Magnetic field effect in photodetachment from negative ion in electric field near metal surface*

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Based on the closed-orbit theory, the magnetic field effect in the photodetachment of negative ion in the electric field near a metal surface is studied for the first time. The results show that the magnetic field can produce a significant effect on the photodetachment of negative ion near a metal surface. Besides the closed orbits previously found by Du *et al.* for the H^- in the electric field near a metal surface (*J. Phys.* B **43** 035002 (2010)), some additional closed orbits are produced due to the effect of magnetic field. For a given ion–surface distance and an electric field strength, the cross section depends sensitively on the magnetic field strength. As the magnetic field strength is very small, its influence can be neglected. With the increase of the magnetic field strength, the number of the closed orbits increases greatly and the oscillation in the cross section becomes much more complex. Therefore we can control the photodetachment cross section of the negative ion by changing the magnetic field strength. We hope that our results may guide future experimental studies for the photodetachment process of negative ion in the presence of external fields and surfaces.

Keywords: photodetachment, closed-orbit theory, magnetic field effect, metal surface

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1. Introduction

It is well known that the external field can considerably affect the photodetachment process of negative ions.[1] Early experiments showed that in the presence of a static electric field, the photodetachment cross section of negative ion displays oscillatory structure.[2] Rau and Wong[3] used the 'frame transformation theory' to explain these oscillations as an interference between the detached electron wave going up and down the electric potential hill. On the other hand, Du and Delos[4] derived a simple formula by using a quantum approach involving a momentum space wavefunction and stationary-phase approximation. This formula is consistent with the much more general closed-orbit theory and can be derived directly from it.[5−8] Based on the physical picture provided by the closed-orbit theory, the oscillations in the photodetachment cross section are interpreted by Du and Delos[4] as interference between the outgoing detached-electron wave and returning detached-electron wave from a closed orbit moving along the electric field direction. Subsequently, photodetachment of H^- in other fields, such as in parallel electric and magnetic fields, in crossed electric and magnetic fields and in electric and magnetic fields with arbitrary orientations has also been investigated theoretically.[9−14] Recently, much attention has been paid to the photo-induced electronic excitations of adsorbates on metal surface.[15] Since H^- has been proposed to be used to probe adsorbate state lifetime and charge transfer during backscattering,[16] the photodetachment of H^- near an interface has attracted much interest. First, Yang *et al.*,[17,18] and Wang and Yu[19] studied the photodetachment of H^- near an elastic interface. Later, the photodetachment of H^- near a metal surface has been investigated by Zhao and Du,[20] and Rui and Yang.[21] In their work, the photodetachment cross section was changed a little only in a small energy range above the threshold. How to control the photodetachment of H^- near a metal surface is an interesting research subject. Yang and Du,[22] Huang and Wang,[23] and Wang *et al.*[24] showed that the photodetachment cross section of H^- near a metal surface can be modified by an external electric field or a magnetic field. Then what will happen if we apply parallel electric and magnetic fields to the photodetachment of H^- near a metal surface? No one has carried out the study. In this paper, based

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on the theoretical study on the photodetachment of H^- in an electric field or magnetic field near a metal surface, we investigate the magnetic field effect in the photodetachment of H^- in the electric field near a metal surface by using the closed-orbit theory. In this system, we fix the value of the electric field and the ion-surface distance and study the influence of the magnetic field strength on the cross section. Our results show that due to the effect of magnetic field, the number of the closed orbits increases greatly and the oscillatory structure in photodetachment cross section becomes much more complicated than the case given by Yang and Du.[22] This study provides a new understanding and will guide the future experimental study on the photodetachment process of negative ion in the presence of external fields and surfaces. Atomic units are used throughout this paper unless specified otherwise.

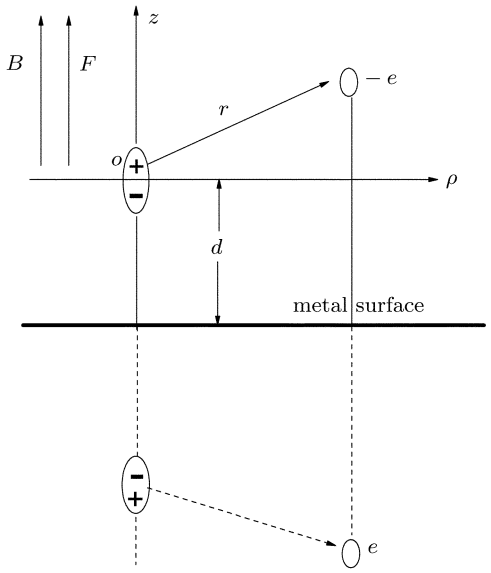


Fig. 1. Schematic diagram of H^- in parallel electric and magnetic fields near a metal surface. The electric and magnetic fields are along the $+z$ axis.

