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Electron impact cross sections for the 2^2P state excitation of lithium†

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Abstract. Electron impact excitation of the $2p\,^2P$ state of Li was studied at 10, 20, 60, 100, 150 and 200 eV. Relative differential cross sections in the angular range 3–120° were measured and then normalised to the absolute scale by using the optical f value. Integral and momentum transfer cross sections were obtained by extrapolating the differential cross sections to 0° and to 180°. The question of normalising electron–metal-atom collision cross sections in general was examined and the method of normalisation to optical f values in particular was investigated in detail. It has been concluded that the extrapolation of the apparent generalised oscillator strength (obtained from the measured differential cross sections) to the zero momentum transfer limit with an expression using even powers of the momentum transfer and normalisation of the limit to the optical f value yields reliable absolute cross sections.

1. Introduction

Cross sections for electron–metal-atom collision processes, especially differential cross sections (DCS), are scarce. The main reason for this is the experimental difficulty which one faces in trying to convert the measured scattering intensities to absolute cross sections. The resonance transition (2^2S–2^2P) in atomic Li is an excellent choice for a systematic study of the problems associated with metal vapour measurements. Li is the simplest of the alkali metals and should thus be amenable to theoretical treatment as well as being a model for the behaviour of the heavier alkalis.

Electron impact excitation of the 2^2P state of Li has been studied in recent years by Williams *et al* (1976) in the scattered electron channel and by Zapesochnyi *et al* (1975) and Leep and Gallagher (1974) in the photon emission channel. A summary of these and earlier measurements has been given by Kennedy *et al* (1977) and by Brandsen and McDowell (1978). The electron scattering measurements have rather large error limits (35%) while the optical measurements require corrections due to cascade contributions and could suffer from radiation trapping problems. The measurements of Zapesochnyi *et al* (1975) and Leep and Gallagher (1974) differ from each other by about 15–20% at energies lower than 60 eV. Theoretical efforts in this area have been summarised by Brandsen and McDowell (1977, 1978).

One encounters several problems in trying to generate accurate differential cross section data for the resonance excitation of metal atoms by electron impact. The

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cross section for this type of process is in general strongly forward peaked and often drops by six orders of magnitude from 0° to 60° scattering angles. This puts a much greater emphasis on an accurate measurement of the shape of the DCS for forward scattering which, in turn, requires high angular resolution, good electron beam collimation and a small target beam size. Although these experimental requirements may usually be met, the establishment of the overall angular distribution is made difficult by direct beam interference at small scattering angles, weak scattering signals at large angles and the transformation of the scattered signal intensities to relative cross sections and the subsequent normalisation of the relative cross sections (effective path length corrections). Once these problems have been suitably addressed, the problem of converting the relative angular distributions to absolute cross sections still remains.

A number of techniques have been used to obtain absolute cross sections from relative measurements. These include the direct measurement of all the pertinent parameters relating the scattering intensity to the cross section, utilisation of a secondary standard, phaseshift analysis, and normalisation to theory, optical excitation functions or optical f values.

The straightforward approach to measuring all the parameters which relate the scattering intensity to the corresponding cross section is not practical at low and intermediate impact energies. In addition to the problems of determining absolute target density distribution, electron beam flux, electron–target beam overlap and instrumental functions, one also has to maintain all these conditions constant throughout the entire measurement period (which is of the order of several days) or re-calibrate frequently during the measurement period.

The utilisation of a secondary standard as a reference has been worked out in connection with permanent gases (Srivastava *et al* 1975, Register *et al* 1980, Trajmar and Register 1980) but runs into difficulty with metal vapours. This is due to the problem of the determination of the relative target density of the metal vapour to the reference gas and to the requirement of identical geometry for the two species.

Phaseshift analysis is applicable to elastic scattering at impact energies below the first inelastic threshold. The impact energy range for the applicability of this approach is, however, very limited, and the transfer of the calibration from this energy range to energies above the inelastic threshold is not a simple matter. Normalisation to theory is not a reliable procedure at the present time since accurate calculations are not available over a wide range of impact energies and scattering angles. Normalisation to optical excitation functions has been used in several cases (e.g. Truhlar *et al* 1970). The optical measurements, however, face the same problems associated with the direct measurements of all experimental parameters. In addition, the results have to be corrected for cascade and radiation trapping and the method generates only integral cross sections.

In the present paper we investigate the problems associated with normalisation to optical f values. We studied the electron impact excitation of the $2p\ ^2P$ state of Li for which a number of experimental and theoretical cross sections are available for consistency checks. We addressed particularly the question of the influence of effective path length correction, the uncertainties in scattering angle and impact energy, the low-angle behaviour of the differential cross section and the procedure of extrapolation to zero momentum transfer. These are the critical factors which determine the accuracy of the cross section data. The investigation yielded differential, integral and momentum transfer cross sections for the $2s\ ^2S_0 \rightarrow 2p\ ^2P_{3/2,1/2}$ (unresolved) excitation process for Li at impact energies of 10, 20, 60, 100, 150 and 200 eV. These are compared with

previous experimental and theoretical results and have been used to calibrate other excitation cross sections of Li as described in a subsequent paper (Vušković *et al* 1980).

