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LETTER TO THE EDITOR

Search for a joint spin–orbit and exchange asymmetry in elastic electron scattering from spin-polarised sodium

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Abstract. Measurements of the asymmetry in the scattering of unpolarised electrons from optically pumped spin-polarised sodium atoms have been carried out at incident electron energies of 20, 54.4 and 70 eV and for a range of scattering angles between 20° and 140°. This asymmetry, which was first proposed by Farago as a means of measuring spin-orbit effects in the presence of a dominant spin-exchange interaction, is less than 1% at all energies and scattering angles studied.

The investigation of exchange and spin–orbit effects in electron scattering from atoms has become increasingly common with the progress being made in polarised beam technologies. To date, most experimental studies have been primarily sensitive to either of these effects, but not to both. For example, electron scattering from heavy closed-shell atoms can be used to investigate directly the spin–orbit interaction, and electron scattering from light, one-electron atoms provides a direct study of exchange. The spin–orbit interaction depends only on the spin orientation of the continuum electron relative to the scattering plane but does not depend on the spin orientation of the target. Exchange, on the other hand, affects the cross section not through the spin orientation of either the target or projectile electrons relative to the scattering plane, but only through their orientation relative to one another, i.e. parallel or antiparallel.

Neither the spin–orbit interaction nor exchange, when working alone, can cause a difference in scattering intensity when an unpolarised electron is incident upon a spin-polarised atomic target oriented 'up' or 'down' with repect to the scattering plane. However, some time ago Farago (1974) proposed that there may be a measurable asymmetry in this situation if *both* the spin–orbit and exchange interaction are present. Based upon the work of Burke and Mitchell (1974) he derived an expression for this asymmetry in terms of the six complex amplitudes, α_1–α_6, which are required to completely characterise the scattering process.

Walker (1974) further developed this concept by performing exploratory calculations of the magnitude of the effect, which he termed an 'interference' between the exchange and spin–orbit processes, for unpolarised electron scattering by the heavier alkali metals, in particular caesium. He found evidence of asymmetries as large as 90% for incident electron energies below about 15 eV and values of 1–2% at an energy of 35 eV. He also made several other observations about the magnitude and angular dependence of these asymmetries which are of relevance to the work we present here.

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Firstly he notes that the maximum magnitude of the asymmetry, which for brevity we will refer to as the 'joint asymmetry', decreases rapidly from about 60% at 1.4 eV to about 1% at 35 eV, whilst the spin-orbit asymmetry remains significant (>50%) over this whole range. Secondly, the angular dependence of the joint asymmetry essentially tracks that of the spin-orbit, particularly at low incident energies. Walker interprets this as an indication that the incident electron is polarised by the spin-orbit interaction (Mott scattering) before it interacts and can exchange with the valence electron. As the incident energy is increased the resemblance between the two calculated asymmetries decreases, possibly as a result of the increasing interaction between the projectile electron and the core electrons and the decreasing interaction with the valence electron. He also notes that, similar to most measurements and calculations of spin asymmetries, the maxima in the joint asymmetry curves occur near the minima in the differential scattering cross section.

In addition to the calculations on caesium, Walker also performed calculations for atomic hydrogen, where he found no effect greater than 0.01% and speculated that the asymmetry should be negligible in both lithium and sodium, based on the presumption that spin-orbit effects would be negligible in both these systems. In view of recent measurements which showed substantial spin-orbit effects in elastic electron scattering from sodium (McClelland *et al* 1987), a quantitative search for the joint asymmetry in sodium was considered of interest in our program of measurements of spin-polarised electron scattering from spin-polarised sodium. We have undertaken measurements of this joint asymmetry at incident electron energies of 20, 54.4 and 70 eV and for scattering angles lying in the range 20–140°.

The experimental apparatus has been described in detail elsewhere (McClelland *et al* 1989) so only a brief outline will be given here. The polarised electron beam is produced by photoemission from a NEA GaAs crystal using a circularly polarised beam from a diode laser operating at 810 nm. The electron polarisation, as measured by 100 keV Mott scattering from a gold foil target, is 28 ± 1% and the electron spin can be flipped up or down, with respect to the scattering plane, by changing the handedness of the laser polarisation with a Pockels cell. The sodium beam is produced from an effusive oven and is spin-polarised by optically pumping with circularly polarised light from a stabilised, single-frequency ring-dye laser which is tuned to the 589.0 nm $3^2S_{1/2}(F=2)\rightarrow 3^2P_{3/2}(F=3)$ hyperfine transition. The atoms are also spin polarised in a direction normal to the scattering plane and their spin is flipped by changing the handedness of the circular polarisation of the laser beam with a rotatable circular polariser. The atomic beam polarisation is 60 ± 1%. The scattered electrons are detected with a channel electron multipler, mounted at the end of a retarding field analyser which rejects all but elastically scattered electrons, and which can rotate in the scattering plane about the interaction volume.

