Relative excitation functions for terms in C II, C III, and C IV populated in the beam-foil interaction

Y. Baudinet-Robinet and P. D. Dumont
Institut de Physique Nucléaire, Bâtiment B-15, Université de Liège, Sart-Tilman, B-4000, Liège, Belgium
(Received 13 January 1983)

Relative populations of terms in C II, C III, and C IV, excited after the passage of C^+ ions through a carbon foil, have been measured as a function of the projectile energy ($0.3 < E < 2.3$ MeV). These excitation functions are shown to depend on the energy of the term and, in C II, a dependence on the core configuration of the term is observed at low projectile energies ($E < 0.6$ MeV). The excitation functions are also compared to the charge-state-fraction curves as a function of the ion energy and this comparison generally allows an unambiguous identification of the charge of the ion emitting an unclassified transition in C II, C III, and C IV.

I. INTRODUCTION

The studies of charge-state distributions and level populations of accelerated ions, at the exit of a carbon foil, should throw light on the complex beam-foil interaction mechanism which is poorly known.

This work is concerned with experimental studies of beam-foil populations (number of ions excited in a given level at the exit of the foil per incident projectile) for carbon ions as a function of the projectile energy (excitation functions). While many equilibrium charge-state distributions in carbon foils have been measured at different beam energies (see for instance data compiled in Ref. 1 and more recent data analyzed in Ref. 2), only few relative excitation functions for beam-foil populations have been determined.[3–13] This work complements previous studies performed in this laboratory using N^+ projectiles.[9]

Different models have been proposed to describe the dominating beam-foil interaction mechanism in particular cases (see for instance Refs. 14—17) but no detailed theory is available at present for calculating the distribution of atomic excited-state populations of the projectile after carbon-foil excitation.

The principal aims of this work are the following:

(a) To measure accurate relative populations for several terms in C II, C III, and C IV using C^+ ions in the energy range 0.3—2.3 MeV.

(b) To determine if it is possible, by comparing the excitation function for the upper term of an unknown transition with the charge-state fraction curves, to identify unambiguously the charge state of the emitting ion.

(c) To study the dependence of excitation functions, for different terms in C II, C III, and C IV, on the electronic configuration, core configuration, excitation energy, etc., of the upper term of the transition studied.

II. EXPERIMENTAL PROCEDURE

The measurement technique has been described in detail previously.[9] C^+ beams of about 0.2 μA (diameter 6 mm) are supplied by a 2-MV Van de Graaff accelerator equipped with an rf source into which CO gas was admitted. Beam light ($300 < \lambda < 1800$ Å) emitted after the carbon foil ($\simeq 13$ $\mu g/cm^2$) is observed with a Seya-Namioka-type spectrometer equipped with a channeltron detector. (For the 1345-Å line in C IV an EMR 542G photomultiplier tube has been used.) The linewidth [FWHM (full width at half maximum)] is about 0.7 Å. The ion energy is changed by steps of 200 keV (or 100 keV) between 0.3 and 2.3 MeV. The background is subtracted (when necessary) from the photon counting.

Precise determinations of beam-foil populations can only be obtained if several conditions are fulfilled as explained in detail in Ref. 9 and summarized hereafter.

(a) High vacuum ($\simeq 10^{-6}$ Torr) in the whole beam transport system,

(b) precise knowledge of the foil position,

(c) line studied not blended and sufficiently intense to obtain good precision in the photon counting,

(d) level studied not repopulated by short-lived cascade, and

(e) lifetime τ of the primary level longer than 0.1

ns [$\tau > b^*/v$ where b^* is the section of the ion beam viewed by the spectrometer ($b^* = 0.23$ mm) and v is the ion velocity].

In these conditions the initial population of a level $N(0)$ is deduced from the intensity $K(y)$ of a line originating from that level and measured at a small distance y ($y > b^*/2$) from the foil by the relation[9]

$$N(0) \simeq \frac{v}{\alpha} K(y) \exp(ky/v) , \quad (1)$$

where α is a constant for a given transition and $-k/v$ is the slope of the straight line fitting the data points situated slightly after the maximum of the intensity curve ($y > b^*/2$) plotted on a semilogarithmic scale. We assume that our light-detector apparatus is not sensitive to the polarization of the signal.

III. RESULTS AND DISCUSSION

The transitions studied are carefully selected to verify conditions (c), (d), and (e) of Sec. II. Lifetimes of the primary and repopulating levels are obtained from beam-foil works.[18–21] Relative populations at the foil are obtained using Eq. (1). The maximum uncertainties in these populations are estimated to be about 15%; they increase when the lifetimes of the levels studied decrease.[9]

In Figs. 1–3, excitation functions are plotted for several terms in C II, C III, and C IV, respectively. The excitation energies of the terms (E_{exc}) decrease from the top to the bottom of the figures. The term studied, its approximate energy, and the wavelength of the transition used are also indicated in the figures.

