Spin-Resolved Collisions of Electrons with Rubidium Atoms: A Search for Relativistic Effects

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Abstract. The search for relativistic effects in electron-alkali scattering is currently a topic of considerable interest. The A_2 spin asymmetry parameter is a direct measure of relativistic effects in the electron-atom collision process, as it is entirely dependent on the spin-orbit effect. We present measurements of the A_2 spin asymmetry for the 5S → 5P transition in rubidium at incident energies of 15, 20, 30 and 50 eV and for elastic scattering at 15, 20, 30, 50 and 80eV. Our results indicate that under these collision conditions, relativistic effects are measurable, in qualitative agreement with the available theory.

INTRODUCTION

Recently there has been a search for relativistic effects in the scattering of electrons from heavy alkalis. This search was partly motivated by theoretical efforts which suggested that such spin-dependent relativistic effects should be measurable. Theoretical attempts to describe the role of the spin-orbit effect in spin polarised electron scattering from one electron atoms were first investigated by Burke and Mitchell [1]. Spin effects are relativistic in nature, as they arise from Dirac's application of relativity to quantum electro-dynamics. The spin-dependent interaction between the incident electron and a target atom is proportional to $\mathbf{L} \bullet \mathbf{S}$, where $\mathbf{S}$ is the spin angular momentum vector of the incident electron and $\mathbf{L}$ is the total orbital angular momentum of the incident electron during the collision process. It was surprising that the effects of this interaction did not appear in measurements of the differential cross section or the Stokes parameters of such heavy elements as cesium [2]. Several theoretical treatments that ignore relativistic effects predicted the differential cross sections and Stokes parameters for these elements with a high degree of accuracy [2].

Andersen and Bartschat [3] demonstrated that these 'conventional' collision parameters are insensitive to spin dependent effects in the scattering process. Instead they identified several generalised Stokes parameters, three spin asymmetries and several so called circular dichroism parameters that are explicitly dependent on spin

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effects. The asymmetries are designated A_1, A_2 and A_{nn}. A_1 represents scattering of unpolarised electrons from polarised atoms, and is known as the interference asymmetry. A_{nn} represents scattering of polarised electrons from polarised atoms, and is called the exchange asymmetry. A_2 represents scattering of polarised electrons from unpolarised atoms, and is called the spin-orbit asymmetry. For elastic scattering it is identical to the Sherman function that describes the elastic scattering of polarised electrons from unpolarised targets [3]. The A_2 asymmetry is due to the spin-orbit effect on the continuum electron, and is thus a reliable indicator of the extent to which relativistic effects occur in the collision process. Experimentally one may build the spin asymmetries from the following equations:

$$NA_{nn} = \left[\left(N^{\uparrow\downarrow} + N^{\downarrow\uparrow}\right) - \left(N^{\uparrow\uparrow} + N^{\downarrow\downarrow}\right)\right] \Big/ P_a \bullet P_e \tag{1}$$
$$NA_1 = \left[\left(N^{\uparrow\downarrow} + N^{\uparrow\uparrow}\right) - \left(N^{\downarrow\downarrow} + N^{\downarrow\uparrow}\right)\right] \Big/ P_a$$
$$NA_2 = \left[\left(N^{\uparrow\uparrow} + N^{\downarrow\uparrow}\right) - \left(N^{\uparrow\downarrow} + N^{\downarrow\downarrow}\right)\right] \Big/ P_e$$

where $N = N^{\uparrow\downarrow} + N^{\downarrow\uparrow} + N^{\uparrow\uparrow} + N^{\downarrow\downarrow}$, and corresponds to the differential cross section, P_a is the target beam polarisation with respect to the scattering plane and P_e is the incident electron beam polarisation with respect to the scattering plane. The first superscript indicates the atomic spin with respect to the scattering plane, while the second superscript indicates the incident electron beam spin with respect to the scattering plane [2]. Measurements of these three spin asymmetries from the heavy alkali cesium clearly showed the existence of relativistic effects in the collision process [2, 4, 5]. Further measurements of these asymmetries in other heavy alkalis would be of enormous value in testing the validity of several relativistic theories. As such, measuring the A_2 parameter for rubidium would help fill a gap in our experimental knowledge and in the testing of theoretical predictions.

EXPERIMENTAL APPARATUS

The apparatus comprises four chambers: the source chamber, the differential pumping stage, the scattering chamber, and a chamber, containing a Mott polarimeter, which is used to determine the polarisation of the incident electron beam. The interaction region is in the centre of the scattering chamber. The differential pumping stage serves as a pressure buffer between the source chamber and the scattering chamber, the pressure ratio being about 1000. The source chamber houses the source of spin polarised electrons itself, and is maintained at a pressure of around 3×10^{-10} mbar.

