Super-elastic scattering from calcium over the complete angular range using a Magnetic Angle Changing device

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Abstract. Until recently it has not been possible to determine differential cross sections for excitation of atoms by electron impact over the complete scattering geometry, due to the physical constraints of the apparatus. The invention in Manchester of the Magnetic Angle Changing (MAC) device which steers electrons to and from the interaction region has now changed this. By utilising super-elastic electron scattering from laser excited atoms within a MAC device, the differential cross sections for electron impact excitation of calcium atoms to the ⁴¹P₁ state have now been determined from near 0° to beyond 180°. The methods used in these experiments are discussed, and results are presented for the Natural frame parameter \( L^\perp \) at energies of 45eV and 55eV. The results are compared to recent calculations using a distorted wave Born approximation.

1. Introduction

The study of electron collisions has a long history in atomic and molecular physics, with excitation¹ and ionization² of the target providing stringent tests of theory. These comparisons are most exact when particles from the collision are measured in coincidence, since the full differential cross section can then be determined. For excitation, the scattered electron is usually correlated in time with photons emitted from the excited state. By ensuring the momenta of the incident and scattered electrons (\( \mathbf{k}_{\text{in}}, \mathbf{k}_{\text{out}} \)) are well defined, the coincidence technique selects a small subset of all possible events, allowing accurate comparison to theory.

Although a powerful technique for determination of cross sections, coincidence methods suffer from low efficiency due to their high selectivity. For excitation studies, the scattered electron is usually detected in coincidence with photons emitted from the excited target, with \( \mathbf{k}_{\text{in}} \) and \( \mathbf{k}_{\text{out}} \) defining a scattering plane. The polarization of the photon is determined, so that a complete description of the radiated light is ascertained. Parameters which characterise the ‘shape’ of the excited target are then calculated usually in the Natural frame¹, which defines a quantization axis orthogonal to the scattering plane. For P-state excitation, the Natural frame parameters are the angular momentum \( L^\perp \) transferred to the charge cloud, the angle \( \gamma \) of the charge cloud with respect to \( \mathbf{k}_{\text{in}} \), and \( P_{\perp} \), which defines the ‘length’ to ‘width’ ratio of the charge cloud. If spin flip occurs, a parameter \( \rho^{\perp}_{00} \) is also measured which relates to the relative ‘height’ of the charge cloud 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 which case no event registers. An alternative technique that yields equivalent information is the super-elastic experiment, which adopts time-reversal of the scattering event. In this method (figure 1), the atom is initially excited from the ground state using laser radiation of well defined polarization directed orthogonal to the scattering plane (1). The incident electrons are directed as shown (2), while the electron detector is positioned where the source would be located in a coincidence study. The detector then measures super-elsastically scattered electrons that have the same energy as incident electrons in a coincidence experiment (3).
Signal counting rates from super-elastic scattering experiments are many times greater than for an equivalent coincidence study, since the photons are directed in a single, well-defined direction. 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 effects of the radiation on the excited atoms to ensure that the natural frame parameters are correctly determined, however these effects can be modelled accurately\(^3\).

\(L_\perp\) (as discussed here) is derived from the ratio of super-elastically scattered electrons produced by changing the handedness of circularly polarized laser radiation.

In this paper, a new type of super-elastic scattering process is discussed which uses a MAC device to access the backward scattering region for the first time. The MAC device\(^4\) uses a well-controlled magnetic field to steer electrons to and from the interaction region. By careful construction of the MAC solenoids, the magnetic field falls off rapidly with radial distance, so that the field in the electron gun and analyser is negligible. The MAC device further ensures that electrons directed radially towards the target region pass through the interaction region situated at the centre of the solenoids. The MAC device hence applies a deflection to the electrons so as to effectively rotate the scattering geometry about the interaction region (see figure 2). In the example shown in this figure, the incident electrons have an energy of 45eV, and the field is 2.5mT at the interaction region. The MAC device is seen to steer electrons into the interaction region so that the incident beam exits at \(~55^\circ\) from the initial direction. Electrons super-elastically back-scattered from the reaction \((\theta_e = 180^\circ)\) are seen to be steered to \(~130^\circ\), where an electron analyser can be located. The MAC device therefore allows data to be collected over angles impossible to access using conventional electron spectrometers, where the electron gun and analyser would collide.

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

**Figure 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 \(~55^\circ\) from the initial direction. Electrons scattered from the interaction region are steered to angles where an electron analyser can be located. The full scattering geometry from \(\theta_e = 0^\circ\) to \(\theta_e = 180^\circ\) can therefore be accessed for the first time.
2. Experimental techniques
To facilitate these new studies, it was necessary to construct a new spectrometer incorporating an electron gun, a momentum selecting electron analyser, MAC solenoids and an atomic beam oven. Figure 3 shows a schematic of the spectrometer built for these studies. The atomic beam is produced by a well collimated oven ensuring the Doppler profile presented to the laser beam is narrow. The electron gun is located next to the oven, and the electron analyser rotates around the scattering plane to access different angles. The MAC solenoids surround the interaction region as shown. The angular range of the analyzer is from near 0° to 145° without the MAC operating, whereas this range increases to greater than 180° with the MAC operating. The laser enters the vacuum chamber through a window in the top flange, and is directed through the interaction region by following a tracer beam emitted from an aligned laser diode inside the chamber. The polarization of the exciting laser is adjusted prior to entering the vacuum chamber.