2. Hamiltonian and closed-orbit

The system is shown schematically in Fig. 1. We assume that the negative ion is at the origin. The metal surface perpendicular to the z axis is located at $z = -d$ and the laser polarization direction is also in the z direction. The external electric field F and magnetic field B parallel to the z axis are applied. Using the electrostatic image method,[20,25] the Hamiltonian for the detached electron in cylindrical coordinates can be written as

$$H = \frac{1}{2}\left(P_\rho^2 + \frac{L_z^2}{\rho^2}\right) + \frac{1}{2}P_z^2 + \omega_{\rm L}L_z - \frac{1}{4(d+z)} + \frac{1}{4d} + \frac{1}{2}\omega_{\rm L}^2\rho^2 + V_{\rm b} + V_{\rm c} + Fz. \quad (1)$$

where $V_{\rm b}(r)$ is a short range, spherically symmetric potential between the detached electron and hydrogen atom;[9] $V_{\rm c}$ is the interaction of the detached electron with the image hydrogen atom, which is also a short-range potential; $\omega_{\rm L} = B/2c$ is the Larmor frequency; B is the magnetic field strength; c is the velocity of light; the expression $-1/4(d+z)$ is the electrostatic image potential between the detached electron and the metal surface, which is a Coulomb-like attractive potential; the expression $1/4d$ is an additional term to ensure $V(z=0) = 0$, which has no influence on the photodetachment process. Due to the cylindrical symmetry of the system, the canonical angular momentum L_z is a constant of motion. For simplicity, we take it as zero.

According to the closed orbit theory,[6,7] the photodetachment process of H^- in parallel electric and magnetic fields near a metal surface can be described as follows: when H^- absorbs photon energy $E_{\rm ph}$, outgoing electron waves are generated. These outgoing waves propagate over a long distance. Due to the effect of the external fields and attractive image potential of the metal surface, these waves cannot propagate to infinity, some of the waves turn back by the surface and the fields and return to the origin. Finally, the returning waves overlap with the outgoing source wave to give the interference pattern in the photodetachment cross section. The closed orbit theory gives a prescription for calculating the oscillations in the cross section once we have all the closed orbits of the detached electron of the system which start and end at the origin.

By solving the Hamiltonian motion equation, we obtain the classical motion equation of the detached electron in the ρ direction as

$$\rho(t) = \frac{1}{\omega_{\rm L}}k\sin\theta_{\rm out}|\sin(\omega_{\rm L}t)| = \frac{1}{\omega_{\rm L}}k_\rho\left|\sin(\omega_{\rm L}t)\right|, \quad (2)$$

where $k_\rho = \sqrt{2E}\sin\theta_{\rm out}$ is the initial momentum of the electron along the ρ direction and $\theta_{\rm out}$ is the outgoing angle between the direction of the momentum and z axis. The motion of the detached electron in the ρ direction is of a sinusoidal oscillation and represents the cyclotron motion of the electron in the magnetic

field. The electron returns to $\rho = 0$ at cyclotron periods $t^{\rho}_{\rm ret} = j\pi/\omega_{\rm L}$, $j = 1, 2\ldots$ is the number of the cyclotron period.

The momentum p_z in the z direction is readily obtained from Eq. (1) as

$$p_z = \sqrt{2\left(E\cos^2\theta_{\rm out} - \frac{1}{4d} - Fz + \frac{1}{4(d+z)}\right)}, \quad (3)$$

where d is the distance between the hydrogen negative ion and the metal surface. Due to the external fields and the attractive electrostatic image potential of the metal surface, the electron will be turned back to the nucleus in a period of time. z_m is the turning point of the closed-orbit and can be obtained by setting p_z to be zero. Let parameter $A = E\cos^2\theta_{\rm out} - 1/4d$, then we will have

