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Absolute cross-section measurements for electron impact ionisation of Li-like N^{4+}, O^{5+} and Ne^{7+} ions

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Abstract. Measured cross sections for single ionisation of Li-like N^{4+}, O^{5+} and Ne^{7+} by electron impact are reported for energies from threshold to 2500 eV. The animated crossed beams method has been employed. In addition to direct ionisation, the $1s^22s \rightarrow 1s2l2l'$ excitation followed by autoionisation is shown to give a significant contribution to the total cross section, and its magnitude has been estimated for all three ions. Comparisons are made with other experimental results and different theoretical predictions. Cross sections for N^{4+} and O^{5+} are in a good agreement with previous results and the first result on Ne^{7+} ionisation is well reproduced by the Coulomb-Born calculations

1. Introduction

Electron impact ionisation of ions is a fundamental process in any discharge or plasma. Accurate measurements of total ionisation cross sections can provide valuable information about the various processes involved. Systematic studies, such as those along an isoelectronic sequence, are desirable to aid the continuing effort to develop theory, predictor formulae and the scaling of the cross sections for the direct process and for the indirect contributions.

Electron impact ionisation of the lithium isoelectronic sequence has been extensively studied. Absolute cross section measurements have been published for the first six members of the sequence: by Zapesochnyi and Aleksakhin (1969) and Jalin *et al* (1973) for the lithium atom; by Falk and Dunn (1983) for Be^+ and by Crandall *et al* (1979, 1986), Rinn *et al* (1987) and Müller *et al* (1988) for B^{2+}, C^{3+}, N^{4+} and O^{5+}, using a crossed beams technique. The direct measurements of Ne^{7+} ionisation have not been reported, yet. Using an analysis of the charge state distribution from an EBIS ion source, Donets and Ovsyannikov (1977) have deduced ionisation cross sections for some highly charged ions, including Ne^{7+}, at the high electron energies. Except for the Li atom, for all the ions an abrupt increase of the total cross section is observed at an electron energy of about four times the ionisation threshold. This has been associated with the process of excitation-autoionisation (EA) via $1s2l2l'$ states (Crandall *et al* 1979, 1986). This process has been clearly seen to increase its relative importance with increasing the ionic charge along the sequence.

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From the theoretical point of view the single electron in the outer shell, and the relatively small number of the electrons make the description of ionisation of Li-like ions somewhat simpler. Numerous theoretical predictions have been performed for both direct and indirect ionisation processes. These have been done by Henry (1979), Sampson and Golden (1979), Younger (1980), Jakubowicz and Moores (1981) and Pindzola and Griffin (1987). Comparisons between theory and experimental data, including our measurements, show that the overall shape of the cross section against energy is well reproduced theoretically, as well as the position and magnitude of the indirect EA contribution.

The question has been raised recently about the possible contribution of resonant-excitation-auto-double-ionisation (READI) to the total single ionisation cross section of Li-like ions via $1s2snln'l'$ states. The process was predicted by Henry and Msezane (1982) and discussed by Crandall *et al* (1986). Pindzola and Griffin (1987) predicted its contribution to be less than 1% of the total ionisation cross section for O^{5+} at the resonance energy. Rinn *et al* (1987) did not show clear evidence of this process for O^{5+}, but Müller *et al* (1988) found the first unambigous experimental evidence of READI for C^{3+} ionisation. The process of resonant-excitation-double autoionisation (REDA), proposed by LaGattuta and Hahn (1981) can also contribute to the total ionisation cross section and it cannot be separated from READI in current experiments above the EA onsets.

In this paper we report and discuss in detail new measurements of electron impact ionisation cross sections for N^{4+} (which have been previously presented, Defrance *et al* 1985), O^{5+} and the first direct cross section measurement of Ne^{7+} ionisation.

2. Method and apparatus

These measurements have been performed using an apparatus specially designed to study the ionisation of highly charged ions by electron impact. The animated crossed beams method (Brouillard and Defrance 1983) has been employed. The experimental set-up is schematically shown in figure 1.

