Auger-electron emission from slow, highly charged ions interacting with solid Cu targets

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Secondary-electron energy spectra were measured for Ar^{q+} ($q=9$ and 16) and the H-like ions N^{6+}, O^{7+}, and Ne^{9+}, incident on solid Cu surfaces at an angle of 10°. The impact energy was varied from $10q$ to $20q$ keV. Auger electrons were detected at various observation angles from 20° to 180° with respect to the incident beam. From the Doppler shift of the projectile Auger electrons, the L Auger electrons of argon and neon are found to be emitted from ions whose flight direction is parallel to the incident beam and the K Auger electrons of nitrogen, oxygen, and neon are observed to be emitted from deflected ions. Evidence is provided for incident Ne^{9+} and Ar^{16+} that the L shells are incompletely filled when the projectiles reach the surface. The data analysis is supported by model calculations.

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I. INTRODUCTION

The interaction of slow, highly charged ions with solid surfaces is a new field that received considerable interest in the past few years [1–5]. A great deal of attention has been devoted to studies of electron emission produced by multicharged ions interacting with a surface [6–10]. Progress has been made in the understanding of secondary-electron production near solid surfaces but various details concerning the reaction mechanisms still remain unclear. In particular, the location along the path of the ions where the Auger transitions take place is a matter of current debate.

It is commonly agreed that, at rather large distances, the incident ion captures electrons from the surface into high-lying Rydberg states via resonance neutralization [1]. Subsequently, the projectile undergoes deexcitation steps by means of Auger transitions which successively fill lower-lying levels. These Auger transitions may proceed until the projectile becomes neutralized. When the incident ions carry inner-shell vacancies, Auger transitions into deeply lying levels can occur, giving rise to the emission of electrons of relatively high energies. This Auger neutralization model introduced by Arifov *et al.* [1] several years ago has become widely accepted in the field of ion-surface collisions.

However, recent studies indicated that the model for neutralization by cascading Auger transitions requires revision. For instance, Folkerts and Morgenstern [10] measured electron spectra arising from the interaction of H-like ions on tungsten and found that the *LMM*-to-*KLL* Auger peak intensity ratio is considerably smaller than expected from the Auger cascade model. Hence, they concluded that the L shell of these ions is filled by additional processes such as resonant charge exchange between inner-shell levels of the projectile and the atoms in the solid. Zeijlmans van Emmichoven, Havener, and Meyer [11] performed computer simulations of Auger transitions in N^{6+} ions incident on Cu and found that the Auger cascade proceeds so slowly that the final Auger transitions into the L and K shell are not expected to take place before the ion hits the surface. Thus, it follows that the projectile reaches the surface as a "hollow atom" carrying several electrons in higher-lying Rydberg orbitals but with an unfilled core [5]. (In the following the term "hollow atom" is used in a wider sense, including the case of partially filled cores.)

To explain their Auger data, Zeijlmans van Emmichoven, Havener, and Meyer [11] proposed relatively fast transitions filling the L shell by, e.g., Auger deexcitation processes involving Cu atoms close to the surface. Furthermore, Meyer *et al.* [12] who performed extensive model calculations including charge transfer between inner shells came to the conclusion that the Auger electrons observed from multicharged ion-atom collision originate nearly exclusively from inside the solid. In previous studies [8–12] it was assumed that the Auger electrons are ejected from *incident* ions, i.e., from ions which are ap-

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proaching the surface or which have entered into the solid but still moving essentially parallel to the incident beam direction. The only indication for Auger-electron emission *after* a deflection of the ions from the surface originates from an indirect observation by de Zwart *et al.* [13] who analyzed the final ionic charge states.

In the present work, we measured spectra of secondary electrons produced by Ar^{q+} ($q=9$ and 16) and by the H-like ions N^{6+}, O^{7+}, and Ne^{9+}, interacting with a Cu surface. We performed a kinematic analysis of the ejected Auger electrons to verify the instantaneous velocity direction of the ion when the Auger transition takes place. For Ar^{9+} ions we found, in partial agreement with previous work [8,12], that *LMM* Auger electrons are ejected from incident projectiles. However, in the case of Ne^{9+} ions we provide direct evidence that *KLL* Auger electrons are ejected *after* a deflection of the ions from the surface. The interpretation of the experimental results is supported by model calculations. It should be noted that preliminary results of our measurements have been recently presented [14].

