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Relativistic electron scattering from freely movable proton/μ^+ in the presence of strong laser field*

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We have investigated the electron scattering from the freely movable spin-1/2 particle in the presence of a linearly polarized laser field in the first Born approximation. The laser-dressed state of electrons is described by a time-dependent wave function which is derived from a perturbation treatment. With the aids of numerical simulations, we explore the dependencies of the differential cross section on the laser field intensity as well as the electron-impact energy. Due to the mobility of the target, the differential cross section of this process is smaller than that of Mott scattering.

Keywords: electron scattering, movable fermion, laser assistance

PACS: 34.80.Qb, 34.80.Dp, 32.80.Wr **DOI:** 10.1088/1674-1056/ab343e

1. Introduction

Electronic scattering is a fundamental physical process in atomic and molecular physics. Its importance has a long time been realized in plasma physics, nuclear physics, as well as astrophysics[1] such as the nuclear fusion in the Sun. The differential cross section (DCS) data of electron scattering from different targets are an important key to open the secret box of the universe. In 1932, Mott[2] obtained the DCS of electron elastic scattering by Coulomb potential without external field. Mott scattering is referred to as spin-coupling inelastic Coulomb scattering. Due to the emergence of laser sources,[3–5] a laser is widely used in both modern applied and fundamental physics owing to the special characteristics of its radiation: laser can provide a unique source of monochromatic, coherent, and intense electromagnetic radiation. This stimulates a constant development of stronger systems such as the chirped amplification (CPA)[6] technique and the extreme light infrastructure (ELI) project,[7] and shorter laser sources such as femtosecond and attosecond pulsed lasers.[8–10] Scattering of an electron by a Coulomb potential of a nucleus in the presence of a strong electromagnetic field was studied since the advent of laser sources in the early 1960s.[4,12,13] Reviews on this field can be found in the textbooks by Faisal,[14] Mittleman,[15] and Fedorov,[16] and some other recent review papers.[1,17,18] Most of these studies were carried out in the regime of non-relativistic collisions and for low- or moderate-field intensities.

There are also some studies carried out to investigate the relativistic scattering in the presence of ultrastrong lasers, for instance, the ELI aims to produce laser with an intensity up to 10^{24} W/cm^2. In such high intensity, a relativistic treatment becomes imperative (even for slow electrons). In the early series work of Ehlotzky *et al.*,[19,20] effects related to the electron spin were neglected and the electron was considered as a Klein–Gordon particle. Szymanowski *et al.*[21] investigated the spin effect of the relativistic potential scattering in the presence of a circularly polarized field. Their expression for the circularly polarized field turned out to be more tractable than that for the general case of elliptical or linear polarizations. Then the electron scattering in the presence of a linearly polarized filed has been worked out by Li *et al.*[22] and for the cases of circularly and elliptically polarized fields by Attaourti *et al.*[23] The scattering of polarized electrons has also been considered in the work of Manaut *et al.*[25] Bai *et al.*[26] generalized the investigation to the multiphoton processes in laser-assisted scattering of a muon neutrino by an electron. Lebed *et al.* studied Coulomb scattering in the presence of one[27] or two[27] laser pulses and discussed the distribution of the differential cross sections. Parametric interference effects of electron–nuclear scattering in two laser pulses were predicted.[27] There have also been some studies using Coulomb effects in atomic scattering theory, which are interesting because of the wide range of electrostatic interactions in plasma physics. Hrour *et al.*[28] gave the scattering of proton by Coulomb potential in circularly polarized laser field considering the distortion of the Coulomb effect. Du[29] and Lebed *et al.*[36] studied the interaction between the electron and the nuclear field when the laser polarization deviates from the incident direction in the first Born approximation. In addition, Hrour *et al.*[30] carried out theoretical analysis of the

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results of proton hydrogen scattering assisted by relativistic laser, and found that the DCS of the process was related not only to the energy of the incident proton, but also to the intensity and frequency of the laser field. Besides the scattering on atomic targets,[31] the electron scattering from molecular targets[32–34] and positronium scattering[35,36] have also been investigated a lot.

In the previous studies of Mott scattering, the target was mostly treated as a fixed potential, few papers investigated on the recoil effect of the target.[1] In 2014, Liu and Li[37] primitively studied the recoil effect in electron–proton scattering in the presence of strong laser field, and gave some typical DCS data for relativistic electron scattering with assistance of an intense monochromatic linearly polarized homogeneous laser field. In this work, we will discuss in detail the laser-assisted electron scattering from a freely movable target, including not only proton, but also positive muon.

