# Angular Momentum Distributions of Autoionizing States Produced by 1.5–5-MeV $C^+$ Ions in Carbon Foils

Y. Yamazaki[(a)] and N. Stolterfoht
*Hahn-Meitner-Institut Berlin, Glienicker Strasse 100, D-1000 Berlin 39, Germany*

P. D. Miller, H. F. Krause, P. L. Pepmiller, and S. Datz
*Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831-6377*

I. A. Sellin
*University of Tennessee, Knoxville, Tennessee 37996, and*
*Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831-6377*

J. N. Scheurer, S. Andriamonje, D. Bertault, and J. F. Chemin
*Institut National de Physique Nucléaire et de Physique de Particules,*
*Centre d'Etudes Nucleaires de Bordeaux-Gradignan, 33107 Gradignan, France*
(Received 31 March 1988)

Orbital angular momentum ($l$) distributions of ions in intermediate $n$ and $l$ states have been compared for 1.5–5-MeV carbon ions traversing C foils and He gases by projectile Auger spectroscopy. The degree of high-$l$ enhancement in C targets is quantitatively established. A picture involving multiple collisions between target atoms and the entrained electrons which accompany the ions explains the results.

PACS numbers: 34.50.Fa

The excited-state distributions of energetic ions penetrating solids have been investigated extensively to obtain information about the mechanics of propagation of swift highly charged and/or highly excited ions in solids.[1-9] Nonetheless, our knowledge about the underlying mechanisms that govern the production and evolution of such highly excited states is still very limited. In particular, a long-standing mystery concerns reconciliation of much direct evidence that low-$l$ states are strongly favored in elementary ion-atom collision processes, with evidence that high-$l$ states are readily formed in ion-solid collisions.[5,9]

In this work, we investigate the $l$ distributions for electrons in orbits whose radii exceed solid lattice spacings as well as screening distances. A fast charged projectile in a solid produces a wake potential,[10] which effectively screens the Coulomb potential of the ion at a distance $\lambda_{sc} \approx v_i/\omega_p$, where $v_i$ is the ion velocity and $\hbar\omega_p$ is the bulk plasmon energy. Because of subsequent electron scattering processes, most of the observed ionic Rydberg or convoy electrons with radii larger than the screening distance might be expected to be formed at or near the exit surface of the foil. When the ion emerges from the foil, the sudden change in projectile screening can cause ionized projectile electrons to project onto bound Rydberg states.[11] A transfer of "free" electrons traveling at $\sim v_i$ in solids, regardless of whether they originate from projectile ionization or target ionization, has previously been proposed as an additional mechanism contributing to convoy electron production (free-electron transfer to projectile continuum).[12] The importance of the exit surface in influencing excited-state characteristics has also been demonstrated by polarization measurements in ion-tilted-foil experiments.[13]

Recently, studies of $l$ distributions of low excited states produced by electron capture into 33.2-MeV/nucleon $Kr^{36+}$ ions in solids have been performed by Rozet *et al.*[14] Their findings were explained by a wake-field-induced Stark mixing of the substates. Burgdörfer has quantitatively analyzed the transport of Rydberg and convoy electrons in solids using a Monte Carlo simulation method.[15] This model takes into account random collisions between target atoms and electrons accompanying projectiles, and suggests that they play a decisive role in enhancing high-$l$ states. Betz *et al.*[5] studied the $l$ distribution of Rydberg states of 4-MeV/nucleon S ions emerging from solids and found that high-$l$ populations are much larger in ion-solid collisions than expected from collisions of ions with separated target atoms. Although substantial advances in understanding have occurred, unsettled controversies provide a continuing stimulus to the field.[5-9]

In this work, we give conclusive evidence for the enhancement of high-$l$ components of intermediate-$n$ states (low Rydberg states) of ions emerging from foils. Our conclusions are based on the direct observation of Auger lines associated with individual $l$ states and their quantitative intensity analysis. Convincing evidence is given for the differences in the $l$ distributions for solids and separated atoms by performing simultaneous measurements with foils and gas targets using the same projectiles.

