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Laser Assisted Excitation (to $n = 2$ Level) of a Hydrogenic Ion Inside a Plasma Medium

CHATTOPADHYAY Arpita and SINHA Chandana

Department of Theoretical Physics, Indian Association for the Cultivation of Science, Jadavpur, Kolkata - 700032, India.

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Abstract

An approach is proposed to study the laser assisted inelastic differential cross sections and collision strengths of a ground state hydrogenic ion for the excitation to $n = 2$ level inside a hot, dense plasma. The effect of plasma screening is considered in the Debye Hückel approximation. The dressed excited states (for $n = 2$ level) of the hydrogenic ion is constructed using first order perturbation theory in the parabolic coordinate representation which is the correct prescription for such laser assisted excitation process. The calculation is performed in the soft photon limit by assuming that the plasma frequency is much higher than the laser frequency. Due to the irradiation by the laser, the electron - ion cross sections as well as collision strengths inside the plasma are found to reduce significantly at all incident energies.

Keywords:

laser assisted, plasma, excitation, target dressing, hydrogenic ion

1. Introduction

The present study addresses to the problem of investigation of the influence of a monochromatic, linearly polarized laser field with field strength $\vec{\varepsilon}_0$ and frequency ω on the electron impact excitation of a hydrogenic ion (*e.g.*, He^+) to its $n = 2$ level in a hot, dense plasma medium. Such studies have direct relevance to different real physical objects such as laser produced plasmas. Further, the inverse bremsstrahlung process plays an important role in the breakdown and the heating of a plasma by a laser beam [1]. Detailed knowledge of spectroscopic and collision properties (*e.g.*, collision strengths, cross sections etc.) of ions are also needed for the interpretation of the line emission from dense, high temperature plasmas [2]. However, not much is known about the combined effects of plasma and laser field on important collision processes [1, 3], though limited studies were made on electron - ion collisions inside a plasma medium [2, 4, 5].

Cross sections for electron impact excitation or ionization of isolated positive ions are finite at threshold because of the long range Coulomb interaction between the collision particles but, inside a dense plasma, partial shielding (Debye Shielding) by neighboring charged particles reduces this electrostatic interaction at large distances. Now when a dense plasma is irradiated with an external laser field, the electromagnetic wave will not propagate through the plasma in the non relativistic case, if the plasma frequency is much greater than the frequency of the electromagnetic wave. However, still there will be transfer of energy from the laser to the plasma [6]. In this case, the average plasma properties will not be altered, if the plasma is fully ionized and the fraction of laser energy absorbed is negligible. Thus under these conditions, it is of good worth to study the effects of plasma screening on the laser assisted electron - ion collision cross sections, particularly at lower incident energies. In presence of the laser field, the electrons and ions inside the plasma will be dressed by the laser. The dressing of the electrons due to the laser field is considered by using plane wave Volkov solution due to the Debye shielding of the electron - ion Coulomb interaction [2] inside the plasma medium. To construct the laser dressed target ion (He^+) wave function, both in ground and excited ($n = 2$ level) states, an elegant method is developed [7] in the framework of first order theory in the parabolic coordinate representation which is the correct prescription for such laser assisted excitation process, particularly when the target (He^+) ion has degenerate eigen states. By virtue of this, the problem arising due to the accidental 'l' (orbital angular momentum) degeneracy of the excited states of a hydrogenic ion is overcome successfully.

Corresponding author's e-mail: tpac@mahendra.iacs.res.in, tpcs@mahendra.iacs.res.in

