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Effect of a laser field on the electron-ion scattering in a dense plasma

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Abstract The effect of a laser field on the inelastic scattering of electrons by one-electron ions in a dense plasma is investigated. The total cross-sections for 1s-2s and 1s-2p transitions are calculated. The laser field modifies the cross-sections by lowering the energy threshold, introducing an anisotropy with respect to the laser polarization, and giving rise to a non-monotonic dependence on the electron energy which is characteristic of multiphoton processes.

1. Introduction

The influence of electrostatic screening on the atomic structure of atoms and ions immersed in dense plasmas has been the subject of intense theoretical and experimental investigation aver the last decades.[1,2,3,4,5] However, the study of plasma effects on important collision processes has only recently received attention. Using the Born approximation and the Debye-Hückel model for the screened Coulomb interaction, Hatton et al[6] have calculated the cross-section for inelastic scattering of electrons by one-electron íons immersed in dense plasmas. They conclude that the effect of the plasma is to appreciably reduce the cross-sections for 1s-2s, 1s-2p and 2s-2p transitions at all energies. These calculations have been extended by Pundir and Mathur[7] to calculate the cross-section of electron scattering by helium ions. Although they use a more sophisticated approach to calculate the cross-section, their results are in qualitative agreement with that of Hatton et al[6] and they conclude that the Born approximation gives the correct threshold and the correct behaviour of the cross-section at high energies of the incident electron.

In the case of dense plasmas produced in laser-fusion experiments, besides the electrostatíc screening of the plasma one has also to consider the dynamic screening due to the laser field. The effect of an intense laser field on important collision processes has been studied by many investigators[8,9,10,11,12,13] after the original work of Kroll and Watson[14]. The laser field is found to have only a small effect on the cross-section for elastic scattering of electrons by atoms[12]. However, it can substantially affect the results for inelastic scattering. In particular, the angular distribution of the ejected electrons is significantly altered in ionizing collisions when photon exchange occurs[11].

2. Model and Formalism

We extend these works to include both the effect of the plasma electrostatic screening and that of an intense laser field on the calculation of the cross-section for inelastic scattering of electrons by one-electron ions. We use the first Born approximation and the Debye-Hückel model for the electrostatic screening of the plasma.

The laser beam is treated as a classical plane electromagnetic wave of frequency ω in the dipole approximation, expressed as $\vec{E}(t) = \vec{E} sin(\omega t)$. This is justifiable grovided the laser wavelength λ_L is sufficiently large to satisfy the conditions $\lambda_L >> \lambda_D$ and $\lambda_L >> |\vec{a}|$.

Here $\lambda_D = v_T/\omega_p$ is the Debye wavelength, $v_T = (k_B\, T/m)^{1/2}$ is the electron thermal velocity, $\omega_p = (4\pi n e^2/m)^{1/2}$ is the plasma frequency, $\vec{a} = e\vec{E}_L/m\omega^2$ is the amplitude of the electron oscillation in the laser field, and m and T are respectively the electron mass and temperature.

We further assume that the laser field is sufficiently small, so as not to affect the bound states of the ion. This is satisfied provided that $E_L < E_{at} = Z^3 e/a_0^2$, where $a_0 = 5.29 \times 10^{-9}$cm is the Bohr radius.

Under these conditions, tbe complete Hamiltonian operator for the electron-ion interaction in the plasma and in the presence of the laser field is given by

$$\hat{H} = \frac{1}{2m}(\hat{p} - \frac{e}{c}\vec{A})^2 + \frac{1}{2m}(\hat{P} - \frac{e}{c}\vec{A})^2 + V_1(R) + V_2(r,R) \ , \qquad (2.1)$$

where

$$\vec{A} = \frac{\vec{E}_L}{\omega} cos\ \omega t \ , \qquad (2.2)$$

$$V_1(R) = -\frac{Ze^2}{R} \ , \qquad (2.3)$$

and

$$V_2(r,R) = -\frac{Ze^2}{r} exp(-r/\lambda_D) + \frac{e^2}{|\vec{r} - \vec{R}|} \exp(-\mid \vec{r} - \vec{R} \mid / \lambda_D). \qquad (2.4)$$

In these expressions the lower case radial variable r and the momentum operator $\hat{p}$ refer to the incident electron and the upper case ones to the bound electron. In our model, the plasma screening of the bound electron is centered at its position, as indicated by the second term in the expression (2.4) for $V_2(r,$R). This is somewhat different from the work of Hatton et al[e] and by Pundir and Mathur[7] who used a model which considera the plasma screening of the bound electron centered at the position of the nucleus. As pointed out by Hatton et al[e], the effect of electrostatic screening on the cross-section is enhanced in the latter model. However, we find the former more consistent with the use of the Debye-Hückel expression for the plasma screening.

