. Fig. 5(b) shows the photodetachment cross section with the moving surface moves very slowly, v=0.0001a.u. Under this circumstance, the moving surface effect on the photodetachment cross section is un-conspicuous. Only at some given energy, the photodetachment cross section gets irregular. As we increase the moving speed of the surface, the moving surface effect becomes obvious, the stair-case structure in Fig. 5(a) begins to disappear. As we can see from Fig. 5(c-f).

In order to show the moving surface effect on the photodetachment cross section of H^- ion in the electric field clearly, we only calculate the oscillating cross section σ_{ret} . Fig. 6(a) is the oscillating cross section when the surface is static, we find the oscillatory pattern is a regular saw-tooth structure. As we gradually increase the speed of the moving surface, the saw-tooth structure disappears. The oscillating amplitude in the cross section becomes decreased and irregular, the oscillating frequency gets increased at first, and then the trend reverses. When the moving speed of the surface is greater than 0.005, the oscillatory structure nearly disappears at low energy region. As the moving surface moves very quick, for example, in Fig. 6(f), v=0.01a.u. the moving surface can weaken the cross section significantly. The reason can be analyzed as follows: After collision with the moving surface, the detached electron will lose some energy, only a portion of the electronic wave is bounced back by the moving surface to the nucleus. Therefore, the interference effect between the returning electron wave with the initial outgoing electron wave gets weakened, which makes the oscillating amplitude decrease with the increase of the moving speed of the surface. As we show in Fig. 6(b-f) clearly.

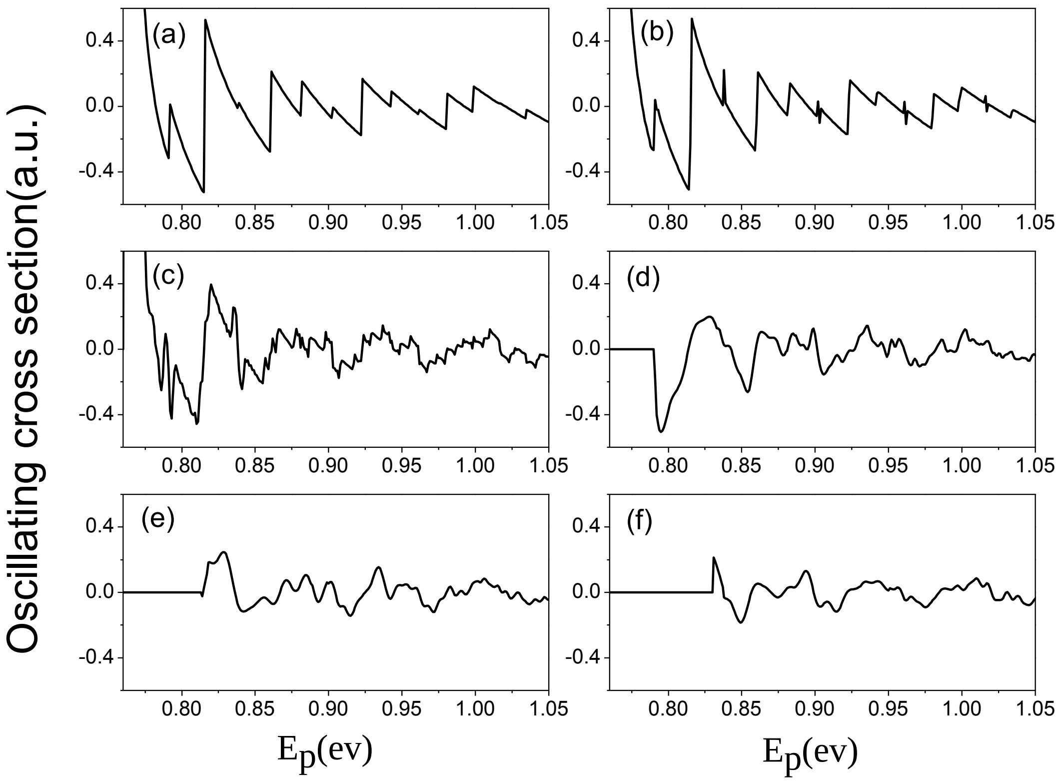

Fig. 6. Dependence of the oscillating cross section on the speed of the moving surface. The initial distance between H^- ion and the surface is fixed to be d_0=200a.u., the electric field strength is F_0=200kV/cm. The speed of the moving surface is as follows: (a) v=0.0a.u, (b) v=0.0001a.u, (c) v=0.001a.u, (d) v=0.005a.u, (e) v=0.008a.u, (f) v=0.01 a.u.

