J. Phys. B: Atom. Molec. Phys., Vol. 11, No. 21, 1978. Printed in Great Britain

LETTER TO THE EDITOR

A measurement of the cross section for electron impact ionisation of C^{2+}

P R Woodruff†, M-C Hublet†, M F A Harrison† and E Brook†‡

† Euratom–UKAEA Association for Fusion Research, Culham Laboratory, Abingdon, Oxon, OX14 3DB, England

Received 24 July 1978

Abstract. The absolute electron impact ionisation cross section of C^{2+} has been measured by the crossed-beams technique for electron energies ranging from below the ionisation threshold to 1 keV. The data are in good agreement with the predictions of the semi-empirical formula of Lotz, but agreement is poorer with calculations based on the binary encounter approximation (Salop) and a scaled Born approximation (McGuire). However, there is good agreement with a Coulomb–Born calculation of Moores. The trapped-ion data of Hamdan *et al* agree in shape, within the experimental uncertainties, but disagree in magnitude.

Much of the energy loss from present-day fusion devices is due to bremsstrahlung and line radiation from highly charged impurity species. In order to make a quantitative assessment of this loss, information on the electron impact ionisation cross sections is needed so that the ionisation rate coefficients can be derived. These, together with the recombination rates, enable the ion state population at a given temperature to be calculated (e.g. Jordan 1969, Summers 1974). The difficulties inherent in measuring ionisation cross sections of highly charged ions have led to various theoretical and semi-empirical methods for estimating them. These have recently been reviewed by Burgess *et al* (1977). An alternative approach is to extrapolate from the known cross sections of lower charge states in the same isoelectronic sequence. In order to supply data for this approach, measurements have been made on C^{2+} to provide the first reported absolute cross section in the beryllium sequence. The data are also directly applicable to assessing the energy loss from carbon, which is a major contaminant in fusion devices.

The crossed-beams technique was used to measure the cross section for electron energies ranging from below the ground-state ionisation threshold to 1000 eV. The results are compared with the predictions of the semi-empirical formula of Lotz (1968), the binary encounter approximation calculations of Salop (1976), the scaled Born approximation calculations of McGuire (1977), and the Coulomb–Born calculations of Moores (1978). The only other experimental data on the C^{2+} cross section are from the trapped-ion-beam measurements of Hamdan *et al* (1978) which are relative and were normalised using the data on the C^{+} cross section measured by Aitken *et al* (1971).

‡ Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, England.

The apparatus was the same as that used previously for the measurement of the electron impact ionisation cross section of Ar^+ (Woodruff *et al* 1978). The duoplasmatron ion source was operated with carbon monoxide under conditions of low pressure and a high arc current in order to optimise the yield of C^{2+} ions. The ion beam energy was 8 keV and the magnitude of the beam entering the interaction region was $1\text{–}2 \times 10^{-10}$ A. The signal count rate was very low because of this low beam current and also because the electron impact cross section is small. There was a background due to stripping of the 8 keV ions and a small, but significant, background from the electron beam, presumably caused by bremsstrahlung photons produced by electron collisions with surfaces. In order to distinguish the signal from these backgrounds, both the electron and ion beams were pulsed (see Harrison 1968) at a frequency of 1 kHz.

The product C^{3+} ions were detected with a Johnston Laboratories MM1 particle multiplier, but it was not possible to make a direct measurement of its efficiency by using a beam of C^{3+} ions. The problem arose because the charge-to-mass ratio of C^{3+} is identical to that of He^+ and the latter ions were always present in the beam extracted from the source. There is some evidence (Tel'kovskii 1956) to suggest that the secondary electron yield depends only on the velocity of the ion and not on its charge state, provided that the velocity is sufficiently high. Therefore the multiplier efficiency was determined using beams of C^+ and C^{2+} ions which had the same velocity as the C^{3+} ions ($3{\cdot}6 \times 10^5$ m s^{-1}). The efficiencies obtained for the two species agreed to within the 90% confidence limits on each measurement and remained constant, to within the experimental errors, throughout the time of the experiment. The multiplier efficiency for the C^{3+} ions was taken to be the mean of these results and its value was $91{\cdot}2 \pm 0{\cdot}5\%$.

