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Electron impact excitation of potassium at 6·7, 16 and 60 eV†

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Abstract. Normalized momentum-transfer cross sections and differential and integral cross sections for elastic scattering and for the excitation of the $4p\,^2P_{3/2,1/2}$ and the $(5s\,^2S_{1/2} + 3d\,^2D_{5/2,3/2})$ levels in potassium are reported at 6·7, 16 and 60 eV impact energies. There is considerable disagreement between the present experimental results and previous optical excitation measurements and theoretical results. Autoionization features associated with the 3p inner-shell excitations, some of which have been observed previously in optical absorption and ejected-electron spectra, have been detected in the electron impact energy-loss spectrum.

1. Introduction

Theoretical and experimental work on potassium has been summarized up to the late sixties in the electron–atom collision reviews of Moiseiwitsch and Smith (1968) and Bederson and Kieffer (1971) respectively. Total cross sections for potassium in crossed-beam experiments using recoil techniques have been measured by Rubin *et al* (1960) (0·6 to 9·0 eV), Perel *et al* (1962) (1 to 10 eV), Visconti *et al* (1971) (0·3 to 9 eV) and Kasdan *et al* (1973) (0·3 to 50 eV). Collins *et al* (1971) have obtained elastic differential and differential exchange cross sections (0·5–1·2 eV) and have reported total cross sections up to 9 eV using the recoil technique. The same method has been applied by Goldstein *et al* (1972) to obtain differential cross sections with spin analysis for the $4s\,^2S_{1/2} \rightarrow 4p\,^2P_{3/2,1/2}$ excitation (3–10 eV) and by Slevin *et al* (1972) to obtain elastic and inelastic differential cross sections at 3·3, 4·4 and 5·2 eV impact energies.

Relative elastic scattering intensities have been measured by McMillen (1934) using a collision cell in the 25° to 160° angular range and 5 to 150 eV energy range and by Gehenn and Wilmers (1971) in a crossed-beam arrangement in the angular range of 25° to 150° from 0·9 to 15 eV impact energies. Hils *et al* (1972) have measured relative elastic scattering of unpolarized electrons at 3·3 eV impact energy from a beam of spin-polarized potassium atoms. Relative elastic and inelastic differential cross sections for electron–potassium scattering have been determined in a crossed-beam experiment by Eyb (1976) from 2 to 3·2 eV and 20°–140° scattering angles.

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He observed resonances in the elastic channel (at 2·4, 2·6 and 2·68 eV). Zero-angle differential cross sections and generalized oscillator strengths for several levels in potassium have been reported by Hertel and Ross (1968, 1969). Volkova and Devyatov (1963), Zapesochnyi and Shimon (1966) and Zapesochnyi *et al* (1975) have reported electron impact excitation function measurements for the $4p\ ^2P_{3/2}$ and $^2P_{1/2}$ resonance transitions.

Integral cross sections for the $4p\ ^2P$ excitations have been calculated by Vainshtein *et al* (1965) (first Born approximation), McCavert and Rudge (1972) (distorted-wave approximation) and Felden and Felden (1973) (correlation model; cross sections calculated relative to H-atom model). Close-coupling results (Karule 1965, Karule and Peterkop 1965) at less than 5 eV and Glauber cross sections (Walters 1973) above 20 eV have been reported. Walters (1976) has smoothly connected the close-coupling and Glauber results to obtain an excitation function for the resonance transition over an extended energy range. He also obtained total cross sections from threshold to 50 eV from the elastic and resonance excitation cross sections and by estimating the cross section for transitions other than the resonance one, and using experimental ionization cross sections. Moores (1976) reported three-state close-coupling calculations for elastic scattering and for the excitation of the $4p\ ^2P$ state from threshold to 5 eV impact energies. Very recently Kennedy *et al* (1977) have calculated cross sections for the resonance transition using the unitarized distorted-wave polarized-orbital method.

Here we report normalized momentum-transfer cross sections and differential and integral cross sections for elastic scattering and for the excitation of the $4p\ ^2P_{3/2,1/2}$ and the $(5s\ ^2S_{1/2} + 3d\ ^2D_{5/2,3/2})$ levels at 6·7, 16 and 60 eV impact energies as well as features which appear in the electron impact energy-loss spectra in the 18–26 eV region and correspond to the excitation of an electron from the 3p inner shell.

