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Super-elastic Electron Scattering Within a Magnetic Angle Changer - Determination of the Angular Momentum Transferred during Electron Excitation over all Scattering Angles.

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By utilising super-elastic electron scattering from laser excited atoms together with a new Magnetic Angle Changing device, it is possible to determine the differential cross sections for excitation of atoms by electron impact over the complete scattering geometry. In the experiments described here, these techniques are combined to reveal the angular momentum transferred to calcium atoms during electron excitation to the 4^1P_1 state, from near zero degrees to beyond 180 degrees for the first time. The results significantly extend all previous data, and are compared to calculations based on a distorted wave Born approximation by Stauffer and colleagues. The experimental techniques are discussed, and results are presented for electron energies of 45eV and 55eV.

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The detailed study of electron collision processes has a long history in the field of experimental atomic and molecular physics, with excitation [1] and ionization [2] of the target continuing to provide stringent tests of the most sophisticated theories. These comparisons are most exact when the momenta and character of the incident and scattered particles are determined in coincidence, since the differential cross section can then be ascertained. For excitation, the scattered electron is usually correlated in time with the radiation emitted from the excited state, whereas for ionization the scattered and ejected electrons which emerge from the reaction are detected in coincidence at different angles. By ensuring the momenta of the incident and scattered electrons are well defined, the coincidence technique effectively selects a small subset of all possible scattering events, allowing accurate comparison to theory.

Although a very powerful technique for determination of cross sections, coincidence methods suffer from low efficiency due to the energy and momentum selectivity of the process under study. This efficiency can be increased by detecting many events simultaneously, and then processing the correlated events following data collection. An example of this for ionization studies is COLTRIMS (Cold Target Recoil Ion Momentum Spectroscopy) [3], which uses combined electric and magnetic fields to steer electrons/ions into and out of the interaction region, their momenta being determined using time of flight and position sensitive techniques. Such methods significantly increase the coincidence detection efficiency, although they are very difficult to control at low incident electron energies between threshold and ~100eV.

For excitation studies, the scattered electron is usually detected at a set angle in coincidence with a photon emitted from the excited target, the incident ($\mathbf{k}_{inc}$) and scattered ($\mathbf{k}_{out}$) electron momenta defining a scattering plane. The polarization of the photon is determined using linear and circular analysers, so that a complete description of the radiated light can be ascertained. Parameters which characterise the 'shape' of the excited target are then calculated from the measured radiation.

It is usual to define these parameters in the Natural frame [1], which places the quantization axis orthogonal to the scattering plane. For excitation to a P-state, the parameters are the angular momentum transferred to the charge cloud during the interaction $L_\perp$, the angle of the charge cloud with respect to the incident electron direction γ, and P_{lin} which defines the 'length' to 'width' of the charge cloud. If spin flip occurs during excitation, a parameter ρ^A_{00} is also defined which relates to the relative 'height' of the charge cloud above the scattering plane at the origin.

The electron-photon coincidence technique is slow since the atom that scatters the detected electron may not radiate in the direction of the photon detector. In this case no correlation occurs, and a random background signal accumulates over time as data is taken. The correlated 'true' coincidence signal is observed as an addition to this background, and occurs at a time dictated by the flight time of the scattered electrons and photons which are detected. The coincidence signal therefore displays a characteristic fast rise-time with a decay given by the natural lifetime of the excited state under study.