The paper is organized as follows. In Section 2, we describe the method used to evaluate the S-matrix transition amplitude in the first Born approximation, as well as the formal expression of scattering DCS, and then give a brief discussion. In Section 3, the numerical results for laser-modified cross sections are presented and their dependencies on several electron and field parameters (e.g., kinetic energy, laser intensity) are discussed in detail. Section 4 summarizes and concludes the present work. Unless specifically stated, atomic units (a.u.) $\hbar = m = e = 1$ are used throughout this work with the matric tensor $g^{\mu\nu} = \mathrm{diag}(1,-1,-1,-1)$.

2. Theory

In this work, we consider only the laser field that can be treated classically whose intensity does not allow pair creation,[38] and its four-potential $A(x)$ satisfies the Lorenz condition $\partial A(x) = 0$. Here, $A(x)$ with linear polarization is described by

$$A(x) = a\cos(kx), \tag{1}$$

where $a = (0, \boldsymbol{a})$, and $\boldsymbol{a}$ is the amplitude of the vector potential of the field. The four wave vector of the field is $k = (\omega/c, \boldsymbol{k})$, where ω and k are the frequency and the wave number, respectively.

The scattering process investigated here involves two fermions, including an electron (e^-) and a proton (p) or positive-muon (μ^+)

$$\mathrm{p}(\mu^+) + \mathrm{e}^- \to \mathrm{p}(\mu^+) + \mathrm{e}^-. \tag{2}$$

The relativistic, asymptotic electron state in the laser field can be described by the Dirac–Volkov function.[39] When normalized in volume V and considering the linearly polarized field, its wave function reads

$$\psi_q(x) = \psi_p(x) = \left(1 + \frac{\not{k}\not{A}}{2c(kp)}\right)\frac{u(p,s)}{\sqrt{2QV}}\,\mathrm{e}^{\mathrm{i}S(x)}, \tag{3}$$

$$S(x) = -qx - \frac{a\cdot p}{c(k\cdot p)}\sin(kx), \tag{4}$$

where the slashed symbols are defined as $\not{a} = a_\mu\gamma^\mu = a^\mu\gamma_\mu$, u represents a bispinor for the free electron with normalization of $\bar{u}u = 2c^2$, and Q refers to the incident energy of electron. $q^\mu = (Q/c, \boldsymbol{q})$ is the averaged four-momentum of electron in the presence of the laser field

$$q^\mu = p^\mu - \frac{\overline{a^2}}{2c^2(k\cdot p)}k^\mu, \tag{5}$$

where $\overline{a^2}$ is the time-averaged square of the four-potential of the laser field. The square of this momentum q^μ is

$$q^\mu q_\mu = m_*^2c^2. \tag{6}$$

The parameter m_* plays the role of an effective mass of the electron in the radiative field

$$m_*^2 = 1 - \frac{a^2}{c^4}. \tag{7}$$

In the first Born approximation, the particle will be treated as a structureless, spin-1/2 Dirac particle. The mass of a proton (p) or a positive-muon (μ^+) is about 1836 or 207 times heavier than that of an electron, respectively. Therefore, its modification by the laser field is not notable, we can treat it as unaffected plane wave in current discussion,

$$\psi_P(x) = \frac{u(P,S)}{\sqrt{2E_PV}}\,\mathrm{e}^{-\mathrm{i}Px}. \tag{8}$$

The S-matrix element for the scattering process takes the form

$$\begin{aligned} S_{fi} &= -\mathrm{i}\int \mathrm{d}^4x\,\overline{\psi}_{q_f}(x)\not{A}(x)\psi_{q_i}(x) \\ &= \mathrm{i}\int \mathrm{d}^4x\mathrm{d}^4y\,\overline{\psi}_{q_f}(x)\gamma^\mu\psi_{q_i}(x)D_\mathrm{F}(x-y)\overline{\psi}_{P_f}(y)\gamma_\mu\psi_{P_i}(y), \end{aligned} \tag{9}$$

with the potential

$$A^\mu(x) = \int \mathrm{d}^4y D_\mathrm{F}(x-y)J^\mu(y), \tag{10}$$

where

$$J^\mu(y) = -\overline{\psi}_{P_f}(y)\gamma_\mu\psi_{P_i}(y), \tag{11}$$

and D_F is the Feynman propagator. For electromagnetic radiation, it is given by

$$D_\mathrm{F}(x-y) = \int \frac{\mathrm{d}^4q}{(2\pi)^4}\,\mathrm{e}^{-\mathrm{i}q\cdot(x-y)}\frac{-1}{q^2+\mathrm{i}\varepsilon}. \tag{12}$$