2. Experimental

The electron impact spectrometer used in these experiments and the experimental procedures have been described earlier by Chutjian (1974) and Williams and Trajmar (1974). An energy-selected electron beam (0·08 eV FHWM) was scattered by a potassium beam which was generated by heating a stainless-steel crucible containing potassium by electron bombardment. The electron current was monitored and trapped by a Faraday cup. Electron scattering intensities were determined as a function of energy loss (ΔE) at fixed impact energies (E_0) and scattering angles (θ) using multichannel scaling techniques. These energy-loss spectra constitute the basic data for the relative cross sections. Changes in electron and target beam intensities do not affect the relative intensities since each energy-loss spectrum is the superposition of many scans. The impact energy is accurate to within $\pm 0{\cdot}5$ eV and the angular resolution is about 2°.

The elastic scattering intensity distribution as a function of angle was determined in a time which was short compared to the instrumental drift. From an effective path-length correction (appropriate for our scattering geometry (Williams and Trajmar 1976) differential cross sections (DCS) for elastic scattering in arbitrary units were obtained. Elastic to inelastic intensity ratios determined from the energy-loss spectra were combined with the elastic cross sections to yield the inelastic DCS. All DCS were extrapolated to 0° and 180° and integrated to obtain the corresponding

integral cross sections. A cross section estimation for the open channels not considered in this series of experiments was made from several energy-loss spectra. The sum of elastic plus inelastic integral cross sections was normalized to the difference between the total cross sections of Kasdan *et al* (1973) and the ionization cross sections of McFarland and Kinney (1965) (6·7 and 16 eV) and Korchevoi and Przonski (1967) (60 eV).

3. Results and discussion

3.1. Differential cross sections

Energy-loss spectra at 6·7, 16 and 60 eV have been obtained at scattering angles ranging from 5° to 130°. Examples of typical spectra are shown in figure 1. From these and other similar spectra, relative cross sections for elastic scattering and for the excitation of the $4p\,^2P_{3/2,1/2}$ and the $(5s\,^2S_{1/2} + 3d\,^2D_{5/2,3/2})$ unresolved states have been obtained and normalized to the absolute scale by the procedure discussed above.

At 6·7 eV, all three DCS are forward peaked (see figure 2). Between 5° and 80° their value decreases by nearly two orders of magnitude. As the impact energy increases, the DCS fall more precipitously. At 16 and 60 eV from 5° to 80° scattering angle, all DCS decrease by about four orders of magnitude (figures 3 and 4). The DCS curves have a minimum around 60° to 80° scattering angle for all impact energies. In figure 4 the DCS calculated by Kennedy *et al* (1977) for the resonance transition at 54·4 eV impact energy using the unitarized distorted-wave polarized-orbital method are compared with the present 60 eV results. There is a good agreement in shape between the theoretical and the experimental values above 25° (except at 120°) but the calculated values are lower by about a factor of two (the estimated experimental errors are about $\pm 50\%$ in this region). The deviations are somewhat larger at angles below 25° and in this range the calculated values are higher than the experimental ones. At 0° the calculated cross section is an order of magnitude larger than the one obtained by extrapolating the experimental data. At low angles the cross section curve rises very steeply and the experimental errors can be somewhat larger than at other angles. At 120° (and higher angles) the theoretical model is not expected to be as accurate as at low angles. The cross sections are given in table 1.

Absolute differential cross sections for elastic scattering and for the excitation of the $4p\,^2P_{3/2,1/2}$ state by the recoil technique were obtained by Slevin *et al* (1972). The technique used some of the kinematic properties of the recoiling atom to obtain DCS over a limited angular range. We compare our 6·7 eV results with the measurements of Slevin *et al* at 5·2 eV (see figures 5 and 6). The agreement in the absolute magnitude of the DCS for elastic scattering and for the excitation of the $4p\,^2P_{3/2,1/2}$ state is quite good in spite of the 1·5 eV difference in impact energy.

Elastic scattering distributions (in arbitrary units) at several impact energies have been reported by McMillen (1934) and Gehenn and Wilmers (1971). For qualitative comparison, we have normalized (at 60°) their 15 eV results to our 16 eV results (figure 7) and McMillen's 50 eV results to our 60 eV results (figure 8). The agreement among these elastic DCS is good. Gehenn and Wilmer's experiments show a second minimum around 125° but this is not seen by McMillen or in the present experiments.

