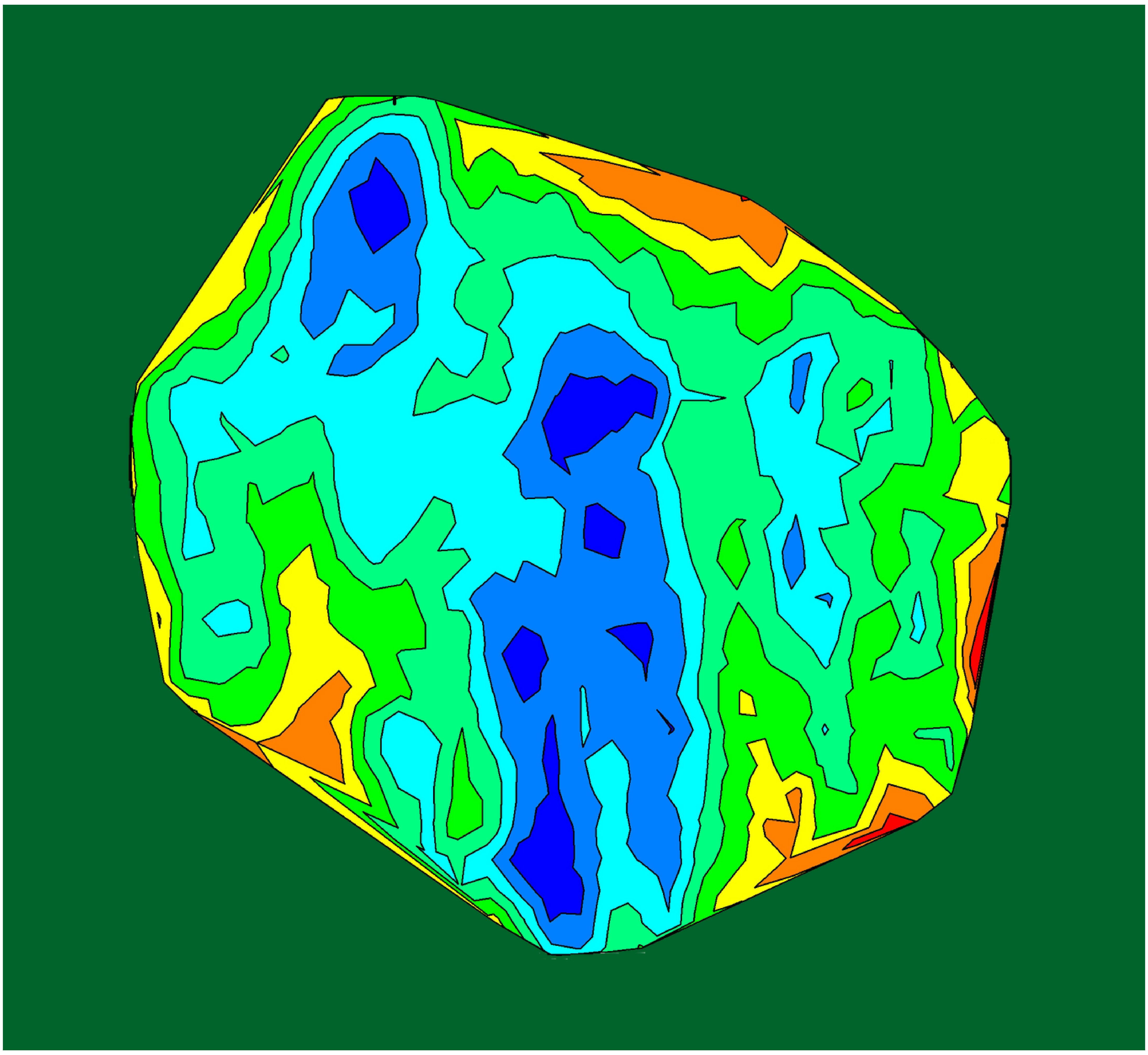
Volume 9, December 2020

ISSN 2542-2545

The HIMALAYAN PHYSICS

A peer-reviewed Journal of Physics



Department of Physics, Prithvi Narayan Campus, Pokhara

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Publisher

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The Himalayan Physics

Volume 9, December 2020

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The Himalayan Physics (HimPhys) is an open access peer-reviewed journal that publishes quality articles which make innovative contributions in all areas of Physics. HimPhys is published annually by Nepal Physical Society (Western Regional Chapter), and Department of Physics, Prithvi Narayan Campus, Pokhara. The goal of this journal is to bring together researchers and practitioners from academia in Nepal and abroad to focus on advanced techniques and explore new avenues in all areas of physical sciences and establishing new collaborations with physics community in Nepal.

