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A measurement of the cross section for electron impact ionisation of Ne^+, Ar^+, Kr^+ and Xe^+

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Abstract. The crossed electron-ion beams technique has been used to measure the absolute cross sections for the single ionisation of Ne^+, Ar^+, Kr^+ and Xe^+ ions at electron energies ranging from the ionisation threshold to 2000 eV. The total error in the cross sections at a 90% confidence level is estimated to be ±5% or less at energies more than a few eV above threshold. In contrast to some previous measurements, the metastable contents of the ion beams are negligible except in the case of Xe^+. The cross section curves for Ar^+, Kr^+ and Xe^+ show significant contributions from excitation-autoionisation and possibly direct ionisation of inner-shell electrons. The present results for Ne^+ and Ar^+ are in excellent agreement with those previously measured in our laboratory. Good agreement is also obtained with the more recent data from the Giessen group for Ne^+, Ar^+ and Xe^+. Comparisons with theoretical calculations show that the scaled Born approximation of McGuire tends to underestimate the cross sections at all energies, but especially at low energies. The semi-empirical formula of Lotz also underestimates the cross sections at low energies. Comparisons are made with other available experimental and theoretical calculations.

1. Introduction

The process of electron impact ionisation of rare-gas ions is not only fundamental to the understanding of collision mechanisms but also has direct applications in astrophysics, atmospheric physics and laboratory plasma physics. The need for a more detailed understanding of the underlying processes within plasmas intended for controlled thermonuclear fusion has accelerated the study of ionisation processes, both theoretically and experimentally. Accurate modelling of plasmas requires reliable cross section data for electron impact ionisation of the impurity ions which are likely to occur in the plasma, including the ions of neon and argon which can be introduced to control the temperature in the boundary region. Krypton gas may also be used in the next generation of Tokamak machines for the same purpose. Therefore, a reliable set of cross section measurements for rare-gas ions is required. The present series of measurements lies within a general programme of acquiring atomic collision data for fusion research.

The ionisation cross section of Ne^+ has previously been measured in this laboratory, first by Dolder *et al* (1963) using the pioneering crossed electron-ion beams technique, and recently repeated by Diserens *et al* (1984) with the same, but much improved, apparatus. The latter cross section is 6% greater than the former near the peak, which is well within the combined error of the two measurements. The Ne^+ cross section has also been measured by the Giessen group (Müller *et al* 1980), but their values are some 20% smaller than those of Diserens *et al.* A more recent measurement by the same group (Achenbach *et al* 1984) using a modified technique shows excellent agreement with the data of Diserens *et al.* As we shall see in § 3.1, the present data are also in excellent agreement with those of Diserens *et al* and Achenbach *et al*, thus confirming the consistency of measurements with the apparatus in its present form.

The ionisation cross section of Ar^+ has also been measured previously in this laboratory (Woodruff *et al* 1978) and elsewhere (Hasted and Awad 1972, Müller *et al* 1980, Müller *et al* 1985), although in all cases over a smaller energy range. Both the more recent data from the Giessen group (Müller *et al* 1985) and our earlier data (Woodruff *et al* 1978) are in excellent agreement with each other and with the present data, but an additional small feature at about 200 eV is now revealed. A plausible explanation of this feature is discussed in § 3.2.

No absolute cross section for electron impact single ionisation of Kr^+ has previously been published. Only relative cross sections as a function of different populations of excited ions in the source have been reported by Latypov and Kupriyanov (1968). However, absolute measurements for single and double ionisation of multiply charged Kr ions (Kr^{2+}, Kr^{3+}, Kr^{4+}) have been made (Gregory *et al* 1983, Gregory 1985, Pindzola *et al* 1984). The present measurements thus complete this ion series.

Two previous measurements of the cross section for Xe^+ have been reported by the Giessen group (Müller *et al* 1980, Achenbach *et al* 1984) using a crossed-beams technique for electron energies ranging from threshold to 830 eV and 700 eV, respectively. Their total errors at the maximum were ±9% and ±11%, respectively, and their values differ by some 30%. Both the shape and the magnitude of the two curves are rather different, particularly in the regions of the maximum. Clearly there is a need to repeat this measurement with a much better absolute accuracy over a wider energy range, as is reported in this paper.

Our previous ionisation measurements on metal ions (Man *et al* 1987a, b, c) have revealed significant contributions to the total ionisation from excitation–autoionisation (in which an inner-shell target electron is excited into an upper level with an energy greater than the next ionisation threshold, and this excited ion then autoionises) and from inner-shell ionisation (in which an electron from an inner shell rather than from the outer shell is removed directly). Such processes are known to dominate increasingly over outer-shell ionisation when the charge state of the ions increases along an isoelectronic sequence (Müller *et al* 1980, Achenbach *et al* 1984, Gregory *et al* 1986). However, as early as 1968 (Peart and Dolder), even the ionisation of some singly charged ions was found to be dominated by inner-shell processes, particularly near the threshold region. It is interesting to examine whether or not inner-shell processes play a significant role in the ionisation or rare-gas ions. Unfortunately most of the ionisation measurements on Ne^+, Ar^+, Kr^+ and Xe^+ so far have been mainly concerned with obtaining an absolute cross section or using the cross section to calibrate apparatus in other measurements. The present data are the first systematic set of measurements made at small energy intervals over the range from threshold to 2000 eV in a search for structures in the cross section curves in an attempt to identify contributions from the different indirect processes mentioned above.

2. Experimental technique

The experiments were performed at the Culham Laboratory using the fast crossed electron-ion beams technique. Both the apparatus and technique used for our measurements are as described briefly in our previous papers (Man *et al* 1987a, b, c) for the measurements on Mo^+, Cr^+ and Ta^+ and in detail by Montague *et al* (1984) in their report on the measurement of the ionisation cross section of ground-state helium atoms. The sputter ion source (described in detail by Man *et al* 1987c), usually used for producing metal ions, was used in the present experiments, but no voltage was applied to the sputter electrode and an appropriate support gas was fed into the arc chamber. The new focusing electron gun was used, as in all of our recent experiments. Further information will be given in another paper by Diserens *et al* (1988).