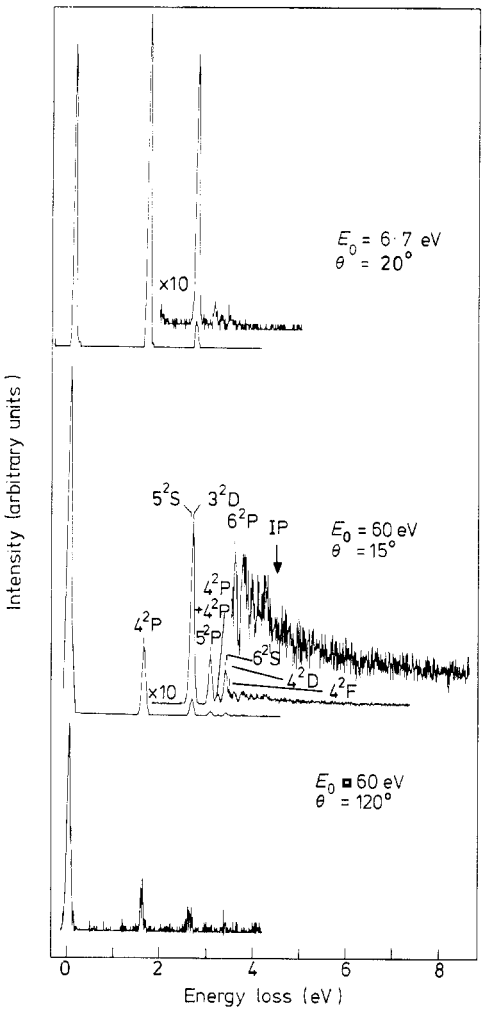

Figure 1. Electron impact spectra of potassium at scattering angles θ and impact energies E_0 shown.

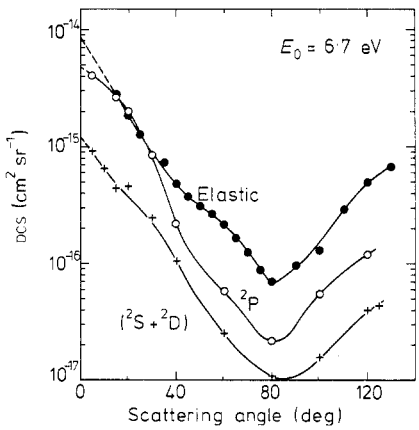

Figure 2. Differential cross sections for elastic scattering and for the excitation of the $4p\,^2P_{3/2,1/2}$ and ($5s\,^2S_{1/2}$ + $3d\,^2D_{5/2,3/2}$) states at E_0 = 6·7 eV.

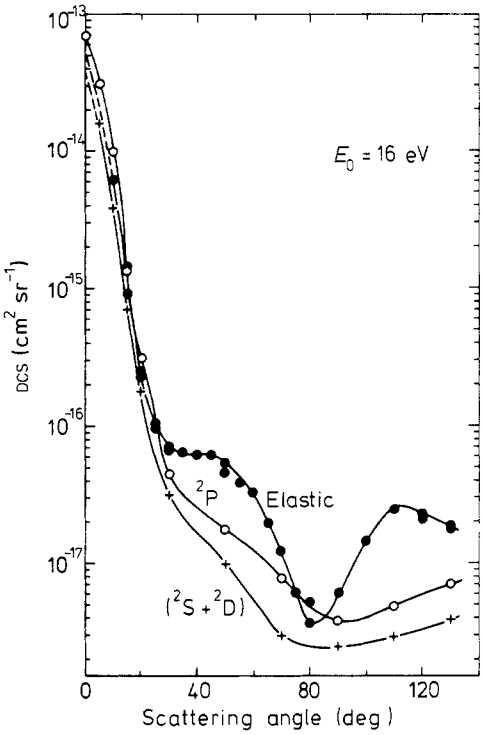

Figure 3. Same as figure 2, except at E_0 = 16 eV.

