J. Phys. B: At. Mol. Opt. Phys. **22** (1989) 1667-1677. Printed in the UK

Spin asymmetries in the low-energy electron impact excitation of 2S→2P transitions in lithium atoms

G Baum, L Frost, W Raith and U Sillmen

Universität Bielefeld, Fakultät für Physik, D-4800 Bielefeld, Federal Republic of Germany

Received 5 January 1989

Abstract. Crossed beams of spin-polarised lithium atoms and spin-polarised electrons with energies up to ten times the first excitation threshold have been used to measure the ratio of singlet to triplet scattering and to see the influence of exchange in excitation. The measured spin asymmetry in the intensity of the fluorescence radiation emitted perpendicular to the two beams shows substantial agreement with several close-coupling theories. Singlet scattering ($A \simeq 1$) dominates near threshold but the asymmetry declines towards zero within about 4 eV, indicating equally large contributions thereafter from angle-integrated singlet and triplet scattering. Measurements of the spin asymmetry in the double differential cross section (DDCS) were also performed, using a hemispherical energy analyser at $\theta = 65$, 90 and 107.5°. A five-state close-coupling calculation provides good agreement with the data up to 6 eV. There are pronounced differences at higher energies, however, especially for the 65° measurement. At all three angles, singlet scattering is dominant near threshold and triplet scattering above 10 eV.

1. Introduction

The goals of the work reported here were to measure directly the relative magnitudes of singlet and triplet scattering in electron impact excitation of the valence-electron 2S→2P transition in lithium atoms, and thereby to test several approximations for the inclusion of the exchange scattering amplitude in theoretical calculations of excitation.

Two distinct experiments were performed, using a spin-polarised electron beam crossed with a spin-polarised beam of lithium atoms. The atom polarisation was guided by a weak magnetic field parallel to the atom beam. Both the electron and the atom spin-polarisation vectors were parallel to this field (see figure 1).

In the first experiment, a photomultiplier was used to measure the fluorescence photon intensity perpendicular to the plane containing the two beams. The relative change in this intensity as the beam spin polarisations are 'flipped' from an antiparallel configuration to a parallel one is the spin asymmetry A in the excitation cross section. This is a measure of the ratio of singlet to triplet scattering (see next section). This spin asymmetry was determined for energies from threshold to approximately ten times the excitation energy of 1.85 eV.

In the second and more detailed experiment, the spin asymmetry in the flux of inelastically scattered electrons was measured at several chosen angles in the plane perpendicular to the atomic beam. The electrons selected were those which had experienced an energy loss equal to the first excitation energy for lithium. Note that the geometry is such that the electron spin direction is perpendicular to the scattering plane, but this does not lead to significant spin-flip processes since the spin-orbit effect

0953-4075/89/101667+11$02.50

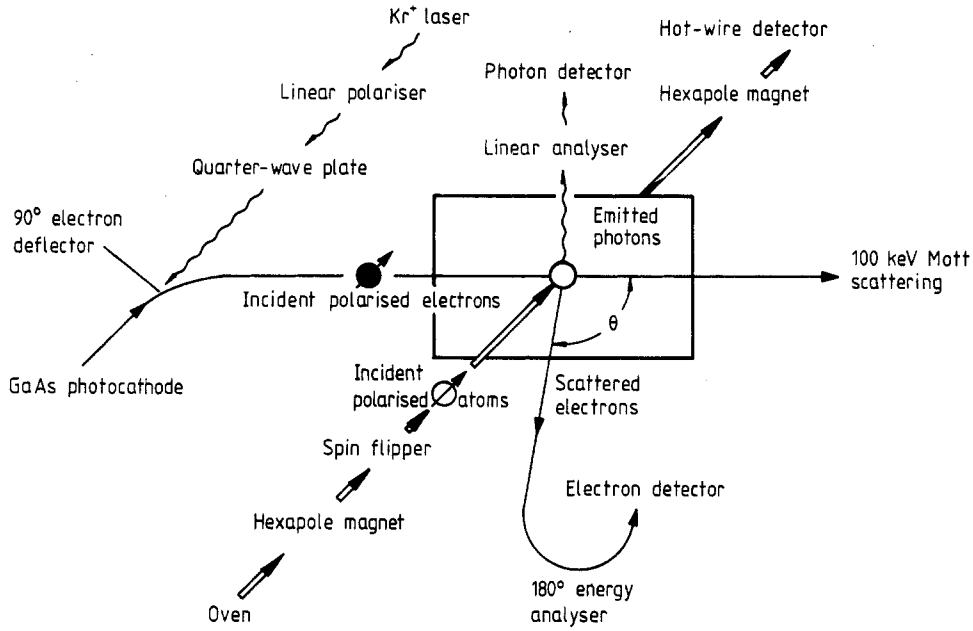

Figure 1. Geometry and major components used in the fluorescence experiment and the DDCS experiment.