The use of the electrostatic screening centered at the position of the bound electron is more consistent from a strict plasma physics point of view. However, since the Debye length is much larger than the Bohr radius, centering the screening cloud either on the bound electron or on the nucleus has little influence on the numerical results. We have used the former approach because it is more convenient when the dynamic screening produced by the laser is also taken into account.

To solve the Schrödinger equation with the Hamiltonian operator (2.1), we use the technique of unitary transformations[15,16]. The wavefunction is given by

$$\psi(r,R,t) = \exp\left(\frac{i}{\hbar}\vec{\delta}.(\hat{p}+\hat{P})\right).\exp\left(\frac{i\eta}{\hbar}\right)\phi(r,R) , \tag{2.5}$$

where

$$\vec{\delta}(t) = \vec{a}_L sin\omega t , \tag{2.6}$$

$$\eta(t) = \frac{e^2}{mc^2}\int A^2(t)dt , \tag{2.7}$$

and $\phi(r,R)$ is the solution of the Schrõdinger equation

$$i\hbar\frac{\partial\phi}{\partial t} = \hat{\hat{H}}\phi \tag{2.8}$$

with the modified Hamiltonian operator

$$\hat{\hat{H}}(r,R) = \frac{\hat{p}^2}{2m} + \frac{\hat{P}^2}{2m} - \frac{Ze^2}{R} + V_2(r,R) \tag{2.9}$$

In deriving this expression, we have explicitly used the condition $E << E_{at}$ to neglect the effect of laser modulation on the position of the bound electron.

The Schrõdinger equation (2.8) is solved using standard perturbation theory. Considering an inelastic scattering process with the ion changing from a state with energy ϵ_n to a state with energy $\epsilon_{n'}, n' \neq n$, we find that the transition probability per unit time is given by

$$W_{n'n} = \frac{2\pi}{\hbar}\sum_{\nu} \left| \frac{4\pi e^2 J_\nu(\vec{K}.\vec{a})}{(K^2+1/\lambda_D^2)}F(K) \right|^2 \delta(\epsilon_{n'}+\epsilon_{k'}-\epsilon_n-\epsilon_k+\hbar\nu\omega), \tag{2.10}$$

where the form factor $F(K)$ is defined as

$$F(K) = \int exp(i\vec{K}.\vec{R})\phi_{n'}^*(R)\phi_n(R)d^3R, \tag{2.11}$$

ϵ_k and $\epsilon_{k'}$ are respectively the energies of the incident electron before and after scattering, $\hbar\vec{K} = \hbar(\vec{k}' - \vec{k})$ is the momentum transferred, v is the number of photons absorbed from the laser field in the collision process, $J_\nu(x)$ is the Bessel function of order v and $\phi_n(R)$ is the wavefunction of the unperturbed ion. Substituting (2.10) into the expression for the differential cross-section $d\sigma/d\Omega$ [17] we find

$$\frac{d\sigma}{d\Omega} = \frac{1}{k}\sum_\nu \alpha(\nu)\left[\frac{2J_\nu(\vec{K}.\vec{a})F(K)}{a_0(K^2+1/\lambda_D^2)}\right]_{K=K(\nu)} \tag{2.12}$$

where

$$\alpha(\nu) = \left[k^2 - \frac{2m}{\hbar^2}(\epsilon_{n'} - \epsilon_n + \hbar\nu\omega)\right] \tag{2.13}$$

$$K(\nu) = \left[(k-\alpha)^2 + 4k\alpha\ sin^2\frac{\theta}{2}\right]^{1/2} \tag{2.14}$$

and θ is the scattering angle. We note that the argument of the Bessel function in (2.12) depends explicitly on the direction of polarization of the laser field. Thus the cross-section becomes anisotropic in the presence of the laser, depending on the angle between the electric field and the direction of the momentum of the incident electron. To calculate the cross-section, we numerically integrate (2.12) over the solid angle.

