Pramāṇa - J. Phys., Vol. 32, No. 1, January 1989, pp. 33–38. © Printed in India.

Influence of the laser field polarization on the electron impact ionization of hydrogen

M K YOUSSEF and M K SRIVASTAVA*

Department of Mathematics, *Department of Physics, University of Roorkee,
Roorkee 247 667, India

MS received 25 March 1988; revised 16 August 1988

Abstract. The triple differential cross-sections for the ionization of hydrogen by electron impact in the presence of a laser field have been calculated in the coplanar asymmetric geometry by using the first Born approximation and the symmetric geometry by using the Coulomb-Born approximation at an incident electron energy of 250 eV. The variation of the triple differential cross-sections, for fixed values of the angles of scattering and ejection, is studied as a function of the linear polarization of the laser field. The changes are quite amenable to experimental investigation.

Keywords. Ionization; laser field; electron impact; hydrogen; polarization effects.

PACS No. 34

1. Introduction

Laser-assisted electron impact ionization of atoms has been considered by several workers during the last decade (Ferrante *et al* 1979, 1982; Mohan 1980; Cavaliere *et al* 1980, 1981; Banerji and Mittleman 1981; Zarcone *et al* 1983; Mandal and Ghosh 1984). They have considered triple differential cross-sections (TDCS) in the presence of a laser field which is weak compared with the characteristic interatomic electric field. The laser frequency is taken to be considerably smaller than any atomic transition frequency of the target and the laser field is treated as a single mode, homogeneous and in the dipole approximation. The calculations have been done mostly in the first Born approximation. In the coplanar symmetric geometry the two outgoing electrons in the final state are described by plane waves while in the case of asymmetric geometry the slower (ejected) electron is represented by a Coulomb wave. It is well known that the first Born approximation is inadequate to describe the angular distribution of the slow electron for a fixed angle of scattering of the faster one and for a given partitioning of energy between the two electrons. The second Born approximation should preferably be used. This is, however, difficult and also perhaps not needed at the present stage. Along with the first Born (B) approximation, following Mandal and Ghosh (1984), we have also used, as a first step, Coulomb Born (CB) approximation which is known to be not too bad in the binary peak region. The two continuum

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*To whom correspondence should be addressed.

electrons in the final state in that case are described by a product of Coulomb functions corresponding to unit charge at the core and modulated by the laser field.

We aim at obtaining experimentally observable results. The laser field has been found to change significantly the shape of the angular distribution of the ejected electron. However, the cross-sections corresponding to the absorption or emission of one photon or two photons are at least one order of magnitude too small compared to those for the no-photon field-free case. The angular variation may, therefore, be a bit difficult to measure. We consider, for a fixed geometry of detectors, the variation of the triple differential cross-sections (TDCS) as a function of the linear polarization direction of the laser field. The laser beam is taken to be perpendicular to the scattering plane.

2. Theory and calculation

The details of the theoretical model are given by Cavaliere *et al* (1980). In the following we point out its salient features and give the final expression:

(i) The laser field is treated classically and taken in the dipole approximation, single mode and homogeneous

$$\mathbf{A}(t) = (c\boldsymbol{\varepsilon}_L/\omega)\cos\omega t. \tag{1}$$

(ii) The non-relativistic Volkov solution is used for the incoming electron.
(iii) The laser electric field is taken to be considerably weaker than interatomic field

$$\varepsilon_{\text{at}} \simeq 5 \times 10^9\ \text{V/cm}.$$

(iv) The momentum provided to the outgoing atomic electron by the electric field of the laser is small compared to the momentum with which it is ejected.
(v) The laser frequency does not lead to any resonant coupling of the target ground state to other levels.

The TDCS for the electron impact ionization of hydrogen in the presence of a laser field, neglecting exchange, is given by

$$\frac{\mathrm{d}^3\sigma}{\mathrm{d}\Omega_a \mathrm{d}\Omega_b \mathrm{d}E_b} = \sum_{n=-\infty}^{\infty} J_n^2(\lambda_n) D(n), \tag{2}$$

where J_n is the Bessel function of order n,

$$\lambda_n = \frac{e}{m\omega^2}\boldsymbol{\varepsilon}_L\cdot(\mathbf{K} - \mathbf{k}_b), \tag{3}$$

$$\mathbf{K} = \mathbf{k}_0 - \mathbf{k}_a \tag{4}$$

and $D(n)$ is the field-free TDCS at energy

$$E_n = k_0^2/2 + n\hbar\omega, \tag{5}$$

scattered electron energy $E_a = k_a^2/2$ and the ejected electron energy $E_b = k_b^2/2$. These are related by