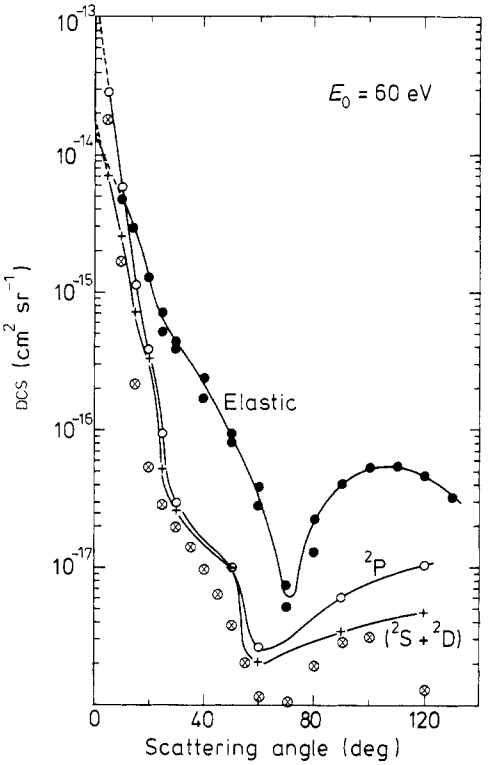

Figure 4. Same as figure 2, except at E_0 = 60 eV. The symbols ⊗ represent the values calculated by Kennedy *et al* (1977) at 54·4 eV.

Our instrumental resolution did not permit us to resolve the $5s\,^2S_{1/2}$ and $3d\,^2D_{5/2,3/2}$ levels. A somewhat higher-resolution energy-loss spectrum was reported by Hertel and Ross (1969) where they achieved separation of the 5^2S and 3^2D excitations and found that at E_0 = 50·5 eV and 0° scattering angle, the 3^2D level exceeds that of the 5^2S by nearly a factor of three. The values of the zero-degree DCS for the 4^2P and for the (5^2S + 3^2D) excitations at 68 eV impact energy were determined by Hertel and Ross (1968) as 12 500 and 177 Å^2 sr^{-1} respectively. Our values are 1150 and 180 Å^2 sr^{-1} (see table 1). The agreement in the (5^2S + 3^2D) excitation is excellent. There is an order of magnitude difference, however, in the 4^2P excitation cross section.

In the 60 eV spectrum at 15° (figure 1) scattering angle a feature corresponding to the (4^2P + 4^2P) double scattering appears. Double scattering could significantly alter the angular distribution of scattered electrons associated with weak transitions (see Chamberlain *et al* 1967). This situation may arise, for example, at impact energies where the elastic cross section is large and strongly forward-peaked compared to cross sections associated with optically forbidden excitations. The double (elastic plus inelastic) to single (inelastic) scattering intensity ratio at a fixed impact energy (E_0) and scattering angle (θ) for the energy-loss process (ΔE) is given (e.g. Rice 1968) by

$$\frac{I_2}{I_1} = \rho \langle l \rangle_{\text{eff}} \frac{\langle \sigma(0, \theta')\, \sigma(\Delta E, \theta - \theta') \rangle_{\theta'}}{\sigma(\Delta E, \theta)}$$

Table 1. Summary of differential cross sections (in units of 10^{-16} cm^2 sr^{-1}).

