The influence of interface modifier on photodetachment of negative ions in an electric field near a metal surface*

Huang Kai-Yun(黄凯云) and Wang De-Hua(王德华)†

School of Physics, Ludong University, Yantai 264039, *China*

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Based on closed-orbit theory, the influence of an interface modifier on the photodetachment of H^- in an electric field near a metal surface is studied. It is demonstrated that the interface strengthens the oscillations in the photodetachment cross section. However, when the electric field environments are different, the strengthening oscillations are caused by different sources. When the electric field direction is upward, the interface enhances the oscillations by shortening the period and the action of the closed orbit. When the electric field direction is downward, the interface strengthens the oscillations either by extending the coherent energy range or by increasing the total number of the closed orbits. We hope that our results will be conducive to the understanding of the photodetachment process of negative ions near interfaces, cavities and ion traps.

Keywords: photodetachment, interface, closed orbit theory

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1. Introduction

A detailed knowledge of the photodetachment of negative ions under various environments has been of great importance for understanding a large variety of processes[1−4] and for optical device designing.[5,6] In the early studies, electric and magnetic fields were often used as the external environments.[7−11] It was found that in the presence of external fields there appears an oscillating structure in the photodetachment cross section of negative ions in contrast with the smooth cross section in a free space. Therefore, researchers managed to control the photodetachment of negative ions by changing the field direction and magnitude. Today, the properties of atoms or ions adsorbed on metal surface in the presence of external electric or magnetic field have attracted a lot of interest. For example, when the scanning tunneling microscope (STM) is applied to the metal surface, the detached electron is influenced both by the electric field created near the STM tip and the image potential caused by the metal surface.[12]. The corresponding researches on the photodetachment of H^- near metal surface in external fields have been carried out in Refs. [13]–[17]. In all these studies, it was pointed out that the magnitude of the external field has a significant influence on the photodetachment cross section. When the distance between the hydrogen negative ion and the metal surface is kept unchanged, the bigger the external field is, the stronger the oscillations in the photodetachment spectrum are. However, when the ion–surface distance and the magnitude of the external field are both constant, how to control the photodetachment of hydrogen negative ion is still an open problem. To our knowledge, nobody has ever given an answer to this question.

To solve this problem, we consider the coherent control of the photodetachment process of the H^- in an electric field near a metal surface by using an elastic interface. The research is based on the closed orbit theory. In this paper, we show that when an elastic interface is added, the oscillations in the photodetachment cross section are strengthened. In addition, we further study the reason for the strengthening effect and find that whether the mechanisms for the strengthening oscillations are different depends on the electric field environments. When the electric

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†Corresponding author. E-mail: jnwdh@sohu.com, kaihuangyun@163.com

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field direction is upward, the interface enhances the oscillations by shortening the period and the action of the closed orbits. When the electric field direction is downward, the interface strengthens the oscillations either by extending the coherent energy range or by increasing the total number of the closed orbits. Atomic units are used throughout this work unless indicated otherwise.

2. Hamiltonian and closed orbits

The schematic diagram of the photodetachment of H^- in an electric field between a metal surface and an elastic interface is shown in Fig. 1. In the cylindrical coordinates (ρ, z, ϕ), a hydrogen negative ion sits at the origin and a z-polarized laser is used for the photodetachment. A metal surface and an elastic interface perpendicular to z-axis are set at $z = -d_1$ and $z = d_2$, respectively. Following the imaging method, an image positive electron and an image hydrogen atom are generated.[18,19] The potentials acting on the electron by the hydrogen atom and its image are both short potentials, which can be neglected when the detached electron moves far from the origin.[8]

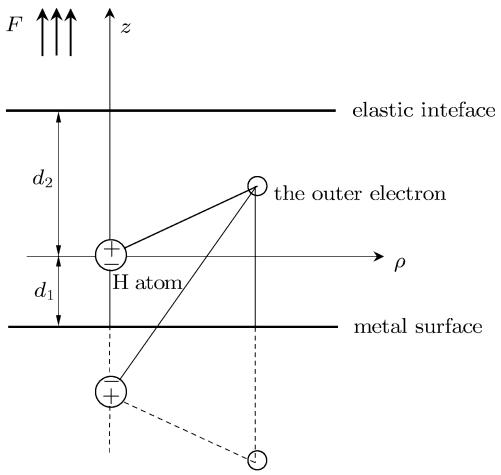


Fig. 1. Schematic representation of H^- in an electric field between a metal surface and an interface, with the electric field F being along the $+z$ axis.

