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# Laser Assisted Single Ionization of a Hydrogenic Ion by Electron Impact

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**Abstract**

Influence of an external linearly polarized, monochromatic laser field in the dynamics of the (e, 2e) process of a hydrogenic ion is studied theoretically. Significant changes are noted in the triple differential cross sections ( TDCS ) by the application of the laser field. The net effect of the laser field is to suppress the field free cross sections in the zeroth order approximation of the ejected electron wave function while in the first order the cross sections are found to be enhanced depending on the incident energy.

**Keywords:**

laser assisted, (e, 2e) process, Coulomb - Volkov , hydrogenic ion

## 1. Introduction

Laser assisted electron - ion collision (excitation, ionization) plays a very vital role in many practical fields, such as in the plasma confinement problem in fusion plasma, laser heating of plasma, high power gas lasers etc. In particular, such collision cross sections are highly needed in the study of laser produced plasma. By virtue of the availability of powerful, tunable lasers, both laser induced and laser assisted collision phenomena are nowadays being observed in laboratories. However, these experiments till now are limited to neutral atoms only. The absence of any experimental data adds further importance to the theoretical study of such a reaction. The present study addresses to the problem of ionization of a hydrogenlike ion by electron impact in the presence of a monochromatic linearly polarized, homogeneous laser field. The calculations are performed in the framework of Coulomb Born approximation where the projectile - screened ion interaction is considered to be the perturbation responsible for the collision while the role of the external laser field is to modify the projectile electron state as well as the initial bound and continuum states of the target ion. The wavefunction of the projectile electron in the combined effect of the long range Coulomb interaction of the screened target ion and the laser field is assumed to be the Coulomb Volkov type proposed by Jain and Tzoar [1] and later used by several workers [2-4]. Although the approximate CV solution presents the advantage of containing the field in all orders (inherent in the plane wave Volkov solution [5]), it completely decouples the electron - laser and electron - screened ion interaction [3]. In the final state wavefunction, the electron - electron correlation effect is taken into account, thereby satisfying the asymptotic three body boundary condition for the ionization process. As a first step the fully (triply) differential cross sections (TDCS) that provides the most detailed information of the ionization process is studied for asymmetric coplanar geometry.

## 2. Theory

The reaction studied is,

$$\mathrm{e}^-(E_i,\vec{k}_i) + \mathrm{He}^+(1\mathrm{s}) \pm \gamma(\omega,\vec{\varepsilon}_0) \rightarrow \mathrm{e}^-(E_1,\vec{k}_1) + \mathrm{e}^-(E_2,\vec{k}_2) + \mathrm{He}^{++} \qquad \text{(A)}$$

A major difficulty in the theoretical investigation of such laser assisted ionization process is to construct the proper laser - dressed continuum wave function of the ejected electron. We consider the laser field strength $\varepsilon_0 \ll 5\times10^{11}$ V/m ( the atomic unit of field strength ). The dressed continuum wave function for the ejected electron $\Phi_{k_2}(\vec{r}_2,t)$ is chosen as [3] ,

$$\Phi_{k_2}(\vec{r}_2,t) = \exp(-iE_{k_2}t)\exp(-i\vec{a}\cdot\vec{r}_2)\exp(-i\vec{k}_2\cdot\vec{\alpha}_0\sin\omega t) \times\Bigg[\psi^{(-)}_{c,k_2}(\vec{r}_2) + \frac{i}{2}\sum_n\left[\frac{\exp(i\omega t)}{E_n-E_{k_2}+\omega} - \frac{\exp(-i\omega t)}{E_n-E_{k_2}-\omega}\right] M_{nk_2}\psi_n(\vec{r}_2) + i\vec{k}_2\cdot\vec{\alpha}_0\sin\omega t\,\psi^{(-)}_{c,k_2}(\vec{r}_2)\Bigg] \qquad (1)$$

where $\psi^{(-)}_{c,k_2}(\vec{r}_2) = (2\pi)^{-3/2}C_2\exp(i\vec{k}_2\cdot\vec{r}_2)\,{}_1F_1\big[-i\alpha_2, 1,$

