Front. Phys. 13(4), 133401 (2018)
https://doi.org/10.1007/s11467-018-0765-3

RESEARCH ARTICLE

New phenomena in laser-assisted scattering of an electron by a muon

Wen-Yuan Du*, **Peng-Fei Zhang**†, **Bing-Hong Wang**‡

Department of Modern Physics, University of Science and Technology of China, Hefei 230026, China
*E-mail: *pmcnpx@mail.ustc.edu.cn, †zhpf@ustc.edu.cn, ‡bhwang@ustc.edu.cn*
Received September 27, 2017; accepted December 24, 2017

The scattering of an electron by a muon in the presence of a linearly polarized laser field is investigated in the first Born approximation. The theoretical results reveal the following: i) At medium and large scattering angles, many multiphoton processes occur during scattering, and these nonlinear phenomena may predict the resonant state of the electron and the muon formed in the collision process. ii) The photoabsorption (inverse bremsstrahlung) dominates the photoemission (bremsstrahlung), causing the cross section to increase. iii) When the laser polarization deviates from the incident direction, the laser-modified total cross section depends considerably on the azimuthal angle of the scattered electron. The dependence of the cross section on the field strength, polarization direction, and electron-impact energy are studied.

Keywords laser-assisted scattering, multiphoton processes, nonlinear effect, generalized Bessel function

PACS numbers 34.50.Rk, 34.80.Qb, 12.20.-m

Frontiers of Physics

1 Introduction

With advances in laser technology since the 1960s, the laser, a new light source with excellent monochromaticity, high brightness, and strong directionality and coherence, has become widely used in industrial, medical, commercial, scientific, information, and military fields.

Lasers are currently indispensable tools for investigating physical processes in areas ranging from atomic and plasma physics to nuclear and high-energy physics. Laser-assisted charged particle–atom collisions have attracted considerable interest over the past few decades owing to their wide applications in plasma confinement, chemical reactions, semiconductor physics, and fundamental understanding of the details of atomic structure and interaction.

Early studies on laser-assisted electrons and ions or atomic scattering processes are well documented in the literature, and overviews of this field are presented in books by Faisal [1], Mittleman [2], and Fedorov [3] and in recent papers [4–6]. Most of these studies investigated the regime of nonrelativistic collisions and low or moderate field intensities. With the advent of very powerful laser sources, yielding intensities in the range of 10^{17}–10^{18} W/cm^2 and higher, it has become important to consider laser-modified and laser-induced processes relativistically. This is because the averaged quiver energy acquired by a classical electron scales as the modulus squared of the field strength, ϵ_0. For contemporary laser sources having intensities around 10^{18} W/cm^2, the averaged quiver energy may well exceed c^2 [7]. Therefore, in a relativistic-intensity laser field, many quantum electrodynamic processes, such as laser-modified Compton scattering [8–11], have become the focus of research. Scattering of an electron by an electron (positron) in the light field was studied in multiple works [12–18]. Several studies have been conducted to theoretically investigate the relativistic potential scattering assisted by an extremely intense laser field. In the treatments [19–21], effects related to the electron spin have been neglected, and the electron has been considered as a Klein–Gordon particle. On the basis of the theory [22, 23], Szymanowski *et al.* [24] and Szymanowski and Maquet [25] investigated the spin effect in relativistic potential scattering in the presence of a circularly polarized field. However, as they stated, the resulting expression for the circularly polarized field was found to be more tractable than that for the general case of elliptical or linear polarization. Then Li *et al.* studied the case of a linearly polarized field [26], Attaourti *et al.* studied the cases of circularly and elliptically polarized fields [27], and Manaut *et al.* investigated the case of polarized electrons [28]. The process of scattering of an electron by a muon in an elliptically polarized plane electromagnetic wave field has been studied in detail in the nonresonant case [29] and in the resonant case [30]. Nonresonant scattering of a relativistic electron by a relativistic muon in a pulsed light field was studied in [31]. There are some excellent recent works on quantum electrodynamics in strong pulsed laser fields, such as nonresonant and resonant quantum electrodynamic processes in a pulsed laser field [32, 33], resonant scattering of ultrarelativistic electrons in the strong field of a pulsed laser wave [34], and the parametric interference effect in nonresonant pair photoproduction on a nucleus in the field of two pulsed light waves [35].

Nonlinear effects in the processes of interaction of an electron with a nucleus or with other charged particles (also with each other) in a wave field have become a focus of study. An earlier study gives the two parameters that govern these nonlinear effects [36]. The first is η_e, which is the classical relativistic-invariant parameter of the intensity of the wave. The second is the quantum Bunkin–Fedorov parameter γ_{0e}, which determines the multiplicity of a multiphoton process [37–39]. Note that a quantum Bunkin–Fedorov parameter is the principal parameter of the multiphoton processes in nonresonant scattering (see Refs. [29, 31]). For $\gamma_{0e} \ll 1$, components with $l = \pm 1$ provide the main contribution to the scattering cross section in the absence of an external field (the domain of applicability of perturbation theory with respect to the external field). If $\gamma_{0e} \gtrsim 1$, then the process of nonresonant scattering becomes a nonlinear (multiphoton) one with respect to the external field. However, as a classical parameter of the intensity of the wave, η_e is the principal parameter of multiphoton processes in resonant scattering [30]. In Ref. [31], it was found that the cross section of nonresonant scattering of a relativistic electron by a relativistic muon in a moderately strong quasimonochromatic laser field differs substantially from the corresponding cross section of the process in the field of a plane monochromatic wave.