2. Experimental procedures

The electron impact spectrometer and the experimental procedures were very similar to those described previously by Williams *et al* (1976), but several improvements in defining the scattering geometry (lower target density, better collimation of target beam, better furnace design) have been introduced. In addition careful consideration was given to the influence of effective path length correction and the uncertainties in scattering angle and in impact energy.

The apparatus used for the present measurements consists of an electron gun, which generates a well collimated energy-selected electron beam with the desired impact energy (E_0), and an electron detector which collects scattered electrons at a particular scattering angle (θ) with respect to the incoming electron beam over a small solid angle ($\sim 10^{-3}$ sr). Both the gun and the electron detector consist of electrostatic cylindrical lenses and hemispherical energy selectors. The signal as a function of energy loss was recorded by using standard pulse counting and multichannel scaling techniques.

The target beam is generated by heating a stainless-steel crucible, containing Li, to about 900 K and effusing the vapour through a 0.1 cm diameter $\times$0.6 cm long tube. The heating was achieved with resistance heating rather than by electron bombardment. This technique allows a very precise control of the crucible temperature. The heating wire is of coaxial type, which assures cancellation of the magnetic field generated by the heater current. The crucible was maintained at a temperature ($T \leqslant 900$ K) such that the vapour pressure of Li (P_0) was less than or equal to 0.1 Torr. Under these conditions the mean free path for Li is larger than the dimension of the tube at the crucible exit and the flow is predominantly molecular. This results in a well collimated target beam which has a diameter of 0.18 cm at the scattering centre. The collimation of the target beam is important for calculating the effective path length correction accurately and at the same time makes efficient trapping of the Li beam possible. Trapping of the beam prevents deposition of Li on the gun and detector elements near the scattering centre and therefore maintains stable operating conditions. At these low temperatures, the dimer concentration in the vapour is negligible ($<1\%$) (Lapp and Harris 1966). The stability of the Li target beam was ensured by monitoring the crucible temperature with an iron–constantan thermocouple. During each set of measurements the temperature was constant to within 5 K. The typical background pressure in the vacuum chamber during the experiment was 1×10^{-7} Torr.

An electron beam current of the order of 1×10^{-7} A (depending on the impact energy) with an energy full width at half maximum of about 0.10 eV was maintained constant to about $\pm 1\%$ over the time required to complete one set of measurements.

The energy-loss feature corresponding to the $(1s^2 2s)\ ^2S_{1/2} \rightarrow (1s^2 2p)\ ^2P_{3/2,1/2}$ transition was generated by recording the scattered electron signal at fixed values of E_0 and θ as a function of energy loss. The total number of electron counts under this feature (with proper background subtraction) was integrated and the intensity distribution determined over the angular range 3–120° at impact energies of 10, 20, 60, 100, 150 and 200 eV. At each energy the procedure used was to measure a set of three

angles consecutively, then return to a reference angle to make sure that the three measurements were made under identical conditions. This is the time period during which the stability of the apparatus is critical. Measurements of 0, ±1 and ±2° were also carried out. However, the direct beam contribution makes these measurements more susceptible to error and they were used only to determine the true zero scattering angle from the symmetry of scattering. We estimate the angular uncertainty as 0.5°. The impact energy scale was not calibrated and may be in error by about 0.5–1.0 eV due to contact potentials.

The measured scattering intensity distribution was converted to relative differential cross sections by utilising the proper effective path length correction factors. These correction factors have been calculated using the procedures described by Brinkmann and Trajmar (1981) using geometrical parameters, the target and electron beam distributions and the cross section behaviour corresponding to the particular measurement. Typical effective path length correction curves are shown in figure 1 for a cross section which decreases by three orders of magnitude (as $\epsilon^{-\alpha\theta}$) from 0 to 90° (10 eV case). At pressures equal to or less than 0.1 Torr (our operating conditions), the correction factor is independent of pressure. This is consistent with the assumption of molecular flow. In the region 3–10°, which is the most critical from the point of view of extrapolating the generalised oscillator strength to zero momentum transfer, the correction factor was calculated to be nearly constant (independent of angle). This is an important fact and makes it possible to use the scattering intensities without any modification to generate the relative generalised oscillator strengths in this angular range. Naturally, the proper correction represented by the overall curve has to be applied in transforming the scattered intensities into cross sections outside this angular range. It should also be noted that the utilisation of scattering data below 3° would require drastic corrections relative to the 3–10° range, and this can introduce large uncertainties.