 

We measured electrons emitted in the decay of autoionizing Rydberg states by the method of zero-degree Auger spectroscopy.[16-19] Electons due to the Coster-Kronig transition $1s^22p5l \rightarrow 1s^22s\epsilon l'$ in $C^{2+}$ were measured for 1.5-5-MeV $C^+$ + C-foil collisions as well as for $C^{2+}$ + He and $C^{3+}$ + He collisions under closely similar experimental conditions. The experiments were performed at the Van de Graaff accelerator at the Centre D'Etudes Nucleaires de Bordeaux-Gradignan (CENBG) and at the EN tandem accelerator at Oak Ridge National Laboratory (ORNL), with use of a spectrometer on loan from the Hahn-Meitner-Institut, Berlin. Carbon beams from 1.5–2.5 MeV and from 2.5–5 MeV were used at CENBG and ORNL, respectively. The target foil was 5 $\mu g/cm^2$ thick, enough to assure charge-state equilibrium, and was mounted perpendicular to the beam. The He target pressure was $\sim 10^{-2}$ Torr and its length was 5 cm. Emergent autoionizing electrons were measured with an energy resolution (FWHM) of 300 meV, corresponding to an energy resolution of $\sim 50$ meV in the projectile rest frame. Details of the apparatus and the zero-degree Auger spectroscopy technique have been given previously.[17]

Figures 1(a)–1(c) show spectra of autoionizing electrons produced by the Coster-Kronig transition $1s^22p5l \rightarrow 1s^22s\epsilon l'$ for 1.5-MeV $C^+$ + C foil, $C^{3+}$ + He, and $C^{2+}$ + He, respectively. The continuum electron background has been subtracted. At the top of the figure, the spectra are compared with theoretical values for the energies and widths of associated terms.[20]

For $C^{2+}$ impact, the autoionizing states are predominantly produced by a single-electron excitation process from the incident metastable ($1s^22s2p\ ^3P$) state which is likely to be produced at the stripper foil of the accelerator. The fraction of this metastable state has been found to be $\sim 75\%$ in the $C^{2+}$ beam.[21] For $C^{3+}$ in He, the autoionizing states are produced by a transfer and excitation process from incident $1s^22s$ ions. In this case, a portion of the spectrum showed a strong forward-backward asymmetry.[17] To take this into account, we averaged spectra by summing the data from forward (0°) and backward (180°) emission [Fig. 1(b)].

The spectra were fitted by a sum of thirteen Gaussian lines associated with autoionizing states with use of the theoretical values for the term energies and widths.[20] The fits are shown in Figs. 1(a)–1(c) by solid lines, which are seen to reproduce accurately most of the detailed features. Near 3 eV, the states are so dense that they were merged into groups represented by broadened lines. The different $l$ contributions to the broadened lines have been obtained by assuming preliminary values for the distribution of high-$l$ states, which were iteratively adjusted to the final fitted results for the $1s^22p5l$-configuration components. The line fitting procedure involves various uncertainties which, however, are significantly smaller than the difference in the $l$ distributions observed for gas and foil targets.