Substituting Eqs. (3), (8), (10)–(12) into Eq. (9) and applying the identities for Bessel functions

$$\mathrm{e}^{\mathrm{i}z\sin(u)} = \sum_{l=-\infty}^{\infty} J_l(z)\,\mathrm{e}^{\mathrm{i}lu}, \tag{13}$$

$$J_{l-1}(z)+J_{l+1}(z)=\frac{2l}{z}J_l(z), \tag{14}$$

we can recast the S-matrix of Eq. (9) in the form

$$S_{fi} = -\mathrm{i}(2\pi)^4\delta^4(P_f-P_i+q_f-q_i-lk) \times\sum_{l=-\infty}^{\infty}\frac{M_{fi}^{(l)}}{4V^2Q_fQ_iE_fE_i}\frac{1}{q^2+\mathrm{i}\varepsilon}, \tag{15}$$

with

$$M_{fi}^{(l)}=\overline{u}(p_f,s_f)\Gamma^{\mu}u(p_i,s_i)\overline{u}(P_f,S_f)\gamma_{\mu}u(P_i,S_i), \tag{16}$$

where

$$\Gamma^{\mu}=\Delta_0\gamma^{\mu}+\Delta_1\gamma^{\mu}\not{k}\not{a}+\Delta_2\gamma^{\mu}\not{a}\not{k}+\Delta_3\gamma^{\mu}\not{a}\not{k}\gamma^{\mu}\not{k}\not{a}. \tag{17}$$

$$\Delta_0=J_l(D), \tag{18}$$

$$\Delta_1=\frac{lJ_l(D)}{2c(k\cdot p_i)D}, \tag{19}$$

$$\Delta_2=\frac{lJ_l(D)}{2c(k\cdot p_f)D}, \tag{20}$$

$$\Delta_3=\frac{J_2(D)+2J_l(D)+J_{l+2}(D)}{16c^2(k\cdot p_i)(k\cdot p_f)}, \tag{21}$$

in which

$$D=\frac{p_f\cdot a}{c(k\cdot p_f)}-\frac{p_i\cdot a}{c(k\cdot p_i)}=\mathcal{E}_0\cdot\left[\frac{\boldsymbol{p}_i}{\omega(k\cdot p_i)}-\frac{\boldsymbol{p}_f}{\omega(k\cdot p_f)}\right], \tag{22}$$

with $\mathcal{E}_0=(\omega/c)\boldsymbol{a}$ being the amplitude of the electric field strength of the laser field.

To calculate the cross section, we need first construct the transition rate per unit volume by diving $|S_{fi}|^2$ the interval of observation T and the spatial volume of the interaction region. By following the steps presented in Ref. [40], the cross section is obtained as

$$\mathrm{d}\sigma = (2\pi)^4\delta^4(P_f-P_i+q_f-q_i-lk)\sum_{l=-\infty}^{\infty}\frac{1}{16Q_iE_iV|J_{\mathrm{inc}}|} \times\frac{1}{q^4}|M_{fi}^{(l)}|^2\frac{\mathrm{d}^3q_f}{Q_f(2\pi)^3}\frac{\mathrm{d}^3P_f}{E_f(2\pi)^3}. \tag{23}$$

Here we derive the $\mathrm{d}\sigma$ in the laboratory frame of reference, in which the initial heavy particle (proton or muon) is at rest and the initial and final momenta of the scattering particles are set as $q_f=(Q',\boldsymbol{q}'),q_i=(Q,\boldsymbol{q}_i)$, and $P_i=(Mc,\boldsymbol{0})$. The flux $|J_{\mathrm{inc}}|=|\boldsymbol{v}_i|/V$, and $\boldsymbol{v}_i$ is the impact velocity. To get the unpolarized cross sections, we must average over the initial states and sum over the final ones. Then

$$|\overline{M}_{fi}^{(l)}| = \frac{1}{4}\sum_{l=-\infty}^{\infty}\mathrm{Tr}[(c\not{p}_f+c^2)\Gamma_{(l)}^{\mu}(c\not{p}_i+c^2)\overline{\Gamma}_{(l)}^{\nu}] \times\mathrm{Tr}[(c\not{P}_f+c^2)\gamma_{\mu}^{(l)}(c\not{P}_i+c^2)\gamma_{\nu}^{(l)}]. \tag{24}$$