has been demonstrated to be very small for 'light' atoms such as sodium (Riley *et al* 1986, McClelland *et al* 1987), and is therefore expected to be negligible for lithium. The spin asymmetry in the DDCS is clearly a more sensitive test of the theoretical calculations: the first experiment is (approximately) equivalent to an integration of this second experiment over all electron scattering angles.

Calculations of excitation cross sections, based on Born approximations, exist for higher energies, where they are considered to be accurate since only direct excitation is significant (see, for example, references in Leep and Gallagher 1974). The inclusion of exchange scattering close to threshold is a more difficult problem.

Scattering experiments on excitation, where either both projectiles are spin polarised or one projectile is polarised and the polarisation of the emitted photon is measured, can determine the magnitudes of the excitation amplitudes or their relative phases directly. This provides a much more sensitive test of calculations than do cross section measurements which average over the spins of the initial and final states.

The usefulness of such crossed polarised-beam experiments has been demonstrated in this laboratory for elastic scattering and ionisation as well as excitation of autoionising states (Baum *et al* 1985, 1986, 1988).

Jitschin *et al* (1984) measured the circular polarisation of the fluorescence radiation due to unpolarised electron impact on polarised sodium atoms and were able to infer the energy range of importance of exchange scattering and to reject several theories in favour of a four-state close-coupling calculation by Moores and Norcross (1972).

Using a similar technique, but with polarised electrons and unpolarised atoms, Ludwig *et al* (1986) were able to determine to within about 5% the magnitude of the direct scattering amplitudes for excitation of the 4^2P state of potassium, for energies up to eight times threshold. Some assumptions concerning cascade effects had to be

made and the partial cross section measurements of Chen and Gallagher (1978) were used. They also found good agreement with the photon polarisation calculated (assuming negligible hyperfine depolarisation effects) from three-state close-coupling amplitudes published by Moores (1976).

McClelland *et al* (1986) measured the spin dependence of the superelastic scattering of a polarised electron beam from an optically pumped and state-selected ($m_L = -1$, or $m_L = 1$) beam of Na ($3P_{3/2}$) atoms. No theoretical predictions existed to compare their data with.

2. Theory

2.1. Formalism

The electron impact excitation of $ns \rightarrow np$ transitions is described by direct and exchange amplitudes, f and g respectively. There are, in principle, separate amplitudes for excitation of each of the three $m_L = 1, 0, -1$ excited states, where the values of m_L refer to the axis of quantisation given by the incident electron beam. Mirror symmetry in the experiments reported here implies $|g_1|^2 = |g_{-1}|^2$ and $|f_1|^2 = |f_{-1}|^2$ so that there are only four independent amplitudes (f_0, g_0, f_1 and g_1), provided that spin-orbit coupling in the atom during the collision can be ignored. This is justified given that the scattering tine ($t \simeq 10^{-15}$ s) is so much shorter than the time scale ($t \simeq 10^{-12}$ s) of spin-orbit coupling.

However, spin-orbit and hyperfine coupling after the collision, but prior to emission of the decay photon, alter the polarisation and angular intensity distribution of the fluorescence radiation. The following paragraphs show the relationship of the excitation amplitudes to the intensity of the fluorescence radiation and to the DDCS, beginning with the latter.

For the experiments reported here, in which the incident projectile and target electron spins are prepared in either parallel or antiparallel states, the relevant DDCS are:

$$\sigma\uparrow\uparrow = |f_0 - g_0|^2 + 2|f_1 - g_1|^2$$
$$\sigma\uparrow\downarrow = |f_0|^2 + |g_0|^2 + 2|f_1|^2 + 2|g_1|^2$$

where the amplitudes are implicitly dependent on the electron impact energy and polar angle θ of scattering and have been normalised so as to account for the kinematical factors.

