Spin currents from Helium in intense-field photo-ionization

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Abstract: Spin dynamics is studied by computing spin-dependent ionization current of He in intense laser field in relativistic field theoretic method. Spin-flip and spin-asymmetry in current generation is obtained with circularly polarized light. The spin-flip is a dynamical effect of intense laser field on an ionized spinning electron. Transformation properties of the up and down spin ionization amplitudes show that the sign of spin can be controlled by a change of helicity of the laser photons from outside.

1. Introduction

Single-photo-ionization and multi-photo-ionization of hydrogen in strong-field circularly polarized laser have been investigated within the framework of Dirac theory in the past for the spin-resolved currents by two of the authors [1] F.F and S.B. In this paper we apply the same “strong field S-matrix approach” (SFA) to compute the spin-flip probabilities and up-spin (u) and down-spin (d) currents from ionization of an ensemble of He-atom subjected to intense circularly polarized laser (CPL). Our choice of He as target is because He atom is more suitable for possible experimental comparison in future. A characteristic aspect of the strong laser field is the coupling of the field with the spin degrees of freedom. In the case of ionization specific spin-information can be traced out for un-polarized target atom. An intensity and frequency-dependent asymmetry between the spin up and down currents that varies according to the direction of electron emission is found. Hopefully the rates of spin-flips in the ionization process and possibly also the spin-asymmetry from target atoms (prepared with or without spin selected initial bound state) could be measured in ‘second generation experiments’. Analysis of such experiments would require a knowledge of the spin-dependence of the ionization rates. No such spin specific ionization rate of He in intense field appeared to have been obtained so far. Explicit analytical formulae are derived for two -electron atom, and results of numerical calculations are presented. Atomic units are considered $\hbar = \mu = m = a_0 = 1$, $c = \alpha^{-1}$. 

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2. Theory

We use a straightforward relativistic generalization of SFA analogous to the non-relativistic KFR approach [2]. In time-reversed S-matrix the system is initially prepared in a state free of transition carrying field. The SFA method allows for the rigorous introduction of arbitrary temporal as well as spatial shape of the laser pulse. The pulse is relatively long but goes to zero at asymptotic time is automatically satisfied [3]. The energy of the photo-electron should be much larger than the binding energy. The photo-electron passes through laser field even after photo-ionization and the effect of atomic field is small. The leading term of S-matrix series for the transition amplitude of single ionization of He by single photon is

\[
S_{s_1-s_2 \rightarrow s_1-s_2} = \frac{\hbar}{\pi m c} \int_{-\infty}^{\infty} \left( \psi_{s_1}^{He^+}(r', t) \psi_{s_2}^{\mu}(r, t) \gamma\gamma A_{\mu} \psi_{s_1}^{He^+}(r, t') \right) dt
\]

where the initial state is a two-electron ground state wave function of He atom. Here we have made an effective ‘Active-single-electron’ (ASE) hypothesis. Accordingly we have assumed two-electron ground state wave function of He as a product wave function of two Dirac-hydrogen wave functions (correctly normalized) with an ‘effective Z’ in each case. We may choose Z-eff. for example, semi-empirically or from known non-relativistic case (or perform a relativistic variational calculation like in non-relativistic case) etc. We have, in fact, initially considered Z-eff = 27/16 (the result of (non-relativistic) simple variational calculation).

\[
\psi_{s_1} (r, t) = \psi_{s_1} (r, t) \psi_{s_2} (r', t').
\]

The final state is chosen as the product of (a) He\(^+\) wave function for one electron and (b) the relativistic Volkov wave-function for the other electron. The part (a) is a Dirac-hydrogen like wave function but with Z=2.