Using the relation $\mathrm{d}^3q_f=\frac{1}{c^2}q'Q'\,\mathrm{d}Q'\,\mathrm{d}\Omega'$ and integrating over the final state electron energy Q_f, we obtain the following scattering DCS:

$$\frac{\mathrm{d}\overline{\sigma}}{\mathrm{d}\Omega'}=\sum_l\frac{\mathrm{d}\overline{\sigma}^l}{\mathrm{d}\Omega'}=\frac{1}{(2\pi)^2}\frac{1}{16Mc^6} \times\sum_l\frac{\boldsymbol{q}'}{\boldsymbol{q}_i}\frac{1}{q^4}\frac{\overline{|M_{fi}^{(l)}|^2}}{Mc^2+Q+l\omega-\frac{Q'}{c^2q'}(q_i\cos\theta+lk\sin\theta\cos\phi)}. \tag{25}$$

The energy conservation derived from the δ-function in Eq. (23) is

$$Q'(Mc^2+Q+l\omega)-c^2(\boldsymbol{q}'\cdot\boldsymbol{q}_i+l\boldsymbol{q}'\cdot\boldsymbol{k}) = m_*^2c^4+Mc^2Q+lc^2(M\omega-\boldsymbol{q}'\cdot\boldsymbol{k}). \tag{26}$$

Now, a brief discussion about the conservation relation in different limits is worthwhile to made here. (i) In the limit of $Q\ll Mc^2$, $l=0$, we should approach the limiting case of scattering at a fixed Coulomb potential, and there is no external laser field. In this case, there is no recoil that $\boldsymbol{q}'=0$, and no photon absorption or emission. Therefore,

$$Q'M=MQ \quad \text{or} \quad Q'=Q. \tag{27}$$

The scattering process here is an elastic one. (ii) In the limit of $Q\ll Mc^2$, but $l\neq 0$, the scattering potential approaches the fixed Coulomb potential with a laser field assisted. The energy conservation relation now is rewritten as

$$Q'=Q+l\omega, \tag{28}$$

which is exactly the case that has been discussed by Li *et al.*[22]

3. Results and discussion

In this section, we present and analyze the numerical results for the electron scattering from the freely movable spin-1/2 particles in the assistant of strong laser field. The influence of the laser parameters (e.g., the intensity, frequency, and direction of the polarization vector) as well as that of the electron parameters on the DCS summed over multi-photon processes are discussed. The origin of the coordinate system is chosen to be on the target before collision, the z-axis is set along with the incident electron momentum $\boldsymbol{p}_i$, the y-axis is set along with the direction of the field wave vector $\boldsymbol{k}$, and the electric-field vector $\mathcal{E}_0$ of the field lies in the xz-plane.

Figure 1 displays the partial differential cross sections $\mathrm{d}\overline{\sigma}^l/\mathrm{d}\Omega$ versus the net photon number l transferred between the colliding system and the laser field. These figures have the same feature as the Mott scattering investigated in Ref. [22]. We would choose the same parameters as those in that paper: the electron-impact energy is $T_{\mathrm{i}}=mc^2=0.511$ MeV (the corresponding Lorentz factor $\overline{\gamma}_{\mathrm{L}}=Q/mc^2=(T_{\mathrm{i}}+mc^2)/mc^2=2$), the field strength is $\mathcal{E}_0=0.01=5.14\times10^7$ V·cm^{-1}, and the photon energy (field frequency) is $\hbar\omega=1.17$ eV. The laser polarization is chosen to be parallel to the incident momentum. At a small scattering angle (1° in Fig. 1(a)), only the multiphoton processes with a few number of photons are important, and

the partial differential cross section $\mathrm{d}\overline{\sigma}^{l}/\mathrm{d}\Omega$ is sharply peaked around $l = 0$. At large scattering angles $\theta = 90^{\circ}$ in Fig. 1(b) and 180° in Fig. 1(c), the processes involving large numbers of photons have significant contributions. The origin of this behavior is given below. The magnitude of $\mathrm{d}\overline{\sigma}^{l}/\mathrm{d}\Omega$ varies in the range of few orders for different l. Furthermore, the contributions of various l-photon processes are cut off at two edges which are asymmetric with respect to $l = 0$. The cutoff for positive l is a consequence of the energy conservation imposed in Eq. (26), while the cutoff for negative values of l can be inferred by the properties of the Bessel function $J_l(D)$ when its argument D is approximately equal to its order l. This has already been pointed out in Refs. [21] and [22].