θ	$E_0 = 6{\cdot}7$ eV			$E_0 = 16$ eV			$E_0 = 60$ eV		
(deg)	Elastic	4^2P	(5^2S + 3^2D)	Elastic	4^2P	(5^2S + 3^2D)	Elastic	4^2P	(5^2S + 3^2D)
0	(88·2)	(48·7)	(13·0)	(548)	(721)	(389)	(138)	(1150)	(180)
5	(60·3)	41·8	9·28	(202)	317	162	(74·7)	276	66·1
10	(40·6)	34·8	6·50	63·5	101	37·5	44·2	52·9	23·0
15	27·8	27·8	4·87	11·5	13·0	6·92	24·7	10·3	6·61
20	18·8	20·9	3·71	2·31	3·17	1·73	11·8	3·39	2·99
25	13·0	13·7	2·90	0·98	1·01	0·61	5·75	0·86	0·48
30	9·28	8·35	2·27	0·69	0·43	0·30	4·02	0·26	0·23
40	4·87	2·32	1·07	0·61	0·23	0·16	1·90	0·14	0·14
50	3·09	1·00	0·52	0·52	0·17	0·09	0·80	0·08	0·06
60	2·13	0·58	0·26	0·30	0·12	0·05	0·29	0·02	0·02
70	1·25	0·33	0·15	0·12	0·07	0·03	0·06	0·03	0·02
80	0·70	0·22	0·11	0·04	0·04	0·03	0·18	0·04	0·03
90	0·91	0·30	0·11	0·06	0·035	0·02	0·37	0·05	0·03
100	1·51	0·56	0·15	0·14	0·04	0·03	0·48	0·07	0·04
110	2·90	0·86	0·25	0·23	0·05	0·03	0·48	0·08	0·03
120	4·87	1·21	0·38	0·21	0·06	0·03	0·42	0·09	0·04
130	6·73	(1·56)	(0·55)	0·17	0·07	0·04	0·29	(0·11)	(0·05)
140	(8·35)	(1·93)	(0·70)	(0·13)	(0·07)	(0·04)	(0·25)	(0·12)	(0·05)
160	(10·9)	(2·60)	(0·93)	(0·14)	(0·09)	(0·05)	(0·46)	(0·13)	(0·05)
180	(12·5)	(3·29)	(1·09)	(0·25)	(0·11)	(0·07)	(1·49)	(0·14)	(0·06)
Q	62·8	30·7	8·3	22·4	31·1	15·0	22·2	24·4	8·0
Q^M	61·7	18·5	6·3	2·4	2·7	1·9	5·5	1·6	0·8
		$Q_I = 5{\cdot}1$			$Q_I = 8{\cdot}4$			$Q_I = 6{\cdot}3$	
		$Q_0 = 5{\cdot}2$			$Q_0 = 21{\cdot}1$			$Q_0 = 7{\cdot}1$	
		$Q_T = 112{\cdot}0$			$Q_T = 98{\cdot}0$			$Q_T = 68{\cdot}0$	

The *symbols* have the following meaning: Q, Q^M, Q_I and Q_T are integral, momentum-transfer, ionization and total cross sections, respectively, and Q_0 is the sum of all other integral cross sections not mentioned specifically. The numbers in parentheses have been obtained by extrapolation.

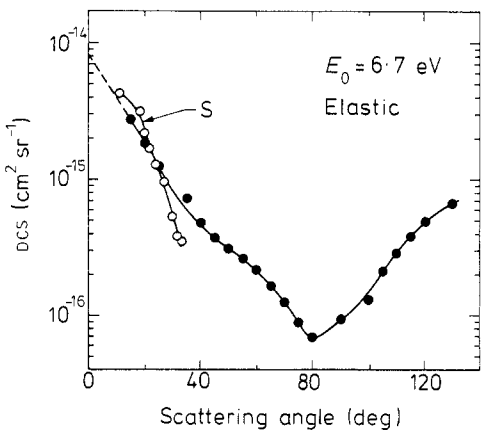

Figure 5. Elastic differential cross sections. S: Slevin *et al* (1972) at 5·2 eV. Full circles joined by full curve are present results at 6·7 eV.

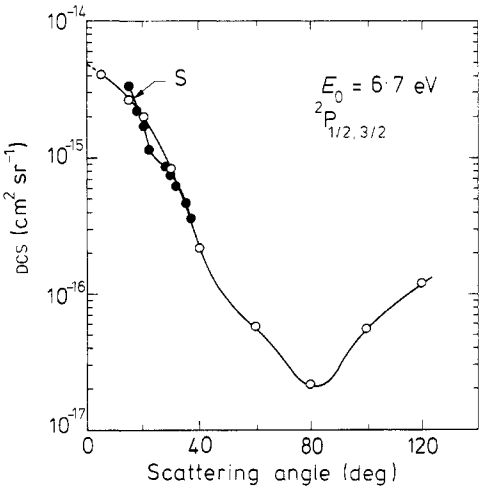

Figure 6. 4p ^{2}P$_{3/2,1/2}$ differential cross sections. S: Slevin *et al* (1972) at 5·2 eV. Open circles joined by full curve are present results at 6·7 eV.