The ion beam is extracted from an ECR ion source (not shown on the figure), which is capable of producing beams of ions in charge states as high as $q = 15$ for argon (Jongen and Ryckewaert 1984). The usual acceleration voltage of the ions is of the order of a few keV. Extracted ions are focused by electrostatic and magnetic lens systems before entering the Wien filter (1) for mass and charge analysis. After passing through a pair of vertical and horizontal plane einzel lenses (2) the beam is further purified by a 60° electrostatic deflector (3) and collimated by a set of apertures (4, 5) before entering the collision region. The electron gun (6) is the same as used in previous experiments (Defrance *et al* 1982). In the subsequent 90° magnetic charge state analyser (7) product ions are deflected along an arc with a fixed radius of curvature of 30 cm onto the detection system. A movable Faraday cup (8) is adjusted to collect the primary ion beam. Product ions are directed by an electrostatic deflector (9) to the channelplate (11) detection system. A movable device (10) can be introduced into the beam in order to measure the absolute detector efficiency (Brouillard *et al* 1983).

The electron gun is schematically shown on the inset in figure 1. A ribbon-shaped electron beam is extracted from a Pierce-type cathode (K)-anode (A) configuration. The pair of plates (B) acts simultaneously as a lens and as a beam deflector in the electron beam sweeping mode of the animated crossed beams technique. The electron

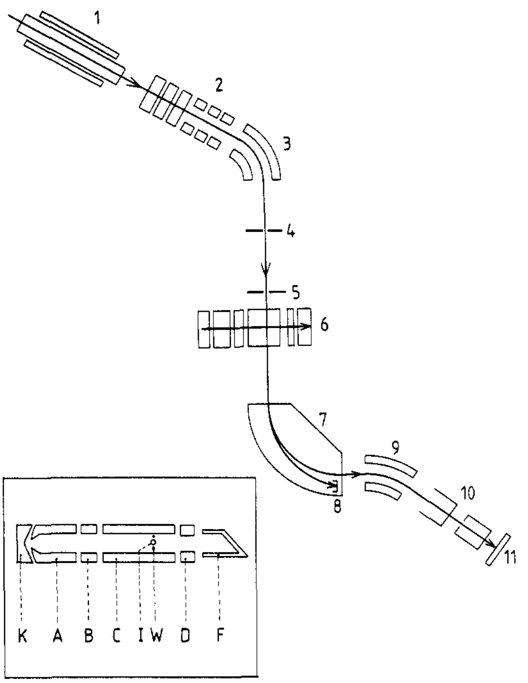

Figure 1. Schematic diagram of the apparatus: 1, Wien filter; 2, electrostatic lenses; 3, electrostatic deflector; 4,5, diaphragms; 6, electron gun; 7, magnetic analyser; 8, movable Faraday cup; 9, electrostatic deflector; 10, moving slit and Faraday cup; 11, detector. The inset shows a schematic diagram of the electron gun: K, cathode; A, anode; B, focusing and deflection electrodes; C, grounded electrodes; I, ion beam; W, two wires parallel to the ion beam; D, suppressors; F, Faraday cup.

beam crosses the ion beam (I) at right angles inside the grounded electrode (C). The electrons are collected in a Faraday cup (F). Suppression plates (D) assure the total beam collection and prevent secondary electrons from interacting with the ion beam.

In the animated crossed beams method, the electron beam is swept across the ion beam in a linear seesaw motion at constant velocity u which is measured by means of two thin wires (W) located on both sides of the ion beam symmetrically, perpendicular to the electron beam trajectory.

3. Cross section measurements

The electron impact ionisation cross section is related to the measured quantities in the following way (Brouillard and Defrance 1983):

$$\sigma = \frac{v_e v_i}{(v_e^2 + v_i^2)^{1/2}} \frac{uK}{(I_i/qe)(I_e/e)}. \tag{1}$$

Here, u is the scanning velocity, K is the total number of events produced during one passage of electrons across the ion beam, v_e and v_i, I_e and I_i, e and qe are the velocities, currents and charges of the electrons and ions, respectively. In order to achieve good precision, careful measurements are needed for all the parameters in equation (1).

