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Differential Cross Section With Volkov-Thermal Wave Function in Coulomb Potential

S. H. Dhobi[1*], S. P. Gupta[2], K. Yadav[2,3], J. J. Nakarmi[1,3], A. K. Jha[4]

[1]Central Department of Physics, Tribhuvan University, Kirtipur 44618, Nepal
[2]Department of Physics, Patan Multiple Campus, Tribhuvan University, Lalitpur 44700, Nepal
[3]Innovative Ghar Nepal, Lalitpur 44700, Nepal
[4]Department of Mechanical and Advance Engineering, Institute of Engineering, Pulchowk Campus, Tribhuvan University, Lalitpur 44700, Nepal

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ABSTRACT

Laser-assisted thermal electron-hydrogen atom elastic scattering was studied in the first-born approximation. The initial and final states of the projectile electron are described by the modified Volkov wavefunctions known as Volkov-Thermal wavefunctions. The laser-assisted thermal electron with energy ranges from 0.511 MeV to 4 MeV was considered to study the differential cross section (DCS) at azimuthal angles 30° and 14.7°, and laser-assisted field photon energy 1 eV to 3 eV are very weak at room temperature is around the room temperature 280 K to 300 K. The destructive interference was observed when a thermal electron absorbed a single photon from the laser field but no interference was found when a thermal electron emitted an electron to the laser field at a scattering angle $\theta = 5°$. The DCS with e_T scattering was found to be greater than a nonthermal electron in presence of laser field with scattering angle and incidence energy of the electron.

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INTRODUCTION

All types of matter exhibit the many distinct ways that electrons interact with one another, and this interaction yields a wide range of information on many fundamental scientific concepts. Electron correlations, polarization processes of electron densities in excited atomic states, electron-electron Moller scattering, plasma screening in dense high-temperature plasmas to Auger electron analysis of materials, and electron transport in low-dimensional quantum materials at low energies are a few examples. The characteristics of condensed matter rely heavily on scattering techniques, as do almost all discoveries pertaining to nuclei and elementary particles.

Theoretical work has been focused on the characterization of fundamental electromagnetic (EM) phenomena in the environment of an intense field as a result of the quick development of high-power lasers [1-3]. The electromagnetic actions of free-charged particles in a such setting are of special interest. In the period 1975–1978, Mitter, Karapetyan, and Fedorov predicted two distinct types of corrections with very different physical origins [4]. The primary phenomena present in external field issues are intensity-dependent resonances and intensity-dependent shifts. In 1965, Bunkin and Fedorov studied resonance and shifting, which are nonlinear bremsstrahlung events, while in 1964, Brown and Kibble investigated nonlinear Compton scattering while ignoring the heat influence on scattering [5].

An exceptional source of monochromatic and coherent electromagnetic spectrum was offered by early laser devices. The fundamental studies of electron scattering phenomena (Thomson, Compton, Mott, and Moller scattering) in the presence of electromagnetic fields therefore experienced a resurgence in the 1960s. Later, it became important to categorize scattering occurrences as linearly (simultaneous absorbance of single photons) or non-linear (simultaneous absorbance of several photons) phenomena due to the high light intensities produced by lasers. Theoretical assessments created

*Corresponding author.
E-mail address: saddam@ran.edu.np
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between 1960 and 2000 took long-lasting laser pulses into account. However, it is now possible to obtain extremely powerful laser pulses with extremely little duration because of the development of the chirped-pulse amplification (CPA) technique by Strickland, Mourou, and Ashkin, who shared the 2018 Nobel Prize in physics [6,7]. But, since the development of scattering 1960s to date, no model has been developed for scattering in the presence of temperature that is thermal scattering in the presence of a laser field.

Dzhumagulova et al. studied the DCS of e-H scattering with energy and scattering angle using Buckingham-type potential in semi-classical dense plasma and found the nature of DCS shifter (down peak) towards higher energy and angle [8]. Although it is commonly known that electrons can act as point particles and have a limitless range of Coulomb potentials, additional research including the accurate measurements of their mutual scattering was still required. Additionally, when particle scattering cannot be directly seen, a first Born approximation (FBA) is typically used as a good beginning guide to the interaction [9].