The interaction between the active electron and the image electron is $V_{ee} = -1/4(d_1 + z)$. The interaction between the detached electron and elastic interface is described as

$$V_{ei} = \begin{cases} 0, & -\infty < z < d_2, \\ \infty, & z \geq d_2. \end{cases}$$

In our paper, we consider the directions of the electric field in two cases: upward and downward. Thus, in the cylindrical coordinates (ρ, z, ϕ), the Hamiltonian of the detached electron is

$$H = \frac{1}{2}(P_\rho^2 + P_z^2) - \frac{1}{4(d_1 + z)} + \frac{1}{4d_1} \pm Fz, \qquad (1)$$

where the plus sign corresponds to the upward electric field, the minus sign corresponds to the downward one and $1/4d_1$ is a constant which is added to shift the potential such that the value of the potential at the origin is zero.

Closed orbit theory[20,21] is able to visualize the photodetachment process of H^- in the present system. First, two different regions of space are identified: 1) a region near the core ($r < R$, with $R \approx 5$ a.u.) where the external fields can be neglected but a quantum description is required; 2) the outer region ($r > R$) where the influence of the external fields is important while the interaction between the detached electron and the residue of the ion can be neglected. When H^- is illuminated by laser, photon energy E_{ph} is absorbed to detach the valence electron from the bound of the hydrogen atom. Initially, the active electron goes out of the origin in the form of electronic waves. Sufficiently far from the hydrogen atom ($r \gg R$), the waves propagate semi-classically, following classical trajectories. Due to the effect of the external environment, some of the trajectories are turned back to the origin and form closed orbits. The electron waves associated with the closed orbits come back to the hydrogen atom and interfere with the outgoing detached electron waves. It is the interference effect that causes the oscillations in the photodetachment cross section. However, those trajectories that cannot travel back to the origin will never meet with the original outgoing wave or produce interference effect. As a result, they have no contribution to the oscillation of the photodetachment cross section. In the next part of this paper, we will not mention those unclosed orbits any more.

By solving Eq. (1), we find that the motion in the ρ direction is free and ρ is expressed as

$$\rho(t) = R\sin\theta + kt\sin\theta, \qquad (2)$$

so closed orbits will form only when the exit angle is equal to 0 or π. Now we separately describe the closed orbits according to the direction of the electric field.

Case 1 $F > 0$.

Because the electric field is upward, the electric force and the image Coulomb force are both downward forces. As a result, there is only one closed orbit formed which moves away from the origin with an angle of $\theta = 0$, reaches its highest point and then be

pulled back to the origin. The momentum P_z in the z-direction can be obtained from Eq. (1) as

$$P_z = \sqrt{2\left(E - \frac{1}{4d_1} + \frac{1}{4(d_1+z)} - Fz\right)}. \quad (3)$$

If the interface is absent, the turning point of the closed orbit can be obtained by setting P_z to be zero. After some calculations, we obtain two points corresponding to $P_z = 0$ as follows:

$$z_{\rm m} = \frac{1}{2F}\left[-\left(Fd_1 - E + \frac{1}{4d_1}\right) + \sqrt{\left(Fd_1 + E - \frac{1}{4d_1}\right)^2 + F}\right], \quad (4)$$

$$z_{\rm n} = \frac{1}{2F}\left[-\left(Fd_1 - E + \frac{1}{4d_1}\right) - \sqrt{\left(Fd_1 + E - \frac{1}{4d_1}\right)^2 + F}\right], \quad (5)$$

where $z_{\rm m}$ is the point that satisfies the actual situation. Let $z_{\rm max}$ be equal to $z_{\rm m}$. In the process of travelling along the closed orbits, the electronic wave changes phase and amplitude, which are very important for constructing the returning wave and for analysing the interference effect between the returning wave and the outgoing wave. We can work them out if we know the travel period T and the action S along the closed orbits of detached electron,[11,22,23] where the travel period means the time taken by the electron to leave from and return to the nuclear. Here the period and action of the closed orbits are given by the following formulas:

$$T = 2\int_0^{z_{\rm max}} \frac{1}{P_z}\,{\rm d}z = \frac{2\sqrt{2}}{\sqrt{F}}\left[\sqrt{z_{\rm m}-z_{\rm n}}E(\lambda,P) + \frac{d_1+z_{\rm n}}{\sqrt{z_{\rm m}-z_{\rm n}}}F(\lambda,P)\right], \quad (6)$$

$$S = 2\int_0^{z_{\rm max}} P_z\,{\rm d}z = \frac{4\sqrt{2F}}{3}\{\sqrt{z_{\rm m}-z_{\rm n}}[(z_{\rm m}+z_{\rm n}+2d_1)E(\lambda,P) - (z_{\rm n}+d_1)F(\lambda,P)] - \sqrt{-z_{\rm m}z_{\rm n}d_1}\}, \quad (7)$$

where $F(\lambda,P)$ and $E(\lambda,P)$ are, respectively, the elliptic integrals of the first kind and the second kind.[24] The two parameters are defined as

$$\lambda = \arcsin\sqrt{\frac{z_{\rm m}}{z_{\rm m}+d_1}}, \quad P = \sqrt{\frac{z_{\rm m}+d_1}{z_{\rm m}-z_{\rm n}}}. \quad (8)$$

