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Electron scattering from Li at 5·4, 10, 20 and 60 eV impact energies†

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Abstract. Differential and integral cross sections for elastic scattering and for the excitation of the 2p ^{2}P, 3p ^{2}P, 4p ^{2}P and 3s ^{2}S states of lithium have been determined and elastic momentum transfer cross sections have been obtained at 5·4, 10, 20 and 60 eV electron impact energies. The cross sections were normalized to the absolute scale by using the total cross section measurements of Kasdan *et al.* The integral elastic scattering cross sections have been compared to calculations utilizing the Glauber and Born approximations and the 2p ^{2}P integral cross section results have been compared with optical excitation function measurements and with close-coupling calculations.

1. Introduction

Electron scattering from sodium, potassium and caesium have been extensively studied, but no direct measurements have been reported for lithium. Perel *et al* (1962) measured total cross sections for lithium using an atomic-beam recoil technique at around 10 eV. Their measurements indicated a large total cross section ($\sim 10^{-14}$ cm^2). Burke and Taylor (1969) calculated total cross sections for Li which were a factor of two higher than the measurements of Perel *et al* (1962). The normalization of Perel's experiments was questioned by Burke and Taylor, and a renormalization was carried out by Bederson and Kieffer (1971). The renormalized results agree well with the calculations. The measurements have been refined and extended to higher energies (3–50 eV) by Kasdan *et al* (1971). Their results are in good agreement with the calculations of Burke and Taylor.

Sarkar *et al* (1973), using the polarized-Glauber approximation, calculated differential and integral elastic cross sections for Li at 2, 10, 100 and 500 eV. In addition, integral elastic cross sections have been calculated by Allis and Morse (1931), Walters (1973) (Glauber approximation) and Inokuti and McDowell (1974) (Born approximation).

Optical excitation function measurements for 2s $\rightarrow$ 2p transition (6708 Å resonance line) have been carried out by Hughes and Hendrickson (1964), Aleksakhin and Zapesochnyi (1966, 1967) and Hafner and Kleinpoppen (1967) in the threshold to 30 eV

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region. Leep and Gallagher (1974) measured the relative optical excitation function and the polarization of the 6708 Å line from threshold to 1400 eV. They normalized their optical excitation function at 1404 eV where the energy dependence should correspond to the Born behaviour. The $2s \rightarrow 2p$ excitation cross section has also been calculated from close-coupling equations by Burke and Taylor (1969) from threshold to 54·4 eV and by Felden and Felden (1973) using the Ochkur approximation.

We report here differential and integral cross sections at 5·4, 10, 20 and 60 eV for elastic scattering and for the excitation of the 2p ^{2}P, 3p ^{2}P, 4p ^{2}P and 3s ^{2}S states.

2. Experimental

The measurements were carried out with an electron-impact spectrometer described previously by Chutjian *et al* (1973) and Williams and Trajmar (1974). An electron beam (0·08 eV FWHM) was scattered by a Li beam (which was generated by heating a stainless steel crucible containing Li) by electron bombardment. The Li vapour effused from a 0·1 cm diameter by 0·4 cm long channel to form the target beam. The electron beam intersected the Li beam about 0·2 cm above the tip of the crucible and it was trapped and monitored by a Faraday cup.

Electron scattering intensities at fixed impact energy (E_0) and scattering angles (θ) were determined as a function of energy loss by pulse counting using a multichannel scaler. Energy-loss spectra with acceptable signal-to-noise ratios were obtained by scanning the spectrum several times. The impact energy scale was not calibrated and it may be in error by $\pm 0{\cdot}5$ eV due to contact potentials. The angular resolution of the spectrometer is between 2° and 3°. No inelastic scattering from Li dimers or double-scattering features were seen. The operating temperature of the beam source was around 900 K. At this temperature the Li dimer concentration is about 2% according to Stull and Sinke (1956). The contribution to elastic scattering from Li_2 therefore is believed to be small compared to the other experimental uncertainties in these experiments.

Ratios of the inelastic scattering intensities to the elastic scattering intensity were determined from each spectrum. The elastic scattering intensity (10°–130°) was measured in a time short compared to the instrumental drift. An effective path-length correction (EPLC) for our scattering geometry converted the elastic intensity distribution to differential cross sections (DCS) in arbitrary units. Products of the inelastic to elastic intensity ratios and the elastic DCS in arbitrary units yielded the inelastic DCS in the same arbitrary units.

