Afyon Kocatepe Üniversitesi
FEN BİLİMLERİ DERGİSİ

3 (1-2)
67-90

Afyon Kocatepe University
JOURNAL OF SCIENCE

ELECTRON-PHOTON COINCIDENCE TECHNIQUE FOR ATOMIC COLLISIONS

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ABSTRACT

A brief review is given on development of electron-photon coincidence studies from electron impact of atoms. The theory of electron-photon correlations is outlined in detail in terms of cross sections of excited atoms and excited state charge clouds. The state of a target atom is determined by the various orientation and alignment parameters and the multipole moments of the excited atom. General considerations, such as coherence effects in impact excitation, the influence of fine and hyperfine structures in correlations are taken into account. The relationship between scattering amplitudes (including their phases) and target parameters is worked out for singlet and doublet transitions.

Key Words: Coincidence, Correlation, Electron Impact, Atom.

ATOM ÇARPIŞMALARINDA ELEKTRON-FOTON ÇAKIŞMA TEKNİĞİ

ÖZET

Bu çalışmada, atomların elektron çarpışmasıyla uyarılmasını incelemek için kullanılan elektron-foton çakışma metodunun gelişimi ayrıntılı olarak açıklanmaktadır. Elektron-foton çakışma tekniği, uyarılmış atomların tesir kesitleri ve elektron bulutları açısından ele alınarak incelenmektedir. Çarpışmadaki hedef atomun yapısı; çarpışma sırasında atoma aktarılan momentum ve uyarılmış yük bulutunun şekli ile ilgili değişik parametreler ve uyarılmış seviyenin multipol momentlerine bağlı olarak belirlenmektedir. Ayrıca atomun uyarılması sırasında ince ve aşırı ince yapı etkisi de göz önüne

alınarak saçılma büyüklükleri ve hedef parametreleri arasındaki ilişki tekli ve ikili geçişler için ayrı ayrı incelenmiştir.

Anahtar Kelimeler: Çakışma, Korelasyon, Elektronla Uyarma, Atom

1. INTRODUCTION

Electron collisions with atoms have attracted considerable interest since the early days of atomic physics, because such processes provide the means of investigating the dynamics of several-particle systems at a fundamental level. This dominant importance of electron impact processes manifests itself in many examples in which problems of fundamental atomic physics are involved. In addition, a detailed understanding of these phenomena is required in other fields of physics. Since the fundamental review, *Impact Excitation and Polarization of the Emitted Light*, p blished [1], electron-photon coincidence studies have developed into a key technique that provides data for performing the most detailed tests of atomic collision models to date.

Before describing the technique of electron-photon coincidences in detail, it is instructive first to consider briefly the traditional kinds of experiments which have been used hitherto in the study of excitation processes. The experimental techniques fall into two main categories.

The first category concerns experiments where observations are made on either the scattered electron or the recoiling atoms. In a scattered electron experiment, an electron beam of given energy is passed through an atom. Using an appropriate energy analyzer, measurements are made on the angular distribution of electrons scattered with an energy loss corresponding to the excitation energy of the state being studied. In a recoil experiment, certain of the kinetic properties of the recoiling atoms are used to distinguish between elastic and inelastic events. Both kind of experiment yield values of the differential cross section.

The second technique involves measurements on the electric dipole radiation, which results from the decay of the excited state. These experiments are of two types: (i) those, which measure the intensity of the emitted light, and (ii) those, which measure its polarisation. In the former, the intensity of light emitted at a particular angle is measured as a function of incident electron energy. Measurements of the polarisation of the emitted light, usually observed at 90^o to the electron beam axis, give information on

the relative population of the magnetic sublevels excited by electron scattering at all angles.

This paper presents a discussion on the electron-photon coincidence technique. It begins with historical development of the theory and a brief discussion on basic formulation of single particle detection and then proceeds to describe the electron-photon coincidence technique.

2. HISTORICAL DEVELOPMENT

In the last decade of the nineteenth century, the ground was prepared for the start of research into electronic and atomic collisions [2]. In 1895 Roentgen discovered X-rays, a discovery that was followed rapidly by numerous investigations of the ionization of gases by X-rays themselves and by the emissions from radioactive substances. The first evidence to establish the existence of the electron is usually considered to be provided by J.J Thomson's experiment in 1897 in which he measured the speeds and the charge to mass ratio (e/m). Electron impact excitation of atomic and molecular systems has been a subject for both experimental and theoretical study since Franck and Hertz demonstrated the loss of energy of electrons passing through mercury vapour in 1914. This work gave them information about the electronic energy levels of the target. Quantitative measurements, mostly of electron impact total cross sections, have been performed in the years from 1920s. A comprehensive review of this early work has been presented by Massey and Burhop[3].