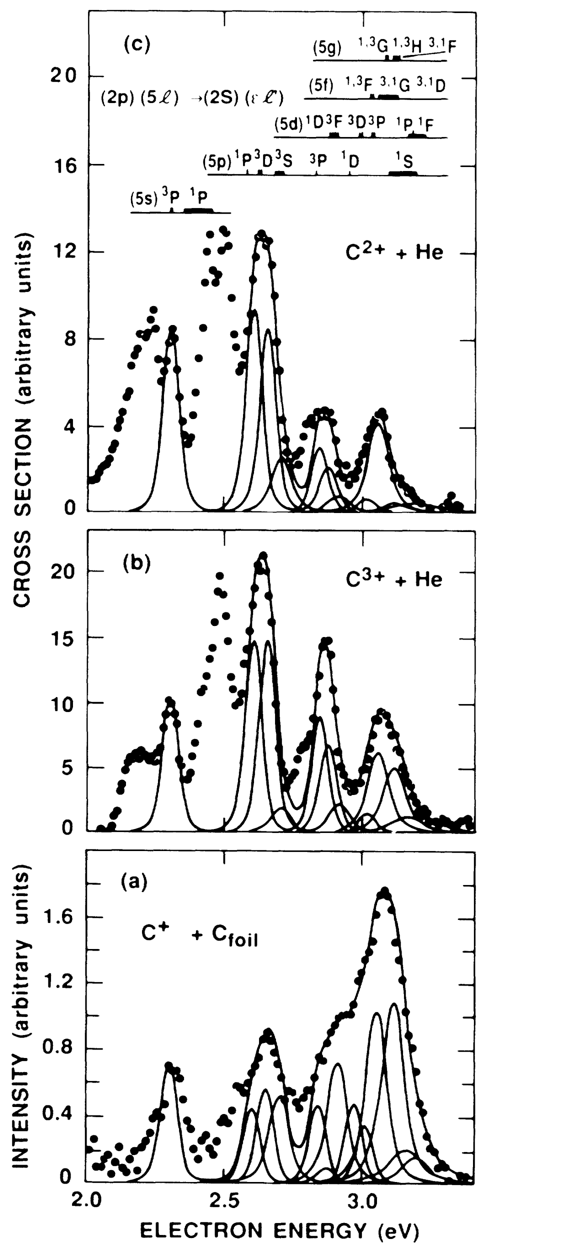


FIG. 1. Spectra of electrons associated with the decay of the configuration $1s^22p5l$ produced in 1.5-MeV (a) $C^+$ + C-foil, (b) $C^{3+}$ + He, and (c) $C^{2+}$ + He collisions. The electron energy refers to the projectile rest frame. The term energies and widths given above the spectra are based on calculations by Griffin (Ref. 20).

Figure 2 shows the $l$ distribution $f(l)$ for 1.5-MeV $C^+$ + C foil, $C^{3+}$ + He, and $C^{2+}$ + He. For C, it is found that high-$l$ components are significantly enhanced in comparison with those for He. It is seen that $f(l)$ is almost constant, i.e., the distribution is not statistical but approximately uniform over the $l$ states (except for $l = 0$). This characteristic $l$ distribution has been observed for all the projectile energies (1.5–5 MeV) stud-

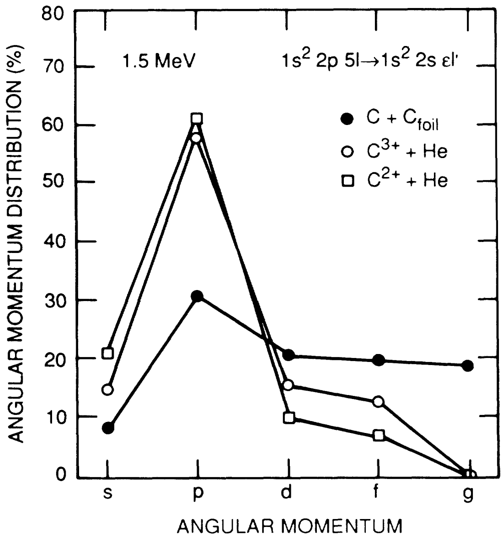


FIG. 2. Angular momentum distribution in $C^{2+}$ $1s^22p5l$ state produced in 1.5-MeV $C^+$+C-foil, $C^{3+}$+He, and $C^{2+}$+He collisions.

ied.

It should be noted that the high-$l$ enhancement for $n=5$ is also observed for $n=6$ and 7, i.e., the enhancement of the high-$l$ component in low Rydberg states in ion-foil collisions seems to be a general feature in this energy range. For $n$ larger than 7, the Auger energy resolution was insufficient to resolve spectral structure.

For He, some unidentified peaks are clearly observed at energies near $\epsilon \sim 2.2$ and $\sim 2.5$ eV. Comparing these energies with related optical measurements,[22] we find that the 2.2- and 2.5-eV peaks match energies expected for states $1s^22s2p4p\ {}^2P, {}^4D$ and $1s^22s2p4p\ {}^4P, {}^2D$ of $C^+$ ions, respectively. These states could be produced by single- and double-electron capture into incident $C^{2+}$ and $C^{3+}$ ions, respectively. The autoionizing electrons from other $1s^22s2p4p$ states are expected[22] to appear near $\sim 2.9$ to $\sim 3.2$ eV, energies which overlap those of the high-$l$ part of the $1s^22p5l$ states. Accordingly, the real fraction of high-$l$ states for He may be even smaller than those indicated in Fig. 2.

For the foil target, the $C^+$ lines at $\sim 2.2$ and $\sim 2.5$ eV are not visible in Fig. 1(a), and the 2.9–3.2-eV region is expected to be relatively free of $C^+$ contamination. This negligible contamination results from the fact that the fraction of $C^+$ is $\sim 10\%$ of that of $C^{2+}$ in the projectile energy region considered here.[23] Hence, for the foil target, the high-$l$ data given in Fig. 2 are expected to represent realistic values.