II. EXPERIMENTAL RESULTS AND DATA ANALYSIS

The experiments were performed at the test bench of the 14-GHz ECR source at the Grand Accelerateur National d'Ions Lourds (GANIL) in Caen using the electron-spectroscopy apparatus [15] from Hahn-Meitner-Institut (HMI) in Berlin. Various species of multiply charged ions, such as Ar^{q+} ($q=9$ and 16) and hydrogen like N^{6+}, O^{7+}, and Ne^{9+}, were used to bombard polycrystalline Cu surfaces. The ions of charge state q were accelerated to energies varying from $10q$ to $20q$ keV. They were magnetically analyzed and collimated to a diameter of about 2 mm before entering into the scattering chamber, where a beam current of a few hundred nA was collected for Ne^{9+} and ~ 10 nA for Ar^{16+}. In the scattering chamber, a base pressure of a few 10^{-7} Torr was achieved by a 1500-l/s turbo pump. This pressure was sufficiently low to avoid charge-exchange collisions for the incident ions but it was not sufficient to retain a clean surface on the Cu target. In particular, it is expected that the Cu surface is covered with a considerable amount of hydrocarbons which may affect the electron emission in ion-surface collision.

Details of the experimental geometry can be seen from the inset in Fig. 1. The ions were directed on a plane Cu plate whose position was fixed at an angle $\psi=10°$ with respect to the incident-beam direction. The ejected electrons were measured using a tandem electron spectrometer which has specifically been designed to measure electrons with high resolution at the angle of 0° relative to the incident beam direction [16]. In this work, we acquired electrons in a wide range of observation angles including 180°. The energy resolution of the spectrometer was 5%, if not otherwise stated. In a few cases, we improved the resolution to 0.5% by decelerating the electrons. Figure 1 shows normalized neon K Auger spectra measured at three different observation angles with respect to the incident Ne^{9+} beam direction. The data in

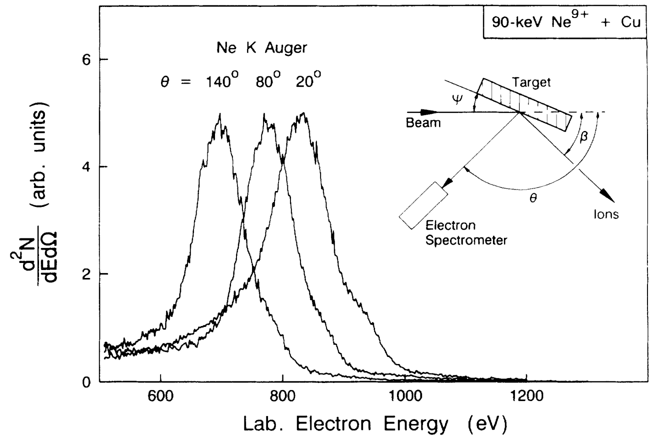

FIG. 1. Neon K Auger spectra for three different observation angles θ with respect to the incident beam direction. The spectra are normalized to the same height. The angle of incidence is $\psi=10°$. The scattering angle is labeled β.

Fig. 1 clearly show the Doppler shift varying with the observation angle θ. The Doppler shift changes the centroid energy of the neon K Auger lines; however, it is seen that the spectral shape of the three lines is rather independent of the angle of observation.

Figure 2 provides further examples of electron spectra for $10q$-keV N^{6+}, O^{7+}, and Ne^{9+} ions incident on Cu, measured at 20°. The spectra exhibit various maxima due to Auger electrons superimposed on a broad continuum due to kinetic electron emission. All spectra show the C K Auger peak indicating carbon covering the Cu surface. Peaks attributed to L and K Auger transitions give evi-

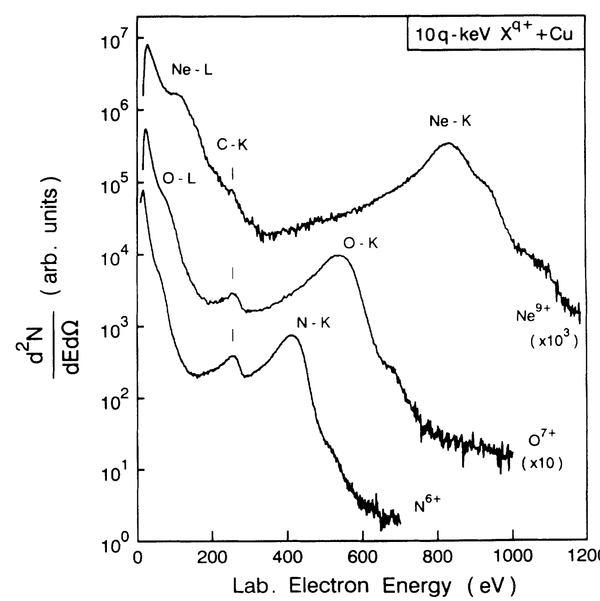

FIG. 2. Electron spectra produced in collisions of 60-keV N^{6+}, 70-keV O^{7+}, and 90-keV Ne^{9+} on a Cu surface under the incidence angle of $\psi=10°$. The electron-energy scale refers to the laboratory rest frame. Electron observation angle is $\theta=20°$ with respect to the incident-beam direction.