The theoretical study of electron scattering by atoms is an enormous field of endeavour with a history dating back to the early 1930 s. Despite this, there remain many unsolved problems. The Coulomb three-body scattering problem is, perhaps surprisingly to the general scientific community, still a subject of intense interest for theoreticians and experimentalists alike. In the atomic physics field the Schrodinger equation, that governs the electron-atom scattering of interest, may often be readily written down. The problem is not so much one of deriving the equations of motion, but rather one of solving the known equations. Therefore, the primary problem is to develop effective numerical techniques for solving known relations that govern interactions of few-body Coulomb systems. The ultimate objective in doing this is to provide useful data for science and technology.

Experimentally the great majority of studies on short-lived excited states have been carried out by observation of either the scattered electron or the

photon from decay of the excited state. In principle photon emission measurements can yield the energy dependence of the cross section for exciting a particular state of the atom [4-6].

Measurement of the angular distribution of scattered electrons following excitation of a particular state leads to an angular differential cross section (DCS). Experimental data on the DCS is available over a wide range of electron energies and scattering angles for many excited states. For impact energies above 20 eV comparison between experiment and theory has been summarized in literature [7-10].

The particle correlation measurements of atomic physics have their foundations in the work of Fano [11]. The first experimental feasibility study of such a coincidence experiment for electron impact excitation was reported by King et al [12]. After the theoretical developments [1,13-15], the first successful experiments were carried out by Eminyan et al [16]. A comprehensive review of all the data was presented by Andersen et al [17] and the subject has also been reviewed in several other papers [18-20].

3. SINGLE PARTICLE DETECTION

3.1. Scattering Processes

Electrons in a beam traversing a gas may undergo either elastic or inelastic scattering. In elastic scattering, the electron changes direction without transforming any of its kinetic energy into internal energy of the target atom. In inelastic scattering, kinetic energy of the scattered electron is transferred to internal energy of the target atom. This transfer of energy is usually (but not necessarily) accompanied by a change in direction. It is usually assumed that the difference in energy between the incident and scattered electron is equal to the energy difference between the initial and final state of target particle (figure 1).

3.2. Radiation from the Atom

The optical excitation of an atomic state describes the dependence on electron energy of the cross section for excitation of that state by collisions between electrons and atoms in a specified lower state.

The radiation of interest originates in transitions between atomic levels, knowledge of the level positions alone does not provide all the information

that one would like to have. Thus, one wishes to know not only the transition wavelengths, but also the relative intensities or polarization of the spectral lines. The relative intensities depend in part on the transition probabilities between the individual levels in the atom`s term scheme. In part, of course, the line intensities depend on how the populations of the radiation-connected levels are established in the excitation modes.

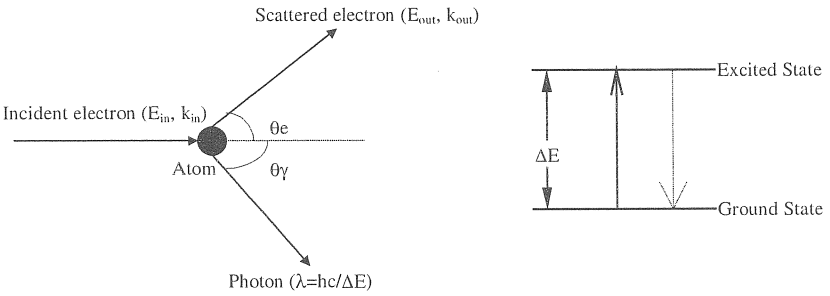

Figure 1. (a) Schematic illustration of crossed electron-atom beam experimental arrangement and (b) atomic energy level diagram.

For many term combinations, the transition probabilities are extremely small, or even zero. The selection rules, which are simply expressions of the order of magnitude of the transition probabilities, determine the line intensities.

During the process of emission, energy is transferred from the source to the electromagnetic field. The flux from the source is usually different in different directions; the proper description of an extended source therefore involves a statement of the radiant flux emitted per unit area of the source per unit solid angle in a specified direction.

3.3. A Simplified Picture

The equilibrium concentration of atoms in a given state does not in general depend only on the rate of electron excitation to that state and of radiative decay from it though this can be a very useful model to use in the expression of experimental results. Atoms (in the interaction region) are illuminated uniformly by an electron beam having energy E. Consider the schematic energy level diagram of figure 2, where the lowest level (g) is the initial level, usually the ground level. We consider ground state atoms of an

element A in two-body collisions with electrons of energy E becoming excited to some state of energy E_j above the ground state. We can represent such exciting collisions by

$$A_g + e(E) \rightarrow A_j + e\ (E\text{-}E_j) \qquad (1)$$

Atoms will be excited to state *j* not only by electron impact, but also as a result of radiative transitions from higher states, *i*, which are themselves populated in various ways. This population by radiative transitions is called the cascade process.