Equilibrium charge-state fractions of carbon ions, at the exit of a carbon foil, have been measured by several authors[22–24] in the energy domain analyzed in this work. These data are plotted as a function of the energy of C ions after the foil in Figs. 1–3 for C II, C III, and C IV-V ions, respectively.

A. C II ion

Excitation functions obtained for C II are given in Fig. 1 for terms with zero, one, and two vacancies in the core $1s^2 2s^2$. The following conclusions are deduced:

(1) Terms with the same configuration and nearby excitation energies have proportional excitation functions (see terms with $2s\,2p\,3d$ and $2s\,2p^2$ configurations in Fig. 1). This conclusion is in agreement with the results of Andresen *et al.*,[7] who have measured excitation functions in C II at low beam energies ($E < 0.5$ MeV).

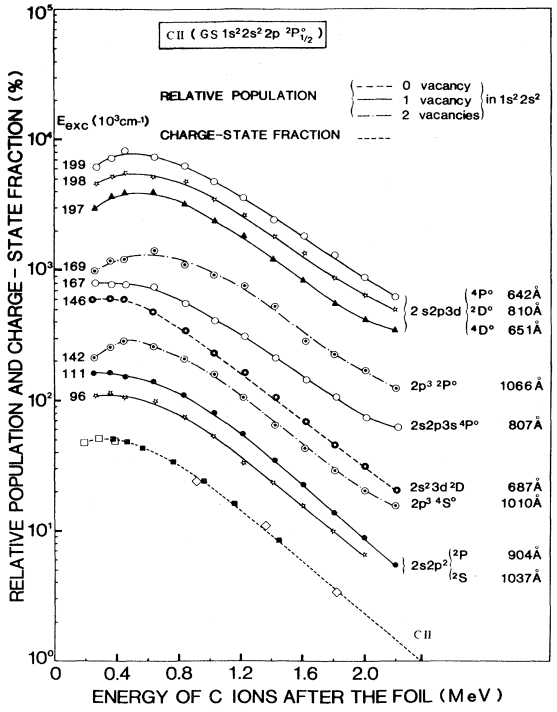

FIG. 1. Relative populations as a function of the energy E of C ions, at the exit of a carbon foil, for several terms in C II. The fraction of C II ions emerging from the foil as a function of E is also given. The data are from Christensen *et al.* (□), Smith and Whaling (■), and Girardeau *et al.* (◇). Here GS stands for ground state.

(2) The relative excitation function for the $2s^2 3d\,^2D$ term which has no vacancy in the core $1s^2 2s^2$ follows the charge-state fraction curve very well. This excitation function decreases more rapidly with the ion energy, for $0.5 < E < 1.0$ MeV, than excitation functions for terms with one vacancy in the core and of nearby energies.

(3) At low energies ($E < 0.6$ MeV), excitation functions for $2p^3$ terms (with two vacancies in the core $1s^2 2s^2$) increase more rapidly with the beam energy than excitation functions for terms of nearby excitation energies with zero or one vacancy in the core (see $2s^2 3d$ and $2s\,2p\,3s$ terms in Fig. 1). This result is in agreement with the measurements of Andresen *et al.*[7] in C II at $E < 0.5$ MeV.

(4) A comparison of all the excitation functions measured for terms with one vacancy in the core seems to indicate that these functions increase more rapidly at low ion energy ($E < 0.5$ MeV) and decrease more slowly at high ion energy ($E > 0.8$ MeV) when the energy of the term increases. Excitation functions for low-lying terms well follow the charge-state fraction curve of C II.

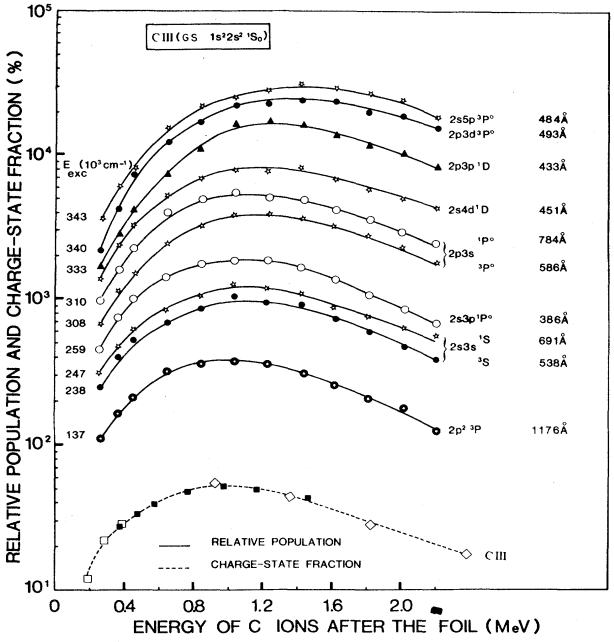

FIG. 2. Relative populations as a function of the energy E of C ions at the exit of a carbon foil, for several terms in C III. The fraction of C III ions emerging from the foil as a function of E is also given. The data are from the same references as those shown in Fig. 1.