Dirac-hydrogen wave function can be written in a convenient form [4]

\[
\Psi_{s_1} (r, t) = N_{s_1} r^{\gamma-1} e^{-k r} \begin{pmatrix} 1 & 0 \\ i\beta^i \cos \theta & i\beta^i \sin \theta \end{pmatrix} = R_{s_1}(r)n_{i}, \phi^s_i.
\]

Where

\[
R_{s_1}(r) = N_{s_1} r^{\gamma-1} e^{-k r}, \quad n_i = (1, i\beta^i \hat{r}), \quad (r, \theta, \phi) \text{ is the spherical co-ordinate of the bound electron.}
\]

\[
\omega^\dagger = \begin{pmatrix} \chi^\dagger \\ 0 \end{pmatrix}, \quad \omega^\dagger = \begin{pmatrix} \chi^\dagger \\ 0 \end{pmatrix}
\]

up and down Pauli-spinors are \(\chi^\dagger = \begin{pmatrix} 1 \\ 0 \end{pmatrix}\), \(\chi^\dagger = \begin{pmatrix} 0 \\ 1 \end{pmatrix}\).
\[ k_b = Z_1, \] is the bound-state momentum and
\[ \beta'_1 = (1 - \gamma'_1) / Z_1 \alpha, \quad Z_1 = \frac{27}{16}, \quad (5) \]

\[ N_{ls} = (2k_b)^{(\gamma'_1+1/2)} \left( \frac{1+\gamma'_1}{8\pi\Gamma(1+2\gamma'_1)} \right)^{1/2}, \quad \gamma'_1 = \sqrt{1-(Z_1\alpha)}, \quad (6) \]

and from (2)
\[ \psi_{ls}^s (r') = R_{ls} (r') \rho'_s \omega^s \]
\[ n'_1 = (1, i\beta'_1 r') \quad (7) \]

In the final state \( \psi_p^{(s)} (\vec{r}, t) \) is the continuum state of the free electron Volkov wave-function dressed in laser field [5], with spin \( s' \) and momentum \( p(p_0, \vec{p}) \). \( k \) is the four-momentum of the laser photon. The Volkov wave-function with the spin \( s \)

\[ \psi_p^{s} (\vec{r}, t) = N_{p_0} e^{-ip+p'[u]} \left[ 1 + \frac{ekA(u)}{2k.p} \right] u_p^s \quad (8) \]

\[ u_p^s \] is the Dirac spinor and \( N_{p_0} = \sqrt{|c/p_0|} \),

\[ u_p^s = \begin{pmatrix} m_1 \chi_s \\ m_2 \sigma \cdot \vec{p} \chi_s \end{pmatrix}, \quad (9) \]

\[ m_1 = \frac{p_0 + c}{2c}, \quad m_2 = \frac{p_0 - c}{2c} \quad (10) \]

In the final state Dirac hydrogen type \( He_{ls}^+ \) wave function \( \psi_{ls}^{He^+(s)} (r', t) \) is assumed to remain unaltered as

\[ \psi_{ls}^{He^+(s)} (r', t) = N'_{ls} e^{\frac{i\sigma_{s'-1} \sigma_{s'2} r' + \sigma_{s'1} \omega r^s_z}} = R_{ls}^{He^+ (r')} \rho'_s \omega^s_z \quad (11) \]

\[ n'_2 = (1, i\beta'_2 r'), \quad k'_b = Z_2, \] is the bound-state momentum of \( He^+ \).

\[ N'_{ls} = (2k'_b)^{\gamma'_2+1/2} \left( \frac{1+\gamma'_2}{8\pi\Gamma(1+2\gamma'_2)} \right)^{1/2}, \quad \gamma'_2 = \sqrt{1-(Z_2\alpha)}, \quad (12) \]

In the general case an elliptically polarized electromagnetic field is given by the vector potential [6]
\[ A_\mu = \frac{A_0}{2c} \left[ \hat{e}(\xi)e^{i\kappa r} + \hat{e}^*(\xi)e^{-i\kappa r} \right] \]
\[ \hat{e}(\xi) = \left[ \hat{\epsilon}_x \cos \left( \frac{\xi}{2} \right) + i\hat{\epsilon}_y \sin \left( \frac{\xi}{2} \right) \right] \]  
(13)

We note that \( \xi = 0 \) for linear polarization and \( \xi = \pm \frac{\pi}{2} \) for circular polarization.

We choose the field propagation direction (z-axis) as the quantization axis, with the spin “up” state defined to be along the positive \( z \) direction.

