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A measurement of the cross section for electron impact ionisation of singly charged tungsten ions

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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 $e + W^+ \rightarrow 2e + W^{2+}$ at energies ranging from below threshold up to 750 eV. The compounded random and systematic errors are estimated to be less than about 5% at energies in excess of 18 eV. The W^+ ions are probably mainly in the ^6D ground state but with a significant fraction in the ^4D metastable state. Other metastable ions may account for a few per cent of the total. Comparison of the present data with the scaled Born prediction of McGuire taking into account both 6s outer electrons and 5d inner-shell electrons shows quite good agreement above about 50 eV, but the theory seriously underestimates the cross section at lower energies. The measured ionisation threshold for the ground-state ion is 16.1 ± 1.0 eV, compared with the 17.7 eV given by Finkelnburg and Humbach from a study of screening constants. There are no other known measurements of the ionisation threshold.

1. Introduction

This paper presents results of a measurement of the cross section for electron impact ionisation of the tungsten ion W^+ to form W^{2+}. The work forms part of a study of impurity elements likely to be encountered in fusion research reactors.

2. Experimental technique

Both the crossed-beam apparatus and the procedure used for this investigation have been described previously by Montague and Harrison (1983). In this particular study the energy of the W^+ target beam (mass number 184) was 2 keV (limited by the available magnetic-field intensity) and the target beam current was typically 4×10^{-10} A. The W^{2+} product ions were detected with an efficiency of 0.56 which remained stable throughout the measurement. The electron beam energy was varied between 12 and 750 eV. At the peak of the cross section a typical electron beam current of 150 μA gave rise to a W^{2+} ion signal of 300 counts/s. The extraneous flux of W^{2+} ions produced by stripping of the target W^+ ions at surfaces and in residual gas, was less than 1% of the electron impact ionisation signal.

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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 at energies less than 18 eV are less than about $\pm 2 \times 10^{-18}$ cm^2, which is too small to show in the figure. At higher energies they are typically less than ±2%. Systematic errors are the same as reported previously (i.e. ±4.0% at a 90% confidence level, see Montague *et al* 1984). A smooth curve is drawn through the experimental points and the values of the cross section Q are taken from this curve and listed in table 1. The total error in Q is compounded from the overall systematic error and the deviations of the experimental points from the curve.

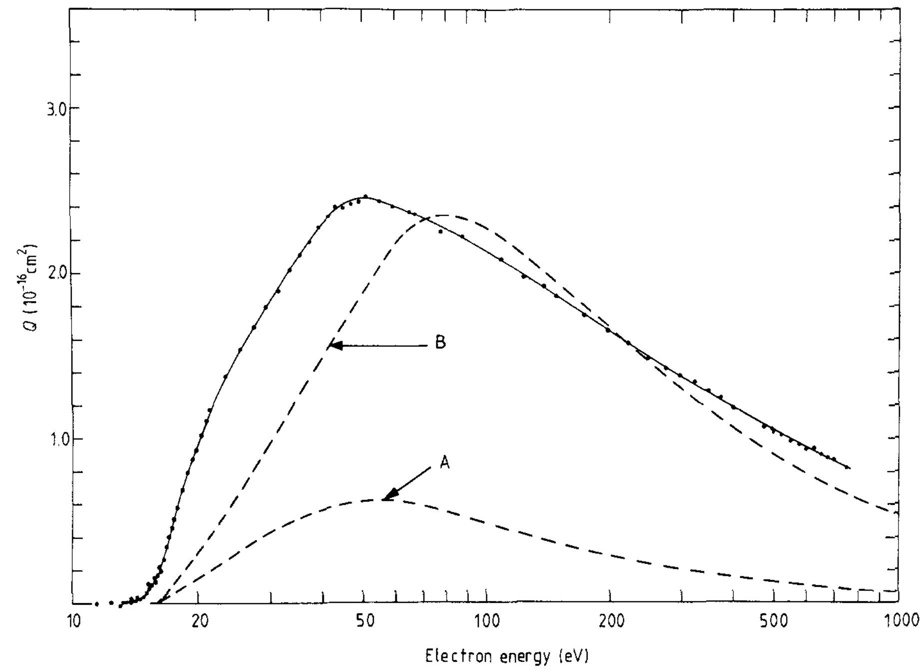

Figure 1. The measured ionisation cross section (Q) for $W^+ \rightarrow W^{2+}$ plotted against electron energy with a smooth curve drawn through the data points. Curve A is the outer-shell ionisation cross section calculated using the McGuire (1979) scaled cross section for the 6s atomic subshell. Curve B is a similar calculation including contributions from the 5d inner-shell electrons.