The signal count rate at the peak of the cross section was 3 s^{-1} for a pulsed electron current with a mean level of 600 μA and a signal-to-background ratio of 1:1. Close to the threshold, the count rate dropped to less than $0{\cdot}1$ s^{-1} for an electron current with a mean level of 125 μA and a signal-to-background ratio of 1:20.

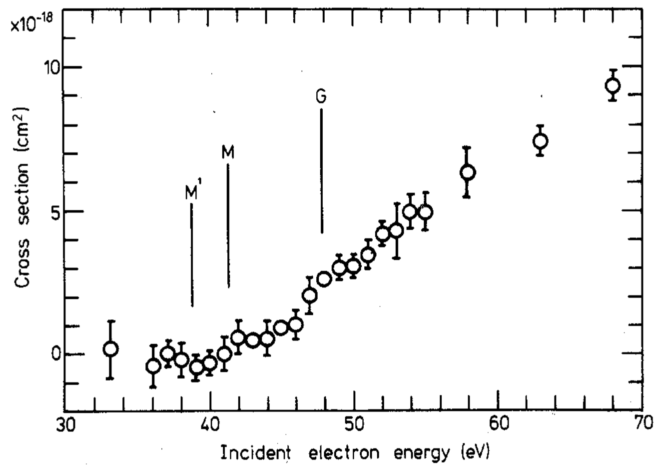

Figure 1. The threshold region electron impact ionisation cross section of C^{2+}. ⏀ present data: error bars represent 90% confidence limits of the random errors; G ground-state threshold at 47·89 eV; M metastable-state threshold at 41·39 eV; M[1] metastable-state threshold at 38·83 eV.

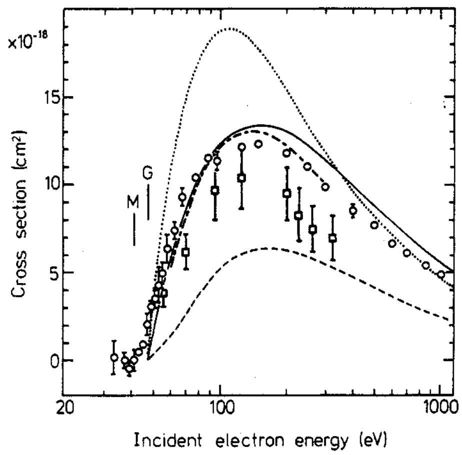

Figure 2. The electron impact ionisation cross section of C^{2+}. ○ present data: 90% confidence limits are shown where they exceed the size of the symbol; G, M as in figure 1; ⌶ trapped-ion data of Hamdan *et al* (1978). The theoretical cross sections shown are: —— semi-empirical formula of Lotz (1968); ····· binary encounter calculation of Salop (1976); ---- scaled Born calculation of McGuire (1977); —-— Coulomb–Born calculation of Moores (1978).

The cross section for the threshold region is shown in figure 1. Error bars represent 90% confidence limits of the random errors. The ground state of C^{2+} is $1s^22s^2\ {}^1S$ which has an ionisation potential of 47·89 eV (Moore 1970). The finite cross section below the ground-state threshold is attributed to ionisation from the $1s^22s2p\ {}^3P^o$ metastable state of C^{2+} which has an ionisation potential of 41·39 eV. This state could further enhance the cross section through autoionising transitions such as

$$1s^22s2p\ {}^3P^o + e \rightarrow 1s^22pnp\ {}^3D + e \qquad n \geqslant 5$$
$$\rightarrow 1s^22s\ {}^2S + e + e$$

which have an onset at 44·07 eV, but these contributions cannot be resolved within the experimental uncertainties. Another possible contribution below the ground-state threshold is ionisation of the $1s^22p^2\ {}^3P$ metastable state to the $1s^22p\ {}^2P$ excited state of C^{3+}, with a threshold of 38·83 eV, but this cannot be identified in the data.