$$k_a^2 = k_0^2 - k_b^2 + 2I + 2n\hbar\omega, \tag{6}$$

where I is the hydrogen ground state energy and n is the number of photons absorbed ($n > 0$) or emitted ($n < 0$) by the laser. The field-free TDCS $D(n)$ is obtained by

$$D(n) = (2\pi)^{-3} \frac{k_a k_b}{k_0} |f|^2, \tag{7}$$

where the scattering amplitude f is given by

$$f_{\mathrm{B}} = -\frac{1}{2\pi} \left\langle \exp(i\mathbf{k}_a\cdot\mathbf{r}_1)\psi^{(-)}_{\mathbf{k}_b}(\mathbf{r}_2) \left| \frac{1}{r_{12}} - \frac{1}{r_1} \right| \phi_H(\mathbf{r}_2) \exp(i\mathbf{k}_0\cdot\mathbf{r}_1) \right\rangle \tag{8}$$

in the first Born (B) approximation and by

$$f_{\mathrm{CB}} = -\frac{1}{2\pi} \left\langle \psi^{(-)}_{\mathbf{k}_a}(\mathbf{r}_1)\psi^{(-)}_{\mathbf{k}_b}(\mathbf{r}_2) \left| \frac{1}{r_{12}} - \frac{1}{r_1} \right| \phi_H(\mathbf{r}_2) \exp(i\mathbf{k}_0\cdot\mathbf{r}_1) \right\rangle \tag{9}$$

in the Coulomb Born (CB) approximation. Here $\psi^{(-)}$ are the appropriate Coulomb functions and ϕ_H is the ground state wavefunction of hydrogen. The laser parameters have been chosen as follows

$$\varepsilon_L = 5 \times 10^7\,\mathrm{V/cm} \simeq 10^{-2}\varepsilon_{\mathrm{at}}$$

$$\hbar\omega = 1{\cdot}17\,\mathrm{eV} \ll \hbar\omega_{1s-2p}.$$

3. Results

We have calculated TDCS at an incident electron energy $E_0 = 250\,\mathrm{eV}$ at $\theta_a = 3°$, $E_b = 5\,\mathrm{eV}$ corresponding to the experimental data of Ehrhardt *et al* (1985) and Lohmann *et al* (1984) in the asymmetric geometry and at $\theta_a = -\theta_b = 45°$ in the symmetric geometry. The target dressing effects which are known to lead to significant contribution at very small scattering angle (or momentum transfer) (Byron and Joachain 1984; Mandal *et al* 1986; Byron *et al* 1987), are not expected to be so in the present cases as the momentum transfer is not very small. These effects have therefore not been considered.

Let us first consider the asymmetric case. In this case one of the outgoing electrons is very energetic while the other is quite slow. The first Born approximation which is here more appropriate than the Coulomb-Born approximation is used. The exchange scattering is not expected to contribute significantly and has, therefore, not been considered. The slow electron angular distribution (variation with respect to θ_b) shows a peak, called the binary peak, along the momentum transfer direction θ_K in the field-free case. For $E_0 = 250\,\mathrm{eV}$, $\theta_a = 3°$ and $E_b = 5\,\mathrm{eV}$, $\theta_K = -52{\cdot}1°$. We keep θ_b fixed at θ_K and vary the polarization direction of the laser. Figure 1 shows the variation in the cross section, corresponding to the exchanges of 0, 1 and 2 photons, as a function of the laser electric field direction θ_L measured with respect to the incident direction. A dramatic change is observed at $\theta_L = 38°$ which corresponds to the electric field