A mathematical model for DCS with a Coulomb potential, an elliptically polarized beam, and single photon absorption is developed by Yadav et al. in 2021. With an elliptically polarized beam, the observation demonstrates that DCS increased with wavelengths and decreased with electron energy. Depending on 1.5 eV laser photons, 1014 W cm-2 laser field intensity, 1.56 radian angle polarization, and electron energies ranging from 0 to 600 eV, the observation determined DCS to be between 10-19 and 10-20 m2 [10]. In order to explore the DCS in the environment of a weak laser field (visible and UV), Dhobi et al. 2022 developed a theoretical model. They discovered that DCS initially drops to a low value before achieving its maximum level when the target emits the energy. In addition, the DCS also increases with the scattering angle [11].

The recent progress in experimental and theoretical studies of laser-assisted electron scattering (LAES) shows different new concepts that were developed, such as optical gating and optical streaking for the LAES processes which can be realized by LAES experiments using ultrashort intense laser pulses, were discussed. However, no thermal effect to any scattering was discussed [12-15]. The strong-field ionization was treated briefly with various theoretical methods to describe strong field ionization beyond the dipole approximation [16]. More laser sources with high repetition rates are being developed, allowing for more compelling experiments [17].

In the strong-field ionization of atomic and molecular systems, the photoelectron is exposed to the long-range Coulomb force which is neglected in the standard theories based on the strong-field approximation (SFA). The approximation is illustrated with numerical examples of strong-field ionization of the hydrogen atom exposed to linearly and circularly polarized laser pulses. The spectra obtained are slightly flattening in comparison with the SFA spectra and this effect is stronger for shorter laser wavelengths [18].

The interaction of atoms and molecules, when subjected to high-intensity laser fields, has recently become an area of significant interest. Such interactions encompass the study of fundamental patterns in both electronic and vibrational processes, as well as several other phenomena, including frustrated double ionization, excitation of Rydberg states, correlated electron emission in multiphoton double ionization, and quantum interference and imaging [19-21].

The dipole approximation utilized disregards the spatial variation of the laser field and thus does not consider the Lorentz force acting on the ionizing electrons due to the magnetic component of the laser field. This assumption is valid in short-wavelength and low-intensity, typically below 800 nm and below 1013 W/cm2, respectively, where the Lorentz force is insignificant. However, in instances of intense laser fields with long wavelengths, the Lorentz force can substantially affect the observed spectra, and momentum distributions, as previously demonstrated [22, 23].

When an electron scatters, its energy can either match that of the incident particle (elastic resonant scattering) or be different from it (inelastic resonant scattering). Even without an excitation ion or atom, an incoming electron can scatter. In this scenario, the electrons as well as the partially screened nucleus of an ion/atom scatter each other by Coulomb potential. The amplitude again for elastic resonance scattering was coherently increased by the scattering amplitude. Franck and Hertz carried out the experimental investigation of the scattering of electrons by an atom, and Massey and Mohr completed the early theoretical investigations [9]. The investigation of electron-atom interactions in the presence of the laser beam has attracted a lot of research attention during the past few decades. This is due to its significance in fields that are applied, like astrophysics, laser and plasma physics, as well as the basic theory of atomic collisions. Because it enables the absorption or emissions of photons during the scattering processes by atoms in the presence of laser-free electrons, laser-assisted scattering is essential.

Due to several applications in scientific fields as well as in the field of nuclear collisions, the investigation of electron-atom collisions in the context of a laser pulse field has attracted a lot of interest. The theoretical study of electron-atom collisions in the context of a laser beam becomes quite difficult when compared to the issues with field-free electron-atom scattering. Certain novel characteristics, including laser frequency, intensity, polarization, and influencing collision interactions, are introduced by the research of collision in the laser field. The goal of this research and the study gap in the literature were studied by adding temperature as a new parameter in place of complexity to examine the DCS inside a thermal conditions.

