Angular momentum effects in electron scattering from atoms

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Abstract. This paper concerns angular momentum-dependent phenomena in excited gas-phase atoms using incident photons or electrons in scattering experiments. A brief overview indicates the main capabilities of experimental techniques and the information which can be deduced about atomic structure and dynamics from conservation of momenta with measurement of polarization and detection of the number of emerging electrons, photons and ions. Maximum information may be obtained when the incident particles and the targets are state-selected both before and after scattering. The fundamental scattering amplitudes and their relative phases, and consequently derived quantities such as the parameters describing the electron charge cloud of the atomic target, have enabled significant advances of understanding of collision mechanisms.

The angular momentum-dependent scattering probabilities change when, for example, the spin-orbit interaction for the target electrons becomes large compared with the Coulomb electron-electron interactions and also when electron exchange and the relative orientation of the electron spins change. Several examples are discussed to indicate significant principles and recent advances. Major contributions to this field from the technology associated with electron spin production and detection time, as well as time-coincidence detection, are discussed. New results from the authors’ laboratory are presented.

1. Introduction
Recent progress in experimental studies of atomic collision processes concerns angular momentum changes associated with (i) polarized colliding particles enabling spin effects, such as electron exchange and spin-orbit interaction, and with (ii) coincidence techniques exploiting symmetry constraints to study scattering dynamics. Theoretical progress using non-perturbative R-matrix close-coupling methods, distorted wave Born approximation (DWBA) methods and propagating complex exterior scaling methods is covered elsewhere [1] and generally indicates advanced numerical and wave function choices enabled a good description of most collision processes involving simple one and two-electron atoms. The meeting places of calculation and experiment are usually derived from a collision model for which the scattering amplitudes and their relative phases can describe the observables. Some background information is given now to indicate the nomenclature and reason behind various observational strategies for conducting scattering experiments.

It was shown long ago, for example Fano [2], Fano and Macek [3], Macek and Hertel [4], that amplitudes and phases could be related readily to state multipole moments, irreducible
components of the collision density matrix and expectation values of the components of angular momenta. These equivalent descriptions allowed the observed characteristics to be described in a physical way such that the geometry and dynamical factors were separable and the observables were readily associated with the symmetry of the experiment. This approach is suited to experiments in which changes are made in the collision system, the colliding particles before collision or the detection system and, for example, is associated readily with the polarization of the particles before and after scattering. For example, classical visualization of an excited atom usually is obtained more readily from an electronic charge distribution which can be derived from the electrostatic potential of a charge distribution. Then after expansion in terms of spherical harmonics and multipole moments, an equipotential surface can be interpreted as a simplified picture of an atom as a surface-charged rigid body from which a classical view of angular momentum can be developed. These early papers point out the situations in which it is advantageous, for reasons of simplicity, to choose an appropriate quantization direction for particular experimental geometries or polarization of a particle or detector properties.

The quasi-classical view can be expanded further to relate the collision times $T$, such as $T_{FS} \gg T_{col}$, to a typical interaction range, $R$, and relative scattering velocity, $V$, in which $hR/(V \Delta E_{FS}) \ll 1$ where $\Delta E_{FS}$ is the atomic energy change in a spin-orbit interaction. Also, for example, if $T_{FS} \approx h/\Delta E_{FS} \gg T_{col}$, the spin-orbit coupling may be weak and the electron spin uncoupled from the orbital angular momentum so that only the orbital angular momentum scattering amplitudes have to be known. The consequential considerations of both the experimental and theoretical approaches may then be simplified. Andersen and Bartschat [5], for example, give a detailed discussion of these aspects of electron scattering.

Various examples of the way in which these fundamental ideas have been implemented could be drawn from the areas of relevance here. For example, in photon impact studies such collision processes include photo-ionization of polarized atoms, resonance effects in multiphoton ionization, spin polarization and rotation in photo-ionization and polarization in multi-photon ionization of atoms in intense laser fields. Also in electron impact scattering the processes include laser-assisted and laser-produced scattering, spin-polarized Auger electrons and polarization effects in inner and outer shell excitation. The experimental techniques and apparatus, which are related particularly to advances in angular momentum-dependent features, include sources and detectors of polarized electrons, particularly position-sensitive detectors, circular and linear polarizers, photon-photon correlation methods, stepwise excitation with electron-photon coincidence techniques, the collision of cooled and polarized atoms and spin-dependent (e,2e) techniques. All these aspects deserve discussion but here we concentrate on aspects of angular momentum transfer in electron impact excitation processes. A second application with an atomic approach to surfaces, particularly with the polarized (e,2e)-in-reflection method, is discussed in a separate paper.

