Measurement of Spin Dependence in Low-Energy Elastic Scattering of Electrons from Lithium Atoms

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The energy dependence of the spin asymmetry in elastic scattering of polarized electrons from Li atoms has been studied for scattering angles of 65°, 90°, and 107.5° and collision energies from 1 to 30 eV. The measured asymmetry shows variations between its extreme values of $+1$ and $-\frac{1}{3}$, and its behavior can best be described by close-coupling calculations.

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In electron-atom collisions the scattering from alkali-metal atoms has been of great interest as a testing ground for theoretical approximations and their underlying physical assumptions. Besides hydrogen, the alkali metals with their single valence electron are well suited for the investigation of spin dependence. Studies with spin-polarized collision partners reveal new and particularly sensitive information on the process and are therefore very desirable. Many differential-scattering experiments have been performed but, so far, only two with spin-polarized electrons and atoms.[1]

Among the various theoretical approximation schemes in electron–alkali-metal-atom scattering the close-coupling method is a very powerful one, at least at low energies where a small number of states will suffice, thus keeping the computational effort within reasonable limits. It has, however, never been tested experimentally on the more stringent and sensitive level of a polarization experiment. The data of pioneer experiments[2,3] were not sufficiently accurate for a decisive test. The question of the correctness of treating certain effects in the close-coupling approximation, in particular electron correlations, was raised.[4] Indeed, the vastly different predictions for the spin behavior from the various calculations motivated the present study.[5] Recent improvements in the technology of electron and atom polarization, production as well as detection, made the measurements possible.[6,7]

Theoretically, lithium is well suited for the spin-polarization studies as its low atomic number allows us to safely neglect spin-orbit–interaction effects. Spin effects can only be caused by the exchange phenomena as a consequence of the exclusion principle. A further advantage of lithium is that it is a simple atom, rather similar to hydrogen. Its large polarizability, 98% of which is accounted for by the $2p$ state, makes it very amenable for close-coupling treatments. Experimentally, the technological difficulties of Li-beam production are responsible for the fact that—despite its fundamental standing—only a few crossed-beam experiments on elastic electron-lithium scattering have been performed so far,[8,9] none using spin-polarized beams. Our experiment utilizes the experience gained in lithium-beam studies on photoionization[10] and electron-impact ionization.[11]

The difference in scattering rate for antiparallel ($\downarrow\uparrow$) and parallel ($\uparrow\uparrow$) configurations of incident electron spins and atomic spins is expressed through the spin asymmetry A, which is defined as

$$A = (d\sigma^{\uparrow\downarrow} - d\sigma^{\uparrow\uparrow})/(d\sigma^{\uparrow\downarrow} + d\sigma^{\uparrow\uparrow}),$$

with $d\sigma$ denoting the differential elastic cross section. This asymmetry is related to the singlet (s) and triplet (t) scattering amplitudes, or to the direct (f) and exchange (g) amplitudes, which are used in the description of the scattering process, as follows:

$$A = (|s|^2 - |t|^2)/4\sigma_0 = \mathrm{Re}(f^* g)/\sigma_0$$

with

$$\sigma_0 = |s|^2/4 + 3|t|^2/4 = |f|^2 + |g|^2 - \mathrm{Re}(f^* g).$$

Thus A expresses the ratio of the difference between singlet and triplet scattering to four times the spin-averaged cross section or, alternatively, the ratio of the term describing the interference between direct and exchange amplitudes to the spin-averaged cross section. For pure singlet scattering it follows that $A = +1$ and for pure triplet scattering $A = -\frac{1}{3}$. Recently, Fletcher *et al.*[1] measured this asymmetry on hydrogen atoms for the special case of 90° scattering and energies from 5 to 30 eV. The usefulness of various types of crossed-beam polarization experiments for extracting detailed information about the scattering process was discussed elsewhere.[12]

For large scattering angles ($\theta \geqslant 60°$) the collisions have small impact parameters and, therefore, the interaction is sensitive to correlation effects which are, in general, important at small distances. In the forward direction the scattering is dominated by the dipole polarizability of the atom. For our investigations we chose large scattering angles in order to work in the region where possible correlation effects might influence the size of the spin asymmetry and where, in particular, the published theoretical results[4,13,14] predict