Data were taken with ion beam energies of 2 and 4 keV, except for Xe^+ which was limited to 2 keV because of the available magnetic field intensity of the mass selecting magnets. Ion current ranged between 9 nA for Xe^+ at 2 keV and 30 nA for Ar^+ at 4 keV. The Ne^{2+}, Ar^{2+}, Kr^{2+} and Xe^{2+} product ions were detected with an electron multiplier (Johnston type MM1) which had measured efficiencies of 0.96 ± 0.02, 0.85 ± 0.02, 0.72 ± 0.02, and 0.65 ± 0.03 at 2 keV and $1.00^{+0.00}_{-0.02}$, $0.99^{+0.01}_{-0.02}$ and 0.92 ± 0.02 at 4 keV, respectively. The cross sections measured at the two ion energies differed by 8, 4 and 0.5%, respectively, for Ne^+, Ar^+ and Kr^+, and these are within the combined error ranges of the measurements. The detector efficiency for Xe^{2+} and the cross section near the peak were repeated at the same energy several weeks later and found to agree to within 1%. The 4 keV data of Ne^+ have been normalised to the 2 keV data for direct comparisons with our previous data (Diserens *et al* 1984) which were also taken at 2 keV. The 2 keV data of Ar^+, on the other hand, have been normalised to the 4 keV data for direct comparisons with our previous 4 keV Ar^+ data (Woodruff *et al* 1978). One must note that these normalisations were only done for convenience; we do not believe that there is any significance in the apparently different cross sections obtained with different ion energies. The 2 and 4 keV Kr^+ and the 2 keV Xe^+ cross sections are presented without normalisation.

The electron beam energy was varied between several eV below the threshold energy and 2000 eV and the maximum electron current used was 400 μA (averaged over the duty cycle of the electron pulses). As examples of the signal and background count rates, for Ne^+ at the peak of the cross section an electron current of 390 μA gave a mean signal count rate of typically 2000 counts/s at 2 keV, and the background count rate arising from interaction of the target beam with the background gas and slit edges was 100 counts/s, giving a signal to background ratio of 200. For Xe^+ at 2 keV, an electron current of 320 μA gave a mean signal count rate of 1100 counts/s and a background count rate of 5 counts/s, giving a signal to background ratio of 220. To minimise any effects due to short-term changes of the product-ion detection efficiency, measurements of the cross section were frequently repeated at a fixed reference energy (usually at 100 eV) and these were used to normalise the cross sections at other energies. Careful measurements were made at these reference energies immediately after measurements of the detection efficiency were made. To make the principal observed thresholds agree with the known ionisation energies of Moore (1971), corrections of between 1 and 2 eV were subtracted from the measured cathode voltage to give the true mean electron energies. The FWHM of the electron beam energy distribution from the type of electron gun and cathode used here has been previously found to be 0.7 eV

(Diserens 1984). The ion beam velocity contributed negligible additions (0.1 eV in the worst case of 4 keV Ne^+) to the collision energy, which was therefore taken to be the mean electron energy.

3. Results and discussions

The present results are shown as the plotted points in figure 1. The open and full circles represent data taken at 4 keV and 2 keV, respectively. The 90% confidence limits due to counting statistics at the peak ranged from 0.1% for 2 keV Ar^+ and 0.9% for 4 keV Ne^+, and they are too small to plot in the figure. A systematic error is introduced into the measurements mainly by uncertainty in the efficiency of the electron multiplier. Sources of systematic errors in measurements using this apparatus are discussed by Montague *et al* (1984). The overall systematic error in the present measurements is estimated to be about ±4% at a 90% confidence level. Tables 1-4 list values of the measured cross sections Q taken from smooth curves drawn through the four sets of experimental data points of figure 1. The total error in Q is compounded by the overall systematic error and an error computed from the deviations of the experimental points from the smooth curve. These errors are shown in the tables as percentages of the total cross sections.

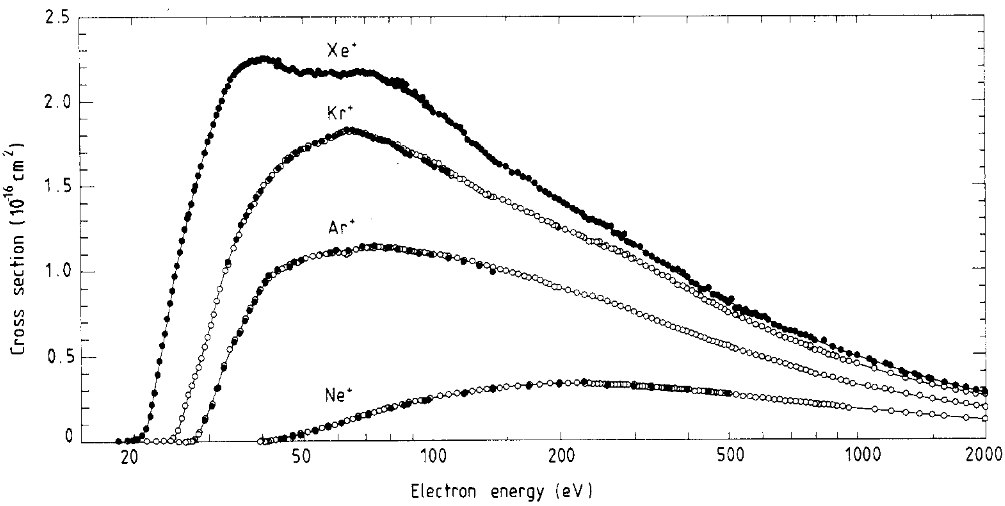

Figure 1. The ionisation cross sections for Ne^+, Ar^+, Kr^+ and Xe^+ as a function of electron energy. The open and full circles represent data taken at ion energies of 4 and 2 keV, respectively. The full curves are the best-fit lines through these experimental points. The cross sections given in tables 1-4 are obtained from these lines.

