PRAMANA
—journal of
physics

Vol. 50, No. 6,
June 1998
pp. 683–698

Electron-photon coincidence studies on electron impact excitation of lighter neutral atoms

RAJESH SRIVASTAVA
Department of Physics, University of Roorkee, Roorkee 247 667, India

Abstract. Recently we applied non-relativistic distorted wave approximation theory to study electron impact excitations in lighter atoms (viz. hydrogen, helium and some alkalis). Excitations from the ground and (or) initially excited metastable S states to next upper excited P and D states have been considered. Results for the differential cross-sections and electron-photon coincidence parameters are obtained. Here the theory and the calculation of various scattering parameters are described briefly and some selected results are presented and discussed.

Keywords. Excitation; electrons; distorted-wave; atoms.

PACS No. 34.80

1. Introduction

Electron-atom scattering has been one of the most studied subject in the atomic and molecular collision physics having many important applications. It is still currently a very rapidly expanding field both theoretically and experimentally. The reason is partly due to the development of highly sophisticated experimental technology with which one can study in a realistic manner the very complex nature of the collision dynamics involved and partly the easy access to fast speed computers with which one can perform cumbersome calculations in a short time. For example, the coincidence detection of a decay photon from an excited atomic state and the exciting scattered electron after excitation is now a well established technique in the study of electron impact excitation of atoms. In fact, the electron-photon coincidence experiments have played a major role in the understanding of an excitation process in a complete sense as well as in the refinement and development of theories for atomic excitations even since the pioneering experiments of Eminyan *et al* [1]. Although various excitation processes in the number of atoms have now been studied using this electron-photon coincidence technique most previous studies have been carried out for 2^2P in hydrogen, $2^{1,3}P$ states of helium and also for excitations in sodium and some inert gases. The field has been extensively reviewed by Andersen *et al* [2], Slevin and Chwirot [3] and Becker *et al* [4].

In the present talk I take up some of the work we recently carried out through our number of theoretical studies on the electron and positron impact excitation of the lighter atoms where relativistic effects are not important and can be neglected. In general our basic emphasis has been to study various excitations in different atoms where theoretical studies are required to supplement and explain the experimental results or to report

improved theoretical results where inferior theoretical results exist or experimental results are not available at all and theoretical data are required for application purposes and to guide experimentalists. In particular, we have been interested in investigating the excitations where change in orbital angular momentum ΔL after excitation is one and more so that the radiation emitted from the excited anisotropic states could be analysed in coincidence with scattered electrons or positrons, giving the different photon-coincidence and angular correlation parameters. For our theoretical study we adopt fully quantum mechanical approach and describe the collision dynamics in the framework of a distorted wave approximation (DWA) theory. This approximation has proved in the recent years to be very reliable and successful for the study of different excitations and other inelastic processes involving impact of electrons or positrons with atomic systems especially at intermediate and high energies where low energy close-coupling/R-matrix methods fail or are difficult to extend accurately (see Bartschat [5]).

We have carried out DWA calculations for the $n = 1$ to $n = 3$ transitions and the $n = 2$ to $n = 3$ and 4 transitions in hydrogen and helium as well as excitation of some of the lowest lying n^2P and n^2D states in lighter alkalis (viz. lithium, sodium and potassium) and reported our various results (see Verma and Srivastava [6–15] and Verma *et al* [16]). The same will be discussed here briefly by giving an outline of the theory and some selected results.

2. Non-relativistic distorted wave approximation theory

2.1 *T-Matrix*

The exact T-matrix for the excitation of an atom (having N bound electrons) from an initial state 'i' to a final state 'f' by impact of electrons is given by (atomic units are used throughout)

$$T_{\rm if} = \langle \Phi_{\rm f}(1,\ldots,N+1)|V|\Psi_{\rm i}^{+}(1,\ldots,N+1)\rangle, \tag{1}$$

where the total interaction potential is

$$V = \frac{-N}{\mathbf{r}_{N+1}} + \sum_{j=1}^{N} \frac{1}{\mathbf{r}_{j,N+1}}. \tag{2}$$

Here $\mathbf{r}_{N+1}$ denotes the combined spin and space coordinate of the projectile electron while $\mathbf{r}_1, \mathbf{r}_2, \ldots, \mathbf{r}_N$ denote those of the bound electrons. The functions Φ and Ψ satisfy the following Schrödinger equations

$$(H_0 - E)\Phi = 0 \tag{3}$$

and

$$(H - E)\Psi = 0, \tag{4}$$

where the superscript plus on Ψ denotes the outgoing-wave boundary condition. The total Hamiltonian of the system is $H = H_0 + V$. Here H_0 is the unperturbed Hamiltonian and E is the total energy of the system. Following the two potential formulation [17] we can write the exact T-matrix (1) alternatively as

$$T_{if} = \langle \chi_f^- | U_f | \Phi_i \rangle + \langle \chi_f^- | W_f | \Psi_i^+ \rangle, \tag{5}$$

where interaction potential is divided according to

$$V = U_f + W_f \tag{6}$$

and the function χ satisfies

$$(H_0 + U - E)\chi = 0 \tag{7}$$

with $U = U_f$ and follows ingoing-wave boundary condition. Here the division of V as expressed by eq. (6) is such that the scattering problem with U_f is aimed to be solved exactly while the effect of the other part (i.e. W_f) can be treated in some approximation. The first term in the T-matrix (eq. (5)) drops out for inelastic transition due to the orthogonal property of the target atomic wave functions, resulting the T-matrix in a form

$$T_{if} = \langle \chi_f^- | W_f | \Psi_i^+ \rangle. \tag{8}$$

Since in the above , Ψ_i^+, the solution of equation (4) cannot be obtained exactly one resorts to some approximation. For this purpose we adopt a distorted wave approximation (DWA). We expand Ψ_i in terms of the usual distorted wave Green function $G_{U_i}^+ = \lim_{\eta \to 0}^+ (E - H_0 - U_i + i\eta)^{-1}$ in the following form [18, 19]:

$$\Psi_i^+ = \chi_i^+ + \sum_{j=0}^{\infty} [G_{U_i}^+ V]^j G_{U_i}^+ W_i \chi_i^+ \tag{9}$$

and use in the T-matrix (8) its first term only, which consequently gives the first-order distorted wave Born approximation to the T matrix as T_{if}^{dw}, i.e.