Fundamental quantum mechanics indicates that it is angular momentum in an atom that is quantised and that the angular momentum transfer between states determines the nature of the emitted radiation. Atomic spin may become visible in emitted radiation for transitions between fine-structure levels and when the spin-orbit interaction, within the atom between excitation and decay, transfers spin orientation into orbital angular momentum; for example when circularly polarised light is produced without resolving the fine structure. An atom may become oriented, for example, if its spin system becomes polarised after electron exchange. For the plane polarization data the expectation values of the second order products of angular momenta are determined while the circular polarization determines the first order angular momentum, along a given quantization axis. From these, and other, fundamental ideas the measurements which enable the visualisation of the size, shape and rotation of the electron charge cloud of an excited state, as depicted in figure 1, were developed over many decades [3, 5] and references therein. The linear momenta of the incident, $k_{in}$, and scattered, $k_{sc}$, electrons
create a well-defined plane of symmetry, the scattering plane, and in the collision the reflection symmetry, with respect to this plane, is conserved. The charge cloud of an atomic $^1P_1$ state is represented in figure 1 with its relative length ($\ell$), height ($h$), width ($w$) and alignment angle ($\gamma$). An additional parameter $P_\ell$ describes the shape of the charge cloud in the scattering plane and is defined as the difference between the length and width, or maximum and minimum density $|\Psi|^2_{\text{max}}$ and $|\Psi|^2_{\text{min}}$, respectively.

There are numerous ways in which observations can be made to obtain various qualitative descriptions of electron scattering processes. A representation of an electron scattering experiment to observe properties such as shape, alignment and orientation of an excited atomic state charge cloud is indicated in figure 2 which shows the reference axes and the electron and photon detectors and scattering angles.

2. Angular momenta from unresolved-spin experiments

In the experiments described in this section, unpolarized electron beams are used. The essential observational requirement is to detect the electron scattered at an angle $\theta$, and the radiated photon from the same quantum ensemble and this can be achieved by detecting them in time-coincidence and selecting an appropriate scattering symmetry. First, we discuss atoms which are excited into a $^1P_1$ state, i.e. s-p excitations from a fully spherically isotropic $s^2$ ground state. For a fully coherent process, the alignment indicates a non-isotropic distribution of magnetic sublevels $|JM>$ with expectation values $<M^2>$=$<J^2>/3$. For symmetry reasons, angular momentum $L_\perp$ can be transferred between the interacting particles only perpendicular to the collision plane, as indicated in figure 1. The atom is oriented if it has a finite expectation value of angular momentum, and in figure 1 that means there is an unequal population of the $m = +1$ and $m = -1$ magnetic sublevels with the quantization axis parallel to the z-axis.

For the particular case of excitation of the $^1P_1$ state of helium, all of the dimensionless electron impact coherence parameters (EICPs) $P_\ell$, $\gamma$ and $L_\perp$ can be determined [5] from the polarization properties of the emitted photons when detected in coincidence with the energy loss electrons.
scattered at an angle $\theta$. The measured quantities are the differential Stokes parameters defined as:

$$I_P(\theta) = [I(0^\circ) - I(90^\circ)], \quad I_P = [I(45^\circ) - I(135^\circ)], \quad I_P = [I(R) - I(L)]$$

(1)

where $I = [I(0^\circ) + I(90^\circ)] = [I(45^\circ) + I(135^\circ)] = [I(R) + I(L)]$ and $I(\varphi)$ corresponds to the number of true electron-photon coincidences with photon polarization vector at an angle $\varphi$ with respect to the direction of the incident electron beam, the $x$ axis in figure 2. Also $I(R)$ and $I(L)$ are the numbers of right and left handed circularly polarized photons, respectively. Measurements of the linear polarization Stokes parameters, $P_1$ and $P_2$, determine the polarization of the charge cloud $P_1$ and alignment angle $\gamma$, while measurements of the circularly polarization Stokes parameter, $P_3$, reveals information on the angular momentum $L_\perp$ where

$$P_1 = \sqrt{P_1^2 + P_2^2}; \quad \gamma = 0.5 \arg(P_1 + iP_2); \quad L_\perp = -P_3.$$  

(2)

The electron-photon coincidence detection method can be used in two different ways to obtain equivalent information on $P_1$ and $P_2$ leading to the determination of $P_1$ and $\gamma$ from the linear polarization measurements. In the angular correlation method electrons scattered at an angle $\theta$ and the decay photons emitted at a variable angle, usually in the scattering plane, are detected in coincidence while, in the polarization correlation method, the scattered electrons are detected in coincidence with the linearly polarized photon detected in the direction of the $z$-axis, as described above. The equivalence of the two methods is evidenced by noting that the axes of the intensity distribution coincide with the axes of the polarization ellipse. The main difference between the two methods concerns the determination of $L_\perp$ for which a circular polarization has to be measured independently. The angular correlation method gives an absolute value only when complete coherence, i.e. $(P_1^2 + P_2^2 + P_3^2)^{1/2} = 1$, is either measured or assumed. These consideration have been applied to various atoms and selected scattering dynamics in the following sections.