3.1. *Discussion on* Ne^+

The Ne atoms in the ion source are most probably in the ground state $2p^6\ (^1S)$. Ne^+ ions are therefore most likely to be $2p^5(^2P)$. Since the ^2P state consists of two sublevels, $^2P_{3/2}$ and $^2P_{1/2}$, which are separated by less than 0.1 eV, both these levels are likely to contribute to the ionisation cross section. There are no known metastable states for

Table 1. Measured cross sections for electron impact ionisation of Ne^+ ions taken from smooth curves 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 (±%)‡
42	0.005	20	220	0.334	4.1
43	0.011	15	240	0.331	4.1
44	0.016	15	260	0.328	4.1
46	0.026	10	280	0.323	4.1
48	0.036	10	300	0.319	4.1
50	0.046	5	330	0.311	4.1
52	0.056	5	360	0.304	4.1
54	0.066	5	400	0.293	4.1
56	0.077	4.2	430	0.285	4.1
58	0.088	4.2	460	0.277	4.1
60	0.100	4.2	500	0.267	4.1
65	0.128	4.2	530	0.260	4.1
70	0.152	4.2	560	0.253	4.1
75	0.175	4.1	600	0.245	4.1
80	0.195	4.1	650	0.236	4.1
85	0.213	4.1	700	0.228	4.1
90	0.228	4.1	750	0.219	4.1
95	0.241	4.1	800	0.212	4.1
100	0.252	4.1	850	0.205	4.1
110	0.269	4.1	900	0.199	4.1
120	0.282	4.1	950	0.193	4.1
130	0.294	4.1	1000	0.187	4.1
140	0.305	4.1	1100	0.176	4.1
150	0.313	4.1	1200	0.166	4.1
160	0.320	4.1	1300	0.156	4.1
170	0.325	4.1	1400	0.148	4.1
180	0.329	4.1	1600	0.134	4.1
190	0.332	4.1	1800	0.124	4.1
200	0.334	4.1	2000	0.115	4.1

† ±1.0 eV.
‡ 90% confidence limits. This error is a combination of systematic and random errors.

Ne^+ in the higher levels so that the presence of a significant population of long-lived highly excited levels in the ion source is not expected. Indeed the absence of structure or non-linearity near the threshold of the Ne^+ curve suggests that this is the case. The threshold observed is then expected to be the ground-ground transition $2p^5(^2P^o) \rightarrow 2p^4(^3P)$ with an energy of 41.1 eV (Moore 1971).

The Ne^+ cross section is one of the most frequently measured electron impact ionisation cross sections because of its relative ease of measurement and its extensive application in a wide area of physics (Dolder *et al* 1963, Müller *et al* 1980, Achenbach *et al* 1984, Diserens *et al* 1984). The emphasis of the present Ne^+ measurement is, however, different from previous measurements. It is to establish that data from the present experimental set-up are consistent with those previously measured in this laboratory, especially with the more recent results of Diserens *et al* who used an apparatus much improved compared with that used in the first measurement by Dolder *et al.* The consistency that we have achieved gives us greater confidence in the

Table 2. Measured cross sections for electron impact ionisation of Ar^+ ions taken from smooth curves 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 (±%)‡
28	0.026	12	140	1.016	4.1
28.5	0.068	12	150	0.997	4.1
29	0.100	12	160	0.978	4.1
29.5	0.148	10	170	0.958	4.1
30	0.187	10	180	0.937	4.1
31	0.289	8	190	0.912	4.1
32	0.393	8	200	0.892	4.1
33	0.481	5	210	0.877	4.1
34	0.559	4.5	220	0.862	4.1
35	0.621	4.3	230	0.850	4.1
36	0.683	4.2	240	0.839	4.1
37	0.743	4.1	250	0.826	4.1
38	0.804	4.1	260	0.810	4.1
39	0.855	4.1	280	0.780	4.1
40	0.910	4.1	300	0.750	4.1
42	0.970	4.1	320	0.720	4.1
44	1.010	4.1	340	0.698	4.1
46	1.035	4.1	360	0.670	4.1
48	1.056	4.1	380	0.650	4.1
50	1.071	4.1	400	0.630	4.1
52	1.082	4.1	430	0.602	4.1
54	1.091	4.1	460	0.579	4.1
56	1.099	4.1	500	0.549	4.1
58	1.102	4.1	530	0.528	4.1
60	1.108	4.1	560	0.508	4.1
62	1.111	4.1	600	0.482	4.1
64	1.116	4.1	630	0.467	4.1
66	1.124	4.1	660	0.451	4.1
68	1.131	4.1	700	0.430	4.1
70	1.137	4.1	750	0.407	4.1
72	1.139	4.1	800	0.387	4.1
74	1.140	4.1	850	0.368	4.1
76	1.139	4.1	900	0.351	4.1
78	1.138	4.1	950	0.338	4.1
80	1.134	4.1	1000	0.324	4.1
83	1.130	4.1	1100	0.301	4.1
86	1.123	4.1	1200	0.281	4.1
90	1.118	4.1	1300	0.265	4.1
93	1.111	4.1	1400	0.250	4.1
96	1.106	4.1	1500	0.238	4.1
100	1.099	4.1	1600	0.327	4.1
110	1.079	4.1	1800	0.305	4.1
120	1.057	4.1	2000	0.287	4.1
130	1.036	4.1			

† ±1.0 eV.
‡ 90% confidence limits. This error is a combination of systematic and random errors.