3. Results and Conclusions

The total cross-sections for 1s-2s and 1s-2p transitions are shown in figures 1 and 2 respectively. In these figures the electron temperature is kept constant at T=10 eV and the plasma density is taken equal to the critical density for a laser field with $\lambda_L = 0.53\mu m$, corresponding to a frequency doubled Nd: Glass laser.

We note from these figures that the cross-section is non-zero below the field-free threshold (E=10.2 eV), exhibiting jumps at several values of the incident electron energy. These jumps in the cross-section correspond to laser-assisted transitions which occur when the electron absorbs the exact number of photons that make the transition allowed by energy conservation. Above the threshold the effect of the laser field, like that of the plasma electrostatic screening, is to decrease the cross-section.

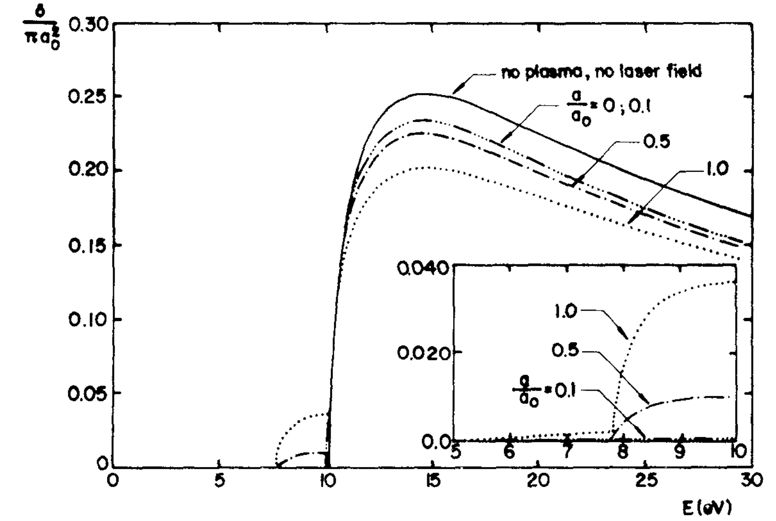


Figure 1a

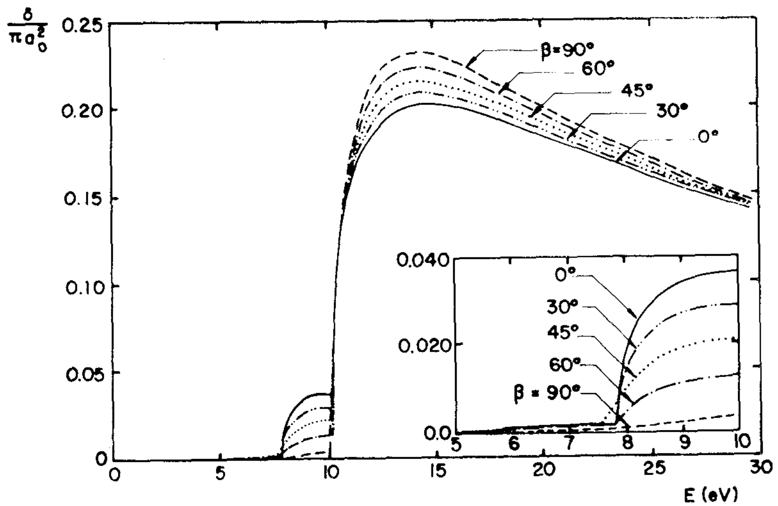


Figure 1b

Fig. 1 - Total cross-section for 1s-2s transitions as a function of the incident electron energy. The laser wavelength is $\lambda_L = 0.53\mu m$, the plasma density is $n = 3.9 \times 10^{21}$ cm^{-3}, and the electron temperature is $T = 10$ eV. In figure 1a the angle between the laser field and the incident momentum is kept fixed at $\beta = 0$, and the laser intensity (measured in terms of a/a_0) is varied. In figure 1b the laser intensity is kept fixed at $a/a_0 = 1.0$ and β is varied. The behaviour of the cross sections below the laser-free threshold is shown amplified in the insert.