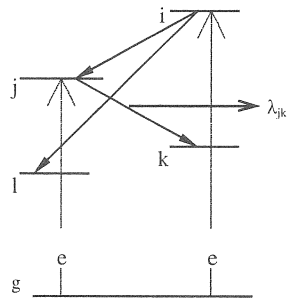

Figure 2. Schematic energy level diagram indicating electron impact excitation (dashedlines) cascade (solidline, $i \rightarrow j$) and emission (solidline, $j \rightarrow k$) processes.

We will write $Q_j(E)$ for the cross section for excitation of the state j from the ground state. The rate of excitation by electron impact is

$N_g Q_j(E) n_e v$ per unit volume,

where N_g and n_e are the number densities of ground state atoms and electrons, respectively, and v is the electron velocity. The electron beam current, i, can be written as $i=n_e evS$, where S is the cross-sectional area of the electron beam and e is the electronic charge. The rate of excitation is thus

$N_g Q_j(E)(i/eS)$ per unit volume.

The rate of de-excitation by radiation is $N_j A_j$ per unit volume, where

$$A_j = \sum_k A_{jk} \tag{2}$$

and A_{jk} is the Einstein transition probability for a spontaneous transition from state j to a lower state k. In general, radiation corresponding to a particular transition will be observed. If ϕ_{jk} is the rate of emission of photons corresponding to the transition from j to state k per unit length of electron beam, then

$$\phi_{jk} = N_j A_{jk} S. \tag{3}$$

Provided that no other process of excitation or de-excitation occurs, we have for an equilibrium situation

$$N_g Q_j(E)(i/eS) = N_j A_j = \phi_{jk}(A_j/A_{jk}S) \tag{4}$$

and hence,

$$Q_j(E) = \frac{A_j}{A_{jk}} \frac{\phi_{jk}}{N_g(i/e)} \tag{5}$$

The determination of the ratio A_j/A_{jk} can often be made with greater precision than the determination of the individual transition probabilities. The assumption that there are no other populating processes is usually false, but the form of equation (5) is still useful in defining an apparent cross section which we will call Q_j^1

$$Q_j^1(E) = \frac{A_j}{A_{jn}} \frac{\phi_{jn}}{N_g(i/e)} \tag{6}$$

where n is upper possible transition levels (n>j).

Figure 2 illustrates the general arrangement for detection of the photon. If we want to look at particular emitted photon, then we can use a filter or monochromator. In general, it is very difficult to measure; (*i*) the exact value of the number densities of ground state atoms (N_g), (*ii*) the cross sectional area of the electron beam (S), (*iii*) the photon detection efficiency with acceptable precision, (*iv*) cascade excitation, (*v*) polarization of radiation and (*vi*) collisional transfer of excitation. That is, the techniques of gas

density measurement and absolute radiometry have inherent problems and difficulties not easily overcome by the experimenter.

3.4. Detection of Outgoing Electron from the Atom

The first measurements of energy losses suffered by electrons in collisions with atoms were carried out in a multiple-collision experiment by Franck and Hertz [21] and then this was used to obtain information about the electronic energy levels of the target [3].

At present there are essentially two methods used to study excitation of atoms through electron-impact excitation and detection of the scattered electrons. One method, introduced by Schulz [22] and usually denoted the *trapped-electron* method, involves the use of an incident electron beam of variable kinetic energy E and the detection of only those electrons which have lost nearly all of their kinetic energy through single collisions with the target particles.

The other *electron scattering method* involves the use of an incident electron beam of fixed (or variable) energy and the detection of electrons which have been scattered by single collisions with the target in a particular (θ_e, θ_γ) direction (or range of angles) after undergoing a particular energy loss.

For the particular process in which an electron collides with a stationary target and then scatters into a given direction, the cross section per unit solid angle is called the *differential scattering cross section (DCS)* and has the units of area per unit solid angle per target particle. The corresponding total cross section is the integral of the DCS over all scattering directions (θ_e, θ_γ). If the target particles are randomly oriented with respect to the incident beam direction, then the DCS will not depend on θ_γ.

Electron-impact spectrometry is concerned with the excitation of atoms and therefore with the measurement of the energy lost by the electron during the scattering process. The experimental method most often used involves the production of a monochromatic beam of electrons (incident beam), the passage of this beam through a gaseous sample of the target particles and the measurement of the scattered electron intensity as a function of the incident electron energy, scattering angle, and energy loss.

The excitation of atomic electronic states by electron impact and the concomitant measurement of the energy loss and direction of the scattered electron can provide information about optically-forbidden states that may not be available from any other method [23]. In particular, a measurement of the energy loss determines the energy of the excited state and, in principle, the corresponding differential excitation cross section contains the information needed to characterize the electronic state of the target.