The various partial and total cross sections Q are defined in an obvious notation, e.g. $Q\uparrow\uparrow_{\mathrm{TOT}} = \int \sigma\uparrow\uparrow \, \mathrm{d}\Omega$ is the total cross section for excitation of the $ns \rightarrow np$ transition by triplet scattering and $Q_0 = \int |f_0 - g_0|^2 \, \mathrm{d}\Omega$ is the partial cross section for the transition leading to the $m_L = 0$ state.

The spin asymmetry in the DDCS is defined as:

$$A = (\sigma\uparrow\downarrow - \sigma\uparrow\uparrow)/(\sigma\uparrow\downarrow + \sigma\uparrow\uparrow)$$

and the spin asymmetry A_{TOT} in the total excitation cross section is defined similarly, using $Q\uparrow\downarrow_{\mathrm{TOT}}$ and $Q\uparrow\uparrow_{\mathrm{TOT}}$.

Since the cross section for singlet ($S = 0$) and triplet ($S = 1$) scattering are given by

$$\sigma_{\mathrm{s}} = |f_0 + g_0|^2 + 2|f_1 + g_1|^2$$
$$\sigma_{\mathrm{t}} = |f_0 - g_0|^2 + 2|f_0 - g_0|^2$$

the asymmetry can usefully be rewritten as:

$$A = (\sigma_{\mathrm{s}} - \sigma_{\mathrm{t}})/(\sigma_{\mathrm{s}} + 3\sigma_{\mathrm{t}}).$$

An experimental determination of A (or A_{TOT}) thus provides a measurement of the ratio r of singlet to triplet scattering for the appropriate cross section:

$$r = \sigma_t/\sigma_s = (1-A)/(1+3A).$$

Also of interest is the excitation cross section σ in the case where one or both beams are unpolarised:

$$\begin{aligned}\sigma &= \tfrac{1}{2}\sigma\uparrow\uparrow + \tfrac{1}{2}\sigma\uparrow\downarrow = \tfrac{1}{4}(\sigma_s + 3\sigma_t)\\ &= \tfrac{1}{2}|f_0|^2 + \tfrac{1}{2}|g_0|^2 + |f_1|^2 + |g_1|^2 + \tfrac{1}{2}|f_0 - g_0|^2 + |f_1 - g_1|^2\\ &= [|f_0|^2 + 2|f_1|^2] + [|g_0|^2 + 2|g_1|^2] - [\mathrm{Re}(f_0 * g_0) + 2\,\mathrm{Re}(f_1 * g_1)]\\ &= \sigma_{DIR} + \sigma_{EXCH} - \sigma_{INT}.\end{aligned}$$

Here the terms have been grouped into direct, exchange and interference between direct and exchange amplitudes. Note that σ_{INT} can be positive or negative and can exceed σ_{EXCH} in magnitude.

Rearrangement of the above equations shows that the asymmetry A is also a measure of the relative importance of the interference term σ_{INT}:

$$A = [\mathrm{Re}(f_0 * g_0) + 2\,\mathrm{Re}(f_1 * g_1)]/\sigma = \sigma_{INT}/\sigma.$$

The quantity A is directly measured in the second experiment. The relationship of the excitation amplitudes to the fluorescent light intensities measured in the first experiment is given below.

2.2. Fluorescence relationships

It was not feasible to determine A_{TOT} from measurements over 4π steradian of the total intensity of the fluorescence radiation. Instead, the intensities were measured at a polar angle of $\gamma = 90°$. The 'magic angle' of 54.7° has sometimes been chosen since there—neglecting recoupling of the states after excitation—the intensities of the radiation from the $\Delta m_L = 0$ and the $\Delta m_L = \pm 1$ transitions are in the same ratio as the partial cross sections and, therefore, the measured intensity is proportional to the total excitation cross section. However, the following discussion demonstrates that, if the angular distribution of the radiation and the effects of spin-orbit and hyperfine coupling are considered, then the measured spin asymmetry at $\gamma = 90°$ is almost identical to A_{TOT}.

