Inverse mean free path of swift electrons in metals irradiated by a strong laser field

JUAN CARLOS MORENO-MARÍN,[1] ISABEL ABRIL,[2] RAFAEL GARCIA-MOLINA,[3]
AND NÉSTOR R. ARISTA[4]

[1]Departament de Física, Enginyeria de Sistemes i Teoria del Senyal, Universitat d'Alacant, Alacant, Spain
[2]Departament de Física Aplicada, Universitat d'Alacant, Alacant, Spain
[3]Departamento de Física, Universidad de Murcia, Murcia, Spain
[4]División Colisiones Atómicas, Instituto Balseiro and Centro Atómico Bariloche, Bariloche, Argentina

Abstract

We analyze the influence of a high-intensity laser field in the inverse mean free path of electrons moving through a degenerate electron gas. Our calculations are based on the random-phase-approximation formalism, in terms of the dielectric function of the medium, where the effects of the laser field are included in the dynamical response. The main effects on the slowing down of the electrons are studied as a function of the intensity and frequency of the laser field, as well as a function of the projectile velocity. A modification of the electron inverse mean free path for plasmon and electron-hole excitations is obtained due to multiphoton-exchange processes.

Keywords: Electron beams; Inverse mean free path; Laser field

1. INTRODUCTION

The study of laser fields interacting with matter has grown in the last years stimulated by important applications emerging in different areas of physics, such as atomic physics (Ferrante, 1983; Nicolaides *et al.*, 1990; More, 1991), materials science (Feit *et al.*, 1998; Dahmani *et al.*, 1999), electron accelerators (Tajima & Dawson, 1979; Kitagawa *et al.*, 1992; Aminanoff *et al.*, 1995), semiconductors (Nunes, 1983; Tronconi & Nunes, 1986), and fusion technology (Nuckolls, 1982; Deutsch, 1990; Yamanaka, 1991; Zweiback *et al.*, 2000). A proper evaluation of the laser effects on the slowing down (energy deposition and range) of charged particles moving through matter will allow a prediction of the behavior of these particles when the target is simultaneously irradiated by strong lasers, as happens in experiments of plasma fusion (Yamanaka, 1991). Despite the fact that these kind of experiments are very complex and involve different phenomena, the knowledge of the laser effects on the energy loss of charged particles should allow us to understand, predict, or simulate the processes that take place in laser-fusion experiments. The recent development of high-intensity laser beams with a broad spectrum of frequencies

(Kugler *et al.*, 1998; Patzel, 1998) opens the possibility of new applications of these interaction processes in the near future.

The inelastic processes that take place during the slowing down of charged particles moving through an electron gas that is irradiated by a strong laser field were analyzed previously (Arista *et al.*, 1989), using a formalism that is based on an extension of the random-phase approximation (RPA), where the radiation field is included in a self-consistent way. A semiclassical approximation for the electromagnetic field of the laser was considered. As a result of this treatment, the effects of the laser field are contained in the dynamical response of the medium to the motion of the external projectile, which is accounted for in the dielectric function of the stopping medium. Within this scheme, the dielectric function of the medium is expressed as a function of the frequencies associated with the harmonics of the laser frequency, and as a consequence, the energy exchange and the scattering rate of the charged particles moving through the electron gas are modified by multiphoton processes.

In this model (Arista *et al.*, 1989), the laser electromagnetic field is treated in the long wavelength limit (dipole approximation), and the incident projectile and the electrons of the medium are considered nonrelativistic particles. These conditions require that the frequency, ω_L and the intensity, I_L, of the laser field satisfy the following restrictions: $\omega_L \ll 2\sqrt{3}\pi c\omega_p/v_F$ and $I_L \ll \frac{1}{2}nc(mc^2)(\omega_L/\omega_p)^2$, where v_F, ω_p

and n are, respectively, the Fermi velocity, the plasma frequency, and the electron density of the medium, c is the speed of light, and m is the electron mass.