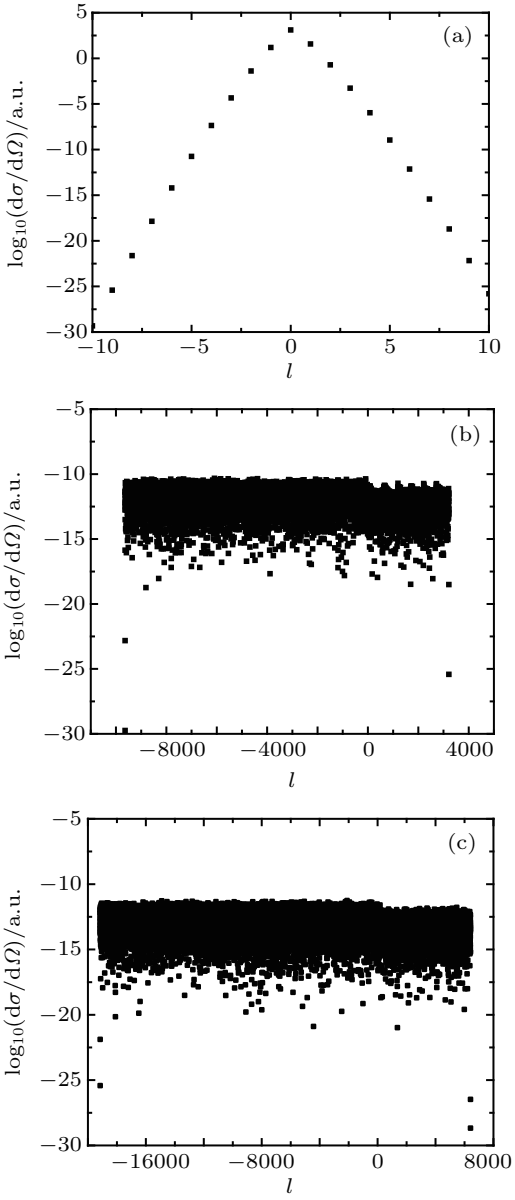


Fig. 1. The multiphoton cross sections verse the number of exchanged photons in the laser-assisted processes of electron scattering with impact energy of $T_{\mathrm{i}} = mc^2 = 0.511$ MeV. The scattering angels are (a) $\theta = 1^{\circ}$, (b) $\theta = 90^{\circ}$, and (c) $\theta = 180^{\circ}$. The laser field is linearly polarized along the incident direction of the electron, the field intensity is $\mathcal{E}_0 = 0.01 = 5.14 \times 10^7$ V·cm^{-1}, and the photon energy $\hbar\omega = 1.17$ eV.

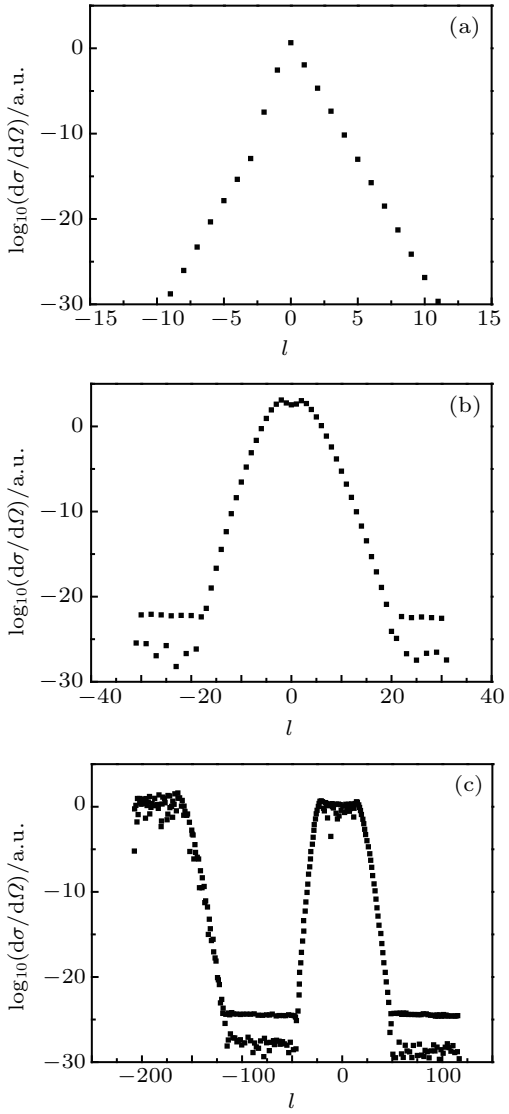


Fig. 2. The multiphoton cross sections verse the number of exchanged photons (l) in the laser-assisted processes of electron scattering with impact energy of $T_{\mathrm{i}} = 0.1mc^2 = 0.0511$ MeV. The scattering angels are $\theta = 1^{\circ}$ for (a) Mott scattering, (b) electron–proton scattering, and (c) e–μ^+ scattering. The laser field is linearly polarized along the incident direction of the electron, the field intensity is $\mathcal{E}_0 = 0.1 = 5.14 \times 10^8$ V·cm^{-1}, and the photon energy $\hbar\omega = 1.17$ eV.

