Super-elastic electron scattering from calcium over all angles.

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Abstract. Experimental results are reported for the Atomic Collision Parameters of calcium over all scattering angles as derived from super-elastic scattering experiments performed using a new Magnetic Angle Changing (MAC) spectrometer. Results at 55eV incident energy are compared to theoretical calculations, and new data at 65eV are reported here for the first time.

1. Introduction.
The super-elastic scattering technique is a powerful method which provides highly accurate collision cross section data for testing state of the art theories. In comparison to more traditional coincidence techniques, super-elastic scattering data accumulates many thousands of time faster, and so can be used over a wide range of incident energies and scattering geometries [1 & references therein]. The method uses a high power continuous wave (CW) laser beam to prepare a target atom in a well defined excited state, the polarization, power and direction of the laser controlling the excited sub-state populations and coherences. An incident electron of well defined energy then de-excites the laser-prepared target, and so carries energy from the interaction in a super-elastic collision process. Since the ‘shape’ of the electron charge cloud in the laser excited target is well controlled, the probability of de-excitation in a given scattering direction depends on this shape. The interaction can be considered as the time-reversal of electron-photon coincidence methods, and so allows the Atomic Collision Parameters (ACPs) to be deduced. In the Natural frame of reference, these parameters are the angular momentum transferred to the target by the electron collision \( L_\perp \), the alignment of the atom given by \( P_{\text{lin}} \), \( \gamma \) and the spin-flip probability \( \rho_{00} \). The experiments described here determine \( L_\perp \), \( P_{\text{lin}} \), and \( \gamma \).

In contrast to all previous super-elastic measurements, the spectrometer used in these studies incorporates a MAC device that allows all scattering angles to be accessed [2]. This device uses a well controlled magnetic \( \mathbf{B} \)-field to steer electrons to and from the interaction region while ensuring no field reaches the electron gun and scattered electron momentum analyzer. Correct adjustment of the MAC currents ensures that all electron scattering angles from \( 0^\circ \) to beyond \( 180^\circ \) can be accessed, allowing the most robust test of collision theories which can be made.

A complexity that arises when using a MAC device for super-elastic studies is that the \( \mathbf{B} \)-field influences the shape of the laser excited target due to Zeeman shifting of the target states. These effects have been modeled using a Quantum Electro-dynamic (QED) theory [3], which considers the dynamics of the laser interactions assuming that the \( \mathbf{B} \)-field produces a small perturbation. In the case of the \( 4^1\text{P}_1 \) state of calcium as studied here, the QED model indicates that \( L_\perp \) can be directly...
determined by ensuring the laser remains on resonance with the appropriate \(|m_j| = \pm 1\) sub-state excited by circularly polarized light, whereas the alignment parameters \(P_{\text{lin}}\) require the effects of the Larmor precession to be considered during excitation by linearly polarized light. Under steady state conditions it has been shown that the alignment angle \(\gamma\) is directly related through a constant offset phase angle to the peak of the super-elastic data obtained by rotating the direction of linearly polarized light, whereas \(P_{\text{lin}}\) is obtained through a simple linear scaling to the data. These offset and scaling factors are due solely to the laser interaction in the \(B\)-field, and so are independent of electron scattering angle. As such, they were determined from experiment by comparing data with and without the MAC operating at lower scattering angles, and then using these experimentally measured factors to determine the ACP’s for higher angles, where only the MAC could be used.

2. The Experimental Apparatus.

Figure 1a shows the apparatus used in the experiments. Calcium vapour is delivered from a well collimated effusive oven which produces an atomic beam of diameter \(\sim 2\) mm in the interaction region. Laser light at \(\sim 423\) nm from a Coherent MBR-110 Ti:Sapphire laser pumping an MBD-200 frequency doubler enters the vacuum chamber through a window on the top flange. The light polarization is varied using a combination of Glan-laser polarizer, \(\lambda/2\) & \(\lambda/4\) plates. The radiation passes axially through the MAC coils and interacts with the atomic beam to prepare atoms in a well defined state. Scattered electrons from the gun that de-excite the laser-prepared atoms are measured by the electron analyzer. The analyzer can rotate from \(\sim 10^\circ\) to \(\sim 140^\circ\), and is prevented from taking data at lower angles due to scattering of the primary electron beam from the analyzer body (thereby producing unacceptably high background counts). Measurements at higher angles are prevented by the physical size of the electron gun and analyzer, as shown in figure 1b. The MAC device is used for scattering angles higher than \(140^\circ\), and effectively steers electrons from this region back into the analyzer.