METHODOLOGY

In the field of theoretical physics known as scattering theory, interactions between waves and particles are studied at vast distances and remote epochs, as opposed to the usual time and size scale of the systems being probed. Because of this, scattering theory is really the best and, in so many cases, the only approach for studying a wide range of systems, such as the micro- or macrocosm. Numerous textbooks provide a general examination of quantum and classical scattering processes. From both theoretical and experimental perspectives, scattering processes were crucial to the growth of science. A single atomic electron system inside a light field with the vector potential $\vec{A}(\vec{r},t)$ and an electric field with the scalar potential (φ) can be modeled by the following Hamiltonian, regardless of gauge, in order to examine DCS in thermal scattering, see Eq. (1).

$$H = \frac{\vec{p}^2}{2} - \frac{1}{2}\left(\vec{A}(\vec{r},t).\vec{p} + \vec{p}.\vec{A}(\vec{r},t)\right) + \frac{\vec{A}^2(\vec{r},t)}{2} - \varphi + \frac{3}{2}k_B T \quad (1)$$

Here p is momentum and corresponding vector potential is described as Eq. (2).

$$\vec{A}(\vec{r},t) = a\, exp\left(i(\vec{k}.\vec{r} - \omega t)\right) = a\, exp(i\vec{k}.\vec{r})\, exp(-i\omega t) \quad (2)$$

Here $a = \sqrt{\frac{8\pi\mathcal{N}_\omega\hbar}{\omega\mathcal{V}}}$ = vector potential amplitude, $\mathcal{V}$ = volume, N_ω = number of photons, $\vec{k}\cdot\vec{r} - \omega t \approx -\omega t$. For a hydrogen-like atom with potential is $\varphi = \frac{Z}{r}$, time-dependent Schrödinger equation (TDSE) describing [24,25] as follows Eq. (3).

$$i\hbar\frac{\partial}{\partial t}X(\vec{r},t) = HX(\vec{r},t) \quad (3)$$

Atomic physics textbooks, like the one written by Bransden and Joachain, contain the answer to Eq. 3 [26]. The wave function that resolves the solution to Eq. 3 and the TDSE is a modified Volkov wave function, see Eqs. (4,5).

$$X_{efT}(\mathbf{r},t) = \frac{1}{(2\pi)^{\frac{3}{2}}}\exp\left\{\frac{-i}{\hbar}\left(E_{efT} + \frac{e^2a^2}{4m}\right)t + i\frac{\boldsymbol{p_{fT}}}{\hbar}.\left(\mathbf{r} + \frac{ea}{m\omega}\sin(\omega t)\right) - i\frac{e^2a^2}{8m\hbar\omega}\sin(2\omega t)\right\} - k_e\nabla T_{efT}\exp(i\omega_{efT}t) \quad (4)$$

$$X_{eiT}(\mathbf{r},t) = \frac{1}{(2\pi)^{\frac{3}{2}}}\exp\left\{\frac{-i}{\hbar}\left(E_{eiT} + \frac{e^2a^2}{4m}\right)t + i\frac{\boldsymbol{p_{eiT}}}{\hbar}.\left(\mathbf{r} + \frac{ea}{m\omega}\sin(\omega t)\right) - i\frac{e^2a^2}{8m\hbar\omega}\sin(2\omega t)\right\} - k_e\nabla T_{eiT}\exp(i\omega_{eiT}t) \quad (5)$$

Here $-k_e\nabla T_e\exp(i\omega t)$ = thermal wave function, ke =electron thermal conductivity, ∇T_e = change in temperature of electron [27]. The DCS with transition and momentum is related as Eq. (6).

$$\frac{d\sigma}{d\Omega} = \frac{p_{efT}}{p_{eiT}}\left(\frac{m(2\pi)^3}{(2\pi)\hbar^2}\right)^2 |T_{efiT}|^2 \quad (6)$$

Where T is matrix for free-free transitions defined [28], and related as Eq. (7).

$$S_{efiT} = \delta_{efiT} - 2\pi i\delta(E_{efT} - E_{eiT})T_{efiT} \quad (7)$$

Here S matrix is defined as Eq. (8).

$$S_{efiT} = \delta_{efiT} - \frac{i}{\hbar}\int_{-\infty}^{+\infty}\langle X_{efT}(\boldsymbol{r},t')|V(\boldsymbol{r})|X_{eiT}(\boldsymbol{r},t')\rangle\, dt' \quad (8)$$