Table 3. Measured cross sections for electron impact ionisation of Kr^+ ions taken from smooth curves 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 (±%)‡
25	0.040	8	110	1.573	4.1
25.5	0.097	7	120	1.520	4.1
26	0.149	6	130	1.472	4.1
27	0.288	5	140	1.432	4.1
28	0.397	4.5	150	1.400	4.1
29	0.513	4.2	160	1.364	4.1
30	0.641	4.1	170	1.332	4.1
31	0.777	4.1	180	1.302	4.1
32	0.911	4.1	190	1.277	4.1
33	1.021	4.1	200	1.251	4.1
34	1.116	4.1	220	1.205	4.1
35	1.202	4.1	240	1.168	4.1
36	1.276	4.1	260	1.131	4.1
37	1.339	4,1	280	1.093	4.1
38	1.394	4.1	300	1.056	4.1
39	1.446	4.1	320	1.020	4.1
40	1.488	4.1	340	0.980	4.1
42	1.557	4.1	360	0.944	4.1
44	1.612	4.1	380	0.911	4.1
46	1.660	4.1	400	0.880	4.1
48	1.693	4.1	430	0.838	4.1
50	1.721	4.1	460	0.800	4.1
52	1.739	4.1	500	0.741	4.1
54	1.754	4.1	530	0.720	4.1
56	1.768	4.1	560	0.691	4.1
58	1.782	4.1	600	0.658	4.1
60	1.800	4.1	650	0.620	4.1
62	1.820	4.1	700	0.586	4.1
64	1.827	4.1	750	0.557	4.1
66	1.827	4.1	800	0.530	4.1
68	1.820	4.1	850	0.508	4.1
70	1.807	4.1	900	0.488	4.1
72	1.796	4.1	950	0.463	4.1
74	1.785	4.1	1000	0.446	4.1
76	1.779	4.1	1100	0.411	4.1
78	1.764	4.1	1200	0.382	4.1
80	1.752	4.1	1300	0.359	4.1
83	1.733	4.1	1400	0.339	4.1
86	1.713	4.1	1500	0.320	4.1
90	1.690	4.1	1600	0.302	4.1
93	1.671	4.1	1800	0.277	4.1
96	1.656	4.1	2000	0.256	4.1
100	1.632	4.1			

† ±1.0 eV.
‡ 90% confidence limits. This error is a combination of systematic and random errors.

Table 4. Measured cross sections for electron impact ionisation of Xe^+ ions taken from smooth curves 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 (±%)‡
20.5	0.022	6	93	2.021	4.1
21	0.047	6	96	1.997	4.1
21.5	0.100	6	100	1.965	4.1
22	0.196	5.5	110	1.882	4.1
22.5	0.348	5.5	120	1.797	4.1
23	0.464	5	130	1.719	4.1
23.5	0.606	4.5	140	1.650	4.1
24	0.716	4.5	145	1.625	4.1
24.5	0.871	4.5	150	1.609	4.1
25	0.967	4.2	160	1.571	4.1
26	1.174	4.1	170	1.528	4.1
27	1.343	4.1	180	1.482	4.1
28	1.505	4.1	190	1.443	4.1
29	1.645	4.1	200	1.409	4.1
30	1.770	4.1	210	1.378	4.1
31	1.881	4.1	220	1.348	4.1
32	1.980	4.1	230	1.315	4.1
33	2.067	4.1	240	1.294	4.1
34	2.132	4.1	250	1.277	4.1
35	2.177	4.1	260	1.253	4.1
36	2.206	4.1	270	1.229	4.1
37	2.223	4.1	280	1.201	4.1
38	2.236	4.1	290	1.172	4.1
39	2.242	4.1	300	1.145	4.1
40	2.245	4.1	320	1.097	4.1
41	2.243	4.1	340	1.055	4.1
42	2.239	4.1	360	1.019	4.1
43	2.227	4.1	380	0.980	4.1
44	2.213	4.1	400	0.946	4.1
46	2.191	4.1	430	0.899	4.1
48	2.180	4.1	460	0.860	4.1
50	2.171	4.1	500	0.812	4.1
52	2.167	4.1	530	0.782	4.1
54	2.162	4.1	560	0.753	4.1
56	2.159	4.1	600	0.719	4.1
58	2.158	4.1	630	0.695	4.1
60	2.158	4.1	660	0.672	4.1
62	2.159	4.1	700	0.643	4.1
64	2.161	4.1	750	0.611	4.1
66	2.168	4.1	800	0.581	4.1
68	2.176	4.1	850	0.557	4.1
70	2.176	4.1	900	0.531	4.1
72	2.171	4.1	1000	0.491	4.1
74	2.161	4.1	1100	0.455	4.1
76	2.147	4.1	1200	0.424	4.1
78	2.130	4.1	1300	0.399	4.1
80	2.115	4.1	1400	0.374	4.1
82	2.107	4.1	1500	0.351	4.1
84	2.096	4.1	1600	0.332	4.1
86	2.078	4.1	1800	0.300	4.1
88	2.061	4.1	2000	0.275	4.1
90	2.046	4.1			

† ±1.0 eV.

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

measurements for Ar^+, Kr^+ and Xe^+, in which greater disagreements have been observed between different sets of measurements than in the case of Ne^+. Furthermore the present data are taken at smaller energy intervals in a search for structures from indirect processes.

