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A measurement of the cross section for electron impact ionisation of Al^+

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Abstract. The crossed ion and electron beams technique has been used to make an absolute measurement of the cross section for the ionisation process $e + Al^+ \rightarrow 2e + Al^{2+}$ at electron energies ranging from below threshold up to 750 eV. The compounded random and systematic errors are estimated to be about ±5% at energies in excess of about 25 eV. The cross section for the ground-state ion is determined from the measured data using a small correction that allows for the presence of about 9% of metastable ions in the Al^+ beam. Comparison of the present data with the predictions of Lotz shows that the latter work appreciably overestimates the ground-state cross section at energies above 35 eV. The scaled Born prediction of McGuire is in closer agreement but it also exceeds the measured cross section above 35 eV. The shape of the Coulomb–Born-exchange cross section of Moores is in fair agreement but the magnitude is lower than the present data.

1. Introduction

Aluminium, iron and refractory metallic elements such as tungsten are employed in the fabrication of plasma containment vessels used for fusion research and atoms sputtered from the internal surfaces of such vessels become ionised by collisions with plasma electrons. The power dissipated from the plasma by atomic radiation is sensitive to the charge state reached by these ions before they return to the wall and, moreover, the rate of sputtering is also affected by the charge state of the returning ions (see, for example, Harrison 1983). It is necessary to know the ionisation cross sections in order to evaluate these interactive processes but there is a sparsity of ionisation data for relevant atoms and their lowly charged ions; consequently a programme of studies to obtain these data has now begun. The crossed ion and electron beam technique is used and the present paper reports an absolute measurement of the cross section for the process $e + Al^+ \rightarrow 2e + Al^{2+}$ over the energy range from threshold to 750 eV.

2. Experimental technique

The crossed beams apparatus used was basically the same as that described by Aitken and Harrison (1971), the electron gun employed in the measurements is discussed by Dixon *et al* (1976), the overlap integral of the beam current profiles was determined in the manner described by Harrison (1966) and a description of the single-particle detector system used for the Al^{2+} ions can be found in Dance *et al* (1967). Recent

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improvements to the apparatus and to the measuring techniques will be described in detail by Montague *et al* (1983) in their report on the measurement of the ionisation cross section of ground-state helium atoms. For the present investigation the PIG ion source was replaced by a sputter ion source based on the design of Hill and Nelson (1965) which was modified to extend the operational lifetime and to optimise the extraction of a beam of 4 keV Al^+ ions into the small acceptance angle of the apparatus. The source was fed with argon gas and the intensity of the Al^+ beam was typically 2×10^{-9} A.

Product Al^{2+} ions were detected by an electron multiplier (Johnston Laboratories MM1) operated as a single-particle detector. Multiplier detection efficiency is a function of incident ion velocity (Peart and Harrison 1981) and the velocity should be greater than about 2×10^5 m s^{-1} to obtain effective operation. Adequate velocity of the product Al^{2+} ions was ensured here by acceleration to the first dynode of the multiplier which was biased to -3 kV. A significant spatial variation of the multiplier efficiency developed during the course of this experiment and this was attributed to localised contamination of the surface; the problem was eliminated by scanning the Al^{2+} beam across the dynode by means of a small alternating electric field. The measured efficiency in this scanned mode was stable within the range 0.79–0.81 for the duration of the measurements.

The crossed beams apparatus was operated in a conventional manner with a pulsed electron beam (480 μs pulse length, 48% duty cycle) and a DC ion beam. The electron energy was varied from 12 eV (i.e., below the ionisation threshold) to 750 eV and the Al^{2+} signal count rate (normalised to the Al^+ ion beam current and effective beam height) was shown to be proportional to the electron beam current at a number of energies distributed over this range. Data at intermediate energies were obtained using single values of electron current which lay in the range 50–150 μA (averaged over the duty cycle). At the peak of the cross section an electron current of 150 μA gave a mean signal count rate of some 100 counts/s with an order of unity ratio for signal to extraneous background Al^{2+} ions. The contact potential of the electron gun was determined to be -2.0 ± 0.5 V by observation of the threshold for ionisation of Ne^+ to Ne^{2+}.

The absolute ionisation cross section at a particular incident electron energy was determined from measurement of the Al^{2+} production rate, the electron and ion beam currents, the effective height of the beam intersection region and the beam velocities. The procedures adopted followed closely those described by Brook *et al* (1978).