The Maslov index is related to the topological structure of trajectory manifold and can be obtained simply by counting the singular points such as caustics and foci along the trajectory.[25] For the current case, Malov index can be easily found by counting the returning points and $\mu = 1$. However, after the interface is added, if $z_{\rm m} > d_2$, then the detached electron will bounce back by the interface before its velocity reaches zero. The highest point where the electron can arrive is $z_{\rm max} = d_2$. Correspondingly the closed orbit period and action will also change, the integral of P_z should be taken from 0 to d_2. In addition, when the electron is reflected by the interface, there is a π phase loss. Therefore, the Maslov index becomes $\mu = 2$. To be clearly understood, we plot the schematic closed orbits in Fig. 2(a) for the cases where the elastic interface is absent and present.

Case 2 $F < 0$.

Obviously, in this case the closed orbits are still along the z axis. The photodetachment process becomes much more complicated because the electric force and the imaging Coulomb force are in opposite directions. As is known, nearing the photodetachment threshold,[22] the metal surface acts like an equivalent electric field with field strength $F_{\rm eq} = 1/4d_1^2$. To describe the photodetachment process clearly, we have our external field as $F = \alpha F_{\rm eq} = \alpha/4d_1^2$.

(I) For $\alpha < 1$. In this case, the actual electric field is weaker than the equivalent electric field. The electron leaving from the hydrogen atom with angle π will run to the metal surface in an accelerated manner and then be absorbed by the metal surface, thereby never turning back. However, for the upward-going electron, things can be different. The potential barrier for the current condition can be calculated by

$$\frac{{\rm d}V(z)}{{\rm d}z} = \frac{\rm d}{{\rm d}z}\left(-\frac{1}{4(d_1+z)} + \frac{1}{4d_1} - Fz\right) = 0. \quad (9)$$

As $F = \alpha/4d_1^2$, we obtain

$$V_{\rm max} = \frac{1}{4d_1}(1-\sqrt{\alpha})^2, \quad (10)$$

which occurs at $z = d_1(1/\sqrt{\alpha} - 1)$.

When the energy of the detached electron is less than $V_{\rm max}$, there is a closed orbit in the system which is similar to the one in case (I) but with different periods and actions. Here,

$$P_z = \sqrt{2\left(E - \frac{1}{4d_1} + \frac{1}{4(d_1+z)} + Fz\right)}. \quad (11)$$

When the interface is present but with $d_2 > z_{\rm max}$, the interface will have no effect on the motion of the detached electron. By setting $P_z = 0$, we have

$$z_{\rm m} = \frac{1}{2F}\left[-\left(Fd_1 + E - \frac{1}{4d_1}\right)\right.$$

$$+\sqrt{\left(Fd_1 - E + \frac{1}{4d_1}\right)^2 - F}\Bigg], \quad (12)$$

$$z_{\rm n} = \frac{1}{2F}\Bigg[-\left(Fd_1 + E - \frac{1}{4d_1}\right) - \sqrt{\left(Fd_1 - E + \frac{1}{4d_1}\right)^2 - F}\Bigg], \quad (13)$$

where $z_{\rm n}$ is the highest point the detached electron can reach. And the period, action and the Maslov index of the closed orbit are as follows:

$$T = 2\int_0^{z_{\max}} \frac{1}{P_z}\,{\rm d}z = \frac{2\sqrt{2}}{\sqrt{F}}\left\{\sqrt{z_{\rm m}+d_1}[F(\delta,q) - E(\delta,q)] + \sqrt{\frac{z_{\rm n}d_1}{z_{\rm m}}}\right\}, \quad (14)$$

$$S = 2\int_0^{z_{\max}} P_z\,{\rm d}z = \frac{4\sqrt{2F}}{3}\left\{\sqrt{z_{\rm m}+d}[(z_{\rm m}+z_{\rm n}+2d_1)E(\delta,q) - (z_{\rm m}-z_{\rm n})F(\delta,q)] - (2d_1+2z_{\rm m}+z_{\rm n})\sqrt{\frac{z_{\rm n}d_1}{z_{\rm m}}}\right\}, \quad (15)$$

$$\mu = 1, \quad (16)$$

$$\delta = \arcsin\sqrt{\frac{(z_{\rm m}+d_1)z_{\rm n}}{(z_{\rm n}+d_1)z_{\rm m}}}, \quad q = \sqrt{\frac{z_{\rm n}+d_1}{z_{\rm m}+d_1}}. \quad (17)$$

However, if $d_2 < z_{\max}$, the integral upper limit becomes $z_{\max} = d_2$ and the Maslov index turns to be $\mu = 2$. When the energy of the detached electron is greater than $V_{\max}$, if the interface is absent, the detached electron will pass through the potential barrier and travel to infinity. Therefore, no closed orbits will form. However, if the interface is present, the electron moving upward will finally be bounced back by the interface and form a closed orbit (see Fig. 2(b)).