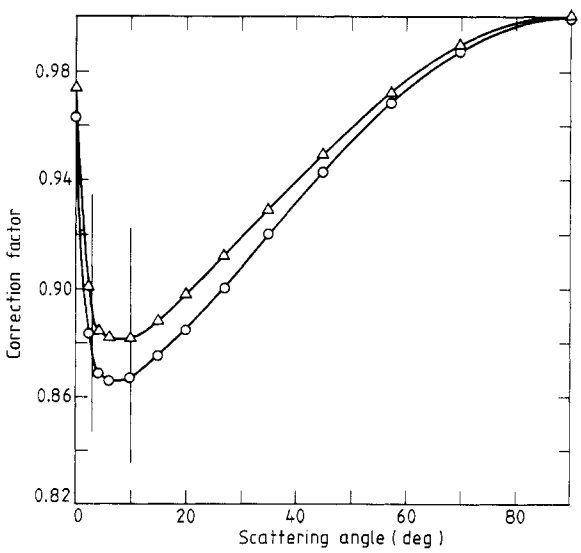

Figure 1. Effective path length correction factors calculated for a typical experiment: △, $P_0 = 0.1$ Torr; ○, $P_0 = 1.0$ Torr.

3. Normalisation of the cross sections to the optical f value

The relative cross sections have been converted to apparent generalised oscillator strengths $f^{AG}(K, E_0)$ using the well known formula (see, e.g., Inokuti 1971)

$$f^{AG}(K, E_0) = \tfrac{1}{2}\Delta E(k_i/k_f)K^2 \mathrm{DCS}(E_0, \theta) \tag{1}$$

where ΔE is the energy loss, k_i and k_f are the magnitudes of the initial and final momenta of the electron and K is the momentum transfer ($K^2 = k_i^2 + k_f^2 - 2k_ik_f \cos\theta$). This expression was originally introduced by Bethe (1930) to relate the Born cross section $\mathrm{DCS}^B(K)$ to the generalised oscillator strength $f^G(K)$ which in turn can be shown to become equal to the optical f value at zero momentum transfer. In equation (1) we define the apparent generalised oscillator strength by the same expression except we use the actual cross section instead of the Born cross section. It was shown by Lassettre *et al* (1969) that

$$\lim_{K\to 0} (f^{AG}(K, E_0)) \to f^{opt} \tag{2}$$

whether the Born approximation is applicable to the scattering process or not. In principle, therefore, an extrapolation of the relative $f^{AG}(K, E_0)$ values to zero momentum transfer and normalisation of the limiting value to f^{opt} is all that is needed to achieve normalisation of cross sections. A number of questions related to this procedure require careful investigations, however, in order to be able to assess the reliability of the resulting cross sections.

For a scattering process at a given impact energy, the physically meaningful lowest momentum transfer is reached at a scattering angle of 0°. There are, however, several reasons why zero and very low-angle measurements yield cross sections with large uncertainties which in turn introduce large errors into the extrapolation to the zero-K limit. The effective path length correction changes very drastically near zero angle for processes with a strongly forward-peaked DCS. This is due to the fact that an instrument with a finite angular resolution integrates the signal over a range of angles (positive and negative) over which the cross section changes very rapidly. Another reason is that the direct beam at zero angle enters the detector and causes background problems. A third reason is that small errors in determining the scattering angle cause large variations in the cross section data. We consider it a better philosophy to extend the measurements down to a few degrees but not all the way to zero: for example, in the present case we only go down to 3°. This avoids the problem with direct beam interference, omits the region where small uncertainties in scattering angle cause the largest uncertainties and, as can be seen from figure 1, no volume correction is necessary for the 3–10° region to obtain all DCS in the same arbitrary units. The extrapolation to 0° can be carried out by fitting the data in the 3–10° range to an analytic expression and using this expression to extrapolate to 0° and to the $K = 0$ limit. The basic question here is what is the proper analytic expression to use and does the extrapolation in the non-physical range (below 0°) make sense?

It has been customary to fit $f^{AG}(K, E_0)$ or, equivalently, $\lg(f^{AG}(K, E_0))$ to a polynomial expression containing only even terms in K and neglecting terms containing K^4 or higher powers of K (see, e.g., Lassettre and Skerbele 1974, Backx *et al* 1975a, b, Shuttleworth *et al* 1977, 1979). This is equivalent to the Born approximation if the coefficient associated with the K^2 term is considered to be energy independent. Dillon and Lassettre (1975), on the other hand, used an expression which included odd-power

terms in K to fit their He 1^1S–2^1P data. Huo (1979) investigated the question of whether one should use only even- or both even- and odd-K terms. By examining the limiting slope of $f^{AG}(K, E_0)$, she found that neither df/dK nor df/dK^2 obeys the Born approximation at $K = 0$. For dipole-allowed transitions she found that $(df/dK)_{K=0}$ is not zero and it is a pure non-Born term. Therefore, she concluded that one should include odd-K terms in the expression for $f^{AG}(K)$. She also showed that df/dK^2 becomes infinite at $K = 0$ except at infinite impact energy.

However, Huo's deductions were based on inferences which were associated with a finite-order Born expansion. Since in many cases the Born series is only slowly convergent, it is not guaranteed that singularities which appear in a finite series Born expansion will remain singularities when the series is properly summed over the infinite expansion which comprises the true solution. Thus, Huo's suggestions must stand as advisory but certainly not conclusive, nor unambiguously proven from an experimental point of view.