3. Results and discussion

The measured cross section is shown by the experimental points in figure 1. The 90% confidence limits of the counting statistics are shown for energies less than or equal to 20 eV by error bars; these limits are too small to plot in the energy range 20–250 eV where they are typically ±2% but they increase to about ±5% at the highest energy. Uncertainties in calibration introduce systematic errors, the largest of which arise from the detection efficiency of the electron multiplier (±3%) and the determination of the effective beam height (±2%). Other errors arise from measurements of the beam currents and they contribute an additional ±2.0%. The estimate of the 90% confidence limits of overall systematic errors (compounded in quadrature from the preceding calibration errors) is ±3.8%.

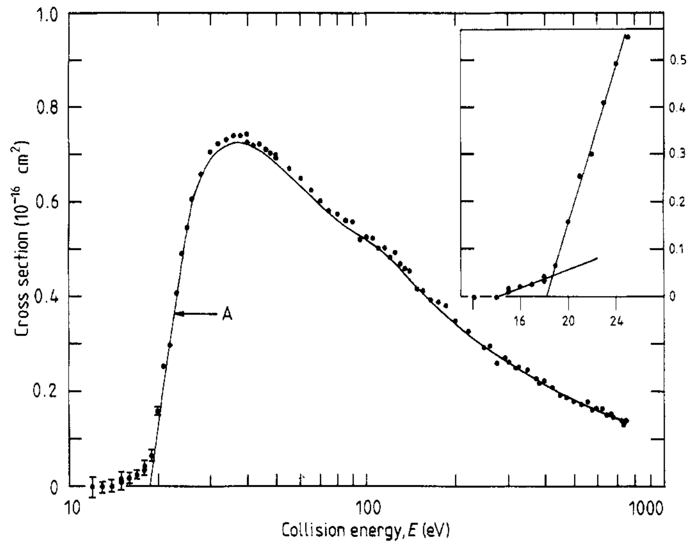

Figure 1. The measured ionisation cross section $Q(E)$ plotted against collision energy E. The inset shows the linear dependence upon energy of the measured data in threshold region and curve A shows the ground-state cross section $Q_g(E)$ derived from the measured data.

The ground state of Al^+ is $3s^2(^1S_0)$ and its threshold energy, χ_{3s^2}, for ionisation to the $3s(^2S_{1/2})$ ground state of Al^{2+} is 18.82 eV. There is also a metastable $3s3p(^3P_{0,2})$ state and the threshold for ejection of the 3p electron (i.e., ionisation to $3s(^2S_{1/2})$) is $\chi_{3p} = 14.18$ eV whereas that for the 3s electron (ionisation to $3p(^2P_{1/2}, \frac{3}{2})$) is $\chi_{3s} = 20.84$ eV. It is apparent from figure 1 that onset of ionisation occurs at the threshold for ejection of the 3p electrons and so it is very probable that the Al^+ beam contained some metastable ions. The apparent cross section in the energy region below the ground-state threshold was found to be a function of the ion source operating conditions and it was minimised by operating the source with high gas pressure and low discharge voltage. Moreover, it was possible to maintain an approximately constant component of metastable ions throughout the duration of the experiment.

The measured cross section $Q(E)$ for an ion beam containing a constant fraction f of metastable ions can be expressed as

$$Q(E) = fQ_m(E) + (1-f)Q_g(E) \tag{1}$$

where $Q_m(E)$ and $Q_g(E)$ are respectively the ionisation cross sections for the metastable and ground-state ions. Cross sections of metastable Al^+ ions are not known but, since the predominant process is direct ejection of an outer shell electron, it is considered that an adequately accurate estimate can be obtained by classical scaling from the ground-state cross section. Thus $Q_m(E)$ is expressed as

$$Q_m(E) = \frac{1}{2}\left[\left(\frac{\chi_{3s^2}}{\chi_{3p}}\right)^2 Q_g\left(E\frac{\chi_{3s^2}}{\chi_{3p}}\right) + \left(\frac{\chi_{3s^2}}{\chi_{3s}}\right)^2 Q_g\left(E\frac{\chi_{3s^2}}{\chi_{3s}}\right)\right] \tag{2}$$

where the factor $\frac{1}{2}$ arises because of the two bound electrons associated with the ground-state. Such scaling may slightly misrepresent ejection of inner-shell electrons from the metastable ions but this discrepancy is unlikely to introduce significant errors because of the small magnitude of the corrections applied to the measured data at energies in excess of 100 eV.