$$T_{if} \simeq T_{if}^{dw} = \langle \chi_f^- | V - U_f | A \chi_i^+ \rangle. \tag{10}$$

Here A is antisymmetrization operator to account for the electron exchange. Again $V = U_i + W_i$ and χ_i^+ satisfies equation (7) with $U = U_i$. Further, expressing

$$\chi_{i(f)}^{+(-)}(1, \ldots, N+1) = \phi_{i(f)}(1, \ldots, N) F^{+(-)}(\mathbf{k}_{i(f)}, N+1) X_{i(f)}(1, \ldots, N+1) \tag{11}$$

and using equation (7), we get,

$$H_T \phi_{i(f)} = \varepsilon_{i(f)} \phi_{i(f)} \tag{12}$$

and

$$[-\tfrac{1}{2}\nabla_{r_{N+1}}^2 + U_{i(f)}(N+1)] F^{+(-)}(\mathbf{k}_{i(f)}, N+1) = [E - \varepsilon_{i(f)}] F_i^{+(-)}(\mathbf{k}_{i(f)}, N+1). \tag{13}$$

Thus F^+ and F^- are the scattered projectile electron distorted wave functions in the initial and final channels respectively with the wave vectors $\mathbf{k}_i$ and $\mathbf{k}_f$. $X_i(X)_f$ is spin function for the composite system in initial (final) state. H_T is the Hamiltonian of the target, ϕ_i and ϕ_f are the bound target-atom wave functions for the initial and final states, associated respectively with eigenenergies ε_i and ε_f such that

$$E = \tfrac{1}{2}k_i^2 + \varepsilon_i = \tfrac{1}{2}k_f^2 + \varepsilon_f. \tag{14}$$

Since except for hydrogen the exact atomic wave functions for different states are not known we take Hartree–Fock wave functions to represent them. Further, for obtaining F^+ and F^- so that the T-matrix (eq. (10)) can be evaluated, we need to define the distortion potentials U_i and U_f which are taken to be individually the sum of spherically averaged static potential, exchange potential and where available dipole form of polarization potential. As in a DWA method, in principle the distortion potential U_i or U_f can be chosen in any arbitrary suitable manner. We have adopted three different ways (see Madison *et al* [20]) i.e. taking in both the initial and final channels either the ground (II) or the excited (FF) distortion potential and as well as taking the initial state distortion in the initial channel and the final state distortion in the final channel (IF). Since polarizability of the atoms are available only in the ground state the polarization is included only in the II model and we call the calculation as IIP model of our DWA. After the distortion potentials are defined we expand the distorted waves F^+ and F^- in terms of partial waves and solve equation (13) numerically. We neglect all spin dependent interactions and therefore total spin S of the system and its z-component are conserved during the collision i.e. $S = X_i \pm 1/2 = X_f \pm 1/2$ and $M_S = M_{S_f} + m_f = M_{S_i} + m_i$. Here m_i is the z-component of projectile electron spin. Finally, by carrying out in a straightforward manner the angular momentum algebra involved and thereafter evaluating the occurring integrals numerically, we obtain the T-matrix (eq. (10)) for a particular excitation of a magnetic sub-state (M_f) for every possible mode of total spin S values i.e. $T^S_{if}(M_f)$. It is to be noted that this is related to the corresponding excitation amplitude $a^S_{M_f}$ by

$$a^S_{M_f} = -\frac{1}{2\pi}\sqrt{\frac{k_f}{k_i}}\,T^S_{if}(M_f). \tag{15}$$

The differential cross section is given by

$$\sigma = \sum_{M_f} \sigma(M_f) \tag{16}$$

with

$$\sigma(M_f) = \langle a_{M_f} a^*_{M_f} \rangle, \tag{17}$$

where $\langle\ \rangle$ indicates spin-averaging i.e.

$$\langle a_{M_f} a^*_{M_f} \rangle = \frac{1}{2(2S_i + 1)} \sum_S (2S + 1) a^S_{M_f} a^{S*}_{M_f}. \tag{18}$$

Here S_i is the total spin of the target atom in initial state.

2.2 *Electron-photon coincidence parameters*

Here we discuss scattering parameters which are involved in detection and analysis of photons emitted from the target atom after excitation and in coincidence with the scattered exciting electron as well as their relation with the scattering amplitude calculated in the earlier section.

2.2.1 *Stokes parameters* (P_1, P_2, P_3 *and* P_4): We have used the collision frame of reference i.e. the geometry where the incident electron is travelling in the z-direction and the collision takes place in x-z plane. Therefore, the usual experimental Stokes parameters, P_i ($i = 1, 2, 3$) measured perpendicular to the collision/scattering plane (i.e. polar angles of detector are $\theta_\gamma = 90°$ and $\phi_\gamma = 90°$) can be defined as

$$P_1 = \eta_3 = \frac{I(0°) - I(90°)}{I(0°) + I(90°)} \tag{19}$$

$$P_2 = \eta_1 = \frac{I(45°) - I(135°)}{I(45°) + I(135°)} \tag{20}$$

$$P_3 = -\eta_2 = \frac{I_- - I_+}{I_- + I_+} \tag{21}$$

where $I(\beta)$ is the intensity of linearly polarized light with electric vector at an angle β with respect to the incident-beam direction and I_+ and I_- are the intensities of circularly polarized light with positive and negative helicity respectively. The P_4 Stokes parameters is defined in the same way as P_1 except that it is measured parallel to scattering plane i.e. $\theta_\gamma = 90°$ and $\phi_\gamma = 0$.