The 2^2P excitation of Li represents an excellent case for shedding some light on the reliability of these extrapolation procedures. This is so because we have accurate experimental angular distributions (present results), integral cross sections (optical excitation functions) and fairly reliable theoretical predictions for low-angle cross sections. The optical f value (0.753) recommended by Martin and Wiese (1976) was used for the ^2P excitation. In figures 2 and 3 the experimental data in the 3–10° region are shown together with the fit to the expression

$$f^{AG}(K, E_0) = f^{opt} + A(E_0)K^N + B(E_0)K^{2N} \tag{3}$$

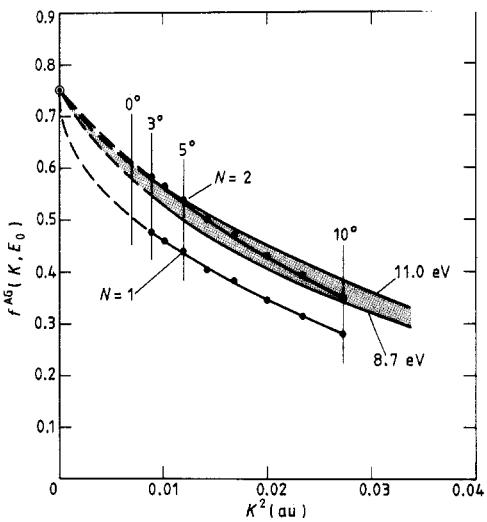

Figure 2. The apparent generalised oscillator strength as a function of K^2. The limiting curves of the shaded area correspond to the 8.7 and 11.0 eV calculations of Walters (1980). The present data at 10 eV (full circles) fitted to equation (3) with $N = 1$ ($f^G = f^{opt} + AK + BK^2$) and $N = 2$ ($f^G = f^{opt} + AK^2 + BK^4$), extrapolated to $K = 0$ and normalised to $f^{opt} = 0.750$ at $K = 0$, are shown by full curves in the region 3–10° and by broken curves below 3°.

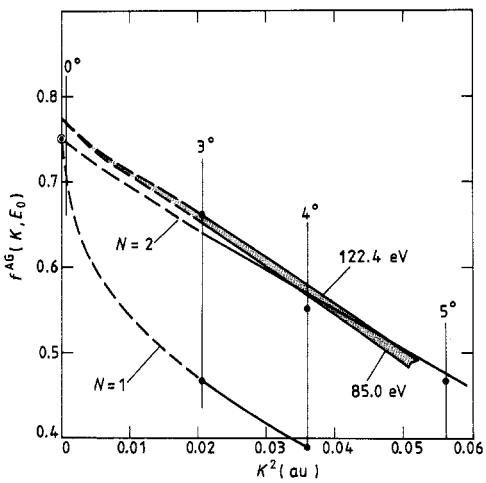

Figure 3. The same as figure 2 except that the present data are at 100 eV and the limiting curves correspond to the 85.0 and 122.4 eV calculations of Walters (1980). Only the region below 5° is shown in order to be able to avoid overcrowding the figure.

with $N = 1$ and 2. The theoretical results of Walters (1980) for neighbouring energies are also indicated. The calculation should be quite reliable at low values of momentum transfer. This belief is supported by the good agreement between theory and experiment for the fit with $N = 2$ and also by the reasonably good agreement between the calculated integral cross sections and those of Leep and Gallagher (1974), although the calculated values are somewhat lower because of the incorrect (lower-value) predictions of theory at high scattering angles. It is evident from these figures that the $N = 1$ fit is not acceptable. It forces the DCS to rise as $\sim K^{-1}$ at low values of K, which in turn results in low DCS values at higher angles. Although both fits are normalised to the proper f^{opt} at $K = 0$, the shape and magnitude of the $N = 1$ fit are inconsistent with theory for $K > 0$. The same conclusions can be drawn from similar figures at every other impact energy. In figure 4 the values of $|f^{AG} - f^{opt}|$ are shown as a function of K^2 on a lg–lg scale. If a simple K^2 dependence for $f^{AG}(K, E_0)$ were assumed,

$$f^{AG}(K, E_0) = f^{opt} + A(E_0)K^2, \tag{4}$$

then

$$\lg |f^{AG}(K, E_0) - f^{opt}| = \lg A(E_0) + \lg K^2 \tag{5}$$

and the curves obtained at various impact energies should all have a slope of unity but intersect the $|f^{AG} - f^{opt}|$ axis at different points. This seems to be the case at all energies for the points associated with scattering angles of 3, 4, 5 and 6°. Deviations from this curve at higher angles indicate the necessity of including the K^4 term in fits such as that with $N = 2$ in figures 2 and 3. The same conclusion can be drawn concerning the theoretical results of Walters (1980).