In addition to the many experimental measurements there are also many theories which are applicable to Ne^+ (Lotz 1968, Moores 1972, McGuire 1977). Figure 2 shows a comparison between the present measured cross section and the other experimental and theoretical results. The present data are in excellent agreement with those of Diserens *et al* both in shape and magnitude. The slight difference at energies of 110–190 eV and 200–450 eV amounts to no more than 3.5% at the worst, well within the combined error of the measurements. The new data again reveal no structure, thus confirming the consistency of measurements with the apparatus and technique in their present forms. However, there is one slight difference between the two curves; the maximum of the present curve is shifted 10 eV higher in energy than the maximum for both previous measurements in this laboratory (Dolder *et al* 1963, Diserens *et al* 1984). The present data are also 6% greater than those measured by Dolder *et al* near the peak, increasing to 11% at higher energies. The shape of the latter curve is slightly different from the present one, particularly at lower energies. In contrast, the curve of Müller *et al* (1980) is some 20% lower in magnitude at the peak. At higher energies it decreases more rapidly with increasing energy than the present cross section and is

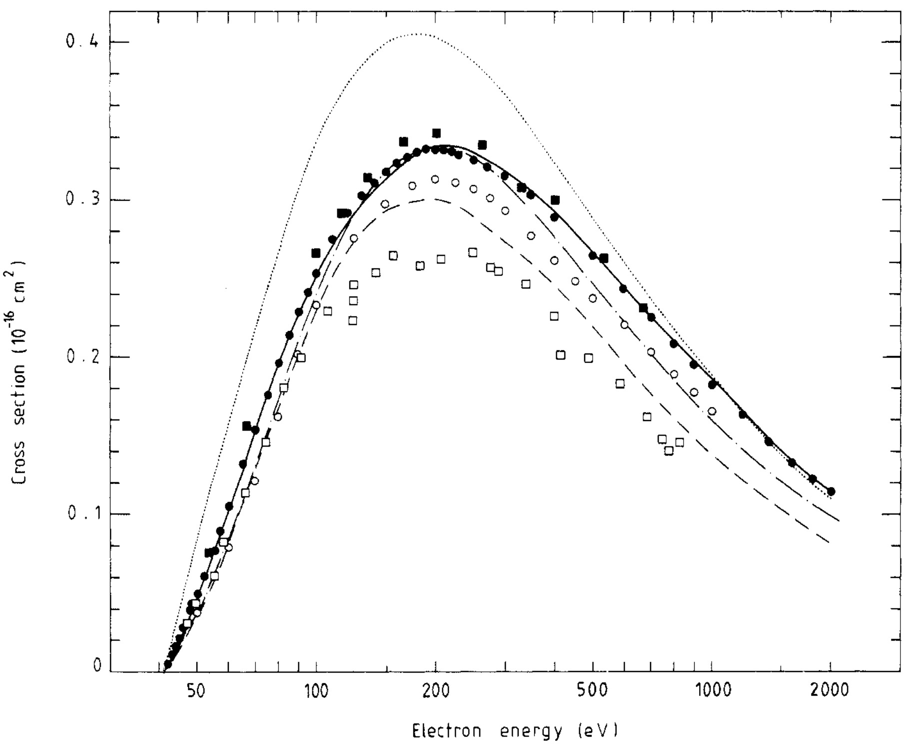

Figure 2. Electron impact ionisation cross section of Ne^+ as a function of electron energy. The present result, ———, is compared with the experimental measurements of Dolder *et al* (1963), ○; Diserens *et al* (1984), ●; Müller *et al* (1980), □; Achenbach *et al* (1984), ■; and the theoretical calculations of Lotz (1969), —·—; Moores (1972), · · · · ; McGuire (1977), - - -, as described in the text.

more than 30% lower at 800 eV. The more recent data from the Giessen group (Achenbach *et al* 1984) using an improved apparatus are generally about 20% greater than those obtained previously from their own group (Müller *et al* 1980). They are in good agreement with the present data, differing by less than 3% at the peak. Their improved apparatus was calibrated using the Ar^+ data of Woodruff *et al* (1978); thus their Ar^+ data necessarily agree with the latter.

Figure 2 also shows three theoretical calculations for Ne^+. The McGuire (1977) cross section calculated using the scaled Born approximation underestimates the cross section at all energies. It is 11% smaller than the present data at 200 eV and 40% lower at 2000 eV and the energy dependence at lower energies is poor, typical of Born approximation calculations. On the other hand, the non-exchange Coulomb–Born approximation of Moores (1972) overestimates the cross section at lower and intermediate energies, particularly below 200 eV, but above 700 eV it is in good agreement with the experimental curve. The Lotz (1968) semi-empirical formula provides the best agreement with experiment at energies around the maximum, but it underestimates the cross section at lower and higher energies.

All these three calculations take into account the contributions from ejection of both 2s and 2p electrons. The contributions were evaluated separately and summed to give the total cross sections. Contributions from the inner 2s electrons at the peak were 13, 12.5 and 24%, respectively, for the three theories outlined in the previous paragraph. Contributions from K-shell ionisation have been neglected because the ionisation energy is some 1000 eV and the contribution is estimated to be less than a fraction of 1%, too small to affect the shape significantly.

3.2. *Discussion on* Ar^+

By analogy with Ne^+, Ar^+ ions in the ion source are also likely to be in the ground state $3p^5(^2P)$. Ar^+, like Ne^+, has no low-lying metastable states and the ionisation threshold for the transition between the Ar^+ and Ar^{2+} ground states, $3p^5(^2P^o) \rightarrow 3p^4(^3P)$ is 27.62 eV. The sharpness of the threshold and the absence of signals below threshold confirm that negligible metastable ions were present in the parent ion beam. Since the core structure of Ar^+ is more complicated than Ne^+, the contribution from the inner electrons is expected to be more significant. This is manifest by unresolved structures in the near-threshold region. There is also strong evidence of structures elsewhere in the curve, particularly near the maximum and at an energy starting around 220 eV. The origin of the enhancement at 74 eV is uncertain, but the enhancement peaking at 250 eV could be due to excitation–autoionisation of inner-shell 2p electrons, although the threshold for this process is expected to be around 250 eV.