Following Blum [21], the relationship between the state multipoles of the excited state of the atom (say, with orbital angular momentum L_f) and the Stokes parameters for the photons emitted through its decay to the state with L' i.e. for $L_f \rightarrow L'$ can be expressed as

$$P_1 = \frac{G(\omega)}{\gamma I_y} \langle L' \| \mathbf{r} \| L_f \rangle|^2 (-1)^{L_f + L'} \begin{Bmatrix} 1 & 1 & 2 \\ L_f & L_f & L' \end{Bmatrix} \times \left(\sqrt{\frac{3}{2}} G_2(L_f) \langle T(L_f)^+_{20} \rangle - G_2(L_f) \mathrm{Re}[\langle T(L_f)^+_{22} \rangle] \right), \tag{22}$$

$$P_2 = -\frac{G(\omega)}{\gamma I_y} |\langle L' \| \mathbf{r} \| L_f \rangle|^2 (-1)^{L_f + L'} \begin{Bmatrix} 1 & 1 & 2 \\ L_f & L_f & L' \end{Bmatrix} G_2(L_f) \mathrm{Re}[\langle T(L_f)^+_{21} \rangle], \tag{23}$$

$$P_3 = -\frac{G(\omega)}{\gamma I_y} |\langle L' \| \mathbf{r} \| L_f \rangle|^2 (-1)^{L_f + L'} \begin{Bmatrix} 1 & 1 & 2 \\ L_f & L_f & L' \end{Bmatrix} G_1(L_f) \mathrm{Re}[\langle T(L_f)^+_{11} \rangle], \tag{24}$$

with

$$I_y = \frac{G(\omega)}{\gamma} |\langle L' \| \mathbf{r} \| L_f \rangle|^2 (-1)^{L_f + L'} \left(\frac{2(-1)^{L_f + L'}}{3\sqrt{(2L_f + 1)}} G_0(L_f) \langle T(L_f)^+_{00} \rangle + \begin{Bmatrix} 1 & 1 & 2 \\ L_f & L_f & L' \end{Bmatrix} \left(\sqrt{\frac{1}{6}} G_2(L_f) \langle T(L_f)^+_{20} \rangle G_2(L_f) \mathrm{Re}[\langle T(L_f)^+_{22} \rangle] \right) \right). \tag{25}$$

The P_4 Stokes parameters can be obtained from the expression for P_1 i.e. from equations (23) and (25) by changing the sign of the state multipole $\langle T(L_f)^+_{22} \rangle$. The curly braces { } denote the Wigner 6j symbol, ω is the frequency of the emitted photon, γ is the decay constant, $|\langle L' \| \mathbf{r} \| L_f \rangle|^2$ is related to the oscillator strength of the radiative decay and $G(\omega) = \omega^4 / 2\pi c^3$. In equations (22)–(25), $G_K(L_f)$ are the perturbation coefficients which take into account the depolarization due to fine-structure splitting. The time averaged

perturbation coefficients are given by

$$G_K(L_f) = \frac{1}{(2S_f+1)} \sum_{J_f} (2J_f+1)^2 \begin{Bmatrix} L_f & J_f & S_f \\ J_f & L_f & K \end{Bmatrix}^2 \quad \text{and } G_0 = 1. \tag{26}$$

Here S_f is the total spin of the excited atom and $J_f = L_f + S_f$ is the total angular momentum. Further, the state multipoles are related to the scattering amplitudes by the following relations

$$\langle T(L_f)^+_{KQ} \rangle = \sum_{M_f M'_f} (-1)^{L_f - M_f} (2K+1)^{1/2} \begin{Bmatrix} L_f & J_f & K \\ M'_f & M_f & Q \end{Bmatrix} \langle a_{M'_f} a^*_{M_f} \rangle. \tag{27}$$

From the property of the $3j$ symbol the values of rank K and component Q of the multipoles are restricted to $K \leq 2L_f$ and $-K \leq Q \leq K$.

The state mulitpoles have different physical meaning. The $\langle T(L)^+_{00} \rangle$ is measure of the overall population of the atomic state and gives the isotropic contribution of the coincidence rate. The $\langle T(L)^+_{1Q} \rangle$ describes the orientation of the atomic state and thus circular polarization of the emitted photons and the $\langle T(L)^+_{2Q} \rangle$ describes the alignment of the atomic state and thus gives anisotropic part of coincidence rate and the linear polarization of emitted photon.

2.2.2 *Parameters of Andersen et al* [2]: To describe the nascent charge cloud of the atom immediately after excitation Andersen *et al* [2] defined the parameters which can be related to the Stokes parameters. These are the alignment angle, γ, linear polarization, P_l, height of the charge cloud, ρ_{00}, and the angular momentum transferred perpendicular to the scattering plane, $L_\perp$. We considered all the transitions where excitation involved is from an initial S state to either P or D excited state which decay by photon emission to lower allowed S or P state and for such cases the parameters are related to Stokes parameters by the following relations

$$\gamma = \tfrac{1}{2} \tan^{-1} (\overline{P}_2 / \overline{P}_1), \tag{28}$$

$$P_l = \sqrt{\overline{P}_1^2 + \overline{P}_2^2}, \tag{29}$$

$$L_\perp = -P_3 \left(\frac{2L_f}{2+\kappa} \right) \tag{30}$$

and

$$\rho_{00} = \frac{\kappa}{2+\kappa} \quad \text{(for excited } P \text{ state)}$$
$$= \frac{3}{2} \frac{\kappa}{2+\kappa} \quad \text{(for excited } D \text{ state)} \tag{31}$$

with

$$\kappa = \frac{(1+\overline{P}_1)(1-\overline{P}_4)}{(1+\overline{P}_4)}.$$

Here $\overline{P}_1, \overline{P}_2, \overline{P}_3$ and $\overline{P}_4$ are the reduced Stokes parameters which may be obtained by using the same relations as for the measured Stokes parameters P_1, P_2, P_3 and P_4 given by equations (22)–(25) but with all the $G_K(L_f)$ taken to be unity.

3. Results and discussion

3.1 *Excitation of the $n = 3$ states of hydrogen and helium from the ground state*

Electron-impact excitation of the $n = 2$ states in hydrogen and helium are fairly well understood, both theoretically and experimentally, but not much attention has been paid to the $n = 3$ excitations from the point of view of angular correlation parameters. Recently new experimental results have been reported for angular correlation parameters for the $n = 3$ excitations. Thus the aim of the study has been to understand the excitations from the ground state to H (3^2P and 3^2D) and He ($3^{1,3}P$ and $3^{1,3}D$) states and compare these with the new experimental data.