Firstly, neglecting fine-structure coupling, the photon intensity angular distributions for $\Delta m_L = \pm 1$ and $\Delta m_L = 0$ transitions are a function of polar angle γ between direction of observation and the incident electron beam and are given by

$$\begin{aligned}I_{+1} &= I_{-1} = \tfrac{1}{2}I_R(1 + \cos^2\gamma)\\ I_0 &= I_P \sin^2\gamma,\end{aligned}$$

where I_R and I_P are constants of proportionality so that the intensity measured at $\gamma = 90°$ is

$$I(90°) = 2I_{+1}(90°) + I_0(90°) = I_R + I_P.$$

But the fluorescence intensity integrated over all angles, I_{TOT}, is proportional to $(2I_R + I_P)$. Substitution of the appropriate amplitudes governing the intensities shows that the spin asymmetry of I_{TOT} is, as required:

$$A_{TOT} = (I\uparrow\downarrow_{TOT} - I\uparrow\uparrow_{TOT})/(I\uparrow\downarrow_{TOT} + I\uparrow\uparrow_{TOT}) = \frac{Q_{0,INT} + 2Q_{1,INT}}{Q_0 + 2Q_1} = \frac{Q_{INT}}{Q}$$

whereas the asymmetry A' in the *measured* quantity $I(90°)$ is equivalent to

$$A' = \frac{Q_{0,\mathrm{INT}} + Q_{1,\mathrm{INT}}}{Q_0 + Q_1}$$

and it is seen that the factor multiplying Q_1 is only 1, instead of 2.

Secondly, by considering fine-structure coupling and using m_J-substate transition probabilities (Kleinpoppen 1971) it can be shown that

$$I(90°) = \tfrac{11}{3} I_{\mathrm{R}} + \tfrac{7}{3} I_{\mathrm{P}}.$$

The spin asymmetry in the measured intensity $I(90°)$ is thus modified, and obtains the form

$$A'' = \frac{Q_{0,\mathrm{INT}} + \beta Q_{1,\mathrm{INT}}}{Q_0 + \beta Q_1}$$

where $\beta = \frac{11}{7}$. This is much closer to the required form for A_{TOT} than is A', since the factor β is near to the required value of 2.

Thirdly, the effects of hyperfine coupling cause a further increase in β, from $\frac{11}{7} = 1.57$ to 1.64 in the case of ^{6}Li and to 1.73 in the case of ^{7}Li (Sillmen 1989). The factor does not depend significantly on the degree of alignment of the nuclear spins in the atom beam, although the latter is important in some experiments where the photon circular polarisation is measured.

To reduce the uncertainty in equating the measured asymmetry to A_{TOT} one can perform fluorescence studies using a linear polariser to measure the intensity either with the polarisation direction parallel to the electron beam, $I(90°)_{\mathrm{P}}$, or at right angles to the beam, $I(90°)_{\mathrm{R}}$. In the fully coupled case one obtains for the spin asymmetry either A''_{P} with $\beta = 0.92$ or A''_{R} with $\beta = 3.2$ (Sillmen 1989). An interpolation between these two values provides a more accurate determination of A_{TOT}. A simple average leads to $\beta \simeq 2$.

2.3. Relevant theoretical work

By means of the above equations, it is possible to compare measurements of the photon signal spin asymmetry and of the DDCS spin asymmetry with theoretical calculations of the scattering amplitudes.

Burke and Taylor (1969a) determined the differential cross sections for lithium using a two-state (2s, 2p) close-coupling approximation. The incident electron scattering functions were calculated according to the Kohn variational principle for each total orbital momentum L and total spin S using direct and exchange scattering potentials. Unfortunately, an insufficient number of partial waves was included and so the results are most valid within about 8 eV of threshold.

Mitroy *et al* (1987) have performed a number of close-coupling calculations for sodium, incorporating up to four channels and allowing for electron correlation in the target state. They have found reasonable agreement with other calculations but significant disagreement with measured differential cross sections. They show that the discrepancies are reduced if the theory is convoluted with the finite acceptance angles of the experimental apparatus. McCarthy (1988) has kindly provided similar calculations for lithium, which are included in figure 3 below. Note that the spin asymmetry measurements on lithium presented here are derived from *ratios* of measured relative cross sections and are much less sensitive to the sources of error discussed by Mitroy *et al* (1987).