Next, we show the influence of the external electric field on the photodetachment cross section of this system. Suppose the speed of moving surface is v=0.001a.u, the initial distance from the surface to the ion is d_0=200a.u.. The result is shown in Fig. 7. Fig. 7(a) shows the photodetachment cross section with the electric field strength is relatively small, F_0=10*kV/cm*. Under this condition, the electric field effect on the photodetachment cross section is very small, and the moving surface effect plays the important role. The photodetachment cross section exhibits a sinusoidal oscillation term plus a series of small oscillatory structures. With the increase of the electric field strength, the electric field effect on the photodetachment cross section becomes much more obvious. Fig. 7(b) shows the photodetachment cross section with the electric field strength F_0=50*kV/cm*. The cross section oscillates in an irregular way, and the sinusoidal oscillation pattern only appears at high energy. As F_0 is increased further, the oscillatory structures in the cross section become much more complex, as we show in Fig. 7(c) and (d).

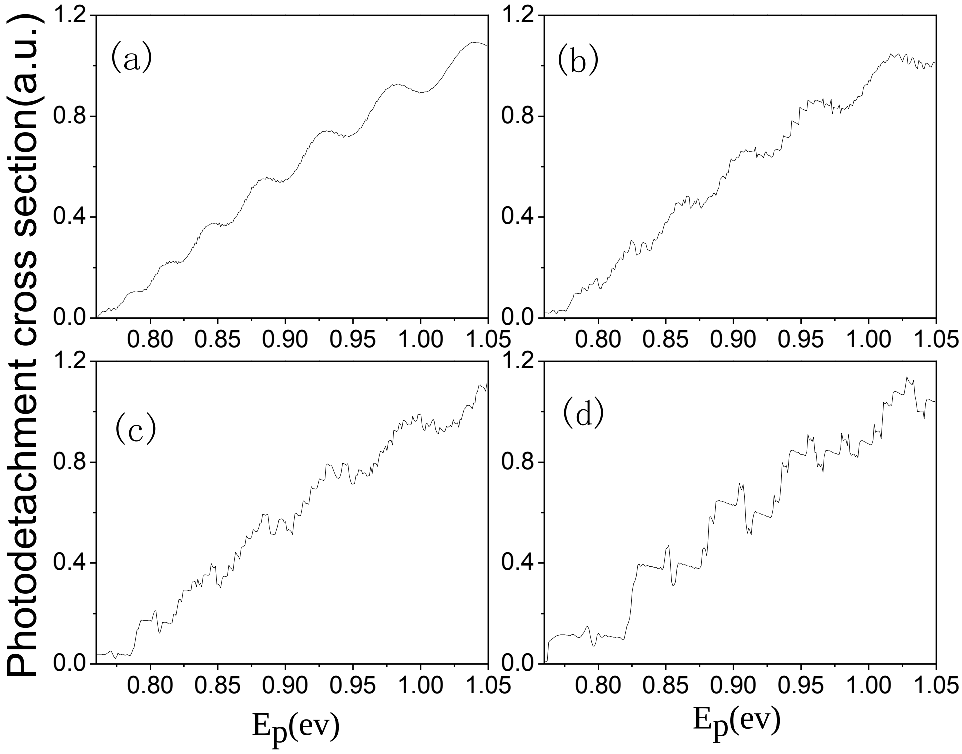

Fig. 7. Influence of the electric field strength on the photodetachment cross section of H^- ion near a moving surface. Suppose the speed of moving surface is v=0.001a.u, the initial distance from the surface to the ion is d_0=200a.u. The strength of the electric field is as follows: (a) F_0=10kV/cm, (b) F_0=50 kV/cm, (c) F_0=100 kV/cm, (d) F_0=300 kV/cm

Finally, in order to show the electric field effect on the photodetachment cross section of H^- ion near a moving surface clearly, we only calculate the oscillating cross section σ_{ret} and show the contribution of the four fundamental closed orbits to the cross section. Fig. 8(a) shows the oscillating cross section with the electric field strength F_0=10*kV/cm*. It is shown that the contribution of the down closed orbit as depicted in Fig. 3(b) which is induced by the moving surface dominates the whole cross section, the contribution of the other types of closed orbit is small. Fig. 8(b) is the case with the electric field strength F_0=50*kV/cm*. We find at low energy region, besides the down orbit, the contribution of the up closed orbit caused by the electric field also becomes significant, which makes the cross section oscillates in an irregular way. When we further increase the electric field strength, all the four fundamental closed orbits have some contribution to the cross section, so the oscillatory structures become much more complicated. As we can see from Fig. 8(c) and (d).