Figure 3 shows a comparison between the present data and the other experimental results and theoretical calculations. There is good agreement, particularly at higher energies, between the present data and those of Woodruff *et al* (1978) from our laboratory, showing consistency of results using this apparatus. The discrepancy at the peak and at low energies is well within the combined errors of the measurements. The present data also clearly reproduce the shoulder which peaks at around 45 eV. This may be due to a process involving excitation of a 3s electron followed by autoionisation. The threshold for this process is 27 eV, similar to the threshold for the ground state of Ar^+. Whatever process produces this structure, it seems real and persistent. Even the limited data from Müller *et al* (1980) show some sign of a shoulder

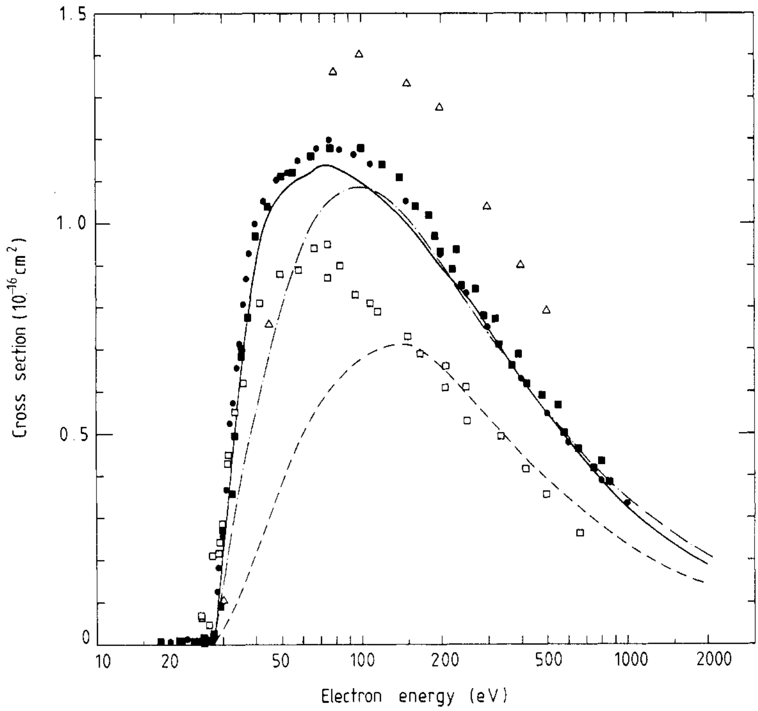

Figure 3. Electron impact ionisation cross section of Ar^+ as a function of electron energy. The present result, ———, is compared with the experimental measurements of Woodruff (1978), ●; Müller *et al* (1980), □; Hasted and Awad (1972), △; Müller *et al* (1985), ■; and the theoretical calculations of Lotz (1968), —·—; McGuire (1977), - - -, as described in the text.

at a similar energy. However, their statistics are not good enough to show the smaller shoulder at around 220 eV. Although the data of Müller *et al* (1980) show some agreement with ours in shape, the magnitude is very much smaller (some 20% smaller at the peak rising to 40% at higher energies). A more recent measurement by the same group (Müller *et al* 1985) using an improved experimental technique based on the 'animated-beam' method shows much better agreement in magnitude with our results than their earlier measurements. But again the scatter in their data is such that no small structures can be unambiguously identified apart from the shoulder around 60 eV. Also shown in the figure are the experimental data of Hasted and Awad (1972) using the trapped-ion mass spectrometry method. Their data were made absolute by normalisation at the peak to the single value of 1.4×10^{-16} cm^2 obtained by Latypov *et al* (1964). The Hasted and Awad measurement for Ar^+ was repeated by Hamdan *et al* (1978) usingthe same technique and agreement was found between them; nonetheless there is considerable disagreement between their data and ours. The disagreement in absolute magnitude is perhaps understandable because of the uncertainty in the calibration, but the disagreement in shape is probably indicative of the doubtful validity of the technique (Holmes 1986).

Figure 3 also shows comparisons of the present data with the calculations of McGuire (1977) and Lotz (1968). We have taken the contributions from all electrons in the four shells, 3p, 3s, 2p and 2s, into consideration in applying the scaled Born approximation of McGuire. The ionisation energies of these shells were taken as 27.6, 41.7, 267 and 340 eV respectively. The ionisation threshold of 3200 eV for the 1s subshell is beyond the measured energy limit and so 1s ionisation does not contribute to the cross section. Despite the inclusion of all the possible terms in the calculation, the McGuire curve shows poor agreement with the present data at all energies. The neglect of Coulomb interactions certainly plays a part in the discrepancy, but neglecting the process of excitation–autoionisation in the calculation may be the major source of discrepancy at low energies. The McGuire curve represents the maximum cross section for the single ionisation process under consideration because, following the creation of an inner-shell hole, an Auger process may occur, leading to multiple ionisation of the target ion. The disagreement with experiment may thus be even worse than shown at the higher energies. The Lotz semi-empirical calculation shown in the figure is calculated for the outer three shells 3p, 3s and 2p. It is in excellent agreement with the present data and with most other experimental measurements at high energies. The neglect of excitation–autoionisation in the calculation is probably also the cause of the discrepancy with the measured cross sections at low energies.

3.3. *Discussion on Kr^+*

The ground state for Kr^+ is $4p^5(^2P^o)$. Again we expect most of the Kr^+ ions to be in this state. Kr^+ is much more complicated than Ne^+ and Ar^+, with more s and p subshells and the additional 3d shell; these shells can be expected to play an important role. The Kr^+ curve in figure 1 shows that there is a very small signal below the threshold energy which indicates the presence of a small fraction of metastable ions in the beam. There are also structures in the curve near the peak and at higher energy. The shape of the curve is very similar to that for Ar^+ although the peak magnitude is 60% larger. The shoulder peaking at around 48 eV is probably caused by excitation–autoionisation or direct ionisation of 4s electrons. The enhancement starting at about 230 eV is probably caused by excitation–autoionisation or direct ionisation of 3p electrons.