(II) For $\alpha = 1$. In this case, the potential barrier is equal to zero. Due to the presence of the interface, there is also only a closed orbit formed. It is like the case where $\alpha < 1$ and $E > V_{\max}$.

(III) For $\alpha > 1$. When the energy of the detached electron is less than $V_{\max}$, there are four fundamental closed orbits. 1) The electron goes up along the $+z$ direction, hits the interface and bounces back to the origin. 2) The electron goes down in the $-z$ direction, reaches its maximum point and then returns to the origin. 3) The electron completes the first orbit and then passes through the origin and continues to complete the second orbit. 4) This orbit is similar to the one of 3) but in the reverse order. The electron completes the second orbit and then the first one (see Fig. 2(c)). The Maslov indices of the first and the second fundamental closed orbits are $\mu_1 = 2$ and $\mu_2 = 1$, respectively. If we denote the periods and the actions of the first and second fundamental closed orbits as T_1, T_2, S_1, S_2, which can be obtained by the integral of P_z from 0 to $z_{\max}$, the periods, actions and Maslov indices for the third and fourth closed orbits can be written, respectively, as

$$T_3 = T_4 = T_1 + T_2, \quad (18)$$

$$S_3 = S_4 = S_1 + S_2, \quad (19)$$

and

$$\mu_3 = \mu_4 = \mu_1 + \mu_2. \quad (20)$$

Therefore, we obtain the period, action and Maslov index for any closed orbit as

$$T_{jn} = T_j + nT_3, \quad S_{jn} = S_j + nS_3, \quad \mu_{jn} = \mu_j + n\mu_3, \quad (21)$$

where the indices j and n are used to label the closed orbits, $j = 1, 2, 3, 4$ and $n = 0, 1, 2, 3, \ldots$. When the energy of the detached electron is greater than $V_{\max}$, there exists only an upward closed orbit which is similar to the first fundamental closed orbit.

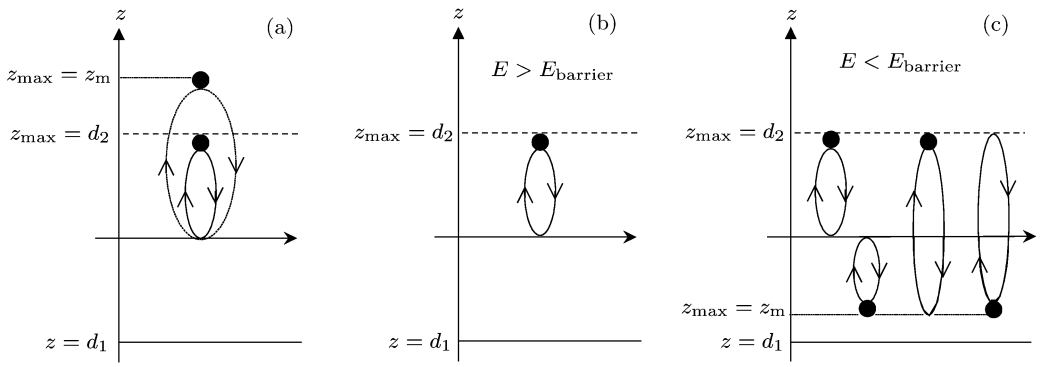


Fig. 2. Closed orbits for the detached electron in an electric field between a metal surface and an interface: (a) the electric field is upward, (b) the electric field is downward and $\alpha < 1$, (c) the electric field is downward and $\alpha > 1$. $E_{\rm barrier}$ represents the value of the system's potential barrier.

3. Photodetachment cross section

Photodetachment cross section is defined as the ratio of transition probability per unit time P to the laser incoming density I.[26] It reveals the probability of photodetachment by absorption of photons of energy $E_{\rm ph}$. When the external environment changes, the cross section changes too. Therefore, we can study the influence of an elastic interface on the photodetachment of H^- in an electric field near a metal surface through the photodetachment cross section. According to the closed orbit theory,[20,21] the cross section of our present system can be expressed as the sum of two terms