dence for the final deexcitation steps filling the L and K shell, respectively. In particular, the Ne^{9+} spectrum indicates a rather pronounced K Auger peak whose main intensity is attributed to KLL Auger transitions. On the high-energy side, the peak exhibits two shoulders. Using the quantum-defect version of the well-known Rydberg formula, we estimated K Auger energies for the case that electrons in shells higher than the L shell participate in the Auger transition. These estimates suggest that the additional spectral structures are primarily due to KLM and KMN Auger transitions. Similar observations were made for K Auger spectra obtained for O^{7+} and N^{6+} impact (Fig. 2).

Particular effort was devoted to the Doppler-shift analysis of the L and K Auger electrons. Under the condition of grazing incidence, it is likely that the angle of incidence is about equal to the angle of reflection. For an incidence angle of 10°, one might not expect much specular reflection of the ions with energies used in this work. Indeed, a great deal of the ions enter into the solid as discussed in more detail below. However, due to the high charge state of the incident ions, their reflection from the solid is stronger than otherwise expected. Therefore, the ions are scattered from shallow layers beyond the surface in a way similar to the case of grazing incidence. Thus, we adopted the picture of specular reflection from the solid.

Hence, for our experiments, we consider a reflected beam whose direction differs with respect to the incident beam direction by the scattering angle β (Fig. 1). Under the condition that the projectiles move parallel to the incident beam direction during the Auger emission, the full angle θ was used for the transformation of the spectrum to the projectile rest frame. Under the alternative condition that the ions are reflected before emitting the electron, the angle θ-β was used for the transformation. This change of angle is sufficiently large that it can be observed in the kinematic shift of the Auger energies. In the kinematic analysis we treated the scattering angle as a fitting parameter yielding results accurate to within $\pm 3°$.

Figure 3 shows neon L Auger spectra produced in 90-keV Ne^{9+}+Cu collisions. The spectra are transformed from the laboratory to the projectile reference frame under the hypothesis that the electrons are ejected by the incident ions [Fig. 3(a)] and by the ions deflected under $\beta=20°$ corresponding to specular reflection [Fig. 3(b)]. In Fig. 3(a) the coincidence of the transformed spectra observed at 20° and 60° clearly shows that the neon L Auger electrons are ejected by ions whose velocity direction is practically equal to that of the incident beam, i.e., the electron ejection occurs *before* a possible deflection of the ions from the surface. This observation leaves open whether the electrons originate from ions approaching the surface or from ions which have already entered into the solid.

Similar results were found for the argon L Auger spectrum produced in 90-keV Ar^{9+}+Cu collisions as shown in Fig. 4. It is noted that the Ar^{9+} spectrum is acquired with an improved energy resolution of 0.5% using the deceleration technique [16] for the electrons. Indeed, in this case where the spectrometer is capable of resolving

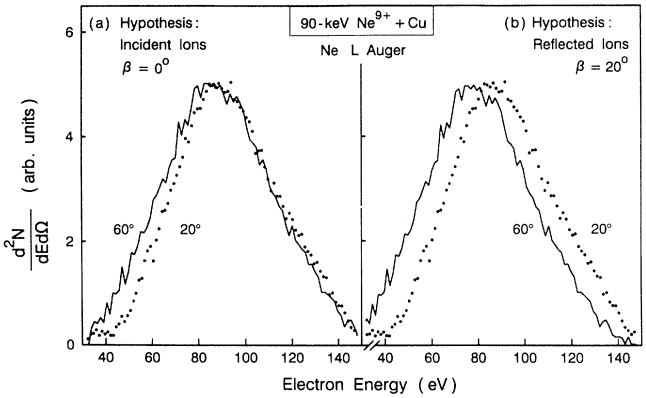

FIG. 3. Neon L Auger spectra produced by 90-keV Ne^{9+} incident under 10° on a Cu surface. Observation angles are $\theta=20°$ and 60° as indicated. The continuous background is subtracted. The spectra are transformed to the projectile rest frame under the hypothesis that electrons are ejected (a) from incident ions and (b) from ions deflected by the surface under $\beta=20°$ corresponding to specular reflection.

finer details, the Auger spectrum shows a rather sharp line structure at 205 eV, superimposed on a broader maximum. A similar structure at 212 eV has been observed by de Zwart *et al.* [8] who studied Ar^{9+} at significantly lower energies. The fact that the line structure is rather narrow suggests that the corresponding Auger electrons originate from the projectile which has still not entered into the solid. Distinction of Auger electrons ejected above and inside the surface has recently been made by Meyer *et al.* [12] studying N^{6+} under grazing incidence.