2. Theory

Within the framework of a first order theory (in the interaction potential), the transition matrix element for such excitation process is given by,

$$S^d_{fi} = -\frac{i}{\hbar}\int_{-\infty}^{\infty} \mathrm{d}t\langle\psi^d_f(\vec{r}_0,\vec{r}_1,t)|V|\psi^d_i(\vec{r}_0,\vec{r}_1,t)\rangle \quad (1)$$

where $\psi^d_i(\vec{r}_0,\vec{r}_1,t)$ and $\psi^d_f(\vec{r}_0,\vec{r}_1,t)$ are the initial and final laser dressed wave functions (to be described below) of the electron - ion system inside a plasma medium and V is the exponentially screened electron - ion Coulomb interaction in the Debye - Hückel [2] approximation,

$$V(\vec{r}_0,\vec{r}_1) = \left(-\frac{Z}{r_0} + \frac{1}{|\vec{r}_0 - \vec{r}_1|}\right)\exp(-r_0/\Lambda) \quad (2)$$

where r_0, r_1 are the positions of the incident and bound electrons respectively with respect to the target ion and Λ is the Debye Huckel screening length given by [2],

$$\Lambda = \left(\frac{4\pi e^2}{k_B T}\sum_j N_j Z_j^2\right)^{-1/2} \quad (3)$$

for a plasma of temperature T that has density N_j of particles with charge Z_j. The potential $V(\vec{r}_0, \overrightarrow{\mathrm{r}_1})$ in Eq. (2) is expected to be a reasonable representation of the plasma screening in the collision, especially where long range contributions dominate. The laser dressed wave functions $\psi^d_i(\vec{r}_0,\vec{r}_1)$ and $\psi^d_f(\vec{r}_0,\vec{r}_1)$ are given as,

$$\psi^d_i(\vec{r}_0,\vec{r}_1) = \chi_i(\vec{r}_0,t)\Phi^d_{000}(\vec{r}_1,t) \quad (4)$$

with $\chi_i(\vec{r}_0,t) = (2\pi)^{-3/2}\exp[i(\vec{k}_i\cdot\vec{r}_0 - \vec{k}_i\cdot\vec{\alpha}_0\sin\omega t - E_{k_i}t)]$; $\vec{\alpha}_0 = \vec{\epsilon}_0/\omega^2$, E_{k_i} being the energy of the incident electron.

$$\Phi^d_i(\vec{r}_1,t) = \exp(-i\vec{a}\cdot\vec{r}_1)\frac{1}{\sqrt{\pi Z}}\exp(-iE_0 t)e^{-Zr_1}$$
$$\left[Z^2 - \sin\omega t\vec{\epsilon}_0\cdot\vec{r}_1\left(1+\frac{Zr_1}{2}\right)\right] \quad (5)$$

The term $e^{-i\vec{a}\cdot\vec{r}_1}$ in the above equation, with $\vec{a} = \vec{\epsilon}_0/\omega$ is introduced to maintain the gauge consistency between the dressed projectile and target wave functions.

$$\psi^d_f(\vec{r}_0,\vec{r}_1) = \chi_f(\vec{r}_0,t)\Phi^d_{n_1n_2m}(\vec{r}_1,t) \quad (6)$$

where $\Phi^d_{000}(\vec{r}_1,t)$ and $\Phi^d_{n_1n_2m}(\vec{r}_1,t)$ denote the dressed target wave functions for the ground and the excited ($n = 2$ level) states respectively constructed in parabolic coordinate system [7]. n_1, n_2, m in Eq. (6) are the parabolic quantum numbers and magnetic quantum number respectively, connected by $n = n_1+n_2+|m|+1$, n being the total principal quantum number. The energy conservation relation for the process is given by,

$$k_f^2 = k_i^2 + 2l\omega + 2(\epsilon_f - \epsilon_i), \quad l = 0, \pm1, \pm2, \ldots \quad (7)$$

where ϵ_i and ϵ_f are the binding energies of the ground and excited states of the hydrogenic ion. The inelastic total differential cross section (DCS) for the transition from the $n = 1$ to $n = 2$ level for a fixed value of 'l' can be written as,

$$\left[\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right]_{tot} = \left[\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right]_{100} + \left[\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right]_{010} + 2\left[\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right]_{001} \quad (8)$$

where $\left[\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right]_{n_1n_2m}$ refers to individual DCS corresponding to different Stark manifolds for the $n = 2$ level.

