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

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Abstract. The cross section for the ionisation process $e + Ni^+ \rightarrow 2e + Ni^{2+}$ has been measured for electron energies from threshold up to 780 eV using the electron-ion beams technique. The total error at a 90% confidence level is estimated to be ±5% for energies greater than 18 eV. There is evidence that the target ion beam contained a substantial fraction of ^4F and ^2F metastable ions as well as ^2D ground-state ions. However, since the ions were produced in a sputter ion source, the measured cross section is directly relevant to ionisation of Ni^+ ions sputtered from the walls of the fusion plasma device. The semi-empirical formula of Lotz grossly overestimates the cross section, whereas the scaled Born cross section of McGuire is reasonably accurate at energies above 60 eV.

1. Introduction

Nickel is a major constituent of stainless steel and other alloys, such as Inconel, currently used in the construction of plasma containment vessels in fusion research. For quantitative modelling of fusion plasmas it is necessary to have accurate ionisation cross section data for all relevant neutral and ionised elements, which include those sputtered from the internal structure of the containment vessel. In a continuing programme of studies to obtain these data, the crossed fast beams technique is used at Culham Laboratory to measure the electron impact ionisation cross sections of atoms and ions likely to occur as impurities in a fusion plasma. Reported measurements from this programme at present include the cross sections for the singly charged ions of aluminium, iron and tungsten (see Montague and Harrison 1983, 1984, Montague *et al* 1984a). In each of these cases there are significant departures from the predictions of Lotz (1969) and McGuire (1977). Further measurements on the singly and doubly charged titanium ions are currently in progress. In this paper we report an absolute measurement of the cross section for the process

$$e + Ni^+ \rightarrow 2e + Ni^{2+}$$

over the energy range from threshold to 780 eV.

2. Experimental technique

The crossed beams apparatus and the experimental procedures used have been described briefly by Montague and Harrison (1983) for their measurements on Al^+

ions and in more detail by Montague *et al* (1984b) in their report on the measurement of the ionisation cross section of ground-state helium atoms. The data were obtained using a 2 keV beam of singly-charged $^{60}Ni^{+}$ ions with a typical intensity of 4×10^{-10} A and an electron beam energy that was varied between 12 and 780 eV. The product Ni^{2+} ions were detected with an electron multiplier operating with an efficiency of 0.43 for the duration of the experiment. At the peak of the cross section (90 eV) an electron current of 150 μA (averaged over the duty cycle of the electron pulses) gave a signal count rate of Ni^{2+} ions of typically 64 s^{-1}. The extraneous flux of Ni^{2+} ions produced by stripping the target Ni^{+} ions on surfaces and in residual gas was less than 2% of the electron impact ionisation signal.

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 smaller than the plotted points. The overall systematic error is compounded from the same sources as previously reported by Montague *et al* (1984a) and is ±4.0% at a 90% confidence level. Table 1 lists the values of the cross section Q taken from a smooth curve drawn through the measured experimental points of figure 1. The total error in Q is compounded from the overall systematic error and an error computed from the deviations of the experimental points from the smooth curve.

The near-threshold ionisation data presented in figure 2 show thresholds at about 16.5 and 18 eV. We interpret the first of these as due to the thresholds for ionisation of the ^2F and ^4F metastable states (at 16.5 and 17.1 eV respectively) and the second as the threshold for ionisation for the ^2D ground state (18.2 eV). In seems likely that

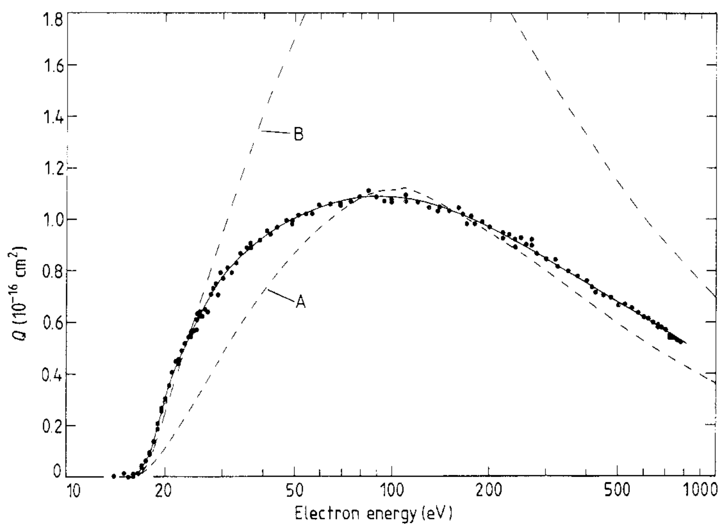

Figure 1. The ionisation cross section of Ni^{+} as a function of electron energy. The plotted points are the experimental measurements and the full curve is the best-fit line through these points. The cross section values in table 1 are obtained from this line. Curve A is computed using the scaled Born approximation of McGuire (1977) and curve B is obtained from the empirical formula of Lotz (1969) (see text for details).