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Pokhara, Nepal

Himalayan Physics Vol-9 (2020)

TABLE OF CONTENTS

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Him. Phys. **9** 93-102, (2020)

Himalayan Physics

Elliptically polarized laser assisted elastic electron-hydrogen atom collision and differential scattering cross-section

Research Article

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Abstract: In the present study, we have investigated scattering of an electron by hydrogen atoms in the presence of the elliptical polarized laser field. We have discussed the polarization effect of laser field on hydrogen atom and effect of the resulted polarized potential on differential scattering cross-section is studied. We assume the scattered electrons having kinetic energy ($\sim$ 3000 eV) and laser field of moderate field strength because it is permitted to treat the scattering process in first Born approximation and the scattering electron was described by Volkov wave function. We found that the differential scattering cross-section area increases with the increase of the kinetic energy of the incident electron and there is no effect of changing the value of polarizing angle on the differential cross-section with kinetic energy. We observed that differential scattering cross-section in elliptical polarization in the high energy region depends upon the laser intensity and the incident energy for a linearly polarized field.

Keywords: Elliptical polarization • Differential cross-section • Polarized potential • Laser assisted collision

1. Introduction

The study of electron-atom collisions in the presence of laser field has attracted much attention these days because of the importance of these processes in different applied fields of science (such as plasma heating or driven fusion) and interest in collision theory. Atomic matter exposed to a fields of strong radiation becomes a broad field of current research both experimentally and theoretically. The development of intense and tunable lasers at relatively moderate laser field intensities has made possible for the observation of multiphoton processes. The theoretical study of electron-atom collisions in presence of a laser field becomes very complex compared with the difficulties associated with the treatment of field free electron-atom scattering. The presence of the laser field introduces some new parameters like laser frequency, intensity, polarization and influence collisional interactions. Presence of photons play the role of a "third body" during the collision, and "dressed" the atomic states [1].Since the target atom does not change its states during the process its own energy can be ignored but the potential can

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simulate the electron-atom collisional interaction. Simply, a laser - assisted elastic electron-atom scattering is a process can be represented as,

$$e_{q_i} + A_i \rightarrow e_{q_f} + l\hbar W + A_i$$

Where the atom A remains in its ground state during the collision while the electron exchanges l quanta with photon field (l≤0 for absorption and l≥0 for emission) to change momenta from q_i to $q_f = q_i{+}\hbar\omega$. This kind of process is referred as a free-free transition and has been studied extensively over last two decades. One of the oldest and most reliable theoretical results in multiphoton physics is Kroll-Watson theorem [2]. It describes the scattering of an electron by a potential in the presence of a low frequency linearly polarized laser field. Most of the theoretical studies in scattering of electron by atoms in an intense radiation field are based on perturbation theory [3] initiated with the well-known work by Kroll and Waston on the soft photon approximation. Recently laser-assisted scattering reviews have been discussed by many workers [3–5].