$$\sigma(E,F,d_1,d_2)=\sigma_0(E)+\sigma^{\rm osc}(E,F,d_1,d_2), \quad (22)$$

where $\sigma_0(E)=16\sqrt{2}\pi^2B^2E^{3/2}/3c(E_{\rm b}+E)^3$ is the smooth background term without any external fields, with $B=0.31522$ being a normalized constant, $E_{\rm b}$ is the binding energy which is approximately 0.754 eV and c is the speed of light with a value of 137 a.u. The second term in Eq. (22) is the oscillating term which corresponds to the contribution of the returning wave travelling along the closed orbit[11]

$$\sigma^{\rm osc}(E,F,d_1,d_2)=-\frac{4\pi}{c}(E+E_{\rm b})\,{\rm Im}\,\langle D\psi_{\rm i}|\psi_{\rm ret}\rangle\,, \quad (23)$$

where $\psi_{\rm i}=B\,{\rm e}^{-k_{\rm b}r}/r$ is the initial wave function of the detached electron and D is the dipole operator.[27] For the z-polarized light, $D=z$. To construct the retuning wave function we start from a spherical surface centred at the origin with radius $R=5$ a.u. If the outgoing wave on the surface of this sphere is denoted by

$$\psi^0(R,\theta,\phi)=-\,{\rm i}\,\frac{4Bk^2}{(k_{\rm b}^2+k^2)^2}\cos(\theta)\frac{{\rm e}^{{\rm i}(kR-\pi)}}{kR}, \quad (24)$$

then in the semi-classical approximation, the wave outside this sphere can be expressed as

$$\psi^{\rm out}(r)=\sum_j\psi^0(R,\theta,\phi)A_j\,{\rm e}^{{\rm i}(S_j-\mu_i\pi/2)}, \quad (25)$$

where the sum runs over all the electron closed orbits, S_j, A_j and μ_j are the action, the amplitude and the Maslov index of the closed orbit j, respectively. Due to the classical motion of the detached electron, the amplitude related to closed orbit (j,n) is given by

$$A_{jn}=\frac{R}{R+kT_{jn}}. \quad (26)$$

Equation (25) is valid for the propagation out of and back to the sphere of radius R. Inside the sphere, the wave function can be approximated by an incoming plane wave as

$$\psi^{jn}_{\rm ret}(r\approx 0)=N_{jn}\,{\rm e}^{\pm\,{\rm i}\,kz}, \quad (27)$$

where the plus sign in the exponent corresponds to the wave propagating in the positive z-direction, the minus sign corresponds to the wave travelling in the negative z-direction, and N_{jn} is a matching factor that can be calculated by the matching procedure. The result is

$$N_{jn}=A_{jn}(R\to 0)\,{\rm e}^{{\rm i}(S_{jn}-\mu_{jn})}\psi^0 \quad (R,\theta=0,\pi). \quad (28)$$

Substituting Eqs. (28) and (27) into Eq. (23) and carrying out the overlap integral, we obtain the oscillating part of the cross section as

$$\sigma^{\rm osc}(E,F,d_1,d_2)=\sum_{jn}h(j)\frac{8\pi^2B^2\sqrt{2E}}{c(E+E_{\rm b})^3T_{jn}}\sin\left(S_{jn}-\mu_{jn}\frac{\pi}{2}\right), \quad (29)$$

where $h(j)$ is a sign factor. For the up and the down closed orbits, $h=-1$, while for the other two fundamental closed orbits, $h=1$. Substituting Eq. (29) into Eq. (22) yields the total photodetachment cross section as

$$\sigma(E,F,d_1,d_2)=\frac{16\sqrt{2}\pi^2B^2E^{3/2}}{3c(E_{\rm b}+E)^3}+\sum_{jn}h(j)\frac{8\pi^2B^2\sqrt{2E}}{c(E+E_{\rm b})^3T_{jn}}\sin\left(S_{jn}-\mu_{jn}\frac{\pi}{2}\right). \quad (30)$$

4. Results and discussion

Using Eq. (30), we investigate the influence of the interface modifier on the photodetachment cross section of H^- in an electric field near a metal surface. In all of our calculations, the distance between H^- and the metal surface is fixed to be $d_1=80$ a.u. When the electric field is along the $+z$ direction, we keep the electric field strength $F=0.3F_{\rm eq}$ and then change the distance between H^- and the interface. Before the interface modification, the maximum height that the electron can reach along the $+z$ axis is $z_{\rm max}=551$ a.u. After the interface is added, the influence of the interface is dependent on the ion-interface distance as can be seen from Fig. 3. For better comparison, we also plot the photodetachment cross section of H^- before modification[14] by the dashed lines. In Fig. 3(a), the interface modifier is located at $d_2=600$ a.u., which is larger than 551 a.u., so the interface has no influence on the photodetachment cross section and the two

lines in Fig. 3(a) are completely coincident. However, if the ion-interface distance is less than 551 a.u., the effect of the interface becomes apparent (see Figs. 3(b)–3(d)). Meanwhile, we can see that with the decrease of the ion–interface distance, the oscillation amplitude increases while the oscillation frequency decreases. The reasons are as follows: because $d_2 < z_{\max}$, some electrons will be bounced back by the interface before its momentum reaches zero. Since the interface prevents the detached electron from moving further, the period of the closed orbit becomes shorter. The closer the interface moves to the hydrogen atom, the shorter the closed-orbit period becomes and thus the larger the oscillation amplitude becomes.