Williams *et al* [22] have reported detailed measurements for angular correlation parameters (ACP) and differential cross section for electron impact excitation of hydrogen atom to the 3^2P states. They also presented converged close-coupling (CCC) approximation calculations. We carried out calculations for the differential cross sections and angular correlation parameters in the distorted wave approximation. Our results agree very well with their results (see Verma and Srivastava [6]). Further, for $3^{1,3}P$ excitation, relatively more theoretical and experimental data are available but our study provides a systematic complete presentation of various results (see Verma and Srivastava [14]). As an illustration in figure 1, ACP results for 3^1P excitation at 80 eV are shown. We find from this figure that though theoretical results qualitatively agree with experiment but quantitative agreement is not so good.

Especially not much is known on the study of the excitation of the D states of atoms. Even for the simplest atoms like hydrogen and helium very little work exists for excitation of the $3D$ state. The reason obviously has been the complexities involved in studying such excitations because of their very low cross sections. Further, it is difficult to resolve the individual $3D$ states both from their fine structure states and from the other neighbouring S and P states in order to be able to measure the cross sections. However, the electron-photon angular and polarization techniques allow us to study the individual D-states by taking advantage of the fact that photons from the decay of $3D$ sub-states can be readily isolated. At the same time they provide very detailed information on the excitation process. We have therefore focused our attention on the $n = 3$ excitations in hydrogen and helium especially dealing with their $3D$ excitations from the ground $1S$ state. In the recent past for these excitations some experimental data have also been reported giving electron-photon coincidence results. For 3^2D excitation in hydrogen experimental ACP results from Chwirot and Slevin [23], Farrell *et al* [24] and Kumar *et al* [25] are available. We performed DWA calculations in the light of these experiments and presented systematic theoretical details also (see Verma and Srivastava [13]). Comparison of the experiment and theory for circular polarization P_3 is given in figure 2. We feel the agreement is reasonably good but results with more reliable theories would be desirable along with more detailed measurements.

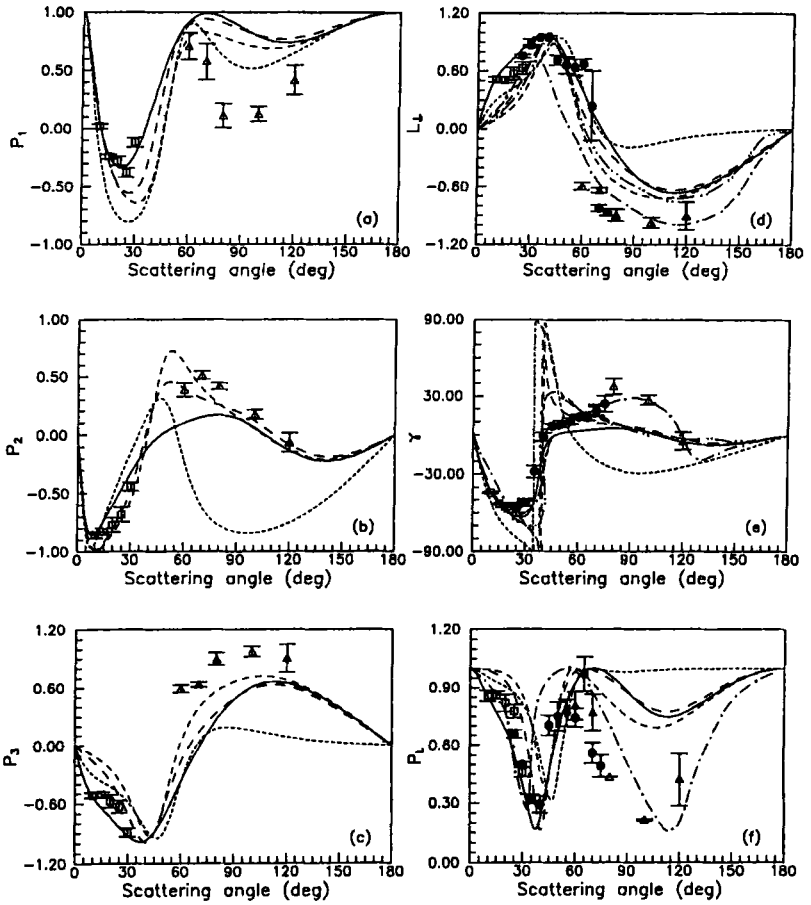

Figure 1. Stokes parameters (P_1, P_2, P_3), $L_\perp$, γ, P_l parameters for the electron excited 3^1P state in helium from the ground 1^1S state at $E_i = 80\,\text{eV}$. ——— Present FF results; - - - - - - Present IF results; — — — Present II results; — — Present IIP results; - - - CCC results (Fursa and Bray [29]); - - - - FOMBT results (Csanak and Cartwright [30]); □ Experiment (Eminyan *et al* [31]); • Experiment (Beijers *et al* [32]); △ Experiment (McAdams and Williams [33]).

For studying 1^1S–$3^{1,3}D$ excitations in helium there has also been some previous calculations using various approximations (see Mikosza *et al* [26]) and Bray *et al* [27] and references therein). We have therefore extended our distorted wave approximation (DWA) theory for this excitation for the calculations of DCS and ACP. Further, we have also extended our calculation to the positron impact excitation of He (3^1D). The results are obtained using different distortion potentials in DWA for Stokes parameters P_1–P_4, coherence parameters $\gamma, P_l, L_\perp$ and ρ_{00} and DCS. These are discussed and compared with the available theoretical and experimental results. We find that the DWA results are sensitive to the choice of the distortion potentials used in the calculation of the distorted waves (see Verma and Srivastava [11]). Figure 3 gives our results for the Stokes