Here, $X(\boldsymbol{r},t)$ denotes the wave equation for an electrons couple with an external electromagnetic wave, and $X(\boldsymbol{r},t)$ denotes the wave function for an electron linked to an external electromagnetic field while also being in the existence of a scattering potential V(r). Solving Eqs. 4 and 5, using Eq. 8 (Jacobi-Anger Expansion: cylindrical waves, Bessel function of the first kind, 1st Born Approximation scattering amplitude, Inverse Fourier transform of the δ function) we get the following, see Eq. (9).

$$S_{efiT} = \delta_{efiT} - 2\pi i \delta\left(E_{efT} - E_{eiT} \pm n\hbar\omega\right) \left[-\frac{1}{(2\pi)^3\hbar}\left\{\frac{2\pi\hbar^2}{m}\sum_{n=-\infty}^{+\infty} J_n\left(-\frac{\mathrm{ie}}{\hbar\mathrm{m}\omega}\boldsymbol{Q}.\boldsymbol{a}\right) f_{Born}^1 - \mathrm{k_e}\left(\nabla\mathrm{T}_{eiT} + \nabla\mathrm{T}_{efT}\right)\frac{\delta(\omega_{\mathrm{efT}} - \omega_{\mathrm{eiT}})}{\delta\left(E_{efT} - E_{eiT} \pm n\hbar\omega\right)}\right\}\right] \tag{9}$$

Comparing Eq. 9 and Eq. 7, we get the Eq. (10).

$$T_{efiT} = \left[-\frac{1}{(2\pi)^3\hbar}\left\{\frac{2\pi\hbar^2}{m}\sum_{n=-\infty}^{+\infty} J_n\left(-\frac{\mathrm{ie}}{\hbar\mathrm{m}\omega}\boldsymbol{Q}.\boldsymbol{a}\right) f_{Born}^1 - \mathrm{k_e}\left(\nabla\mathrm{T}_{eiT} + \nabla\mathrm{T}_{efT}\right)\frac{\delta(\omega_{\mathrm{efT}} - \omega_{\mathrm{eiT}})}{\delta\left(E_{efT} - E_{eiT} + n\hbar\omega\right)}\right\}\right] \tag{10}$$

Now from Eq. 10 and Eq. 6, we get the Eq. (11).

$$\frac{d\sigma}{d\Omega} = \frac{p_{efT}}{p_{eiT}}\left|\left\{J_n\left(-\frac{ie}{\hbar m\omega}\boldsymbol{Q}.\boldsymbol{a}\right) f_{Born}^1 - \frac{m}{2\pi\hbar^2}k_e\left(\nabla\mathrm{T}_{eiT} + \nabla\mathrm{T}_{efT}\right)\frac{\delta(\omega_{efT}-\omega_{eiT})}{\delta(E_{efT}-E_{eiT}+n\hbar\omega)}\right\}\right|^2 \tag{11}$$

The first term of Eq. 11 is the same as obtained by Kim in 2022 in his PhD work [29] while the second term is new and has not obtained at the date because authors exclude the thermal scattering environment of electron in laser field.

Using first order Bessel function and born first approximation for coulomb potential and substituting the value of $\boldsymbol{Q}$ and $\left(\frac{p_{efT}}{p_{eiT}}\right)$ we get the following from Eq. (12).

$$\frac{d\sigma}{d\Omega} = \left(1 \pm \frac{n\hbar\omega}{E_{eiT}}\right)^{\frac{1}{2}}\left\{\frac{e^3a^2\cos^2\xi}{2m\hbar^6\omega^2E_{eiT}\left[\left(1\pm\frac{n\hbar\omega}{E_{eiT}}\right)-2\left(1\pm\frac{n\hbar\omega}{E_{eiT}}\right)^{\frac{1}{2}}cos\theta+1\right]} + \left|\frac{m}{2\pi\hbar^2}k_e\left(\nabla\mathrm{T}_{eiT} + \nabla\mathrm{T}_{efT}\right)\frac{\delta(\omega_{efT}-\omega_{eiT})}{\delta(E_{fT}-E_{iT}\pm n\hbar\omega)}\right|^2\right\} \tag{12}$$