For the specific case of 50 eV electrons exciting the $1s2p^1P_1$ state of helium, and observing the radiated photons of 58.43 nm wavelength in coincidence with the energy-loss electrons scattered through 70°, the charge cloud may appear similar to that in figure 1. Experimental results for this particular excitation process have been obtained mainly using the angular correlation method due to its simplicity compared with the polarization measurements in the vacuum-UV region. Some representative experimental data for the angular behavior of the differential cross section $\sigma(\theta)$, the linear polarization $P_1$, and the alignment angle $\gamma$ of the charge cloud and the momentum transfer $L_\perp$, at an electron impact energy of 50 eV together with predictions of the CCC and RMPS models, are shown in figure 3. For reasons of clarity in the next two figures only a subsection of published data is shown. The choice illustrates the agreement that can be obtained between different experiments and the agreement of experimental data with calculations.

There are two important properties of the electron coherence parameters displayed in figure 3. The first concerns the quantum completeness of the data set. In an ideal situation, which is the case of excitation of the helium $1s2p^1P_1$ state, a perfect scattering experiment determines all the scattering amplitudes and their relative phases. For an $S \rightarrow P$ excitation and the geometry of figure 1, the transition into the $M_L = 0$ state is forbidden due to conservation of symmetry in the scattering plane, so only the scattering amplitudes $f_{-1}$ and $f_{+1}$ need be considered. This process is determined by the three parameters, the absolute differential cross section $\sigma = |f_{-1}|^2 + |f_{+1}|^2$ and two more dimensionless parameters determining the relative magnitudes and phases of the amplitudes. In this sense the parameter set $\{\sigma; L_\perp; \gamma\}$ is sufficient, and their determination constitutes a perfect scattering experiment [13]. These data serve as a benchmark for other studies.
Figure 3. Differential cross section $\sigma(\theta)$, $L_\perp$, $P_z$, and $\gamma$ for electron impact excitation of the $2^1P_1$ state of helium at 50 eV. Experimental data: $\sqcap$, Cartwright et al [7]; $\blacklozenge$, Beijers et al [8]; $\bigcirc$, McAdams et al [9]; $\blacktriangle$, Eminiyan et al [10]; Theory: bold line, CCC Fursa and Bray [11]; thin line, RMPS Bartschat et al [12].

The second property concerns the relative nature of the electron impact coherence parameters which permits a sensitive comparison between the theoretical and experimental data as no absolute calibration is needed. Inspection of figure 3 indicates good agreement between experimental and theoretical predictions for all four parameters. The behavior of the momentum transfer $L_\perp$ from the electrons to the atom and its influence on the atomic state polarization $P_z$ and the alignment angle $\gamma$ can be traced from the angular behavior of the parameters. First, at small scattering angles $L_\perp$ is positive and at large angles negative and this indicates a change in orientation equivalent to the change of direction of rotation of the electron charge cloud. Also the behavior of $P_z$ and $\gamma$ has some common features which can be traced to the behavior of the expectation value of orbital momentum, $L_\perp$. For those scattering angles where a nearly-circular state ($L_\perp \approx +1$ or $L_\perp \approx -1$) is created, excitation of the $M_L = +1$ or $M_L = -1$ magnetic sublevel is predominant, both $P_z$ and $\gamma$ exhibit a rapid variation, which for the alignment angle $\gamma$ involves the change of sign between the forward and backward scattering.

The insight gained into the importance of the angular momenta in such a scattering process is made more apparent by comparing the parameters $\sigma$, $P_z$, and $L_\perp$ for helium with the same parameters for the two more complex atoms, Mg ($Z = 12$) and Ca ($Z = 20$), as shown in figure 4. These atoms, with a low atomic number and a quasi two-electron configuration similar to helium and small fine structure splitting i.e. weak spin-orbit interaction between atomic electrons, are expected to conform to $LS$ coupling and be representative of light metal atoms. The ground state of these two atoms is still a spherically isotropic $s^21S$ state, and excitation into a first optically allowed $nsnp^1P_1$ state is expected to be fully coherent.
Figure 4. Differential cross sections $\sigma$, $L_\perp$ and $P_\ell$, for Ca at 25 eV and Mg at 40 eV compared with corresponding He values at 200 eV. Experimental results: •, Murray and Cvejanović [14]; ■, Filipović et al [15]; □, Brown et al [16]. Theory: Full line, for Ca, Kawazoe et al [17] (R-matrix model); for Mg, CCC model, Fursa and Bray [18]; dashed line, CCC theory for He at 200 eV, Fursa and Bray [11].