One consequence of using a MAC device is that the excited sub-states of the target are no longer degenerate. For the super-elastic studies presented here, calcium was excited to the 41P1 state by circularly polarized radiation at ~423nm. The quantization axis of the laser polarization is hence parallel to the magnetic field direction, and so the laser-excited states can be represented as shown in figure 4. The magnetic field removes the degeneracy of the |L,m_L> = |1,+1> sub-states coupled to the ground state by circularly polarized radiation. To measure $L_\perp$ it is therefore necessary to re-tune the laser frequency by twice the Zeeman shift for each selected polarization so as to remain in resonance. $L_\perp$ is then determined from the super-elastic signal $S_{Polar}(\theta)$ using the expression:

$$L_\perp = \frac{S_{LHC}(\theta_L) - S_{RHC}(\theta_R)}{S_{LHC}(\theta_L) + S_{RHC}(\theta_R)}$$

(1)
The experiments were conducted for electron energies $E_{\text{eV}}^{\text{out}} = 45-55$, coinc $= 45$, $55$, and the beam current was $\sim 5 \mu$A. The oven was operated at a constant temperature of 1060K. The laser intensity at the interaction region was $\sim 40\text{mW/mm}^2$, and the rates of super-elastically scattered electrons varied from $\sim 10\text{Hz}$ to $\sim 3\text{kHz}$, depending on the scattering angle and laser polarization direction. The vacuum chamber pressure was $\sim 1 \times 10^{-6}$ torr for all measurements.

Data were collected over a period of 8 months with the MAC device both operational and non-operational. This allowed a comparison to be made between the results at equivalent scattering angles, and further allowed an accurate determination of the cross section beyond $180^\circ$ for the first time. A full set of data was obtained for the Natural frame parameters $L_\perp$, $P_{\|}$, $\gamma$ during this time, however only the $L_\perp$ parameter is presented here.

3. Results and discussion

Figure 5 shows the experimental results, where $L_\perp$ is derived as in equation (1). At 45eV, the new results are compared to the super-elastic scattering data of Law and Teubner, who measured $L_\perp$ from $\theta_e \sim 0^\circ$ to $\theta_e = 90^\circ$. The early electron-photon coincidence measurements of Kleinpoppen and co-workers from $\theta_e = 10^\circ$ to $\theta_e = 50^\circ$ are also shown. It is clear that the quality of the super-elastic data is far higher than for the coincidence measurements, which suffers from low counting rates and long data accumulation times.

The new results presented here include measurements from $\theta_e = 14^\circ$ to $\theta_e = 145^\circ$ taken without the MAC operating, and data up to and beyond $\theta_e = 180^\circ$ taken with the MAC field. Experimental results with and without the MAC are in close agreement where overlap exists, differences being due to small changes in contact potentials around the interaction region due to calcium deposition. Data was taken using a range of magnetic fields at this energy.

The results at 55eV are again shown from $\theta_e = 14^\circ$ to $\theta_e = 145^\circ$ without the MAC operating, and for selected angles from $\theta_e = 14^\circ$ to beyond $\theta_e = 180^\circ$ with the MAC operating. A larger field of 1.8mT was required for the 55eV results due to the higher electron energy. No other experiments have been conducted at this energy for comparison.

The calculations of Stauffer and colleagues are shown for comparison, convoluted with the experimental angular response. The model is in very good agreement over the complete angular range, apart from at $\theta_e = 60^\circ$ where the minimum is underestimated, and at $\theta_e = 100^\circ$ where the minima are overestimated. The maxima and their positions are reproduced well. In particular, the sharp peak at $\theta_e = 140^\circ$ observed for the first time in these data is in very good agreement with theory. It is clear that the model has described the physics of the collision for this parameter well at these energies.
It is interesting to note that experimental results for elastic scattering from inert gas targets which use a MAC device\cite{11} show significant discrepancies with other calculations by Stauffer and colleagues\cite{12}. Since the theoretical derivation of the Natural frame parameters is more complex than for elastic cross sections, it is noteworthy that such excellent agreement is found here. These new results tend to confirm that previous experimental elastic scattering data with the MAC device are reliable. The discrepancy between theory and experiment for elastic scattering may therefore be due to the increased importance of polarization effects at lower incident energies.

4. Conclusions and future work

New results have been presented for the angular momentum imparted during the collision of an electron with calcium excited to the $4^1P_1$ state, as represented by the $L_{\perp}$ parameter. These results were collected using a new type of super-elastic spectrometer designed and built in Manchester which uses a MAC device. The results have been presented for scattering angles up to and beyond 180° for the first time.

Figure 5. Derived values of the angular momentum parameter $L_{\perp}$ from experimental data for outgoing electron energies 45eV and 55eV, at angles from $\theta_e = 0^\circ$ to beyond $\theta_e = 180^\circ$. Results at 45eV are compared to the super-elastic data of Law and Teubner\cite{7} and to the coincidence data from Kleinpoppen and co-workers\cite{8}. The theoretical calculations of Stauffer and colleagues\cite{10} are also shown. For details, see text.

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and excellent agreement with theory has been found. A full set of Natural frame parameters has also been determined during these studies, however these results are not shown here.

Future experiments presently being setup in Manchester include the use of a 4-element MAC device to ensure that the magnetic field at the interaction region is zero, and the use of potassium and rubidium as targets. By adopting a MAC device which does not lift the degeneracy of the sub-states, it will then be possible to determine a complete set of Natural frame parameters for these alkali targets.

New results will also be taken where the incident energy is reduced towards threshold, so as to link the intermediate and low energy regimes. By spanning the regimes where different theories are considered to be accurate (such as CCC and DWBA models), it is expected that new models will be developed which find success over all energies. In particular, in the region around 10eV and below, theoretical results presented at the ICPEAC conference (2007) indicate that significant discrepancies occur between models for a calcium target. These energy regimes are difficult to explore experimentally due to the low energy required from the electron gun, however they clearly require investigation. It is in this region that the next experiments will be targetted.

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