3.1. *The electron beam*

The electron energy is corrected for contact potential and the kinetic energy of ions is taken into account to obtain the absolute collision energy. The maximum electron energy is 3 keV. Based on previous experiments, the electron energy spread (full width at half maximum-FWHM) is estimated to be less than 1.7 eV.

The scanning velocity, u, of the electron beam across the ions is determined by measuring the time difference t between successive crossings of the electron beam over the wires (W), for a given amplitude V_1 of the sweeping AC voltage. During the measurements, this amplitude is reduced to a lower value V_2, so that the electron beam does not reach the wires. This procedure eliminates the production of secondary electrons by the wires. The scanning velocity is then given by the ratio:

$$u = dV_2/tV_1. \tag{2}$$

Here $d = 7.9$ mm is the distance between the wires.

3.2. *The ion beam*

The primary ion beam intensity is determined by measuring the current to the magnetic analyser (7). The magnetic field assures total collection of ions and prevents secondary emission of electrons or ions from significantly affecting the measurements. The Faraday cup is placed in position to intercept ions moving along the trajectory with radius

$$R' = R(q+1)/q \tag{3}$$

where R is the main radius of 30 cm. All diaphragms and slits between the collision region and the primary and product ion detectors are dimensioned to ensure an essentially total ion transmission. The total detection efficiency γ is determined by the controlled beam attenuation method (Brouillard *et al* 1983). The signal delivered by the detector is stored in a multichannel analyser which is synchronised with the electron beam sweeping voltage. The primary ion current is integrated over the measurement time in order to eliminate errors due to the beam fluctuations. Typical working conditions in the present experiment are; $I_e = 2$ mA, $I_i = 20$ nA, $K = 0.1$, $u = 40$ cm s^{-1} and $\gamma = 0.61$.

The total systematic uncertainty of the measurements is estimated to be less than 5%. This includes uncertainties due to determination of kinematic parameter (0.5%), beam currents (0.5%), detection efficiency (1.7%) and scanning velocity (1.7%).

4. Results and discussion

The results of the cross section measurements, with electron energy, are listed in table 1 for N^{4+}, table 2 for O^{5+} and table 3 for Ne^{7+}. The errors listed in the tables represent one standard deviation of the counting statistics, only. The results are shown graphically in figures 2, 3 and 4, respectively, and compared with the experimental results of Crandall *et al* (1979), Crandall *et al* (1986), Donets and Ovsyannikov (1977), and with various theoretical predictions.

For the N^{4+} ion ionisation, there is a reasonable agreement between our measurements and the experimental results of Crandall *et al* (1979). However, the shape of the cross section differs slightly: the maximum of the direct ionisation cross section is about 10% higher in our data. The magnitude and the position of the excitation-autoionisation contribution seem to be in a good agreement in these two sets of data.

Table 1. Absolute cross sections for electron-impact ionisation of N^{4+} with energy. The uncertainties are one standard deviation of the counting statistics.

Electron energy (eV)	Cross section (10^{-19} cm^2)	Uncertainty (10^{-19} cm^2)	Electron energy (eV)	Cross section (10^{-19} cm^2)	Uncertainty (10^{-19} cm^2)
90	−0.53	0.49	360	14.25	0.57
96	−0.14	0.27	370	14.20	0.59
100	0.11	0.28	380	14.25	0.56
120	7.60	0.47	400	14.46	0.59
150	11.94	0.89	420	14.92	0.63
180	14.87	0.75	440	15.13	0.63
200	16.51	0.80	500	14.45	0.68
220	16.02	0.79	800	12.75	0.11
250	16.10	0.54	1000	11.63	0.12
270	16.45	0.56	1200	9.94	0.69
300	15.80	0.58	1500	9.06	0.73
320	14.81	0.74	2000	7.54	0.58
340	14.49	0.58			

Table 2. Absolute cross sections for electron-impact ionisation of O^{5+} with energy. The uncertainties are one standard deviation of the counting statistics.