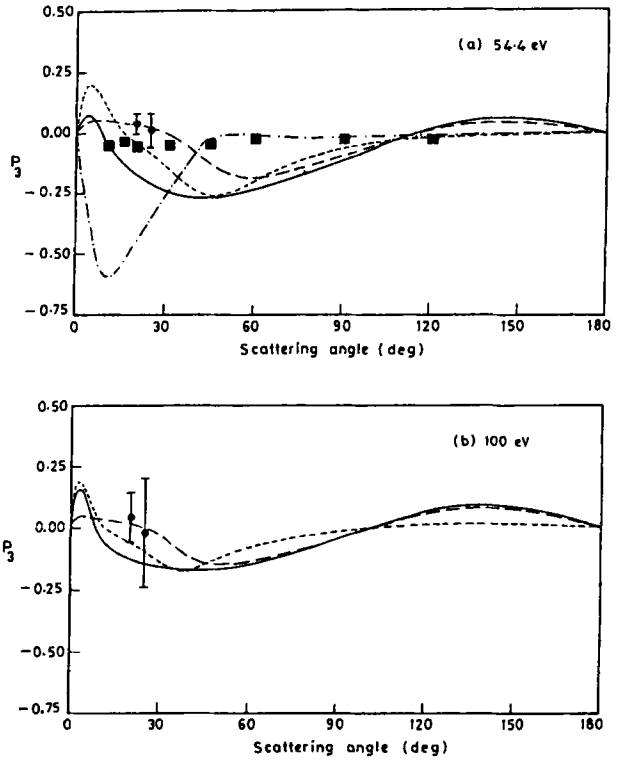

Figure 2. Stokes parameter P_3 for the cascade L_α radiation from the electron excited 3^2D state of hydrogen from the ground 1^2S state at (**a**) $E_i = 54.4\,\text{eV}$ and (**b**) $E_i = 100\,\text{eV}$. ——— Present FF results; - - - - - - Present IF results; – – – Present II results; • Experiment (Kumar *et al* [25]); □ Experiment (Farrell *et al* [24]); · · · six-state close coupling (Kumar *et al* [25]).

parameters in case of 3^1D excitation by electrons. We see that no single theoretical calculation reproduces the experimental data.

3.2 *Excitation from the initially excited $n = 2$ states of hydrogen and helium*

This work concerns with the excitation of atoms by electrons and positrons. There are extensive studies available dealing with the excitation of atoms from the ground state. Excitation of atoms from their initially excited state to higher states has received relatively less attention though these are equally of fundamental importance and have several important applications such as modeling laboratory and astrophysical plasmas etc. Inspite of such importance it is only recently that the study of these excitations have got renewed interest and more theoretical and experimental data are becoming available.

In the present part of study we focussed our attention on the simplest atoms like hydrogen and helium for which excitation from the ground state to few upper states is almost fairly becoming well understood and much is needed to study their excitation from

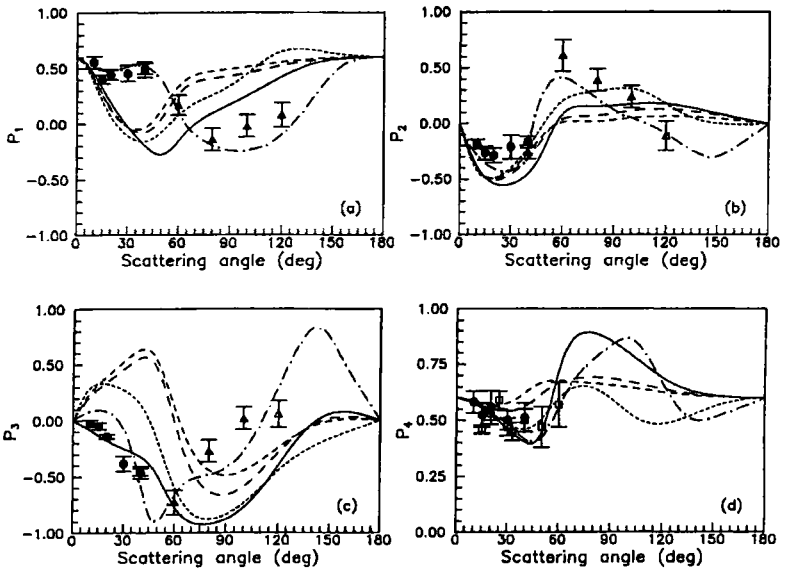

Figure 3. Stokes parameter P_1–P_4 for the electron impact 1^1S–3^1D excitation of helium at $E_i = 40$ eV. —— Present FF results; - - - - - - Present IF results; – – – – Present II results; — — Present IIP results; · · · CCC results (Bray [27]); □ Experiment (Batelaan *et al* [34]); • Experiment (Mikosza *et al* [26]); △ Experiment (Donnelly and Crowe [35]).

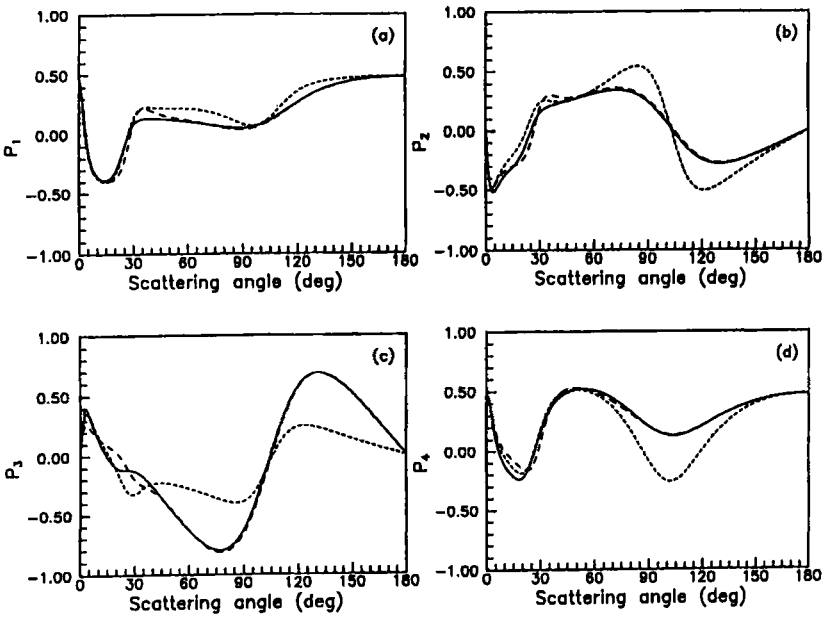

Figure 4. Stokes parameters P_1–P_4 for the electron impact 2^2S–3^2D excitation of hydrogen at $E_i = 20$ eV. ——— Present FF results; - - - - - - Present IF results; – – – – Present II results; — — Present IIP results.

excited states. For helium couple of studies both theoretical and experimental dealing excitation from the 2^1S, 2^3S states to higher states are available. On the other hand, for hydrogen first Born total cross section results are only reported. We have therefore taken up systematic theoretical calculation of excitation from the $n = 2$ states to the $n = 3$ and 4 in hydrogen by impact of electrons and positrons. For the purpose of describing collision dynamics distorted wave approximation theory is used and calculations are performed to obtain differential cross section and total cross section results for 2^2S–n^2L ($L = 0, 1$ and 2) while the angular correlation parameters are obtained for the excitation of the P and D states which provide further insight of the collision phenomena as well as a stringent test of the theory. The details about the theory and the formulae along with the results can be seen in our paper (Verma and Srivastava [7, 15]). However, figure 4 gives our DWA results for Stokes parameters for the 2^2S–3^2D excitation by electrons at $E_i = 20$ eV. There are no other results for comparison.