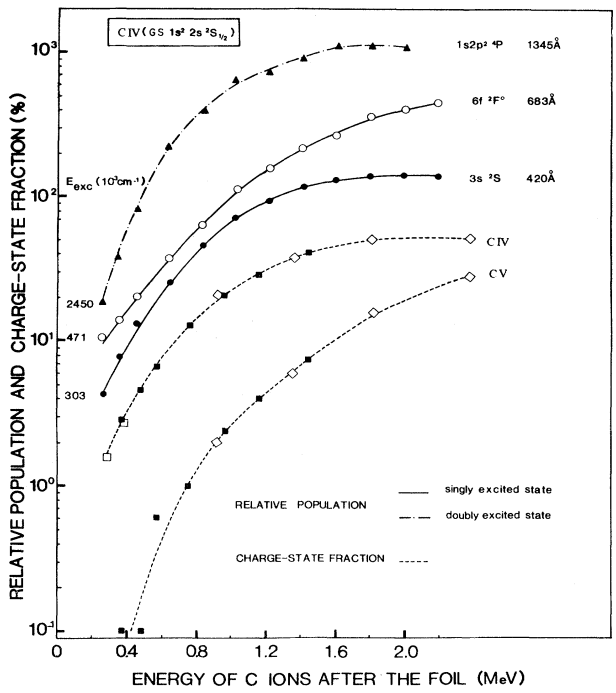

FIG. 3. Relative populations as a function of the energy E of C ions, at the exit of a carbon foil, for three terms in C IV. The fractions of C IV and C V ions emerging from the foil as a function of E are also given. The data are from the same references as those shown in Fig. 1.

B. C III ion

Excitation functions obtained for several terms in C III with one or two vacancies in the core $1s^2 2s^2$ are shown in Fig. 2. The following trends are observed:

(1) For terms of nearby energies no significant difference is observed between relative excitation functions for terms with one and two vacancies in the core ($2snl$, $2pnl$, and $2p^2$ configurations).

(2) The excitation functions increase more rapidly (at low ion energies) and decrease more slowly (at high ion energies) when the energy of the term increases; the maximum of the excitation function being shifted towards higher ion energies for higher-lying terms.

(3) The population of the low-lying $2p^2\,{}^3P$ term is proportional to the fraction of C III ions after the foil.

C. C IV ion

In the wavelength region analyzed, only three transitions in C IV verified the selection criteria of Sec. II. One of them (1345 Å) is a transition between doubly excited quartet system of C IV. The upper term $1s\,2p^2\,{}^4P$ of this transition is expected to be repopulated by short-lived cascades from $1s\,2pnd\,{}^4D^o$ terms.[25] As these cascades have not been observed in the analysis of the beam-foil decay curves for two fine-structure levels of the $1s\,2p^2\,{}^4P$ term[26] we have supposed that they were weak and have measured the excitation function for that term.

The following trends can be deduced from the analysis of the results presented in Fig. 3:

(1) At ion energies higher than 1 MeV the excitation function increases more rapidly with the beam energy for the higher-lying term ($6f\,{}^2F$) than for the lower-lying term ($3s\,{}^2S$).

(2) The population of the lower term studied ($3s\,{}^2S$) is proportional to the fraction of C IV ions after the foil.

(3) The excitation function for the doubly excited term ($1s\,2p^2\,{}^4P$) increases much more rapidly at low energies ($E < 0.6$ MeV) than the excitation functions for the singly excited terms, this trend is not observed at higher energies. Let us note that the charge-state fraction curve for C V, shown also in Fig. 3 for comparison, is steeper than the excitation function for the doubly excited term $1s\,2p^2\,{}^4P$.

IV. CONCLUSIONS

We conclude with the following:

(1) Excitation functions of low-lying states in C II, C III, and C IV closely follow the charge-state—fraction curves confirming that the major part of a charge-state component is made up of ground-state and low-lying excited states.

(2) For a carbon ion in a given charge-state, relative excitation functions depend on the energy of the term excited. In particular, excitation functions for terms of the same core configuration and different excitation energies are not proportional.