A small wafer of GaAs produces the spin polarised electron beam. Deposition of small amounts of cesium and oxygen produce a negative electron affinity (NEA) surface, such that the conduction band minimum is higher in energy than the vacuum states. A near infrared diode laser, wavelength 820nm, is incident upon the surface of the crystal, and excites electrons from the valence to conduction band. The laser is incident via a linear polariser and a liquid crystal retarder (LCR). The incident laser light is thus circularly polarised, and the orientation, left hand circularly polarised (LHC) or right hand circularly polarised (RHC), can be changed manually or by computer control of the LCR applied voltage. For a discussion of GaAs spin-polarised sources, see [6]. As the interaction region is at ground, a negative potential applied to the crystal determines the energy of the ensuing electron beam.

A 90-degree electrostatic deflector guides the emitted electrons into an extensive electron optics train. The electron optical elements guide and focus the electron beam to the interaction region of the experiment. A Faraday cup is used to monitor the incident beam current. The Faraday cup is on a turntable, thus it can be moved to the side in order to conduct a measurement of the beam polarisation using the Mott chamber. An oven, containing rubidium, positioned at 120 degrees to the electron optics, is heated to provide the atomic beam of rubidium. A hemispherical electrostatic energy analyser mounted on the opposite side of the chamber is capable of detecting electrons scattered through angles 30-110 degrees in the scattering plane.

For the spin asymmetry measurements presented here, the number of counts for a particular spin orientation at a particular angle is recorded in the angular range 30-110 degrees in five-degree steps. The spin orientation at each angle is varied (around once every 10 seconds), so as to average over noise and any possible instrumental asymmetries. Normally one hundred of these spin flips is conducted at each angle. Up to 70 scans over the whole angular range may be taken in order to gain favourable statistics for a single asymmetry measurement.

RESULTS

Results for the A_2 asymmetry for elastic and inelastic electron scattering at an incident energy of 15eV are presented in Fig. 1. Results at incident energies of 20, 30 50 and 80eV are presented in figure 2. Only elastic results are reported for the 80eV measurement, as the inelastic differential cross section, at this energy, was too low to conduct a measurement. Importantly, the asymmetry is non-zero for both elastic and inelastic scattering at all energies. This indicates that spin-dependent effects are measurable at these intermediate energies. At lower angles the asymmetry is essentially zero for all results. This is not surprising as large asymmetries generally only occur near minima in the differential cross section [7]. The magnitude of the asymmetries overall are around one third of those seen for cesium [2, 4, 5]. Given the considerably different nuclear charge of rubidium and cesium, and the dependence of A_2 on the spin-orbit effect, this result is understandable.

Comparing the inelastic results, there appear to be similar trends and magnitudes across all energies except the 50eV result. The 15, 20 and 30eV results all show generally similar magnitude asymmetries (around 4% maximum values), though the 30eV result exhibits an apparently large asymmetry of 11.5% at 80 degrees. Assuming that the large asymmetry at 30eV is due to scatter in the data, the 50eV result exhibits the largest asymmetry (around 7%) of the inelastic results. On making a similar comparison as a function of energy for the elastic results, one finds that there the magnitude of the respective asymmetries is similar across all incident energies. Indeed the largest asymmetries for each particular energy vary from 4% (80eV) to 6% (20eV). Thus there is little variation in the magnitude of the asymmetries over this energy range for elastic scattering. There appears to be little difference in the magnitude of the asymmetries upon comparison of the elastic and inelastic results.

In each case, the results are presented with the applicable theory. Two theoretical approaches are presented here: a semi-relativistic Breit-Pauli R-matrix approach, with and without pseudostates, and a fully relativistic Dirac-Fock calculation. The first approach is a calculation by Bartschat; for details see Guinea et al [8]. The second is that of Stauffer [9].

The Dirac-Fock calculation has only been applied in this case to inelastic scattering at energies of 20eV to 50eV. The R-matrix approach has been applied at all energies with a variety of states in the expansion. Qualitatively, there is good agreement between theory and experiment, in that the theory predicts non-zero asymmetries at all energies. The magnitude of the asymmetries, as predicted by the BP 37 calculation is generally good. The exceptions to this are for both the 15eV results and the 20eV inelastic result. Of notable interest is the apparent angular shift that exists between the R-matrix theory and the results at all energies. The angular discrepancy between theory and experiment appears to be improving with the 37 state calculation, though the predicted magnitude in the cases noted above is still rather poor. The 37 state calculation generally appears to perform well in comparison to the 5 state calculation, which does not include pseudostates. A more complete calculation with a larger number of pseudostates would be useful in determining if the angular distribution and magnitude of the R-matrix prediction improves in comparison to the experimental results. Both qualitatively and quantitatively the RDW calculation is very good across those results it is compared with.