The previous formalism (Arista *et al.*, 1989) has been applied to study the energy loss of protons (Abril *et al.*, 1992). In this article, we will use this formalism to evaluate the effects of laser irradiation on the slowing down of electrons moving through metals. We analyze these effects as a function of the laser characteristics (frequency ω_L and intensity I_L) and as a function of the electron velocity v. For brevity, we do not reproduce the derivation of the basic formulae since they were developed in detail in Arista *et al.* (1989) and Abril *et al.* (1992). In what follows, atomic units ($\hbar = e = m = 1$) will be used.

2. THEORETICAL BACKGROUND

The slowing down of electrons in solids can be characterized by their inverse mean free path (IMFP), a magnitude that measures the probability per unit path length that an incident electron will suffer a process of inelastic interaction with the stopping medium. The current formalism (Arista *et al.*, 1989; Abril *et al.*, 1992) yields general expressions for the IMFP of the incident projectiles undergoing inelastic scattering in an electron gas when a strong laser field is present. The electron IMFP in the presence of a laser field, μ_N, describes excitations of the target assisted by simultaneous absorption or emission of N photons of the laser frequency and for a given orientation of the electron velocity with respect to the direction of the laser electric field (Arista *et al.*, 1989; Abril *et al.*, 1992)

$$\mu_N = \frac{1}{\pi^2 v} \int \frac{d^3k}{k^2} J_N^2(\mathbf{k}\cdot\mathbf{a})\, \mathrm{Im}\left[\frac{-1}{\epsilon(k,\Omega_N)}\right],\qquad (1)$$

where $J_N(x)$ is a Bessel function of the first kind of order N, ϵ is the dielectric function of the medium, $\mathbf{k}$ and Ω_N are, respectively, the momentum and energy transferred to the solid, and v is the electron velocity. $\mathbf{a}$ is the quiver amplitude given by $\mathbf{a} = -\mathbf{E}_L/(\omega_L^2)$, where $\mathbf{E}_L$ is the laser electric field; the absolute value of the quiver amplitude is related to the laser intensity I_L through $a = (8\pi/c)^{1/2} I_L^{1/2}/\omega_L^2$.

The energy transferred to the target in a scattering event is given by $\Omega_N = \mathbf{k}\cdot\mathbf{v} - k^2/2 - N\omega_L$ and must be positive, as it corresponds to a system that can only absorb energy. The values of Ω_N are related to the frequencies associated with harmonics of the laser frequency and the number of photons, N, involved in the process; $N > 0$ (< 0) means a process with emission (absorption) of N photons. The term $J_N^2(x)$ in Eq. (1) is related to the inelastic scattering of electrons accompanied by multiphoton absorption ($N < 0$) or emission ($N > 0$) processes, which are important for strong laser fields. Note that the incident electron can gain or lose energy, depending on the energy exchange with the radiation field. The presence of the laser field also appears in the dielectric function (see Eq. (1)), which describes the screening and the dynamical response of the solid to an external perturbation. This formalism provides a self-consistent description of the inelastic processes connecting particle–solid–laser interactions.

We consider here two cases of particular interest: (1) when the laser electric field is polarized in the direction of the electron velocity (Arista *et al.*, 1989) (parallel orientation), and (2) a random average over the angular orientation (random orientation).

In the case of parallel orientation ($\mathbf{a}\|\mathbf{v}$), the electron IMFP can be written as

$$\mu_N = \frac{2}{\pi v} \int_0^\infty dk \int_{-1}^1 du\, J_N^2(kau)\, \mathrm{Im}\left[\frac{-1}{\epsilon(k,\Omega_N)}\right],\qquad (2)$$

where $\Omega_N = kvu - k^2/2 - N\omega_L$.

However, multiple scattering processes produced by elastic scattering on target ions after the electron beam penetrates the medium will change the initial orientation of the electron velocity with respect to the laser electric field. Therefore, we also calculated the random angular average (between the laser electric field and the electron velocity) of the IMFP, $\langle\mu_N\rangle$, which is given by

$$\langle\mu_N\rangle = \frac{2}{\pi v} \int_0^\infty dk \int_{-1}^1 du\, \mathrm{Im}\left[\frac{-1}{\epsilon(k,\Omega_N)}\right]\int_0^1 dx\, J_N^2(kax).\qquad (3)$$