The possibility of observing laser-assisted electron impact atomic excitation in the presence of a strong field [6], is much more difficult to observe. In the laser-assisted collisions, titled as simultaneous electron-photon excitation (SEPE), the electron-target system can absorb or emit one or more photons from the laser field, living the atom in excited state. Several experiments have been performed, in which exchange of one or more photons between the electron-atom system take place and the laser field has been observed in laser assisted elastic and inelastic [7, 8] electron-atom collisions. The collision in presence of electromagnetic field can be treated in such a way that the electron-field coupling is dominant process. The target is transparent to the field and hence protontarget coupling can be ignored. Here we discussed such intensity of the electromagnetic field where the photon-field interaction can be neglected. Therefore such problems attract workers to begin the theoretical analysis by considering the problem of the scattering of an electron by a potential in the presence of a laser field. Mason and Newell (1982) reported experimental evidence of simultaneous electron-photon excitation of atoms. Most of the experimental studies have been performed with noble gases [9] and a recent on being with a Nd: YAG laser by Abdelkader et al.[10]. They considered He-target and laser field of low field experimentally under two states (i) SEPE, with incoming electron energy below the excitation threshold of the metastable 23S state, the electron collides with atoms in their ground state 11S, where the laser supplies the needed energy to achieve excitation and (ii) SEPE from higher excited states has been also observed [7]. Shinha et al.[3] studied on the free-free transition for an electron-hydrogen atom system in the ground state at very low incident energies in the presence of an external homogeneous, monochromatic, and linearly polarized laser field. The incident electron is considered to be dressed by the laser field in a nonperturbative manner by choosing the Volkov solutions in both the initial and final channels. The laser-assisted differential as well as total elastic cross sections are calculated for single-photon absorption or emission in the soft photon limit, the laser intensity being much less than the atomic field intensity.

Hydrogen atom is one of the simplest atom to deal with and can be used to gather interesting feature of the problem. The free - free process can theoretically be studied at various levels. The motive of this paper is to study effect of various collision and laser parameters on the collision process under elliptically polarized laser assisted elastic electron-hydrogen atom collision. There only exist a few works on non-perturbative approaches for such problems. In this paper we shall present the result of a detailed calculation of differential cross-section for laser assisted electron-hydrogen collisions. The interaction between the field and the projectile is treated as non-perturbative by using Volkov wave [11] and we confined our attention in elliptical polarization for polarized potential. Initially we suppose a collision event in which an incoming electron with momentum k_i that interact with a hydrogen atom initially in the state i in the presence of a single mode laser beam moving to the excited state j with the exchange of l photons between the electron and the laser field. We have used the first Born approximation, to treat the electron- atom interaction.

2. Theory and Method of calculation

Volkov- wave function

Let us consider an elastic collision between a fast(non-relativistic) electron of mass m and charge (-e) and a hydrogen target in its ground state where spin effects can be neglected, in the presence of laser field assumed to be described as a monochromatic, single mode and homogeneous electromagnetic field. Working in the Coulomb gauge, we have for the vector potential of a field propagating along the Z-axis,

$$A(t) = A_0 \left\{ \hat{x}\cos(\omega t) + \hat{y}\sin(\omega t)\tan\left(\frac{\eta}{2}\right) \right\} \tag{1}$$

where A_0=CE_0/ω F_0 and ω are the electric field amplitude and frequency respectively. Here,η measures the degrees of ellipticity of the field. For linear polarization,$\eta = 0$, for circular polarization,$\eta = \pi\ /\ 2$ and for elliptical polarization, $-\pi/2 \leq \eta \leq \pi/2$ .The wave function of the projectile embedded in the field is given by the non-relativistic Volkov wave function:

$$\chi^{\mathrm{LG}}(\vec{r},t) = (2\pi)^{-3/2}\exp\left(i\vec{k}\cdot\vec{r} - \frac{i}{\hbar}\int_{-\infty}^{t}\left(\frac{P^2}{2m} + \frac{e}{mc}\vec{A}\cdot\vec{P}\right)dt \right)$$

$$= (2\pi)^{\frac{-3}{2}}\exp\left(i\vec{k}\cdot\vec{r} - \frac{i}{\hbar}\int_{-\infty}^{t}\frac{P^2}{2m} - \frac{e}{mc}\vec{A}_0(t)\left\{\hat{x}\cos\frac{\eta}{2}\cos\omega t + \hat{y}\sin\frac{\eta}{2}\sin\omega t\right\}\cdot\hbar k dt \right)$$