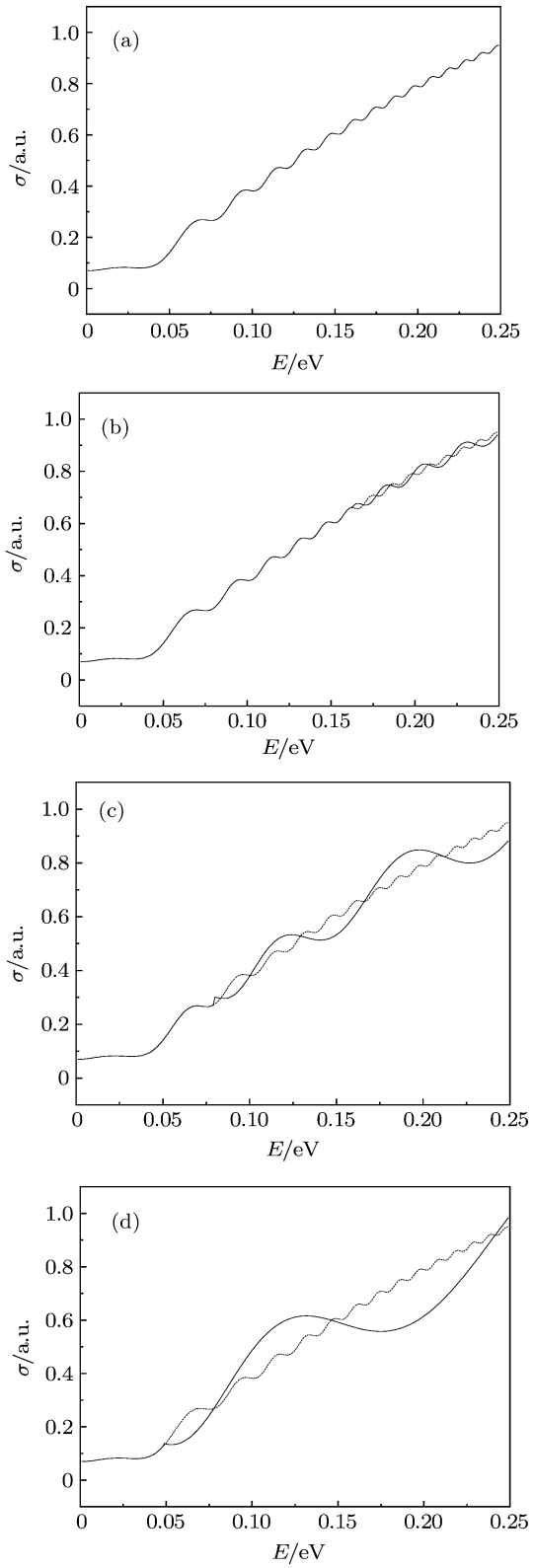


Fig. 3. Dependences of the photodetachment cross section on ion–interface distance when the electric field is upward and the metal surface is fixed at $d_1 = 80$ a.u. The dashed line and the solid line represent the photodetachment cross sections before and after modification respectively. (a) $d_2 = 600$ a.u., (b) $d_2 = 300$ a.u., (c) $d_2 = 100$ a.u., (d) $d_2 = 50$ a.u.

When the direction of the electric field is downward, we separately discuss the influence of the interface according to the values of α. When $\alpha = 0.01 < 1$, the results are displayed in Fig. 4. In this case, the interface is located at $d_2 = 400$ a.u. The solid line and the short dashed line represent the cases with and without interface, respectively. From this figure we find that when the energy of the detached electron is greater than 0.0688 eV, which is just the potential barrier, the oscillations without interface disappear while the oscillations with interface still exist. This figure suggests that the interface can enlarge the energy range of producing oscillations in the photodetachment cross section. This is sensible because the detached electron that has energy large enough to pass through the potential barrier will be bounced back by the interface after it has been added.