The cross section for the full range of electron energies is shown in figure 2 and listed in table 1, together with the 90% confidence limits and the maximum systematic errors. The latter errors were assessed in the same way as that described by Brook *et al* (1978). The data of Hamdan *et al* (1978) are also shown and, within their experimental uncertainties, they agree in shape with the present data. However, they are about 20% lower in magnitude, but this might be accounted for by uncertainties in the normalisation procedure applied by Hamdan *et al.*

The present data are also compared with three theoretical estimates of the cross section. The dotted curve in figure 2 is the calculation of Salop (1976) using the binary encounter approximation, in which the effects due to exchange are neglected. This cross section is higher than the experimental data at low energies, but at high energies the agreement is quite good. The broken curve is the scaled Born approximation calculation of McGuire (1977) in which no account is taken of the Coulomb field of the ion. Thus no agreement can be expected at low energies, but even at

Table 1. The cross section for $C^{2+} + e \rightarrow C^{3+} + e + e$.

Electron energy† (eV)	Cross section (10^{-18} cm^2)	Random error ($\pm 10^{-18}$ cm^2)	Systematic error ($\pm 10^{-18}$ cm^2)
37·1	0·02	0·44	0·002
41	−0·05	0·62	0·003
42	0·58	0·56	0·04
43	0·47	0·24	0·03
44	0·57	0·63	0·03
45	0·92	0·18	0·05
46	1·04	0·53	0·06
47	2·05	0·65	0·13
48	2·66	0·32	0·24
49	3·03	0·36	0·24
50	3·09	0·43	0·16
52	4·18	0·42	0·25
54	4·95	0·69	0·32
58	6·35	0·83	0·32
63	7·40	0·52	0·38
68	9·32	0·57	0·47
78	10·42	0·23	0·46
88	11·52	0·25	0·54
98	11·33	0·56	0·56
123	12·16	0·11	0·58
148	12·31	0·18	0·60
198	11·78	0·21	0·55
248	10·98	0·27	0·58
298	9·85	0·20	0·45
398	8·50	0·38	0·39
498	7·70	0·14	0·35
598	6·64	0·26	0·31
698	6·13	0·23	0·28
848	5·38	0·19	0·25
998	4·87	0·19	0·22

† ±0·6 eV.

high energies the calculated values are some 50% low. The chain curve is a recent Coulomb–Born calculation of Moores (1978) whose method should provide the most accurate theoretical data presented here. Indeed it is in best agreement with the present measured cross section.

The cross section for ionisation from the ground state has also been calculated using the semi-empirical formula of Lotz (1968) and is shown by the full curve. In calculating this cross section, the small contribution from ionisation of the 1s shell has been neglected since a vacancy in this shell will decay by the Auger process to give a C^{4+} ion. The calculation underestimates the cross section at low energies but the small discrepancy might be reduced if account is taken of the contribution from the metastable state. At high energies the calculation exceeds the data by about 10%.

We should like to thank Dr D L Moores for communicating his results prior to publication and Dr R S Pease, the Director of Culham Laboratory, for supporting this study. One of us (M-CH) acknowledges the receipt of a Euratom scholarship and one of us (EB) acknowledges financial support from the UKAEA.

References

Aitken K L, Harrison M F A and Rundel R D 1971 *J. Phys. B: Atom. Molec. Phys.* **4** 1189–99
Brook E, Harrison M F A and Smith A C H 1978 *J. Phys. B: Atom. Molec. Phys.* **11** 3115–32
Burgess A, Summers H P, Cochrane D M and McWhirter R W P 1977 *Mon. Not. R. Astron. Soc.* **179** 275–92
Hamdan M, Birkinshaw K and Hasted J B 1978 *J. Phys. B: Atom. Molec. Phys.* **11** 331–7
Harrison M F A 1968 *Methods of Experimental Physics* vol 7A, ed B Bederson and W L Fite (New York: Academic Press) pp 95–115
Jordan C 1969 *Mon. Not. R. Astron. Soc.* **142** 501–21
Lotz W 1968 *Z. Phys.* **216** 241–7
McGuire E J 1977 *Phys. Rev.* A **16** 73–9
Moore C E 1970 *Selected Tables of Atomic Spectra* NSRDS-NBS3
Moores D L 1978 *J. Phys. B: Atom. Molec. Phys.* **11** L403–5
Salop A 1976 *Phys. Rev.* A **14** 2095–102
Summers H P 1974 *Mon. Not. R. Astron. Soc.* **169** 633–40
Tel'kovskii V G 1956 *Dokl. Akad. Nauk.* **1** 334–6
Woodruff P R, Hublet M-C and Harrison M F A 1978 *J. Phys. B: Atom. Molec. Phys.* **11** L305–8