Measurements of electron impact ionization cross sections of Mg^{2+} ions and a note on the classical scaling law

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Abstract. A crossed-beam method has been used to study the reaction $Mg^{2+}+e \rightarrow Mg^{3+}+2e$ for electron energies which ranged from threshold (78 ev) to 3 kev. The cross section attained a maximum value of $1{\cdot}38 \times 10^{-17}$ cm² at 300 ev. The results are compared with partial cross sections (for single ionization) of neon and Na^{+}, which are the two lower members of the neon sequence. The scaling law for isoelectronic ions, which follows from Thomson's classical theory, is seen to become more accurate with increasing ionic charge for this sequence.

1. Introduction

Thomson's (1912) classical theory implies that electron impact ionization cross sections σ of two members of an isoelectronic sequence are related to their ionization energies χ by

$$\frac{\sigma_1}{\sigma_2} = \left(\frac{\chi_2}{\chi_1}\right)^2 \tag{1}$$

provided that the electron energies are expressed in terms of the respective ionization energies. In view of the crude assumptions on which this equation is based, it is surprising that it holds for several isoelectronic pairs. For example, experimental results for atomic hydrogen and He^{+} obey this law closely at electron energies greater than a few times threshold (Dolder *et al.* 1961). Similar scaling has also been observed for helium and Li^{+} (Lineberger *et al.* 1966, Peart and Dolder 1968 a) and for argon and K^{+} (Hooper *et al.* 1966, Peart and Dolder 1968 b).

If this law were universally true, it would provide a valuable bridge between results for lowly charged ions, which can conveniently be studied in the laboratory, and highly charged species which are important in many laboratory and astrophysical plasmas. Unfortunately, the inadequacy of equation (1) has been illustrated by comparing scaled measured cross sections for neon and Na^{+} (Hooper *et al.* 1966, Peart and Dolder 1968 b). However, Seaton (1968, private communication) pointed out that, for hydrogenic ions, equation (1) can be rigorously deduced from quantum theory, but then it is true only in the limits of infinite ionic charge Z and fast (non-relativistic) electrons. It therefore seems possible that equation (1) might be a good approximation for the more highly charged members of non-hydrogenic sequences.

To test the convergence of equation (1) for the neon sequence measurements have been made of cross sections for

$$Mg^{2+} + e \rightarrow Mg^{3+} + 2e. \tag{2}$$

Mg^{2+} is the next member after Na^{+} in the series of neon-like ions.

There is a second reason for studying neon-like ions. Peach (1968) recently used Ochkur's approximation to calculate electron impact ionization cross sections for neon and argon, but her results were about twice as large as the corresponding measurements, even at high electron energies. A substantial part of this disparity might be due to the omission of the effects of correlation between electrons in the outer subshell. The measurements which now exist for neon, Na^{+} and Mg^{2+} would provide independent checks for any improved calculation of neon-like structures.

2. Apparatus and method

With the exception of the ion source, the apparatus has already been described by Peart and Dolder (1969, to be referred to as I). A beam of Mg^{2+} ions was bombarded by an electron beam and steady electric and magnetic fields were used to separate the parent (Mg^{2+}) and product (Mg^{3+}) ions. The two-stage selector, described in I, was necessary to give adequate dispersion between ions which differed in charge by a factor of less than 2.

A P.I.G.-type ion source was used which was developed from a design by Neff (1963). The source was heated to maintain magnesium at a vapour pressure of order 10^{-2} torr and electrons from a tungsten filament oscillated in this vapour to produce ions which were extracted and accelerated. After deflection in a magnetic field a pure collimated beam of Mg^{2+} was obtained which had a rectangular cross section 3 mm $\times$ 1 mm and a current of 5×10^{-9} A for a source potential of 2 kv.

The current of Mg^{3+} ions, formed by bombarding the Mg^{2+} beam with electrons, was typically 10^{-17} A. This was too small to be measured by an electrometer so the ions were individually detected and counted as described in I.

The detector efficiency was measured by selecting tenuous beams of Mg^{3+} ions ($\sim 10^{-15}$ A) from the source. These were first deflected into a Faraday cup so that their current could be measured by an electrometer. This result was then plotted against the count rate which the same beam produced when it was deflected on to the detector. This procedure was repeated for a number of beam currents and the efficiency was deduced from the gradient of the accurately linear result which was obtained.

The energy with which ions struck the detector depends partly upon the source potential and partly upon the voltage applied to the first dynode of the detector. Table 1 shows measured efficiencies of the detector for various source potentials and ion energies on striking the detector.

Table 1

Ion source potential (kv)	Ion energy (kev)	Detection efficiency (%)
1·0	14·4	88
1·5	15·9	90
2·0	17·4	89
2·5	18·9	90·5
3·0	20·4	89
3·5	21·9	87

No significant dependence of efficiency on energy was found, and the mean efficiency was taken to be 89%.