The data for Mg [16] were obtained using the polarization correlation method with detection of the 4.35 eV energy-loss electron in coincidence with the 285.2 nm radiated photon. The experiment by Murray and Cvejanović [14] for Ca used a third method which can be considered as a time-inverse polarization correlation method. Polarized (linear or circular) laser light (wavelength of 422.7 nm) is used to pump the atom into a well-defined $M_L$ state and observations are made of the super-elastic scattering of electrons at a variable angle $\theta$ from the already aligned and oriented atoms. The advantage of this method is its good time efficiency compared to the relatively slow coincidence experiments; here the intensity of the scattered electrons, with an energy gain of 2.93 eV only, is measured so that better statistical accuracy with measurements on a finer mesh of scattering angles can be achieved. The disadvantage is the limited applicability
to transitions which can be pumped efficiently by lasers. Energies at which data were recorded correspond roughly to ten times the excitation thresholds for both Ca and Mg and the parameters are compared in figure 4 with corresponding values for helium $^1S^2S^1P_1$ state at 200 eV, again at roughly ten times the excitation energy. The helium data were calculations using convergent close-coupling theory [11].

A brief inspection of figure 4 indicates some common characteristics as well as significant differences between He and Ca and Mg, but also between the two metal atoms. All the parameters for Ca and Mg show angle-dependent structures in contrast with He for which parameters change rather smoothly. Of special interest here is the relationship between the maxima and minima in the differential cross sections and the structures in the angular behavior of the different electron impact coherence parameters. The physical origin of these effects was modeled in the calculations of Madison et al [19] which explained the observed behavior in helium by quantum mechanical interference phenomena. The main factors determining the positive $L_\perp$ at small scattering angle are nuclear attraction and distortion of the $\ell_p = 0$ and 1 incident electron partial waves, while distortion of the $\ell_p = 0$ and 2 is the most important for negative values at large scattering angles.

A particular difference is observed in the momentum transfer at forward and backward scattering angles in Ca and Mg. In Ca, a circular state is created in a large range of backward scattering angles between approximately 100° and 150°, while only smaller values up to approximately $L_\perp = 0.5$, are measured and predicted at scattering angles less than 90°. In contrast, two circular states with $L_\perp \approx \pm 1$ are created in forward scattering in Mg, i.e. at angles $\theta < 90°$, while only a small momentum transfer happens at scattering angles $\theta > 100°$. As the structure of these two atoms in terms of ground state electron configuration is very similar, the observed differences can be used to improve our understanding of momentum transfer in complex atoms. The behavior of the momentum transfer $L_\perp$ has been discussed for sodium [20], calcium [21], and magnesium [22]. A review by Cvejanović et al [23] of the data for the alkaline earth atoms indicated the generality of the observations.

As the final topic in this section an example of Stark-mixed states is discussed briefly to indicate an angular momentum consideration. The transitions discussed so far are the normal dipole transitions in which the atomic system changes parity. However levels of opposite parity may be Stark-mixed with an external weak electric field to carry information on the levels of both parity and on their degree of coherence [24]. For an atomic hydrogen target, quantum beats arise from the $S-P$ coherence, for example, and from the Stark mixing in the subsequent time development of the atomic fine and hyperfine superposition states. These features may be deduced from figure 5 which shows two examples of the remarkable time development of the circular Stokes parameters $IP_3$ for a positive (left) and negative (right) electric field of 250 V/cm, an incident electron energy of 350 eV and an electron scattering angle of 3°. The phase difference between the positive and negative field beat structures is about 180° while the calculated behavior was modeled with a neglect of the coupling to the $m_j = 3/2$ states which appeared to be reasonable for the weak electric field. It is noted that the data were limited by the large value of the $2^2P$ cross section relative to the $2^2S$ cross section for the scattering energy and angle. Measurements at larger angles where the ratio of $2^2P$ to $2^2S$ approaches unity would enhance the beat structure and make interpretations of the changing values of the interference more clear. However other observations of the linear polarization showed much smaller amplitudes of the beat structure than observed for the circular polarization, as shown in figure 5, i.e. the populations of the magnetic sublevels reflected the transfer of angular momentum along the quantization axis and the collision mechanism favored the unequal populations of the $m = +1$ and $m = -1$ sublevels for the particular scattering conditions.
3. Observation of electron exchange and spin-orbit interaction in experiments with spin polarized particles