Electron energy (eV)	Cross section (10^{-19} cm^2)	Uncertainty (10^{-19} cm^2)	Electron energy (eV)	Cross section (10^{-19} cm^2)	Uncertainty (10^{-19} cm^2)
125	−0.13	0.47	580	7.63	0.38
200	5.65	0.35	590	7.76	0.39
250	6.15	0.31	600	7.58	0.30
300	7.54	0.38	700	7.30	0.28
350	7.37	0.29	790	7.28	0.43
400	8.15	0.20	800	6.99	0.29
450	7.72	0.33	890	7.34	0.54
500	7.39	0.31	900	7.11	0.33
540	7.10	0.34	1000	7.02	0.32
550	7.60	0.27	1500	5.50	0.26
560	7.67	0.27	2000	5.45	0.32
570	7.55	0.32	2500	4.24	0.30

The EA contribution will be further discussed later. The results of Donets and Ovsyannikov (1977) are smoothly extrapolated to our data at higher electron energies. Different theoretical predictions are converging to the experimental results as the theories become more sophisticated, both for direct ionisation and excitation-autoionisation.

For O^{5+}, there is a good agreement between various existing experimental results. The data of Crandall *et al* (1986) are in excellent agreement with our data, including the magnitude and position of the EA contribution via $1s2l2l'$ resonances. The data of Donets and Ovsyannikov (1977) are also in excellent agreement with our measurements. The Coulomb–Born exchange approximation of Jakubowicz and Moores (1981) and results of Sampson and Golden (1979) reproduce the measured cross sections over a wide energy range, including the EA contribution.

Table 3. Absolute cross sections for electron-impact ionisation of Ne^{7+} with energy. The uncertainties are one standard deviation of the counting statistics.

Electron energy (eV)	Cross section (10^{-19} cm^2)	Uncertainty (10^{-19} cm^2)	Electron energy (eV)	Cross section (10^{-19} cm^2)	Uncertainty (10^{-19} cm^2)
220	0.17	0.27	800	2.94	0.14
230	−0.19	0.25	825	2.83	0.25
236	0.15	0.37	850	2.68	0.22
239	0.26	0.24	860	2.41	0.24
250	0.32	0.27	870	2.64	0.28
300	1.81	0.27	875	2.62	0.36
350	1.93	0.27	880	2.61	0.28
400	2.48	0.31	900	3.13	0.20
500	2.64	0.18	920	2.99	0.30
600	3.24	0.20	925	2.79	0.14
650	2.95	0.18	950	3.20	0.27
700	3.08	0.26	1000	3.15	0.20
750	2.78	0.35	1500	2.79	0.21
775	2.87	0.39	2000	2.47	0.24

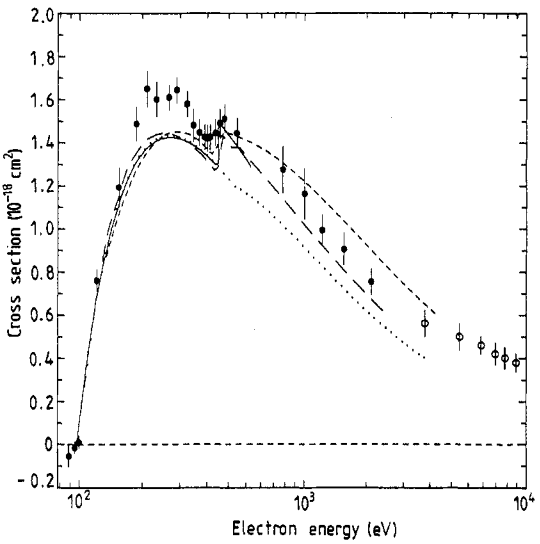

Figure 2. Cross section for electron-impact ionisation of N^{4+}: ●, our results; ○, Donets and Ovsyannikov (1977); - - - -, Crandall *et al* (1979); · · · ·, Younger (1980); — —, Sampson and Golden (1979); ——, CBX, Jakubowicz and Moores (1981). The error bars are one standard deviation statistical uncertainties, only.