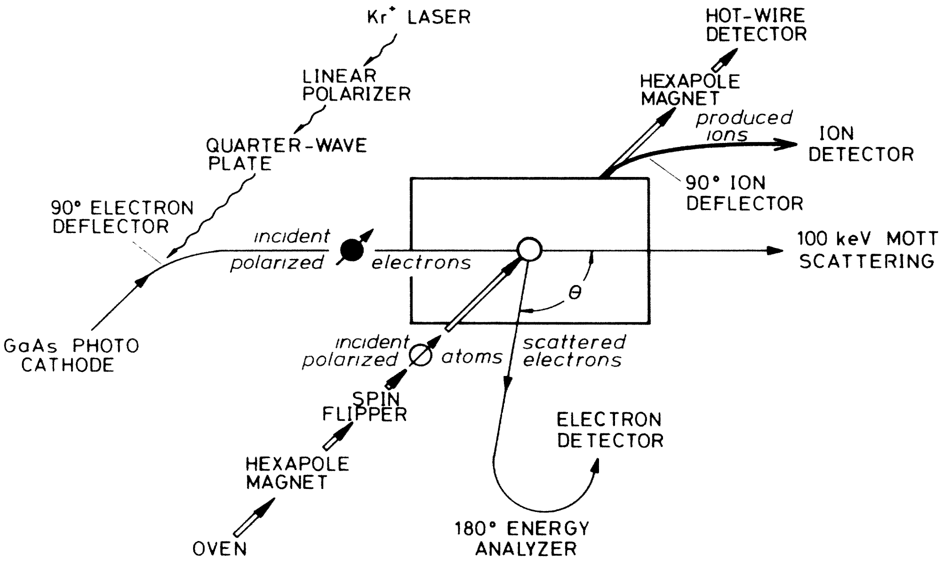

FIG. 1. Schematic diagram of experiment.

interesting structure in the asymmetry which can be used for a crucial comparison of the different approximations. The energy range for our studies extends from 1 eV, a lower limit set by experimental conditions, to about 30 eV, above which spin exchange is of little importance.

A schematic diagram of the experimental setup is shown in Fig. 1. The polarized electron beam is produced by photoemission from a GaAs crystal using circularly polarized light from a Kr-ion laser operating at the 752-nm line. With use of standard procedures for cleaning and activating the crystal surface, an electron beam, stable in intensity and polarization over many hours, is obtained with the light focused onto an area 0.2 mm in diameter. The quantum yield is about 10^{-3}. The photoelectron beam is bent electrostatically through 90°, thereby transforming the polarization from longitudinal to transverse. Polarization reversal is accomplished by a 90° rotation of the quarter-wave plate. A Mott scattering polarimeter is used to measure the electron polarization, which is typically in the range of 0.25 to 0.35. The energy spread of the beam is measured by observing the onset of the ionization process, which also allows a calibration of the energy scale. The energy spread is about 0.2 eV; the uncertainty in the energy scale is 0.05 eV. The electron currents are in the range of 100–500 nA. The atomic beam of ^{6}Li is polarized by high-field state selection in a permanent hexapole magnet. An identical magnet, located downstream of the collision region, serves as an analyzer for the atomic-beam polarization. Perfect high-field state selection will lead to a polarization of $P_a = 1/(2I+1)$ in the low magnetic field of the collision region; for ^{6}Li with nuclear spin $I = 1$ this amounts to $P_a = 0.33$. Nonperfect state selection reduces the polarization further. The analyzer magnet, combined with beam-polarization reversal, allows a measurement of this polarization. For ^{6}Li we mesured $P_a = 0.29$. The spin flipper[15] is used for reversal of the atomic-beam polarization. This is very desirable for the asymmetry measurements, as only very small instrumental asymmetries are connected with such a reversal. The beam density in the collision region is typically 10^9 atoms/cm^3; the intensity and polarization is stable over many hours.

The electron beam is decelerated from the transport energy (1000 eV) to the desired scattering energy with a four-element lens system. The elements surrounding the scattering center are gold plated to provide a well-defined contact potential. The differentially scattered electrons are observed under fixed angles of 65°, 90°, or 107.5° in the plane perpendicular to the electron and atomic beams. A four-element lens system accepts scattered electrons in a solid angle of 24 msr and focuses them onto the entrance aperture (2 mm diameter) of the 180° spherical spectrometer which has a radius of 2.5 cm for the central trajectory and an energy resolution of 0.3 eV. The uncertainty in the scattering angle of ±3° is mainly given by the divergence of the incoming electron beam; the errors from geometrical setting and from bending of trajectories in the magnetic field (50 mG in the center) are negligible. The background counting rate of the electron multiplier results mainly from beam electrons hitting the edge of a lens element behind the scattering region. By carefully minimizing the current collected on this element the background counts are also minimized.