The initial and significant studies of spin angular momentum effects in electron scattering have been developed and reviewed by Kessler [25] and Hanne [26] and references therein. Basically, the spin-orbit \( SL \) interaction between the continuum electron and a target atom results in different scattering potentials seen by electrons with different spin projections. This interaction leads to a difference of the fractions of scattered electrons with spin-up and spin-down, relative to a given quantization axis, which is defined as the spin polarization \( \tilde{P} \). In this way unpolarised electrons become polarized through scattering and an existing polarization \( \tilde{P} \) may be analysed through the left-right asymmetry in a differential cross section which is energy and angle dependent. There are many combinations of angular momentum effects which can be pursued, depending on the relative strengths of electron exchange and the spin-orbit interaction in the target atoms and whether the target atom is initially polarized. In general, the spin asymmetry in scattering from spin-1/2 targets may arise from pure exchange, from the spin-orbit interaction or a combination of both exchange and spin-orbit effects.

In a pioneering experiment, Baum \textit{et al} [27] determined spin asymmetries for polarized electrons incident on polarized lithium atoms for which the spin-orbit interaction is negligible (for a very light atom) and electron exchange is the dominant spin effect. Their work gave a general discussion of the major components of such an experiment and was a landmark in showing how to perform a crossed polarised-particle beams scattering experiment and gave a general discussion of the major components of such an experiment. Their approach enabled the direct determination of spin-dependent scattering amplitudes and their relative phases. Spin asymmetries, of the inelastically scattered electrons after exciting the \( ^2S \) to \( ^2P \) transitions, were measured at angles of 65°, 90° and 107.5° in the double differential cross section and then the integral of the previous measurements was measured by detecting the photon intensities at 90° for spins up and down. In this way the ratio of singlet to triplet scattering was shown to be large near the threshold of 1.85 eV and near zero about 6 eV above threshold; thus the singlet scattering was large nearer threshold and by about 6 eV the singlet and triplet scattering probabilities are about equal. An asymmetry can occur even if the scattering angle is not defined,
Figure 6. Representation of the change in the polarization vector in a scattering process. Symbols are as follows:

\[ P_x' = \frac{T_x P_x - U_{xy} P_y}{1 + S_A P_z} \quad P_y' = \frac{T_y P_y + U_{yx} P_x}{1 + S_A P_z} \quad \text{and} \]

\[ P_z' = \frac{S_u + T_z P_z}{1 + S_A P_z} \text{ with } \sigma_u = (1 + S_A P_z). \]

i.e. when averaged over all angles, and in that way integral and differential measurements can be performed, as shown for example for elastic [28], excitation [27] and ionization [29] processes.

Further developments of this approach can determine in principle a quantum mechanically complete scattering experiment by measuring the changes of the components of the polarization vector. These changes are defined simply, as indicated in figure 6 by the \( T \) and \( U \) contraction and rotation vectors, respectively, by the left/right asymmetry \( S_A \) and the polarisation-after-scattering \( S_P \). While it is physically intuitive to discuss length and angles of vectors it is very difficult to measure all the \( S, T, U \) parameters, so measuring one or a few of these parameters provides valuable information for understanding collision processes. For example, for the special case where both the photons and the initial electron polarization directions are perpendicular to the scattering plane, the spin-up/down asymmetry \( S_P \), given by the difference over the sum of the intensities of the emitted photons corresponding to spin up and spin down electrons respectively, may be measured relatively easily. As a step in this direction, we have measured the spin up/down asymmetry for 26 eV and 60 eV incident 30% polarized electrons exciting the \( 5^p \) \( ^3 \) state of krypton atoms, as shown in figure 7 [30], using the polarized electron-photon (\( \lambda = 826.3 \) nm) coincidence technique.

The spin up-down asymmetry may be non-zero due to either the "fine structure" effects [31] or the spin-orbit interaction for the continuum electrons or the combined effects of both mechanisms. The mechanism for spin up-down asymmetry due to fine-structure effects arises for the excitation of \( 5^p^6 \rightarrow 5^p^56\ell \) of krypton (826.3 nm) because an oriented ionic \( 5^p^5^2P_{1/2,3/2} \) core may be produced since the cross sections for exciting the \( M_l = \pm 1 \) magnetic sublevels of the ionic \( ^2P \) core are different (for a quantization axis perpendicular to the scattering plane). This orbital orientation causes a spin orientation of the ionic core when the final \( J \) state is resolved, here by detection of the radiated 826.3 nm photon in coincidence with the energy-loss scattered electron. The spin of the excited electron is thus defined because of the conservation of the spin angular momentum. Then a spin-up/down asymmetry may be observed since the cross sections for spin-up/down incident electrons are different. While the asymmetry was observable there was a significant difference between the observations and the calculations from a relativistic distorted wave approximation which indicated a stronger angular dependence and larger asymmetries.