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$-i(k_2 r_1 + \vec{k}_2 \cdot \vec{r}_1)\big]; \alpha_2 = \dfrac{Z}{k_2}; \vec{\alpha}_0 = \vec{\varepsilon}_0/\omega^2, E_{k_2}$ being the energy of the ejected electron and the Coulomb normalization constant $C_j = \exp(\pi\alpha_j/2)\Gamma(1 + i\alpha_j)$ and $M_{n,k_2} = \left\langle \psi_n \middle| \vec{\varepsilon}_0 \cdot \vec{r}_2 \middle| \psi^{(-)}_{c,k_2} \right\rangle$. The term $e^{\overrightarrow{-i\alpha \cdot r_2}}$ in the eqn. (1), with $\vec{a} = \vec{\varepsilon}_0/\omega$ is introduced to maintain the gauge consistency between the dressed projectile and target wave functions.

It may be noted that the zeroth order solution for the ejected electron wave function, is given by the first term of Eq. (1), which is simply the Coulomb Volkov solution as used for the dressed incident or scattered (unbound) electron '1'.

The ionization amplitude in a first order (in the interaction potential) approximation for the laser assisted (e, 2e) process for the hydrogenic ion is given by,

$$T_{if} = -i \int_{-\infty}^{\infty} \mathrm{d}t \left\langle \Psi_f^- \middle| V_i \middle| \psi_i \right\rangle \qquad (2)$$

The asymptotic initial state $\psi_i$ in Eq. (2) is given by,

$$\psi_i = \Phi_i^d(\vec{r}_2, t)\chi_i(\vec{r}_1, t) \qquad (3)$$

where

$$\chi_i(\vec{r}_1, t) = (2\pi)^{-3/2}\exp[i(\vec{k}_i \cdot \vec{r}_1 - \vec{k}_i \cdot \vec{\alpha}_0 \sin\omega t - E_{k_i} t)]$$
$$\times C_i \times {}_1F_1\left[i\alpha_i, 1, i(k_i r_1 - \vec{k}_i \cdot \vec{r}_1)\right];$$
$$\alpha_i = \frac{Z-1}{k_i}$$

and $\Phi_i{}^d(\vec{r}_2, t)$ is the dressed ground state wave function of the hydrogenic ion given by,

$$\Phi_i{}^d(\vec{r}_2, t) = \exp(-i\vec{a} \cdot \vec{r}_2)\frac{1}{\sqrt{\pi Z}}\exp(-iE_0 t)e^{-Zr_2}$$
$$\left[Z^2 - \sin\omega t \vec{\varepsilon}_0 \cdot \vec{r}_2\left(1 + \frac{Zr_2}{2}\right)\right]$$

The perturbation $V_i$ in Eq. (2) is given by,

$$V_i = -\frac{1}{r_1} + \frac{1}{r_{12}} \qquad (4)$$

and the final state wave function $\Psi_f^-$ satisfying exact asymptotic 3 body incoming wave boundary condition for the ionization process is chosen as,

$$\Psi_f^- = \Phi_{k_2}(\vec{r}_2, t) \times \chi_{k_1}(\vec{r}_1, t) \times C_3$$
$$\times {}_1F_1\left[-i\alpha_3, 1, -i(k_{12} r_{12} + \vec{k}_{12} \cdot \vec{r}_{12})\right],$$
$$\vec{k}_{12} = \frac{1}{2}\left(\vec{k}_1 - \vec{k}_2\right) \text{ and } \vec{r}_{12} = \vec{r}_1 - \vec{r}_2.$$

The expression for the triple differential cross section (TDCS) for the process (A) accompanied by the transfer of $l$ photons is given by,

$$\frac{\mathrm{d}^3\sigma_{ion}}{\mathrm{d}\Omega_1 \mathrm{d}\Omega_2 \mathrm{d}E_2} = \frac{k_1 k_2}{k_i}\left|T^l_{if}\right|^2 \qquad (5)$$

## 3. Results and discussions

To study the influence of the laser field $(\omega, \vec{\varepsilon})$ on the dynamics of the (e, 2e) process (A) we have chosen the following laser parameters, the frequencies being in the soft photon limit, $\varepsilon_0 = 5 \times 10^7$ V/m and $\omega = 0.117$ eV ($CO_2$ laser). The laser field is chosen to be parallel to the incident momentum direction.