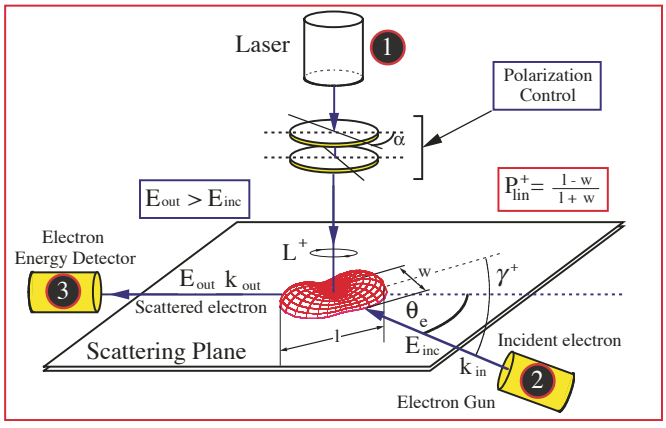

FIG 1. The super-elastic scattering geometry, which is the time-inverse of the electron-photon coincidence technique. Electrons of momentum $\mathbf{k}_{in}$ are directed at atoms prepared in an excited state by resonant laser radiation. Scattered electrons are detected with momentum $\mathbf{k}_{out}$ as a function of the scattering angle θ_e, so as to determine the Natural frame parameters $L_\perp, \gamma, P_{lin}$.

A different technique can be used to derive equivalent data as for coincidence measurements. This is the super-elastic scattering experiment, and adopts time-reversal of the scattering events to provide the required information. In this case (figure 1), the atom is initially excited from the ground state using laser radiation directed orthogonal to the scattering plane, whose polarization is well defined (1). An electron is directed from the gun in the opposite direction to the electron detected in a coincidence experiment (2), the kinetic energy of these electrons being equal. Finally, an electron detector is positioned where the electron source was located in coincidence studies, so as to measure electrons which have gained energy (super-elastically scattered) from the laser-prepared atom (3). These electrons then have the same energy as the incident electrons in coincidence measurements.

By adopting this time-inverse method, signal from the scattering event accumulates many times faster than for coincidence studies, since the photons from the laser beam are always directed into the interaction region in the same direction. In this case, time correlation techniques are not required, and data is accumulated by counting the rate of super-elastically scattered electrons as a function of the laser polarization. It is necessary to carefully consider the absorption, stimulated and spontaneous emission effects of the laser radiation on the excited atoms to ensure that the Natural frame parameters are correctly defined, however these effects can be modelled accurately and can be determined from the fluorescence emitted during laser excitation [7]. The angular momentum parameter $L_{\perp}$ is derived from the ratio of super-elastically scattered electrons produced by changing the handedness of circularly polarized laser radiation, whereas γ and P_{lin} are derived from linearly polarized radiation. The super-elastic scattering technique is therefore a powerful method to determine collisional cross sections for comparison to theory.

In this letter, a new type of super-elastic scattering process is discussed which uses a new technique to steer electrons to and from the interaction region using well controlled magnetic fields. This Magnetic Angle Changing (MAC) device was invented in Manchester [4], and uses precisely machined solenoids surrounding the interaction region to ensure that the magnetic field within the coil region is finite, yet is zero beyond this region. By carefully designing the solenoids, two important criteria are met. The first is that the magnetic field within the electron gun and electron analysers is zero, so that electrons travel within these components un-deviated by magnetic fields. The second is that electrons directed radially towards the interaction region from the electron gun always pass through the interaction region at the centre of the solenoids, whereas electrons that leave the interaction region also travel along radial paths once outside the field region. It is therefore only necessary to align the gun and analyser to the interaction region prior to energising the solenoids, to ensure that incident electrons pass through the interaction region and scattered electrons are detected by the analyser.

The MAC device hence acts to steer electrons into and out of the interaction region so that their angles are changed, as shown in figure 2. In this example, the incident electron beam has an energy of 45eV, and the current through the solenoids

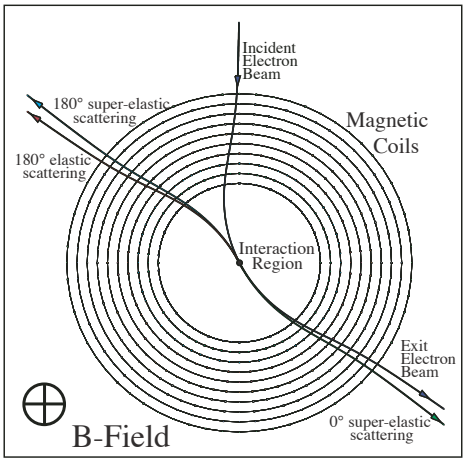

FIG 2. Electron trajectories due to the MAC field for an incident energy of 45eV and a B-field at the interaction region of 2.5mT. The incident electron beam passes through the interaction region and exits at an angle ~50°. Electrons scattered from the interaction region are then steered to angles where an electron energy analyser can be located. The full scattering geometry from $\theta_e = 0°$ to $\theta_e = 180°$ can therefore be accessed for the first time.