The connection between the observables and the scattering amplitudes has been given by Mette et al [32], and also Guo et al [33], for the specific case of the spin-resolved triple differential ionization cross sections of xenon. The most recent publication [34] enable earlier work to be traced and will not be discussed further here.

Our final example is for the special case of excitation of the \( 6^3P_J \) states of mercury where the
Münster group [35, 36, 37] showed in a series of separate experiments how all of the $S$, $T$ and $U$ parameters can be measured when the $J$ sublevels of the $6^3P_{0,1,2}$ level are separated. The lack of subsequent complete experiments indicates the difficulty of the measurements even though there is still a significant demand for such data. Their data for the $6^3P_1$ excitation (observing the 254 nm photons in the decay to the $6^1S_0$ state) for an incident electron energy of 8 eV and the $6^3P_2$ state excitation at 40 eV are shown in figure 8. The angular differential excitation cross sections (noting the change of scale in the figure) display the usual angular behaviour for singlet and triplet transitions at this relatively low energy. The extensive data at 40 eV indicate a generally good agreement between measurement and the relativistic distorted-wave calculations of Srivastava et al [38] and of Bartschat and Madison [39] and so indicate the general applicability of their basic scattering model. The model gives a good understanding of angular momentum effects observed in such measurements since the difference arises from the different $J$ values and the relative values of exchange and the spin-orbit interaction, apart from the different incident energies. For a light atom for which $LS$-coupling may apply, the orbital orientation $L_\perp$ is identical to the total angular momentum component $J_\perp$; however in contrast for a heavy atom such as mercury the orientation of $J_\perp$ may depend on the spin projection onto the quantization axis. In figure 8 it is seen in the 40 eV data that the $S_A$ parameter changes in sign numerous times as do the theoretical predictions. The model indicated the suitability of the intermediate coupling scheme with a superposition of pure $LS$-coupled $^1P_1$ and $^3P_1$ states to explain the shape of the spin asymmetry $S_A$ where the singlet admixture did contribute significantly to the scattering process by observing. It was deduced for these scattering dynamics that, for excitation of the $^3P_1$ state, spin-flips due to the spin-orbit interaction are small so they must originate mainly from electron exchange and this result is in contrast to excitation of the $6^1P_1$ state for which exchange is very small and the spin-orbit interaction causes a difference in spin-up/down cross sections.

**Figure 7.** Spin up/down asymmetry for 26 eV and 60 eV incident polarized electron energy. Full lines are RDW calculations. (from Yu et al [30])
Figure 8. The differential cross section and the S, T and U parameters as a function of the electron scattering angle for mercury atoms at (a) 8 eV for the $6^3P_1$ and (b) 40 eV for the $6^3P_2$ states. (from Andersen and Bartschat [5] p. 183)

4. Spin-related angular momentum effects in electron and photon impact
Measurements of the integrated Stokes parameters using spin polarized electrons is a powerful experimental approach characterized by high efficiency and high sensitivity. Integral here means that scattered electrons are not detected, so the intensity of the detected photons is integrated over all the electron scattering angles. The experimental geometry of figure 2 indicates the linear momentum and the transversely polarized spin vector of the incident electron beam define the x and z axes respectively. Then the three Stokes parameters can be defined as in equation (1) and with the same photon polarization conditions, but now direct photon intensities rather than the yield of true coincidences, are measured. The incident electron spin and linear momentum vectors define a plane of symmetry which enables angular momentum-dependent interpretations of the Stokes parameters. This definition of the parameter $P_1$ indicates it has the same value
irrespective of the spin polarization. Similarly in experiments with unpolarized electrons, a cylindrical scattering geometry applies and both $P_2$ and $P_3$ are always zero. However, in experiments with spin polarized incident electrons planar symmetry applies and the parameters $P_2$ and $P_3$ can have non-zero values as a consequence of the spin-orbit interaction ($P_2$), and exchange or a combination of exchange and spin-orbit interaction ($P_3$). These deductions [41] offer an efficient way to study these spin effects and their dependence on atomic structure and electron correlation effects.