The present study concerns with the zero photon transfer ($l = 0$) as well as the single photon absorption / emission ($l = \pm 1$) processes. It may be mentioned that for the present laser parameters the absorption and emission cross-sections are almost identical.

Figures 1 – 3 demonstrate the angular distributions of the ejected electron ($\theta_2$) for three different incident energies (150, 250 and 1,000 eV). The energy of the ejected electron ($E_2$) is kept at a low value, *e.g.*, $E_2 = 5$ eV for the Figs. 1 and 2, while for Fig. 3, $E_2 = 10$ eV.

A significant modification is noted in the TDCS due to the application of the laser field. As may be noted from the figures 1 – 3, for the zero photon transfer case using the zeroth order wave function (retaining only

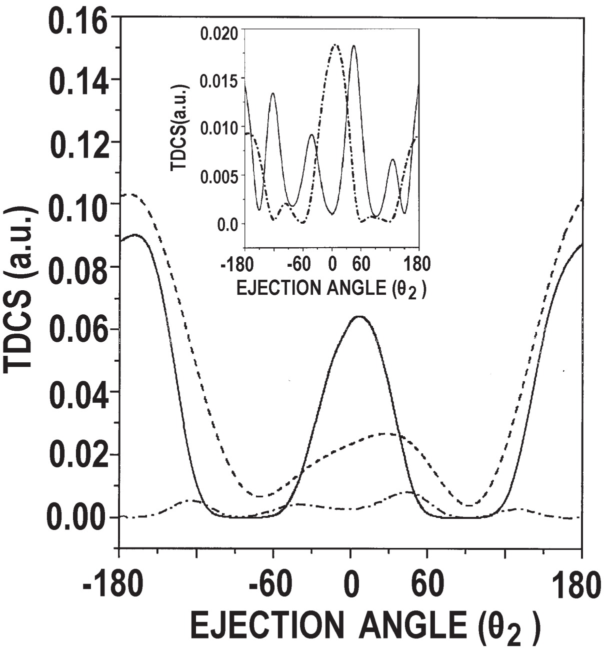


Fig. 1 The TDCS (in a.u.) as a function of the ejected electron angle $\theta_2$ for the ionization of $He^+$ ion from the ground sate by electron impact in the presence of a laser field. The incident electron energy $E_{k_i} = 150$ eV, the ejected electron energy is $E_{k_2} = 5$ eV and the scattering angle $\theta_1 = 3^o$. Laser parameters used : $\varepsilon_0 = 5 \times 10^7$ V/m and $\omega = 0.117$ eV ($CO_2$ laser). The number of photon absorbed is taken to be $l = 1$. Solid Curve : considering full dressing of the ejected electron, Dash dot curve : considering the zeroth order approximation for the ejected electron, Dashed curve : the field free TDCS for the ejected electron. Inset : The above mentioned TDCS but for $l = 0$ and without the field free curve.

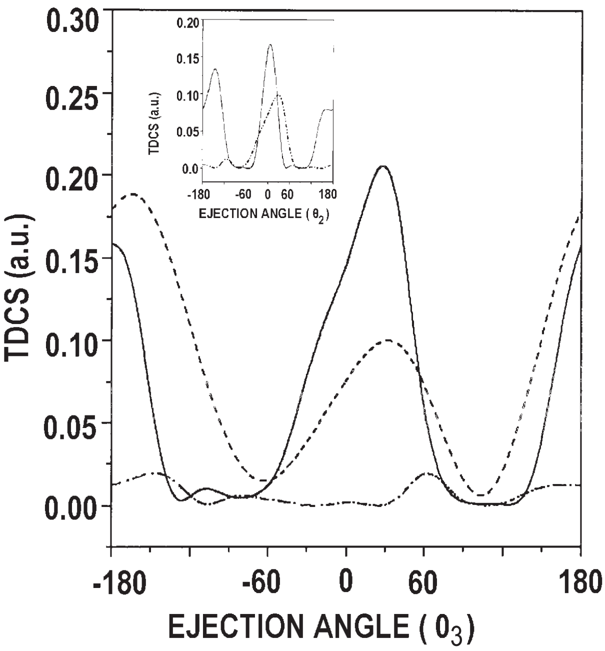


Fig. 2 Same as Fig. 1, but for the incident electron energy $E_{k_i} = 250$ eV.