Of the four rare-gas ions studied in this paper, Kr^+ has been investigated the least in the past. Relative cross sections as a function of source conditions have been reported by Latypov *et al* (1964) and Latypov and Kupriyanov (1968) using the constant-intensity colliding beam method. In these experiments the Kr^+ ions were produced by bombarding Kr atoms with electrons of energy E_1. The ion beam was accelerated across a potential difference of 2.8 kV and collided with a beam of electrons of energy E_2 to produce Kr^{2+}. By keeping E_2 constant they obtained the dependence of the ionisation cross section for Kr^+ as a function of E_1. A close examination of the measured cross section enabled them to infer the different fractions of various long-lived excited ions in the source since the production of Kr^{2+} is closely related to the conditions of the production of Kr^+. By measuring the cross sections as a function of E_2 at a fixed E_1 for different values of E_1, the shape of the curves can reveal contributions by the various fractions of long-lived excited ions. At $E_1 = 25$ eV, just above the ionisation energy of Kr^+, the Kr^+ beam is expected to contain very few excited ions. The fact that their curve is smooth without structures and that the threshold is at the expected ionisation energy of ground-state Kr^+ indicates that the previous statement is correct. However, as E_1 increases, the ionisation cross section increases and structures near the peak and at higher energies appear because there are increasingly greater fractions of metastable and long-lived excited states in the Kr^+ beam. The ionisation thresholds are also shifted to lower energies.

Without a detailed knowledge of the fraction of the different states of krypton ions in their source or knowledge of the relative magnitudes of the cross sections, it is difficult to compare their results with ours. But by looking only at the shape of the curves one does see a resemblance of their curve at $E_1 = 45.3$ eV with ours (except below the ground-state threshold and above 300 eV where their cross section converges to a limiting value). The negligible cross section below the threshold in our case, indicating the absence of metastable ions, implies that the similarity is fortuitous.

Figure 4 shows a comparison between the present data and the scaled Born approximation calculation of McGuire (1977, 1979). We have included the first five outer shells, 4p, 4s, 3d, 3p and 3s, in the calculation and have taken the ionisation energies to be 24.6, 38, 105, 226 and 304 eV respectively. The calculation underestimates the cross section at all energies, particularly at lower energies where Coulomb effects and excitation–autoionisation are likely to be important but are neglected. We are unable to compare the semi-empirical formula of Lotz (1968) with our Kr^+ data as we did with the Ne^+ and Ar^+ data because Lotz parameters have not been published for ions heavier than Ar^+.

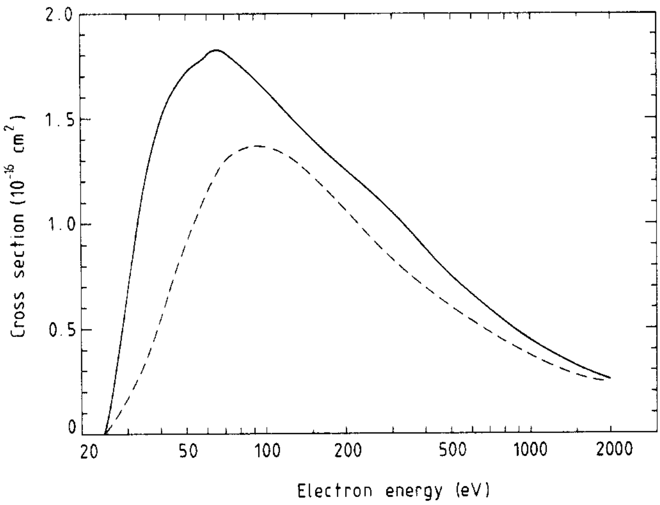

Figure 4. Electron impact ionisation cross section of Kr^+ as a function of electron energy. The present result, ———, is compared with the theoretical calculation of McGuire (1977, 1979), - - -, as described in the text.

3.4. *Discussion on Xe^+*

Xe^+ is the most complicated rare-gas ion studied here. The increased number of subshells enhances the contribution of the inner-shell electrons to the cross section. Although the ground state for Xe^+ is $5p^5$ ($^2P^o$), which is similar to the other rare-gas ions previously considered in this section, in this case it is even more likely for electrons in the other subshells to be ionised because the binding energies of these subshells are smaller. In examining the threshold region of the Xe^+ curve (figure 1), we cannot say that the Xe^+ from the source contains no metastable or long-lived excited states. The main threshold is at 21.2 eV, corresponding to the ground- to ground-state transition, but ionisation actually starts at 20 eV. The present results show a clear double peak in the cross section, with possibly some smaller peaks in between, and further structures occurring at higher energies. The first of the two peaks (at around 40 eV) is probably due to excitation-autoionisation of 5s electrons and the second (at around 70 eV) due to excitation-autoionisation of the 4d electrons. It is not possible to identify all the structures at higher energies, but an enhancement around 260 eV is quite obvious and there seems to be a small enhancement at around 160 eV. The latter is likely to be due to excitation-autoionisation or direct ionisation of 4p electrons and the former to excitation-autoionisaion or direct ionisation of 4s electrons.

There are two previous measurements of the cross section for Xe^+ (Müller *et al* 1980, Achenbach *et al* 1984), both from the Giessen group, which however differ considerably (see figure 5). The latter result is some 30% larger at the peak than their earlier one. In fact the recent measurements of Achenbach *et al* (1984) are consistently some 20-30% larger than the earlier results of Müller *et al* (1980) for all the rare-gas ions (see figures 2 and 3), probably as a result of improved experimental apparatus and technique.