Then, in this work we will evaluate the IMFP of electrons in metals when they are irradiated by a laser for the two cases considered previously. Metals are well described by a degenerate free electron gas, where the Lindhard dielectric function (Lindhard, 1954) gives the response of the target to an external perturbation. This model treats separately the two basic modes of energy absorption by the electrons of the medium: collective (or plasmon) excitations and individual (or electron-hole pair) excitations. Therefore it is possible to obtain separately the laser effects on the electron IMFP due to the plasmons and electron-hole excitations of the target. The electron IMFP for electron-hole excitations can be obtained from Eqs. (2) and (3) taking the energy loss function (ELF), $\mathrm{Im}[-1/\epsilon(k,\Omega_N)]$, corresponding to the individual excitations (Lindhard, 1954). The ELF for plasmon excitations is described by an undamped resonance line (Pines, 1964):

$$\mathrm{Im}\left[\frac{-1}{\epsilon(k,\Omega_N)}\right] = \frac{\pi}{2}\frac{\omega_p^2}{\omega_k}\left[\delta(\Omega_N - \omega_k) - \delta(\Omega_N + \omega_k)\right],\qquad (4)$$

where ω_k is the dispersive plasmon frequency, given by $\omega_k^2 = \omega_p^2 + b_2 k^2 + b_4 k^4$ (Servier, 1972). From Eqs. (2) and (4), the electron IMFP for plasmon excitation assisted by emission or absorption of N photons, when the laser electric field is polarized in the direction of the electron velocity, is given by

$$\mu_N^p = \frac{\omega_p^2}{v^2} \int \frac{dk}{k\omega_k} J_N^2\left[\frac{a}{v}\left(k^2/2 + N\omega_L + \omega_k\right)\right]. \quad (5)$$

This expression must verify the restriction $-1 < (k^2/2 + N\omega_L + \omega_k)/(kv) < 1$ and also Pauli's exclusion principle, which implies that $\omega_k < (v^2 - v_F^2)/2$.

On the other hand, the electron IMFP for plasmon excitation, for the random orientation case described before, according to Eqs. (3) and (4), is given by

$$\langle\mu_N^p\rangle = \frac{\omega_p^2}{v^2} \int \frac{dk}{k\omega_k} \int_0^1 dx\, J_N^2(kax), \quad (6)$$

and it must verify the same restrictions as Eq.(5).

3. RESULTS

We present results corresponding to the electron IMFP in aluminum and cesium targets for the cases of parallel and random orientation previously considered. The parameters used to describe these targets are given in Table 1.

In Figure 1 we show the laser effects on the electron IMFP in an aluminum target, for the case of parallel orientation, as a function of the projectile velocity. We present separately the contributions due to excitation of plasmons (Fig. 1a) and electron-hole pairs (Fig. 1b), with simultaneous absorption ($N = -1, -2, -3$) or emission ($N = 1, 2, 3$) of one, two, and three photons, as well as the IMFP without photon exchange ($N = 0$). The laser characteristics are given by $\omega_L/\omega_p = 1.05$, which corresponds to a wavelength of $\lambda_L = 747$ Å, and $I_L = 5\cdot10^{16}$ W/cm². As a reference, we have also depicted by dashed lines, the electron IMFP without laser field.

In general, we find that the contributions to the electron IMFP for plasmon and electron-hole excitations are modified significantly by the presence of an intense laser field, due to the simultaneous photon absorption and emission processes. At low electron velocities, the photon absorption processes are dominant, while photon emission processes begin to be most important as the velocity of the projectile increases. The inelastic processes corresponding to absorption or emission of a single-photon, accompanied by the emission of a plasmon or an electron-hole pair, have the largest probability, whereas processes that involve several photons are significantly less important. We also observe

Table 1. *Parameters used to describe the aluminum and the cesium targets*[a]

Target	ω_p (a.u.)	k_c (a.u.)	ω_c (a.u.)	b_2 (a.u.)	b_4 (a.u.)
Aluminum	0.58	0.684	0.867	0.51	0.8
Cesium	0.126	0.361	0.186	0.067	0.59

