WHAT PHYSICS CAN WE LEARN FROM INTEGRATED STOKES PARAMETER MEASUREMENTS MADE WITH POLARIZED ELECTRONS?

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I. INTRODUCTION

Much of the basic physics of electron-atom scattering can be learned by looking at light emitted by atoms excited during the scattering process. Any beam of light can be completely characterized in terms of its Stokes parameters IP_1 IP_2, IP_3, and I [1]. In a well-designed experiment, the light's intensity, I, is directly proportional to the excitation cross section for the state emitting the light. The polarization parameters IP_i give additional information about different aspects of the excitation process. Because it is very difficult to measure absolute light intensities, the quantities routinely measured are the relative Stokes parameters, P_1, P_2, and P_3. Seventy five years ago, Skinner and Appleyard carried out the first studies of polarization in electron-atom collisions [2]. They used Hg as a target and made "integrated polarization measurements," meaning that they did not detect the scattered electrons. In such an experimental configuration, with unpolarized incident electrons, the only relative Stokes parameter that can be non-zero is

$$P_1 = \frac{I_{\parallel} - I_{\perp}}{I_{\parallel} + I_{\perp}} \ , \tag{1}$$

where I and $I_\perp$ refer to the intensity of light with electric field direction parallel and perpendicular, respectively, to the incident electron beam axis.   In such experiments, P_1 can be related directly to the second moment of the electron density distribution along the beam axis, i.e., the excited atom's shape, prolate or oblate. Through the Wigner-Eckart theorem, it can also be written in terms of the m_L sublevel cross sections[3].

As technology has improved, more sophisticated experiments have been carried out, involving detection of the light in coincidence with the scattered electron, the use of incident polarized electrons, and detection of scattered electron polarization. For reviews of these general topics, the reader is referred to references [4] and [5]. Perhaps the state-of-the-art experiment in this regard was carried out at the University of Münster, in which polarized electrons were used to excite Hg atoms (once more!), and the scattered electrons, energy- and angle-selected, were detected in coincidence with UV photons for which all the polarization parameters were measured [6]. Such studies have revealed the complexity of the multi-electron scattering process. It is generally true that more detailed experiments of this type provide a closer look at the collision physics and provide the most stringent possible tests of modern scattering theories. There are some situations though, in which integrated measurements, where the scattered electrons are not detected, have advantages. The purpose of this paper is to point these out, and to discuss the physics that one can learn from such measurements.

As an example (to be discussed in more detail in Section IV), let us consider electron-impact excitation of Xe atoms. Since Xe is a relatively heavy atom, one might ask if the continuum electron experiences magnetic spin-orbit forces during the excitation process. It is clear that these forces play an important role in elastic scattering; Mott asymmetries (corresponding to the "Sherman function") in such collisions can be appreciable [5]. Moreover, in Hg at least [7], there appears to be little difference in the spin-orbit forces exerted on elastically-scattered electrons and ones that excite the target. It is thus reasonable to expect such effects in Xe as well, albeit at a reduced level because of its lower nuclear charge. One could envision making such a test by looking for a differential cross section dependence on the spin of the incident electron when detecting electrons scattered to large angles (where spin-orbit forces would be the largest) in coincidence with a photon characteristic of the excited state of interest. Unfortunately, such spin effects can occur in inelastic scattering even if relativistic forces are negligible. They are the result of the "fine-structure" effect, and can be observed when the total angular momentum, J, of the target's final state is resolved [8]. Thus a left-right asymmetry in such an experiment is not a "clean" signature of Mott scattering of the continuum electron.

These effects can be observed unambiguously, however, in an integrated measurement. It was pointed out a number of years ago that the relative Stokes parameter P_2 will be non-zero in integrated experiments only if a) the incident electrons are spin-polarized along the axis of the detected photon emission and b) either the excited target is not well-LS coupled or spin-orbit forces act on the continuum electron [9]. The Stokes parameter P_2 is defined as

$$P_2 = \frac{I_{45^o} - I_{135^o}}{I_{45^o} + I_{135^o}} \quad , \tag{2}$$

where the intensity expressions now refer to linearly-polarized light along axes at 135^o or 45^o relative to the electron beam axis. Thus if one chooses an LS-coupled excited target state, measurement of a non-zero value of P_2 would constitute a detection of Mott scattering [10]. This experimental advantage is bought at a price: by making an integrated measurement the relativistic effects, which can be very large at specific electron scattering angles, tend to be reduced by the angle averaging. Nonetheless, they would not generally average to zero.