Linear-response theory predicts[10] that the Coulomb potential of fast projectiles traveling in a conducting material is screened at a distance $\lambda_{sc} \sim v_i/\omega_p$. Thus, few electronic states in solids with average radii larger than $\lambda_{sc}$ should be expected to survive. The average radius is given[24] by $\langle r_{n,l}\rangle \sim [3n^2 - l(l+1)]/2Z_c$ for hydrogenlike states with core charge $Z_c$. The average radius of the $5l$ electron of $C^{2+}$ is $\geq 9$ a.u. which is considerably larger than $\lambda_{sc} \sim 2.5$ a.u.; i.e., stationary $1s^22p5l$ states should not exist in the foil. Accordingly, the autoionizing states observed are expected to be formed at or near the exit surface of the target. However, the picture of an atomic-like electron capture from the target near the last layer is unlikely because the $l$ distributions observed in C differ significantly from those obtained in He (Fig. 2). Therefore, we consider alternative models,[9,11,12,15] beyond the simple pictures of producing Rydberg and convoy electrons in single-collision events.

In Burgdörfer's theory,[15] it is assumed that inside the solid a charge cloud consisting of electrons transiently accompanying the projectile propagates under the influence of the projectile's Coulomb field. The electrons are shown to be strongly phase-space correlated over a wide range of $Z_c$. The entrained electrons accompany the projectile for a certain average distance, during which they undergo multiple transitions (for example, of the type $nl \rightarrow n'l' \rightarrow n''l''$). This "correlation length" is enhanced by trapping in bound states but limited by collisions that remove them from the charge cloud, as they become convoy electrons. This correlation length was shown to significantly exceed the mean free path of an electron traveling freely in the solid.[15,25]

In harmony with a free-bound transition mechanism at the surface originally proposed by Betz *et al.*,[11] we note that the observed low Rydberg states are likely to be formed upon emergence. Upon exit, whatever entrained electrons remain find themselves suddenly in a deeper potential because of the disappearance of the screening. The increase of the potential is roughly estimated by

$$\Delta V \sim Z_c[1-\exp(-\langle r_{n,l}\rangle/\lambda_{sc})]/\langle r_{n,l}\rangle ,$$

which amounts to 6.5–9 eV for the $5s$-$5g$ electrons in question. Accordingly, if the electron's energy (kinetic plus potential energy in the screened field) in the projectile frame is smaller than the increase in the binding energy, they will project onto Rydberg states. When the total energy of the electron has a small positive value, it will be observed as a convoy electron. Hence, the production of Rydberg and convoy electrons are complementary processes of common origin.

In the above picture, the enhancement of high angular momenta is qualitatively understood as follows. Scattering events may increase the average values of momentum and distance of the entrained electrons with respect to the projectile. Accordingly, after multiple collisions with target atoms characteristic of electron propagation in solids, the entrained electrons are expected, in accord with the Monte Carlo calculations,[14] to acquire high $l$. In the sudden approximation inherent in the "shake-down" process, high-$l$ values are expected to be preserved when the Rydberg electrons are formed.

A possible mechanism to further enhance high-$l$ states arises from the fact that $\langle r_{n,l} \rangle$ becomes smaller as $l$ becomes larger for the same principal quantum number $n$. For instance, the average radius of the $5l$ electron of $C^{2+}$ ranges from $\sim 9$ a.u. ($g$ state) to 13 a.u. ($s$ state). Hence, taking into account that the potential increase upon exit is larger for smaller $r$, it may be expected that high-$l$ Rydberg states are more readily formed.

Summarizing, we have measured the $l$ distribution of low Rydberg states produced in 1.5-5-MeV $C^+$+C-foil collisions, which directly revealed strong enhancements of high-$l$ components. Multiple collisions of entrained electrons in solids and their shakedown into Rydberg states upon exit provide a compelling explanation of the observations, one in harmony with recent Monte Carlo calculations.

We acknowledge helpful discussions with J. Burgdörfer. We thank R. Köehrbrück for his assistance in fitting that data. The research at ORNL is sponsored by the U.S. Department of Energy, Office of Basic Energy Sciences, Division of Chemical Sciences, under Contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc. The work of I.A.S. and Y.Y. was supported in part by the National Science Foundation. N. S. acknowledges support by the Centre National de la Recherche Scientifique.