$$= (2\pi)^{\frac{-3}{2}}\exp(i\vec{k}\cdot\vec{r} - \frac{i}{\hbar}\frac{\hbar^2 k^2}{2m}t$$
$$- \frac{i}{\hbar}\int_{-\infty}^{t}\frac{e}{mc}\vec{A}_0(t)\left\{\hat{x}\cos\frac{\eta}{2}\cos\omega t + \hat{y}\sin\frac{\eta}{2}\sin\omega t\right\}\cdot\hbar\vec{k}dt\Bigg)$$

$$= (2\pi)^{\frac{-3}{2}}\exp(i\vec{k}\cdot\vec{r} - \frac{iE_k t}{\hbar}$$
$$- \frac{ie}{mc}\vec{A}_0(t)\int_{-\infty}^{t}\left\{\hat{x}\cos\frac{\eta}{2}\cos\omega t + \hat{y}\sin\frac{\eta}{2}\sin\omega t\right\}\cdot\hbar\vec{k}dt\Bigg)$$

$$= (2\pi)^{\frac{-3}{2}} \exp(i\vec{k}.\vec{r} - \frac{iE_k t}{\hbar}$$
$$-\frac{ie}{mc}\vec{A}_0(t)\left[\hat{x}\cdot\vec{k}\int_{-\infty}^{t}\left\{\cos\omega t dt + \hat{y}\cdot\vec{k}\int_{-\infty}^{t}\tan\frac{\eta}{2}\sin\omega t\right\}dt\right]\Bigg)$$
$$= (2\pi)^{\frac{-3}{2}} \exp\left(i\vec{k}\cdot\vec{r} - \frac{iE_k t}{\hbar} - \frac{ie}{m\omega c}\vec{A}_0(t)\left[(\hat{x}\cdot\vec{k})\sin\omega t - (\hat{y}\cdot\vec{k})\tan\frac{\eta}{2}\cos\omega t\right]\right)$$

Put $\hat{x}.\vec{k} = \mathrm{R}\cos\gamma_k$,$(\hat{y}.\vec{k})\tan\frac{\eta}{2} = \mathrm{R}\sin\gamma_k$ where $\mathrm{R} = \frac{ie}{m\omega c}\vec{A}_0(t)$. Then

$$\chi(\vec{r},t) = (2\pi)^{\frac{-3}{2}} \exp\left(i\vec{k}\cdot\vec{r} - \frac{iE_k t}{\hbar} - [R\cos\gamma_k\sin\omega t - R\sin\gamma_k\cos\omega t]\right)$$

$$= (2\pi)^{\frac{-3}{2}} \exp\left(i\vec{k}\cdot\vec{r} - \frac{iE_k t}{\hbar} - R\sin(\omega t - \gamma_k)\right).$$

This is the required form of the Volkov wave function, where

$$R = \alpha_0\left[(\vec{k}\cdot\hat{x})^2 + (\vec{k}\cdot\hat{y})^2\tan^2\frac{\eta}{2}\right]^{1/2} = \alpha_0 D_0 k$$

$$D_0 = \left[\cos^2\theta + \sin^2\theta\tan^2\frac{\eta}{2}\right]^{1/2}$$

$$\tan\gamma_k = \frac{\vec{k}\cdot\hat{y}}{\vec{k}\cdot\hat{x}}\tan\frac{\eta}{2}$$

$$\alpha_0 = \frac{eE_0}{m\omega^2}$$

Calculation of S-matrix element

The S matrix element is given by

$$S = \frac{-i}{\hbar} < \chi_{\vec{k}_f} V \chi_{\vec{k}_i} > \tag{2}$$

which is related to the transition amplitude from the momentum state $k_{(}\vec{i})$ to $\vec{k_f}$ by

$$S_{k_f k_i} = \frac{-i}{\hbar}\iint_{-\infty}^{t} \chi^*_{\vec{k}_f} V \chi_{\vec{k}_i} d^3r dt \tag{3}$$

where $\vec{k}_i$ is the initial wave vector of the particle and $\vec{k}_f$ is the final wave vector of the scattered particle. Substituting for $\chi_{\vec{k}_i}$ and $\chi_{\vec{k}_f}$, we get

$$S_{k_f k_i} = \frac{-i}{\hbar}\iint_{-\infty}^{t}(2\pi)^{\frac{-3}{2}}\exp\left[\left(-i\vec{k}_f\cdot\vec{r} + \frac{iE_{k_f}t}{\hbar} + iR\sin(\omega t - \gamma_k)\right)\right]V(\vec{r})(2\pi)^{\frac{-3}{2}}\exp\left[\left(i\vec{k}_i\cdot\vec{r}\right.\right.$$
$$\left.\left. - \frac{iE_{k_i}t}{\hbar} - iR\sin(\omega t - \gamma_k)\right)\right]d^3r dt$$