Integrated measurements have other advantages as well. Count rates for direct photon signals averaged over all electron emission angles are usually much higher than those in coincidence measurements, permitting better statistical precision with which to test theory. When compared with energy analysis of scattered electrons alone, optical measurements have inherently higher resolution, allowing more complete characterization of the final target state. The increased collision symmetry of integrated measurements eliminates potential systematic errors in the determination of scattering angles, which can be quite serious in cases where the differential scattering cross section has a strong angular dependence. Finally, as we shall see, the state-of-the-theory is sufficiently poor that even relatively crude integrated measurements can point out real problems, especially in the case of heavy multi-electron atoms.

In the rest of this paper, we discuss specific examples of the kinds of physics that can be studied in integrated Stokes parameter measurements. These experiments can be broken up into five general categories:

1) Assessment of the relative importance of direct vs. exchange excitation.
2) Isolation of magnetic effects in the collision.
3) Study of negative ion scattering resonances.
4) High-precision tests of theory.
5) Electron polarimetry.

The range of examples we have chosen is by no means exhaustive, but does represent the complete range of basic physics issues in each category.

II. STANDARD EXPERIMENTAL APPARATUS

Figure 1 shows the polarized electron apparatus we use in Lincoln to measure integrated Stokes parameters with noble gas targets. It is similar to others that have been used around the world [see, e.g., references 11-14]. The transversely polarized electrons are extracted from a GaAs source of compact design [15]. A differential pumping chamber maintains four orders of magnitude pressure differential between the source and the target region. Spurious longitudinal magnetic fields can alter the transverse spin direction of the electrons. The effect of such fields is eliminated by a solenoidal spin rotator just upstream of the target chamber. Electrons entering this last chamber are focused through the cylindrical target cell and are measured, for the purposes of beam current normalization, on an electrode downstream. A cell instead of an effusive needle target was used to produce higher target density and thus better counting statistics. Turbo-molecular pumps (instead of ion pumps) are used on all sections of the apparatus because of the high noble gas pumping load in the system.

Light emitted by target atoms along the direction of electron polarization is collimated by a lens that also serves as a vacuum barrier for the target chamber. It is analyzed using an optical polarimeter with 5 cm diameter optical elements. Great care has been used in selecting components for the entire apparatus that produce low magnetic fields. The earth's field is compensated with a large external electromagnet, and the fields due to the turbo-pumps are cancelled with current-carrying coils wrapped around the target chamber.

III. DIRECT vs. EXCHANGE EXCITATION

One of the most basic questions one can ask when considering excitation of atoms by electrons is whether the incident electron was scattered by the target, with an attendant energy loss corresponding to the discrete energy increase of the atom, or, instead, switched places with a target electron thus "taking up residence" in the excited atom. The former process is usually referred to as a "direct" process; the latter process is called "exchange [5]." These collision channels are shown schematically in Figure 2. The use of polarized electrons as incident projectiles in conjunction with the measurement of P_3 for light emitted along the axis of electron polarization allows one to answer this question. The relative Stokes parameter P_3 is defined as

$$P_3 = \frac{I_{RHC} - I_{LHC}}{I_{RHC} + I_{LHC}} \quad , \tag{3}$$

where I_{RHC} and I_{LHC} refer to right-handed and left-handed circularly polarized light, respectively. Any non-zero value of P_3 in such a measurement constitutes evidence for exchange excitation. In the case of pure LS coupling in the excited state, spin triplets can only be excited by exchange, whereas spin singlets or doublets can be excited either by direct or exchange processes.