$$z_m = \frac{1}{2F}\Big[-(Fd - A) + \sqrt{(Fd + A)^2 + F}\,\Big]. \quad (4)$$

The time at which the electron returns to the x–y plane is

$$t^z_{\rm ret} = 2\int_0^{z_m} \frac{1}{p_z}\,{\rm d}z. \quad (5)$$

The action of the closed orbit along the z axis is

$$S_z(E) = \int_0^{z_m} p_z\,{\rm d}z. \quad (6)$$

Both integrals in Eqs. (5) and (6) can be expressed analytically using special functions, respectively, as[26]

$$t^z_{\rm ret} = \frac{2\sqrt{2}}{\sqrt{F}}\left[\sqrt{z_m - z_n}E(\lambda,\gamma) + \frac{d + z_n}{\sqrt{z_m - z_n}}F(\lambda,\gamma)\right], \quad (7)$$

and

$$S_z(E) = \frac{4\sqrt{2F}}{3}\Big\{\sqrt{z_m - z_n}\Big[(z_m + z_n + 2d)E(\lambda,\gamma) - (z_n + d)F(\lambda,\gamma)\Big] - \sqrt{-z_m z_n d}\Big\}, \quad (8)$$

where $z_n < 0$ is another point corresponding to $p_z = 0$ in Eq. (3) and is given by

$$z_n = \frac{1}{2F}\Big[-(Fd - A) - \sqrt{(Fd + A)^2 + F}\,\Big]; \quad (9)$$

$F(\lambda,\gamma)$ and $E(\lambda,\gamma)$ are, respectively, the elliptic integrals of the first kind and the second kind.[22,26] The two parameters are defined as

$$\lambda = \sqrt{\frac{z_m + d}{z_m - z_n}}, \qquad 0 \le \lambda \le 1,$$
$$\gamma = \arcsin\sqrt{\frac{z_m}{z_m + d}}, \quad 0 \le \gamma \le \frac{\pi}{2}. \quad (10)$$

In this system, a closed orbit occurs whenever the electron goes out with energy and outgoing angle $\theta_{\rm out}$ satisfies $t^z_{\rm ret} = t^{\rho}_{\rm ret}$. It is obvious that one closed orbit always exists: it lies on the positive z axis and the electron is attracted back to the origin by the image potential of the metal surface and the electric field. At very low energies, this is the only closed orbit that exists, which is called the parallel orbit, denoted as $j = 0$ orbit. The period of this orbit is $t_{\parallel}(E) = t^z_{\rm ret}\big|_{\theta_{\rm out}=0}$.

If we increase the electron energy, the return time of the parallel orbit is also increased until, at the first bifurcation energy, it is exactly equal to one cyclotron period $t_{\rm c} = \pi/\omega_{\rm L}$. At this point, a new returning orbit is created, which we call the $j = 1$ orbit. Increasing the energy further, the return time of the parallel orbit continues to increase. As we increase the energy, a second bifurcation energy occurs, at which the return time of the parallel orbit is exactly twice the cyclotron period. At this point another new returning orbit is created, which is denoted as $j = 2$ orbit. Increasing the energy still further takes us through a discrete set of bifurcation energies, where at each such an energy one new orbit is created. The j-th new closed orbit has a return time equal to j cyclotron periods. Therefore, at any given energy, the total number of returning orbits is equal to the smallest integer greater than $t_{\parallel}(E)/t_{\rm c}$. Some of the closed orbits are given in Fig. 2.

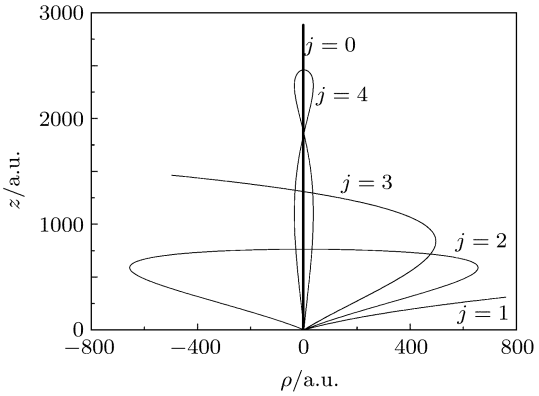


Fig. 2. Some closed orbits of the detached electron in parallel electric and magnetic fields near a metal surface, with ion–surface distance $d = 100$ a.u., electric field strength $F = 10$ kV/cm, magnetic field strength $B = 60$ T and detached electron energy $E = 0.196$ eV.