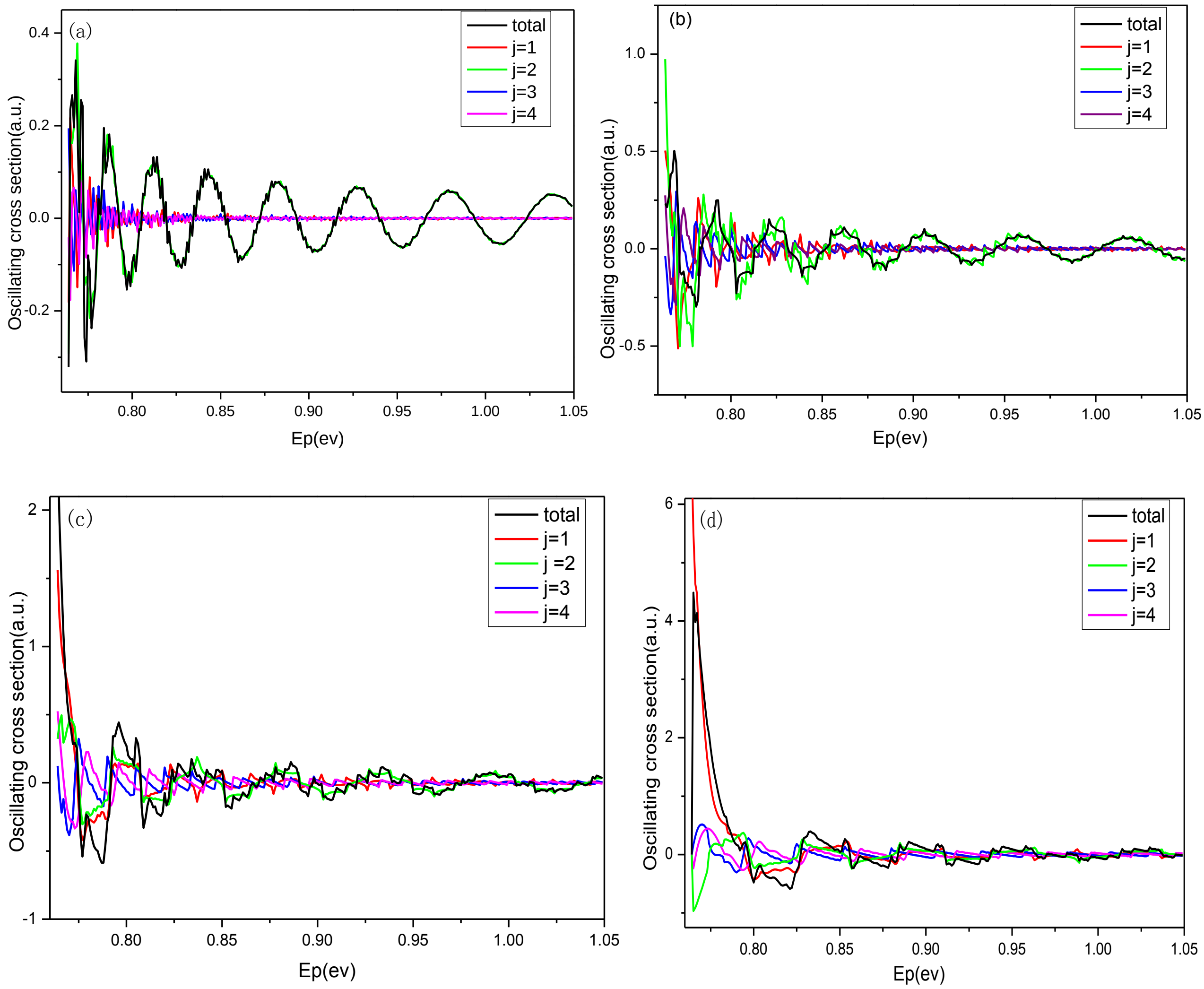

Fig. 8. Influence of the electric field strength on the oscillating cross section of H^- ion near a moving surface. Suppose the speed of moving surface is v=0.001a.u, the initial distance from the surface to the ion is d_0=200a.u. The strength of the electric field is as follows: (a) F_0=10 kV/cm, (b) F_0=50 kV/cm, (c) F_0=100 kV/cm, (d) F_0=300 kV/cm. The black line in each figure denotes the contribution of all the four fundamental closed orbits. The contributions of the four different types of closed orbits to the photodetachment cross section are denoted by different lines (color online)

5. Conclusions

In summary, we have investigated the moving surface effect on the photodetachment dynamics of negative ion in an electric filed. The closed orbits of the detached electron in the electric field near a moving surface have been found. It is found due to the effect of the electric field, the number of the closed orbit is increased greatly. In addition, an analytical formula for the photodetachment cross section of this system has been put forward in the frame work of the closed orbit theory. This formula is universal and can be applied to the photodetachemnt of non-hydrogen negative ion. The calculation results suggest the photodetachment cross section of this system depends on the moving speed of the surface, the initial distance from the surface to the ion and the electric field strength sensitively. The photodetachment cross section exhibits an irregular oscillatory pattern in general, which is quite different from the photodetachment of H^- ion in the electric field near a static surface (the latter is a regular stair-case structure).

The results in this work have some possible application. For example, the results may be used in determining the speed of the moving surface in an ion trap experiment. After a laser is applied to the trapped negative ion in the electric field, we can measure the photodetachment cross section. By comparing the photodetachment cross section with the results calculated by using the formula given in this work, we can determine the "effective distance *d*" from the surface to the ion. From this "effective distance *d*", one can determine the speed of the moving surface.

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