sets the magnetic field to 2.5mT at the interaction region. The MAC device is seen to steer the electrons into the interaction region so that the incident beam exits at an angle ~50° from the initial beam direction. By contrast, electrons that super-elastically backscatter from the reaction ($\theta_e = 180°$) are steered to an angle ~135°, where an electron analyser can be located. The MAC therefore allows data to be collected over scattering angles which are impossible to access using conventional electron spectrometers.

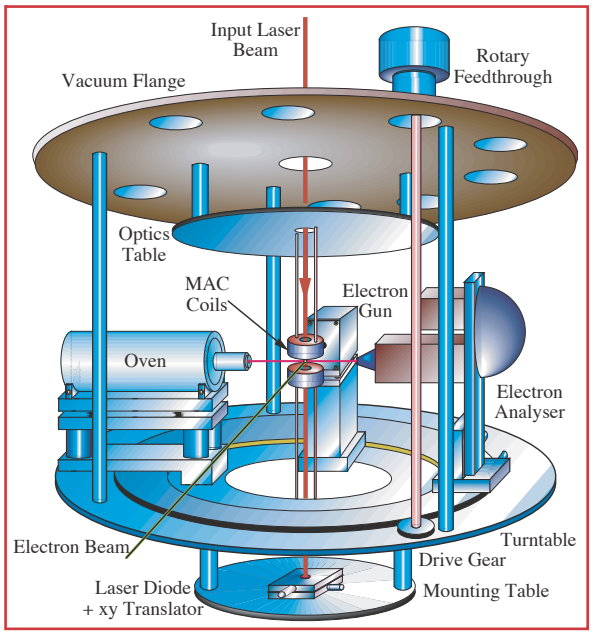

FIG 3. The super-elastic spectrometer. Atoms emitted from the oven are laser excited by the input laser beam which follows a tracer beam from the laser diode inside the vacuum chamber. The electron gun is located next to the oven, and the analyser rotates on a turntable driven by a rotary feed-through. The MAC coils surround the interaction region as shown.

Figure 3 shows a representation of the spectrometer constructed for these studies. The atomic beam is produced by a well collimated oven so that the Doppler profile presented to

the laser beam is low [5]. The electron gun is located next to the oven, and the electron analyser [6] rotates around the scattering plane on a turntable driven by a rotary feed-through, so as to access different angles. The MAC solenoids surround the interaction region as shown, and the laser beam enters the vacuum chamber through a window on the top flange. The exciting laser is accurately directed through the interaction region by following a tracer diode laser beam emitted from inside the chamber. The polarization of the exciting laser is controlled external to the vacuum chamber. By changing the laser polarization, it is therefore possible to determine $L_\perp$, γ and P_{lin}.

A complication arises for these super-elastic scattering studies when the MAC is operated, since the excited sub-states are no longer degenerate. For the super-elastic scattering studies presented here, calcium was excited to the 4^1P_1 state by circularly polarized laser radiation at ~423nm. Since the quantization axis of the laser radiation is then parallel to the magnetic field generated by the MAC, the laser excited states are as shown in figure 4. The magnetic field removes the degeneracy of the $|L,m_L\rangle = |1,\pm1\rangle$ sub-states which are coupled to the ground state by circularly polarized radiation as shown. To measure $L_\perp$ it is therefore necessary to re-tune the laser frequency for each selected polarization state by twice the Zeeman shift, so as to remain in resonance throughout measurements. $L_\perp$ is then determined from the super-elastic signal $S_{Polzn}(\theta_e)$ using the expression:

$$L_\perp = \kappa \frac{S_{LHC}(\theta_e) - S_{RHC}(\theta_e)}{S_{LHC}(\theta_e) + S_{RHC}(\theta_e)} \qquad (1)$$

where κ is an optical pumping term which depends on the laser coupling of the ground and excited sub-states [7]. In the case of calcium, $\kappa = 1$.