Eventually \( \vec{p} = (p_x, p_y, p_z) \) is the momentum vector of the ionized electron with \( \theta_p, \phi_p \) as its spherical angles and photon-momentum vector \( \vec{k} = (0,0,k) \). The photon polarization vectors of CPL and LPL respectively are given below.

\[ \hat{e}(\pi/2) = \frac{1}{\sqrt{2}}(\hat{\epsilon}_x, i\hat{\epsilon}_y, 0) = \frac{1}{\sqrt{2}}(1,i,0) \]
\[ \hat{e}(0) = (1,0,0) \]  
(14)

The electromagnetic field vector for circular polarization

\[ \vec{A}_c = \frac{A_0}{c} \left[ \hat{\epsilon}_x(\xi)\cos(\omega t - \vec{k}\vec{r}) - \hat{\epsilon}_y(\xi)\sin(\omega t - \vec{k}\vec{r}) \right] \]

\[ = \frac{A_0}{2c} \left[ \hat{e}(\xi)e^{i\vec{k}\vec{r}} + \hat{e}^*(\xi)e^{-i\vec{k}\vec{r}} \right] \]  
(15)

For linear polarization electromagnetic field vector is

\[ \vec{A}_l = \frac{A_0}{2c} \left[ \hat{e}(0)e^{i\vec{k}\vec{r}} + \hat{e}^*(0)e^{-i\vec{k}\vec{r}} \right] \]

The transition amplitude for single ionization is given by [7]
\[ S_{s_1 s_2 \rightarrow s'_1 s'_2} = -2\pi i \delta(2\varepsilon_b - \varepsilon'_b + \varepsilon_{\text{kin}} - \omega)T_{s_1 s_2 \rightarrow s'_1 s'_2} \] (16)

and energy conservation gives

\[ \omega = 2\varepsilon_b - \varepsilon'_b + \varepsilon_{\text{kin}} \]

where \( \varepsilon_b = c(c - \sqrt{c^2 - k_b^2}) \) is the binding energy of each electron in the ground state of \( \text{He}_{1s} \) and \( \varepsilon'_b = c(c - \sqrt{c^2 - k_b'^2}) \) is the binding energy of the electron in \( \text{He}^+_{1s} \).

\( \varepsilon_{\text{kin}} = c(\sqrt{c^2 + p^2} - c) \) is the kinetic energy of the free electron. The spin specific reduced \( T_{s \rightarrow s'} \) matrix is

\[ T_{s_1 s_2 \rightarrow s'_1 s'_2} = I_1 I_2 \] (17)

where

\[ I_1^{s, s'} = \frac{N_{p_b} eA_0}{2c} N_{1s} \int r^{1-\gamma} \exp(-k_b r) \exp(-i\tilde{q} \cdot \tilde{r}) \bar{u}_{s_1} \varepsilon^{s} \varepsilon_{s_b} \omega_{s_b} d^3 r \] (17a)

and the overlap integral

\[ I_2^{s_1 s_2 \rightarrow s'_1 s'_2} = \int R^{\text{He}^+_{1s} (r') \rightarrow \text{He}_{1s} (r) (r') (\overline{\psi}_{s_2} \varepsilon^{s_2} \varepsilon_{s_b} \omega_{s_b}) d^3 r' \] (17b)

It can be easily shown that [1]

\[ I_1^{s, s'} = \frac{N_{p_b} eA_0}{2c} \int R_{1s} (r) \exp(-i\tilde{q} \cdot \tilde{r}) \bar{u}_{s_1} \varepsilon^{s} \varepsilon_{s_b} \omega_{s_b} d^3 r \]

\[ = \frac{N_{p_b} eA_0}{2c} N_{1s} \int r^{1-\gamma} \exp(-k_b r) \exp(-i\tilde{q} \cdot \tilde{r}) \bar{u}_{s_1} \varepsilon^{s} (\gamma_0 - i\beta'_b \tilde{q} \cdot \tilde{r}) \omega_{s_b} d^3 r , \quad \gamma_0, \omega_{s_b} = \omega_{s_b} \]

\[ = L\bar{u}_{s_1} \varepsilon^{s} (\gamma_0 - \beta'_b g(q) \tilde{r} \cdot \tilde{q} \omega_{s_b} \omega_{s_b} = \omega_{s_b} \]

\[ = L M_{s_1 \rightarrow s'_1} = T_{s_1 \rightarrow s'_1} \] (18)