In principle it is possible to design a scattering geometry which changes very little with scattering angle and therefore requires only a small correction to the measured intensities. In practice other requirements (signal intensity, angular resolution, etc) force one to make a compromise among conflicting requirements. The effective path-length correction can be calculated if the scattering geometry is accurately known (which is seldom the case) or if it can be experimentally determined for the instrument with a target for which the cross sections are known (usually He). Unfortunately, when dealing with high-temperature targets neither method can be applied with high accuracy. For the present measurements, the effective path-length correction was estimated by applying both methods. The target beam density was taken as a beam with $\cos^2\theta$ distribution. The electron beam was considered cylindrically symmetric with a Gaussian density distribution falling to 1/e of its peak (axis) value

at the boundary of the cylinder and the view cone and other geometrical factors were known. Each volume element within the view cone was considered as the source of the scattering signal and was weighted for the target density, for the electron beam density and for the solid angle of acceptance. A $50 \times 40 \times 40$ grid integration was then performed in the r, θ, ϕ coordinates. The observed signal at a given scattering angle is then proportional to the integral value of this weighted volume (and of course to the cross section). The limits of integration were determined by the surface of the view cone and the electron beam cylinder. The 90° volume was taken as unity and the reciprocal of the relative weighted volume was used as the effective path-length correction. The angular distribution of elastic scattering intensity of He was determined with a scattering geometry similar to the one used in the Li measurements. From these intensities and from the known He DCS an effective path-length correction was also obtained. Based on these two methods, a correction factor of 0·46 (0°), 0·67 (10°), 0·84 (20°) and 1·00 ($\geqslant$30°) was applied to convert the experimental scattering intensities to relative cross sections.

Elastic scattering data below 10° scattering angle could not be obtained because of the direct-beam contribution; therefore, a low-angle intensity calibration was performed for the 2p ^{2}P transition from 0°–30° scattering angle. DCS were obtained by applying the EPLC. This DCS was normalized to that obtained for the same transition from elastic ratio data in the overlapping angular region. The errors associated with the effective path-length correction become progressively worse at angles below 10°. This uncertainty is carried over to the DCS.

The DCS were extrapolated to 0° and 180° and integrated to obtain the corresponding integral cross sections. A cross section estimation for open channels not considered in the present investigation was made from suitable energy-loss spectra. The sum of elastic plus inelastic integral cross sections in arbitrary units was normalized to the difference between the total cross section of Kasdan *et al* (1974) and the ionization cross section of Aleksakhin *et al* (1967) at each impact energy. This placed the elastic and inelastic cross sections on the absolute scale. On the basis of the errors associated with the various steps in the above procedure, we estimate that the overall error (square root of the sum of the squares of the individual errors) is $\pm 35\%$. The total cross sections of Kasdan were given with $\pm 12\%$ error. We estimate the error due to the uncertainty in the integration of the DCS presented to be $\pm 20\%$ (which includes EPLC uncertainty at low angles and extrapolation to 180° scattering angle). The largest probable error comes from estimating the contribution due to open channels not considered—$\pm 25\%$.

3. Results and discussion

Energy-loss spectra for the scattering of electrons by Li at 5·4, 10, 20 and 60 eV have been obtained at scattering angles from 0°–135°. Figure 1 shows typical spectra for $E_0 = 20$ eV and scattering angles 15° and 130°. The assignments have been made with the aid of Moore's (1949) tables. Cross sections for the electron-impact excitation of three P states ($2p\ ^2P_{3/2,1/2}$, $3p\ ^2P_{3/2,1/2}$, $4p\ ^2P_{3/2,1/2}$) and one S state ($3s\ ^2S_{1/2}$) have been obtained in this work. There may be some contribution to the $3p\ ^2P_{3/2,1/2}$ peak by the $3d\ ^2D_{3/2,5/2}$ excitation since these two transitions are not resolved. Careful examination of the peak position leads us to the conclusion that the 3d excitation is a small fraction of the observed feature. Likewise, we believe that the $4d\ ^2D_{3/2,5/2}$

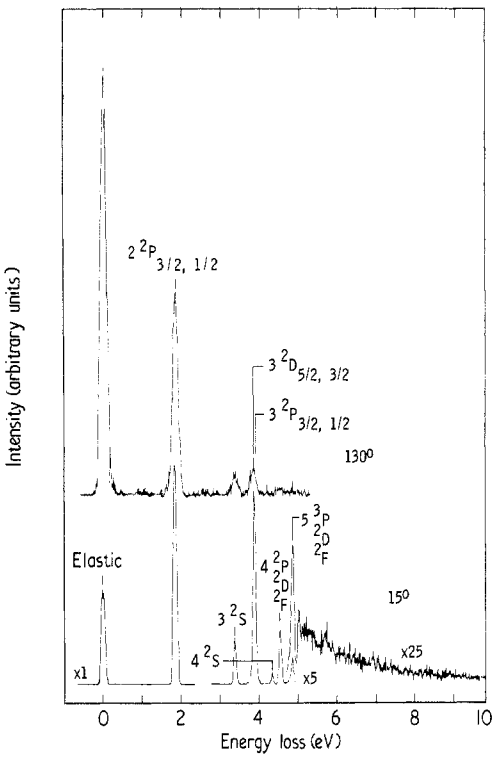

Figure 1. Electron-impact spectra of lithium at 15° and 130°, and 20 eV impact energy.