The total cross section (σ) for the excitation to $n = 2$ level is obtained by integrating the total differential cross section over the solid angle, i.e.,

$$\sigma = \int\left[\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right]_{tot}\mathrm{d}\Omega \quad (9)$$

The corresponding collision strength for the process is defined as,

$$\Omega = k_i^2\sigma \quad (10)$$

3. Results and discussions

The present study concerns with the laser assisted excitation (to $n = 2$ level) process of a hydrogenic ion (He^+) for the zero photon transfer ($l = 0$) as well as for the single photon absorption / emission ($l = \pm1$) cases. It may be mentioned that for the present laser parameters the absorption and emission cross-sections are almost identical. The laser field is chosen to be parallel to the incident momentum direction. We have used atomic unit (a.u.) throughout our results and graphs. The present results are reproduced with those of Whitten *et al*. [4] (without the laser field) by setting the laser parameters equal to zero.

Figure 1 demonstrates a comparative study of the laser assisted differential cross sections (DCS) for the excitation ($n = 2$) of He^+ for zero photon and single photon transfers ($l = 0, \pm1$) and the corresponding field free (FF) case using the laser parameters $\epsilon_0 = 2.57\times10^9$ V / m (0.005 a.u.) and $\omega = 1.17$ eV (0.043 a.u.) (Nd - Yag laser) at an incident energy $E_i = 100\,\mathrm{eV}$, with the Debye screening length $\Lambda Z = 10$ a.u.. Figure 1 reveals that the laser field suppresses the FF DCS throughout the angular range, the suppression being more for larger scattering angles. It is also apparent from figure 1 that the FF DCS falls off monotonically with increasing scattering angle, while the field assisted ($l = 0, \pm1$) curves exhibit some oscillations due to the presence of the Bessel function $j_l(x)$ in the transition matrix element. These oscillations are perhaps a characteristic of the single mode nature of the laser field, since with multimode laser, such oscillations are absent due to the

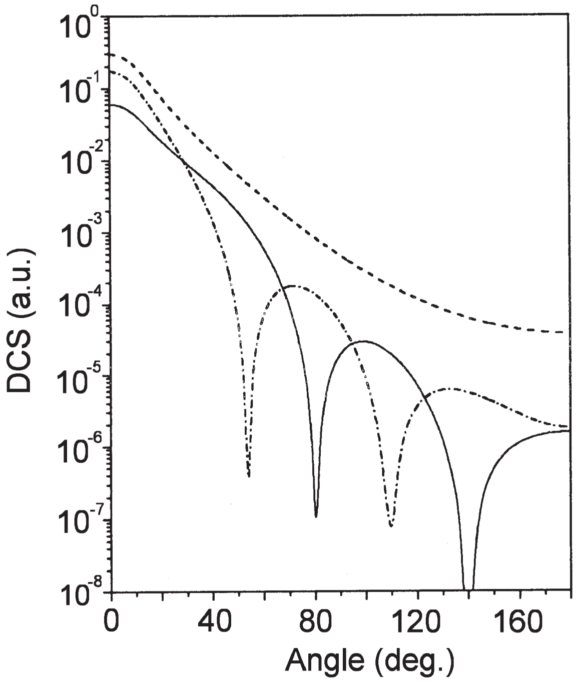

Fig. 1

Fig. 1 Laser assisted inelastic (to $n = 2$ level) differential cross sections (a.u.) of a He^{+} ion inside a plasma against the scattering angle (in degree) using laser field strength 0.005 a.u. and laser frequency $\omega = 0.043$ a.u. at an incident electron energy $E_i = 100$ eV, with the Debye screening length $\Lambda Z = 10$ a.u. Solid Curve : $l = \pm 1$ results, dash dot curve : $l = 0$ results, dashed curve : field free results.