where \( L = \frac{N_{p_b} N_{1s} eA_0}{2c} C_0(q) \), \( T_{s_1 \rightarrow s'_1} \) is the transition matrix element for hydrogen with effective charge \( Z = Z_1 \) and

\[ M_{s_1 \rightarrow s'_1} = \bar{u}_{s_1} \varepsilon^{s} V(q) \omega_{s_b} \] (18a)

\[ V(q) = (1, -\beta'_b g(q) \tilde{q} \cdot \tilde{q}) , \quad \tilde{q} = \tilde{p} - \tilde{k} = q \hat{q} \] (19)

\[ C_0(q) = \frac{4\pi}{q} \frac{\Gamma(\gamma'_1 + 1)}{q^{\gamma'_1 + 1} / \Gamma(\gamma'_1 + 1)} \sin((\gamma'_1 + 1) \tan^{-1}(q/k_b)) , \] (20)

\[ (k_b^2 + q^2)^{\gamma'_1 / 2} \]
\[ g(q) = \left[ \frac{k_b \gamma + 1}{q} \right] \left[ \frac{1}{1 + \left( \frac{k_b}{q} \right)^2} \frac{\sin\left( \frac{1}{\gamma} \tan^{-1}\left( \frac{q}{k_b} \right) \right)}{\sin\left( \frac{1}{\gamma + 1} \tan^{-1}\left( \frac{q}{k_b} \right) \right)} \right] \]  

(21)

The overlap integral

\[ J_{s':s}^{s':s} = \int \overline{\sigma}_{s'} \left[ 1 - \beta_{s'} \beta_{s''} \right] \omega x_{s'} = \int \left( 1 - \beta_{s'} \beta_{s''} \right) \delta_{s',s''} \]  

(22)

Since from equations below (7) and (11)

\[ \overline{\sigma}_{s'} \beta_{s'} \beta_{s''} \omega x_{s'} = \overline{\sigma}_{s'} \left( \gamma' n'_{s'} \right) \omega x_{s'} \]
\[ = \overline{\sigma}_{s'} \left( \gamma' n'_{s'} - i \beta_{s'} \gamma' \gamma' \right) \omega x_{s'}, \]
\[ = \left( 1 - \beta_{s'} \beta_{s''} \right) \delta_{s',s''} + \overline{\sigma}_{s'} \left( \beta_{s'} \gamma' \gamma' \right) \omega x_{s'} - \overline{\sigma}_{s'} \left( \beta_{s'} \gamma' \gamma' \right) \omega x_{s'} \]  

(23)

and on substituting equation (23) in (17b), the 2nd and 3rd terms containing \( \gamma' \) will be zero on integration over \( d^3 r' \).

\[ J = \int N_{s'} r^{s'-1} e^{-k r'} N_{s''} r^{s''-1} e^{-k r'} d^3 r' \]
\[ = N_{s'} N_{s''} 4\pi \int_0^\infty r^{s'-1} e^{-k r'} dr' \]
\[ = N_{s'} N_{s''} 4\pi \Gamma(\nu + 1)/s^{\nu+1}, \]

where, \( \nu = \left( \gamma' + \gamma'' \right), s = k' + k'' \).  

(24)

Equation (24) is obtained on using Laplace Transform

\[ \int_0^\infty x^\nu e^{-sx} dx = \Gamma(\nu + 1)/s^{\nu+1}, \quad \nu > -1, \quad \text{Re} s > 0 \]

The 4-momentum of the ionized electron is \( p(p_0, \vec{p}) \)

\[ p_0 = \sqrt{c^2 + \vec{p}^2} = \kappa_0 + \sqrt{c^2 - (2k_b - k_b')^2}, \]
\[ k_b = Z_1 = \frac{27}{16}, \quad \text{and} \quad k_b' = Z_2 = 2, \]

\[ \kappa_0 = \frac{\omega}{c}, \quad \vec{k} = k_0 \vec{k}, \quad \omega \] being the photon energy.