It is apparent that the slope $K = (\Delta Q/\Delta E)$ of the measured cross section below the ground-state threshold is approximately constant and so is the slope above the χ_{3s} threshold; this fact is used to determine the metastable fraction f. The ratio R of these slopes can be expressed as

$$R = \frac{K}{fK_{3p}} = \frac{(1-f)K_g + fK_m}{fK_{3p}} \tag{3}$$

where K is the slope of the measured cross section in the energy range $21 < E \leqslant 25$ eV and K_{3p} the slope of the cross section for ejection of the 3p electron from the metastable ion, the product fK_{3p} being measured directly in the energy range $14.2 < E < 18.8$ eV. The slopes K_g and K_m refer respectively to the ground-state ion cross section and to the sum of the cross sections for ejection for 3p and 3s electrons from the metastable ion. Using the scaling described in equation (2) it is possible to express the ratio as

$$R = \frac{(1-f)K_g + \frac{1}{2}fK_g[(\chi_{3s^2}/\chi_{3p})^3 + (\chi_{3s^2}/\chi_{3s})^3]}{\frac{1}{2}fK_g(\chi_{3s^2}/\chi_{3p})^3} \tag{4}$$

and this yields a value $f \simeq 8.7\%$.

The ground-state cross section, $Q_g(E)$, is determined using equations (1), (2) and (4) and the derived data points are plotted in figure 2 where a smooth curve A has been drawn through the points; the results taken from this curve are listed in table 1. The derived ground-state curve is also shown by curve A in figure 1 so that the magnitude of the adjustment, $\delta Q(E)$, to measured cross section data can be observed;

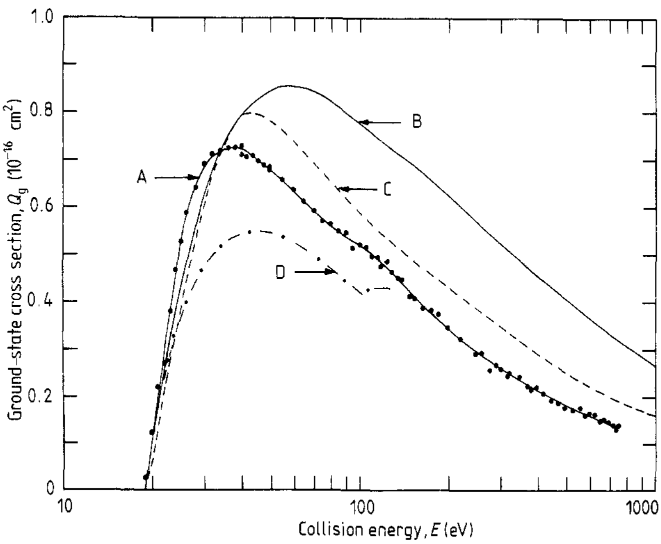

Figure 2. The ground-state cross section. The data points for $Q_g(E)$ are derived from the measured cross section $Q(E)$ and a smooth curve A is drawn through these points. The random errors in $Q_g(E)$ are determined by the deviation of the points from curve A. Curve B is the Lötz (1968) cross section, Curve C that obtained using the McGuire (1977) scaling procedure and Curve D is a Coulomb–Born-exchange calculation of Moores *et al* (1980).

Table 1. The derived ground-state cross section $Q_g(E)$ taken from a smooth curve fitted through the adjusted data points.

Mean electron energy† E (eV)	Derived ground-state cross section Q_g (10^{-16} cm^2)	Adjustment to measured Q δQ (10^{16} cm^2)	Compound error in Q_g‡ E_g (±% of Q_g)
19	0.015	−0.050	58.5
20	0.120	−0.037	7.7
21	0.212	−0.041	5.2
22	0.300	+0.001	4.5
23	0.388	−0.017	4.3
24	0.466	−0.025	4.1
25	0.530	−0.017	4.0
26	0.587	−0.020	4.0
28	0.652	−0.007	4.0
30	0.688	−0.018	3.9
32	0.707	−0.018	3.9
34	0.721	−0.011	3.9
36	0.727	−0.013	3.9
38	0.727	−0.013	3.9
40	0.725	−0.015	3.9
42	0.717	−0.003	3.9
45	0.707	−0.010	3.9
50	0.682	−0.015	3.9
55	0.657	−0.013	4.0
60	0.635	−0.014	4.0
70	0.593	−0.009	4.0
80	0.562	−0.013	4.0
90	0.538	−0.019	4.0
100	0.522	−0.004	4.0
110	0.503	+0.001	4.0
120	0.482	0.000	4.1
130	0.461	−0.008	4.1
150	0.420	0.000	4.2
170	0.387	−0.007	4.2
200	0.345	−0.004	4.3
220	0.323	−0.003	4.4
230	0.312	−0.008	4.4
250	0.296	+0.003	4.5
260	0.288	−0.008	4.5
280	0.275	−0.005	4.6
300	0.262	+0.001	4.7
350	0.236	−0.009	4.9
400	0.214	−0.009	5.0
450	0.197	+0.004	5.2
500	0.182	+0.003	5.4
550	0.172	−0.006	5.6
600	0.161	−0.004	5.8
650	0.152	+0.002	6.0
660	0.150	−0.001	6.1
700	0.144	−0.003	6.2
750	0.137	−0.003	6.4