3. Formula for photodetachment cross section

According to the closed orbit theory,[6,7] the photodetachment cross section of this system can be split

into two parts

$$\sigma(E) = \sigma_0(E) + \sum_{j=0}^{j_{\max}} \sigma_{\rm osc}^{j}, \tag{11}$$

where $\sigma_0(E)$ is the overlap integral of the direct part with the source function, which is a smooth background term in the cross section,[4]

$$\sigma_0(E) = \frac{16\sqrt{2}B_0^2\pi^2E^{3/2}}{3c(E_{\rm b}+E)^3}, \tag{12}$$

where E is the energy of the detached electron; $E_{\rm b}$ is the binding energy of H^- and approximately 0.754 eV; the normalization constant $B_0 = 0.31552$.

The second part is the oscillating term which corresponds to the contribution of the returning wave traveling along the closed orbit[24]

$$\sigma_{\rm osc}^{j=0}(E) = \sigma_0 \frac{3}{2\pi} |R_{j=0}| \sin(-S_j + \mu_j\pi/2), \tag{13}$$

$$\sigma_{\rm osc}^{j\neq0}(E) = \sigma_0 \frac{3}{2\pi} |R_{j\neq0}| \cos^2\theta_{\rm out}^{j\neq0} \times \sin\left(-S_j + \frac{\pi}{4} + \mu_j\pi/2\right). \tag{14}$$

In the above formulas, $j_{\max}$ is the total number of the closed orbits, which is given by $j_{\max} = {\rm int}[t_\parallel(E)/t_{\rm c}]$; μ_j is the Maslov index, which is equal to the total number of singular points through which the electron passes on its journey;

$$R_j = \left|\frac{f_{\rm out}^{(+)j}}{f_{\rm ret}^{(-)j}}\right| \left|\frac{J_j(t_0)}{J_j(t_{\rm ret})}\right|^{1/2}$$

is called the recurrence amplitude, which involves the ratios between Jacobians at $t = t_0$ and $t = t_{\rm ret}$ and the ratios between the outgoing and the returning quantum waves,[11] with $f_{\rm out}^{(+)j}(kr) = {\rm e}^{{\rm i}kr}/kr$ and

$$J(t) = \rho(t)\frac{\partial(z,\rho)}{\partial(t,\theta)}$$

being the Jacobian at time t.[6,7]

For the parallel closed orbit ($j = 0$) along the z axis, since $\rho(t)$ equals zero for all the time, the returning wave is approximated by a plane wave directed along the z axis, $f_{\rm ret}^{(-)j=0} = {\rm e}^{\pm{\rm i}kz}/2\pi$. The Jacobians at $t = t_0$ and $t = t_{\rm ret} = T_\parallel$ are given by

$$J_{j=0}(t_0) = \sqrt{2E}r^2\sin(\theta_{\rm out}^j), \tag{15}$$

$$J_{j=0}(t_{\rm ret}) = \frac{1}{\omega_{\rm L}^2}(\sqrt{2E})^3\sin(\theta_{\rm out}^j)\sin^2(\omega_{\rm L}T_\parallel). \tag{16}$$

Then

$$R_{j=0} = \left|\frac{f_{\rm out}^{(+)j=0}}{f_{\rm ret}^{(-)j=0}}\right| \left|\frac{J_{j=0}(t_0)}{J_{j=0}(t_{\rm ret})}\right|^{1/2} = \frac{\pi\omega_l}{E\sin(\omega_l t_\parallel)}. \tag{17}$$

For the other closed orbits:

$$f_{\rm ret}^{(-)j} = (2\pi)^{-3/2}(k_\rho\rho)^{-1/2}\,{\rm e}^{-{\rm i}k_\rho\rho}\,{\rm e}^{{\rm i}k_z z}\,{\rm e}^{{\rm i}\pi/4}$$

and the Jacobians at $t = t_0$ and $t = t_{\rm ret} = T_\parallel$ are given by

$$J_j(t_0) = \sqrt{2E}r^2\sin(\theta_{\rm out}^j), \tag{18}$$

$$J_j(t_{\rm ret}) = -2E\cos(\theta_{\rm out}^j)\sin(\theta_{\rm out}^j)(-1)^j\left[\frac{\partial t}{\partial\theta}\right]_{Z_{\rm ret}}\rho_{\rm ret}. \tag{19}$$