[a]ω_p is the plasmon frequency, k_c and ω_c are the cutoff wave number and frequency at which plasmons decay into electron-hole pairs, b_2 and b_4 are the plasmon dispersion parameters.
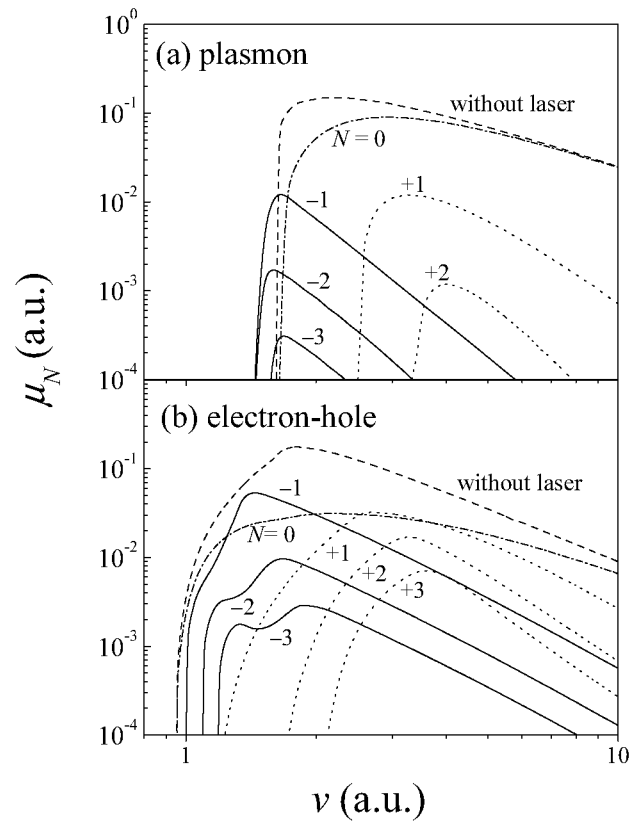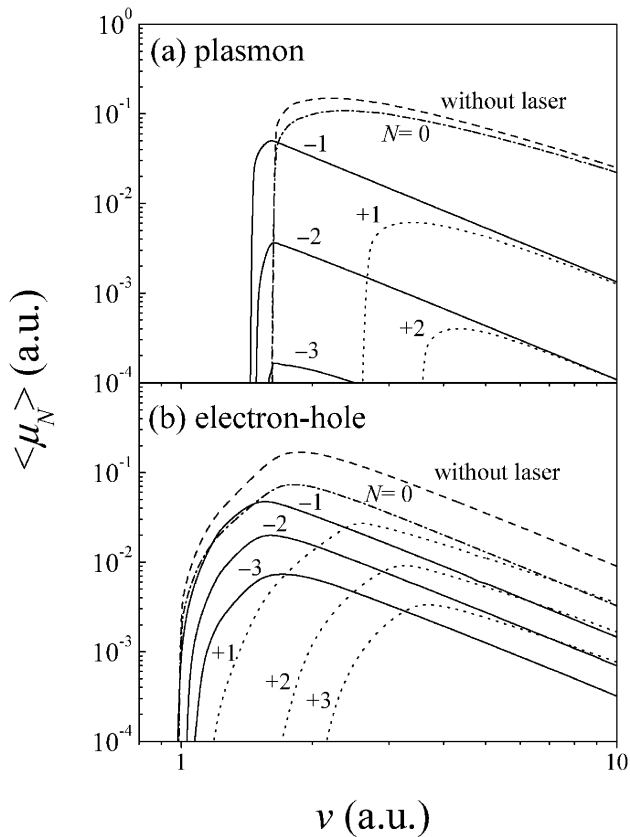

Fig. 1. Electron IMFP in an aluminum target as a function of the electron velocity, due to (a) plasmon and (b) electron-hole excitations accompanied by multiphoton processes. The present calculations are for parallel orientation of the laser electric field with respect to the electron velocity v. The label in each curve indicates the different contributions due to absorption $N < 0$ (solid lines) and emission $N > 0$ (dotted lines) of N photons, and the case without photon exchange $N = 0$ (dash-dotted line). The laser frequency and intensity are, respectively, $\omega_L/\omega_p = 1.05$ and $I_L = 5\cdot10^{16}$ W/cm². The dashed line represents the IMFP without laser field.

shifts in the velocity thresholds, to lower velocities for absorption processes ($N < 0$) and to larger velocities for emission processes ($N > 0$). In particular, we find that the presence of the laser field makes possible to excite plasmons at velocities below the normal threshold velocity ($v_{th} = 1.6$ a.u. for aluminum); this may occur because the presence of the laser field in the interaction of the incident projectile with the medium provides a mechanism that transfers the energy of the absorbed photon to the plasmon field.