In this paper, we investigate the laser-assisted relativistic scattering of an electron by a muon in the frame of the Born approximation. A numerical calculation is performed to evaluate the partial differential cross sections of multiphoton processes and the cross section summed over all these processes. The nonlinear effects in the scattering process, such as multiphoton processes and characteristic cutoff phenomena, are given intuitively. The multiphoton processes might predict the resonant state of the electron and the muon formed in the collision process. We calculate the total differential cross section in a medium-intensity laser field and find that the cross section depends on the field intensity, frequency, polarization direction, and electron-impact energy. We also investigate the recoil effect in relativistic scattering of an electron from a freely movable muon.

The paper is organized as follows. In Section 2, we derive the expression for the differential cross section of an electron scattered by a muon in a linearly polarized laser field. In Section 3, we present the numerical results for the laser-modified cross section and discuss the dependence of the total cross section on the scattering angles and various parameters of the laser. Section 4 presents a brief summary and conclusions. Natural units $\hbar = c = 1$ and the Minkowski metric tensor $g^{\mu\nu} = diag(1, -1, -1, -1)$ are used throughout this paper.

2 Theory

Consider the scattering process $\mathrm{e}^- + \mu^- \to \mathrm{e}^- + \mu^-$ in a linearly polarized laser field. For mathematical simplicity, the laser field is taken to be a monochromatic linearly polarized plane wave with the classical four-potential,

$$\boldsymbol{A}(x) = \boldsymbol{a}\epsilon^{\mu}\cos\phi, \tag{1}$$

where $\boldsymbol{a} = \boldsymbol{\mathcal{E}}_0/\omega$, and $\boldsymbol{\mathcal{E}}_0$ is the strength of the laser field. $\phi = kx$, where $k = (\omega, \boldsymbol{k})$, and ω and $\boldsymbol{k}$ are the frequency and wave number, respectively. ϵ is the polarization four-vector satisfying $\epsilon k = 0$ and $\epsilon^2 = -1$. The wave function of the muon can be described by the Dirac function as

$$\psi_{\mu^-}^{i,f}(x) = \frac{1}{\sqrt{2E_{i,f}V}} u(P_{i,f}, S_{i,f})\mathrm{e}^{-\mathrm{i}P_{i,f}x}. \tag{2}$$

The laser-assisted electron wave function can be described by the Dirac–Volkov state [40]:

$$\psi_e^i(x) = \frac{1}{\sqrt{2Q_iV}}(1 + \frac{e\not{k}\not{A}}{2kp_i})u_e(p_i, s_i)\mathrm{e}^{\mathrm{i}S_{p_i}[\phi(x)]}, \tag{3}$$

$$\psi_e^f(x) = \frac{1}{\sqrt{2Q_fV}}(1 + \frac{e\not{k}\not{A}}{2kp_f})u_e(p_f, s_f)\mathrm{e}^{\mathrm{i}S_{p_f}[\phi(x)]}, \tag{4}$$

with

$$S_{p_{i,f}}[\phi(x)] = -p_{i,f}x - \int_0^{\phi}\left(e\frac{p_{i,f}A(\phi')}{kp_{i,f}} - e^2\frac{A^2(\phi')}{2kp_{i,f}}\right)\mathrm{d}\phi', \tag{5}$$

where the subscripts i and f indicate the incoming and outgoing electron (muon) wave function. Further, $u_{p_{i,f},s_{i,f}}$ are free Dirac spinors satisfying $\sum_s u_e(p,s)\bar{u}_e(p,s) = \not{p} + m_e$. The laser-assisted kinetic momentum of the electron is called the effective momentum q^{μ} and has the form

$$q^{\mu} = p^{\mu} - \frac{e^2\overline{A^2}}{2(kp)}k^{\mu}. \tag{6}$$

Its square is $q^2 = m_*^2 = m_e^2 + e^2a^2/2$, where m_* acts as the effective mass of the electron in the field.

The scattering process of the electron and muon is a weak interaction process; it can be described by the lowest Feynman diagrams. The scattering amplitude can be written as

$$S_{fi} = -\mathrm{i}e^2 \int \mathrm{d}^4x \int \mathrm{d}^4y \bar{\psi}_e^f(x)\gamma_\mu \psi_e^i(y) \times D^{\mu\nu}(x-y)\bar{\psi}^f_{\mu^-}(x)\gamma_\nu \psi^i_{\mu^-}(y), \quad (7)$$

where $D_F(x-y) = \int \frac{\mathrm{d}^4k'}{(2\pi)^4}\frac{-4\pi}{k'^2+\mathrm{i}\varepsilon}\mathrm{e}^{-\mathrm{i}k'(x-y)}$ is the Feynman propagator for photons [41].

