Atomic physics

Electron-scattering experiments

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ELECTRON-EXCHANGE and spin–orbit effects are inherent in the quantum description of atoms. In 1926 Heisenberg explained the existence of two species of helium, ortho- and para-helium, by considering exchange interactions between the two electrons of the atom and also spin–orbit effects. Such spin effects also appear in electron–atom scattering, and these have been studied in various ways since the early 1970s. An interesting result is now reported by J.J. McClelland, M.H. Kelly and R.J. Celotta (*Phys. Rev. Lett.* **58**, 2198–2200; 1987), who have measured for the first time the competition between exchange and spin–orbit interactions in collisions of electrons with sodium atoms.

It is spin–orbit interactions that account for the splitting of the helium atomic-energy levels. The two electrons can have their spins parallel (spin-triplet or **S**=1 states) or antiparallel (spin-singlet or **S**=0 states). The magnetic moment of the spinning electrons interacts with the orbital motion as **L.S**, where **L** is the orbital angular momentum.

For atomic collisions, electron-spin effects are also important in different types of energetic interactions such as Coulomb-direct, Coulomb-exchange and spin–orbit. They can be investigated by using polarized electrons and polarized atoms as initial scattering particles and measuring of the spin of the electrons and/or the atom after the collision, and also by measuring a collisional asymmetry effect of the scattered electron. In their recent paper McClelland *et al.* report a study of exchange and spin–orbit effects in collisions between partially polarized sodium atoms and electrons (Fig. 1).

The scattering of spin-polarized electrons by spin-polarized 'one-electron' atoms (such as hydrogen or the alkali atoms) can be described as follows. The spin polarization of the electrons and atoms is denoted by specifying the direction of the spin orientation as parallel (↑) or antiparallel (↓) to an arbitary axis of quantization (more loosely described as spin-up or spin-down). Typical scattering reactions can be written as:

$$e(\uparrow) + A(\downarrow) \rightarrow A(\downarrow) + e(\uparrow) \quad (1)$$

or

$$e(\uparrow) + A(\downarrow) \rightarrow A(\uparrow) + e(\downarrow) \quad (2)$$

where A represents the atom. Reaction (1) is the Coulomb-direct process in which there is no electron or spin exchange. Reaction (2) is the Coulomb-exchange process in which the two electrons exchange each other without changing their spin directions. A third scattering reaction, with the spins initially parallel to each other, would not allow changes in the spin directions under a spin conservation law:

$$e(\uparrow) + A(\uparrow) \rightarrow A(\uparrow) + e(\uparrow); \quad (3)$$

Quantum mechanically these three reactions can be described by the complex scattering amplitudes f, g and $f-g$, respectively, giving all possible information on the process. The squared amplitude of a given interaction is proportional to the scattered intensity of the electrons. Alternatively, the electron–atom collision process can be described by singlet (S) and triplet (T) scattering amplitudes depending on the joint antiparallel or parallel spin directions of the collisional and target electron, respectively, with $f = ½(S+T)$, $g = ½(S-T)$.

In their experiment, McClelland *et al.* measured the intensities of the scattered electrons as a function of the electrons' initial energy and scattering angle. They did so for the four possible combinations of spin orientation: spins parallel, up or down; and the spins antiparallel (again with two possibilities, each one up or down). They define an asymmetry factor A^{exch} for the exchange process as the difference between the intensities for the parallel and antiparallel processes (normalized to the sum of the intensities, and the degree of polarization of the intitial beams).

This measured quantity can be related to the scattering amplitudes of interest by

$$A^{exch} \propto \frac{\mathrm{Re}(f^*g)}{\sigma} = \frac{1-|T|^2/|S|^2}{1+3|T|^2/|S|^2} \quad (4)$$

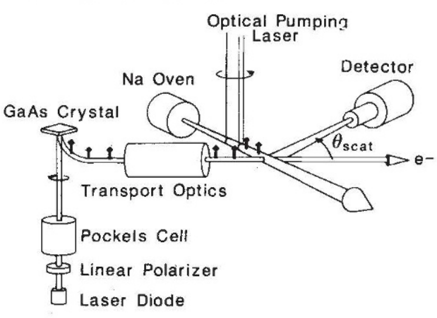

Fig. 1 Apparatus in the electron–atom scattering of McClelland *et al.* Photoelectrons are generated from the GaAs crystal by circularly polarized laser light. (The Pockels cell alternates the direction of polarization.) Similarly, the sodium atoms are polarized by 'optical pumping' using a second laser. In both cases, the polarization of the laser light is efficiently transferred to the absorber. The scattered electrons are collected by a movable detector.

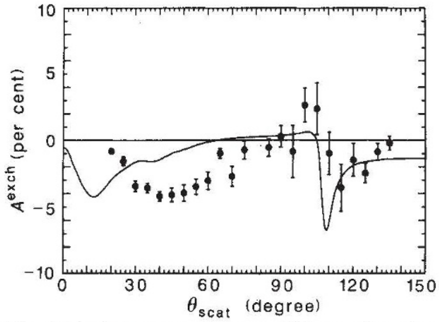

Fig. 2 Exchange asymmetry A^{exch} as a function of electron scattering angle. Experimental data points by McClelland *et al.*; theoretical curve represents a two-state close coupling calculation. The error bars are one standard deviation derived from counting statistics.

where σ is the differential cross-section, a function of the kinetic energy of the electrons and their scattering angle.

Figure 2 shows measured data of this exchange asymmetry A^{exch} for sodium atoms at incident electron energy of 54.4 eV as a function of the electron scattering angle θ_{scat}. The negative values of A^{exch} between 30 and 60° can be attributed to a negative term of interference between the exchange- and direct-scattering amplitude or alternatively as a slight dominance of the triplet-scattering amplitude. The 'oscillation' around 108° can be interpreted as the result of the singlet and triplet cross sections having minima at slightly different scattering angles.

Considerable discrepancies are seen, however, between theory and experiment for A^{exch}, although their behaviour is qualitatively similar. Are the discrepancies the result of inadequate treatment of exchange interactions in the calculation or of the combined effects of exchange and spin–orbit interactions? Spin–orbit effects result from the orbital motion of the projectile electron through an electric field (caused by the distortion of the atoms) and the interaction of the magnetic moment of the electron with the motional magnetic field.

Substantial influences from spin–orbit interactions on the electron-scattering process have been reported with heavier closed-shell atoms as targets where electron-spin experiments lead to a complete description of the collision process (for example, Wübker, W., Möllenkamp, R. & Kessler, J. *Phys. Rev. Lett.* **49**, 272; 1983). Such spin–orbit interactions are particularly important in electron scattering with heavy atoms but they have generally been ignored in experiments using lighter atoms. The new experiment of McClelland *et al.*, especially the data close to θ_{scat} = 108°, shows that asymmetry measurements can allow a complete description of electron collisions with light atoms. □

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