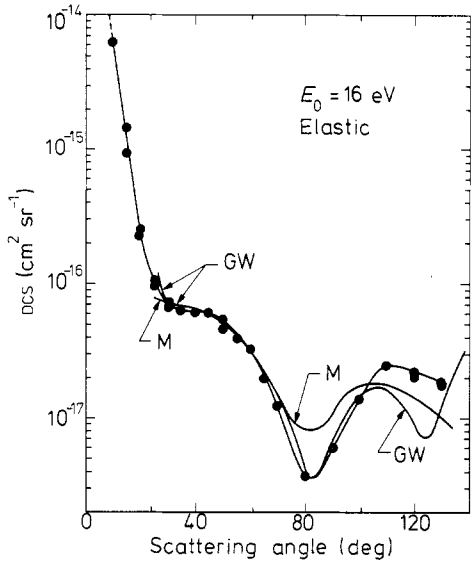

Figure 7. Elastic differential cross sections. GW: Gehenn and Wilmers (1971) at 15 eV; M: McMillen (1934) at 15 eV. Full circles joined by full curve are present results at 16 eV.

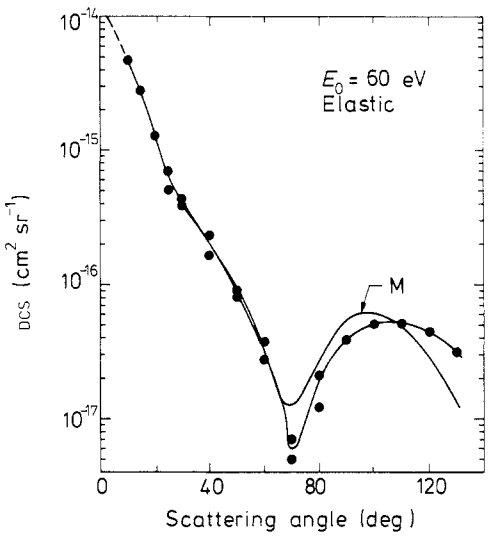

Figure 8. Elastic differential cross sections. M: McMillen (1934) at 50 eV. Full circles joined by full curve are present results at 60 eV.

where ρ is the target density; σ is the differential cross section, the quantities in brackets are averaged over all combinations of θ' and $\theta - \theta'$ and $\langle l \rangle_{\text{eff}}$ is a complicated geometrical factor. The complexity of the quantity in brackets makes it a difficult task to assess accurately the effect of double scattering. The usual procedure is to study the scattering cross section as a function of pressure and subsequently extrapolate the cross section to zero pressure (see e.g. Dillon and Lassettre 1975).

In the case of potassium certain conditions prevail which make it possible to assess the importance of double scattering. The DCS for elastic scattering and for the excitation of the resonance state are about the same in magnitude and show a similar angular behaviour. A consequence of this large inelastic cross section is that double inelastic scattering for the resonance state is easy to observe (double elastic or elastic plus inelastic double scattering is indistinguishable from the corresponding elastic or inelastic single scattering). Furthermore, because of the similarity of the elastic and inelastic cross sections the effect of double elastic scattering on the elastic cross sections and the effect of elastic plus inelastic scattering on the inelastic cross sections can be estimated from the double inelastic scattering. We estimate that less than around 2% of the electrons contributing to elastic and resonance scattering peaks are doubly scattered at 60 eV impact energy at all angles.

The total cross sections of Kasdan *et al* (1973) have a reported uncertainty of $\pm 12\%$. We estimate the errors associated with the measurements, namely extrapolation and integration of the respective DCS, to be about $\pm 40\%$ and errors arising from estimation of open channels, for which DCS are not reported, to be about $\pm 25\%$. The uncertainty in our cross sections is, therefore, about $\pm 50\%$ (square root of the sum of the squares of the individual errors). The relative values of the differential cross sections are estimated to be accurate to within $\pm 20\%$ at each impact energy.