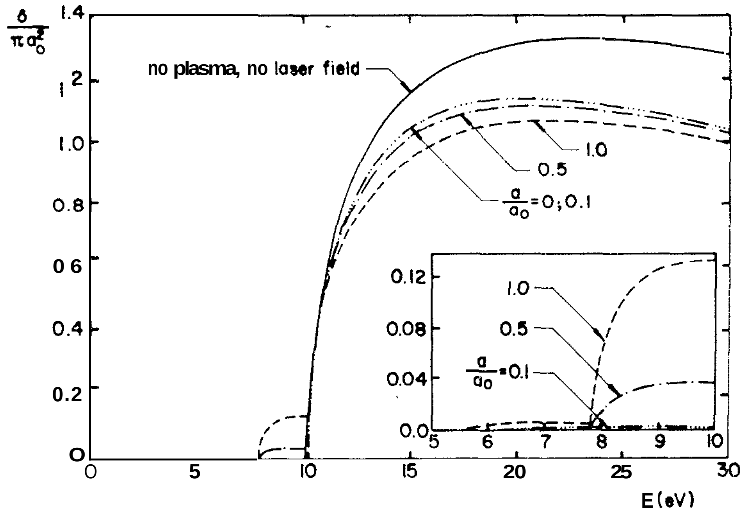
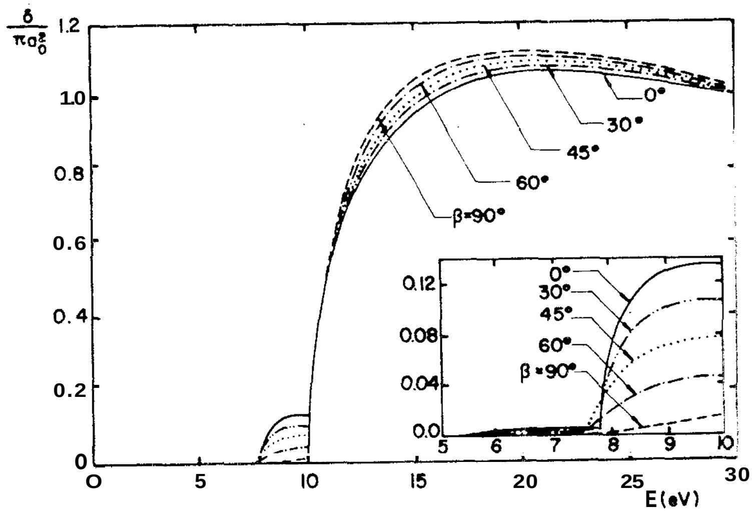


Figure 2a



Figun 2b

Fig. 2 - The same as figure 1 for 1s-2p transitions.

In figures **1a** and **2a,** the angle β between the electric field and the momentum of the incident electron is kept constant at $\beta = 0$ and **the** laser intensity is varied. In figures **1b** and 2b, the laser intensity **is** kept constant at $a/a_0 = 1.0$ and the angle β is varied from 0 to 90 degrees. As expected, the **effect** of the laser field is more pronounced when the electric field is parallel to the momentum of the incident electron. The effect of electrostatic plasma screening is pronounced in these examples because the Debye wavelength λ_D **is** rather **small** for an electron temperature of T=10 eV. As the electron temperature is increased, the effect of the eletrostatic screening decreases substantially but the effect of the laser field remains approximately the same.

In our calculations the laser intensity has been varied up to $a/a_o = 1.0$. This is an upper limit for the validity of our approximations and for such intensities the effect of the laser field on the atomic structure of the target ion should be taken into account[11,18]. This will be the subject of a future publication. However, even for $a/a_0 = 1.0$, our preliminary results indicate that the features shown in figures 1 and 2 are qualitatively correct.

A direct experiment to measure the change predicted by our model for the scattering cross-section would be very difficult to carry out. However, our results could indirectly be tested by changing the expression for the cross-section in numerical simulations of laser-fusion experiments. This is çertainly beyond the scope of the present paper.

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Resumo

O efeito de um campo de laser no espalhamento inelástico de eletrons por íons hidrogenoides, em um plasma denso é examinado. As seções de choque totais para as transições 1s-2s e 1s-2p são calculadas. O campo de laser modifica as seções de choque abaixando a energia do limiar e introduz uma anisotropia com respeito a polarização do laser. Surge uma dependência não monotonica na energia do elétron que é característica de processos de multifótons.