Using the value of R,

$$S_{k_f k_i} = \frac{-i}{\hbar} \frac{1}{(2\pi)^3} \iint_{-\infty}^{t} \exp\left[-i\left(\vec{k}_f - \vec{k}_i\right)\cdot\vec{r}\right] \exp\left[\frac{(E_{kf} - E_{k_i})\, t}{\hbar}\right] V(\vec{r}) \times \exp\left[i\left(\vec{k}_f - \vec{k}_i\right)\alpha_0 A_0 \sin\left(\omega t - \gamma_k\right)\right] d^3r dt$$

If $\delta = \vec{k}_f - \vec{k}_i$ be the momentum transfer, then

$$S_{k_f k_i} = \frac{-i}{\hbar} \hat{V}(\Delta) \int_{-\infty}^{t} e^{i(\Delta,\vec{\alpha}_0) A_0 \sin(\omega t - \gamma_k)} e^{i\left(E_{kf} - E_{k_i}\right)^t} \hbar dt$$

where

$$\hat{V}(\Delta) = \frac{1}{(2\pi)^3} \int e^{-i\Delta\cdot\vec{r}} V(\vec{r}) d^3 r$$

Since $V(\vec{r})$ is independent of time (t), we can seperate time and space integration so that $\hat{V}(\delta)$ can be taken outside the time integration. We know that the generating function of the Bessel Polynomial is [12]

$$e^{ix\sin\phi} = \sum_{-\infty}^{\infty} J_n(x) e^{ni\phi}$$

with x = $\Delta.\alpha_0\ D_0$ and $\phi = \omega t$, we get

$$e^{i\Delta\cdot\alpha_0 A_0 \sin\omega t} = \sum_{l=-\infty}^{\infty} J_l\left(\Delta . D_0 \alpha_0\right) e^{il\omega t}$$

So, the S-matrix element becomes

$$\begin{aligned} S_{k_f k_i} &= \frac{-i}{\hbar} \hat{V}(\Delta) \int_{-\infty}^{t} \sum_{l=-\infty}^{\infty} J_l\left(\Delta . D_0 \alpha_0\right) e^{il\omega t} e^{i\left(E_{k_f} - E_{k_i}\right)\frac{t}{\hbar}} e^{i\gamma_k l} dt \\ &= \frac{-i}{\hbar} \int_{-\infty}^{t} T^l_{kfk_i} e^{i\left(E_{k_f} - E_{k_i} + l\hbar\omega\right)\hbar} dt \end{aligned} \tag{4}$$

where

$$T^l_{k_f k_i} = \hat{V}(\Delta) \sum_l J_l\left(\Delta . D_0 \alpha_0\right) e^{il\gamma_k}$$

This is the transition matrix from the momentum state k_i to k_f. Here, $T^l_{k_f k_i}$ is time independent, so it can be taken outside from the time integration. Thus,

$$S_{k_f k_i} = \frac{-i}{\hbar} T^l_{kfk_i} \int_{-\infty}^{t} e^{i\left(E_{k_f} - E_{k_i} + l\hbar\omega\right)\frac{t}{\hbar}} dt \tag{5}$$

Calculation of transition matrix and differential cross-section

The relation for the differential cross-section of electron with transfer of l photon is

$$\frac{d\sigma}{d\Omega} = \frac{m^2}{(2\pi)^2\hbar^4}\frac{k_f}{k_i}\left|T^l_{k_f k_i}\right|^2 \tag{6}$$

where

$$\left|T^l_{k_f k_i}\right|^2 = \sum_l J_l^2\left(\Delta.D_0\alpha_0\right)|\hat{V}(\Delta)|^2 \tag{7}$$

and

$$\hat{V}(\Delta) = \frac{1}{(2\pi)^3}\int e^{-i\Delta\cdot\vec{r}}V(\vec{r})d^3r \tag{8}$$