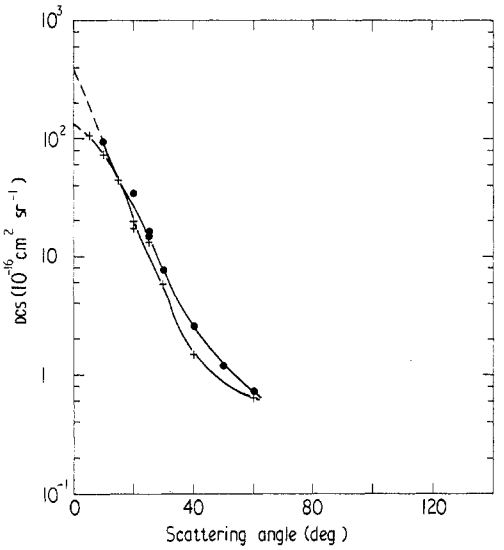

Figure 2. Differential cross sections for elastic scattering and for the excitation of the 2p ^{2}P states at 5·4 eV. ●, elastic; +, 2p ^{2}P.

and 4f $^2F_{7/2,5/2}$ excitations represent small contributions to the observed 4p $^2P_{3/2,1/2}$ feature. In potassium, where the 4^2P and 4^2D excitations are well separated, Hertel and Ross (1968) observed that the former is stronger by three orders of magnitude at 0° scattering angle.

At 5·4 eV impact energy, most of the scattering is associated with the elastic and 2p ^{2}P channels. The DCS for them are roughly parallel to each other (see figure 2). The cross sections are forward-peaked and fall two orders of magnitude from 5°–60° scattering angles. This strongly forward peaking is somewhat unusual at this low energy. H, He and other rare gases show much more isotropic scattering. One can interpret this behaviour as the manifestation of the importance of polarization effects.

Differential cross sections for elastic scattering and the excitation of the 2p ^{2}P, 3p ^{2}P, 4p ^{2}P and 3s ^{2}S states at 10 eV impact energy are shown in figure 3. The DCS for elastic and 2p ^{2}P scattering are nearly equal in magnitude to 25° scattering angle. At angles greater than 25° the 2p ^{2}P excitation curve falls below that for elastic scattering. Both DCS curves possess mimima at around 95° scattering angle. The 3p ^{2}P, 4p ^{2}P and 3s ^{2}S DCS distributions have similar shape—falling rapidly from 5° to 40° scattering angles, then nearly isotropic from 40° to 130°. The eikonal approximation results of Sarkar *et al* (1973) for elastic DCS are also shown for comparison in figure 3. The calculation and the experiment are in considerable disagreement.

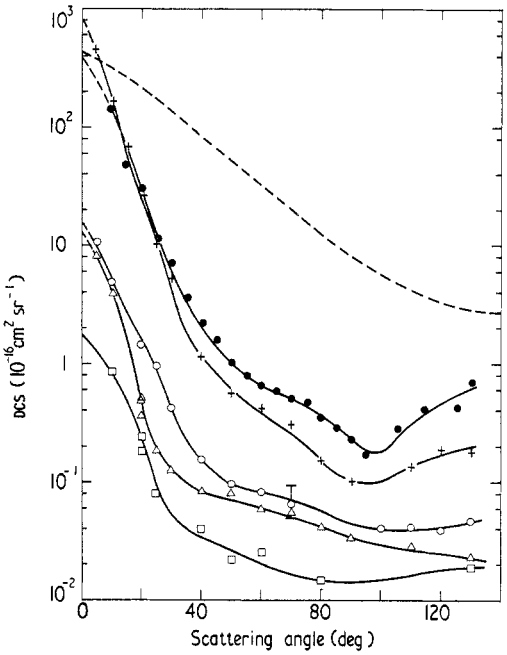

Figure 3. Differential cross sections for elastic scattering and for the excitation of the 2p ^{2}P, 3p ^{2}P, 4p ^{2}P and 3s ^{2}S states at 10 eV. Broken curve, Sarkar *et al* (1973) calculations for elastic scattering at 10 eV. ●, elastic; +, 2p ^{2}P; ○, 3p ^{2}P; △, 3s ^{2}S; □, 4p ^{2}P.