One of the major drawbacks of integrated Stokes parameter measurements is that of cascade contamination. Since the scattered electrons are not detected their energy loss is unknown, and it is possible for incident electrons to excite a state lying above that responsible for the fluorescence of interest. These higher lying states can subsequently decay into the upper state of the transition being studied. Thus any value of P_3 other than that dictated by a pure exchange excitation of light emitted by, e.g., the triplet state of a two-electron system, is due to the influence of cascading from higher-lying singlet levels. (Predominantly "singlet" states can decay into triplet states if they are not "pure," i.e., have a triplet component. This is true of so-called "intermediately-coupled" states.) One way to eliminate this problem is to make measurements only in the electron energy range between the threshold for excitation of the primary state and the threshold for excitation of the lowest-lying state above it that can decay into it.

As examples of such experiments, we consider the results for Cs obtained by Eschen *et al*. at the University of Münster [12], and Kr, measured in our laboratory [16]. The Münster group considered excitation by transversely polarized electrons of the 8 $^2S_{1/2}$ and 6 $^2P_{3/2}$ states from the 6 $^2S_{1/2}$ ground state. Measuring P_1 and P_3 of the emitted light along the electron polarization axis, they determined the quantity D/Q for the 8 $^2S_{1/2}$ state. Here D is the direct integrated excitation cross section for the S state, and Q is the total (direct+exchange) excitation cross section. For the $^2P_{3/2}$ state, they measured

$$\frac{D^*}{Q^*} = \frac{3D_1 + 2D_0}{3Q_1 + 2Q_0}, \tag{4}$$

where the subscripts on the right-hand side of the equation refer to the m_L value within the excited P state for the individual cross sections ($D_{-1} = D_1$ due to the symmetry of the collision). Both D*/Q* and D/Q are directly proportional to P_3 [12]. When exchange excitation is negligible, these quantities equal one; when direct excitation is unimportant, they approach zero. Thus D/Q and D*/Q* are measures of the importance of exchange in the collision.

The data obtained at Münster are shown in Figure 3. Qualitatively, the energy dependence of the exchange contribution to the total cross section is easy to understand. As the speed of the incident projectile increases, the probability that it will switch places with the target electron decreases. The energy range over which this occurs sets the scale for the energetics of the collision. Note that even at threshold, direct processes play a significant role in the excitation, in that D(*)/Q(*) never falls below 0.3. This result is predicted qualitatively by the theoretical calculation of Bartschat, Thumm, and Norcross [17]. Another interesting aspect of these data is that the exchange excitation “decays” away with increasing projectile energy at about the same rate for both $^2S_{1/2}$ and $^2P_{3/2}$ production. This is somewhat surprising in that ^2S excitation is optically forbidden, while ^2P excitation is optically allowed. Since the collision dynamics for producing the two states are thus significantly different, it is interesting that the energy dependencies of their respective direct-to-exchange ratios are so similar.

In Kr, we focus on excitation of the $5p^56p$ manifold, and specifically, the intermediately-coupled 6 ”$^3D_2$” state, which can be written as a linear combination of true Russell-Saunders states:

$$\psi(\text{”}{}^3D_2\text{”}) = \alpha|{}^3D_2\rangle + \beta|{}^3P_2\rangle + \gamma|{}^1D_2\rangle \tag{5}$$

where $\alpha = -0.210$, $\beta = 0.874$, and $\gamma = 0.438$. The collision geometry in this experiment [16] was the same as that used by Eschen *et al.*; P_3 is plotted as a function of electron energy in Figure 4. In this case, the non-monotonic nature of the data is caused by the excited target structure. Immediately above threshold, exchange excitation of the $^3D_2$ component dominates, and P_3 has a global maximum. As electron energy increases, the exchange cross section falls rapidly, causing an attendant decrease in P_3. Excitation of the wavefunction’s singlet component cannot result in non-zero P_3 values. At higher energies, the cross section maxima for exchange excitation of levels above the 6^3D_2 state are reached. This leads to its oriented population via cascade, and a secondary maximum in the value of P_3. Thus these data allow us not only to assess the importance of exchange in simple excitation of the state in question, but give us information about the importance of cascading in the optical excitation function as well. Other work on exchange excitation of this type has been reported in references [18-24].