In continuation of the above study the extension is made to study the excitation of the metastable 2^3S state to $n^{1,3}L$ ($n = 2$, 3 and 4 and $L = 0$, 1 and 2) states of helium. For such excitations there are already available some experimental results and theoretical DWA, R-matrix, eikonal approximation and first Born level calculations. In these the total cross sections and (or) differential cross sections for the 2^3S–n^3L transitions in helium ($n = 3$ and $L = 0$, 1 and 2) are reported. However, for 2^3S–n^1L excitations in helium only total cross section results are available. Thus a detailed study for such excitations in distorted wave approximation is carried out.

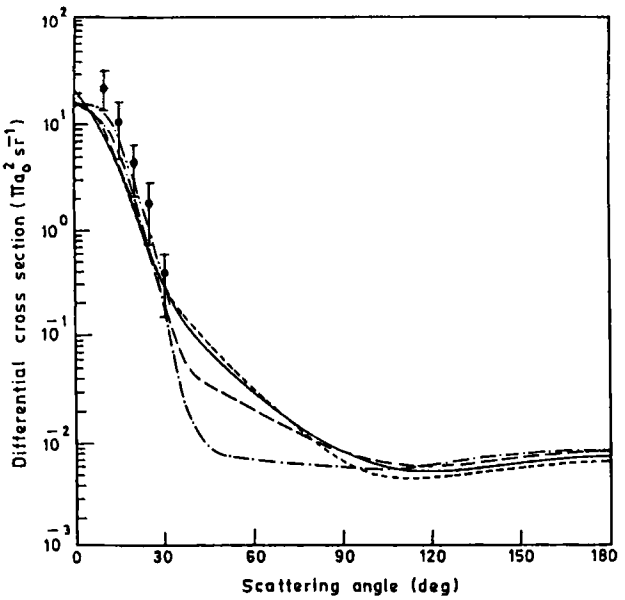

Figure 5. Differential cross sections in units of $\pi a_0^2 sr^{-1}$ for the electron impact 2^3S–3^3D excitation of helium at final electron energy of 20 eV. ——— Present FF results; - - - - - - Present IIP results; – – – – Present II results; - · - FOMBT results (Csanak *et al* [36]); - ··· - DMET results (Mansky and Flannery [37]); • Experiment (Muller-Fiedler *et al* [38]).

The results are compared with the available experimental and theoretical results for 2^3S–2^3P, 3^3S, 3^3P and 3^3D excitations. An overall agreement with the experimental data is obtained. Further, our calculation suggests that the inclusion of the polarization potential may have a significant effect in some cases. The differential cross section calculations for 2^3S–4^3S, 4^3P and 2^3S–2^1S, 2^1P, 3^1S, 3^1P, 3^1D and 4^1P excitations have been carried out for the first time and these are therefore compared with the first Born level results. Whereas the total cross section results obtained for 2^3S–$n^{1,3}L$ ($n = 2$, 3 and 4 and $L = 0$, 1 and 2) excitations are compared with the available experiments and theories. Except for a few special cases the different theoretical calculations give almost the same values of the total cross sections. The results of the theory and results are given in our paper (Verma *et al* [7] and Verma and Srivastava [15]). Figure 5 shows DCS results for 2^3S–3^3D excitation in helium. Here comparison of theories with experiment is good.

3.3 *Excitations in lithium, sodium and potassium*

We find among the lighter alkalis the resonance excitation in lithium and sodium has received extensive attention and several theoretical and experimental results are available for both differential cross sections and angular correlation parameters as well as spin parameters. Potassium though being similar to sodium has not received adequate attention but now it has attracted interest from theorists and experimentalists. From this view point

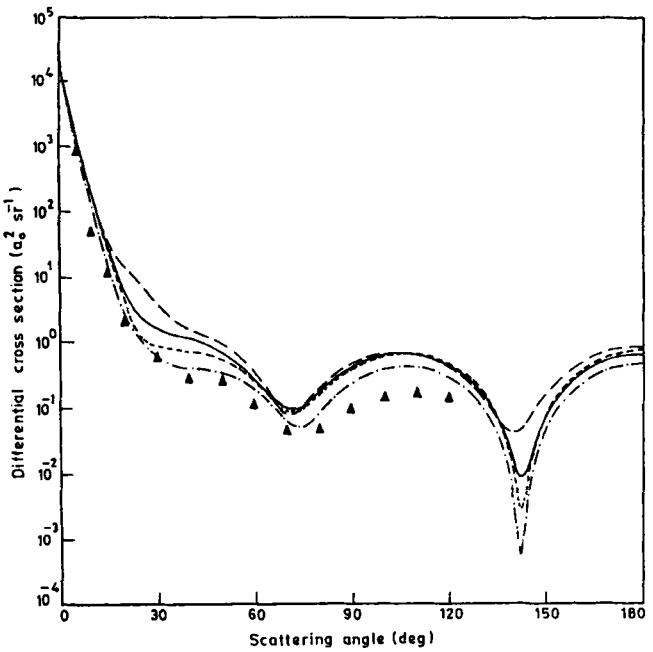

Figure 6. Differential cross sections in units of $a_0^2 sr^{-1}$ for the electron impact 4^2S–4^2P excitation of potassium at $E = 40$ eV. ——— Present FF results; - - - - - Present IF results; – – – – Present IIP results; · · · CCC results (Bray *et al* [28]); △ Experiment (Vuskovic and Srivastava [39]).