Then

$$R_{j\neq0} = \left|\frac{f_{\rm out}^{(+)j}}{f_{\rm ret}^{(-)j}}\right| \left|\frac{J_j(t_0)}{J_j(t_{\rm ret})}\right|^{1/2} = \frac{(2\pi)^{3/2}\sin\theta_{\rm out}^j}{(\sqrt{2E})^{3/2}\sqrt{\cos\theta_{\rm out}^j\left|\left[\frac{\partial t}{\partial\theta}\right]_{Z_{\rm ret}}\right|}}, \tag{20}$$

where $[\partial t/\partial\theta]_{z_{\rm ret}}$ can be calculated from Eq. (7); $\theta_{\rm out}^j$ is the outgoing angle of the j-th closed orbit; S_j is the action of the closed orbit, which can be split into two parts, i.e., along the z axis and along the ρ axis and expressed as

$$S_j(E) = S_z(E) + S_\rho(E). \tag{21}$$

The action of the closed orbit along the ρ axis is

$$S_\rho(E) = \int_0^\rho p_\rho\,{\rm d}\rho = E\sin^2\theta_{\rm out}^j t_j, \tag{22}$$

where $t_j = j\pi/\omega_l$ is the period of the j-th closed orbit. So the total action of the closed orbit is

$$S_j(E) = \frac{4\sqrt{2F}}{3}\Big\{\sqrt{z_m - z_n}\,[(z_m + z_n + 2d)E(\lambda,\gamma) - (z_n + d)F(\lambda,\gamma)] - \sqrt{-z_m z_n d}\Big\} + E\sin^2\theta_{\rm out}^j t_j. \tag{23}$$

4. Numerical results and discussion

Using Eq. (11), we calculated the photodetachment cross section of H^- in parallel electric and magnetic fields near a metal surface. In our calculations, we keep the ion–surface distance $d = 100$ a.u. and electric field strength $F = 10$ kV/cm unchanged. The photon energy is varied between 0.76 eV and 1.0 eV and the magnetic field strength B is increased from 1.0 T to 80 T. The results are given in Fig. 3.

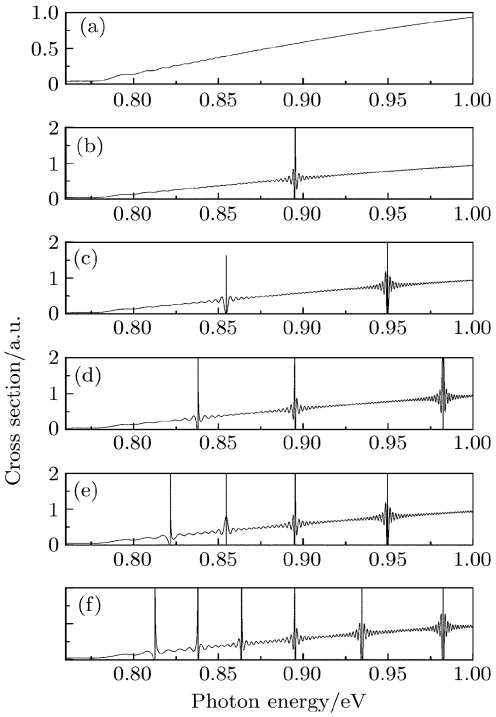


Fig. 3. Photodetachment cross section of H^- in parallel electric and magnetic fields near a metal surface with fixing electric field $F = 10$ kV/cm and ion-surface distance $d = 100$ a.u., the magnetic field strength are as follows: (a) $B = 1$ T, (b) $B = 20$ T, (c) $B = 30$ T, (d) $B = 40$ T, (e) $B = 60$ T, and (f) $B = 80$ T.