4. WHY DO WE NEED A COINCIDENCE EXPERIMENT?

The electron-photon coincidence measurement is a powerful technique which can give additional information on a collision process that the traditional collision experiment cannot. In summary, all of the single particle techniques yield differential and total cross sections. In each case, the experimental results involve averages over fundamental collision parameters. For example, measurements of DCSs do not distinguish between excitation to the different degenerate sublevels, but since the analyses of the radiation takes place without regard to the electrons, these experiments of necessity involve an average over all electron scattering angles. Again, important detail is lost in the averaging process.

4.1. Lost Information

Coincidence experiments involve detection of two particles, the scattered electron and emitted photon. In our case the general scheme is:

$$e^- + A \rightarrow A^* + e^- \qquad A^* \rightarrow A + h\nu. \tag{7}$$

In contrast, more traditional experiments detect only one of these two particles i.e., the electron is detected and the photon ignored or the photon is detected and the electron ignored [24].

When the scattered particle is ignored, either the polarization or intensity of the decay radiation is analyzed [25]. The former gives information on the relative population of the magnetic sublevels with the intensity allowing a measurement of total excitation cross sections. If the electron is not detected then we are summing over all momentum transfer to the atom. In other

words, we do not uniquely define the excited state, it is an average. Similarly a measurement of an electron differential cross section does not distinguish between excitation to the different degenerate sublevels of the atom and detail is lost. A coincidence experiment, which takes both the scattered electron and emitted photon into account, provides the maximum information possible.

4.2. Photon Labeling

It sometimes happens that the optical excitation function of a level cannot be measured, because the only spectrum line in an accessible spectral region is too close in wavelength to some other line of the same element (a number of examples occur in the spectra of the rare gases). A much greater problem occurs in the measurement of inelastic electron scattering because the resolution of electron spectrometers is inferior to that of optical spectrometers and because atomic energy levels converge toward the ionisation potentials. Because optical detection of excitation is usually made by observing transitions other than those back to the ground state, the wavelengths of transitions from states that are very close in energy are frequently well separated. It is therefore possible to identify an electron that has excited a specific state by observing the scattered electrons in delayed coincidence with the photons that result from excitation of that state.

4.3. Cascade Excitation

We consider the simplified energy level diagram shown in figure 2. The number of processes, which must be considered, depends on the experimental situation. In eq. (5), the population of the state j, which complicates the foregoing discussion, has been ignored. In any experiment where the electron energy is sufficiently high to excite states above the one of interest, cascade must be taken into account. This population by radiative transitions is called the cascade process (eq. 6). Normally the absolute cross section for excitation of the *j* state is $Q_j(E) \approx \phi_{jk}$. In general the state *i* will also be excited leading to additional j→k transitions by cascade from the i→j state and hence to uncertainties in Q_j. By detection of only scattered electrons, which have excited the j state in coincidence with the j→k photons, these uncertainties are eliminated.

The detection of photons emitted in a given direction in delayed coincidence with electrons scattered into a small solid angle provides a technique for precisely this kind of measurement. It will be shown by coincidence

technique, how a study of the excitation into different magnetic sublevels is directly related to the way in which angular momentum is transferred to the atom during the collision process, thus providing explicitly details of the collision dynamics.

5. THE THEORY OF THE ELECTRON-PHOTON COINCIDENCE MEASUREMENTS

The theory of electron-photon coincidence studies is discussed in this section. Firstly we begin by giving the definition of an excitation and then define appropriate co-ordinate systems. After that we will deal with correlation analysis which consists of polarization and angular correlations. In angular correlation analysis we will start with the simplest case of $He(2^1P)$ and then carry on with the more complex case of $H(2^2P)$ and $He^+(2^2P)$, and also outline the complications in getting from helium to the hydrogen case. Discussion for the theory of angular and polarization correlation studies will be presented in terms of relevant parameterizations (Andersen, Stokes and reduced Stokes parameters) used for describing the excited states of atoms after a collision.

5.1. Excitation of Atoms by Electron Impact

Excitation of an atom by an electron can be described by the following formula,

$$e|k_{in}\rangle + A|\alpha\rangle \rightarrow A|\alpha^*\rangle + e|k_{out}\rangle \qquad (8)$$

where $|\alpha\rangle$ denotes the state of A before the collision and $|\alpha^*\rangle$ after the collision. The initial particles are characterized by momentum $\mathbf{k}_{in}$ and scattered particles by $\mathbf{k}_{out}$ as seen in figure 1a. If the initial particle and atom are in pure states, the initial state of the whole system may be described by a pure state $|\alpha, k_{in}\rangle$. In this case, the final system can also be described by a pure state $|\alpha^*, k_{out}\rangle$ after the collision. Here, the term of pure state refers to a fully coherent superposition of the basis states. For example, the atom in a state $|\alpha\rangle$ is described by a linear superposition of basis states (nJM)