There are no other measurements for Ne^{7+} ionisation to be compared with our data, except those of Donets and Ovsyannikov (1977), and they reasonably extrapolate to our data at the high energy side. The Lotz (1968) formula accurately predicts the maximum of the direct cross section below the EA onset. There is similar agreement with results of CBNX calculations by Jakubowicz and Moores (1981). The CBX result by Jakubowicz and Moores (1981) includes the interference between the direct ionisation and the EA. Their result underestimates the measured cross section just below the

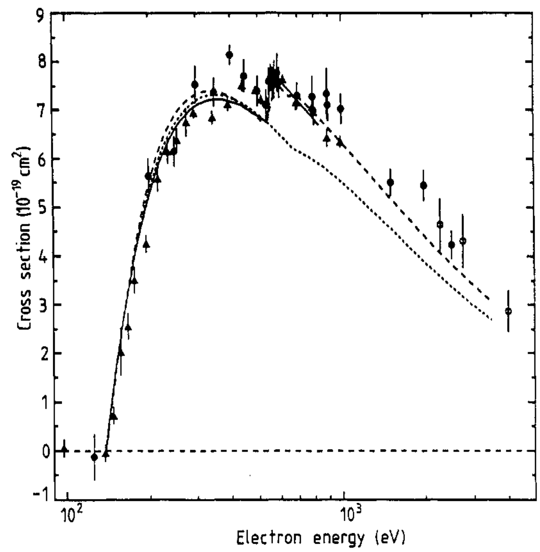

Figure 3. Cross section for electron-impact ionisation of O^{5+}: ●, our results; ○, Donets and Ovsyannikov (1977); ▲, Crandall *et al* (1986); ····, Younger (1980); — —, Sampson and Golden (1979); ——, CBX, Jakubowicz and Moores (1981). The error bars are one standard deviation statistical uncertainties only.

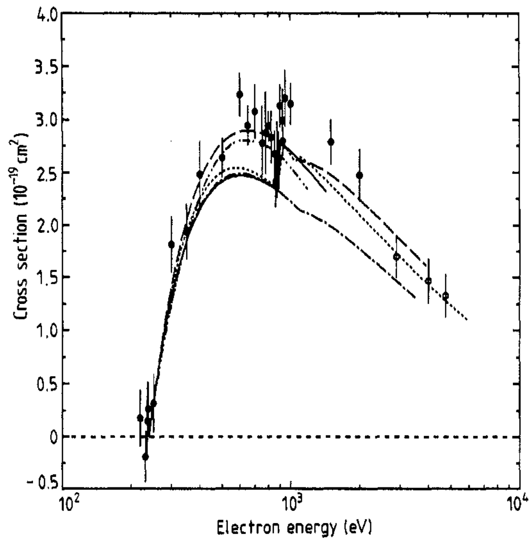

Figure 4. Cross section for electron-impact ionisation of Ne^{7+}: ●, our results; ○, Donets and Ovsyannikov (1977); —·—, Younger (1980); ····, Sampson *et al* (1979); ——, CBX, and —·—, CBNX, Jakubowicz and Moores (1981); — —, Lotz (1968). The error bars are one standard deviation statistical uncertainties, only.

EA onset by about 15%, while the EA contribution is well reproduced. The effects of interference do not yet seem to be well described theoretically.

The DCBX calculations by Younger (1980) slightly underestimate the direct cross section magnitude in all three cases.

In order to further compare the measurements it is convenient to scale the cross sections along the isoelectronic sequence. For Li-like ions it has already been done by Crandall *et al* (1986). Figure 5 shows our measured cross sections for N^{4+}, O^{5+} and Ne^{7+} scaled by the square of the outer-shell electron ionisation potential against the energy in units of the ionisation potential. The scaled cross sections are in good agreement with each other.