Another interesting feature is the difference between the "no-photon" line ($N = 0$) and the IMFP without laser field. It shows a decrease of the IMFP even in the case where there is no photon exchange. This effect is produced by the $J_0^2(x)$ term in Eq. (1) and subsequent equations, and it means a reduction in the effective interaction between the electron and the plasma due to the radiation field.

The results of the IMFP for the case of random orientation in an aluminum target are shown in Figure 2 for the same laser characteristics as in Figure 1. The IMFPs for the various processes are generally larger (although not in all the
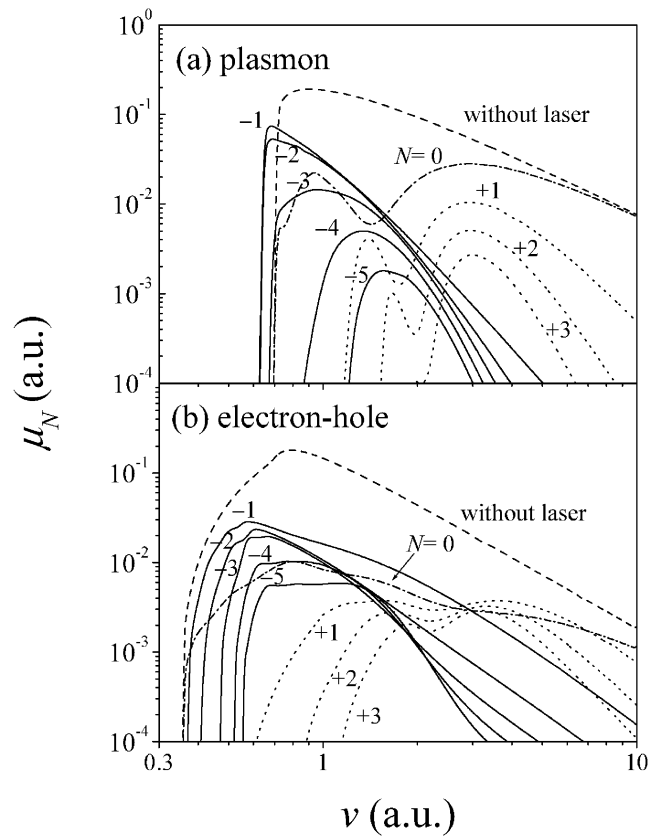
Fig. 2. Same as in Figure 1, but for random orientation of the laser electric field with respect to the electron velocity v.

Fig. 3. Electron IMFP in a cesium target as a function of the electron velocity, due to (a) plasmon and (b) electron-hole excitations accompanied by multiphoton processes. The present calculations are for parallel orientation of the laser electric field with respect to the electron velocity v. The label in each curve indicates the different contributions due to absorption $N < 0$ (solid lines) and emission $N > 0$ (dotted lines) of N photons, as well as no-photon interactions $N = 0$ (dash-dotted line). The laser frequency and intensity are, respectively, $\omega_L/\omega_p = 1.05$ and $I_L = 5 \cdot 10^{15}$ W/cm^2. The dashed line represents the IMFP without laser field.

cases) than for the case of parallel orientation; we also observe that the high-velocity decline for plasmon excitation processes is in this case much less pronounced.

The electron IMFP in a cesium target is shown in Figure 3a,b, corresponding also to plasmon and electron-hole excitations accompanied by multiphoton processes. The laser frequency is $\omega_L/\omega_p = 1.05$, which corresponds to a wavelength of $\lambda_L = 3584$ Å, and the laser intensity is now one order of magnitude lower than in Figure 1, $I_L = 5 \cdot 10^{15}$ W/cm^2. By comparison with Figure 1, we find a still larger influence of the laser field on the excitation processes, even though the laser intensity in this case is much lower. Excitation of plasmons at velocities below the normal threshold ($v_{th} = 0.68$ a.u.) are also possible. Since the probability of excitations is more strongly modified by multiphoton processes, we find that higher-order terms with respect to the radiation field must be considered (within the same range in the scale of IMFP values). The "no-photon" line ($N = 0$) shows an interesting interference effect and a strong reduction of the effective intensity of the particle–plasma coupling (leading to a decrease of the IMFP) at intermediate velocities.