For $l = 0$ i.e., when there is no photon transfer during scattering,

$$\frac{d\sigma}{d\Omega} = \frac{m^2}{(2\pi)^2\hbar^4}\sum_l J_l^2\left(\Delta.D_0\alpha_0\right)|\widehat{V}(\Delta)|^2 \tag{9}$$

and

$$\left(\frac{d\sigma}{d\Omega}\right)^{\text{free-free}} = \left(\frac{d\sigma}{d\Omega}\right)^{\text{field free}}\sum_l J_l^2\left(\Delta.D_0\alpha_0\right) \tag{10}$$

Using the sum rule

$$\sum_l J_l^2\left(\Delta.D_0\alpha_0\right) = 1 \tag{11}$$

we get

$$\left(\frac{d\sigma}{d\Omega}\right)^{\text{free-free}} = \left(\frac{d\sigma}{d\Omega}\right)^{\text{field free}} \tag{12}$$

Thus, in this limit, free free cross-section is equal to the cross-section in the absence of the laser field. Here,

$$\left|T^l_{k_f k_i}\right|^2 = \sum_l J_l^2\left(\Delta.D_0\alpha_0\right)|\hat{V}(\Delta)|^2$$

For spherically symmetric potential, $V(\vec{r})$ = V(r). Therefore,

$$\hat{V}(\Delta) = -\frac{1}{2\pi^2}\int_0^\infty \frac{\sin(\Delta r)}{\Delta}V(r)dr \tag{13}$$

If we choose $V(\vec{r})$ as polarized potential, i.e.,

$$V(r) = -\frac{\alpha_p}{2\left(r^2+d^2\right)^2}$$

then the Fourier transform of the polarized potential is given by

$$\hat{V}(\Delta) = \frac{\alpha_p}{16\pi d} e^{(-\Delta d)}$$

So that,

$$|\widehat{V}(\Delta)|^2 = \left| \frac{\alpha_p}{16\pi d} e^{(-\Delta d)} \right|^2 = \frac{\alpha_p^2}{256\pi^2 d^2} \left[1 - \frac{2\Delta d}{1!} + \frac{(2\Delta d)^2}{2!} - \cdots \right]$$

The higher order terms can be neglected for small momentum transfer. To calculate $\sum_l J_l(\Delta.D_0.\alpha_0)$ all we have to do is to replace x by $\Delta.D_0.\alpha_0$ in expression of Bessel function under l=1 that corresponds to stimulated Bremsstrahlung (one photon emission) at low frequency we get [13]

$$J_l \left(\Delta.D_0 \alpha_0 \right) = \frac{\Delta D_0 \alpha_0}{2}$$

and

$$\left| T^l_{k_f k_i} \right|^2 = \sum_l J_l^2 \left(\Delta.D_0 \alpha_0 \right) |\hat{V}(\Delta)|^2$$

$$= \frac{\Delta^2 D_0^2 \alpha_0^2}{4} \left(\frac{\alpha_p^2}{256\pi^2 d^2} - \frac{2\alpha_p^2 \Delta}{256\pi^2 d} + \frac{\alpha_p^2}{256\pi^2 d^2} \frac{(2\Delta d)^2}{2} \right)$$

Here, the higher order terms of the momentum transfer can be neglected. Therefore

$$\left| T^l_{k_f k_i} \right|^2 \approx \frac{\alpha_0^2 D_0^2 \alpha_p^2}{1024\pi^2 d^2} \Delta^2$$

and

$$\frac{d\sigma}{d\Omega} = \frac{m^2}{(2\pi)^2 \hbar^4} \frac{k_f}{k_i} \frac{\alpha_0^2 D_0^2 \alpha_p^2}{1024\pi^2 d^2} \Delta^2 \tag{14}$$