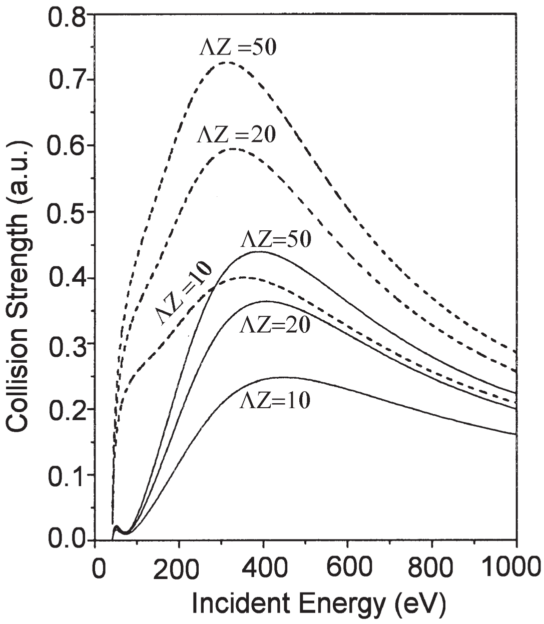

Fig. 2

Fig. 2 Solid curves: No photon transfer ($l = 0$) collision strength (a.u.) versus incident energy (eV) for three values of Debye screening length $\Lambda Z = 10$, 20 and 50 a.u. with the presence of the laser field. Laser parameters are same as in figure 1. Dashed curves: Collision strengths without the laser field, i.e., the field free (FF) case.

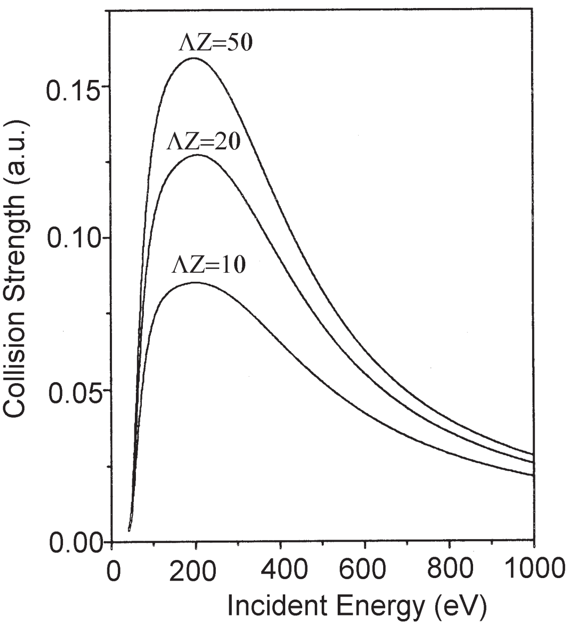

Fig.3

Fig. 3 Same as in Fig. 2, but for $l = \pm 1$ with the presence of the laser filed.

averaging over the amplitude fluctuations of the multimode field [7].

Figures 2 and 3 demonstrate the inelastic (n = 2) collision strength against the incident energy (in eV) for e – He^{+} ion system inside a plasma for three different Debye screening lengths (ΛZ = 10, 20 and 50 a.u.) using the same laser parameters as in Fig 1. Figure 2 exhibits the zero photon (l = 0) exchange collision strength along with the FF results, while figure 3 represents the corresponding single photon transfer (l = ±1) case. The laser assisted collision strengths in both the Figs. 2 and 3 exhibit a broad peak, depending on the screening length. However, for l = 1, the peaks of the collision strength (Fig. 3) become sharper than those for l = 0 case. Further, the peaks of the collision strength shift towards higher / lower incident energy for $l = 0/\pm 1$ as compared to the FF case. This shift could probably be attributed to the effective change in the Debye Screening length due to the irradiation of the laser field.

As in the case of the angular distributions, the presence of the laser field suppresses the field free (FF) collision strengths significantly for both zero and single photon transfers, the suppression being much more enhanced for the single photon transfer case (Fig. 3) that for the zero photon exchange (Fig. 2). The suppression of the collision strength could be physically explained as follows. The laser field effectively weakens the perturbation causing the excitation process, felt by the projectile electron, resulting in a reduction of the collision cross sections / strengths [7].

Finally the combined effect of the plasma and the laser field on the inelastic collision strength / cross sections of a hydrogenic ion is the reduction of the cross sections in two steps. In the first step, the Debye-Hückel screening of the plasma (without the laser field) reduces the inelastic e - ion cross sections significantly [4] and these cross sections are further reduced when the plasma is irradiated by the laser field.

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