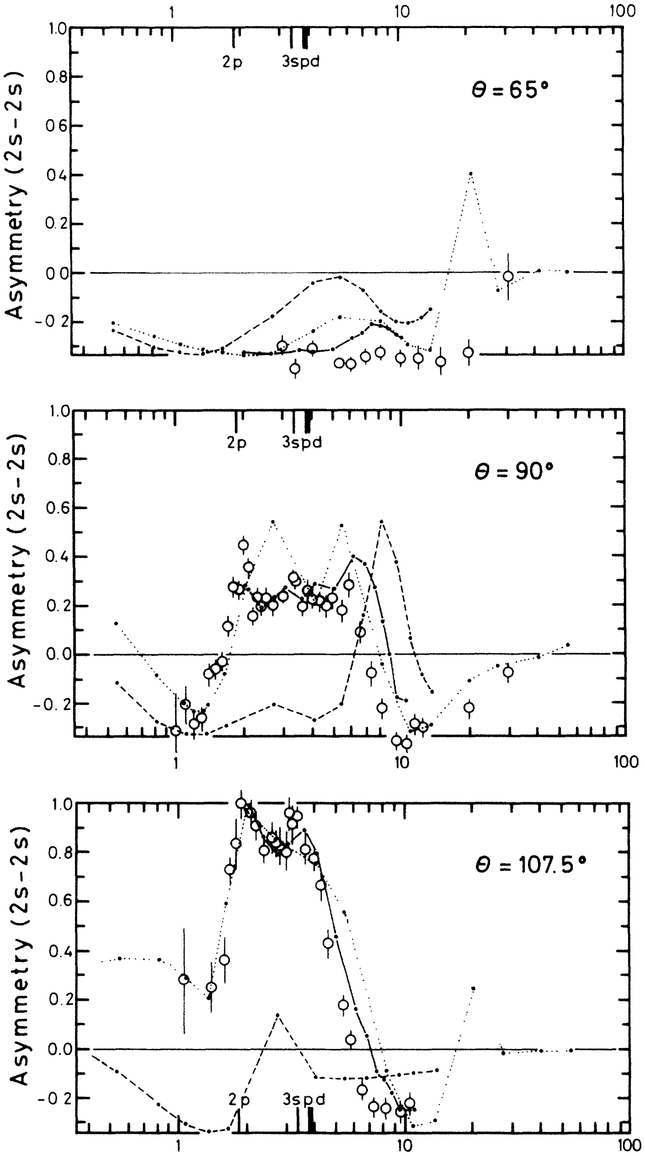

FIG. 2. Measured spin asymmetry $A(2s\rightarrow 2s)$ as a function of scattering energy for scattering angles of $\theta = 65°$, 90°, and 107.5°. The data points (open circles) are shown with one-standard-deviation error bars. Theoretical results shown are: (i) Two-state close-coupling calculation of Burke and Taylor (Ref. 13) (dotted line). (ii) Modified polarized-orbital calculation of Bhatia *et al.* (Ref. 4) (dashed line). (iii) Five-state close-coupling calculation of Moores (Ref. 14) (solid line).

At every chosen energy, data are accumulated in sequential sets, each consisting of six runs with the following pattern of relative spin orientations: ↑↓, ↑↑, ↑-, ↓↑, ↓↓, ↓-. The arrows indicate the spin directions of electron and atomic beams and the hyphen symbolizes the closed atomic-beam flag for measurements of the background. Each run lasts for the same length of time, typically 1 to 2 s, with the gate of the corresponding scaler open for data accumulation. Beam parameters are changed under computer control and 0.5 s are allowed to turn the quarter-wave plate, switch the operating mode of the spin flipper, or operate the beam flag between runs. The atomic polarization is recorded together with each data set, and the electron polarization is measured about every two to three hours. Test measurements with unpolarized electrons indicated that instrumental asymmetries are smaller than 0.001.

Figure 2 shows our measured asymmetry values as a function of energy for the three angles investigated. The errors are dominated by counting statistics. For 65° the asymmetry is $-\frac{1}{3}$ over a broad energy range, indicating that the triplet cross section is dominant and the singlet cross section negligible. For 90° singlet and triplet scattering are competing against each other in the range from 2 to 8 eV, with triplet dominance below and above. For 107.5° the asymmetry increases at the $2p$ threshold rapidly to $+1$ and remains very high up to 4 eV. Here singlet scattering is dominant and the triplet contribution is negligible. From 4 to 8 eV the asymmetry changes rapidly, with triplet dominance around 10 eV.

The comparison with theory shows good agreement with close-coupling calculations, up to energies of the highest-lying state included in the expansion. At higher energies the agreement is less satisfactory. It is remarkable that the agreement is good for all of the three angles, as contributions from many partial waves with different angular dependences must be taken into account, and that this agreement even holds for details like, for example, the peak structure at 107.5°. The five-state $(2s\text{-}2p\text{-}3s\text{-}3p\text{-}3d)$ close-coupling calculation with its inclusion of many finer physical details (addition of correlation terms, provision for core polarization, generation of special target wave functions) is superior to the simpler two-state $(2s\text{-}2p)$ calculation in the respective range of validity of these approximations, as one should expect. It is quite surprising that the $(2s\text{-}2p)$ calculation is doing well overall. Larger deviations, as seen around 20 eV at 65° and 107.5°, might indicate some convergence problem of the expansion. Calculational methods using polarized orbitals have shown very contradictory results.[16] As an example, for these calculations we show in Fig. 2 the data of a more recent treatment. Clearly, for all angles studied, particularly for the backward-scattering angle, there is severe disagreement with our data. Further theoretical work is needed in order to find the reason for this disagreement.

Our results for spin-polarized elastic electron scattering on lithium atoms have proven to be a stringent test of collision theory. The good agreement between experiment and close-coupling theory, within its range of validity, gives confidence to this theoretical approach, not only for broad features but also for finer details. This recognition will be helpful in the discussion and assessment of other electron-scattering cross sections.

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