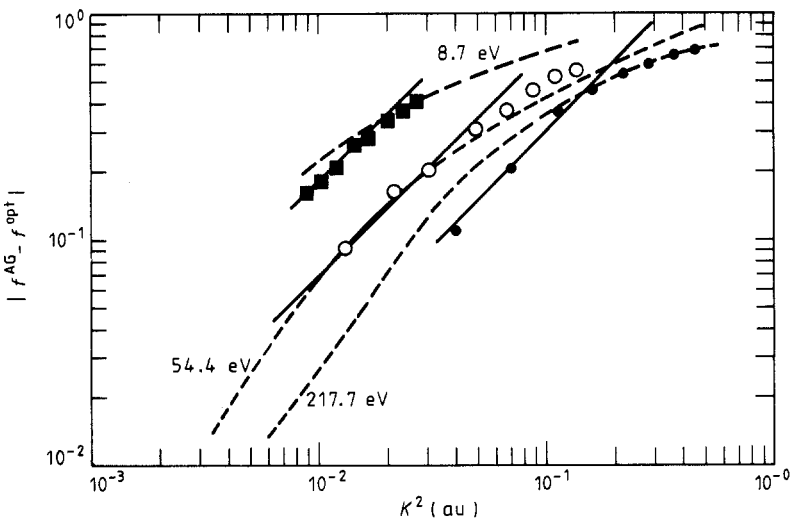

Figure 4. The values of $|f^{AG}(K, E_0) - f^{opt}|$ obtained from the present data are shown as a function of K^2 on a lg–lg plot at impact energies of 10, 60 and 200 eV by the symbols ×, ○ and ●, respectively. The broken curves represent the theoretical results of Walters (1980) at 8.7 and 212.7 eV. The straight lines through the data points indicate a fit to $|f^{AG}(K, E_0) - f^{opt}| = \text{constant} \times K^2$ (equations (4) and (5)).

The extrapolation to K values lower than that corresponding to 0° leads to a non-physical region. At high impact energies this region is very small and one can assume that the f^{AG} value at 0° has approached the $f^{AG}(K=0)$ value sufficiently closely. At low impact energies this is not the case. In the present case the $f^{AG}(0°, E_0)$ values are lower than f^{opt} by 17.5, 6.8, 1.1, 0.5, 0.3 and 0.1% at 10, 20, 60, 100, 150 and 200 eV respectively. Both the present results and the theoretical results of Walters indicate, however, that the extrapolation through this non-physical region can be done for Li by using equation (3) with $N=2$ at all energies ranging from about 10 to 200 eV. It is interesting to note that for an experiment where the lowest angle of scattering is θ_L the impact energy, $E_{0,min}$, which yields a minimum in K is not infinitely high as for the case of 0° scattering but is given as

$$E_{0,min}^2 - (\Delta E)E_{0,min} - \tfrac{1}{4}(\Delta E)^2 \cot^2 \theta_L = 0.$$

For the 2^2P excitation of Li with θ_L equal to 0, 1, 3, 5 and 10° this expression yields infinity, 53.9, 18.6, 11.5 and 6.2 eV for $E_{0,min}$, respectively.

Table 1. Summary of differential cross sections for the excitation of the 2^2P state. The values in parenthesis were obtained by extrapolation.

	DCS (10^{-16} cm^2 sr^{-1})					
θ (deg)	10 eV	20 eV	60 eV	100 eV	150 eV	200 eV
0	(1186)	(2977)	(10 114)	(17 169)	(25 984)	(34 803)
3	499	718	415	261	172	124
4	416	463	215	124	81.9	59.9
5	334	307	127	67.7	45.6	26.3
6	259	213	73.7	37.2	26.3	14.2
7	208	146	46.4	21.3	14.3	7.68
8	160	103	27.9	13.0	9.17	4.36
9	125	72.8	17.5	8.17	5.46	2.29
10	96.1	55.7	11.9	4.86	3.39	1.39
12	54.4	32.9	5.85	1.97	1.38	0.325
14	30.86	20.1	—	—	—	—
15	26.1	16.5	2.07	0.555	0.333	0.079
20	10.9	5.43	0.420	0.085	0.057	0.014
25	4.86	2.05	0.092	0.031	(0.011)	0.0047
30	2.33	0.759	0.040	0.018	(0.0048)	(0.0017)
35	1.54	0.376	0.023	0.013	(0.0019)	(0.00085)
40	1.19	0.238	0.017	0.0087	(0.00095)	(0.00066)
45	0.892	0.183	0.012	0.0068	(0.00048)	(0.00038)
50	0.783	0.164	0.0099	(0.0049)	(0.00048)	(0.00028)
60	0.592	0.106	0.0082	(0.0030)	(0.00048)	(0.00028)
70	0.359	0.0610	0.0092	(0.0023)	(0.00048)	(0.00028)
80	0.245	0.053	0.011	(0.0019)	(0.00048)	(0.00028)
90	0.211	0.057	0.012	(0.0016)	(0.00048)	(0.00028)
100	0.236	0.071	0.012	(0.0012)	(0.00048)	(0.00028)
110	0.263	0.071	0.012	(0.0012)	(0.00048)	(0.00028)
120	0.287	0.060	0.011	(0.0011)	(0.00048)	(0.00028)
140	(0.476)	(0.060)	(0.011)	(0.00098)	(0.00048)	(0.00028)
160	(0.843)	(0.060)	(0.011)	(0.00098)	(0.00048)	(0.00028)
180	(1.19)	(0.060)	(0.011)	(0.00098)	(0.00048)	(0.00028)

We therefore came to the conclusion that, based on the consistency of all available information, the best procedure for normalising the relative experimental DCS values to the optical f value should be carried out by utilising equation (3) with $N = 2$. The validity of this conclusion for the other alkali metals is being investigated and preliminary results support the present approach. The situation may or may not be similar for other metals.