The current interest in open-shell atoms, particularly $s$-subshell photo-ionization, concerns electron correlations in the form of interchannel coupling, particularly in the metallic atoms of Ca, Mg (discussed above) and Zn (discussed below) and in the spin polarization of photoelectrons, in the angular distributions and in the cross sections for the neon valence subshells [42, 43]. Our work on electron impact excitation processes in neon has shown the polarization of the decay photons depends on the different $LS$-mixing properties of the intermediate coupled states. The triplet components indicate exchange and spin-orbit interaction are important while for states with a large singlet component the spin-orbit interaction may be dominant. These comments apply in general to the transitions indicated in figure 9. Here we draw attention to the $\lambda = 703.3$ nm transition from the $2p^53p[1/2]_1$ to the $2p^53s[3/2]_2$ state. Figure 10 shows a strong resonance at $18.7 \pm 0.2$ eV in all the polarised excitation functions and that is in contrast with the magnitudes of the linear polarisations of those resonances which are seen in figures (a), (c) and (e) to be small. The near-zero values of $P_1$ and $P_2$ clearly indicate the influence of the dominant (98.2%) $^3S$ component of the state $LS$-composed wave function and of the $\Delta J$ value of -1 for the transition. The large circular polarisation $P_3$ indicates the electron exchange process is the dominant excitation mechanism. The small non-zero negative values of the $P_2$ parameter may be attributed to the effects of the negative ion resonances since the spin-orbit coupling effect within the atom is expected to be small for this state.

Our observations have provided a detailed description of the angular momentum changes in the excitation and decay processes of this $3p$ manifold of states [40]. The spin-orbit interaction within the atom is large and $LS$-coupling for the $J = 1$ states in the neon $3p$ manifold is apparent. The polarizations of the emitted photons depend on the different $LS$ mixing properties of the intermediately coupled states. For the states having a dominant triplet component, both the exchange and the spin-orbit interaction within the atom are important in the excitation, while the spin-orbit interaction plays the dominant role for the state dominated by a singlet component. For transitions coming from a common upper state, those with $\Delta J = 1$ have larger
Figure 10. Integral Stokes parameters (a,c,e) and corresponding polarized photon intensities (b,d,f) for the 703.3 nm transition from the 2p$^5$3p[1/2]$_1$ to the 2p$^5$3s[3/2]$_2$ state. In bottom figures open diamonds correspond to $I(0^\circ)$, $I(45^\circ)$ and $I(\sigma^-)$; full diamonds to $I(90^\circ)$, $I(135^\circ)$ and $I(\sigma^+)$. (from Yu et al [40])

linear polarizations than those with $\Delta J = 0$ and $-1$. For the transitions coming from the upper states with a different core state, those with a $^2P_{1/2}$ core have larger linear polarization than those with a $^2P_{3/2}$ core. The resonances have a more significant influence on the alignment of the excited states with a $J = 1/2$ core than for states with a $J = 3/2$ core.

The above studies are now moving in the direction of resonance phenomena and interchannel coupling where $j$-dependent spin effects can cause significant differences in partial wave amplitudes and their interference. An indication of spin effects is obtained from the photoionization of s-subshells in closed-shell atoms for which any deviation of the angular distribution parameter beta from 2.0 of the s-subshell photoelectrons is due necessarily to dynamical differences of the $p_{1/2}$ and $p_{3/2}$ transition amplitudes [44]. Strong resonances are indicated in figure 11 in the relative cross section and angular asymmetry parameter beta as a function of the incident photon energy for the Xe 5s-photoelectrons in the region of the 4d $\rightarrow$ mp $(m \geq 6)$ excitations. The resonances are associated with deviations of the angular distribution anisotropy parameter, $\beta$, from the nominal value of two which are enhanced by spin effects. This example is clear since without spin effects there is only a single $LSJ$ term $^1P_1$ describing the final state of ion plus electron and beta must equal two.

With the success of this study questions arise about the changes in the shift of the energy and the width of an isolated resonance when observed in different vector correlation parameters. Grum-Grzhimailo et al [45] discuss the earlier data and observed in Xe that the autoionizing $4d^{-1}5/2^6p$ ($J = 1$) resonance in the orientation and alignment parameters for the ionic ($^3P_2$)$6p_{3/2}$ and ($^1D_2$)$6p_{1/2}$ states in the total ion yield produced effectively different values of both the energy and the width, as shown in figure 12. However they fitted constant values for both the
energy and width by allowing for the different partial $D_{5/2}$ and $D_{3/2}$ differential cross sections, which could even explain different signs as well as magnitudes of the shifts. These effects have been discerned in photon impact studies using the large intensities from a synchrotron and the associated good wavelength resolution. They do not appear to have been detected in electron impact observations where the energy resolution, although good, does not rival that of a photon beam.