Using relation $\delta\left(E_{fT} - E_{iT} \pm n\hbar\omega\right) = \delta(E_{fT} - E_{iT})\delta(E_{fT} \pm n\hbar\omega)$ [30] then Eq. 12 become the following, see Eq. (13).

$$\frac{d\sigma}{d\Omega} = \left(1 \pm \frac{n\hbar\omega}{E_{eiT}}\right)^{\frac{1}{2}}\left\{\frac{e^3a^2\cos^2\xi}{2m\hbar^6\omega^2E_{eiT}\left[\left(1\pm\frac{n\hbar\omega}{E_{eiT}}\right)-2\left(1\pm\frac{n\hbar\omega}{E_{eiT}}\right)^{\frac{1}{2}}cos\theta+1\right]} + \left|\frac{m}{2\pi\hbar^2}k_e\left(\nabla\mathrm{T}_{eiT} + \nabla\mathrm{T}_{efT}\right)\frac{1}{\delta(E_{efT}\pm n\hbar\omega)}\right|^2\right\} \tag{13}$$

Since the scattering is elastic, therefore Eq. 13 become the following, see Eq. (14).

$$\frac{d\sigma}{d\Omega} = \left(1 \pm \frac{n\hbar\omega}{E_{eiT}}\right)^{\frac{1}{2}}\left\{\frac{e^3a^2\cos^2\xi}{2m\hbar^6\omega^2E_{eiT}\left[\left(1\pm\frac{n\hbar\omega}{E_{eiT}}\right)-2\left(1\pm\frac{n\hbar\omega}{E_{eiT}}\right)^{\frac{1}{2}}cos\theta+1\right]} + \left|\frac{m}{2\pi\hbar^2}k_e\left(\nabla\mathrm{T}_{eiT} + \nabla\mathrm{T}_{efT}\right)\right|^2\right\} \tag{14}$$

Quantum scattering theory has challenges and advances, because this theory deal with DCS with huge applications. Different authors study single, double, and triple DCS between electron and hydrogen in laser, but they neglect the thermal effect which is a drawback. In this work, the authors include thermal effect of electron and study the effect of DCS in presence of laser field. To study the DCS, the authors used scattering angle 5°, azimuthal angle (laser field and thermal electron) 14.7° and 30°, laser-assisted photon energy 1 eV, 2 eV, and 3 eV, photons concentration (intensity) of 106 photon per mm3, and energy of thermal electron ranges from 0.511 MeV to 4 MeV. The temperature of thermal electron is considered at 280 K before scattering and 300 K after scattering at electron thermal conductivity of 20 W m-1 K-1. The model is advanced among the existence laser assist electron scattering in Coulomb potential because existing laser scattering neglected temperature, while in present work temperature is considered to electron, though not for target. The DCS in this work is taken in natural log term.

RESULTS AND DISCUSSION

DCS laser-assisted thermal electron

Meltzer et al. calculated the DCS using R-matrix and found DCS decrease with increasing the incidence electron of energy. In this work, the authors calculate DCS for laser assisted thermal electron using S and T matrix and found the same nature as obtained by Meltzer et al as Fig. 1 if observed the downward peak, peak was found increase more downward. This shows that with increasing the energy of incidence electron the DCS goes decrease and hence one can select the best region of scattering for different application [31].

The destructive interference took place when thermal electron of 1 MeV, 2 MeV, and 3 MeV assisted by 1 eV, 2 eV, and 3 eV laser photon at azimuthal angle 14.7°, 30° and scattering angle 5°. These angles were choosen because at the points, interference between two wavefunction is clearly observed during computing the equation than other angles. The destructive interference of two wavefunction photon and thermal electron is increased with the energy of thermal electron. The destructive interference caused the decrease in DCS of scattering as shown in Fig. 1, generalized with downward peaks. The shifting of DCS of e-H scattering with energy was also obtained Cionga et al. in 2001 at lower frequency of photon at $\theta = 5^o$ for dressed state, but they neglect the thermal effect. Therefore the DCS found by Cionga et al. is smaller than in present work [32].

Bunkin and Fedorov 1965 studied resonance and shifting phenomena in nonlinear bremsstrahlung. Brown and Kibble 1964 also studied resonance and shifting of DCS for nonlinear Compton scattering in the presence of an intense external field. While studying the DCS they neglect the thermal effect in scattering. The downward peak is due to destructive interference where energy get loss of laser assisted thermal electron-H scattering in coulomb field.