The space-time integrations in Eq. (7) can be performed by the standard method of Fourier series expansion using the generating function of the generalized Bessel function. The latter can be expressed via an ordinary Bessel function according to

$$B_n(\xi,\eta) = \sum_{\lambda=-\infty}^{\infty} J_{n-2\lambda}(\xi)J_\lambda(\eta). \quad (8)$$

We obtain

$$S_{fi} = i\frac{(2\pi)^4 4\pi e^2}{4V^2\sqrt{Q_iQ_fE_iE_f}}\sum_{l=-\infty}^{\infty}\frac{M_l}{(P_i-P_f)^2+\mathrm{i}\epsilon} \times \delta^4(q_f - q_i + P_f - P_i + lk), \quad (9)$$

in which

$$M_l = \bar{u}(p_f,s_f)\Gamma^\mu u(p_i,s_i)\bar{u}(P_f,S_f)\gamma_\mu u(P_i,S_i), \quad (10)$$

with

$$\Gamma^\mu = \Delta_0\gamma^\mu + \Delta_1\gamma^\mu \not{k}\not{\epsilon} + \Delta_2\gamma^\mu\not{\epsilon}\not{k} + \Delta_3\gamma^\mu\not{\epsilon}\not{k}\gamma^\mu\not{k}\not{\epsilon}, \quad (11)$$

where

$$\Delta_0 = B_l(\xi,\eta), \quad (12)$$

$$\Delta_1 = \frac{ea[B_{l-1}(\xi,\eta)+B_{l+1}(\xi,\eta)]}{4kp_i}, \quad (13)$$

$$\Delta_2 = \frac{ea[B_{l-1}(\xi,\eta)+B_{l+1}(\xi,\eta)]}{4kp_f}, \quad (14)$$

$$\Delta_3 = \frac{e^2a^2[2B_l(\xi,\eta)+B_{l-2}(\xi,\eta)+B_{l+2}(\xi,\eta)]}{16kp_ikp_f}, \quad (15)$$

with

$$\xi = ea\left(\frac{\epsilon p_f}{kp_f} - \frac{\epsilon p_i}{kp_i}\right), \quad (16)$$

$$\eta = e^2a^2\left(\frac{1}{8kp_f} - \frac{1}{8kp_i}\right). \quad (17)$$

Here, we do not consider the polarization effects of the electron and muon. To calculate the total scattering cross section, we sum over the final spin states and average over the initial spin states because the muon has a spin of 1/2, like the electron. The total cross section can be obtained as

$$\begin{aligned}\bar{\sigma} &= V\int\frac{\mathrm{d}^3\boldsymbol{q}_f}{(2\pi)^3}V\int\frac{\mathrm{d}^3\boldsymbol{P}_f}{(2\pi)^3}\frac{1}{4}\sum_{s_is_fS_iS_f}\frac{|S_{fi}|^2}{VTJ_\nu V^{-1}}\\ &= \sum_l \frac{e^2}{4\sqrt{(P_iq_i)^2 - m_\mu^2m_e^2}}\int\frac{\mathrm{d}^3\boldsymbol{q}_f}{2Q_f}\int\frac{\mathrm{d}^3\boldsymbol{P}_f}{2E_f}\\ &\quad\times\delta^4(q_f - q_i + P_f - P_i + lk)\frac{1}{4}\sum_{s_i,s_f,S_i,S_f}\frac{|M_l|^2}{(P_i-P_f)^4}.\end{aligned} \quad (18)$$

J_ν is the incoming current in the laboratory system and is given by $\sqrt{(P_iq_i)^2 - m_\mu^2 m_e^2}/(E_1Q_1V)$. The total differential cross section can be decomposed into a series of discrete partial differential cross sections for different numbers of photon transfers:

$$\frac{\mathrm{d}\bar{\sigma}_{tot}}{\mathrm{d}\Omega} = \sum_{l=-\infty}^{\infty}\frac{\mathrm{d}\bar{\sigma}_l}{\mathrm{d}\Omega}. \quad (19)$$

We want to calculate the total differential cross section for electron scattering into a given solid-angle element $\mathrm{d}\Omega$ centered around the scattering angle θ. Therefore, the differential quantity has to be integrated over all momentum variables expect for the direction of dq_f. The volume element can be written as $\mathrm{d}^3\boldsymbol{q}_f = |\boldsymbol{q}_f|^2\mathrm{d}|\boldsymbol{q}_f|d\Omega$, and $|\boldsymbol{q}_f|d|\boldsymbol{q}_f| = Q_2\mathrm{d}Q_2$, with the help of $\frac{\mathrm{d}^3P}{2E} = \int_{l=-\infty}^{\infty}\mathrm{d}^4P\delta(P^2 - M_0^2)\Theta(P_0)$ and $\int \mathrm{d}xf(x)\delta[g(x)] = [f(x)/|g'(x)|]|_{g(x)=0}$. Thus, by integrating over $d|\boldsymbol{q}_f|$ and d^4P_f, the partial differential cross section can be written as