Similar insight into the role of spin-dependent interactions with negative ion resonances has been observed in our recent studies of electron impact excitation of zinc using spin polarized electrons. An energy level diagram showing the neutral, negative ion and autoionizing states of zinc and the observed 636.2 nm emission line is shown in figure 13. The incident electron excites the atom and is bound temporarily into a discrete state of the excited negative ion. Decay by auto-detachment of the electron leaves the atom in different excited states of the neutral atom which then decay by photon emission. Here we study the spin-orbit and exchange effects which are observable in the high precision measurement of the integral Stokes parameters $P_2$ and $P_3$ of the 636.2 nm photons emitted in the decay of the $4s4d^1D_2$ state of zinc shown in figure 13. All
three Stokes parameters reveal clear variation due to negative ion resonances. The structures were fitted to Fano profiles, fitted curves are also shown in figure 14 [46], to show the negative ion states had energies $E_r(1) = 10.97$ eV, $E_r(2) = 11.33$ eV and widths of $\Gamma(1) = 0.25$ eV and $\Gamma(1) = 0.25$ eV, respectively. Two aspects of these data are discussed. First, the dominant partial wave in which each resonance occurs can be identified often from the angular behavior of a differential cross section for electron impact excitation. An example showing the yield of electrons scattered at an angle $\theta = 30^\circ$ after exciting $4s\,4p\,^1D_2$ states of zinc is shown in figure 14(d) [47]. Also the polarization of the emitted radiation can be linked to the angular momentum of the negative ion state but the procedure has been applied so far only in the near-threshold region of the excited neutral states in mercury [48] where considerable simplifications can be applied. In the present case of negative ion states in the autoionizing region, where the electron is most likely attached to a $3d^94s^24p$ excited core, the negative ion is a good example of a highly correlated system where two electrons move outside a $3d^94s^2$ ion core and a large number of states of different symmetries (different $L$ and $S$ states if $LS$-coupling applies) can be formed. The Stokes parameters $P_2$ and $P_3$ then reveal information on electron exchange and the spin-orbit interaction. Also the angular behavior of the differential cross section can assist in the assignment of symmetry of the state.

For a relatively light atom such as zinc, the spin-orbit interaction between the continuum electron and the atom is negligible and the effects responsible for the fine structure of the atom are probed. These spin effects might be influenced and amplified by configuration mixing and electron correlations in the negative ions, especially when electrons with high angular momentum are involved in a re-arrangement process. For the particular case of the decay of the negative ion into the $4s\,4p\,^1D_2$ state, the results in figure 14 indicate the different role of the spin-dependent interactions in the two observed negative ions. The lower energy resonance with a $[5/2]$ ion core is observed in both $P_2$ and $P_3$ and this indicates an observable effect of both the spin-orbit and exchange interaction. The higher energy resonance with a $[3/2]$ ion core is observed only in $P_3$ and with positive values indicating the dominant role of exchange and the absence of spin orbit interaction. Also the energies and width of both resonances, obtained from a fitting procedure of a Fano profile to the three Stokes parameters, are mutually consistent. These are the first high precision experimental results and they indicate further experimental and theoretical studies are justified to establish the precise details of the scattering processes and the characterization of the negative ion states.

Figure 13. Energy level diagram for zinc atoms showing the detected photon wavelength of 636.2 nm and the observed two resonances (thick lines).
Figure 14. The Stokes parameters $P_i$ ($i = 1, 2, 3$) for excitation of the $\lambda = 636.2$ nm photons in zinc as a function of the incident polarized electron energy and $\theta = 30^\circ$ differential electron excitation function for the $4s4p^3P_{1,2,3}$ neutral states of zinc using unpolarized electron beam. Both set of data, polarization of the $4s4p^3D_1$ decay photons, and differential cross section for the $4s4p^3P_{1,2,3}$ channel show the resonance effects in the auto-ionizing region of zinc.

5. Conclusion
The intended audience for this paper was the attendees at the 7 AISAMP in Chennai. This paper was intended to provide some background to the angular momentum concepts underlying current electron and photon scattering experiments which are aimed at observing electron correlation effects mainly via scattering dynamics. Neither the references nor topics are intended to be comprehensive although the references provide a traceable history of the development of the topics discussed. Our second paper at this symposium indicates an extension of our approach to the interaction of spin-polarised electrons with surfaces, particularly an oxygen-covered tungsten crystal.

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References
[1] Bartlett P L 2006 J. Phys. B: At. Mol. Opt. Phys. 39 R379–424
[2] Fano U 1957 Rev. Mod. Phys. 29 74