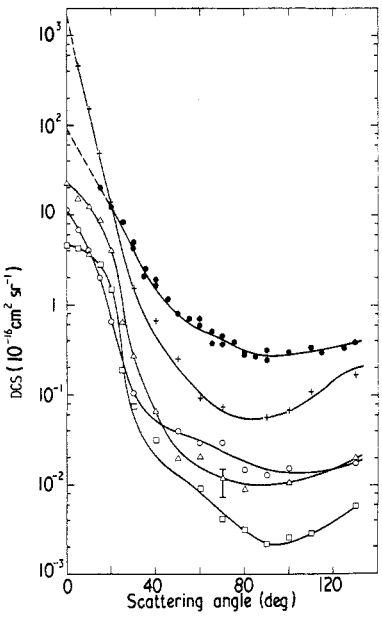

Figure 4. DCS for elastic scattering and for the excitation of the 2p ^{2}P, 3p ^{2}P, 4p ^{2}P and 3s ^{2}S states at 20 eV. ●, elastic; +, 2p ^{2}P; ○, 3p ^{2}P; △, 3s ^{2}S; □, 4p ^{2}P.

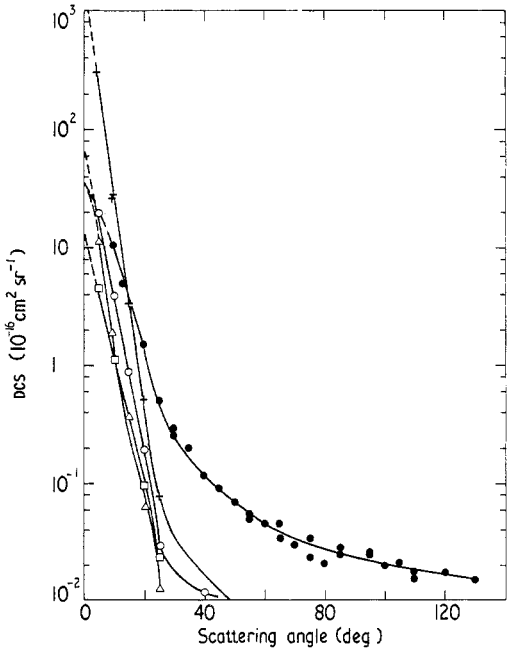

Figure 5. DCS for elastic scattering (●) and for the excitation of the 2p ^{2}P (+), 3p ^{2}P (○), 4p ^{2}P (□) and 3s ^{2}S (△) states at 60 eV.

Table 1. Integral cross sections (10^{-16} cm^2).

eV	Elastic	Momentum transfer	3s ^{2}S	2p ^{2}P	3p ^{2}P	4p ^{2}P
5·4	49	8·0	—	49	—	—
10	40	4·4	1·9	44	3·0	0·34
20	19	5·2	1·1	36	2·7	0·50
60	4·5	0·43	0·84	28	1·8	0·52

As the impact energy is increased ($E_0 = 20$ eV) the inelastic scattering distributions become more strongly forward-peaked (see figure 4). The DCS for elastic and inelastic scattering are quite similar. At angles less than 15°, the magnitude of the 2p ^{2}P excitation exceeds that for elastic scattering. All ^{2}P DCS have a shallow minimum around 100° scattering angle. The cross section distributions become even more strongly forward-peaked at 60 eV impact energy as shown in figure 5. The 2p ^{2}P DCS falls five orders of magnitude by 80° scattering angle.

A summary of integral cross sections are given in table 1 and shown in figure 6. In the figure, the experimental results of Kasdan *et al* (1971) and the calculated values of Inokuti and McDowell (1974), Sarkar *et al* (1973), Walters (1973) and Burke and Taylor (1969) are also shown for comparison. The IM and S theory predicts elastic cross sections that are outside the present error limits. They are definitely too high if the Kasdan results are correct because the accuracy of the inelastic to elastic cross section ratios are the most accurate direct results of the present measurements.