IV. TESTS FOR MAGNETIC INTERACTIONS

As mentioned in the Introduction, measurements of P_2 can provide unambiguous tests of relativistic (spin-orbit) effects in atomic collisions. If the target is excited to a state that is well-LS coupled, P_2 can be non-zero only if appreciable magnetic forces have acted on the continuum electron [9,10]. Our group has searched systematically for such effects in excitation of the heavy noble gases, specifically in the excitation of np^6 ground states to the $np^5(n+1)p\ ^3D_3$ states [10,16]. These levels are well-LS coupled. One might make a crude estimate of the magnitude of P_2 by integrating the elastic Sherman function for Xe over electron scattering angle, as weighted by the spin-averaged differential scattering cross section [25,26]. This procedure yields an average asymmetry, <A>. At 10 eV, for example, one finds

$$\langle A\rangle = \int_0^{\pi} S(\vartheta)\frac{d\sigma}{d\vartheta}(\vartheta)d\vartheta = +0.03. \qquad (6)$$

A value of P_2 at this level can be easily measured. (While one might not expect an estimation based on elastic scattering to be valid for an inelastic process [8], Madison and Shelton [7] have shown that, at least for the case of Hg, the elastic and inelastic Sherman functions are very similar.)

Figure 5 shows recent P_2 data for excitation of the 5^3D_3 state in Kr, along with an R-matrix calculation of this parameter [27]. The vertical line near the middle of the graph designates the energy at which cascading levels can begin to be excited. Thus comparison between experiment and theory is strictly meaningful only at lower energies. Our data are consistent with zero in this lower energy regime, but they are also consistent with the theoretical prediction. Note that just above threshold, the R-matrix calculation predicts values of P_2 in excess of 5%. Unfortunately, Stokes parameters just above the excitation threshold are extremely difficult to measure. We have also measured P_2 to high accuracy with Xe, Ne, and Ar targets at the cascading threshold [16,28] for maximum statistical precision. In these experiments we achieved absolute uncertainties between 0.1% in P_2 for Ne and 0.9% with Xe. All measured values were consistent with zero, indicating that spin-orbit forces acting on the continuum electron are very small in the excitation process, even for Xe.

When non-LS-coupled states are excited, the values of P_2 can become appreciable, as shown in Figure 6 [16,27]. Since Mott scattering is presumably negligible in these cases as well, the scattered electron leaves the collision complex with axial symmetry. Another way to say this is that immediately after the collision, the excited charge cloud must be aligned along the axis of collision symmetry. Due to the strong internal magnetic interaction that leads to intermediate coupling of the excited state, however, atoms which have been excited by exchange will, over the fine-structure relaxation time, rotate through an angle in the plane perpendicular to the electron spin axis (Figure 7). This rotation leads to the non-zero values of P_2 observed. In the case of Ne [29], the similarity in energy dependence between, e.g., P_2 for the 3p'$[3/2]_1$ and the 3p'$[1/2]_1$ states in the $2p^5 3p$ manifold is intriguing, but not well understood at this point. It is clear, however, that final target structure plays an important role in the excitation process.

V. CHARACTERIZATION OF NEGATIVE ION RESONANCES

Formation of negative ion resonances is often an important excitation channel in electron-atom collisions [30]. This mechanism, $e^- + X \rightarrow X^- \rightarrow X + e^-$, shown schematically in Figure 8, can dominate the excitation process, especially if the energy of the resonance is close to the excitation threshold. Resonance formation can have a dramatic effect on the value of the integrated Stokes parameters [31]. Conversely, measurement of the Stokes parameters near threshold, especially with polarized electrons, can be used as a tool to assign specific angular momenta to these resonances, thus providing qualitative information about the dynamics of the excitation process. Two good examples of this come from experiments done at Münster with Hg [22], and at Perth with Ne [32]. In the first case (Figure 9) excitation to the 6 $^3P_1$ state, which is fairly well LS-coupled, was investigated. Here two features within 1 eV of threshold are apparent. Using the polarization data in conjunction with angular momentum coupling algebra, and including restrictions based on the spin and orbital angular momenta of candidate resonant states, these are most likely ^4P resonances at ~5.0 eV and ^2D resonances at ~5.4 eV. The P_3 data provide particularly dramatic evidence of the strong spin-orbit resonant coupling in the near-threshold region. From a “background” exchange polarization value of between 0.3 and 0.4, corresponding to simple insertion of spin into the $^3P_1$ system, the electron actually reverses spin direction in the region of the resonance, even though the resonance lifetime is less than 10^{-13} s! The resonances also affect P_2. Direct Mott scattering of the continuum electron is fairly small, given the low values of P_2 above 6 eV. However, strong magnetic forces associated with the target resonance state act on the continuum electron during the period of its residence in the atom.