$$|\alpha\rangle = \sum A_{nJM} |nJM\rangle \qquad (9)$$

where n is the radial, J and M are angular momentum quantum numbers. If the fully coherent initial state can be transferred to another fully coherent final state as illustrated in the following expression;

$$|\alpha k_{in}\rangle \rightarrow \sum_{\alpha'} |\alpha^{*} k_{out}\rangle = F|\alpha k_{in}\rangle \qquad (10)$$

where **F** describes the collision process, this is called perfect scattering [26-28] and completely determines scattering matrix (α k_{in}| F | α^{*} k_{out}) or the corresponding scattering amplitudes, $f_{\alpha,\alpha^{*}}(\theta_e)$. In such cases all of the quantum numbers of A before and after the collision as well as $\mathbf{k}_{in}$ and $\mathbf{k}_{out}$ are measured.

However, the cases in which such detailed information can be obtained are quite rare. Normally various scattering amplitudes are undefined and much less detail may be available. Thus, due to lack of knowledge, these kinds of systems cannot be described as pure states (fully coherent) but only mixed states (incoherent or partially coherent). This might still be possible even if the initial state of the whole system is known completely [17].

On the other hand, describing the spin of an ensemble of electrons with the polarization vector components P_x, P_y, P_z the degree of polarization P is given by $P^2 = P_x^2 + P_y^2 + P_z^2$. Obviously its value is independent of the reference frame and $0 \leq P \leq 1$. Therefore there are two extreme cases:

- P=1 implies a fully coherent state described by a linear superposition of basis states,

- P=0 where all basis states are equally populated independent of the frame. Any intermediate situation is possible and P gives an accurate measure of it.

In a specific experiment we must distinguish strictly between the polarization of the atomic state and the way it is detected. Often the emitted light is used to determine the state population amplitudes, in a manner described below. The light emitted may be incoherent, even though the states populated in the collision are coherent or vice versa:

- Fine and hyperfine structure may lead to depolarization of the atomic states created in the collision process,

- The selection rules for optical transitions may lead to a mixture of different polarization states of the emitted photon may exclude certain excited atomic states from being observed.

The fully coherent and the incoherent cases will be exemplified in the helium and the hydrogen cases, respectively.

5.2. Defining a Scattering Plane and Basis Sets

The aim of collisional alignment and orientation studies is to determine the excited atom A as completely as possible after a collision. In an electron-photon correlation experiment, a scattering plane is defined by the momentum vectors of interacting particles, $\mathbf{k}_{in}$ and $\mathbf{k}_{out}$ (figure 1a).

Figure 3 illustrates schematically the geometry and the atomic charge cloud after an excitation. The charge cloud distribution exhibits reflection symmetry with respect to the scattering plane provided the initial state distribution is spherically isotropic. The charge cloud shown in figure 3 has an alignment; for instance, it is found in a nonisotropic distribution of magnetic sublevels $|JM\rangle$ with expectation values $\langle M^2\rangle \neq \langle J^2\rangle/3$. It has also an orientation; a finite expectation value of its angular momentum.

For symmetry reasons, the angular momentum of the relative motion of the interacting particles can only be transferred perpendicular to the collision plane. Therefore, if the scattered particles have no initial orientation, the final angular momentum of the atom will be perpendicular to the collision plane as indicated by $\mathbf{L}_\perp$ in figure 3. For an excited P-state, the aligned and oriented atom A after the collision is fully characterized by the relative height (**h**), width (**w**), length (l) and alignment angle (γ) of the charge cloud and by its inherent angular momentum ($L_\perp$). This provides the essentially frame-independent parameterization.

Basically there are three coordinate frames, but only two of them have been used most conventionally in the field. The standard collision frame, which is characterized by (x^c, y^c, z^c), is often used to describe the theoretical results, while the experimental results are often related to the natural frame characterized by (x^n, y^n, z^n). The z^c ($z^c=x^n$) component in the collision frame is parallel to the incoming relative momentum vector $\mathbf{k}_{in}$, and $x^c=y^n$ axis is defined such that $\mathbf{k}_{out}$ points into the first or second quadrant of the (x^c, y^c) plane. The $y^c=z^n$ axis is parallel to the angular momentum transferred.

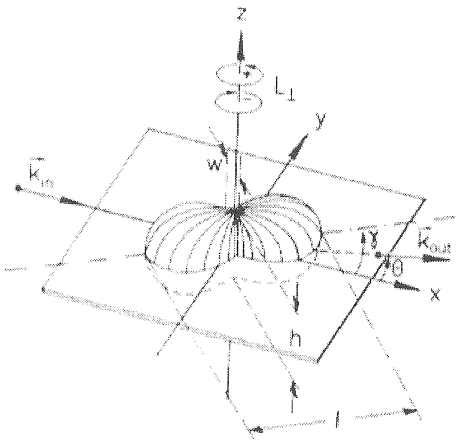

Figure 3. The schematic illustration of an excited p-state charge cloud drawn in the collision and the natural frames.