Using eqns. (18), (18a) and (22) we get

\[ T_{s_1,s_2 \rightarrow s'_1,s'_2} = \left( T^{H(s_1)}_{s_1 \rightarrow s_1} \right) J_{s_1,s_2} \left( 1 - \beta_{s'} \beta_{s''} \right) \delta_{s_1,s_1'} \delta_{s_2,s_2'} = LI_{s_2,s_1} M_{s_1 \rightarrow s_1} \]  

(25)
From (16) transition rate per unit time
\[ dW_{\text{transition}} = \frac{1}{2} \left| S_{s_i s_2 \rightarrow s_i' s_2'} \right|^2 \left( \frac{d^3 p}{(2\pi)^3} \right) \]  

(26)

Explicit analytical expressions of the spin-specific probabilities of ionization per unit time,
\[ \frac{dW_{s_i s_2 \rightarrow s_i' s_2'}}{d\Omega} = \left[ 2\pi \delta(E_f - E_i) \right] |T_{s_i s_2 \rightarrow s_i' s_2'}|^2 \frac{P_0 |\vec{p}| dE}{(2\pi)^3} \]
\[ = |T_{s_i s_2 \rightarrow s_i' s_2'}|^2 \frac{c P_0 |\vec{p}| dE}{(2\pi)^3} \]  

(27)

The usual spin unresolved ionization rate for an unpolarized target atom is easily obtained by simply adding the four spin-specific rates and dividing by 2 (for the average with respect to two degenerate initial spin states)
\[ \frac{dT}{d\Omega} = \frac{1}{2} \left[ \frac{A_0}{2c} N_{p_0} N_{s}^2 N_{s}' c_0(q) \right]^2 \]
\[ \left[ \frac{4\pi (\gamma_2' + \gamma'_1)}{(k_2 + k'_1)^{\gamma_2' + \gamma'_1 + 1}} \right] \sum_{(s,s') = u, d} |M_{s \rightarrow s'}|^2 \frac{c P_0 |\vec{p}| dE}{(2\pi)^3} \]  

(28)

The spin-up (up) and the spin-down (dn) electron currents can now be obtained from Eqs. (17)–(20) as
\[ \frac{dW_{\text{up}}}{d\Omega} = \frac{1}{2} \left( \frac{dW_{\text{up}}}{d\Omega} + \frac{dW_{\text{dn}}}{d\Omega} \right) \]  

(29)
\[ \frac{dW_{\text{down}}}{d\Omega} = \frac{1}{2} \left( \frac{dW_{\text{up}}}{d\Omega} + \frac{dW_{\text{dn}}}{d\Omega} \right) \]  

(30)

Any asymmetry in the two currents is characterized by ensembled averaged asymmetry parameter \( \langle A \rangle \) associated with the un-polarized target atoms, defined by
\[ \langle A \rangle = \frac{\left( \frac{dW_{\text{up}}}{d\Omega} - \frac{dW_{\text{down}}}{d\Omega} \right)}{\left( \frac{dW_{\text{up}}}{d\Omega} + \frac{dW_{\text{down}}}{d\Omega} \right)} \]  

(31)

2.1 circular polarization

The polarization vector of the CPL
\[ \hat{e}_c = \frac{1}{\sqrt{2}} (1, i, 0) \]
For different spin-transitions with CPL, matrix element (25) $M_{s \rightarrow s'}$ becomes

$$M_{u ightarrow u}^{c} = \sqrt{2} m_{2} \sin \theta_{p} e^{-i \phi},$$

$$M_{u ightarrow d}^{c} = \sqrt{2} m_{1} \beta_{1} \frac{g(q)}{|q|} \left[ \bar{p} \cos \theta_{p} - |k| \right] - m_{2} \sqrt{2} \cos \theta_{p},$$

(32)

$$M_{d ightarrow u}^{c} = 0.$$  

(33)

$$M_{d ightarrow d}^{c} = \sqrt{2} m_{1} \beta_{1} \frac{g(q)}{|q|} |p| \sin \theta_{p} e^{-i \phi},$$

(34)

2.2 linear polarization

The polarization vector of the LPL

$$\hat{e}_{l} = (1,0,0)$$

For different spin-transitions, the matrix elements become

$$M_{u ightarrow u}^{l} = - \left( m_{2} \sin \theta_{p} e^{-i \phi} + m_{1} \beta_{1} \frac{g(q)}{|q|} p_{p} \sin \theta_{p} e^{i \phi} \right)$$