3.2. Generalized oscillator strengths

Lassettre *et al* (1969) have shown that by extrapolating the generalized oscillator strength to zero momentum transfer one obtains the optical oscillator strength whether the Born approximation holds or not. The generalized oscillator strength defined by Bethe (1930) is

$$f_{0n}^{G} = \frac{W}{2}\frac{K_0}{K_n}(\Delta K)^2 \times \text{DCS}$$

where W is the excitation energy, K_0 and K_n are the momenta before and after collision, respectively, and ΔK is the momentum transfer. Generalized oscillator strengths obtained from the present cross sections for the $4p\,^2P_{3/2,1/2}$ states are plotted as a function of (momentum transfer)^2 for 6·7, 16 and 60 eV in figure 9. At 60 eV, the value of the generalized oscillator strength extrapolated to zero momentum transfer is nearly equal to the optical oscillator strength for the $^2P_{3/2,1/2}$ states (0·968) reported by Marr and Creek (1968). At 6·7 and 16 eV any reasonable extrapolation to zero momentum transfer would predict an optical f value far different from the measured one, indicating that this procedure has no physical meaning at these energies.

3.3. Integral and total cross sections

The $4p\,^2P_{3/2,1/2}$ integral cross sections are compared in figure 10. The present results, the calculations of Vainshtein *et al* (1965), McCavert and Rudge (1972), Walters (1976) and Felden and Felden (1973) and the excitation measurements of Zapesochnyi and Shimon (1966) and Zapesochnyi *et al* (1975) are shown. The present normalized cross sections for the $4p\,^2P_{3/2,1/2}$ states are significantly lower than either the optical or the theoretical results but agree reasonably well with the calculations of Felden and Felden. Walters (1976) uses the close-coupling results of Karule (1965) and Karule and Peterkop (1965) (lower than 5 eV) and the Glauber cross sections of Walters (1973) (greater than 20 eV) to obtain (by a smooth connection) resonance transition cross sections from threshold to 50 eV. Walters' curve also lies considerably above our experimental points. The calculation of Kennedy *et al* (1977) agrees well with

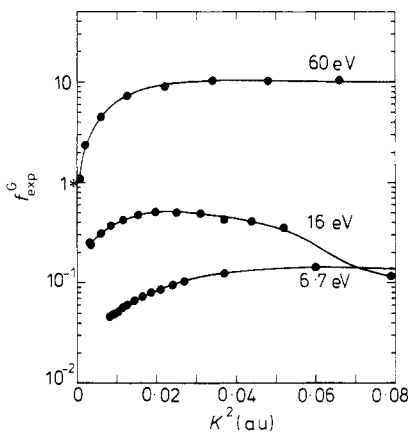

Figure 9. Generalized oscillator strengths plotted as a function of (momentum transfer)^2. The asterisk on the vertical axis indicates the optical f value of Marr and Creek (1968).

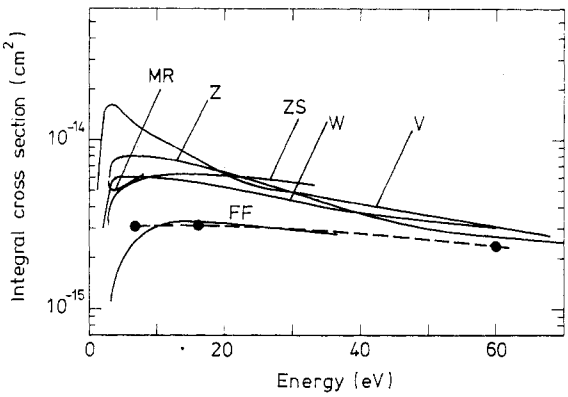

Figure 10. Integral excitation cross sections for the $4p\,^2P_{3/2,1/2}$ state. V: Vainshtein *et al* (1965) (Born approximation); W: Walters (1976) (close-coupling plus Glauber approximation); MR: McCavert and Rudge (1972) (distorted-wave approximation); FF: Felden and Felden (1973) (correlation model); ZS and Z: Zapesochnyi and Shimon (1966) and Zapesochnyi *et al* (1975) (excitation function measurements). Full circles joined by broken curve are present results.

the measurements of Zapesochnyi *et al* (1975). The reason for the discrepancy between the present results and the calculations and optical excitation measurements is not clear at the present time. We applied the same experimental and normalization procedure to Li (Williams and Trajmar 1976) as that applied in the present work to K and obtained excellent agreement in the case of Li with the optical excitation measurements and theoretical results. Further work is required to determine accurately the low-angle differential cross sections (which are the major contributions to the integral cross section) and to apply different normalization procedures before the disagreement for the K results can be resolved.