Particular attention has been paid to determine the EA contribution to the total ionisation cross sections. In order to estimate the EA cross sections, the following procedure is adopted. First, an estimate of the direct ionisation cross section is determined by fitting the experimental data below the first excitation-autoionisation threshold. For this purpose we have used the first two terms of the semi-empirical formula proposed by Bell *et al* (1982), in the form:

$$\sigma_d = \frac{1}{IE}[A \ln(E/I) + B(1 - I/E)]. \tag{4}$$

Calculated values of the parameters A and B are listed in table 4, in units of $10^{-14}\,\mathrm{cm}^2\,\mathrm{eV}^2$. The excitation-autoionisation cross sections σ_{EA} are estimated by subtracting extrapolated direct contribution σ_d from the measured values, over the energy region of interest.

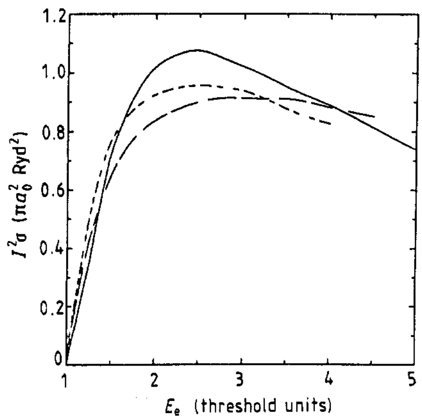

Figure 5. Scaled cross section for electron-impact ionisation of N^{4+}, O^{5+} and Ne^{7+} plotted against electron energy in threshold units: - - - -, N^{4+}; — —, O^{5+}; ——, Ne^{7+}.

Table 4. Estimated values of the parameters A and B in equation (4), in units of $10^{-14}\,\mathrm{cm}^2\,\mathrm{eV}^2$.

Ion	I (eV)	A	B
N^{4+}	97.9	2.74	2.15
O^{5+}	138.1	3.91	0.124
Ne^{7+}	239.1	3.93	0.96

Table 5. Excitation–autoionisation cross section at the maximum in 10^{-19} cm^2.

Ion	Our results	Crandall *et al* (1986)	Henry (1979)	Sampson *et al* (1979)	Jakubowicz and Moores (1981)
N^{4+}	1.70 ± 0.46	1.6 ± 0.4	1.27	2.0	2.0
O^{5+}	0.62 ± 0.19	0.8 ± 0.3	0.74	1.1	1.2
Ne^{7+}	0.46 ± 0.14	—	—	0.47	0.46

The maximum values of σ_{EA} are given in table 5, along with similar experimental data and with some theoretical results.

For N^{4+}, our data are in good agreement with those of Crandall *et al* (1979) and the theoretical predictions of Sampson and Golden (1979). We should note that the procedure adopted here is slightly different from that adopted by Crandall *et al* (1979). In their case, the estimated value for the cross section for the direct ionisation process is obtained by normalisation of the theoretical data of Younger (1980) to their experimental data below the excitation–autoionisation threshold. However, that should not change the results significantly.

For O^{5+}, our estimated value is in very good agreement with that of Crandall *et al* (1986) and with the theoretical results of Sampson and Golden (1979) and Jakubowicz and Moores (1981).

The EA cross section magnitude for Ne^{7+} can be compared with the CBX calculations of Jakubowicz and Moores (1981) and Sampson *et al* (1979). The agreement is remarkable.

Close examination of figures 2, 3 and 4 returns attention to the discussion by Crandall *et al* (1986) of READI in O^{5+}. Figure 3 suggests a possible contribution of this process between 400 and 550 eV, but it seems meaningless to make any estimation of it with the present statistics. Similarly, the contribution of REDA to these measurements is not clearly discernable with the present statistics.

5. Summary

We have reported here the results of absolute cross section measurements for electron impact ionisation of Li-like N^{4+}, O^{5+} and Ne^{7+}, obtained by use of the animated crossed beams method. For all three ions our results on direct ionisation are in a good agreement with other experimental data and with various theoretical predictions. The cross sections for excitation–autoionisation are inferred from the measured data and compared with existing experimental and theoretical data. The process of EA can be well described by the excitation theory.

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