(36)

$$M_{d ightarrow u}^{l} = - M_{u ightarrow u}^{l}$$

(37)

$$M_{u ightarrow d}^{l} = m_{2} \cos \theta_{p} - m_{1} \beta_{1} \frac{g(q)}{|q|} \left[ \bar{p} \cos \theta_{p} - |k| \right],$$

(38)

$$M_{d ightarrow d}^{l} = - M_{u ightarrow d}^{l}$$

(39)

3. Results and discussions

In this paper strong field effect has been explored in the frequency range 400 to 2000 eV to calculate spin-dependent single-ionization current from He by single photon using relativistic Dirac theory and SFA model. Here two-electron wave function of He is considered as a product wave function of two Dirac-hydrogen wave functions. Following important results are found with circularly polarized laser:

a) There is a sharp reduction in the energy spectrum of the total ionization rates which indicates enhancement of stabilization effect in CPL.

b) The peak value of the rate of the angular distribution lies 6 degree above the plane of polarization.

c) There is asymmetry between ‘up-spin current and ‘down-spin currents’.

d) Helicity of the spin-dependent current depends on the helicity of the beam.

Ionization cross section by linearly polarized laser in the above model is computed to compare the present result with existing theoretical result [8].
3.1 Spin-symmetric current:

With left CPL at relativistic intensities, the angular differential (AD) rates for $u \rightarrow u$ (uu) current is higher than those from $d \rightarrow d$ (dd) current (fig2). At intensities $10^{18}$ W/cm² and frequency 500eV the peak values of the uu-rate and dd-rate are respectively $1.9 \times 10^{13}$ and $1.75 \times 10^{13}$ per sec. The difference between uu and dd rates decreases inversely with frequency. The peak occurs at 84 deg. These rates increase with intensities (fig3).
3.2 Spin-flip current:

AD rate for spin-flip ionization current due to spin-up electron turning to spin-down (u→d (ud)) has maxima in the forward direction and falls rapidly with angle at frequencies near and below 500eV. Dips for ud-rates are at 129 deg. and 155 deg. for frequencies 400 and 500 eV respectively (fig. 4). As frequency increases above 600 eV, ud-rate decreases more slowly with angle (fig. 5). The d→u (du) rate is found to be identically zero with positive helicity (i.e. left circularly polarized light).
3.3 Spin-averaged current:
The peak value of the total current averaged over initial spin and summed over final spin, is found to be at an angle of 84 deg (fig. 6) i.e. 6-deg. above the polarization-plane. At intensities $10^{18}$ and $10^{20}$ W/cm$^2$ and at frequency 500eV, peak-currents are $1.05 \times 10^{13}$ and $1.5 \times 10^{15}$ per sec. respectively. The known results of ionization-rate increasing with intensity and decreasing with frequency are obtained.

![Figure 6: Spin-average ionization rate vs angle of electron emission from the beam direction, at two intensities and frequencies:](image)

3.4 Spin-asymmetry: parameter
Asymmetry parameter $<A>$ (eq. 31) for one-photon ionization between up-spin current and down-spin current is independent of intensity and depends only on frequency.

![Figure 7: Asymmetry parameter vs angle of electron emission from the beam direction at frequencies 500 eV (black curve), 800 eV. (green curve) and 1500 eV. (red curve).](image)

At frequencies 500, 800 and 1500eV percentage asymmetries are (fig. 7) respectively 2.5%, 1.5% and 0.5% respectively. As such spin-asymmetry parameter decreases with the increase of frequency.
3.5 Energy spectrum:
Fig. 8 gives the spin-dependent energy spectrum of the total rate. At any intensity ud-rate decreases with energy faster than uu or dd-rate. However, as energy increases dd-rate remaining always less than uu-rate comes closer to it.

![Image of Fig. 8](image1)

Fig. 8 Spin specific (uu, dd, ud) ionization rate vs photon energy at intensities $10^{19}$ W/cm$^2$ and $10^{17}$ W/cm$^2$.

a) $10^{19}$ W/cm$^2$ (uu, dd, ud)

b) $10^{17}$ W/cm$^2$ (uu, dd, ud)

Fig. 9 shows energy spectrum at three different intensities namely $10^{17}$, $10^{18}$ and $10^{19}$ W/cm$^2$. The spin-average total rates increase with intensity but decrease asymptotically with increase of energy.