In the five-state close-coupling (2s-2p-3s-3p-3d) calculations for lithium, by Moores (1986), the integro-differential equations for the T matrix were solved with the aid of the computer program IMPACT, due to Crees *et al* (1978). For higher impact energies, partial waves up to $L \simeq 70$ were required. Up to $L \simeq 20$ the calculations were performed separately for $S = 0$ and $S = 1$. Beyond that the program IMPACT is inaccurate and so the matrix elements were instead obtained directly or by extrapolation from the Bethe formula.

The choice of target wavefunctions is critical for close-coupling calculations, especially at higher excitation energies where resonances occur and above the ionisation threshold where flux into 'unobserved' channels must be modelled. McCarthy (1988) constructed the target wavefunctions from Hartree-Fock wavefunctions of the 1s, 2s, 2p, 3s and 3p states, including all single and double excitations within the set. This configuration interaction calculation gave, however, results almost identical to the single-configuration results. Moores calculated the wavefunctions using first a $1s^2$ core wavefunction, derived from a single-configuration Thomas-Fermi statistical model calculation for Li^+. This was then used as the 'target' in the program IMPACT for the $Li^+ + e^-$ problem, where the single channel was chosen from the sequence 2s to 3d. An empirical core polarisation term was added to the target (Li^+) potential in the calculations and a free parameter adjusted so as to reproduce measured quantum defects, thus guaranteeing exact excitation thresholds.

3. Experimental apparatus

The geometry and major components of the apparatus are shown in figure 1. The only major changes from previous descriptions (Baum *et al* 1985, 1986) are the installation of a photomultiplier for the photon intensity measurements and of a hemispherical electron energy analyser for the DDCS measurements.

The photoemission polarised-electron source provides currents of up to 1 μA in the scattering region (e.g. at an impact energy of 10 eV), with a typical polarisation $P_e = 0.3$ which is stable over many hours and with an energy width of about 0.25 eV FWHM. A Kr-ion laser operating at $\lambda = 752$ nm and a GaAs(100) crystal, as photocathode, were used. The electron beam polarisation was measured frequently using a standard Mott polarimeter operated at 100 keV. The beam intensity was monitored at the exit of the scattering chamber and was found to be stable.

The ^{6}Li oven is equipped with thermo-coax heaters and is housed in a separate vacuum chamber ($P = 10^{-6}$ mbar). A hexapole magnet is used to obtain high-field state selection, producing a polarisation (limited by low-field hyperfine coupling) of 29%. The beam density (10^9 atoms/cm^3 at the interaction region) and polarisation were monitored during data collection using a second hexapole magnet as analyser and a hot-wire (Langmuir-Taylor) detector. The direction of the polarisation of the atom beam could be reversed with respect to the direction of the magnetic guiding field, using a 'spin flipper' developed in this laboratory (Schroeder *et al* 1983). The strength of the magnetic guiding field, varied between 5 and 10 μT, had no discernible effect on the measured asymmetries.

The photon detector required for the fluorescence experiment consisted of a photomultiplier (RCA type C31034-02), interference filter (670 ± 10 nm), linear analyser (dichroic film) and focusing lens (acceptance angle $\pm 20°$) mounted vertically above the interaction region, i.e. at 90° to the plane of the two crossed beams and hence

perpendicular to the spin vectors (see figure 1). Calculations concerning the influence of the relatively large acceptance angle on the measured asymmetry gave only an insignificant correction.

The electron detector used in the DDCS experiment was a 180° hemispherical analyser ($R_0 = 2.54$ cm, $\Delta E \simeq 0.2$ eV FWHM, cf Kuyatt *et al* 1967), with a four-element focusing lens (acceptance angle ±3.5°) and a channel electron multiplier (CEM). It was constructed from molybdenum and had a surrounding mu-metal magnetic shield. The observed energy loss spectrum for lithium fully resolved the first excitation peak from the elastic peak, which also contained most of the background of electrons scattered from material surrounding the interaction region, and showed a ratio of signal to background of about 5:1 when the lithium beam was gated on and off. The analyser, once mounted at the desired angle, could not be turned while in the vacuum.

Several precautions were taken during the course of the two experiments in order to minimise systematic errors. Firstly, the ionisation spin asymmetry (Baum *et al* 1985) at 11 eV incident energy was used to monitor the product $P_e P_a$. It was measured several times during each experiment. Secondly, the beam polarisation vectors were set collinear to each other by turning one polarisation vector against the other magnetically (±30° rotation) and by looking for the maximum in the ionisation asymmetry. Thirdly, the fluorescence measurements were made with the linear polariser of the photon detector set with its preferred axis parallel to as well as at right angles to the electron beam.