![FIG 1. The apparatus, and restrictions on scattering angle without the MAC operating. For details, see text.](image)

To ensure the input laser beam is accurately aligned, a visible laser diode (VLD) is located inside the apparatus to provide an external tracer beam once the chamber is evacuated. The VLD is adjusted using a set of non-magnetic oil-free vacuum XY translators [4] as shown. A liquid nitrogen cold trap [5] opposite the oven ensures calcium vapour does not deposit onto sensitive components inside the chamber. The direct electron beam from the gun (\(I_{\text{beam}} \sim 5\) \(\mu\)A) is dumped into an extended Faraday cup which allows both un-deflected and MAC-deflected electrons to be caught.
For the experiments described here the incident electron energy ranged from 55eV to 65eV, and so the pass energy of the analyzer was set 2.93eV higher so as to measure super-elastically scattered electrons. Results at 55eV were collected using the MAC device in operation, whereas the very recent results at 65eV were taken without the MAC operating. As such, the data at 55eV covers the angular range up to and beyond 180°, whereas the results at 65eV are confined to angles from 15° to 125°.

3. Experimental Results.

Figure 2 shows the results at 55eV and 65eV for the angular momentum transferred to the atom during the collision, as measured by $L_{\perp}$. The results at 55eV are compared to the relativistic distorted wave calculations of Stauffer and colleagues [6]. A difference is seen between theory and experiment around 50° where the experimental data is more pronounced than suggested by theory, but overall the agreement is very good for this parameter. Experimental results with and without the MAC operating are also shown. The data at 65eV is similar in form to that at 55eV as might be expected. There is no theory at present with which this data can be compared.

Figure 3 shows the results for $\gamma$ & $P_{lin}$ at these energies. Once again there is impressive agreement between theory and experiment for the alignment angle $\gamma$, where theory passes through almost every data point. Experimental determination of $\gamma$ has a high accuracy due to the number of measurements taken at each scattering angle, culminating in an accurate fit to data. Again, the new results at 65eV closely follow the trend at 55eV, although we do not have any calculations with which to compare these results. The results for $P_{lin}$ also compare well to theory [6], apart from at the higher scattering angles taken with the MAC, where experiment indicates a lower value of this parameter than theory. The dip around 25° is not as pronounced as predicted by the calculation, but once again theory is clearly including the important collision physics in the interaction. Again, the new results at 65eV follow a similar trend to those at 55eV, with a deep minimum in $P_{lin}$ being predicted at lower scattering angles, as well as a shallower dip around 90°.
FIG 3. Results for $\gamma$ & $P_{lin}$ at 55eV & 65eV incident energies, compared to theory at 55eV[6].

4. Conclusions.
We have demonstrated the advantage that a MAC device brings to the super-elastic scattering process, and have shown that measurements can now be obtained for the atomic collision parameters over a wide range of scattering angles. The impressive agreement noted between theory and experiment clearly indicates that the important collision processes have been included at these intermediate energies, and we are confident the new data at 65eV will also show agreement once calculations are carried out at this energy.

The QED model derived for the interaction of laser radiation with atoms immersed in a magnetic field has been used to predict the effects on the super-elastic scattering process, and close agreement has been found between these predictions and experiment as seen above. This model is now being used in other work involving magnetic fields, including atom trapping and manipulation experiments where these effects are important. As such, this model is expected to have wide applicability in different fields.

The apparatus is currently being modified to allow data to be collected at energies approaching the threshold for excitation. These are challenging experiments due to the low scattering yield and due to the difficulty working with calcium and low energy electron beams. It is in this region that differences between various excitation models have been predicted [7], and it will be particularly interesting to see if the high accuracy data produced by the super-elastic technique can distinguish between different models. Experimental results from these studies are expected to be produced in the near future.

References
[1] M Hussey et al, J Phys B At Mol Opt Phys 41 055202 (2008)
[2] F H Read and J M Channing, Rev Sci Inst 67 2372 (1996)
[3] A J Murray et al, Phys Rev A 77 013409 (2008)
[4] A J Murray et al, Meas Sci Tech 16 N19 (2005)
[5] A J Murray, Meas Sci Tech 13 N12 (2002)
[6] R K Chauhan et al, J Phys B At Mol Opt Phys 38 2385 (2005)
[7] O Zatsarinny et al, J Phys B At Mol Opt Phys 40 4023 (2007)