$$\frac{\mathrm{d}\sigma_l}{\mathrm{d}\Omega} = \frac{e^4}{8m_\mu}\frac{|\boldsymbol{q}_f|^2}{|\boldsymbol{q}_i|}\frac{1}{(P_i-P_f)^4Q_f|g'(|\boldsymbol{q}_f|)|}\sum_{s_is_fS_iS_f}|M_l|^2\Bigg|_{P_f=P_i+q_i-q_f-lk;|\boldsymbol{q}_f|=\sqrt{\frac{A^2C^2}{(A^2-B^2)^2}-\frac{C^2-B^2m_*^2}{A^2-B^2}}-\frac{AC}{A^2-B^2}}, \quad (20)$$

with

$$g'(|\boldsymbol{q}_f|) = -2m_\mu|\boldsymbol{q}_f|/Q_f - 2Q_i|\boldsymbol{q}_f|/Q_f + 2|\boldsymbol{q}_f|/Q_f l\omega + 2|\boldsymbol{q}_i|\cos\theta - 2l\omega\sin\theta\sin\phi. \quad (21)$$

Here $A = |\boldsymbol{q}_i|\cos\theta - l\omega\sin\theta\sin\phi$, $B = m_\mu + Q_1 - l\omega$, $C = m_*^2 + m_\mu Q_i - m_\mu l\omega - Q_il\omega + l\boldsymbol{q}_i\cdot\boldsymbol{k}$, θ is the scattering angle of the incoming electron, ϕ is the polarization angle of the outgoing electron, and

$$\sum_{s_{i,f},S_{i,f}} |M_l|^2 = \frac{1}{16m_\mu^2 m_e^2} Tr[(\not{p}_f + m_e)\Gamma^\mu(\not{p}_i + m_e)\Gamma^\nu] \times Tr[(\not{P}_f + m_\mu)\gamma_\mu(\not{P}_i + m_\mu)\gamma_\nu]. \quad (22)$$

The trace work can be performed using FEYNCALC.

3 Numerical results and discussion

In this section, we present and discuss the numerically obtained cross section of scattering of a muon and an electron in a linearly polarized laser field. We set the incident electron momentum p_i along the z axis. To simplify the calculation process, we use a fixed target in the laboratory frame. We evaluate the cross section in the rest frame of the incoming muon with an initial energy $E_i = m_\mu$. The direction of the field wave vector k is along the y axis, whereas the polarization vector ε_0 perpendicular to k lies in the xz plane. Considering the relativistic effect, we set the incident electron kinetic energy to 10^6 eV.

Every $\mathrm{d}\sigma_l/\mathrm{d}\Omega$, considering four-momentum conservation $q_f - q_i + P_f - P_i + lk = 0$, can be interpreted as the partial differential cross section that describes the process with a final momentum determined by $\boldsymbol{q}_f - \boldsymbol{q}_i + \boldsymbol{P}_f - \boldsymbol{P}_i + l\boldsymbol{k} = 0$ and l photon energy transmission from the laser field ($l > 0$ for emission, and $l < 0$ for absorption). This is the multiphoton effect for elastic scattering: redistribution of the total energy and momentum between two participating particles and the external field.

Figure 1 shows the partial differential cross sections $\mathrm{d}\bar{\sigma}_l/\mathrm{d}\Omega$ versus the net photon number l transferred between the colliding system and the laser field. We display the partial differential cross section at three scattering angles [$\theta = 1°, 90°, 180°$]. The strength and frequency of the laser field are $\varepsilon_0 = 5.18 \times 10^7$ V/cm and $\omega = 1.17$ eV, respectively. The laser polarization is chosen to be parallel to the incident electron momentum. At a small scattering angle [$\theta = 1°$ in Fig. 1(a)], only a few multiphoton processes are important, and the partial differential cross section $\mathrm{d}\bar{\sigma}_l/\mathrm{d}\Omega$ is sharply centered around $l = \pm 1$. At large scattering angles [$\theta = 90°$ in Fig. 1(b) and $\theta = 180°$ in Fig. 1(c)], a number of multiphoton processes make significant contributions. This nonlinear behavior may possibly arise from the resonant state of the electron and the muon formed in the collision process. The magnitude of $\mathrm{d}\overline{\sigma_l}/\mathrm{d}\Omega$ varies in a range of a few orders for different l. These oscillations result from the periodic variation of the generalized Bessel function $\boldsymbol{B}(\xi, \eta)$ [42]. Furthermore, the contributions of various l-photon processes are cut off at two edges that are asymmetric with respect to $l = 0$. The symmetry axis of the generalized Bessel function is at $l = -2\eta$. The cutoff for positive l is a consequence of the energy conservation imposed on Eq. (18). On the other hand, the origin of the cutoff for negative values of l can be inferred by the properties of the generalized Bessel function $\boldsymbol{B}(\xi, \eta)$ when its arguments ξ and η satisfy the approximate relation $l = \pm|\xi| \pm 2|\eta|$. This has already been pointed out in [42]. The result shown in Fig. 1(b) indicates that the