Figure 3(a) shows the cross section when the magnetic field strength B is 1 T. Under this condition, the only possible closed orbit which makes a contribution to the photodetachment cross section is the $j = 0$ orbit. The oscillatory structure is small and simple, which likes the case of the photodetachment of H^- in the electric field near a metal surface.[22] With the increase of the magnetic field strength, its effect can be seen clearly. Figure 3(b) shows the cross section with the magnetic field strength $B = 20$ T, and the cross section is different from that in Fig. 3(a). In this case, the Lorentz force acting on the detached electron is strong enough to pull the electron back to the origin. When the photon energy is increased to $E_p = 0.894$ eV, the return time for z motion is exactly equal to one cyclotron period. Therefore, a new closed orbit occurs, which produces a large oscillation in the cross section. Figure 3(c) indicates the cross section when the magnetic field strength B is increased to 30 T. This figure suggests that when the photon energy is less than 0.854 eV, the cross section has a smoothly rising background with small oscillations. As the energy $E_p = 0.854$ eV, a new closed orbit ($j = 1$ orbit) appears, which makes an obvious oscillation at this energy. At $E_p = 0.949$ eV, the second closed orbit ($j = 2$ orbit) appears. As the energy is larger than 0.949 eV, there are altogether three closed orbits contributed to the cross section. Therefore the oscillation in the cross section becomes much more obvious. With magnetic field strength further increasing, there is a sequence of boundary energies at which new orbits bifurcate from them, so the oscillatory structures in the cross section become much more complicated, as we can see from Figs. 3(d)–3(e). In Fig. 3(f), we increase the magnetic field strength B to the value of 80 T. Under this circumstance, the influence of the magnetic field becomes much stronger. The Lorentz force acting on the detached electron is very strong. The cyclotron period in the ρ motion $t^{\rho}_{\rm ret} = j\pi/\omega_{\rm L}$ becomes small. Then after a short period of time, the electron will be turned back by the external fields and the metal surface to the origin. Hence the number of the closed orbits is great. When the energy E_p approaches to 0.982 eV, there are altogether 7 closed orbits and a set of sharp peaks appear in the cross section. The oscillation in the cross section becomes much more complicated and the photodetachment cross section is similar to that in the case of the photodetachment of H^- in parallel electric and magnetic fields.[11]

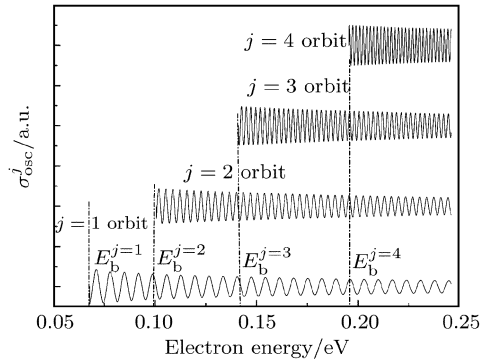


Fig. 4. Oscillatory photodetachment cross section of H^- in parallel electric and magnetic fields near a metal surface. Contributions made by each closed orbit are shown in the plot, with ion–surface distance $d = 100$ a.u., electric field strength $F = 10$ kV/cm, and magnetic field strength $B = 60$ T.

The energy at which a new closed orbit appears is called bifurcation energy, denoted as $E^j_{\rm b}$.[11] As the detached electron energy equals the bifurcation energy, a new closed orbit occurs which produces a large ripple that beats against all the others. In order to show the oscillation in the cross section, caused by each closed orbit clearly, we plot the oscillatory part of the cross section $\sigma^j_{\rm osc}$ corresponding to each closed orbit. The results are given in Fig. 4. With the magnetic field $B = 60$ T, the first bifurcation energy is $E^{j=1}_{\rm b} = 0.06777$ eV, which corresponds to the $j = 1$

closed orbit plotted in Fig. 2. The second bifurcation energy is $E_{\rm b}^{j=2} = 0.10055$ eV, which corresponds to the $j = 2$ closed orbit, the third bifurcation energy that corresponds to the $j = 3$ closed orbit is $E_{\rm b}^{j=3} = 0.14113$ eV and the fourth bifurcation energy that corresponds to the $j = 4$ closed orbit is $E_{\rm b}^{j=4} = 0.19551$ eV. The contribution of each closed orbit to the cross section is shown clearly in this figure.

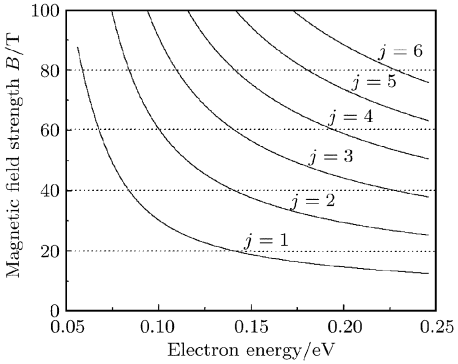


Fig. 5. Bifurcation energies of the detached electron in the electric field near a metal surface at different magnetic fields and ion–surface distance $d = 100$ a.u.