In order to investigate Ar ions with higher incident charge states, we performed experiments using 320-keV Ar^{16+} projectiles. Examples for Ar L Auger spectra are given in Fig. 5 showing data for the observation angles $\theta=20°$ and 40°. The spectra are transformed into the incident projectile frame of reference. The kinematic

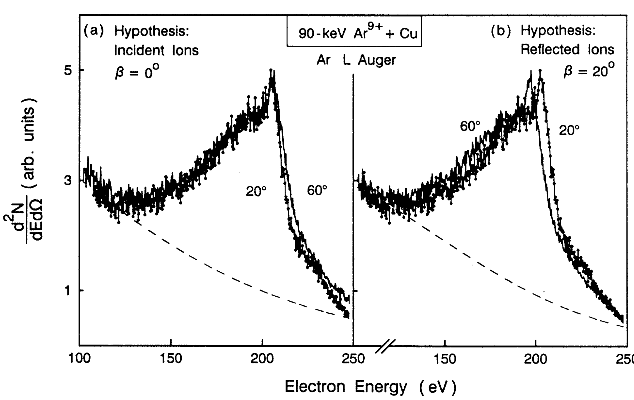

FIG. 4. Argon L Auger spectra produced by 90-keV Ar^{9+} incident under $\psi=10°$ on a Cu surface. Observation angles are $\theta=20°$ and 60°. The spectra are transformed to the projectile rest frame under the hypothesis that electrons are ejected (a) from incident ions and (b) from ions deflected by the surface under $\beta=20°$. Energy resolution is 0.5%.

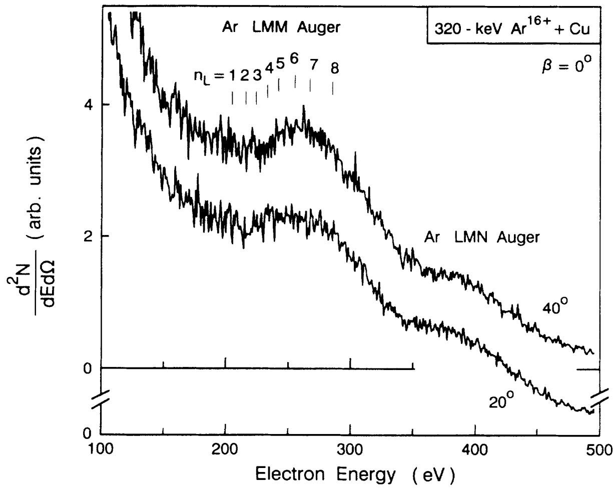

FIG. 5. Argon L Auger spectra produced by 320-keV Ar^{16+} incident under $\psi=10°$ on a Cu surface. Observation angles are $\theta=20°$ and 40°. The spectra are transformed to the projectile rest frame under the hypothesis that electrons are ejected from incident ions (with $\beta=0°$). The markers indicate Ar L Auger energies roughly estimated by the Rydberg formula under the assumption of n_L projectile L-shell vacancies and a filled M shell.

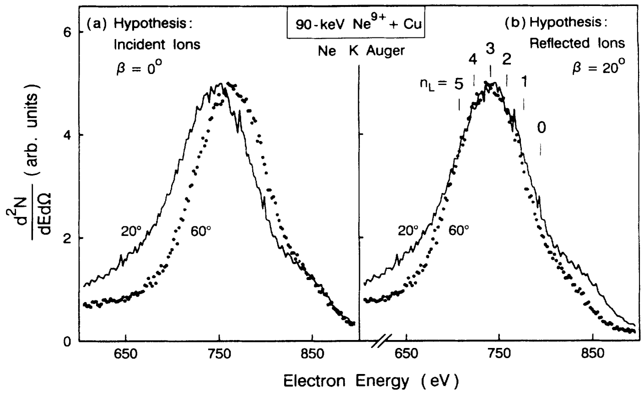

FIG. 6. Neon K Auger spectrum produced by 90-keV Ne^{9+} incident under $\psi=10°$ on a Cu surface. Observation angles are $\theta=20°$ and 60°. The transformation to the projectile rest frame is performed under the hypothesis that electrons are ejected (a) from incident ions and (b) from ions deflected by the surface under $\beta=20°$ corresponding to specular reflection. The markers indicate mean Ne K Auger energies obtained from Ref. [24] assuming n_L projectile L-shell vacancies.