Figure 2 shows the cross sections at small scattering angle ($\theta = 1^{\circ}$) versus the number of transferred photons at $T_{\mathrm{i}} = 0.1mc^2 = 0.0511$ MeV, $\mathcal{E}_0 = 0.1$ a.u. $= 5.14 \times 10^8$ V·cm^{-1}, and the photon energy $\hbar\omega = 1.17$ eV. Comparisons among Figs. 2(a)–2(c) show that the transfer of photons is enhanced when the strength of the laser field is increased and the number of photons also increases with decreasing the mass of the target. For Mott scattering and e–proton scattering, the contributions of various l-photon processes, like the case of Fig. 2(a), are cut off at two edges which are nearly symmetric with respective to $l = 0$. For the lighter target positive-muon, the contributions show considerable asymmetry in the range with negative l, although there exist symmetric characters at $|l| \leq 120$. This shows that due to the non-fixed property of the target, the transferring of photons becomes more feasible and the DCS becomes smaller than that of the laser-free case. Another no-

table feature in Fig. 2(c) is the modulation of differential cross section verse l. Both the asymmetry and modulation appear only in large angles for Mott scattering,[22] but now they appear on the e–μ^+ scattering. Because for the lighter target, due to the recoil effect, the multiphoton process becomes important. For example, for Mott scattering and e–p scattering, the cutoff l is about 12 and 32, respectively. For the positive muon, whose mass is only about 11% of proton's mass, the cutoff l increases to 120 and -210 for absorption and emission, respectively. The magnitude of differential cross section varies in a range of a few orders for different l. Such oscillations result from the periodic variation of the Bessel function $J_l(D)$, like the case of large angle of Figs. 1(b) and 1(c).

Figure 3 shows the differential cross sections summed over all multiphoton processes, as given by Eq. (25). Both the Mott scattering and Mott with laser-assisted scattering processes are included for comparison. Figure 3(b) shows more details of Fig. 3(a) at small scattering angles. From the comparison, we can see that, at small angles, the summed cross sections are almost unmodified by the presence of the laser field. In the backward direction ($\theta = 180°$), the modification of the cross sections by the laser field in the geometry $\mathcal{E}_0 \parallel \boldsymbol{p}$ is most significant.[22]

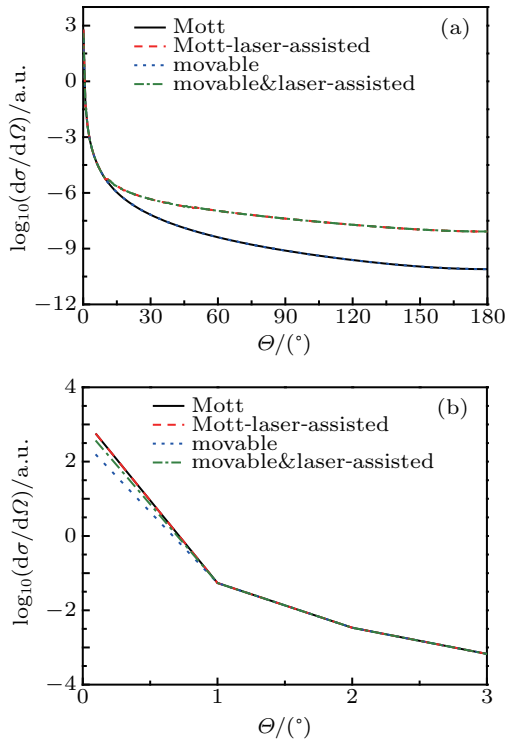


Fig. 3. The differential cross sections summed over all multiphoton processes. Panel (a) shows the range from 0° to 180°, while panel (b) shows the detail of the small scattering angles. The parameters of electron and laser are the same as those in Fig. 1.

When referring to Fig. 3(b), it is noted that there are no significant modifications in Mott scattering by laser assistance, however, for movable-target scattering the revisions are relatively large: the cross sections of the laser-assisted collision are slightly grater than those of the laser-free case. Because of the recoil effect, when the scattering angles are small, the cross sections are much smaller than those of the fixed target.