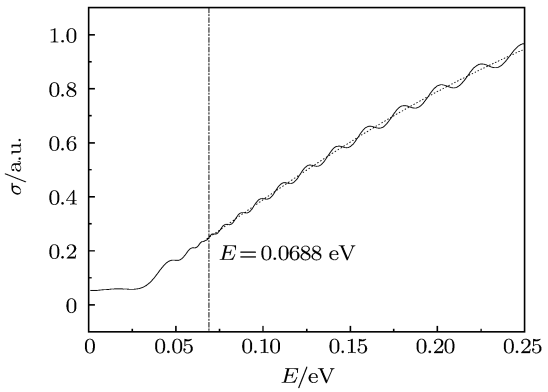


Fig. 4. Photodetachment cross sections of the H^- versus detached electron energy before (dotted line) and after (solid line) the interface modification , with electric field being downward, $\alpha = 0.01 < 1$, metal surface fixed at $d_1 = 80$ a.u. and the interface modifier located at $d_2 = 400$ a.u.

Figure 5 shows the case of $\alpha = 1$. In this case, the electric field force and the equivalent electric field

force caused by the metal surface cancel out with each other. If the interface is absent, the ejected electron either propagates to infinity or hits the metal surface and then is absorbed by the metal surface, thereby forming no closed orbits. Therefore, the photodetachment cross section is just a smooth curve. However, if the interface is present, it will reflect the upward-going electron back to the origin and form one closed orbit which causes the oscillations in the cross section. This case is similar to the one of the photodeachment of H^- near an elastic surface.[23]

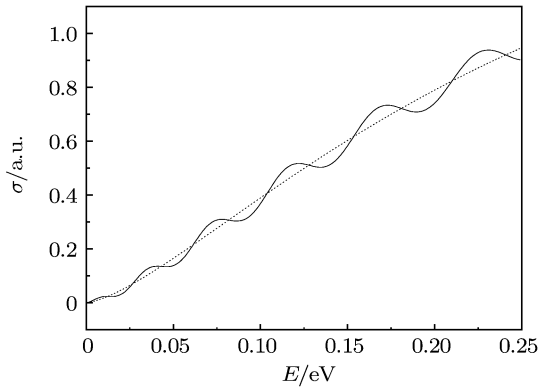


Fig. 5. Photodetachment cross sections of the H^- versus detached electron energy before (dotted line) and after (solid line) the interface modification, with electric field being downward, $\alpha = 1$, metal surface fixed at $d_1 = 80$ a.u. and the interface modifier located at $d_2 = 200$ a.u.

When $\alpha > 1$, the electric field force is larger than the equivalent electric field force. Under this condition, the interface can influence the photodetachment cross section by increasing the number of the closed orbits. To demonstrate this, we take $\alpha = 7$ and $d_2 = 800$ a.u. In the case of Fig. 6, the potential barrier $V_{\max} = 0.2303$ eV. When the energy of the detached electron is less than the potential barrier, the detachment electron is trapped in the potential well and the electron waves are bounced back and forth between the interface and the point where the potential barrier occurs. The oscillations shown in the solid line result from the superposition of the four fundamental closed orbits and their repetitions. However, before modification the upward-going electron will travel to infinity because the electric field force is greater than the equivalent electric force. Thus, the modified spectrum displays a more complicated oscillating structure in contrast with the smooth oscillation without the interface. When the energy of the detached electron is higher than the potential barrier, the detachment electron escapes from the potential well, the returning wave is just reflected by the interface, thus only one closed orbit appears under this situation. However, in the case that the interface is absent, no closed orbit is formed. Therefore, the cross section with the interface becomes much smoother while the cross section without the interface becomes a straight line.

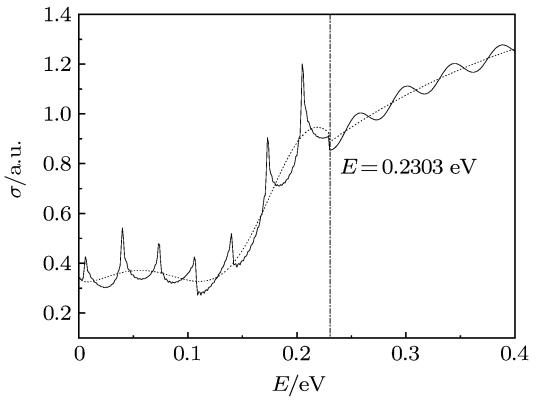


Fig. 6. Photodetachment cross sections of the H^- versus detached electron energy before (dotted line) and after (solid line) the interface modification, with electric field being downward, $\alpha = 7 > 1$, metal surface fixed at $d_1 = 80$ a.u. and interface modifier located at $d_2 = 800$ a.u.