In the natural coordinate frame, there are two possible basis sets, the atomic and the molecular basis set. The atomic basis set (figure 4a) is defined by the magnetic quantum numbers M and the molecular basis set (figure 4b) by the orbitals $|P_x\rangle$, $|P_y\rangle$ and $|P_z\rangle$ or alternatively $|\sigma\rangle$, $|\pi^+\rangle$ and $|\pi^-\rangle$.

The description of the excited state is independent of whichever basis set is chosen. Thus, in the following text, we will use the atomic basis sets of the natural frame and indications for the sets will no longer be present (for deteails see ref. [17]).

5.3. Correlation Studies

Determination of the collision-induced alignment and orientation parameters of the atomic charge cloud is observed from a simultaneous determination of the scattering angle of the interacting particles and the shape or angular momentum of the excited atom. While the scattering angle is determined as in standard differential scattering experiments, information about the excited atomic state is obtained from the subsequently emitted radiation. One must correlate the two types of information, the scattering angle and the radiation characteristics of the atom, and the term "correlation" is used to characterize these experimental approaches.

Correlation studies of excited atoms are divided into two parts; namely polarization and angular correlations:

• Polarization correlation analysis, i.e., a measurement of the Stokes parameters P_1, P_2, P_3, P_4 in one or several suitably selected directions in space.

• Angular correlation analysis, in which the angular distribution of the photons containing the collision center is mapped. This is equivalent to a measurement of the two linear light polarizations P_1 and P_2. The correlation approach, therefore, gives less information than polarization correlation; nevertheless, it is often used in cases where photon polarization analysis is difficult, such as VUV region of emitions [9].

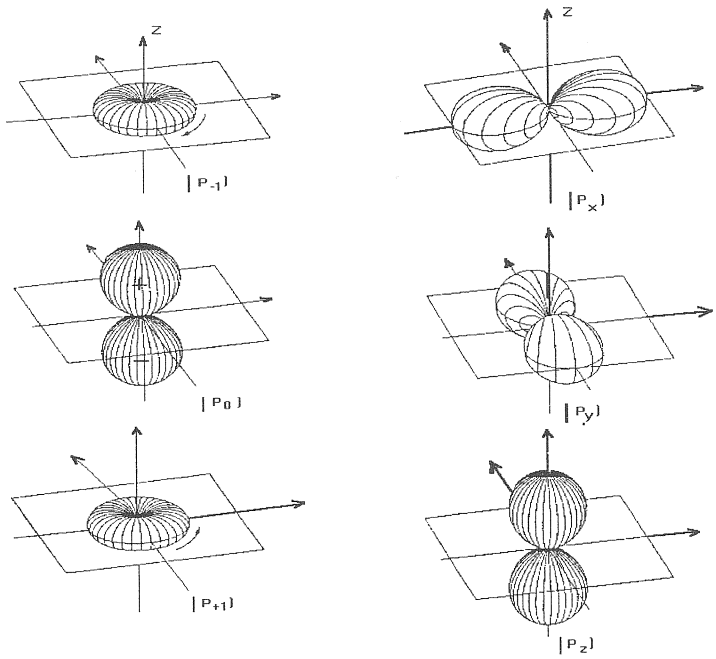

Figure 4. (a) The atomic basis, (b) The moleculer basis.

The study of electron impact excitation processes using either the *electron-photon polarization* or *electron-photon angular correlation method* are now well established in atomic collision physics. In principle correlation methods can provide a complete quantum mechanical description of excitation processes. In practice this is true for only a limited number of cases, for example, S-P excitation in helium. The experimental data relate directly to the way in which angular momentum is transferred to the atom during the collision process, and is thus intimately associated with the collision

dynamics. These experiments provide a very sensitive test of theoretical approximations developed to predict the excitation process.

5.4. Polarization Correlations

It consists of a determination of the polarization characteristics of the radiation emitted by the excited atoms and detected in coincidence with the appropriate scattered electrons. In the polarization correlation method, the shape of the charge cloud in the scattering plane is given by the intensity distribution of the radiation emitted perpendicular to the scattering plane following transmission by a rotating linear polariser. The polarization of the light emitted in a particular direction can be completely described by the three Stokes parameters which are;

$$P_1 = \frac{I(0^\circ) - I(90^\circ)}{I(0^\circ) + I(90^\circ)} \tag{11a}$$

$$P_2 = \frac{I(45^\circ) - I(135^\circ)}{I(45^\circ) + I(135^\circ)} \tag{11b}$$

$$P_3 = \frac{I(RHC) - I(LHC)}{I(RHC) + I(LHC)} \tag{11c}$$

where $I(\phi)$ is the intensity of light with polarization vector in the ϕ direction, and I(RHC), I(LHC) are the intensities of the radiation characterized by helicity -1 and +1 respectively. By setting ϕ=0°, 90°, 45° and 135° one can obtain the respective intensities of the linearly polarized components of the light emitted perpendicular to the scattering plane.