At each energy and scattering angle four intensities are measured, corresponding to the different relative orientations of electron and atomic spin. These intensities, $I^{\uparrow\uparrow}$, $I^{\uparrow\downarrow}$, $I^{\downarrow\downarrow}$, and $I^{\downarrow\uparrow}$, where the arrows indicate the electron and atom spins respectively, can then be arranged to construct the exchange, spin-orbit and joint asymmetries which are defined by

$$A_{\mathrm{exch}}=\frac{1(I^{\uparrow\downarrow}+I^{\downarrow\downarrow})-(I^{\uparrow\uparrow}+I^{\downarrow\downarrow})}{P_eP_a(I^{\uparrow\downarrow}+I^{\downarrow\uparrow})+(I^{\uparrow\uparrow}+I^{\downarrow\downarrow})} \tag{1.1}$$

$$A_{\mathrm{SO}}=\frac{1(I^{\uparrow\uparrow}+I^{\uparrow\downarrow})-(I^{+}k+I^{\downarrow\downarrow})}{P_e(I^{\uparrow\uparrow}+I^{\uparrow\downarrow})+(I^{\downarrow\uparrow}+I^{\downarrow\downarrow})} \tag{1.2}$$

$$A_{\text{joint}} = \frac{1(I^{\uparrow\uparrow} + I^{\uparrow\downarrow}) - (I^{\downarrow\uparrow} + I^{\downarrow\downarrow})}{P_a(I^{\uparrow\uparrow} + I^{\downarrow\uparrow}) + (I^{\uparrow\downarrow} + I^{\downarrow\downarrow})} \tag{1.3}$$

where P_e and P_a are the electron and atom polarisations respectively. Note that although these experiments are carried out with a polarised electron beam, the joint asymmetry is averaged over the electron beam polarisation. The energies studied are representative of situations where (i) the exchange interaction is dominant over the spin–orbit (20 eV, Buckman *et al* 1989), (ii) the two have comparable magnitudes (54.4 eV, McClelland *et al* 1987) and (iii) the deepest minimum in the elastic differential cross section occurs (70 eV and 103°). This minimum was found by a systematic search over a range of scattering angles for energies less than 100 eV.

The results are shown in figures 1 and 2. Figures 1(*a*) and (*b*) depict the joint asymmetry at 20 and 54.4 eV respectively, over an angular range of 20° to 140°. The measurements on both of these curves indicate that, at these energies, any asymmetry due to this effect is less than 1% over the entire angular range. The one apparent exception to this at 115° and 20 eV (1.8 ± 0.8%) is entirely consistent with this observation given the stated experimental error of ±1 standard deviation estimated from counting statistics. At 70 eV (figure 2(*a*)–(*c*)) we have restricted our measurements to the region near the deep minimum in the elastic scattering cross section at about 103°. In this case for a comparison we also show the exchange (figure 2(*a*)) and spin–orbit (figure 2(*b*)) asymmetries which were measured at this energy. Again the data indicate that the joint asymmetry (figure 2(*c*)) is essentially zero, even at a scattering angle of 105° where the exchange asymmetry is −12% and the spin–orbit asymmetry about −5%. Also shown in figure 2(*b*) is a full relativistic static potential calculation of the spin–orbit asymmetry by Gregory and Fink (1974) which shows good qualitative agreement with the measured values, similar to the situation at 54.4 eV (McClelland *et al* 1987). The present data represent the first attempt to measure the joint asymmetry in elastic electron scattering by a one-electron atom. In keeping with the theoretical predictions of Walker (1974) this asymmetry is small, less than 1% for scattering by sodium at all energies above 20 eV. It is possible that measurements at lower energies with this target, where the exchange interaction is predicted to be stronger, may reveal a non-zero effect. Such measurements are planned in this laboratory. It is more likely that