![Image of Fig. 9](image2)

Fig. 9 Spin-average total rate vs photon energy at intensities $10^{17}$ W/cm$^2$ (black curve), $10^{18}$ W/cm$^2$ (blue curve) and $10^{19}$ W/cm$^2$ (green curve).

3.6 Total cross section:
Total cross section (fig. 10) for ionization is computed for left circularly polarized laser in the energy range 300 to 2000 eV. Cross section is obtained on dividing the total rate by the incident flux (=Intensity/photon frequency in a.u.). As such single-photon ionization cross section is independent of intensity but decreases with energy. Total cross-sections by left circularly polarized laser give lower value as compared to the linearly polarized laser. Present result by CPL and LPL is found to be above the MBPT calculation by Andersson and Burgdorfer [8].
4. Conclusion

An interesting prediction of the present theory is that a helical photon (e.g. circularly polarized) can flip the helicity of the ionized electron (at any intensity). Furthermore, the photon can distinguish the sense of the spin (with respect to its own sense of helicity) through the difference in the rates of ‘up→down’ vs ‘down→up’ spin transitions. It vanishes only if the ‘weak’ components of the Dirac-electron states are neglected. We briefly discuss this effect below.

The asymmetry \(<A>\) between up-spin and down-spin current exists even when the two degenerate initial spin states of the target atom are assumed un-polarized. They have been recently investigated for ionization of H-atom in intense circularly polarized laser fields at low and high frequencies [1]. Asymmetry obtained here are quite large of the order of 2.5% in magnitude and they are well within the current resolution of spin-analyzers in the laboratory [9] to be observed experimentally. This indicates a dominance of the spin-up electron current over the spin-down current at all angles of observation by left CPL.

![Fig. 10 Total ionization cross section vs. photon energy.](image)

Present theory:
- CPL - black curve
- LPL - green curve

Theory by Andersson and Burgdorfer (1993):
- LPL - red circle

In the present case there is no spin-orbit interaction arising from the derivative of the atomic potential, either in the initial state (ground s state) or in the final state (Dirac plane-wave Volkov state). Surprisingly, the asymmetry remains present even when the retardation (i.e. the laser magnetic field in the laboratory \(\vec{B} = \frac{\vec{k} \times \vec{E}}{|\vec{k}|}\)) is neglected (\(\vec{k}=0\)). So the origin of the spin-flip under the above circumstances is a consequence of the Lorentz invariance [6] in which the electric field in the laboratory (even in the absence of retardation) is Lorentz-transformed, in the moving frame of the emitted electron, into a mixed electric and magnetic field with a (motional) magnetic field component \(\vec{B}' \approx \vec{E} \times \vec{p}/c\) in a.u.. Thus the finite spin-flip probability is due, even in the absence of retardation effect, to the coupling of the motional magnetic field \(\vec{B}'\) with the magnetic moment \(\sigma = -\frac{1}{4c^2}\sigma\) a.u. of the electron in its frame of reference.
Again we find the weak component of the Dirac wave-functions in free and bound state contain factors like $m_2$ and $\beta_1$ respectively. These factors present in eqs (27) and (32), are responsible for spin-flip. Again it is worth noting that the spin-specific matrix element can be altered by changing the helicity of the beam. This can be seen by replacing the left circular polarization vector $\vec{\epsilon}(\xi = +\pi/2)$ by right circular polarization vector $\vec{\epsilon}(\xi = -\pi/2)$ in $|M_{s'\rightarrow s}|$ of eq.(28) and observing that following transformations holds in eqns. (26) to (29):

$M^c_{u\rightarrow d} \rightarrow M^*_{d\rightarrow u}$, $M^c_{d\rightarrow u} \rightarrow M^*_{u\rightarrow d}$, and $M^c_{d\rightarrow u} \rightarrow M^*_{u\rightarrow d}$. Hence asymmetry $<A>$ will change its sign on changing the helicity of the beam from left circular polarization to right circular polarization.

In conclusion, we have analyzed the spin-response in single ionization in the laser field of 2-electron He atom in the frequency range 300eV to 2000eV. Angular dependence of asymmetry $<A>$ for an ensemble of an un-polarized He atom on frequency and photon-helicity is discussed. These spin-effects are expected to be present in any 2-electron atom or ion.

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