The spin asymmetry measurements were made in a manner that allowed detection and elimination of instrumental asymmetries. All results reported here are weighted averages over many individual runs taken under comparable conditions. Each run consisted of eight separate measurements of the signal count rate for different combinations of the electron and atom spin direction together with four background measurements. Variations in the electron beam intensity of up to 2% occurred with the 'left' and 'right' spin direction. This depended on the alignment of the quarter-wave plate with respect to the laser beam in the GaAs source. The data were, therefore, evaluated separately for the left and right electron beam polarisations and the asymmetries then combined. Combining the asymmetries such that an unpolarised incident electron beam is simulated, we were also able to test for spin-orbit effects in the scattering from polarised Li atoms. These asymmetries were found to be zero within the statistical error of ±0.02 (Sillmen 1989).

4. Results and discussion

4.1. Fluorescence asymmetry from (2s-2p) excitation

The spin asymmetry in the photon intensity, measured at $\gamma = 90°$, is shown in figure 2, as a function of the electron impact energy E. The data points are given for parallel and rectangular orientation of the axis of the linear polariser to the electron beam. No significant difference can be seen between the two cases. As can be inferred from the discussion above, this permits the combination of the data for each energy and an identification of the result with A_{TOT}. The value of the parameter β is of little importance in determining the size of the asymmetry, if $Q_1 \ll Q_0$ or if $Q_{1,INT} \simeq 0$. The former is the case in the near-threshold region, as has already been shown in measurements with unpolarised particles (Leep and Gallagher 1974), whereas the latter applies if the asymmetry is itself close to zero.

The spin asymmetry drops very rapidly from large positive values in the near-threshold region to values close to zero in the region from 6 to 20 eV. This indicates an overwhelming singlet behaviour near threshold but equal contributions to the excitation cross section from singlet and triplet scattering at higher energies. The theoretical curve from the five-state close-coupling calculation of Moores (1986) is shown in figure 2. It is in good agreement with the data. The results of Burke and Taylor (1969a)—calculated from their published R matrices (Burke and Taylor 1969b)—are in agreement with the data up to an energy of 6 eV, but give an asymmetry of about 0.07 thereafter, which is consistently higher than our values. In the discussion of their two-state close-coupling model for lithium, Burke and Taylor (1969a) suggested that the dominance of singlet scattering near the 2p threshold is due to ^{1}P and ^{1}D resonances, with the ^{1}D resonance having a broad structure ($\simeq$0.5 to 1 eV).

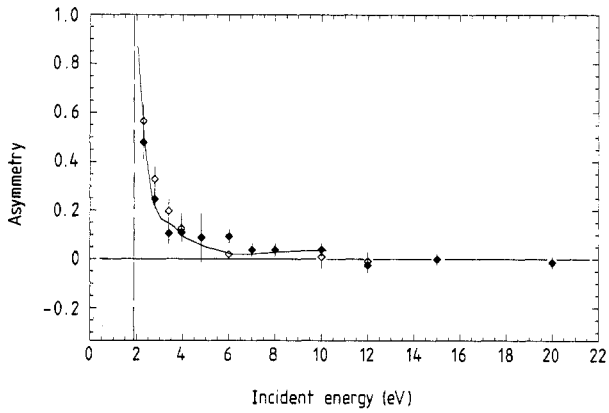

Figure 2. Measured spin asymmetry (with ± one standard deviation error bars) in the fluorescence photon intensity for lithium as a function of the incident energy, with the axis of a linear polarising filter parallel (open diamonds) and perpendicular (full diamonds) to the electron beam.

From the steep change of the asymmetry within about 1 eV of threshold it is evident that the singlet and the triplet excitation cross sections have quite a different dependence on the excess energy $(E-E^*)$. That is, if both cross sections followed a common power law, for example $(E-E^*)^{0.5}$, but with different proportionality coefficients, then the spin asymmetry would be independent of energy. If such behaviour existed near threshold it would have to be confined to a region which is smaller than our energy resolution ($\Delta E \simeq 0.25$ eV FWHM).