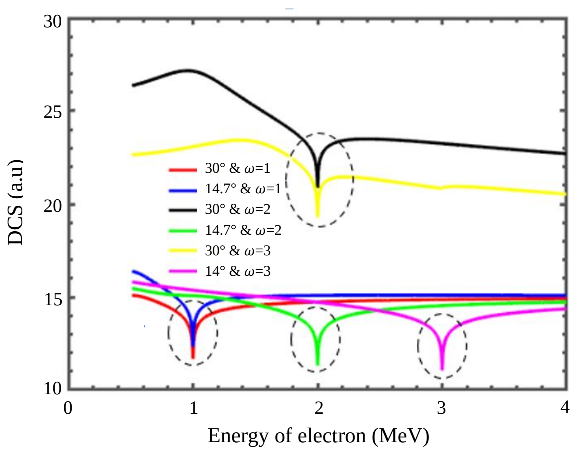

Fig. 1. DCS with laser assisted thermal electron energy absorption of single photon at $\theta = 5^o$.

The DCS with laser assisted e-H scattering in literature was found to be less then DCS with laser assisted thermal electron -H scattering in present work. The DCS of laser assisted photon energy 2 eV and 3 eV at higher azimuthal angle 30° was found to be higher. The down peak region (black circle) is like well in which the thermal electron and laser assisted photons goes destructive interference, which in the same region, no interference took place and thermal electron behaved similar to laser assisted e-H scattering. The destructive region is the region where the photon absorption take place in form of laser field. Before the destructive interference formed, the thermal electron is assisted by laser field photon. In destructive region, the photon is loss or absorbed by electron, and after that the electron is assisted by laser field photons.

Figure 2 represent the DCS with thermal electron energy in laser field. The DCS is decreased in presence of laser with thermal energy of electron, with emission of single photon by electron to laser field. During the emission of photon destructive interference was not observed at any considered laser field photons (1 eV, 2 eV, and 3 eV) but resonance take place which caused slight increase in DCS as discussed by Bunkin and Fedorov [5]. In this case the emitted and laser field photon both assist electron, the DCS with emission of photon by electron was found lower than absorption of photon from laser field to electron. In addition, there is no formation of interference between photons and thermal electron during the emission of photon by thermal electron.

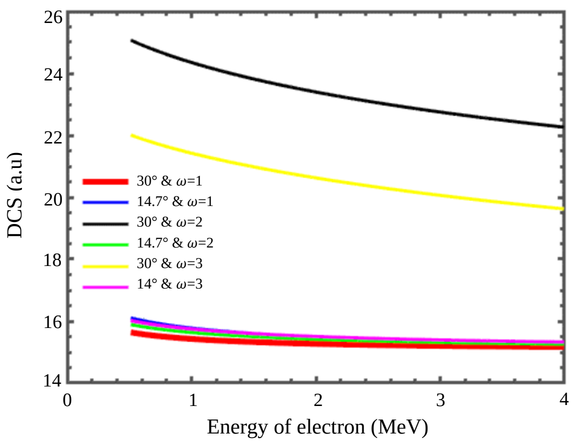

Fig. 2. DCS with laser assisted thermal electron energy emission of single photon at $\theta = 5^o$.

DCS laser assisted thermal electron with scattering angle

The DCS with scattering angle of laser-assisted thermal electron for absorption of single electron is shown in Fig. 3. Makhoute et al. in 2019 studied the DCS of electron-hydrogen in laser field ($\omega = 1.17$ eV) with scattering angle for absorption [33] similar to authors at $\omega = 1$, angle 30° and 14.7° of thermal electron assisted by laser field. The DCS for e-H scattering at 100 eV and 1000 eV, with the scattering angle decreasing with increasing angle from 0 to 180° as obtained by Jablonskia et al. [34], but they exclude the temperature and laser field parameters. Therefore, the DCS obtained in this work was found to be greater than DCS obtained by Jablonskia et al. DCS with scattering angle is found symmetrical. It means that the absorption of photon took place at two angles of incidence on target. The absorption of one photon caused an increase of the DCS, while the other caused a decreasie of DCS as shown in Fig. 3. Increasing the decreased DCS depends upon the scattering angle and the azimuthal angle. The interference was obtained at scattering angle at around zero, around the peak the phase angle of two wavefunction shift towards interference. However, for higher energy laser-assisted photon of thermal electron, no interference of thermal electron and photon wave function was found when thermal electron is assisted by 2 eV and 3 eV laser field photons. The destructive interference causes the symmetry of DCS with scattering.