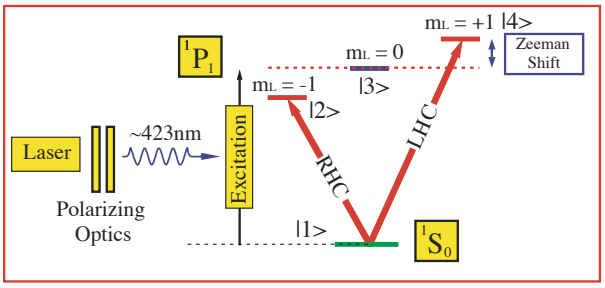

FIG 4. Laser excitation of Calcium to the 4^1P_1 state at ~423nm using circularly polarized radiation. The $m_L = \pm1$ excited sub-states are shifted in energy due to the magnetic field, and so the laser frequency must be altered to ensure atoms remain in resonance when the laser polarization is adjusted to perform $L_\perp$ measurements.

Determination of γ and P_{lin} is more involved than for $L_\perp$, since the laser beam is linearly polarized for these measurements, and so the natural quantization axis of the laser (along the laser polarization axis) and the **B**-field from the MAC are orthogonal. A common axis must be defined, and it is sensible to again choose this along the **B**-field. In this case the laser polarization must be represented as a superposition of RH and LH circularly polarized radiation, and the interaction is considerably more complex. A full description of the techniques required to determine γ and P_{lin} from the data will be presented in a future paper [8].

The experiment using the MAC device was conducted for outgoing electron energies $E_{out}^{super} = E_{inc}^{coinc} = 45eV, 55eV$. The electron energy from the gun was set 2.93eV lower than these energies, with the beam current set between 2μA and 5μA. The calcium oven was operated at a constant temperature of 1060K. The laser intensity at the interaction region was ~40mW/mm^2, and the rates of super-elastically scattered electrons varied from ~10Hz to ~5kHz, depending on the selected scattering angle. The vacuum chamber pressure was ~1 x 10^{-6} torr for all measurements.

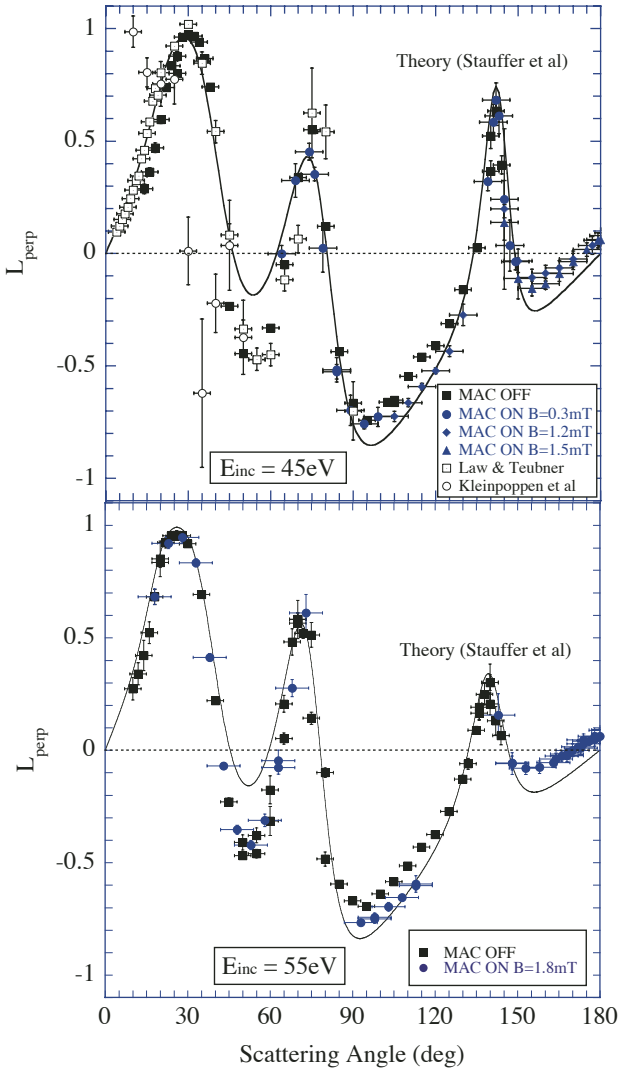

FIG 5. Derived values of the angular momentum parameter $L_\perp$ from experimental data for outgoing electron energies 45eV and 55eV, at angles from $\theta_e = 0°$ to $\theta_e = 180°$. The results at 45eV are compared to the super-elastic data of Law and Teubner [9] and to the coincidence data from Kleinpoppen and co-workers [10]. The theoretical calculations of Stauffer and colleagues [12] are also shown. For details, see text.