Cascading contributions could influence the measured asymmetry. To estimate the possible size of this effect the three states 3s, 3p and 3d with thresholds at 3.38, 3.83 and 3.88 eV have been considered. The worst case was assumed, in which each excitation shows the same asymmetry as the 2p excitation, shifted by the respective threshold differences. The cross-section-weighted asymmetries were then compared with the theoretical A_{TOT} for the 2p state. In the narrow energy range from 3.4 to 5 eV the cascading contributions varied from zero at the extrema to a maximum of +0.1 at 4 eV. Because of the uncertainties involved in this estimate, no corrections to the data are made.

Since the excitation cross section peaks at forward scattering angles for incident energies larger than twice the threshold value, the asymmetry A_{TOT} will likewise obtain

most of its contributions from the forward angular range and will reflect the spin-dependent behaviour there.

4.2. DDCS asymmetry

The predictions of Burke and Taylor (1969a) influenced our choice of experimental scattering angle for the DDCS measurements on lithium. At energies of the order of 5 eV, the calculated cross section is at a minimum between about 60° and 120°, so that the interference term σ_{INT}—which determines the size of the spin asymmetry—will be relatively more important. It is in this angular range that various theories can be sensitively tested.

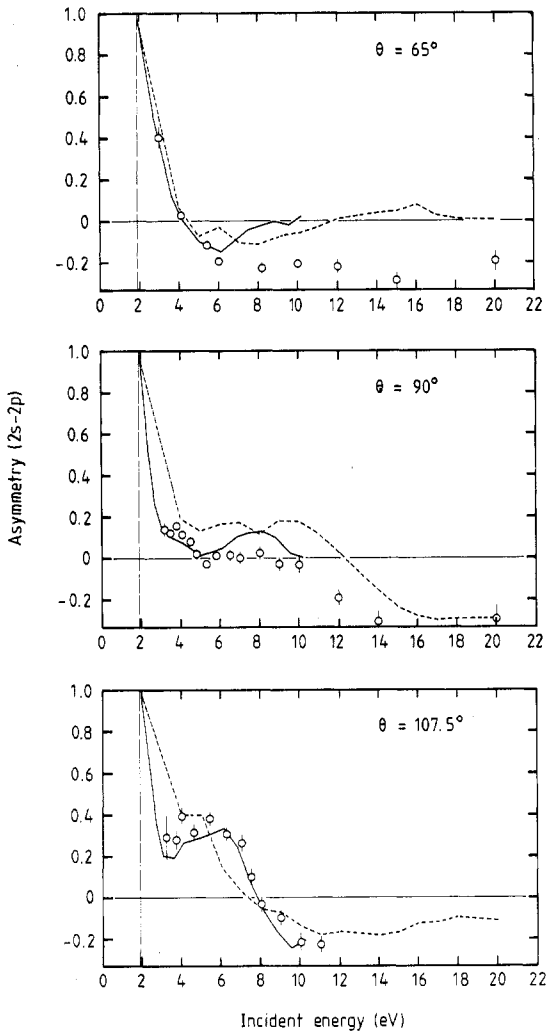

Figure 3. Spin asymmetry in the lithium DDCS for $\theta = 65$, 90 and 107.5°: open circles are experimental points (with ± one standard deviation error bars); the full curve is a five-state close-coupling calculation by Moores (1986); the broken curve is a four-state close-coupling calculation by McCarthy (1988).

Figure 3 shows our measured asymmetry values as a function of energy for the three angles investigated. It is seen that at all three angles singlet scattering dominates within about 2 eV of threshold whereas at about 12 eV scattering is almost pure triplet. There is some indication around 6 eV of a local maximum or plateau, but the level varies from $A \simeq -0.2$ at 65° to $A \simeq 0.0$ at 90° to about $A \simeq +0.3$ at 107.5°.

A comparison is given with the five-state close-coupling calculation by Moores (1986) and with a four-state close-coupling treatment which recently became available to us (McCarthy 1988). The five-state results show better overall agreement with our measurements than do the four-state results. It is noteworthy that the discrepancies between the two theoretical treatments are in general quite sizeable and that neither of them match the almost pure triplet scattering at 65° for impact energies of 10 to 30 eV.