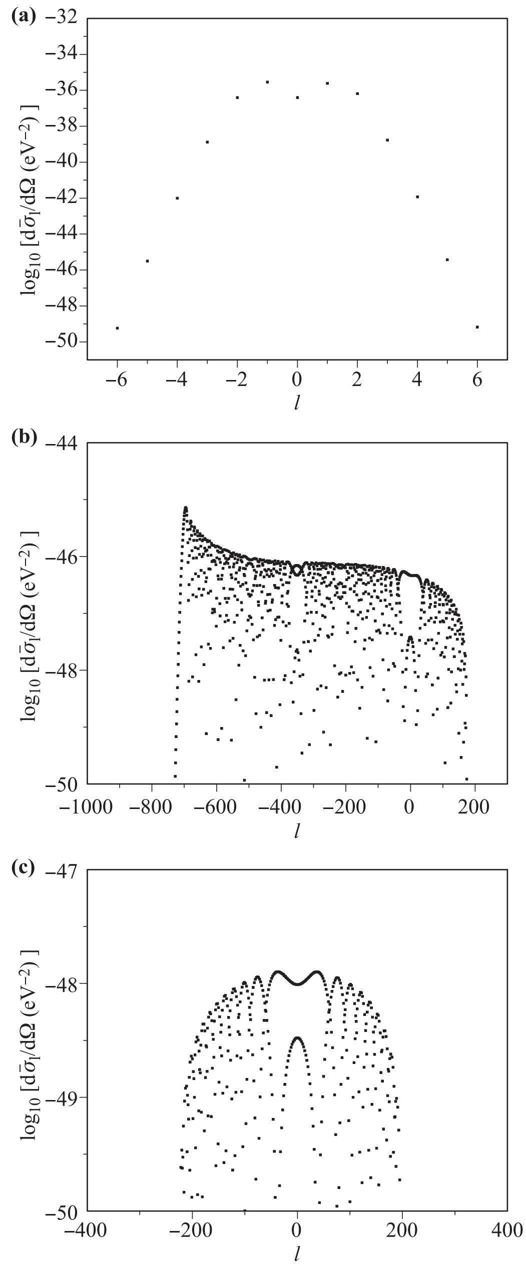

Fig. 1 Multiphoton cross section of laser-assisted scattering of a muon by an electron at an electron-impact energy of $T_i = 0.511$ MeV as a function of the number of photons involved, l. The scattering angles are **(a)** $\theta = 1°$, **(b)** $\theta = 90°$, and **(c)** $\theta = 180°$. The laser field is linearly polarized along the incident direction of the electron. The field strength is $\varepsilon_0 = 5.18 \times 10^7$ V·cm^{-1}, and the photon energy $\hbar\omega = 1.17$ eV.

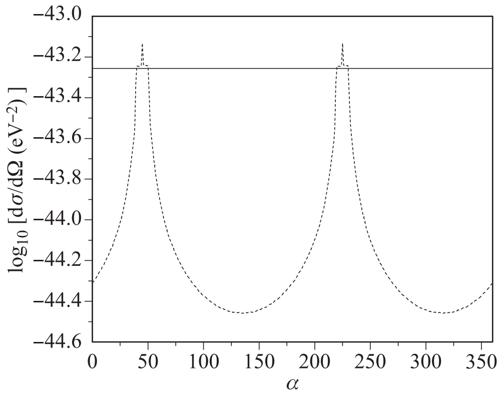

Fig. 2 Summed differential cross section versus the polar angle of the polarization vector of the field (the polarization vector $\boldsymbol{\mathcal{E}}_0$ varies in the zx plane) for $\theta = 90°$ and $\phi = 0°$. Solid and dashed lines show the cross section without and with the laser, respectively. The impact energy and laser parameters are the same as in Fig. 1.

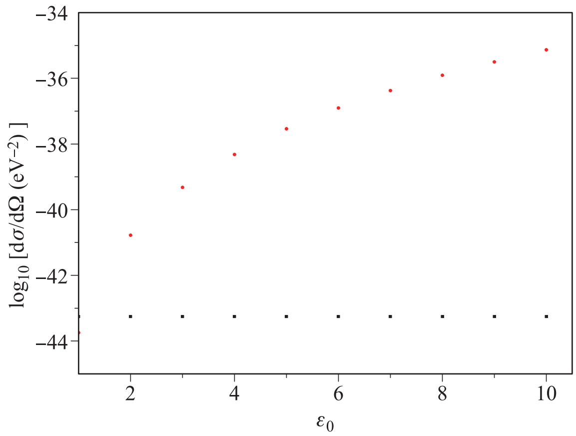

Fig. 3 Laser strength dependence of the summed differential cross section at $\theta = 90°$ and $\phi = 0°$ for the field frequency $\hbar\omega = 1.17$ eV. Black and red symbols are the results for the laser-free and laser-assisted cross sections, respectively. The impact energy and laser parameters are the same as in Fig. 1.

photon absorption processes dominate the photon emission ones.

Figure 2 shows the dependence of the total cross section on the (linear) polarization direction of the field. The polarization dependence is approximately periodic. This is explained by the arguments ξ and η of the generalized Bessel function. When the magnitude of the field strength and the momenta of the electron and muon in the initial and final states are fixed, the scalar product of $\boldsymbol{\mathcal{E}}_0$ and $\boldsymbol{p}$ (or $\boldsymbol{p}'$) varies periodically with the polar angle $\boldsymbol{\theta}$ of $\boldsymbol{\mathcal{E}}_0$. At $\alpha = 45°$ and $225°$, the total cross section has two symmetrical peaks because at these angles the argument ξ has the minimum value; the generalized Bessel function is inversely proportional to ξ, so it has the maximum value. When the polarization angle is close to 45° (or 225°), fewer photons are exchanged with the laser field during scattering, and the effect of the laser field is smaller.