analysis of the Ar L Auger spectra indicates that the electrons are emitted from argon projectiles whose flight direction is equal to the incident beam direction. The original spectra exhibit a rather strong C K Auger peak originating from carbon layers on the copper surface as was shown in our previous work [14]. Since the intensity of the C K Auger peak was found to vary only weakly with the observation angle we were able to subtract this peak out of the electron spectra. This was done to simplify the spectral analysis of the Ar L Auger peaks. In Fig. 5 the spectra show the Ar LMM and Ar LMN Auger peaks whose centroid energies are about 275 and 385 eV, respectively. The centroid energy of the LMM peak is significantly higher than the corresponding energy of 205 eV for Ar^{9+} incident on Cu (Fig. 4). This finding is due to various L vacancies in the Ar projectile as discussed below.

For the K Auger spectra produced by Ne^{9+} impact on Cu, we find a completely different behavior than for the L Auger spectra of Ar^{9+} and Ar^{16+}. It is seen from Fig. 6(a) that the transformed spectra obtained for observation angles of 20° and 60° do not coincide. Therefore, it is concluded that the K Auger electrons are not ejected from projectiles whose velocity direction is equal to the incident-beam direction. Rather, coincidence of the transformed spectra is achieved under the hypothesis that the Auger electrons are ejected after a deflection of the ions by $\beta=20°$ corresponding to specular reflection [Fig. 6(b)]. Likewise, from our experimental results for N^{6+} and O^{7+} we came to the same conclusion, i.e., that the K-shell vacancy of the projectile survives the interaction of the ion with the surface. Examples for N^{6+} incident on Cu are given in Fig. 7 which shows that the transformed N K Auger spectra coincide best if a scattering angle of $\beta=14°$ is assumed. Moreover, a scattering angle of 16° was found for O^{7+}. These findings indicate an important difference in the L Auger electron emission from Ar^{9+} and the K Auger emission from N^{6+}, O^{7+}, and Ne^{9+} near the Cu surface.

It should be added that with regard to the hydrocarbon layers deposited at the Cu surface, we also measured Auger spectra produced by ion impact on a pure carbon solid. The C data show characteristic differences to the Cu results. For example, the kinematic analysis of spectra produced by O^{7+} impact on C yields the result that the O K Auger electrons are emitted from ions whose flight direction is equal to the incident one, contrary to the data obtained for Cu. Therefore, in the case of the

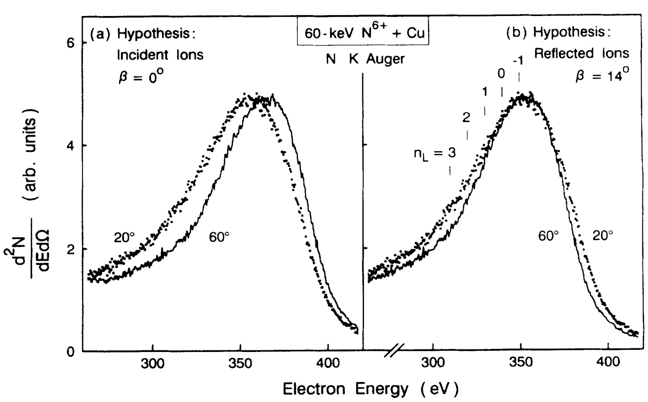

FIG. 7. Nitrogen K Auger spectrum produced by 60-keV N^{6+} incident under $\psi=10°$ on a Cu surface. Observation are $\theta=20°$ and 60°. The transformation to the projectile rest frame is performed under the hypothesis that electrons are ejected (a) from incident ions and (b) from ions deflected by the surface under $\beta=14°$. The markers indicate mean N K Auger energies obtained from Ref. [11] assuming n_L projectile L-shell vacancies.

Cu experiments it is likely that the ions penetrate the C layers without much effect and, because of the higher mass and charge of the Cu atoms, are subsequently reflected from the solid. This finding suggests that the layers formed by the light carbon atoms are rather transparent for the incident and reflected ions. The same transparency might be expected for the Auger electrons produced in the solid, as the hydrocarbons form an insulator. It should be emphasized, however, that the unknown thickness of the C layer deposited on the Cu surface causes uncertainties in the interpretation of the experimental data. Hence, the following discussion is sometimes limited to qualitative arguments.