4. Results and discussion

The differential cross sections are listed in table 1 and are compared with other results in figures 5–8. The only other experimental DCS available are those of Williams *et al* (1976). The two sets of data agree in general within a factor of two but the present results were obtained with greater care and with improved experimental conditions, and are therefore believed to be more accurate. Comparison is made with the Glauber calculations (without core potential) of Walters (1980), with the unitarised distorted-wave polarised orbital method (UDWPO II) of Kennedy *et al* (1977) and with the close-coupling calculations of Issa (1977). A comparison of these and several other earlier calculations is made by Brandsen and McDowell (1978). The Glauber results are in excellent agreement with the present data at low scattering angles, but the model underestimates the cross sections at high scattering angles. The same comment applies to the UDWPO II results at 10 and 20 eV, but at higher energies the agreement

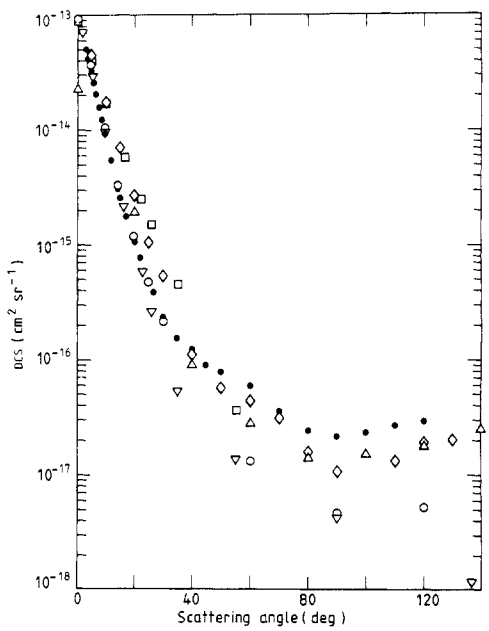

Figure 5. Differential cross sections for $2^2S \rightarrow 2^2P$ excitation at an impact energy of 10 eV: ●, present results; ◇, Williams *et al* (1976); ▽, Walters (1980) (11.0 eV); ○, Kennedy *et al* (1977) (12.1 eV); △, Issa (1977); □, Born approximation (Walters 1980).

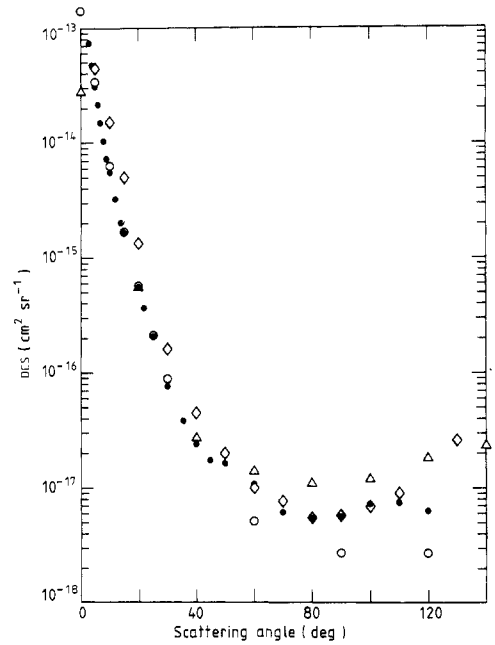

Figure 6. The same as figure 5 except that $E_0 =$ 20 eV.

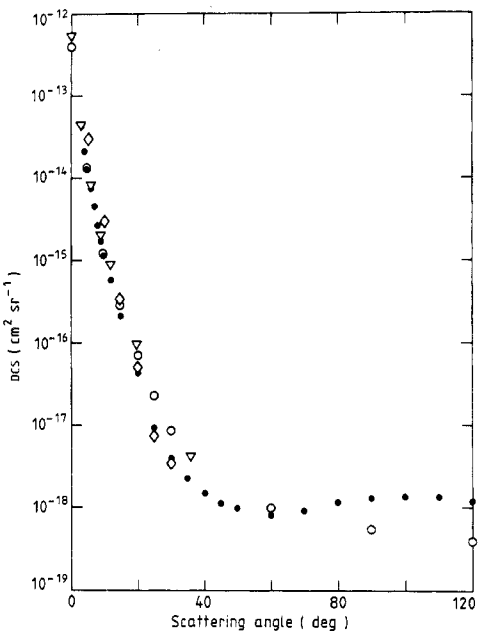

Figure 7. The same as figure 5 except that $E_0 =$ 60 eV and the results of Kennedy *et al* (1977) and Walters (1980) are at 54.4 eV.