Walters (1976) employed the same procedure for obtaining elastic cross sections as the one he used for the resonance excitation. Our measurements for elastic scattering at 6·7 and 16 eV are in good agreement with the results of Walters but at 60 eV our integral cross section is 2·6 times larger (see figure 11). The relative cross sections (Q_{00}/Q_{2p}) are known in the present experiments to an accuracy of about $\pm 40\%$ but they differ from the ratios calculated from Walters' cross sections by nearly a factor of three at all energies. This indicates that the calculated resonance cross sections are too high. Our estimation of cross sections other than the elastic and resonance ones are also significantly different from Walters' (1976) estimates. A summary of our integral cross sections is included in table 1.

Walters summed the elastic, resonance and 'other' integral cross sections plus the appropriate ionization cross sections to obtain total cross sections from threshold to 50 eV. These total cross sections are plotted together with those of Kasdan *et al* (1973) and Brode (1929) in figure 11. The total cross sections of Kasdan *et al* deviate from those of Brode and of Walters but they are in good agreement (not shown) with the experiments of Collins *et al* (1971) and Visconti *et al* (1971), and with the calculations of Karule (1965) and Karule and Peterkop (1965).

3.4. 18–25 eV energy-loss region

Beutler and Guggenheimer (1933) detected two strong autoionization features in the absorption spectrum of K at 662·4 Å (18·71 eV) and 653·31 Å (18·97 eV). Hudson

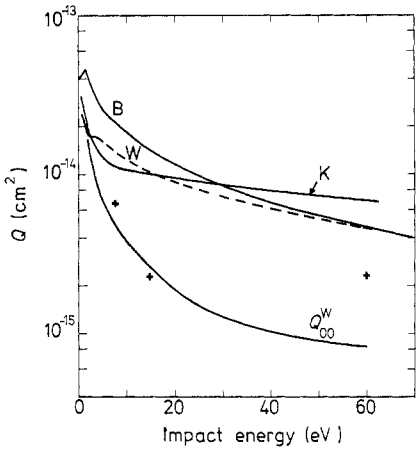

Figure 11. Total cross sections. K and B: Kasdan *et al* (1973) and Brode (1929) (experimental measurements); W: Walters (1976) (close-coupling plus Glauber approximation). Elastic cross sections. Q_{00}^W: Walters' (1976) calculations; +: present results.

and Carter (1967) have measured the corresponding atomic absorption cross sections. These and several additional states in the 20–24 eV region have also been observed by electron impact on K by Ottley and Ross (1975) by looking at the energy spectrum of ejected electrons at 90° at 29 eV and 500 eV impact energies. Recently, the optical absorption spectrum of K has been studied by Mansfield (1975) using a BRV continuum source. He found 140 new features in the 700 Å (17·7 eV) to 350 Å (35·4 eV) region and assigned them to excitations of the inner 3p subshell. In figure 12 an energy-loss spectrum of the same region is shown. The strong optical absorptions are indicated and coincide with the features observed in our spectrum. Ottley and Ross found the ejected-electron peaks corresponding to these autoionizing levels with

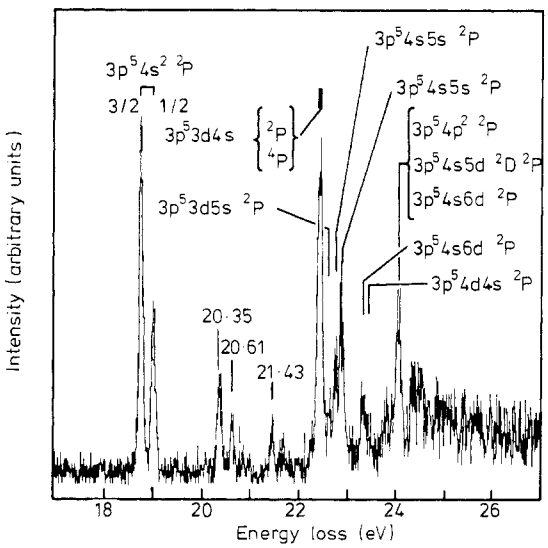

Figure 12. Electron impact energy-loss spectrum (18–26 eV) at 5° scattering angle and 100 eV impact energy.

500 eV incident electrons. They also found ejected electrons associated with autoionizing features at 20·61 and 21·40 eV when the impact energy was 29 eV. We observe an additional feature at 20·35 eV in the energy-loss spectrum.

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