III. DISCUSSION OF THE RESULTS

The distinct difference between the L Auger emission from Ne^{9+}, Ar^{9+}, and Ar^{16+} and the K Auger emission from N^{6+}, O^{7+}, and Ne^{9+} gives rise to intriguing questions. In the following we shall focus our attention on the Ar^{9+} and Ne^{9+} projectiles. It is unlikely that the different observations for these ions are due to differences in the Auger cascade mechanism for filling the L and K vacancies. When the Ar^{9+} or Ne^{9+} ions approach the surface, projectile Rydberg states with principle quantum numbers near $n \approx 10$ are filled via charge-exchange processes. We would not expect a significant time difference from one or two additional steps out of the ~ 20 steps in the cascade ladder whose descend is required to finally reach the L or K shell. In this connection, it is important to note that LMM Auger transitions are usually not faster than KLL Auger transitions. On the contrary, the normal Ar L Auger transitions are (slightly) slower than the Ne K Auger transitions [17].

In any case, we suppose that the details of the final Auger cascade steps are not really important for the present analysis. Charge transfer into the incident ion starts at distances [18] as large as ~ 25 Å. Using this value as starting point, 90-keV Ar^{9+} and Ne^{9+} ions incident under 10° need about 10^{-14} sec to reach the surface. As shown recently [5,11], this times is too short to complete the Auger cascade and, thus, the projectile hits the surface as a hollow atom. Therefore, to explain the measured L and K Auger transitions we conclude that the associated M and L shells receive electrons *within* the solid. It should be recalled that the LMM and KLL Auger transitions require at least two electrons in the M and L shell, respectively. The M-shell radii of Ar^{9+} and Ne^{9+} are of the same order as the dynamic screening length $\lambda_{sc} = v_i / \omega_p$ in Cu where v_i is the incident velocity and ω_p is the plasma frequency [19]. Hence, it is expected that the projectile M shell is filled instantaneously when the ions enter into the solid. (This does not rule out that the M shell is already partially filled by the Auger cascade.) To transfer electrons into the L shell certain violent collisions are required as discussed below. In this case, near-resonance charge exchange between inner shells [20,21] may play an important role.

Since the L and M shells receive electrons inside the solid, it is likely that the related Auger process takes place inside the solid, too. In this case, one has to take into account that electron-solid interactions change the energy and flight direction of the electrons. These solid-state effects may considerably broaden the Auger spectra. In particular, the broadening produced by the change of the electron flight direction is expected to be important. This kinematic broadening, which is unique for the Auger emission from a moving particle, results from the superposition of Doppler-shifted energies for electrons ejected at different angles and finally reaching the same detector. It should be emphasized that this broadening effect produces a profile which is essentially symmetric with respect to the centroid energy of the Auger line. Contrary to this, the broadening effect due to the energy loss creates an asymmetric profile since it reduces the spectral intensity in the main peak and enhances its low-energy side [22]. It should be added that both broadening effects are expected to vary with the observation angle due to a variation of the effective escape depth of the electrons in the solid.

Returning to Fig. 4 it is noted that the Ar L Auger spectra exhibit asymmetric profiles involving a certain enhancement at lower energies (not accounting for the underlying electron continuum). This suggests that a considerable part of the electrons originate from inside the solid. A smaller fraction may be due to electrons ejected from the incident ions before hitting the surface. This part is likely to be associated with the sharp line structure at 205 eV noted above. On the other hand, from Fig. 6 it is seen that the Ne K spectra are essentially symmetric. Also, the spectral profiles do not change significantly as the observation angle varies. Moreover, it is noted that the present Ne K Auger spectra produced in ion-solid collisions are similar to those obtained in ion-gas collisions [23], e.g., in collisions of 100-keV Ne^{+} on Ne. Therefore, it is likely that the Ne K Auger-electron emission occurs outside the solid or close to the surface. This finding is consistent with the kinematic analysis of the Auger spectra which indicates electron ejection from reflected ions emerging from the solid.