Figure 5 shows the results of the experiments, where the $L_\perp$ parameter is derived as in equation (1). At 45eV, the new results are compared to the super-elastic scattering data of Law and Teubner [9], who measured $L_\perp$ for scattering angles $\theta_e \sim 0°$ to $\theta_e = 90°$. The early electron-photon coincidence measurements of Kleinpopppen and co-workers [10] from $\theta_e = 10°$ to $\theta_e = 50°$ are also shown for comparison. It is clear

that the coincidence measurements are of much poorer quality due to the difficulty with this technique, and the long accumulation times that are necessary.

The new results presented here include measurements from $\theta_e = 14°$ to $\theta_e = 145°$ taken without the MAC operating, and data up to (and beyond, not shown) $\theta_e = 180°$ taken with the MAC operating with different **B**-fields. The results with and without the MAC operating are in close agreement, differences being due to small changes in the contact potentials around the interaction region which occurs due to calcium deposition [11].

Data was taken using a range of **B**-fields since it was found that the MAC produced significant amounts of noise on the signal at certain angles, making data collection in these regions impossible. This noise is thought to emanate from electrons scattered from the walls of the vacuum chamber which re-enter the MAC and are then steered into the analyser. This effect has been seen before, and can be resolved by changing the solenoid field to steer the unwanted electrons away, as was done here. We are currently looking to resolve this problem in future experiments.

The results at 55eV are again shown from $\theta_e = 14°$ to $\theta_e = 145°$ taken without the MAC operating, and for angles from $\theta_e = 14°$ to $\theta_e = 180°$ with the MAC operating with a **B**-field of 1.8mT (a larger **B**-field is required since the electron energy is higher). In this case, only one set of data was collected with the MAC operating, since the agreement with and without the MAC was excellent. No other experiments have been conducted at this energy for comparison.

The calculations of Stauffer and colleagues [12] are also shown for comparison with the experimental data, convoluted with the experimental angular response. It is clear that this model is in very good agreement with all super-elastic data that has been taken, apart from the minimum at $\theta_e \approx 60°$ which is underestimated at both energies, and the minima at the higher energies that are overestimated. The maxima and their positions are reproduced well, and the sharp peak at $\theta_e \approx 150°$ agrees with the experimental data (which is observed here for the first time). It is clear that the theoretical model has described the physics of the collision for the $L_\perp$ parameter well at these energies.

It is of interest to note that experimental results for elastic scattering from inert gas targets which also use a MAC device [13] show significant discrepancies with other calculations by Stauffer and colleagues [14], who use a similar theory to calculate elastic cross sections for these targets. This has remained an open question, since it was not certain whether this discrepancy evolved from the use of the MAC device in the experiments, or was due to incompleteness in the theory. Since the theoretical derivation of the Natural frame inelastic scattering parameters is more involved than for elastic cross sections, it is surprising that such excellent agreement is found here compared to that for elastic scattering, since both experiments use a MAC device for their operation. Both elastic and inelastic scattering experiments carefully compare the data in angular regions which can be accessed with and without the MAC operating. Hence the new results presented here tend to confirm that previous data taken in the region beyond that which can be accessed conventionally are reliable. The discrepancy for elastic scattering from noble gas targets is therefore more likely due to the data being taken at low incident energies (between 5eV and 20eV), and for heavier targets, rather than being due to a systematic problem in the experiment.

The results presented here are for the $L_\perp$ parameter, and for a full analysis of the interaction it is also necessary to provide data for P_{lin} and γ. These results are currently being collected at the energies presented here. Once they have been fully analysed, the full set of results will be presented in a future paper [8].

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