[a]On leave from the Research Laboratory for Nuclear Reactor, Tokyo Institute of Technology, Meguro-ku, Tokyo 152, Japan.

[1]N. Bohr and L. Lindhard, Kgl. Dan. Vidensk. Selsk. Mat.-Fys. Medd. **26**, No. 12 (1954).

[2]J. D. Garcia, Nucl. Instrum. Methods **90**, 295 (1970), and **110**, 245 (1973).

[3]B. Andersen *et al.*, Phys. Scr. **20**, 65 (1979).

[4]K. Dybdal *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. B **13**, 581 (1986).

[5]J. Rothermel *et al.*, Nucl. Instrum. Methods **194**, 341 (1982); H.-D. Betz *et al.*, Phys. Rev. Lett. **50**, 1193 (1983).

[6]Cüneyt Can *et al.*, Phys. Rev. A **35**, 3244 (1987).

[7]E. P. Kanter, D. Schneider, and Z. Vager, Phys. Rev. A **28**, 1193 (1983).

[8]G. Schiwietz, D. Schneider, and J. Tanis, Phys. Rev. Lett. **59**, 1561 (1987).

[9]M. Breinig *et al.*, Phys. Rev. A **25**, 3015 (1982).

[10]P. M. Echenique, R. H. Ritchie, and W. Brandt, Phys. Rev. B **20**, 2567 (1979).

[11]H.-D. Betz *et al.*, Phys. Rev. Lett. **50**, 34 (1983), and in *Forward Electron Ejection in Ion Collisions,* edited by K. O. Groeneveld, W. Meckbach, and I. A. Sellin (Springer-Verlag, Berlin, 1984), p. 115.

[12]Y. Yamazaki and N. Oda, Phys. Rev. Lett. **52**, 29 (1984); Y. Yamazaki, in *Proceedings of the Third Workshop on High Energy Ion-Atom Collisions,* edited by D. Berenyi and G. Hock, Lecture Notes in Physics Vol. 294 (Springer-Verlag, New York, 1988), p. 322.

[13]Y. Nojiri and B. I. Deutch, Phys. Rev. Lett. **51**, 180 (1983).

[14]J. P. Rozet *et al.*, Phys. Rev. Lett. **58**, 337 (1987).

[15]J. Burgdörfer, in *Proceedings of the Third Workshop on High Energy Ion-Atom Collisions,* edited by D. Berenyi and G. Hock, Lecture Notes in Physics, Vol 294 (Springer-Verlag, New York, 1988), p. 344; J. Burgdörfer and C. Bottcher, in *Proceedings of the Fifteenth International Conference on the Physics of Electronic and Atomic Collisions, Abstracts of Contributed Papers,* edited by J. Geddes *et al.* (North-Holland, Amsterdam, 1988), p. 608.

[16]M. Suter *et al.*, Z. Phys. A **289**, 433 (1979).

[17]A. Itoh *et al.*, Phys. Rev. A **31**, 684 (1985).

[18]Y. Yamazaki *et al.*, Phys. Rev. Lett. **57**, 992 (1986).

[19]N. Stolterfoht *et al.*, Phys. Rev. Lett. **57**, 74 (1986); F. W. Meyer *et al.*, in *Proceedings of the Fifteenth International Conference on the Physics of Electronic and Atomic Collisions, Book of Invited Papers,* edited by H. B. Gilbody *et al.* (North-Holland, Amsterdam, 1988), p. 673.

[20]D. C. Griffin, private communication; D. C. Griffin, M. S. Pindzola, and C. Bottcher, Phys. Rev. A **31**, 568 (1985).

[21]S. Datz *et al.*, Bull. Am. Phys. Soc. **31**, 974 (1986); N. Stolterfoht, Phys. Rep. **146**, 315 (1987).

[22]S. Bashkin, *Atomic Energy and Grotrian Diagrams* (North-Holland, Amsterdam, 1975), Vol. 1.

[23]A. B. Wittkower and H. D. Betz, At. Data **5**, 113 (1973).

[24]H. A. Bethe and E. E. Salpeter, *Quantum Mechanics of One- and Two-Electron Atoms* (Springer-Verlag, New York, 1957).

[25]I. A. Sellin *et al.*, J. Phys. B **19**, L155 (1986); R. Schramm *et al.*, J. Phys. B **18**, L507 (1985).