The comparison of Figs. 4 and 6 indicates another distinct difference between the ions Ar^{9+} and Ne^{9+}. In accordance with previous work [3,9] it may be concluded from the 205-eV line structure in the Ar L Auger spectrum that the outer M shell is completely filled when the Auger transition takes place. However, the centroid energy of 740 eV of the Ne K Auger spectrum [Fig. 6(b)] provides evidence for an outer L shell which is incompletely filled when the Auger transitions occur. Figure 6(b) shows markers indicating the mean energy of Auger lines attributed to a given number of Ne L shell vacancies. These data have been extracted from previous work [24] where a functional one-to-one correspondence between the mean number of L-shell vacancies in Ne and the corresponding K Auger centroid energy has been reported. The markers show that, on the average, about three electrons are missing in the outer L shell at the instant of the KLL Auger transition.

Recently, Folkerts and Morgenstern [10] measured Ne K Auger spectra produced by 150-eV Ne^{9+} ions incident under 45° on a polycrystalline W surface. They came to the controversial conclusion that the Ne L shell is completely filled at the instant of the K Auger decay. In principle, different Ne K Auger spectra are possible because of the lower energy used in the previous experiments. However, in our opinion, the Ne K Auger spectra by Folkerts and Morgenstern [10] show also that the major part of the K Auger transitions involves an incompletely filled L shell. On the other hand, recent studies [10,11] of Ne^{6+} ions interacting with surfaces indicate that the N L shell is "overfilled" (i.e., containing six electrons) when the K Auger transition occurs. The overfilled L shell is confirmed by our data for N^{6+} impact [Fig. 7(b)]. In view of this result it is noted that N^{6+} needs less electrons to fill the L shell than Ne^{9+} and that the nitrogen L-shell electrons are less tightly bound.

Clear evidence that projectiles are still highly charged when they hit the surface is obtained for Ar^{16+} impact. Figure 5 indicates the number of Ar L vacancies by markers whose position was roughly estimated by means of the quantum-defect Rydberg formula mentioned above. It is seen that for Ar^{16+} ions incident on Cu the L shell is still nearly empty during the major part of the observed Auger transition. Thus, the present data clearly confirms that the ions reach the surface as hollow atoms. The same result has previously been obtained by Briand *et al.* studying x-ray spectra induced by Ar^{17+} and Ar^{18+} impact on Ag. It is recalled that for Ar^{16+} impact the L Auger electrons have been found to be ejected from ions whose flight direction is parallel to the incident one. This may be understood from the relatively high energy of the 320-keV Ar^{16+} ions which enter into the solid without being appreciably deflected.

However, significant reflection occurs at lower energies, i.e., for 90-keV Ar^{9+} and Ne^{9+}, as shown by model calculations carried out using of the TRIM code by Biersack and collaborators [25]. We also performed preliminary calculations of ion trajectories in solids using rather flexible scattering potentials which may be adjusted to the high incident charge state of the projectiles. In addition, we gained information about the energy and angular straggling of electrons escaping from the solid. Although the calculations are still preliminary, they allow for specific conclusions characteristic for the behavior of the ions near the surface. Two extreme cases were studied. Firstly, in view of the previous Auger neutralization model by Arifov *et al.* [1] we performed calculations under the assumption that the ions have reached their equilibrium charge state when they arrive at the solid. Secondly, with regard to the fact that the projectile hits the surface as a hollow atom, we performed calculations under the alternative assumption that the projectile retains its incident charge state along its trajectory in the solid. In the latter case, the ion scattering is found to be enhanced but not as significantly as calculated by Meyer *et al.* assuming bare Coulomb potentials for both collision partners.

Our model calculations show that the majority of the projectiles enters into the solid. However, a significant amount of ions ($\sim 30\%$) leaves the solid after a few collisions with atoms in shallow layers beyond the surface. Also, the exit angle $(\beta-\psi)$ maximizes at a value $\leq 10°$, i.e., about equal to the incidence angle. This result supports the approximation in our Doppler analysis using a single scattering angle. Moreover, we found typical penetration depths of only ~ 5 Å for the ions studied here. These data appear to confirm our picture of Auger-electron emission from ions reflected from the solid. Nevertheless, our analysis indicates that Auger electrons are emitted inside the solid and that they may still be influenced by solid-state effects.

Hence, particular arguments would be useful supporting the symmetric profiles of the Ne *KLL* spectra which do not show much influence by solid-state effects. Furthermore, it remains to explain the controversial findings that the Ar *LMM* and Ne *KLL* Auger electrons are ejected from incident and reflected ions, respectively. To interpret both phenomena it is pointed out that the processes of violent ion scattering and electron transfer into the projectile L shell are closely related. The mechanism of ion reflection in collisions with atoms in a shallow region beyond the surface generally involves at least one scattering event with angles larger than 10°. In this case the collision partners approach each other to distances less than 0.2 a.u. Since this distance coincides with the radii of the L shells of Ar^{9+} and Ne^{9+} it is likely that one or more L-shell vacancies are filled in such violent collision. In particular, the L shell may be filled by resonant electron transfer from the K shell of carbon, which is located on the Cu surface. This process is rather likely, since the Ar L and C K shell match in energy [21].