In the Perth experiment, near-threshold excitation of the Ne 3p[1/2]1 state was studied [32]. The excitation channel is dominated by a resonance immediately above threshold. The configuration of the resonance is $2p^5 3p^2$, where the $2p^5$

core must have J_c = 3/2, since the 3p[1/2]1 state into which it decay has this value of J_c. The two outer p electrons of the negative ion resonance can only be in ^1S or ^1D levels, since ^3P resonances have excitation energy below that of the Ne 3p manifold. Moreover, one can assume that only the lowest orbital angular momentum channels contribute to the resonance excitation, since it is so close to threshold. Yu *et al*. thus show that the ^1S and ^1D J = 3/2 resonances will yield P_3 values of 0.33 (for incident electron polarization of unity), whereas the remaining ^1D J = ½ resonance results in P_3 = 0.17. Thus the data of Figure 9 allow an assignation of J = 3/2 to the resonance channel, although one cannot definitely exclude the ^1D J = ½ level. The role of P_3 measurements (and thus electron polarization) in this latter experiment is crucial in providing data with which to determine the dynamics of the excitation process.

VI. HIGH-PRECISION TESTS OF THEORY

With a few exceptions, it is safe to say that the theory for electron scattering from light atoms is in good shape. Specifically, one can point to H, He, and the alkalis lighter than K as being well understood. Recent developments both in theory and computer power have provided cross section calculations for the most important collision channels that have good accuracy. Unfortunately, the same cannot be said at this time for “hard” targets – those with high Z and/or several active electrons. The difficulties in developing a multi-electron relativistic theory of electron atom scattering are formidable. Beginning with the work of Madison and Shelton on Hg [7], and continuing through the first R-matrix calculations of the Belfast group [33] up to the present [see, e.g., refs. 34-38], the successes of theory in providing a detailed picture of the scattering dynamics from complex targets have been limited. This problem represents the “final frontier” in electron atom scattering. The major advantage of integrated Stokes parameter measurements in testing the new theories is that they can provide highly precise data, relatively free of the potential for systematic error, to quickly eliminate incorrect theoretical approaches with a high degree of confidence. Following this, more difficult , stringent tests involving, e.g., differential coincidence measurements can be applied.

As representative examples, we consider results for excitation of Cs [12,13] and Kr [27]. Two R-matrix techniques have been applied to the Cs case: the semi-relativistic Breit-Pauli calculation of Nagy et al. [39], and the fully-relativistic Dirac calculation of Thumm, Bartschat, and Norcross [35]. These are shown in Figure 10 in conjunction with the data of the Münster and Mainz groups for the 6 $^2P_{3/2}$ to 6 $^2S_{1/2}$ transition. While it is clear that neither theory is doing an adequate job of predicting experimental measurements, it is also apparent that at least one of the two experiments suffers from systematic error. More work, both theoretically and experimentally, is in order for this case.