Figure 4 reveals the dependence of the summed cross sections on the laser field strength. The field strength enters into the determining equations of the cross section through the argument D of the Bessel functions in Eqs. (18)–(21) and through the a-dependent terms in Eq. (21). Although for each multiphoton process, the Bessel functions in the partial cross section oscillate with the field strength, the summed cross section increases steadily by about two orders of magnitude as the field strength increases from 0 to 10^8 V·cm^{-1}. The stronger of the field and the more distortion of the electron state lead to, consequently, the more enhancement of the cross sections.

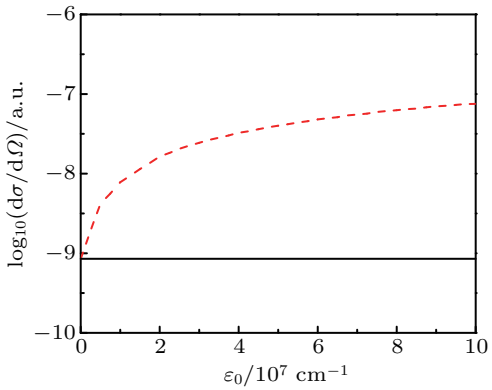


Fig. 4. The cross section of scattering versus the field intensity at $\theta = 90°$ and $\phi = 0°$. The solid line is the laser-free case, and the dashed line is the dependence on different laser intensities. The photon energy $\hbar\omega = 1.17$ eV.

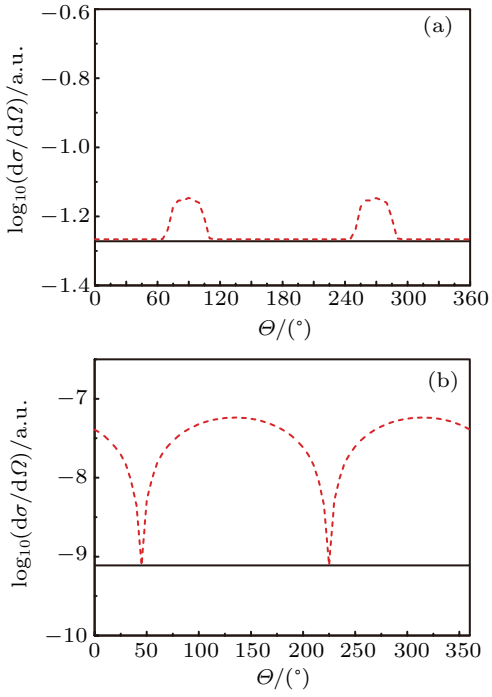


Fig. 5. The summed unpolarized DCS versus the polar angle of the polarization vector of the field at $\mathcal{E}_0 = 5.14 \times 10^7$ V·cm^{-1}, (a) $\theta = 1°$, or (b) $\theta = 90°$, and $\phi = 1°$. The solid line shows the DCS of the laser-free case, and the dashed one for that of the laser-assisted case. Impact energy of electron is the same as that in Fig. 1.

Figure 5 gives the dependence of the summed cross sections on the (linear) polarization direction of the field. Figure 5(a) shows that, at small scattering angles, there is little modification when $\mathcal{E}_0 \parallel \boldsymbol{p}$, and the modification reaches peaks at $\Theta = 90^\circ$ and $\Theta = 270^\circ$ ($\mathcal{E}_0 \perp \boldsymbol{p}$). Figure 5(b) shows the case of scattering angle $\theta = 90^\circ$. The polarization dependence is approximately periodic. As what has been discussed in Ref. [22], this is attributed to the periodic nature of the argument D (shown in Eq. (22)) of the Bessel functions. When the magnitude of field strength and momenta of electron in both initial and final states are fixed, the scalar product between $\mathcal{E}_0$ and $\boldsymbol{p}$ (or $\boldsymbol{p}'$) varies periodically with the polar angle Θ of $\mathcal{E}_0$.

4. Conclusion

We have studied the electron scattering from freely movable fermions in the presence of a radiation field. We derived the DCS of electron scattering from movable proton and positive muon. In the case of $M \to \infty$, it becomes Mott scattering. The calculated results for the linear polarization case show that the DCS of scattering is greatly enhanced by the presence of laser field, and reduced compared to the Mott scattering under the same situation. The scattering process is modified decisively due to the multi-photon absorptions and emissions. It can exchange an amount of photons with the laser field depending on various properties of the field, impact energy, and the mass of the collision target. The treatment of this work can be readily extended to the case of a general polarized field and even the cases of Müller scattering and Bhabha scattering.