In order to demonstrate the influence of the interface clearly, Figure 7 shows how the cross section varies with d_2 with electric field. In Fig. 7, the detached electron energies are all set to be 0.2 eV. The direction of the electric field in Fig. 7(a) is upward while in the other three panels the directions are all downward and with $\alpha < 1$, $\alpha = 1$ and $\alpha > 1$ respectively. The common point of the four panels is that with the increase of the ion–interface distance, the amplitude of the oscillation decreases. This indicates that the influence of the interface modifier has a relationship with the ion–interface distance. The larger the ion–interface distance is, the weaker the influence of the interface becomes. In addition, we can see that the changes of the photodetachment cross section with d_2 display different patterns in the four panels, of which the pattern in Fig. 7(d) is the most complicated. The reason is as follows: as we analysed previously, the influence mechanisms of the interface modifier in the four panels are different. In Fig. 7(a), the interface affects the cross section by changing the closed orbit period and action; in Figs. 7(b) and 7(c), the interface affects the cross section by extending the coherent energy range; in Fig. 7(d), the interface affects the cross section by increasing the total number of the closed orbits. Due to these different mechanisms, the effects of the interface modifier are displayed in different patterns as shown in the four panels.

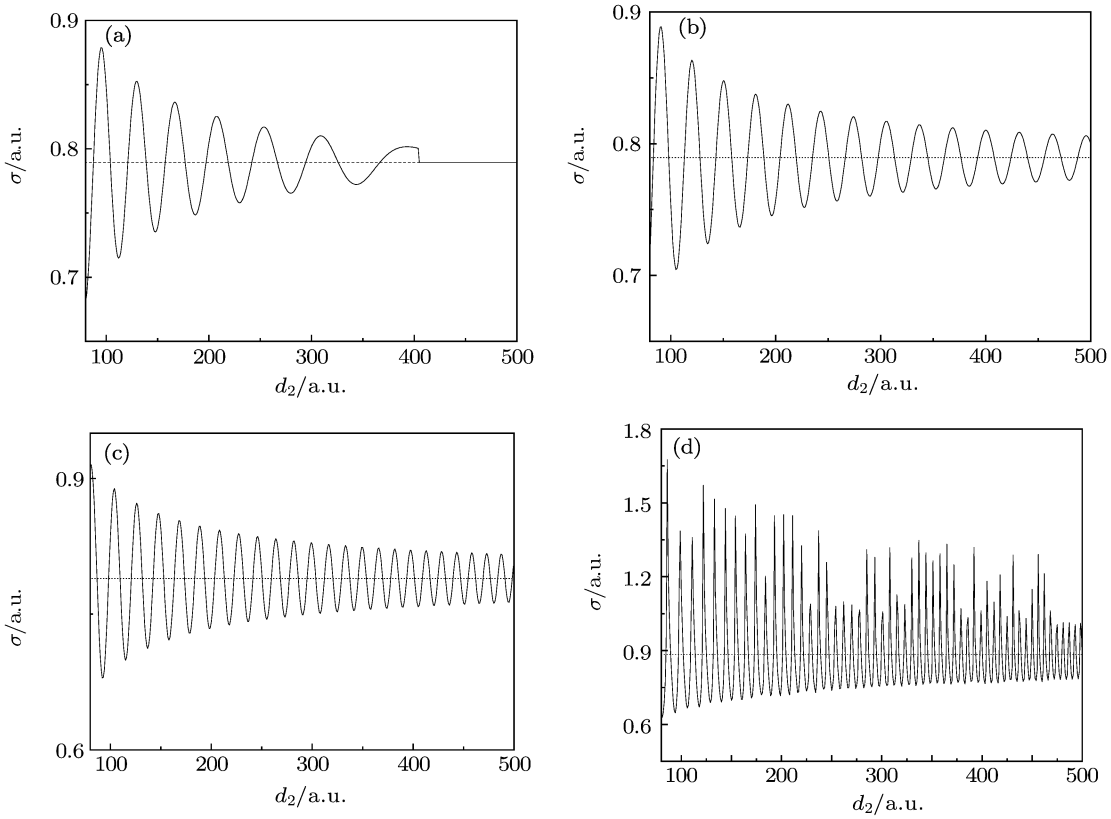


Fig. 7. Photodetachment cross sections of H^- under different electric field environments versus the distance between the interface and the hydrogen atom. The detached electron energies are set to be 0.2 eV. The direction of the electric field in (a) is upward while in the other three panels the electric field directions are all downward with (b) $\alpha < 1$, (c) $\alpha = 1$ and (d) $\alpha > 1$ respectively.

5. Conclusion

We investigate the influence of an interface modifier on the photodetachment of H^- in an electric field near a metal surface. We find that the interface strengthens the oscillations in the photodetachment cross section. However, the mechanisms for strengthening the oscillations are different under different electric field environments. When the electric field is upward, the interface can strengthen the oscillations by shortening the period and the action of the closed orbit. When the electric field is downward, the interface strengthens the oscillations either by extending the detached electron energy range or by increasing the total number of the closed orbits. We hope that our results are conducive to the understanding of the photodetachment process of negative ions near interfaces, cavities and ion traps.[28,29]

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