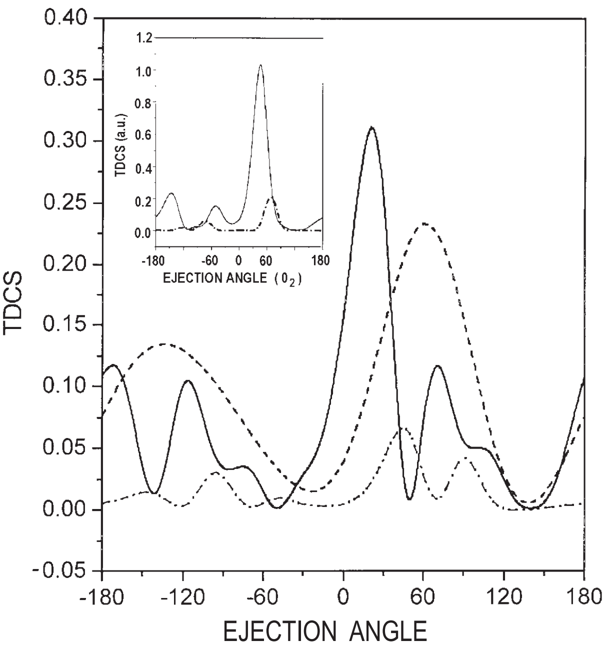


Fig. 3 Same as Fig. 1, but for the incident electron energy $E_{k_i} = 1000$ eV and $E_{K_2} = 10$ eV.

the first term in Eq. (1)) for the dressed ejected electron, the recoil peak is strongly affected (reduced) by the laser field as compared to the binary one for all incident energies. In contrast, considering the full dressing of the ejected electron (using full Eq. (1)) the situation is found to be reversed particularly in the higher energy regime (Figs. 2, 3). Figures 1 – 3 also reveal that for the single photon transfer ($l = \pm 1$), the overall TDCS is strongly suppressed as compared to the field free one, in the aforesaid zeroth order approximation. On the contrary, the full dressing gives rise to a significant enhancement in the binary peak and some reduction in the recoil peak magnitude with respect to the field free results. Thus, the significant difference between the zeroth order and the first order results indicate the dominance of the higher order contributions (arising from Eq. (1)) that increase with decreasing incident energy. From Figs. 1 – 3, it is also noted that some secondary structures (in both the binary and recoil regions) appear in presence of the field, which could be attributed to the properties of the Bessel function ($J_{0,1}$) occurring in the expression of the transition amplitude (Eq. 2), the number of oscillations being dependent on the argument ($\vec{\alpha}_0 \cdot (\vec{k}_1 + \vec{k}_2 - \vec{k}_i)$) of the Bessel functions.

Table 1 displays the binary ($b$) to recoil ($r$) peak intensity ratio ($b/r$) of the TDCS for some incident energies with $l = 0$ and $\pm 1$. In the field free case, the salient feature of the (e, 2e) TDCS results for an ionic target is the presence of an intense recoil peak [6] (except for very high incident energy, *e.g.*, $E_i = 1,000$ eV, not shown in the Table 1) even larger than the binary one (i.e., the binary to recoil intensity peak ratio, i.e., $b/r < 1$), an unusual feature for a neutral target. The aforesaid strong recoil peak for the ionic target could be attributed to the strong elastic scattering from the nucleus. Now in the presence of laser, this feature is not maintained, e.g., for $l = 0$ case, the ratio $b/r$ is $> 1$ for all incident energies (vide Table 1) while for $l = \pm 1$, the ratio $b/r$ increases with respect to the field free case with increasing incident energy and becomes $> 1$ for higher incident energies (vide Table1).

| Incident Energy ( eV ) | $b/r$ for field free case | $b/r$ for $l = 0$ case | $b/r$ for $l = \pm 1$ case |
|---|---|---|---|
| 150 | 0.2576 | 1.2912 | 0.7099 |
| 250 | 0.5273 | 1.2159 | 1.285 |
| 500 | 0.9204 | 2.3138 | 1.8673 |

Table 1 The binary ($b$) to recoil ($r$) peak intensity ratio ($b/r$) of the TDCS for different incident energies and for $l = 0$, $l = \pm 1$ cases as well as for field free case.

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