† ±0.5 eV.
‡ 90% confidence limits obtained using equation (5).

this amounts to about 2.0% at the peak and decreases to less than 1% at the highest energies studied; $\delta Q(E)$ is also listed in table 1. It is difficult to quantify errors introduced by this procedure: a maximum uncertainty of $\pm 0.2f$ in determination of the metastable component is probably realistic so that the corresponding uncertainties in $Q_g(E)$ are likely to be less than $\pm 1\%$ at $E > 24$ eV. The possible error is of course greater at low energies, for example at 20 eV it would be as high as $\pm 6.0\%$.

The random errors quoted here for the derived cross section $Q_g(E)$ are determined by the deviation of the adjusted data points from the smooth curve A. These errors appear to be independent of the magnitude of the cross section and their 90% confidence limit is $\pm 7 \times 10^{-19}$ cm^2 irrespective of electron energy. This random error is compounded in quadrature with the systematic calibration error ($\pm 3.8\%$) to yield the compound error, $E_g(E)$, in the derived ground-state cross section,

$$E_g(E) = \pm\left[0.038^2 + \left(\frac{7 \times 10^{-19}}{Q_g(E)}\right)^2\right]^{1/2} \times 100 \qquad (\%) \qquad (5)$$

and this is also listed in table 1. It will be noted that this compound error generally exceeds the likely uncertainties arising from the adjustment applied to the measured data in order to account for the metastable ion component in the Al^+ beam.

The semi-empirical formula of Lötz (1968) is frequently used to provide ionisation cross section data for plasma modelling. Curve B of figure 2 shows the ground-state cross section predicted by Lötz for both outer- and inner-shell ionisation (i.e., for the $3s^2$ and $2s+2p$ configurations). It is apparent that the Lotz prediction is in rather poor agreement with the experimental data; its peak occurs at a higher energy and the magnitude is appreciably greater at energies in excess of 35 eV. Bell *et al* (1982) have compared the Lötz prediction with both experimental and theoretical cross sections for many of the light atoms and ions. In general, the agreement is much better than in the present case. Indeed the present inadequacies of the Lötz formula precluded its application for the estimation of the metastable component of the Al^+ beam.

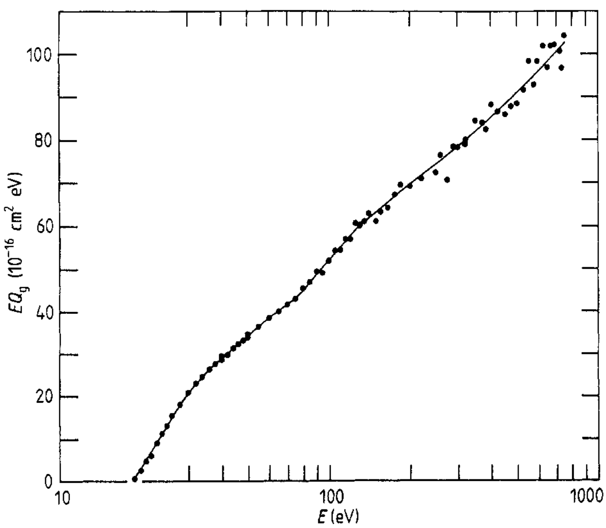

Figure 3. Bethe plot of $EQ_g(E)$ against $\log E$.

Curve C shows the ground-state cross section (outer shell plus inner 2p shell) which has been estimated by applying the scaled-Born procedure of McGuire (1977). This predicted cross section is in closer agreement but its magnitude is also greater at energies above 35 eV. A Coulomb–Born-exchange calculation of Moores *et al* (1980) is shown by curve D; the shape of the ground-state cross section, which also includes contributions from the 2p inner shell, is in somewhat better agreement with the present experiment although the magnitude is smaller.

A Bethe plot of the derived ground-state cross section $Q_g(E)$ is presented in figure 3. The change in slope which is apparent at about 90 eV might be attributed to the onset of inner-shell ionisation but the causes of variation in slope above this energy have not been identified.

Acknowledgments

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