The heaviest noble gases are doubly difficult to treat theoretically, because they have six active electrons in their outer shell and can also produce significant relativistic effects. Figures 5 and 6 show recent data from our laboratory on impact excitation of the Kr $4p^5 5p[5/2]\ ^3D_3$ and $4p^5 5p[5/2]\ ^3D_2$ states [27]. As mentioned previously, the $^3D_3$ state is well-LS coupled, whereas the $^3D_2$ state exhibits intermediate coupling. We notice that the agreement between the fully-relativistic Dirac R-matrix theory of Bartschat and Zeman is in qualitative agreement with the $^3D_3$ results (notice the zero suppression of the figure). The same calculation fails to predict the $^3D_2$ data. At this point, it appears that the main difficulty theoretically is the incorporation of the structure of the target in the scattering calculation. This problem is exacerbated when the final target state is intermediately coupled. Thus the measurements here point to a specific improvement that must be attempted in the next generation of relativistic calculations.

VII. ELECTRON POLARIMETRY

In 1969, Farago and Wykes [40] proposed a novel method to measure the polarization of a beam of electrons. Their scheme involved exchange excitation of one the group IIB elements (Zn, Cd, Hg) in the $ns^2\ ^1S_0$ ground state to the $ns(n+1)s\ ^3S_1$ excited state. Subsequent decay to the $nsnp\ ^3P_J$ excited state would yield integrated values of P_3 proportional to the incident electron polarization assuming a) that the upper $^3S_1$ state is well-LS coupled and b) that the fine structure of the ^3P_J levels was resolved in the transition. This method was demonstrated eleven years later with a Zn target [24]. The value of P_3 was measured along the incident electron axis with longitudinally polarized electrons. Subsequently, Gay proposed that He could be used more easily as a polarimetric target [41]. This is true even though the fine structure of the $3\ ^3P \rightarrow 2\ ^3S$ transition to be monitored is not optically resolvable (see Figure 11). One can think of the orbital and spin angular momentum orientations of the He as two pendula, weakly coupled by the spin-orbit interaction. Because the $3\ ^3P$ state must be excited by an exchange collision, one is guaranteed that the “spin” pendulum will have a non-zero amplitude immediately following the collision. On the other hand, the “orbital” pendulum is initially at rest because the collision geometry forbids orbital orientation immediately following the collision. As time progresses, some of the spin orientation is transferred back-and-forth in a reversible, oscillatory manner (“quantum beating”) to the orbital orientation via this magnetic coupling. If the state decays when the orbital orientation is non-zero, it will emit a circularly polarized photon, meaning that P_3 will be non-zero. This polarization can be related *kinematically*, through angular momentum coupling algebra, to the electron polarization. It is for this reason that optical electron polarimetry is inherently more accurate than single-scattering Mott polarimetry [5], which relies on dynamical calculations of analyzing power.

The use of He for electron polarimetry was first demonstrated by the Münster group in 1987 [42]. Even more recently, Gay *et al*. proposed the use of heavy noble gases as improved alternates to He [28]. These atoms have the advantage of having higher excitation cross sections and higher analyzing powers than He. In the case of the heavy noble gases, the coupled pendulum analogy no longer holds, because one observes excitation of specific fine-structure levels. Thus the orbital orientation of the specific excited state is no longer a function of time, given that the state is an eigenfunction of the atom's Hamiltonian.

The general optical polarimeter equation for the electron polarization, P_e, can be written as

$$P_e = \frac{P_3}{(a + bP_1)}, \tag{7}$$

where a and b are kinematically determined constants associated with the target and transition in question. Thus we see that one determines the electron polarization through P_3, and the analyzing power is measured *in situ* via P_1. Moreover, the assumption that LS coupling holds for the target state (and that Mott scattering is negligible; see Sec. VI), which is required for the validity of equation 7, can also be checked *in situ* by measurement of P_1. The technique of optical electron polarimetry is thus self-checking and experimentally robust.

Any polarimeter's "figure-of-merit" is defined as its analyzing power squared times its efficiency, i.e., the number of detected events divided by the incident particle current [5]. The figure-of-merit is in turn related to the time required to measure a given electron polarization to a set statistical uncertainty. The so-called "ideal" figure-of-merit for the noble gases is shown as a function of electron excitation energy in Figure 12. This quantity, which is apparatus-independent, is defined as the apparent optical excitation cross section times the measured square of the analyzing power. For most situations, Ar is the best polarimetric target. An exception to this would be if, for example, the photon detector was insensitive to light at 811 nm, the relevant Ar transition wavelength. We also note that while electron optical polarimeters are easy to build, operate, and are very accurate, they have such low efficiency that their use with beam currents below 50 nA is not practical. They are thus best suited for analysis of source polarization, and are particularly useful in the development of novel polarized electron sources. Because of their high accuracy, they can also be used to define an electron polarization "standard." Ultimately, one could envision using such standards in tests of the weak decays in nuclear physics and subsequent searches for departures from the Standard Model.