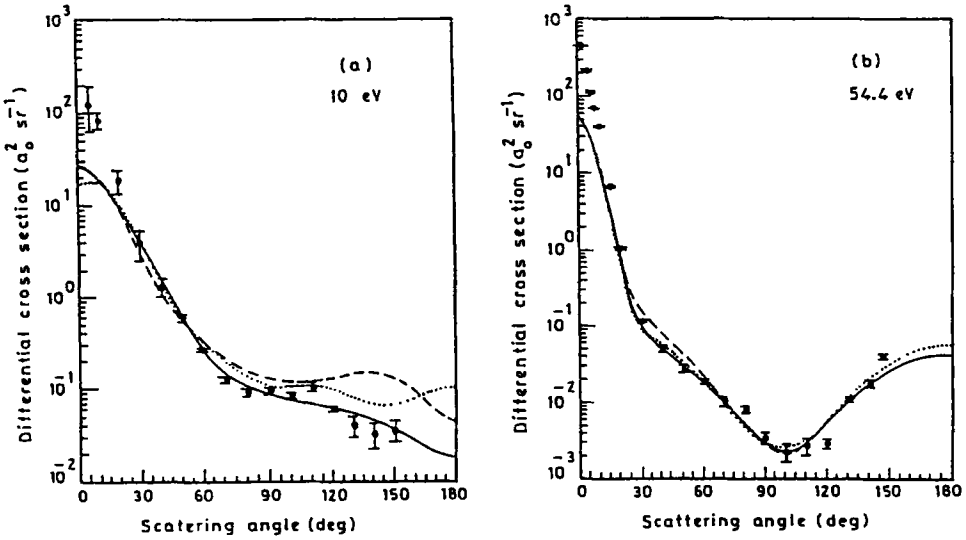

Figure 7. Differential cross sections in units of $a_0^2 sr^{-1}$ for the electron impact 3^2S–3^2D excitation of sodium at E_i = (**a**) 10 eV and (**b**) 54.4 eV. ——— Present FF results; - - - - - - Present IF results; – – – – IIP results; • Experiment (Marinkovic *et al* [40]).

it is interesting to study the electron impact resonance excitation in potassium at intermediate incident electron energies. For 4^2S–4^2P excitation in potassium some experimental and theoretical results are available (see Bray *et al* [28] and references therein).

Again encouraged by several previous successful applications of the DWA calculations to explain experimental DCS and ACP data for alkalis, we considered it for the present calculations as well. A detailed calculation for DCS, alignment and orientation parameters and spin asymmetry has been carried out. Comparison of the experimental data and the theoretical results is made. The spin averaged DCS results are found to show overall good agreement with the other available theoretical results though all the theoretical results tend to lie above the experimental data but the structures are reproduced successfully. Further, our results for spin resolved $L_\perp^s$, $L_\perp^t$, and spin averaged $L_\perp$ and asymmetry parameter are in reasonably good agreement with the only available coupled channel optical method results of Bray *et al* [28]. In addition the results of P_l and γ have been obtained for the first time. The details of the theory along with the results are presented in our paper [8]. As an illustration we have shown in figure 6 our DCS results favourably compare with other theories and the experiment.

We carried out first systematic study of the electron impact excitation of the 3^2D state from the ground state of lithium, sodium and potassium. The DWA results for DCS and total cross sections as well as ACP results are obtained in the energy range 10–100 eV. Our cross section results show good agreement where available with other theories and experiment. See for example, figure 7 showing the DCS results for sodium compared with recent experimental data. Our Stokes parameter results are also shown in figure 8 and there are no other theory or experiment to compare. Rest of our results are given in our paper [10].