Table 1. Measured cross section for electron impact ionisation on Ni^+ ions taken from a smooth curve drawn through the experimental points

Mean electron energy E (eV)†	Measured cross section $Q(E)$ (10^{-16} cm^2)	Total error in Q (±%)‡	Mean electron energy E (eV)†	Measured cross section $Q(E)$ (10^{-16} cm^2)	Total error in Q (±%)‡
15.5	0.001	560	55	1.028	5.0
16	0.004	180	60	1.048	5.0
16.5	0.011	26	65	1.062	5.0
17	0.035	7.5	70	1.072	5.0
17.5	0.057	5.4	75	1.080	5.0
18	0.090	5.4	80	1.085	5.0
18.5	0.137	5.0	90	1.087	5.0
19	0.198	5.0	100	1.086	5.0
20	0.300	5.0	110	1.079	5.0
21	0.398	5.0	120	1.070	5.0
22	0.450	5.0	130	1.060	5.0
23	0.507	5.0	150	1.034	5.0
24	0.555	5.0	175	1.000	5.0
25	0.603	5.0	200	0.966	5.0
26	0.645	5.0	225	0.933	5.0
27	0.685	5.0	250	0.902	5.0
28	0.718	5.0	300	0.843	5.0
29	0.750	5.0	350	0.793	5.0
30	0.776	5.0	400	0.749	5.0
31	0.800	5.0	450	0.710	5.0
32	0.820	5.0	500	0.677	5.0
34	0.856	5.0	550	0.646	5.0
36	0.884	5.0	600	0.617	5.0
38	0.907	5.0	650	0.592	5.0
40	0.931	5.0	700	0.567	5.0
42	0.950	5.0	750	0.545	5.0
45	0.974	5.0	780	0.531	5.0
50	1.005	5.0			

† ±1.0 eV.

‡ 90% confidence limits. This error is a combination of systematic and random errors.

the Ni^+ target beam will contain ions mainly in the $3d^9(^2D)$ ground state and the $3d^84s(^4F)$ and $3d^84s(^2F)$ metastable states because these are the only states accessible by direct removal of an electron from the $3d^84s^2(^3F)$ ground state of the Ni atom and the $3d^94s(^3D)$ metastable state at 0.1 eV, which is also likely to be populated in the ion source. There are many other low-lying metastable states of Ni^+ (e.g. ^2D, ^4P, ^2P and ^2G), but significant concentrations in the beam would require the less-likely presence of ^1D, ^1S, ^3P and ^1G atoms in the source.

The most probable direct processes forming Ni^{2+} ions from the mixed-state target Ni^+ beam are

$$3d^9\,{}^2D \to 3d^8\,{}^3F \qquad \text{(threshold 18.2 eV)}$$

$$3d^8(^3F)4s\,{}^4F \to 3d^8\,{}^3F \qquad \text{(threshold 17.1 eV)}$$

$$3d^8(^3F)4s\,{}^2F \to 3d^8\,{}^3F \qquad \text{(threshold 16.5 eV).}$$

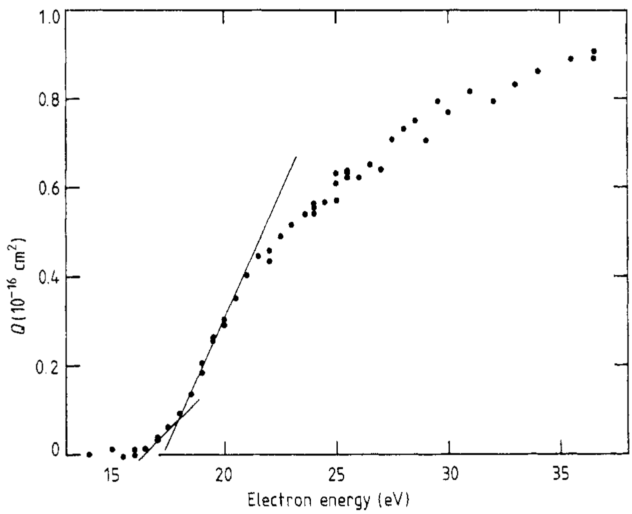

Figure 2. The measured ionisation cross section of Ni^+ in the near-threshold region. The lowest threshold at about 16.5 eV is interpreted as being due to the presence of ^2F and ^4F metastable ions whereas the second threshold at about 18 eV is due to ^2D ground-state ions. The electron energy scale is obtained by subtracting a contact potential of 3.0 V from the measured cathode potential.

In addition the most probable inner-shell ionisation processes are

$$3d^8(^3F)4s\ ^4F \rightarrow 3d^7(^4P)4s\ ^5P \qquad \text{(threshold 25.9 eV)}$$

$$3d^8(^3F)4s\ ^2F \rightarrow 3d^7(^4P)4s\ ^3P \qquad \text{(threshold 26.3 eV).}$$

Autoionisation via excitation of a 3p electron may occur at a much higher energy. Such autoionising states occur above about 65 eV.

We are not able to identify positively the composition of the target beam nor the contributing ionisation processes, but the measured cross section is of practical relevance because the impurity ions in a fusion plasma are formed in a similar manner to those extracted from the sputter ion source used for these measurements.

In figure 1 we also show for comparison cross sections calculated using McGuire's (1977) formulation (curve A) and Lotz' (1969) semi-empirical method (curve B). In both cases the calculations are made for the ejection of 4s, 3d and 3p electrons and the populations of the initial Ni^+ states are taken to be the ratio of their statistical weights (i.e. $[^2D]:[^4F]:[^2F]=5:9:5$). The McGuire calculation as usual underestimates the cross section at most energies, particularly below 60 eV. Neither formulation includes any allowance for excitation-autoionisation but in this case the omission cannot account for the low-energy discrepancy of the McGuire calculation because the threshold energy for this process is so high. By means of the formula of Burgess and Chidichimo (1983), we estimate that excitation-autoionisation and direct ionisation of 3p electrons account for less than 12% of the total ionisation at energies up to 1000 eV.

The Lotz formula overestimates the cross section and shifts the peak to a higher energy than the experimental results. The good agreement at low energies is fortuitous. The discrepancies of this formula and the McGuire result are remarkably similar to the case of Fe^+ reported previously (Montague *et al* 1984a).

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