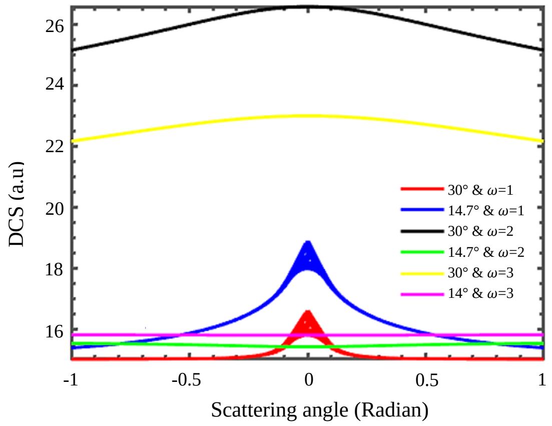

Fig. 3. DCS with scattering angle absorption of photon from laser assisted thermal electron.

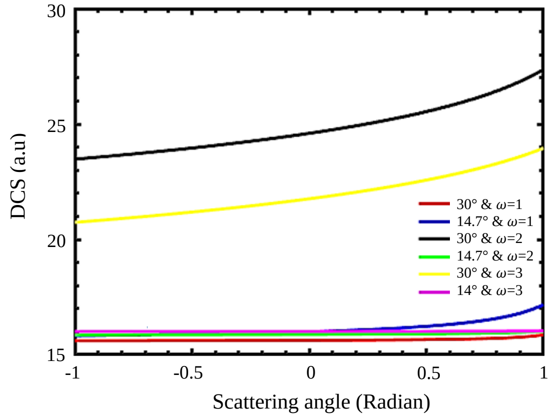

Fig. 4. DCS with scattering angle emission of single photon to laser assisted thermal electron.

Li et al. also obtained DCS for electron-atomic-hydrogen free-free transition at impact energy E_i = 50 eV, field amplitude (intensity) E_0 = 10^8 V cm^{-1}, and photon energy (field frequency) ω = 1.17 eV for one-photon absorption and emission, and has same nature of DCS as obtained in Figs. 3 and 4, respectively, in certain range of scattering angle [35].

The DCS with scattering when photon is emitted to the field by electron increases with scattering, and the symmetry nature was not obtained as absorption case. This is because the emission and assisted photon guide the thermal electron without any interference (with resonance as discussed by Bunkin and Fedorov) between them. Thus, the peaks were not observed in emission case of photon by electron and the DCS with scattering angle at considered azimuthal angle. Laser photon energy was found to be greater when photon is absorbed by thermal electron from laser field than emitted to laser field by electron.

The DCS of thermal electron with temperature before and after scattering was found in 15.5 a.u. to 16 a.u. when photon emitted by electron, and 15 a.u. to 16.5 a.u. when photon is absorbed by electron. The difference is because of resonance take place in emission while interference take palce in absorption.

CONCLUSION

Volkov function was modified for thermal electron and first Born approximation was used to calculate T-matrix to study the DCS of the thermal electron. The DCS with thermal electron is found to be greater than non-thermal in presence of laser field when compare with literature of DCS of non-thermal electron. In addition, the destruction interference between photon and thermal electron was observed when thermal electron absorbed the photon from laser field, but no interference was observed when thermal electron emit photon to laser field. The higher DCS with thermal electron held remove the difficulties on experimental of DCS than that of no thermal case.

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AUTHOR CONTRIBUTION

S. H. Dhobi: Paper Writing, Originating the Idea, Development of theory, and contributing to its development. S. P. Gupta, J. J. Nakarmi and K. Yadav: Supervised, discussion on finding and theory verification. A. K. Jha: Supervised, Proof reading and contributing on discussion.

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