The case of random orientation in the cesium targets is illustrated in Figure 4 for the same laser characteristics as in Figure 3. We find here the largest effects of the laser field

(i.e., largest IMFPs) in the case of plasmon excitation assisted by photon absorption as it may be observed in the curves for $N < 0$ in Figure 3a. In particular, the process of plasmon excitation accompanied by the absorption of a single photon ($N = -1$) shows a maximum IMFP value comparable to the one without laser. However, the processes of electron-hole excitations, in Figure 3b, show a lower intensity than those for the aluminum target.

Finally, in Figures 5 and 6 we analyze in more detail the dominant process of plasmon excitation accompanied by single photon absorption, μ^p_{-1}, in the case of cesium targets, as a function of electron velocity v.

Figure 5 shows the electron IMFP for two laser frequencies: $\omega_L/\omega_p = 1.05$ and 1.5 (curves denoted a and b respectively), which correspond to $\omega_L \sim \omega_p$ and $\omega_L \sim \omega_c$, respectively; here ω_c is the maximum plasmon frequency allowed by the dispersion curve (cf. Table 1). The cases of parallel and random angular orientation are shown in the same figure to allow a direct comparison. The laser intensity
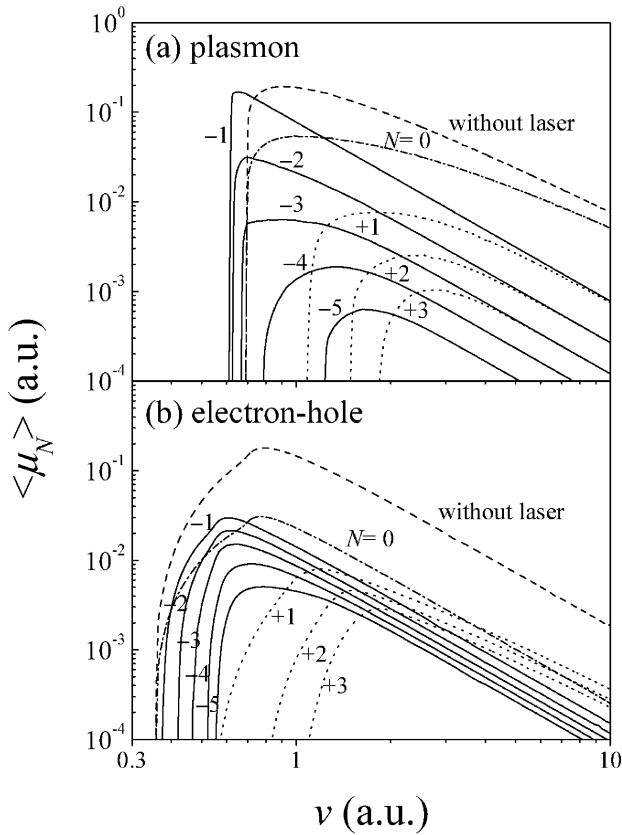
Fig. 4. Same as in Figure 3, but for random orientation of the laser electric field with respect to the electron velocity v.

is $I_L = 10^{15}$ W/cm^2. We find that the probability to excite a plasmon increases when the laser frequency is similar to the plasmon frequency (curves a), because the photon frequency is in resonance with some plasmon mode along the plasmon dispersion curve. The IMFP for random orientation is considerably larger than for parallel orientation at high electron velocities.

Figure 6 shows the dependence of the electron IMFP on the laser intensity, for a range of intensities between 10^{14} and 10^{17} W/cm^2 and for a fixed laser frequency $\omega_L/\omega_p = 1.05$. The solid (dotted) curves correspond here to random (parallel) angular orientations. As expected, the probability of exciting plasmons increases as laser intensity increases; however, we note that the dependence of the IMFP on laser intensity is approximately linear for low laser intensities, but a saturation effect arises with increasing intensities. Similar calculations for other cases show the increasing relevance of multiphoton processes for high laser intensities; these results agree with the fact that when an electromagnetic field is strong enough, many photons may be emitted or absorbed in a single scattering event (Kroll & Watson, 1973).