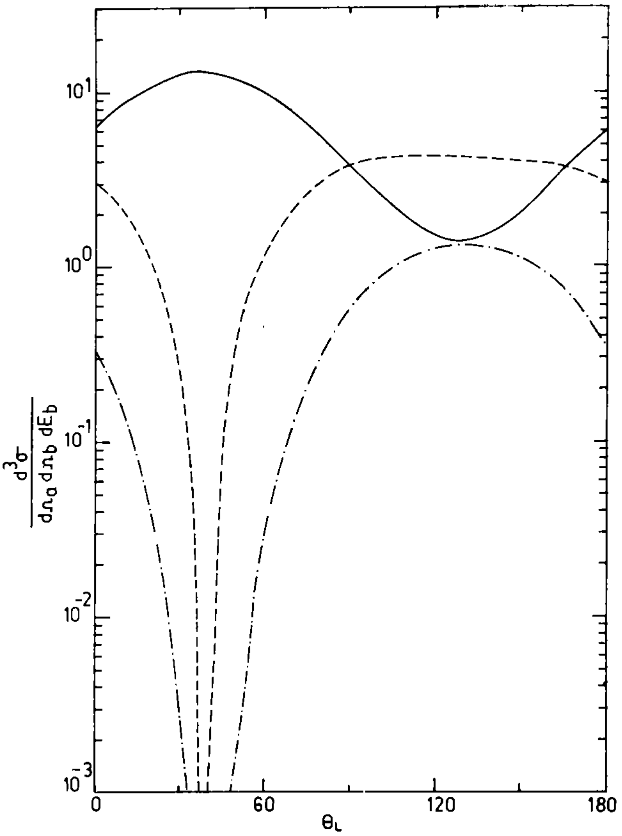

Figure 1. Triple differential cross-sections in atomic units for the ionization of hydrogen by electron impact at $E_0 = 250$ eV, $E_b = 5$ eV, $\theta_a = 3°$ and $\theta_b = \theta_K = -52{\cdot}1°$ plotted as a function of the laser electric field direction. $n = 0$——; $n = 1$--; $n = 2$—.—.

perpendicular to the momentum transfer direction (which is here the same as the direction of $\mathbf{k}_b$). At this θ_L, the zero-photon TDCS shows a relatively mild maximum while the one- and the two-photon results exhibit a very sharp dip. These changes are the result of the presence of $J_n(\lambda_n)$ in equation (2) and the dip corresponds to the $\lambda_n = 0$. Figure 2 shows similar variation in the symmetric kinematical arrangement. The calculations have been done in Coulomb-Born approximation which treats both the outgoing electrons on the same footing. In this arrangement, the direct (f) and the exchange (g) scattering amplitude are identical, with the result that

$$\tfrac{1}{4}|f+g|^2 + \tfrac{3}{4}|f-g|^2 \equiv f^2.$$

The exchange amplitude, therefore, need not be evaluated. Here, the condition $\lambda_n = 0$ corresponds to the electric field perpendicular to the incident direction.

To conclude the triple differential cross-sections show a dramatic and measurable variation with laser polarization direction. The asymmetric geometry is expected to be relatively better suited for this investigation since the cross-sections are a bit larger in this case.

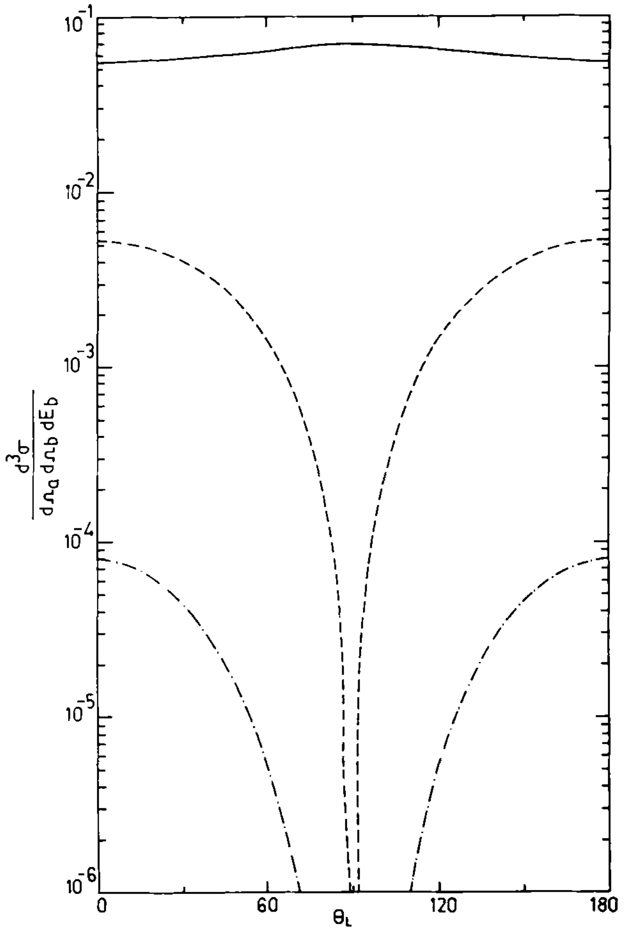

Figure 2. Triple differential cross-sections in atomic units for the ionization of hydrogen in the symmetric geometry at $E_0 = 250$ eV and $\theta_a = -\theta_b = 45°$ plotted as a function of the laser electric field direction. $n = 0$——; $n = 1$– –; $n = 2$—.—.

Acknowledgement

One of us (MKY) would like to thank the Government of India for financial support.

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