The asymmetry values from the two-state close-coupling calculation of Burke and Taylor (1969a) are not included in figure 3. Below 5 eV incident energy these values follow closely the four-state curve at 90 and 107.5°, but deviate towards higher asymmetries at 65°. Above 5 eV they exhibit large excursions in positive and negative directions, indicating possible convergence problems in the expansion. Clearly the two-state treatment is giving a less satisfactory description for the 2p excitation than for the case of elastic scattering where we had earlier measured the asymmetry at the same angles (Baum *et al* 1986).

5. Conclusions

Measurements of the spin asymmetry in the $2P \rightarrow 2S$ fluorescence photon signal for lithium at $\gamma = 90°$ over a wide range of energies have confirmed existing theories which predict a strong dominance of singlet scattering near threshold. The monotonic decrease in the asymmetry as a function of collision energy is reasonably well described by theory.

Measurements of the spin asymmetry in the DDCS for excitation of the 2p state of lithium at three different angles show that a five-state close-coupling calculation by Moores (1986) provides best agreement with the data. However, the calculations at 65°, between 6 and 20 eV, are still qualitatively and quantitatively in disagreement with the data, showing essentially no asymmetry when, in fact, the measurements show almost pure triplet scattering ($A \simeq -\frac{1}{3}$).

Emphasis in future calculations on the strength of the lower-order partial waves at different energies and angles would allow more detailed comparison of the various theories. Further angular distribution measurements, particularly at an impact energy of about 12 eV where a large asymmetry exists and where the discrepancy with present theories (e.g. at 65°) is strong, would provide a decisive 'benchmark'. A new spectrometer capable of scanning the range of 5 to 150° is under development in this laboratory.

Acknowledgments

This work was supported by the University of Bielefeld and by the Deutsche Forschungsgemeinschaft (Sonderforschungsbereich 216). The collaboration of A Bock in some of the measurements reported here is gratefully acknowledged. D L Moores kindly provided extra tabulations of the *T*-matrix elements and I E McCarthy extra calculations of the DDCS asymmetry for lithium.

References

Baum G, Moede M, Raith W and Schröder W 1985 *J. Phys. B: At. Mol. Phys.* **18** 531-8
Baum G, Moede M, Raith W and Sillmen U 1986 *Phys. Rev. Lett.* **57** 1855-8
Baum G, Raith W and Schröder W 1988 *J. Phys. B: At. Mol. Opt. Phys.* **21** L501-7
Burke P G and Taylor A J 1969a *J. Phys. B: At. Mol. Phys.* **2** 869-77
—— 1969b *Report HL 63/2392* AERE Harwell
Chen S T and Gallagher A C 1978 *Phys. Rev.* A **17** 551-60
Crees M A, Seaton M J and Wilson P M H 1978 *Comput. Phys. Commun.* **15** 23-83
Jitschin W, Osimitsch S, Reihl H, Kleinpoppen H and Lutz H O 1984 *J. Phys. B: At. Mol. Phys.* **17** 1899-912
Kleinpoppen H 1971 *Phys. Rev.* A **3** 2015-27
Kuyatt C E and Simpson J A 1967 *Rev. Sci. Instrum.* **38** 103-11
Leep D and Gallagher A 1974 *Phys. Rev.* A **10** 1082-90
Ludwig N, Bauch A, Naß P, Reichert E and Welker W 1986 *Z. Phys.* D **4** 177-83
McCarthy I E 1988 Private communication
McClelland J J, Kelley M H and Celotta R J 1986 *Phys. Rev. Lett.* **56** 1362-5
—— 1987 *Phys. Rev. Lett.* **58** 2198-200
Mitroy J, McCarthy I E and Stelbovics A T 1987 *J. Phys. B: At. Mol. Phys.* **20** 4827-50
Moores D L 1976 *J. Phys. B: At. Mol. Phys.* **9** 1329-49
—— 1986 *J. Phys. B: At. Mol. Phys.* **19** 1843-51
Moores D L and Norcross D W 1972 *J. Phys. B: At. Mol. Phys.* **5** 1482-505
Riley J L, Teubner P J O and Brunger M J 1986 *J. Phys. B: At. Mol. Phys.* **19** 129-36
Schröder W and Baum G 1983 *J. Phys. E: Sci. Instrum.* **16** 51-6
Sillmen U 1989 *Doctoral Thesis* University of Bielefeld (unpublished)