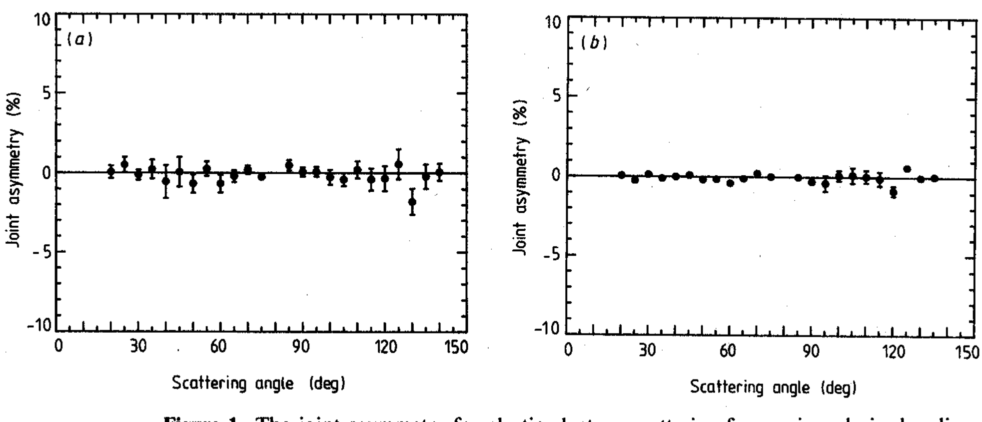
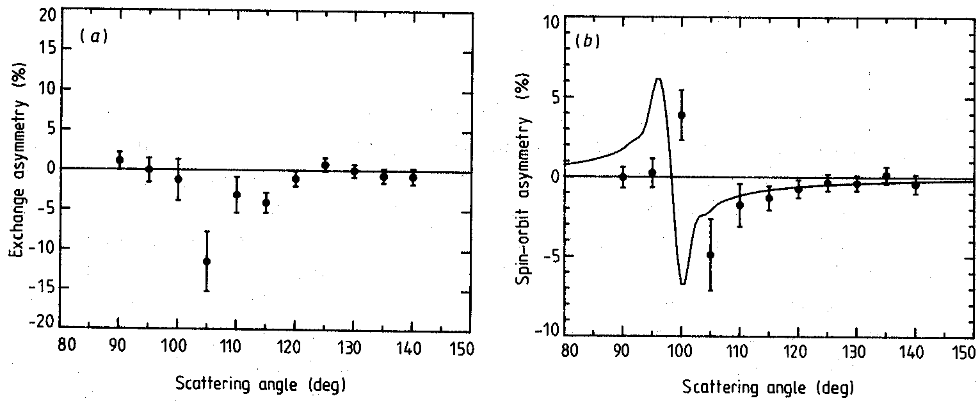


Figure 1. The joint asymmetry for elastic electron scattering from spin-polarised sodium at (*a*) 20 eV, (*b*) 54.4 eV.



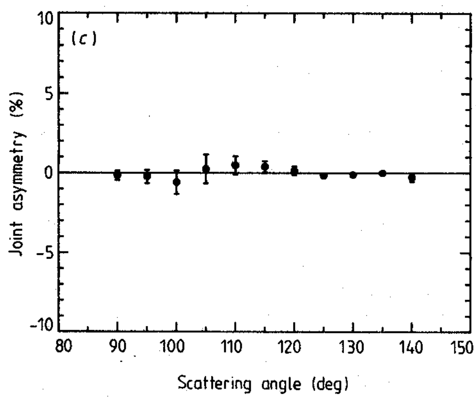


Figure 2. (*a*) Exchange, (*b*) spin–orbit and (*c*) joint asymmetries for elastic electron scattering from spin-polarised sodium at an incident energy of 70 eV. The full curve in (*b*) is a relativistic calculaion by Gregory and Fink (1974) at 75 eV.

investigations of this effect with heavier one-electron atoms such as caesium or rubidium will be more successful in this regard.

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Please note the following corrected equations:

$$A_{exch} = \frac{1}{P_e P_a} \frac{(I^{\uparrow\downarrow} + I^{\downarrow\uparrow}) - (I^{\uparrow\uparrow} + I^{\downarrow\downarrow})}{(I^{\uparrow\downarrow} + I^{\downarrow\uparrow}) + (I^{\uparrow\uparrow} + I^{\downarrow\downarrow})} \tag{1}$$

$$A_{so} = \frac{1}{P_e} \frac{(I^{\uparrow\uparrow} + I^{\uparrow\downarrow}) - (I^{\downarrow\uparrow} + I^{\downarrow\downarrow})}{(I^{\uparrow\uparrow} + I^{\uparrow\downarrow}) + (I^{\downarrow\uparrow} + I^{\downarrow\downarrow})} \tag{2}$$

$$A_{joint} = \frac{1}{P_a} \frac{(I^{\uparrow\uparrow} + I^{\downarrow\uparrow}) - (I^{\uparrow\downarrow} + I^{\downarrow\downarrow})}{(I^{\uparrow\uparrow} + I^{\downarrow\uparrow}) + (I^{\uparrow\downarrow} + I^{\downarrow\downarrow})} \tag{3}$$