The ground-state configuration of W^+ is $(5d^4 6s)^6D$ and, in analogy with the $(3d^6 4s)^6D$ ground state of Fe^+ (see discussion by Montague *et al* 1984), it is to be expected that the W^+ beam must contain a substantial component of $(5d^4 6s)^4D$ metastable W^+ ions and probably lesser concentrations of other metastable or long-lived states. Unfortunately there are strong departures from *LS* coupling for this complicated ion, the term designations are very uncertain, and an accurate spectroscopically determined ionisation energy for the ground state is not available (see Moore 1958). Indeed the only pointer to the likely ionisation threshold is the interpolated value of 17.7 ± 0.5 eV provided by Finkelnburg and Humbach (1955) from a study of screening

Table 1. Measured cross section for electron impact ionisation of W^+ ions 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 (±%)‡
13.5	0.01	200.0	55	2.45	4.2
14	0.02	100.0	60	2.41	4.2
14.5	0.03	66.8	65	2.37	4.2
15	0.05	40.2	70	2.34	4.2
15.5	0.10	20.4	75	2.30	4.2
16	0.16	13.1	80	2.27	4.2
16.5	0.25	8.9	85	2.23	4.2
17	0.37	6.7	90	2.20	4.2
17.5	0.50	5.7	95	2.17	4.2
18	0.62	5.1	100	2.14	4.2
18.5	0.72	4.9	110	2.07	4.2
19	0.81	4.7	120	2.01	4.2
20	0.97	4.5	130	1.96	4.2
21	1.10	4.2	150	1.86	4.2
22	1.23	4.2	170	1.77	4.2
23	1.33	4.2	200	1.65	4.2
24	1.43	4.2	220	1.59	4.2
25	1.51	4.2	230	1.56	4.2
26	1.59	4.2	250	1.50	4.2
27	1.66	4.2	270	1.45	4.2
28	1.72	4.2	300	1.38	4.2
29	1.78	4.2	350	1.28	4.2
30	1.84	4.2	400	1.19	4.2
31	1.89	4.2	450	1.12	4.2
32	1.95	4.2	500	1.05	4.2
33	2.00	4.2	550	1.00	4.2
34	2.05	4.2	600	0.95	4.2
35	2.10	4.2	650	0.90	4.2
36	2.15	4.2	700	0.87	4.2
37	2.19	4.2	750	0.83	4.2
38	2.23	4.2			
39	2.27	4.2			
40	2.30	4.2			
41	2.33	4.2			
42	2.35	4.2			
43	2.38	4.2			
44	2.40	4.2			
45	2.42	4.2			
46	2.43	4.2			
47	2.44	4.2			
48	2.45	4.2			
49	2.45	4.2			
50	2.46	4.2			
52	2.46	4.2			

† ±1.0 eV.
‡ 90% confidence limits.

constants. The near-threshold ionisation data are presented in figure 2 where the electron beam energy scale is based upon a contact potential of -1.65 V which was derived from the onset of the Ne^{2+} ionisation signal measured using a Ne^{+} beam. These data, which are shown in figure 3, were obtained immediately before and after the W^{+} measurements.

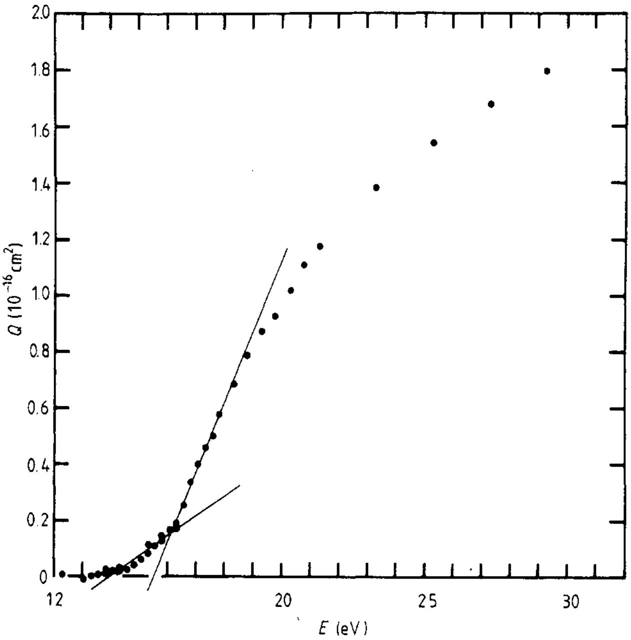

Figure 2. The measured ionisation cross section (Q) for $W^{+} \rightarrow W^{2+}$ in the near-threshold region plotted against electron energy (E).