Figure 3 reveals the dependence of the total differential cross section on the laser strength. The field strength enters the determining equation for the cross section through the arguments ξ and η of the generalized Bessel function $\boldsymbol{B}(\xi, \eta)$ in Eq. (8) and through the A-dependent terms in Eqs. (10)–(15). Although for each multiphoton process, the generalized Bessel functions in the partial cross section oscillate with the field strength, the summed cross section increases steadily by several orders as the field strength increases from 1 to 10. As the field strength increases, the electron state becomes more distorted, and thus the cross section is more strongly modified. Therefore, the cross section increases because the electron's energy increases after it absorbs laser photons.

Figure 4 indicates that at the polar scattering angle $\theta = 90°$, the summed differential cross section depends strongly on the azimuthal angle ϕ of the scattered electron. In contrast to nonrelativistic scattering, in which the cross section is symmetric about $\phi = 180°$, the cross section for relativistic collision does not show such symmetry. From a mathematical point of view, this asymmetry makes sense because of the factor kp_f that occurs in the denominator in Eqs. (14) and (15), and the arguments ξ and η of Eqs. (16) and (17) [which in turn enter the generalized Bessel function $\boldsymbol{B}(\xi, \eta)$ in Eqs. (12)–(15)]. At $\phi = 90°$ and $270°$, the argument ξ of the generalized Bessel function vanishes; the generalized Bessel function becomes the Bessel function, and the cross section in the presence of the laser has the maximum value,

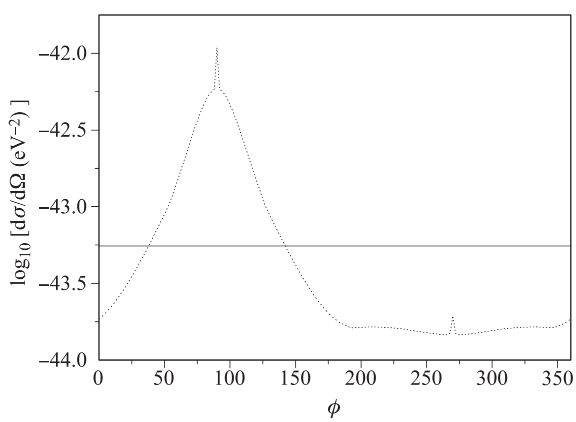

Fig. 4 Azimuthal angle dependence of the total differential cross section for the geometry $\boldsymbol{\mathcal{E}}_0 \perp \boldsymbol{p}$ at the scattering angle $\theta = 90°$. Solid and dotted lines represent the result without and with the laser, respectively. The impact energy and laser parameters are the same as in Fig. 1.

because at these angles the factor kp_f has the minimum value. From a physical point of view, we can explain this asymmetry in terms of Eq. (6). A kinematic electron in the laser field will receive an increment in the direction of field propagation. Therefore, in this direction, the cross section will increase. Similarly, the electron receives a reduction in the direction opposite to field propagation, and the cross section in this direction decreases.

Figure 5 shows the total cross section versus the kinetic energy of the incident electron at the scattering angles $\theta = 90°$ and $\theta = 180°$. Obviously, with increasing incident energy, the total cross section decreases. In Fig. 5(a), by comparing the total cross section in the laser-free case at different scattering angles ($\theta = 90°$ and $180°$) with that at a field strength $\varepsilon_0 = 5.18 \times 10^7$ V/cm, we find that the laser-assisted cross section coincides with the laser-free cross section at the scattering angle $\theta = 90°$. At $\theta = 180°$, there is a little modified with the laser-assisted cross section. Overall, the total cross section for a moderately strong field coincides with the cross section of an electron scattered by a muon in the absence of an external field. This is in agreement with a previous work [29]. In Fig. 5(b), the field strength is $\varepsilon_0 = 5.18 \times 10^8$ V/cm; at the higher laser strength, the cross sections are greatly enhanced at both $\theta = 90°$ and $\theta = 180°$. At the scattering angle $\theta = 180°$ (backward scattering) in particular, the modification of the total cross section is most significant. The recoil effect of the free muon acts to "soften" the collision, which can increase the interaction time, and therefore we can observe enhancement. As the recoil effect becomes stronger, the enhancement of the interaction time and total cross section become larger. However, when the incident energy of the electron increases to a certain extent, the scattering cross section becomes smaller than that in the laser-free case, and the effect of the laser field on the cross section is reduced.