Finally, in order to show the variation of the bifurcation energy with magnetic field, we plot the electron bifurcation energy E versus magnetic field strength, see Fig. 5. The result suggests that at weak magnetic field and low energy, the number of the closed orbit is small. With the increase of magnetic field, the number of the closed orbits increases. From this figure, we can obtain the bifurcation energy and the number of the closed orbits corresponding to each magnetic field easily. For example, at $B = 60$ T, there are four intersections, which indicates there are altogether five closed orbits that make contributions to the cross section. This result is in excellent agreement with the results given in Figs. 3(e) and 4.

5. Conclusions

In summary, we have studied the magnetic field effect on the photodetachement of negative ion in the electric field near a metal surface. An analytical formula for the photodetachment cross section of this system is derived. It is found that the magnetic field can produce significant effect on the photodetachement of negative ion near surfaces. The resulting cross sections are complicated because of the coexistence of the external fields and the metal surface. As the magnetic field strength is very small, its influence can be neglected and the cross section is similar to that in the case given by Yang and Du.[22] With the increase of magnetic field strength, the number of the closed orbits increases greatly and the oscillations in the cross section become much more complex. As the magnetic field strength is very strong, the cross section likes the photodetachment cross section of H^- in parallel electric and magnetic fields.[11] Our results suggest that the atoms or ions adsorbed in surface and external fields show quite different spectroscopic properties from those without external fields or surface. This study provides a general framework for the understanding of the photodetachment process of H^- in the presence of external fields and surface and may have some potential applications in the field of surface physics.

References

[1] Fabrikant I I 1980 *Sov. Phys. JETP* **52** 1045
[2] Bryant H C, Mohagheghi A, Stewart J E, Donahue J B, Quick C R, Reeder R A, Yuan V, Hummer C R, Smith W W, Stanley Cohen, William P Reinhardt and Lillian Overman 1987 *Phys. Rev. Lett.* **58** 2412
[3] Rau A R P and Wong H 1988 *Phys. Rev.* A **37** 632
[4] Du M L and Delos J B 1988 *Phys. Rev.* A **38** 5609
[5] Du M L and Delos J B 1987 *Phys. Rev. Lett.* **58** 1731
[6] Du M L and Delos J B 1988 *Phys. Rev.* A **38** 1896
[7] Du M L and Delos J B 1988 *Phys. Rev.* A **38** 1913
[8] Du M L 2004 *Phys. Rev.* A **70** 055402
[9] Peters A D and Delos J B 1993 *Phys. Rev.* A **47** 3020
[10] Peters A D and Delos J B 1993 *Phys. Rev.* A **47** 3036
[11] Peters A D, Jaffe C and Delos J B 1997 *Phys. Rev.* A **56** 331
[12] Peters A D, Jaffe C and Delos J B 1994 *Phys. Rev. Lett.* **73** 2825
[13] Liu Z Y and Wang D H 1997 *Phys. Rev.* A **55** 4605
[14] Liu Z Y and Wang D H 1997 *Phys. Rev.* A **56** 2670
[15] Petek H, Weida M J, Nagano H and Ogawa S 1999 *Science* **288** 239
[16] Sjakste J, Borisov A G and Gauyacq J P 2004 *Phys. Rev. Lett.* **92** 156101
[17] Yang G C, Zheng Y Z and Chi X X 2006 *J. Phys.* B: *At. Mol. Opt. Phys.* **39** 1855
[18] Yang G C, Zheng Y Z and Chi X X 2006 *Phys. Rev.* A **73** 043413
[19] Wang D H and Yu Y J 2008 *Chin. Phys.* B **17** 1231
[20] Zhao H J and Du M L 2009 *Phys. Rev.* A **79** 023408
[21] Rui K K and Yang G C 2009 *Surf. Sci.* **603** 632
[22] Yang B C and Du M L 2010 *J. Phys.* B: *At. Mol. Opt. Phys.* **43** 035002
[23] Huang K Y and Wang D H 2010 *Chin. Phys.* B **19** 063402
[24] Wang D H, Tang T T and Wang S S 2010 *Journal of Electron Spectroscopy and Related Phenomena* **177** 30
[25] Ganesan K and Taylor K T 1996 *J. Phys.* B: *At. Mol. Opt. Phys.* **29** 1293
[26] Gradshteyn I S and Ryzhik I M 1980 *Tables of Integrals, Series and Products* (New York: Academic) pp. 266–268