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FIGURE CAPTIONS

Figure 1. Scale diagram of GaAs polarized electron source and target cell for the measurement of Stokes parameters [15]. Shown are: 1) GaAlAs diode laser beam (780 nm); 2) GaAs photocathode; 3) cylindrical spin rotator; 4) electrostatic focussing elements; 5) differential pumping chamber; 6) isolation gate valve; 7) solenoidal spin rotator; 8) target gas cell; 9) light-collecting lens; 10) magnetic dipole beam steering elements; 11) beam exit to Faraday cup. Reprinted with permission of the American Institute of Physics (AIP).

******* FIGURE 1 SHOULD BE FULL-PAGE WIDTH ***********************************

Figure 2. Schematic diagram of direct and exchange excitation processes. Direct processes are generally labeled with an "f" to designate scattering amplitude or a "D" to designate a probability or cross section. Exchange processes are labeled with a "g" for scattering amplitude or an "E" for a probability or cross section. Exchange excitation is monitored by measurement of the Stokes parameter P_3. For well-LS-coupled states excited from a singlet ground state, triplet levels can only be populated by exchange, whereas singlet and doublet states can be excited by either direct or exchange processes.

Figure 3. Data from ref. [12] on the relative importance of direct excitation of Cs by polarized electrons (see text). Reprinted with permission of the Institute of Physics (IOP).

Figure 4. Circular polarization of light emitted by the $4p^5 5p[5/2]\ ^3D_2$ state of Kr excited by polarized electrons (see text) [16].

Figure 5. Values of the three Stokes parameters for flourescence of the $4p^5 5p[5/2]\ ^3D_3$ state of Kr excited by polarized electron impact [27]. The thin line represents the results of a relativistic R-matrix calculation of Zeman and Bartschat. The thickened line represents this calculational result convoluted with the measured energy width of the electron beam used to make the measurements. The vertical partition shows the electron energy at which cascading states begin to be excited. The threshold of the $^3D_3$ state is 11.44 eV. Values of P_2 and P_3 have been normalized to the electron polarization value to which they are proportional. Reprinted with the permission of the AIP.

Figure 6. Figure showing the same information as Figure 5, except for the $4p^5 5p[5/2]\ ^3D_2$ state. Reprinted with the permission of the AIP.

Figure 7. Schematic diagram showing the rotation of an excited non-well-LS coupled D state following excitation by electrons polarized transversely to the plane indicated. Reprinted with permission of the AIP.

Figure 8. Schematic diagram of resonance scattering.

Figure 9. Data of reference [22] showing values of P_2 (η_1 in the figure's notation) and P_3 ($-\eta_2$) for $6\ ^1S_0 - 6\ ^3P_1$ excitation of mercury by polarized electrons. The photon intensities contributing to the polarization ratios are shown in the top panels of the diagram. Reprinted with permission of the IOP.

Figure 10. Values of P_3 for the $6\ ^2P_{3/2}$ to $6\ ^2S_{1/2}$ transition in Cs as measured in refs.[12] (open circles) and [13] (closed circles). Solid line and dashed line represent calculations of ref. [17]; dashed-dot curve theory of ref. [39]. Vertical line represents the excitation threshold of the $6\ ^2P_{3/2}$ state (see text). Reprinted with the permission of the IOP.

Figure 11. Energy level and dynamics of He optical electron polarimetry (see text).

Figure 12. Ideal figure-of-merit for the noble gas polarimetric transitions *vs.* incident electron energy [28]. This quantity is defined as the apparent optical excitation cross section times the measured square of the analyzing power. Reprinted with the permission of the AIP.