Substituting for $\Delta^2 = k_i^2 \left[\left(1 - \frac{l\hbar\omega}{E_{k_i}} \right) - 2 \left(1 - \frac{t\hbar\omega}{E_{k_i}} \right)^{\frac{1}{2}} \cos\theta + 1 \right]$

$$\frac{d\sigma}{d\Omega} = C \left(1 - \frac{l\hbar\omega}{E_{k_i}} \right)^{\frac{1}{2}} E_0^2 E_{k_i} \lambda^4 \left[\left(1 - \frac{l\hbar\omega}{E_{k_i}} \right) - 2 \left(1 - \frac{l\hbar\omega}{E_{k_i}} \right)^{\frac{1}{2}} \cos\theta + 1 \right] \tag{15}$$

where

$$C = \frac{me^2 \alpha_p^2 D_0^2}{32768\pi^8 \hbar^6 d^2 c^4} \tag{16}$$

is a constant. Here,l=1 corresponds to stimulated Bremsstrahlung (one photon emission) and l=-1 corresponds to inverse Bremsstrahlung (one photon absorption) in the presence of polarized potential $V(r)$. The various quantities in Equation (16) are

$$D_0 = (\cos^2\theta + \sin^2\theta\tan^2\tfrac{\eta}{2})^{\frac{1}{2}}$$

m =mass of the electron, k_i = initial momentum vector of the electron, E_{k_i} = initial kinetic energy of the incident electron, $\hbar\omega$ = photon energy of the laser, l = no. of the photon transfer during interaction, θ = scattering angle,Δ = momentum transfer, E_0 = amplitude of the electric field of the laser

3. Results and Discussion

In the present paper work, we have also studied the elastic scattering of an electron-atom interaction by absorbing photons from the elliptical polarized laser field. We have considered hydrogen atom and the effect of polarized potential in scattering is studied by considering high electron energy ($\sim$ 3000 eV) and laser field of moderate intensities i.e. $E_0 = 10^7$ V/cm and frequency,$f = 3.5 \times 10^{15}$ Hz, photon energy $\hbar\omega = 0.117$ eV and I = 6×10^{36} W/cm^2.

We have calculated the differential scattering cross-section in the case of inverse Bremsstrahlung as

$$\frac{d\sigma}{d\Omega} = \frac{m^2\alpha_p^2 D_0^2}{4096\pi^4\hbar^4 d^2}\left(1+\frac{\hbar\omega}{E_{k_i}}\right)^{\frac{1}{2}}\frac{e^2E_0^2}{m^2\omega^4}k_i^2\left[\left(1+\frac{\hbar\omega}{E_{k_i}}\right) - 2\left(1+\frac{\hbar\omega}{E_{k_i}}\right)^{\frac{1}{2}}\cos\theta + 1\right] \tag{17}$$

in the presence of polarized potential V(r) where

$D_0 = (\cos^2\theta + \sin^2\theta\tan^2\frac{\eta}{2})^{\frac{1}{2}}$.