Using the Stokes parameters then we can obtain the charge density as

$$I(\phi) = K[1 + P_l \cos 2(\theta_\gamma - \gamma)] \tag{12}$$

where K is constant. We can also obtain similar definitions by using *reduced Stokes parameters* for the charge distribution of the excited $H(2^2P)$ [29] and ionized-excited $He(2^2P)$ [30] immediately after the collision. The density of the charge distribution can be obtained in terms of $\overline{P}_l$ and γ,

$$I(\phi) = K[1 + \overline{P}_l \cos 2(\theta_\gamma - \gamma)] \tag{13}$$

where

$$\bar{P}_l = (\bar{P}_l^2 + \bar{P}_2^2)^{1/2} \tag{14}$$

$$\gamma = \frac{1}{2} \arg(\bar{P}_l + i\bar{P}_2) \tag{15}$$

The angular momentum of the charge cloud (the orientation parameter) can be written as

$$\bar{P}_3 = -2\sqrt{2}\, I = -L_\perp. \tag{16}$$

The relationship between the Stokes and the reduced Stokes parameters is,

$$\bar{P}_{1,2} = \frac{7}{3} P_{1,2} \text{ and } \bar{P}_3 = P_3 \tag{17}$$

5.5. Angular Correlations

In the *electron-photon angular correlation method*, the angular distribution of the decay photon is measured in coincidence with the electron scattered in a particular direction. There are two possible cases which are fully coherent and incoherent cases. We will discuss the both cases, respectively.

5.5.1. The Fully Coherent Case

The most widely studied case in the field of collisional alignment and orientation investigations is the electron impact excitation of helium to the 2^1P_1 state due to its experimental convenience and the fact that theoretical interpretation of the experimental data is straightforward.

$$e_i\,(E_0, k_{in}) + He(1^1S_1) \rightarrow He(2^1P_1) + e_s(E_{out}, k_{out}, \theta_e) \tag{18}$$

where e_i denotes the incoming electron before the collision and e_s the scattered electron into a scattering angle of θ_e in the collision plane after the collision. For helium, the L-S coupling scheme can be assumed and the influence of the spin-orbit interaction during the collision neglected.

The basic argument for this, the Percival Seaton hypothesis [31], is that the collisional interaction time ($\cong 10^{-15}$s) is much shorter than the spin precession time due to the spin-orbit interaction ($\cong 10^{-12}$s) so that the spin of the electrons is space-fixed during the interaction. Thus the spin of the system

and its orientation in space is conserved during the collision, its value being that of the free electron, 1/2.

The excitation of a specific 2^1P_1 substate $|M\rangle$ is described by a scattering amplitude $a_M = a_M^D + a_M^E$ which may be decomposed into a direct part, a_M^D and an exchange part, a_M^E [32]. These two parts are, however, in principle experimentally indistinguishable and are independent of the initial orientation of the electron spin. The excitation process is thus fully coherent and the excited ^1P state may be described as a coherent superposition of degenerate magnetic sublevels. In the natural frame using the atomic basis set this can be expressed as

$$|^1P_1| = a_1|1\rangle + a_0|0\rangle + a_{-1}|-1\rangle \tag{19}$$

Additionally, since no spin flip can occur, the reflection symmetry of the atomic wave function with respect to the collision plane is conserved during the collision. The initial isotropic $^1S_0$ state has reflection symmetry +1, so the $^1S_1$ state has the same symmetry. After taking the symmetry arguments described in section (5.2) into account, expression (19) becomes

$$|^1P_1| = a_1|1\rangle + a_{-1}|-1\rangle \tag{20}$$

since the $a_0|0\rangle$ orbital has negative reflection symmetry and cannot be populated. Therefore, the excited state can be described by two complex amplitudes which we assume to be normalized to unity;

$$\sum_m |a_m|^2 = 1 \tag{21}$$

The shape of the resulting charge cloud can be obtained from the following wave function

$$\left|\Psi(n^1P)\right\rangle = a_1\left|1\right\rangle + a_{-1}\left|-1\right\rangle \tag{22}$$

The angular part of the charge distribution may be expressed in terms of P_l and γ;

$$P_1 = 2|a_1||a_{-1}| \tag{23a}$$

$$\gamma = -\frac{1}{2}\arg(a_1\, a_{-1}) \pm \pi/2 \qquad (23b)$$

where P_l is the relative difference between the length and width, γ is the charge cloud alignment angle and also $\gamma = -(\theta_\gamma)_{min}$, where $(\theta_\gamma)_{min}$ is the angle where the coincidence between the scattered electron and the emitted photon is minimum ($-\pi/2 \le \gamma \le \pi/2$).