The data presented in figure 2 show a strong threshold at 16.1 eV and a weaker threshold at about 14 eV which we interpret as the thresholds for the ^{6}D ground state and ^{4}D metastable state. We conclude that the measured threshold for ionisation of ground-state W^{+} differs significantly from the prediction of Finkelnburg and Humbach and that a better value is 16.1 ± 1.0 eV. The spread in the electron beam energy and the uncertainty of the interpretation do not allow a better accuracy to be claimed. It is not possible to identify the individual ionisation components from other excited W^{+} ions, but as in the case of Fe^{+} we can argue that (i) it is unlikely that these excited ions influence the magnitude of the measured cross section at electron energies in excess of about 30 eV, and (ii) the low-energy data are strongly related to sputtered tungsten in a fusion device.

The cross sections for ground-state W^{+} calculated using the scaled cross sections for atomic subshells (McGuire 1979) for the outer shell (curve A) and the outer-plus-inner shell (curve B) are shown in figure 1. The calculation underestimates the measured cross section at energies below about 50 eV but it is in fair agreement at higher energies up to 750 eV. This underestimation at low energies appears to be characteristic of this model, but could be due to strong autoionisation through promotion of inner-shell electrons (for example the 5p electrons).

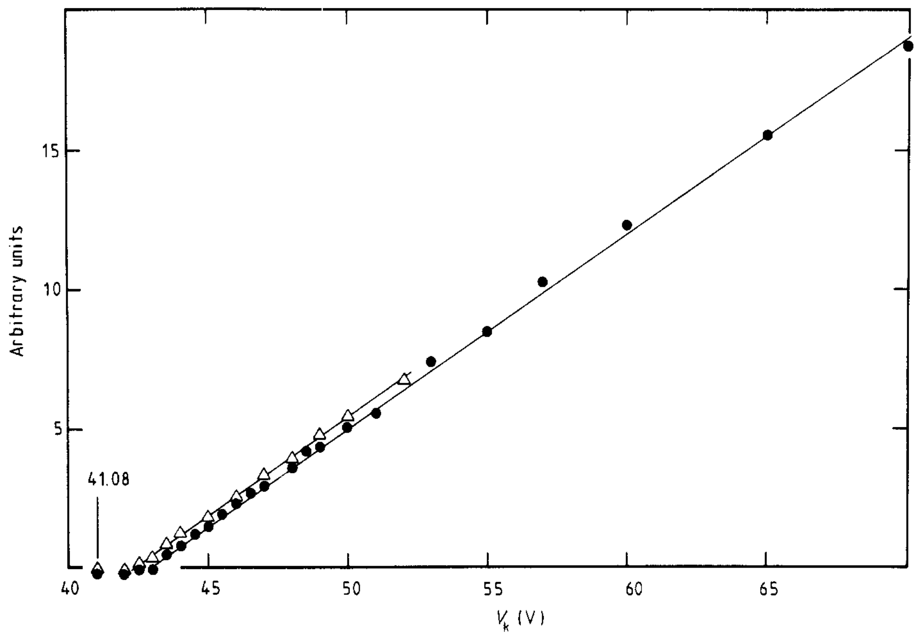

Figure 3. The onset of ionisation of Ne^+. The ionisation signal is plotted against the cathode potential (V_k) of the electron gun. The ionisation energy of Ne^+ is 41.08 eV, which indicates that the contact potential is −1.65 V. These data were obtained just before (●) and just after (△) the W^+ data shown in figure 2.

The McGuire calculation shows that a substantial component of inner-shell ionisation is to be expected at energies not much above the ground-state threshold. There is no experimental indication of the onset of inner-shell ionisation but, as was argued for Fe^+, the threshold may be obscured by progressive contributions from a number of low-lying states of W^+.

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