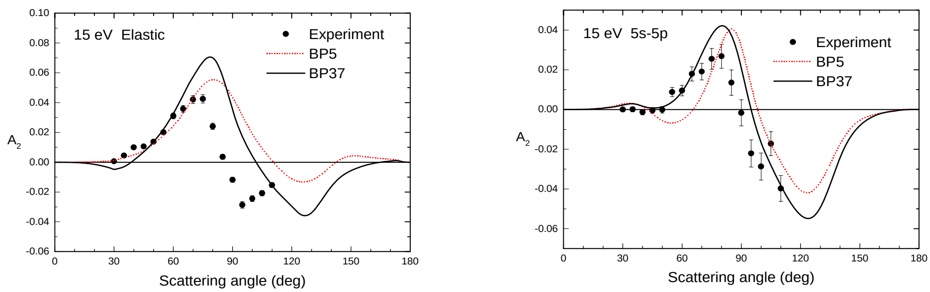

FIGURE 1. Results for the A_2 asymmetry for elastic and inelastic electron scattering from rubidium at an incident energy of 15eV.

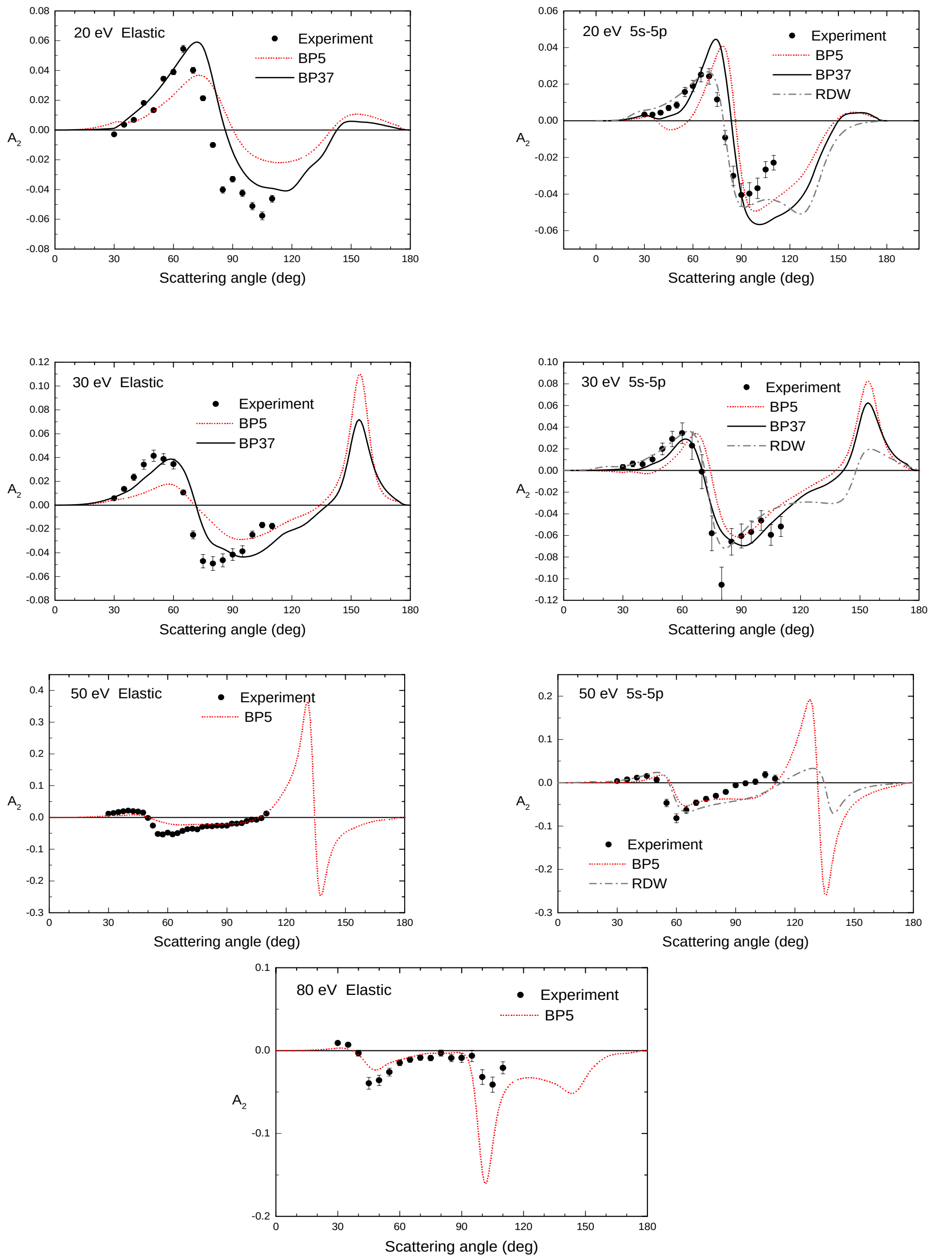

FIGURE 2. The A_2 asymmetry for elastic and inelastic electron scattering from rubidium at 20, 30 and 50eV incident energy, and for elastic scattering at 80eV incident energy.

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