In all crossed-beam experiments involving ions the initial state of excitation of the ions must be well defined, otherwise the results will be ambiguous. Many excited states will be populated in the ion source but all except the metastable levels will have ample time to decay before the ions reach the interaction region. Mg^{2+} is known to have a metastable level 53 ev above the ground state, but tests showed that the measured cross section did not change when the energy of electrons in the source exceeded that necessary to populate the metastable state. Normally, the potential of the ion-source anode did not exceed 50 v. It was also verified that the measured cross section fell to zero below the ionization threshold of unexcited Mg^{2+} (78 ev).

The remaining techniques used to measure the cross sections have already been described in I.

3. Results

The present results are summarized in table 2 and plotted in figure 1 (curve Mg^{2+}). The errors have been assessed and represented as described in I. Figure 1 shows measured cross sections for Ne, Na^+ and Mg^{2+} plotted against electron energies which are expressed in units of the respective ionization energies. The measured cross sections for Na^+ (Peart and Dolder 1968 b) and neon have been scaled with respect to Mg^{2+} by equation (1), and, in the case of neon, absolute partial cross sections (i.e. for single ionization only) at the lower energies were deduced from absolute total cross sections (Schram *et al.* 1966) and

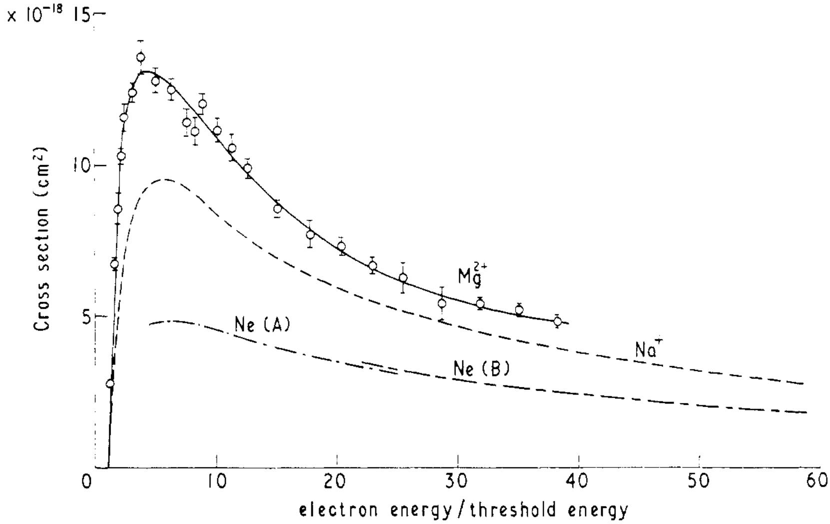

Figure 1. The full curve locates the measured cross section for Mg^{2+} plotted against the electron energy in units of the ionization threshold. These are compared with classically scaled measurements, which are identified in the text, for the single ionization of Na^+ and neon. The ionization energies of neon, Na^+ and Mg^{2+} are, respectively, 21·6, 47·3 and 78·2 ev.

relative partial cross sections (Bleakney 1930). These results are represented by the curve labelled Ne (A). At higher energies the absolute partial cross sections measured by Schram, Boerboom and Kistemaker (1966) have been scaled and plotted as curve Ne (B).

Table 2. Cross sections for the single ionization of Mg^{2+} ions by electron impact

Electron energy (ev)	Cross section (10^{-17} cm²)	Random error (±%)	Electron energy (ev)	Cross section (10^{-17} cm²)	Random error (±%)
75	<0·04		800	1·139	3
100	0·272	5	900	1·078	4
125	0·682	2	1000	1·009	3
150	0·874	6	1100	0·885	3
175	1·052	2	1200	0·876	3
200	1·179	4	1400	0·784	6
250	1·267	2	1600	0·744	4
300	1·382	4	1800	0·680	3
400	1·303	3	2000	0·635	8
500	1·273	3	2250	0·551	10
600	1·162	4	2500	0·549	3
650	1·132	4	2750	0·530	4
700	1·223	3	3000	0·490	4

The random errors are 90% confidence limits at each electron energy and the systematic errors are assessed to be less than ±8% at all energies.

The figure shows that the relative difference between scaled curves for Mg^{2+} and Na^+ is much less than the difference between the scaled cross sections of Na^+ and neon. This is consistent with a fairly rapid convergence of the scaling law with increasing Z.

Convergence has also been noted for scaled threshold photoionization simple cross sections calculated by Seaton (1958) for the neon sequence. For hydrogen-like ions theory predicts that $\chi\sigma_p$ is constant, where σ_p is the photoionization cross section at the threshold energy χ. For the neon sequence, however, the calculated values of $\chi\sigma_p$ for neon, Na^+, Mg^{2+} and Al^{3+} were respectively in the ratio 110 : 380 : 420 : 460. These ratios cannot be directly compared with the present results in spite of the fact that cross sections for ionization by photons and fast electrons are related (e.g. Seaton 1959). These relations are, however, only valid in the limit of Bethe's approximation and the electrons in the present experiments probably had insufficient energy to satisfy this assumption.

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