References

[1] Vélez F C, Kaminski J Z and Krajewska K 2019 *Atoms* **7** 34
[2] Mott N F 1932 *Proc. R. Soc. A* **135** 429
[3] Brown L S and Kibble T W B 1965 *Phys. Rev.* **133** A705
[4] Kibble T W B 1966 *Phys. Rev.* **150** 1060
[5] Goldman I I 1964 *Phys. Lett.* **8** 103
[6] Strickland D and Mourou G 1985 *Opt. Commun.* **56** 219
[7] The extreme light infrastructure (ELI) project
[8] Krausz F and Ivanov M 2009 *Rev. Mod. Phys.* **81** 163
[9] Sansone G, Benedetti E, Calegari F, Vozzi C, Avaldi L, Flammini R, Poletto L, Villoresi P, Altucci C, Velotta R, Stagira S, Silvestri S D and Nisoli M 2006 *Science* **81** 314
[10] Zhao K, Zhang Q, Michael C, Wu Y, Wang X W and Chang Z H 2012 *Opt. Lett.* **37** 3891
[11] Li J, Ren X, Yin Y, Zhao K, Chew A, Cheng Y, Cunningham E, Wang Y, Hu S, Wu Y, Chini M and Chang Z 2017 *Nat. Commun.* **8** 186
[12] Nikishov A I and Ritus V I 1964 *Sov. Phys. JETP* **19** 1191
[13] Narozhny N B, Nikishov A I and Ritus V I 1965 *Sov. Phys. JETP* **20** 622
[14] Faisal F H M 1987 *Theory of Multiphoton Processes* (New York: Plenum)
[15] Mittleman M H 1993 *Introduction to the Theory of Laser-Atom Interactions* (New York: Plenum)
[16] Fedorov M V 1997 *Atomic and Free Electrons in a Strong Light Field* (Singapore: World Scientific)
[17] Francken P and Joachain C J 1990 *J. Opt. Soc. Am. B* **7** 554
[18] Ehlotzky F, Jaroń A and Kamiński J Z 1998 *Phys. Rep.* **297** 63
[19] Kamiński J Z and Ehlotzky F 1999 *Phys. Rev. A* **59** 2105
[20] Panek P, Kamiński J Z and Ehlotzky F 1999 *Can. J. Phys.* **77** 591
[21] Szymanowski C, Véniard V, Taïeb R, Maquet A and Keitel C H 1997 *Phys. Rev. A* **56** 3846
[22] Li S M, Berakdar J, Chen J and Zhou Z F 2003 *Phys. Rev. A* **67** 063409
[23] Attaourti Y, Manaut B and Taj S 2004 *Phys. Rev. A* **70** 023404
[24] Manaut B, Taj S and Attaourti Y 2005 *Phys. Rev. A* **71** 043401
[25] Bai L, Zheng M Y and Wang B H 2012 *Phys. Rev. A* **85** 013402
[26] Lebed A A 2015 *Laser Phys.* **25** 055301
[27] Roshchupkin S P and Lebed A A 2014 *Phys. Rev. A* **90** 035403
[28] Hrour E, Taj S, Chahboune A and Manaut B 2017 *Laser Phys.* **27** 066003
[29] Du W Y, Zhang P F and Wang B B 2018 *Front. Phys.* **13** 133401
[30] Hrour E, Taj S, Chahboune A, Idrissi M E and Manaut B 2016 *Can. J. Phys* **94** 645
[31] Jiao L G, Zhou Y J and Yu R M 2009 *Chin. Phys. Lett.* **26** 023401
[32] Li J M, Yao Y K, Sun L H, Shan X Y, Wang C and Lu X H 2019 *Chin. Phys. Lett.* **36** 048201
[33] Jiang J, Dong C Z, Xie L U, Wang J G, Yan J and Fritzsche S 2007 *Chin. Phys. Lett.* **24** 691
[34] Jia S Q 2019 *Chin. Phys. Lett.* **36** 010401
[35] Cheng Y J and Zhou Y J 2011 *Chin. Phys. Lett.* **28** 093402
[36] Yu R M, Cheng Y J, Jiao L G and Zhou Y J 2012 *Chin. Phys. Lett.* **29** 053401
[37] Liu A H and Li S M 2014 *Phys. Rev. A* **90** 055403
[38] Bula C 1996 *Phys. Rev. Lett.* **76** 3116
[39] Volkov D M 1935 *Z. Phys.* **94** 250
[40] Bjorken J D and Drell S D 1964 *Relativistic Quantum Mechanics* (New York: McGraw-Hill)