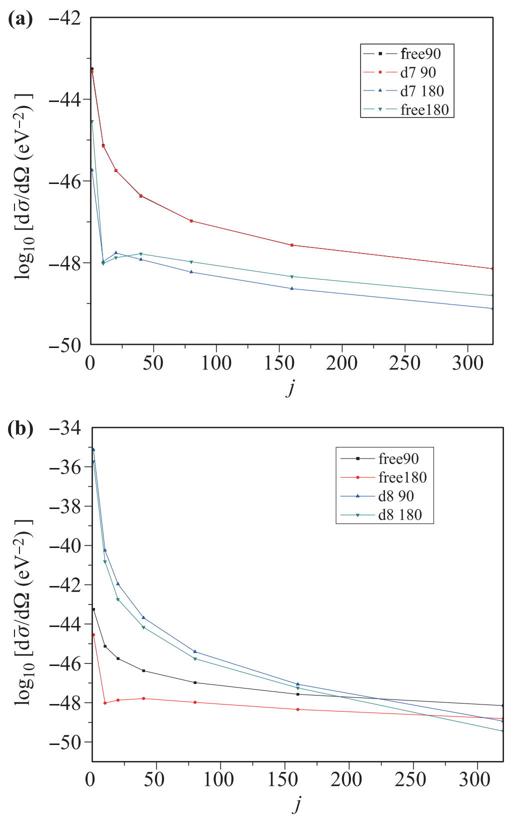

Fig. 5 Total cross sections at scattering angles $\theta = 90°$ and $180°$ versus the kinetic energy of the incident electron for the polarization geometry $\boldsymbol{\mathcal{E}}_0 // \boldsymbol{p}$. j is the incident energy of the electron. free90 and free180 represent the cross section in the laser-free case, whereas d7 90 and d7 180 represent the cross section in the presence of the laser at $\varepsilon_0 = 5.18 \times 10^7$ V/cm, and d8 90 and d8 180 represent the cross section at $\varepsilon_0 = 5.18 \times 10^8$ V/cm. The other laser parameters are the same as in Fig. 1.

4 Conclusions

The general features of scattering of an electron by a muon are clearly modified when a radiation field is present. The colliding system can exchange a large number of photons with the laser field; depending on the properties of the field and the scattering geometry, a large number of multiphoton processes may arise from the resonant state of the electron and the muon formed in the collision process. Our work reveals new phenomena arising from nonlinear effects in the laser-assisted scattering process, which differ from those reported in previous investigations [29, 31]. The theoretical results for the case of linear polarization show that the cross section is greatly enhanced by the presence of the laser field within a wide energy range of the impact electron. The photoabsorption (inverse bremsstrahlung) dominates the photoemission (bremsstrahlung). At stronger laser fields, the cross section enhancement becomes more notable.

Acknowledgements This work was partially supported by the National Natural Science Foundation of China (NSFC) under Grant Nos. 11275186, 91024026, and FOM2014OF001 and the National Basic Research Program of China under Grant Nos. 2007CB925200 and 2010CB923301.

References

1. F. H. M. Faisal, Theory of Multiphoton Processes, New York: Plenum, 1987
2. M. H. Mittleman, Introduction to the Theory of Laser-Atom Interactions, New York: Plenum, 1993