Variation of differential cross-section against kinetic energy of electron

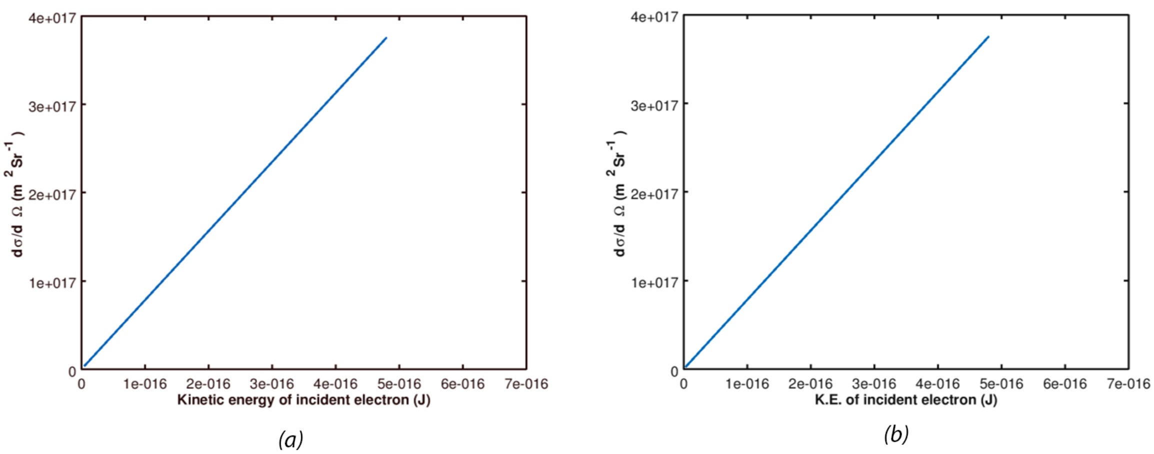

Figure 1. Variation of $d\sigma/d\Omega$ with K.E. of the incident electron at the polarizing angle (η). (a) $\pi/4$, (b) $\pi/8$

From Fig. 1(a), we see that $d\sigma/d\Omega$ increases as the K.E. of the incident electron increases. From Fig. 1(b), we see that there is no effect of changing the value of η on the variation of $d\sigma/d\Omega$ with K.E.

Variation of differential cross-section area with polarizing angle (η)

We observed that $\sigma/d\Omega$ in elliptical polarization in the high-energy region depends upon the laser intensity and the incident electron energy for a linearly polarized field. For the simplest geometry, the ellipticity of laser field affects the angular distribution of scattered electron as compared to the case of linear polarization and circular polarization because it destroys the axial symmetry of the angular distribution that exists for η=0 with respects to the direction of polarizing vector. From Fig. 2, for η=0, $d\sigma/d\Omega$ is minimum and equal to 0.56×10^{-11} m^2/Sr.

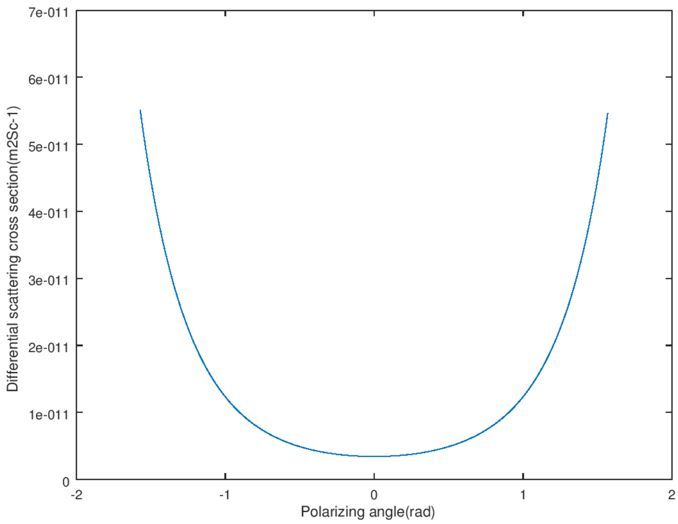

Figure 2. Variation of $d\sigma/d\Omega$ with polarizing angle (η)

Again, at η=±1 , $d\sigma/d\Omega$ increases asymptotically and the maximum value of $d\sigma/d\Omega$ is equal to 0.56×10^{-11} m^2/Sr. The differential cross-section varies with polarizing angle like U-shape about η=0 and at η=0, it has minimum value and increases substantially for $\eta = \pm |\eta|$.

4. Conclusion

It is generally observed that when electrons are scattered from the atom in the presence of laser field, a new effect is observed which are not accessible in ordinary electron atom scattering. The collisions have the basic peculiarities of being processes in which, three sub systems are present. First, the electron, second the target and the third radiation field. The last one provided energy and momentum and is characterized by the polarization of the electric field, which introduces in collision process a new physical axis. In the present study we concluded that the differential scattering cross-section of an electron depends upon kinetic energy of the incident electron, i.e. higher the kinetic energy, differential scattering will be higher, but independent of polarizing angle. We observed that differential cross-section in elliptical polarization in highenergy region depends upon the laser intensity. The differential scattering cross-section obtained in our results for elliptical polarization is greater than the result obtained by Flegel et al. generally differential cross-section for elliptical polarization is greater than those of linear and circular polarization.

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