We can also define the angular momentum expectation value, $L_\perp$, perpendicular to the collision plane in the natural frame. It should be noted that $L_\perp$ cannot be determined directly from an angular correlation measurement. However, its magnitude is determined from

$$|L_\perp| = \sqrt{1 - P_l^2} \qquad (24)$$

5.5.2. The Incoherent Case

As being the simplest atom, atomic hydrogen has been a testing ground for most of the theoretical works dealing with the more sophisticated problems. However, correlation studies with atomic hydrogen are more complicated than for atomic helium. In principle it introduces a new situation in the analysis and interpretation of the coherence and correlation experiment since an atomic doublet state is excited. For example $H(2^2P)$ [33] and $He^+(2^2P)$ [34]. Excitation process of hydrogen atom in ground state (1^2S) to first excited state (2^2P) is expressed as

$$e_i + H(1^2S_{1/2}) \rightarrow H(2^2P_{1/2,3/2}) + e_s(\theta_e) \qquad (25)$$

and for simultaneous ionization-excitation of helium case

$$e_i + He(1^1S_1) \rightarrow He^+(2^2P_{1/2,3/2}) + e_s(\theta_e) + e_e \qquad (26)$$

When discussing the complications of the analysis of coherence and correlation experiments in the present case we must distinguish three different aspects:

(i) The H(2p) and H(2s) states are nearly degenerate, therefore, coherence between s and p excitation can be detected in principle [35]. However, most experiments to date have been performed with low electrical

and magnetic fields so that no coupling between the s and p-states occurs once the collision process is over. Only the 2p state can decay radiatively and the data analysis may be restricted to the 2p excitation itself.

(ii) The excitation process happens in about 10^{-15}s. The emission of the light occurs after a time interval of about 10^{-9}s. This life time is long compared to the Larmor precession time ($\cong 10^{-12}$s) of the electron spin and it can be assumed that the atom has completely relaxed into its $2^2P_{1/2}$ and $2^2P_{3/2}$ states before emitting the photon which carries the information for the atomic charge cloud.

The intensity distribution $I(\theta_\gamma)$ in a correlation experiment can be described in terms of Andersen Parameters; $\overline{P}_l$ and γ by taking the depolarization of the original charge cloud due to fine structure relaxation into account. In the collision plane

$$I(\theta_\gamma) \propto 1\text{-}b\,\overline{P}_l \cos 2(\theta_\gamma - \gamma) \tag{27}$$

where $\overline{P}_l$ is the linear polarization of the nascent charge corresponding to the relative difference between the length (l) and width (w) of the charge cloud shown in figure 3,

$$\overline{P}_l = \frac{l-w}{l+w} \tag{28}$$

and γ is the alignment angle of the charge cloud and it is given in eq. (23b).

The coefficient b in eq. (27) takes account of the fine structure depolarization. For a P→S transition and assuming the nascent charge cloud has no height in the z direction,

$$b = 3G_2/(4\text{-}G_2) \tag{29}$$

where G_2 can be extracted from the following expression:

$$G_2 = G_2(t) = \frac{1}{3}[1+2\cos(w_{fs}t)] \tag{30}$$

where G_2=1/3 for the present case so that the constant b in expression (27) is b=3/11 [17].

(iii) Although the direct and exchange process could not be individually detected in the e-He case, there is a possibility of distinguishing these processes in the present case by spin analysis of both the scattered and the atomic electron before or after the collision. Also the excited atomic 2p-state can no longer be described by a single pure state as was possible in the e-He case.

Consequently, in the present, one cannot in general extract $|L_\perp|$ from $\overline{P}_1$ (eq.24). A full determination of all measurable quantities is only possible by determination of γ, $\overline{P}_1$ and the circular polarization P_3.

6. DISCUSSION

In this paper, we have outlined the studies for excitation of an atom by electron impact. The goal of the type of a work is the determination of special parameters to explain an excited atomic state. Here, it is shown that one must determine as much parameter as possible after the collision.

Therefore, one can completely determine an excited state after an electron-atom collision using above descriptions. A full determination of an excited state is only possible by observation of the parameters P_1, γ and $L_\perp$ (or P_3). P_1 and γ are directly measured from an angular correlation experiment whereas $L_\perp$ is extracted from the measured parameters. However, the three parameters are directly measured in a polarization correlation experiment. Nevertheless, the direction of angular momentum ($L_\perp$) can not be observed in both type of experiment.

Acknowledgements: The authors would like to thank Prof. A. Crowe for helpful discussions and his guidance. MD acknowledges support from Government Planning Organization, through grant 2002K120110 and Afyon Kocatepe University Scientific Research Project Commission, through grant 031-FENED-07.

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