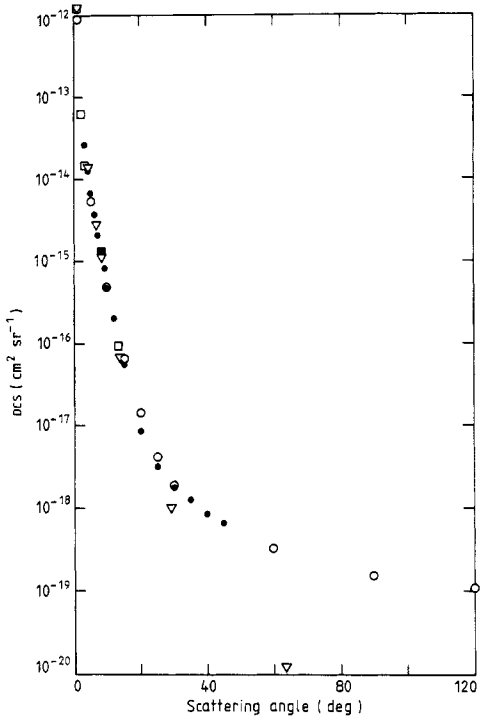

Figure 8. The same as figure 5 except that $E_0 =$ 100 eV and the results of Walters (1980) are at 122.4 eV.

is quite good even at high scattering angles. The close-coupling results give a better overall agreement at medium and high scattering angles. At very small scattering angles, however, this theory calculates cross sections which are lower by about a factor of three than the other results. The Born approximation (Walters 1980) gives good agreement with the present data, with the UDWPO II results and, naturally, with the Glauber calculation at low angles. However, it underestimates the cross sections at angles higher than about 20°.

The integral cross sections are shown in figure 9 and listed in table 2 together with the momentum transfer cross sections. At high energies all results are in good agreement except the data of Williams *et al* (1976), which were influenced by the large uncertainties of the low-angle DCS. At low impact energies the data of Zapesochnyi *et al* (1975) seem to be too high, while the Glauber results are too low because of the underestimation of the high-angle DCS. This inadequacy does not influence the results at higher energies because of the extremely small contribution from the high-angle DCS to the integral cross section. Both the UDWPO II and the close-coupling methods predict cross sections which are too large at low impact energies.

In estimating the errors associated with the DCS, we considered the statistical error in the intensity measurements, the effect caused by shifting the impact energy by ±0.5 eV, and the scattering angle by ±0.5, the uncertainty caused by the effective path length correction and the uncertainties in normalising the data to the optical f value. We have not assigned any error to the optical f value recommended by Martin and Wiese (1976). The results of this consideration are given in table 3. The error

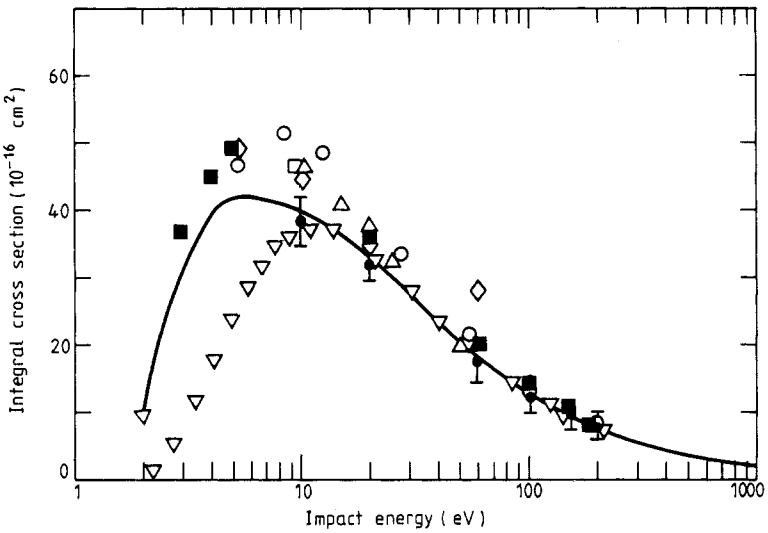

Figure 9. Summary of integral cross sections: ■, Zapesochnyi *et al* (1975); ——, Leep and Gallagher (1974); ●, present results; ◇, Williams *et al* (1976); ▽, Walters (1980); ○, Kennedy *et al* (1977); △, Issa (1977).

Table 2. Summary of integral and momentum transfer cross sections.