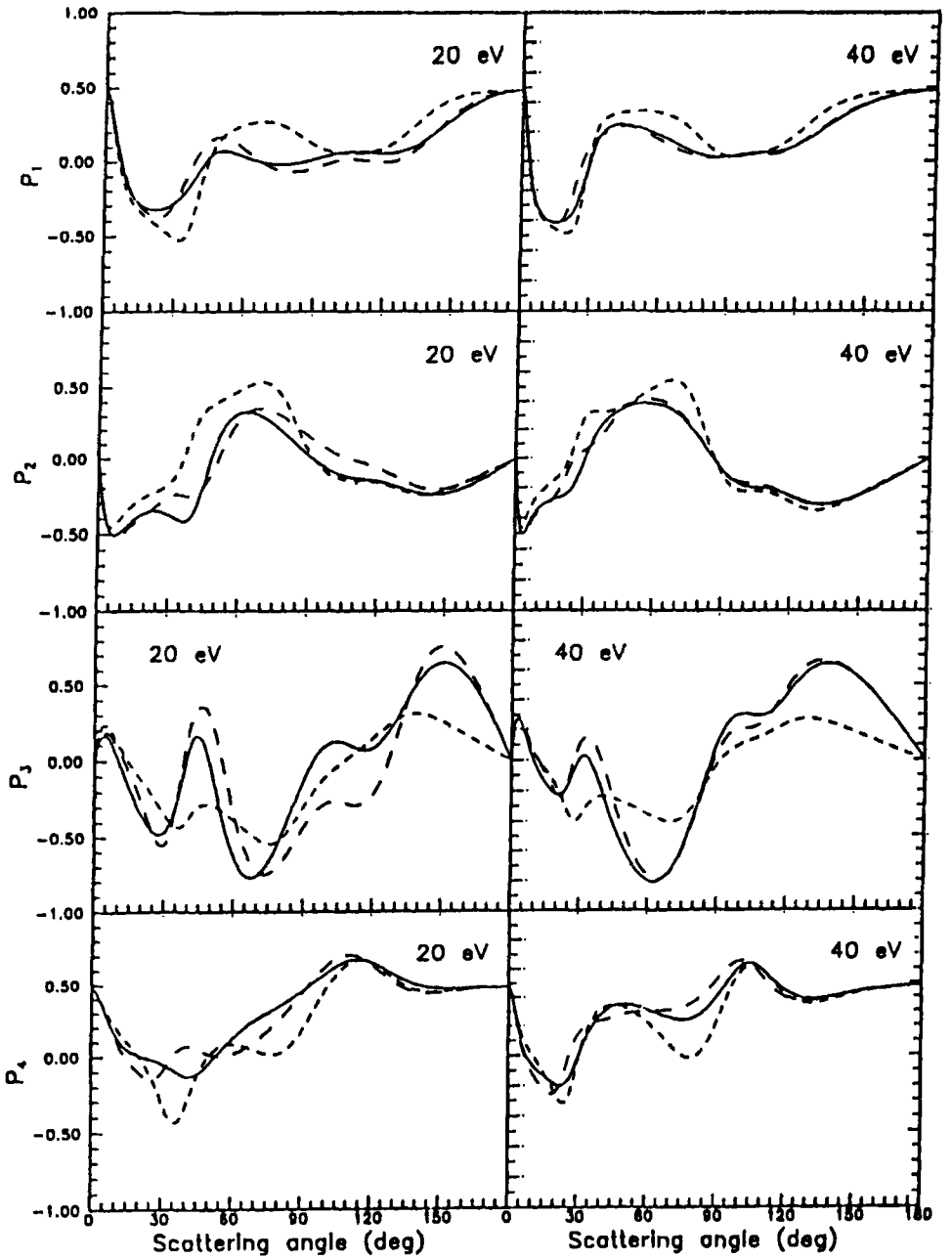

Figure 8. Stokes parameters for P_1–P_4 for the electron excited 3^2D state of sodium from the ground 3^2S state at $E_i = 20$ and 40 eV. ——— Present FF results; - - - - - - Present IF results; – – – – Present IIP results.

4. Conclusion

In the present talk we have given an outline of the DWA theory which we have applied to the excitation of lighter neutral atoms by electrons. Some details about the calculation of the Stokes parameters as well as alignment and orientation parameters are described. Selected few results for different excitations are also shown and compared with available other theories and experiment. We hope our work will simulate more similar theoretical and experimental work in order to provide meaningful comparison and definite conclusions.

Acknowledgements

The work presented here has been carried out in collaboration with Ms. Surbhi Verma. The author is thankful to CSIR and UGC, New Delhi for financial assistance.

References

[1] M Eminyan, K MacAdam, J Slevin and H Kleinpoppen, *Phys. Rev. Lett.* **31**, 576 (1973)
[2] N Andersen, J W Gallagher and I V Hertel, *Phys. Rep.* **165**, 1 (1988)
[3] J A Slevin and S Chwirot, *J. Phys.* **B23**, 165 (1990)
[4] K Becker, A Crowe and J W McConkey, *J. Phys.* **B25**, 3885 (1992)
[5] K Bartschat, *Computational Atomic Physics* (Springer, Berlin, 1996)
[6] S Verma and R Srivastava, *Phys. Rev.* **A50**, 2269 (1994)
[7] S Verma and R Srivastava, *Hyp. Int.* **89**, 469 (1994)
[8] S Verma and R Srivastava, *J. Phys.* **B28**, 4823 (1995)
[9] S Verma and R Srivastava, *J. Phys.* **B29**, L135 (1996)
[10] S Verma and R Srivastava, *J. Phys.* **B29**, 3215 (1996)
[11] S Verma and R Srivastava, *Can. J. Phys.* **74**, 509 (1996)
[12] S Verma and R Srivastava, *Can. J. Phys.* **74**, 521 (1996)
[13] S Verma and R Srivastava, *J. Phys.* **B30**, 1341 (1997)
[14] S Verma and R Srivastava, *J. Phys.* (communicated) (1998)
[15] S Verma and R Srivastava, *J. Phys.* (communicated) (1998)
[16] S Verma, R Srivastava and Y Itikawa, *J. Phys.* **B28**, 1023 (1995)
[17] C J Joachain, *Quantum Collision Theory* (North Holland, Amsterdam 1975)
[18] K H Winters, *J. Phys.* **B11**, 149 (1978)
[19] H R J Walters, *Phys. Rep.* **116**, 1 (1984)
[20] D H Madison, K Bartschat and R Srivastava, *J. Phys.* **B24**, 1839 (1991)
[21] K Blum, *Density Matrix Theory and Applications* (Plenum, New York, 1981)
[22] J F Williams, A T Stelbovics and I Bray, *J. Phys.* **B26**, 4599 (1993)
[23] A Chwirot and J A Slevin, *J. Phys.* **B20**, 3885 (1987)
[24] D Farrell, S Chwirot, R Srivastava and J A Slevin, *J. Phys.* **B23**, 315 (1990)
[25] M Kumar, A T Stelbovics and J F Williams, *J. Phys.* **B26**, 2165 (1993)
[26] A G Mikosza, R Hippler, J B Wang and J F Williams, *Z. Phys.* **D30**, 129 (1994)
[27] I Bray, D V Fursa and I E McCarthy, *Phys. Rev.* **A51**, 500 (1995)
[28] I Bray, D V Fursa and I E McCarthy, *Phys. Rev.* **A47**, 3951 (1993)
[29] D V Fursa and I Bray, *Phys. Rev.* **A52**, 1279 (1995)
[30] G Csanak and D C Cartwright, *Phys. Rev.* **A38**, 2740 (1988)
[31] M Eminyan, K MacAdam, J Slevin, H C Standage and H Kleinpoppen, *J. Phys.* **B8**, 2058 (1975)
[32] J P M Beijers, D H Madison, J Van Eck and H G M Heideman, *J. Phys.* **B20**, 167 (1987)
[33] R McAdams and J F Williams, *J. Phys.* **B15**, L247 (1982)
[34] H Batelaan, J van Eck and H G M Heideman, *J. Phys.* **B24**, L397 (1991)

[35] B P Donnelly and A Crowe, *J. Phys.* **B21**, L637 (1988)
[36] G Csanak, D C Cartwright and F da Paixão, *Phys. Rev.* **A48**, 2811 (1993)
[37] E J Mansky and M R Flannery, *J. Phys.* **B25**, 1591 (1992)
[38] R Muller-Fiedler, P Schlemmer, K Jung, H Hotop and H Ehrhadt, *J. Phys.* **B17**, 259 (1984)
[39] L Vušković and S K Srivastava, *J. Phys.* **B13**, 4849 (1980)
[40] B Marinkovic, V Pejcev, D Fillpovic, I Candez and L Vušković, *J. Phys.* **B25**, 5179 (1992)