Relative optical excitation function measurements of the 6708 Å line ($e^- + Li(2s\ ^2S) \rightarrow e^- + Li(2p\ ^2P)$) have been obtained by Leep and Gallagher (1974). Their measurements extend from threshold (1·85 eV) to 1400 eV. The optical excitation measurements were normalized by making the high energy part of the curve conform to Born predictions and by taking appropriate estimates for cascade. There is very

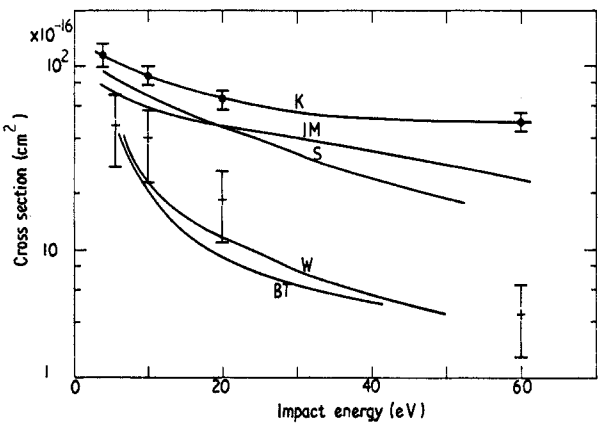

Figure 6. Integral elastic cross sections. IM, Inokuti and McDowell (1974); S, Sarkar *et al* (1973); W, Walters (1973); BT, Burke and Taylor (1969); crosses, present results; K, total cross section Kasdan *et al* (1971).

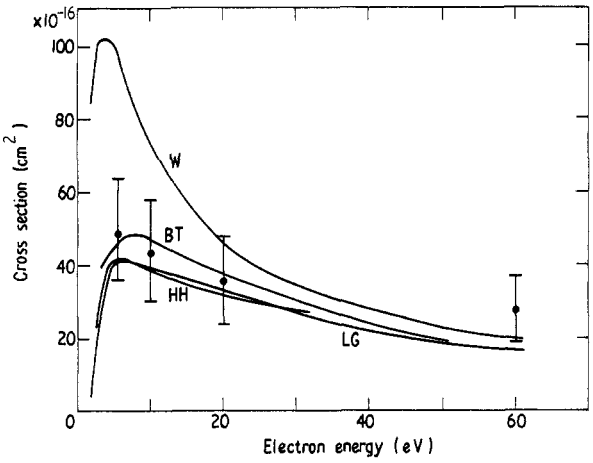

Figure 7. Integral cross sections for the excitation of the 2p ^{2}P state (6708 Å). W, first Born approximation from Walters (1973); BT, close-coupling calculation of Burke and Taylor (1969); points, present results; HH, excitation function measurements of Hughes and Hendrickson (1964); LG, excitation function measurements of Leep and Gallagher (1974).

close agreement with these measurements and those of Hughes and Hendrickson (1964) as shown in figure 7. The relative data of Hafner and Kleinpoppen (1967) (not shown) agree well in shape with the above excitation functions. The close-coupling calculations of Burke and Taylor (1964) lie about 10% higher (figure 7). The optical excitation measurements by Aleksakhin *et al* (1966, 1967) (not shown) lie much lower than all the above results. The Ochkur approximation calculations of Felden and Felden (1973) are a factor of two lower than the present measurements and the first Born approximation calculations of Walters (1973) for the 6708 Å resonance transition are larger than our results at 20, 10 and 5·4 eV. McCavert and Rudge (1971) have calculated cross sections for the electron-impact excitation of Li, Na and K. Where comparison is possible, their result for the $2s \rightarrow 2p$ excitation at 9·2 eV is 46×10^{-16} cm^2 while our experimental result is 44×10^{-16} cm^2 at 10 eV. At 5·5 eV, they calculate a cross section of 50×10^{-16} cm^2 for this transition while our result at 5·4 eV is 49×10^{-16} cm^2. In our work, the 3p ^{2}P and 3d ^{2}D transitions were not resolved, but the combined cross section is $3{\cdot}0 \times 10^{-16}$ cm^2 at 10 eV. McCavert and Rudge report $4{\cdot}1 \times 10^{-16}$ cm^2 for these transitions at 9·2 eV impact energy. There is a considerable difference between our experimental result for the $2s \rightarrow 3s$ transition at 10 eV ($1{\cdot}9 \times 10^{-16}$ cm^2) and their calculation at 9·2 eV ($0{\cdot}32 \times 10^{-16}$ cm^2). Within the experimental error of our experiments there is good agreement between our results and those of Leep and Gallagher, Hughes and Hendrickson and the calculations of Burke and Taylor at 5·4, 10 and 20 eV. Our result based on the Kasdan *et al* measurements (1971) at 60 eV for the resonance transition is slightly higher than the excitation function measurements, close-coupling calculations and the Born approximation. While it is true that the probable error due to consideration of open channels not included at this energy is a few per cent higher than at the other impact energies, the uncertainty of the reported 2p ^{2}P integral cross section is nearly the same as that in the 5·4, 10 and 20 eV points.

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