	$Q(10^{-16}\,\text{cm}^2)$					
E_0 (eV)	a	b	c	d	e	$Q^M(10^{-16}\,\text{cm}^2)$
10	39.5	46	46.8	39.8	38.0	8.4
20	32.5	36	33.0	33.9	31.1	2.3
60	18.0	20	18.8	18.9	17.5	0.39
100	12.9	14	13.1	13.5	12.4	0.13
150	9.2	10	9.7	10.4	9.63	0.062
200	7.3	8	7.4	8.5	7.56	0.034

[a] Leep and Gallagher (1974) (by interpolation).
[b] Zapesochnyi *et al* (1975) (read off figure 2).
[c] Walters (1980) (by interpolation).
[d] Present results using equation (3) with $N = 1$.
[e] Present results using equation (3) with $N = 2$.

estimation for the integral cross sections are also given. In addition to the DCS errors, the errors coming from the overall effective path length correction and from the high-angle extrapolation have been added for the integral values. The total error was calculated as the square root of the sum of the squares of the individual errors in each case. The momentum transfer cross sections are slightly more uncertain than the integral cross sections because of the important contribution from the high-angle DCS which we obtained by extrapolation beyond 120°.

The main significance of the present study is that the experimental angular distribution (combined with a normalisation to optical f value), the integral excitation cross sections and the low-angle theoretical predictions can be combined into a coherent picture. This procedure yields differential and integral cross sections for the 2^2P

Table 3. Summary of errors contributing to the differential and integral cross sections.

Source of error	Error (%)					
	10 eV	20 eV	60 eV	100 eV	150 eV	200 eV
E_0	8	0.4	0.4	0.3	0.2	0.2
θ	3	1.5	1.5	1.0	1.0	0.3
I, statistical	2	2	2	2	2	2
Volume correction (3–10°)	1	1	1	1	1	1
Normalisation	10	10	10	6	5	5
Total error in DCS	13	10	10	$6\frac{1}{2}$	6	$5\frac{1}{2}$
Additional errors in Q						
Volume correction (3–10°)	5	5	5	5	5	5
Extrapolation	5	10	3	2	5	5
Total error in Q	15	15	12	8	9	9

excitation of Li which are estimated to be accurate to about 15%. Furthermore, the present investigation indicates that the proper expression for fitting the experimental angular distribution and for extrapolation to the $K = 0$ limit should be done with a power-series expansion which contains only even powers of K (at least for the resonance transition of alkali metals). It is somewhat surprising that the extrapolation procedure and normalisation work even at an impact energy of 10 eV. One has to consider, however, that this energy is more than five times the threshold energy for the excitation of the 2^2P state and that we are dealing with very small momentum transfer values. It would be interesting to apply more rigorous theoretical justification for the even-power fitting than the theoretical models applied so far. The present investigation has also shown that accurate low-angle data are essential for applying this approach to normalisation of the cross sections.

References

Backx C, Tol R R, Wright G R and Van der Wiel M J 1975a *J. Phys. B: At. Mol. Phys.* **8** 2050
Backx C, Wright G R, Tol R R and Van der Wiel M J 1975b *J. Phys. B: At. Mol. Phys.* **8** 3007
Bethe H A 1930 *Ann. Phys., Lpz* **5** 325
Brandsen B H and McDowell M R C 1977 *Phys. Rep.* **30** 208
—— 1978 *Phys. Rep.* **46** 249
Brinkmann R T and Trajmar S 1981 *J. Phys. E: Sci. Instrum.* **14** 245
Dillon M A and Lassettre E N 1975 *J. Chem. Phys.* **62** 2373
Huo W M 1979 *J. Chem. Phys.* **71** 1593
Inokuti M 1971 *Rev. Mod. Phys.* **43** 297
Issa M R 1977 *Thesis* University of Durham (and private communication)
Kennedy J V, Myerscough V P and McDowell M R C 1977 *J. Phys. B: At. Mol. Phys.* **10** 3759
Lapp M and Harris C P 1966 *J. Quant. Spectrosc. Radiat. Transfer* **6** 169
Lassettre E N and Skerbele A 1974 *J. Chem. Phys.* **60** 2464
Lassettre E N, Skerbele A and Dillon M A 1969 *J. Chem. Phys.* **50** 1829
Leep D and Gallagher A 1974 *Phys. Rev.* A **10** 1082
Martin G A and Wiese W L 1976 *Phys. Rev.* A **13** 699
Register D F, Trajmar S and Srivastava S K 1980 *Phys. Rev.* A **21** 1134

Shuttleworth T, Burgess D E, Hender M A and Smith A C H 1979 *J. Phys. B: At. Mol. Phys.* **12** 3967
Shuttleworth T, Newell W R and Smith A C H 1977 *J. Phys. B: At. Mol. Phys.* **10** 3307
Srivastava S K, Chutjian A and Trajmar S 1975 *J. Chem. Phys.* **63** 2659
Trajmar S and Register D F 1980 in *Electron Molecule Collisions* ed K Takayanagi and I Shimamura (New York: Plenum)
Truhlar D G, Rice J K, Kuppermann A, Trajmar S and Cartwright D C 1970 *Phys. Rev.* A **1** 778
Vušković L, Trajmar S and Register D C 1980 to be published
Walters H R J 1980 private communication, see also 1973 *J. Phys. B: At. Mol. Phys.* **6** 1003
Williams W, Trajmar S and Bozinis D 1976 *J. Phys. B: At. Mol. Phys.* **9** 1529
Zapesochnyi I P, Postoi I V and Aleksakhin I S 1975 *Sov. Phys.-JETP* **41** 865