The apparatus used for the cross section measurement of Achenbach *et al* was in fact calibrated using the absolute data of Woodruff *et al* (1978) for Ar^+ from our laboratory. It is therefore not surprising that these results show better agreement with the present results. There is almost perfect agreement between the present measurements and those of Achenbach *et al* above 80 eV; even the structure at 260 eV is

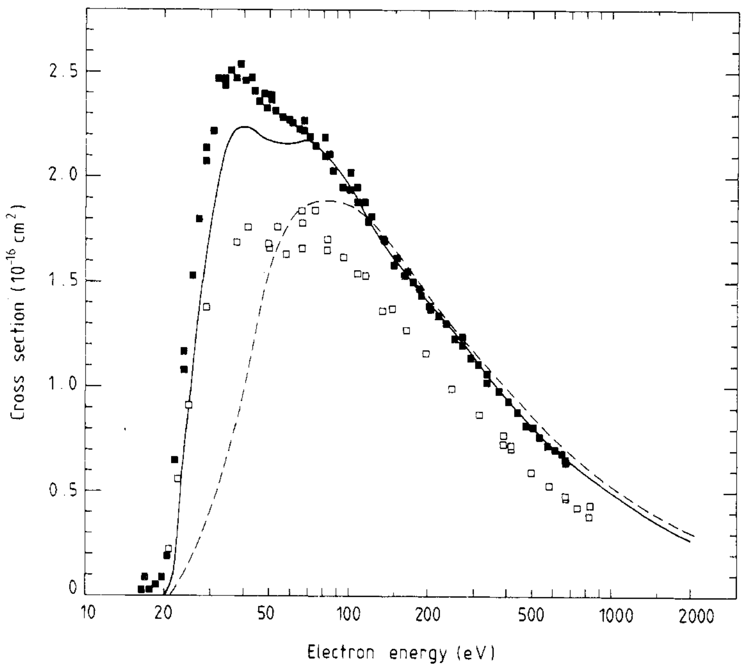

Figure 5. Electron impact ionisation cross section of Xe^+ as a function of electron energy. The present result, ———, is compared with the experimental measurements of Müller *et al* (1980), □; Achenbach *et al* (1984), ■; and the theoretical calculation of McGuire (1977, 1979), - - -, as described in the text.

reproduced. However, at lower energies there are significant differences. The data of Achenbach *et al* do not show the smaller second peak seen in our curve and their first peak is much larger. This could be an indication of different metastable-state populations in the parent Xe^+ beams in the two experiments, in which different types of ion source have been used. A lower threshold than for the ground- to ground-state transition and a non-zero signal below threshold indicate that the Xe^+ ion beam used by Achenbach *et al* contained a greater metastable fraction than ours. Although the cross section of Müller *et al* is significantly lower than ours, it does show a peak corresponding to our second peak.

Figure 5 also shows a comparison between the present data and the scaled Born approximation of McGuire (1977, 1979). We have again included the five outer shells, 5p, 5s, 4d, 4p and 4s, in the calculation and have taken the ionisation potentials to be 21.2, 32, 77, 157 and 220 eV, respectively. The McGuire curve is in good agreement with the experimental data at energies above 120 eV, although slightly larger. Perhaps this is attributable to the fraction of the target ions that are multiply ionised through Auger decay and are thus not detected in our experiment. The agreement is much better for Xe^+ than for Kr^+ because there is a much greater contribution from the 4d electrons in Xe^+, an order of magnitude greater than the contribution from the 3d electrons in Kr^+. There are, however, considerable differences at low energies. These discrepancies are likely to be caused by the fact that excitation–autoionisation was not taken into account in the calculation. No Lotz parameters are available for Xe^+, so a comparison with the Lotz semi-empirical formula is not possible.

4. Summary and conclusion

Measurements on electron impact ionisation of rare-gas ions (figure 1) show that the general magnitude of the cross sections increases with increasing atomic number along the group, in agreement with the expectations from the decreasing ionisation energy of the outer electrons. The cross sections between thresholds and the maxima increase more sharply along the group probably due to greater contributions from excitation–autoionisation of the increasing number of inner-shell electrons and thus the increasing number of autoionising states. A noticeable increase in metastable or long-lived excited states in the ion beam is seen from an increasing ionisation signal below the ionisation energy of the ground-state ions, but the population is seen to be negligible except in the case of Xe^+ where it is no more than a few per cent. Nonetheless this could have a significant effect on the near-threshold region for Xe^+ and could partly account for the sharp rise in the cross section. There are also increasingly more structures on the curves for higher members of the group, especially near the peak and at higher energies. This ranges from no identifiable structure on the Ne^+ curve to a double peak and several unresolved structures for Xe^+. These structures are very likely to be due to direct inner-shell ionisation or indirect inner-shell excitation–autoionisation.

The cross sections for Ne^+ and Ar^+ are in excellent agreement with results previously measured in our laboratory (Dolder *et al* 1963, Diserens *et al* 1984, Woodruff *et al* 1978), indicating the consistency of our measurements (figures 2 and 3). The present measurements are also in good agreement with the more recent results from the Giessen group (Achenbach *et al* 1984, Müller *et al* 1985) taken with an improved apparatus and technique. But the earlier Giessen results, with more scatter in the data, are always 20–30% lower in magnitude. The same situation exists for Xe^+.

The scaled Born approximation calculation of McGuire (1977), which excludes excitation-ionisation, consistently underestimates the cross section at low energies for all ion species studied here. The semi-empirical formula of Lotz (1969) for Ne^+ and Ar^+ similarly underestimates the cross sections for the same reason. It seems for a theory to predict successfully the ionisation cross section of low-charge-state ions that excitation-autoionisation, direct ionisation of inner-subshell electrons and Coulomb effects have to be fully taken into account. The inconsistency of agreement between experiment, theory and the Lotz semi-empirical formula for the low-charge-state ions examined here once again emphasises the need for accurate experimental measurements of such ionisation cross sections. Ionisation measurements of doubly charged rare-gas ions are presently in progress in this laboratory and will be reported in a later paper.

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