(3) It is possible to assign an unidentified transition to a particular charge state (if the upper level of the transition has not a "too" short lifetime and is not repopulated by short-lived cascades) by comparing the excitation function of its upper term to the charge-state fraction curves (see Figs. 1—3). Moreover transitions between doubly excited terms in C IV could be identified using this technique.

(4) Relative excitation functions in C II for terms with nearby energies seem to depend on the number of vacancies in the core $1s^2 2s^2$ at low projectile energies ($E < 0.6$ MeV). This situation is not observed in C III while in isoelectronic N IV, a dependence of relative excitation functions on the number of vacancies in the core $1s^2 2s^2$ has been observed previously.[9] Thus extension of conclusions concerning excitation functions to nearby isoelectronic ions seems unjustified.

ACKNOWLEDGMENTS

We thank H. P. Garnir for fruitful discussions and J. Breulet for her help during the measurements. This work was supported financially by the Belgian Institut Interuniversitaire des Sciences Nucléaires.

[1]A. B. Wittkower and H. D. Betz, At. Data 5, 113 (1973).
[2]Y. Baudinet-Robinet, Nucl. Instrum. Methods 190, 197 (1981); Phys. Rev. A 26, 62 (1982).
[3]H. G. Berry, J. Bromander, and R. Buchta, Nucl. Instrum. Methods 90, 269 (1970).
[4]N. Andersen, W. S. Bickel, R. Boleu, K. Jensen, and E. Veje, Phys. Scr. 3, 255 (1971).
[5]R. Hallin, J. Lindskog, A. Marelius, J. Pihl, and R. Sjödin, Phys. Scr. 8, 209 (1973).
[6]B. Dynefors, I. Martinson, and E. Veje, Phys. Scr. 12, 58 (1975); 13, 308 (1976); in *Beam-Foil Spectroscopy,* edited by I. A. Sellin and D. J. Pegg (Plenum, New York, 1976), Vol. 1, p. 231.
[7]B. Andresen, S. B. Jensen, P. S. Ramanujam, and E. Veje, Phys. Scr. 20, 65 (1979).
[8]G. Heine, H. H. Bukow, and H. v. Buttlar, J. Phys. (Paris) Colloq. 40, C1-269 (1979).
[9]Y. Baudinet-Robinet, H. P. Garnir, P. D. Dumont, and B. Renier, Phys. Rev. A 23, 655 (1981).
[10]W. Nitsche, P. H. Heckmann, E. Träbert, and H. v. Buttlar, Z. Phys. A 299, 301 (1981).
[11]A. Lindgård, S. Mannervik, B. Jelenković, and E. Veje, Z. Phys. A 301, 1 (1981).
[12]A. Denis, J. Desesquelles, M. Druetta, and D. J. Pegg, Nucl. Instrum. Methods 194, 319 (1982).
[13]C. Jupén, B. Denne, J. O. Ekberg, L. Engström, U. Litzén, I. Martinson, W. Tai-Meng, A. Trigueiros, and E. Veje, Phys. Rev. A 26, 2468 (1982).
[14]J. D. Garcia, Nucl. Instrum. Methods 110, 245 (1973).
[15]E. Veje, Phys. Rev. A 14, 2077 (1976).
[16]Summary of a round table discussion held at the Fifth International Conference on Beam-Foil Spectroscopy [J. Phys. (Paris) Colloq. 40, C1-356 (1979)].
[17]T. Åberg and O. Goscinski, Phys. Rev. A 24, 801 (1981).
[18]M. C. Poulizac and J. P. Buchet, Phys. Scr. 4, 191 (1971).
[19]M. C. Poulizac, M. Druetta, and P. Ceyzeriat, J. Quant. Spectrosc. Radiat. Transfer 11, 1087 (1971).
[20]M. C. Buchet-Poulizac and J. P. Buchet, Phys. Scr. 8, 40 (1973).
[21]M. C. Buchet-Poulizac, thesis, Lyon, 1974 (unpublished).
[22]P. L. Smith and W. Whaling, Phys. Rev. 188, 36 (1969).
[23]R. Girardeau, E. J. Knystautas, G. Beauchemin, B. Neveu, and R. Drouin, J. Phys. B 4, 1743 (1971).
[24]B. Christensen, E. Veje, and P. Hvelplund, Phys. Rev. A 18, 2042 (1978).
[25]C. Jacques, E. J. Knystautas, R. Drouin, and H. G. Berry, Can. J. Phys. 58, 1093 (1980).
[26]A. E. Livingston and H. G. Berry, Phys. Rev. A 17, 1966 (1978).