4. CONCLUSIONS

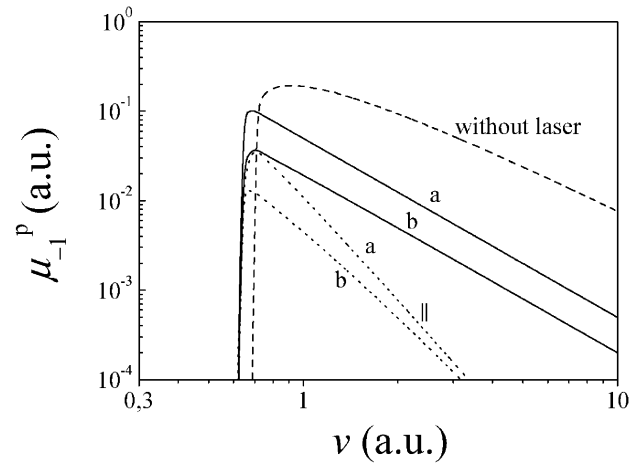We have discussed the effects of a strong laser field on the slowing down of electrons in an electron gas, based on a

Fig. 5. Electron IMFP in a cesium target due to plasmon excitations accompanied by single photon absorption, μ^p_{-1}, for the cases of parallel orientation (dotted lines) and random orientation (solid lines). The curves denoted a and b correspond, respectively, to $\omega_L/\omega_p = 1.05$ and 1.5. The laser intensity is $I_L = 10^{15}$ W/cm^2. The dashed line represents the IMFP without laser field.

previously developed formalism which describes excitations of plasmons and electron-hole pairs, with simultaneous emission or absorption of photons. The dependence of the electron IMFP on the laser intensity and frequency has been studied in detail as a function of the electron velocity, for the cases of parallel and random orientations of the incident velocity with respect to the laser electric field. We have calculated separately the probability of exciting plasmons and electron-hole pairs in an inelastic electron scattering event assisted by multiphoton processes. Our results indicate that the electron IMFP is significantly modified by
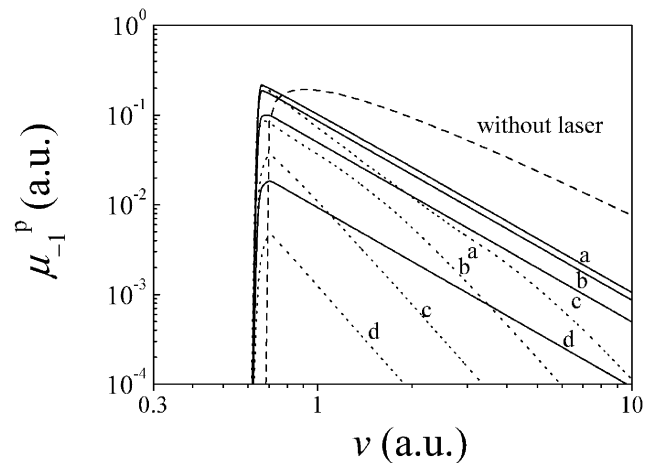

Fig. 6. Electron IMFP in a cesium target due to plasmon excitations accompanied by single photon absorption, μ^p_{-1}, for the cases of parallel orientation (dotted lines) and random orientation (solid lines). The various curves correspond to the following laser intensities: (a) 10^{17} W/cm^2, (b) 10^{16} W/cm^2, (c) 10^{15} W/cm^2, and (d) 10^{14} W/cm^2. The laser frequency is $\omega_L/\omega_p = 1.05$. The dashed line represents the IMFP without laser field.

multiphoton processes, depending on the target and on the laser field frequency and intensity. We also show the possibility of exciting plasmon at velocities below the normal threshold velocity in simultaneous photon-absorption events.

The effects described here may be relevant in experiments using high-intensity laser fields; in particular, they may be of considerable interest in current research on inertial fusion using laser beams.

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