3. M. V. Fedorov, Atomic and Free Electrons in a Strong Light Field, Singapore: World Scientific, 1997
4. P. Francken and C. J. Joachain, Theoretical study of electron–atom collisions in intense laser fields, *J. Opt. Soc. Am. B* 7(4), 554 (1990)
5. F. Ehlotzky, A. Jaroń, and J. Z. Kamiński, Electron–atom collisions in a laser field, *Phys. Rep.* 297(2–3), 63 (1998)
6. F. Ehlotzky, Atomic phenomena in bichromatic laser fields, *Phys. Rep.* 345(4), 175 (2001)
7. H. M. Milchberg and R. R. Freeman, High-field interactions and short-wavelength generation, *J. Opt. Soc. Am. B* 13(2), 314 (1996)
8. D. D. Meyerhofer, High-intensity-laser-electron scattering, *IEEE J. Quantum Electron.* 33(11), 1935 (1997)
9. P. Panek, J. Z. Kamiński, and F. Ehlotzky, Laser-induced Compton scattering at relativistically high radiation powers, *Phys. Rev. A* 65(2), 022712 (2002)
10. A. I. Voroshilo, S. P. Roshchupkin, and V. N. Nedoreshta, Resonant scattering of photon by electron in the presence of the pulsed laser field, *Laser Phys.* 21(9), 1675 (2011)
11. V. N. Nedoreshta, S. P. Roshchupkin, and A. I. Voroshilo, Nonresonant Compton scattering in an intense pulsed laser field, *Laser Phys.* 23(5), 055301 (2013)
12. S. P. Roshchupkin, Resonant effects in collisions of relativistic electrons in the field of a light wave, *Laser Phys.* 6(5), 837 (1996)
13. C. Szymanowski, V. Véniard, R. Taïeb, A. Maquet, and C. H. Keitel, Mott scattering in strong laser fields, *Phys. Rev. A* 56(5), 3846 (1997)
14. C. Szymanowski, R. Taïeb, and A. Maquet, Laser-Assisted scattering of polarized electrons at high field intensities, *Laser Phys.* 8(1), 102 (1998)
15. O. I. Denisenko and S. P. Roshchupkin, Resonant scattering of an electron by a positron in the field of a light wave, *Laser Phys.* 9(5), 1108 (1999)
16. E. A. Padusenko, A. A. Lebed, and S. P. Roshchupkin, Resonant interference effect in scattering of an electron by an electron in the field of two pulsed laser waves, *Universal Journal of Physics and Application* 7(3), 274 (2013)
17. P. Panek, J. Z. Kamiński, and F. Ehlotzky, Analysis of resonances in Møller scattering in a laser field of relativistic radiation power, *Phys. Rev. A* 69(1), 013404 (2004)
18. S. S. Starodub and S. P. Roshchupkin, Interaction of the nonrelativistic electrons in the pulsed field of two laser waves, *Eur. Phys. J. D* 44(2), 401 (2007)
19. F. Ehlotzky, Sum rules in relativistic potential scattering in a strong laser field, *Opt. Commun.* 66(5–6), 265 (1988)
20. J. Z. Kamiński and F. Ehlotzky, Asymmetries and dark angular windows in relativistic free-free transitions in a powerful laser field, *Phys. Rev. A* 59(3), 2105 (1999)
21. P. Panek, J. Z. Kamiński, and F. Ehlotzky, Angular and polarization effects in relativistic potential scattering of electrons in a powerful laser field, *Can. J. Phys.* 77(8), 591 (1999)
22. M. M. Denisov and M. V. Fedorov, Bremsstrahlung effect on relativistic electrons in a strong radiation field, *Sov. Phys. JETP* 26, 779 (1968)
23. S. P. Roshchupkin, The effect of a strong light field on the scattering of an ultrarelativistic electron by a nucleus, *Zh. Eksp. Teor. Fiz.* 109, 337 (1996)
24. C. Szymanowski, V. Věniard, R. Taïeb, A. Maquet, and C. H. Keitel, Mott scattering in strong laser fields, *Phys. Rev. A* 56(5), 3846 (1997)
25. C. Szymanowski and A. Maquet, Relativistic signatures in laser-assisted scattering at high field intensities, *Opt. Express* 2(7), 262 (1998)
26. S. M. Li, J. Berakdar, J. Chen, and Z. F. Zhou, Mott scattering in the presence of a linearly polarized laser field, *Phys. Rev. A* 67(6), 063409 (2003)
27. Y. Attaourti and B. Manaut, Comment on "Mott scattering in strong laser fields"? *Phys. Rev. A* 68(6), 067401 (2003)
28. B. Manaut, S. Taj, and Y. Attaourti, Mott scattering of polarized electrons in a strong laser field, *Phys. Rev. A* 71(4), 043401 (2005)
29. V. N. Nedoreshta, A. I. Voroshilo, and S. P. Roshchupkin, Nonresonant scattering of an electron by a muon in the field of plane electromagnetic wave, *Laser Phys. Lett.* 4(12), 872 (2007)
30. V. N. Nedoreshta, A. I. Voroshilo, and S. P. Roshchupkin, Resonant scattering of an electron by a muon in the field of light wave, *Eur. Phys. J. D* 48(3), 451 (2008)
31. E. A. Padusenko, S. P. Roshchupkin, and A. I. Voroshilo, Nonresonant scattering of relativistic electron by relativistic muon in the pulsed light field, *Laser Phys. Lett.* 6(3), 242 (2009)
32. S. P. Roshchupkin, E. A. Padusenko, and A. I. Voroshilo, Quantum electrodynamics resonances in a pulsed laser field, *Laser Phys.* 22, 6 (2012)
33. S. P. Roshchupkin, A. A. Lebed', and E. A. Padusenko, Nonresonant quantum electrodynamics processes in a pulsed laser field, *Laser Phys.* 22, 10 (2012)
34. A. A. Lebed', E. A. Padusenko, and S. P. Roshchupkin, Resonant scattering of ultrarelativistic electrons in the strong field of a pulsed laser wave, *Laser Phys.* 26(2), 025302 (2016)
35. A. A. Lebed', E. A. Padusenko, S. P. Roshchupkin, and V. V. Dubov, Parametric interference effect in nonresonant pair photoproduction on a nucleus in the field of two pulsed light waves, *Phys. Rev. A* 95(4), 043406 (2017)
36. A. I. Nikishov and V. I. Ritus, Quantum effects in the interaction of elementary particles with an intense electromagnetic field, *Trudy FIAN* 111, 5 (1979)

37. F. V. Bunkin and M. V. Fedorov, Bremsstrahlung in a strong radiation field, *Zh. Eksp. Teor. Fiz.* 49, 1215 (1965)

38. M. M. Denisov and M. V. Fedorov, Bremsstrahlung effect on relativistic electrons in a strong radiation field, *Zh. Eksp. Teor. Fiz.* 53, 1340 (1967)

39. M. V. Fedorov, An Electron in a Strong Light Field, Nauka, Moscow, 1991 (in Russian)

40. D. M. Volkov, On a class of solutions of the Dirac equation, *Z. Phys.* 94(3–4), 250 (1935)

41. W. Greiner and J. Reinhardt, Quantum Electrodynamics, 4th Ed., Springer-Verlag, 2009

42. E. Lötstedt and U. D. Jentschura, Recursive algorithm for arrays of generalized Bessel functions: Numerical access to Dirac–Volkov solutions, *Phys. Rev. E* 79(2), 026707 (2009)

43. H. J. Korsch, A. Klumpp, and D. Witthaut, On two-dimensional Bessel functions, *J. Phys. A* 39(48), 14947 (2006)