The filling of L-shell vacancies has completely different consequences for the Auger-electron creation by Ar^{9+} and Ne^{9+} projectiles. The Ar^{9+} ion involves only one L vacancy whose filling inhibits further L-Auger transitions. Thus, little Auger emission is expected from reflected Ar^{9+} ions, in agreement with the present experimental results. On the other hand, Ne^{9+} involves a completely empty L shell whose filling opens the channel for the Ne *KLL* Auger process. Therefore, K Auger-electron is favored for neon ions reflected from the solid. If the reflection takes place in a shallow region beyond the surface one would expect that the ions leave the solid in such a short time that the Auger electrons are ejected outside the solid. This would support the finding that the Ne K Auger spectrum are nearly free of solid-state effects.

Finally, some controversial aspects are pointed out in connection with the interpretation of the Ne L Auger spectra. From Fig. 3 it was already noted that Ne L Auger electrons are likely to be ejected from the incident projectiles. Hence, Ne L Auger electrons originate from ions approaching the surface or moving in the solid without having changed much their incident-flight direction. The latter case is supported by the fact that the M shell of the projectile is likely to be filled immediately after its penetration into the solid. Regardless of the details of the incident Auger-electron emission, Fig. 3 suggests that not many Ne L-shell vacancies survive a reflection of the projectile. This inference, however, appears to be inconsistent with the finding that the projectile L shell is partially empty during the K Auger transitions (Fig. 6).

It is possible that the Ne L shell is filled rather early but that the violent collisions causing the projectile deflection produce new L-shell vacancies. Indeed, creation of ~ 3 L-shell vacancies has been observed [23] in violent *single* collisions of 100-keV Ne^{+} with Ne. In any case, the filling of the L-shell vacancies following the K Auger transitions should give rise to L Auger electrons originating from reflected projectiles. The appearance of such L Auger electrons, in turn, would be inconsistent with the kinematic analysis shown in Fig. 3. This inconsistency could be removed by the assumption that L Auger electrons from reflected projectiles are buried in the continuous background. Indeed, a significant amount of L Auger electrons are missing as can be concluded from the L- to K-shell Auger intensity ratio for which the relative small value of 1.3 was found. This ratio has been studied in some detail by Folkerts and Morgenstern [10] who proposed "side-feeding" effects to explain the missing L Auger electrons.

Alternatively, a certain amount of L Auger electrons may be considered lost in the dominant low-energy background between ~ 10 and ~ 40 eV. The background subtracted Ne L Auger spectrum (Fig. 3) was obtained assuming a negligible contribution of Auger electrons in the 10–40-eV region. This assumption, which was made for reasons of simplicity, may be unrealistic. The energy of the L Auger electrons decreases with decreasing number of L vacancies (see Fig. 5 and Ref. [11]). In particular, the *LMM* transition energies are supposed to be shifted to values as low as 10 eV. (Thus, it appears that the Ne L Auger peak is not only produced by *LMM* transitions but also by *LMN* transitions.) Likewise, the L Auger energies are shifted even further to lower values when the Ne K shell vacancy becomes filled. Therefore, after the reflection of the neon projectile and the associated K Auger transitions, a significant amount of the ejected L Auger electrons may be lost in the low-energy background. Further experimental and theoretical work is planned to shed light on mechanisms of Ne L Auger electron ejection near surfaces.

IV. CONCLUSIONS

We studied electron emissions from Cu surfaces interacting with slow, highly charged ions. The experiments were made under non-UHV conditions so that hydrocarbons are expected to deposit on the Cu surfaces. Thus, because of the unknown thickness of the surface covering, some uncertainties are involved in the interpretation of the experimental results. However, the phenomena observed in this work are rather significant so that definite conclusions can be made even within the uncertainties originating from the surface covering. Nevertheless, intriguing questions remain open with respect to the complex mechanisms occurring in multicharged ions interacting with a surface.

We report on the first observation that, for incident N^{6+}, O^{7+}, and Ne^{9+} ions, the K Auger electron are emitted from the projectiles after reflection from a shallow region beyond the surface. There are various indications for this Auger emission from the reflected ions: (i) The Doppler-shifted Auger spectra coincide if the electrons are assumed to be emitted from ions reflected by the surface, (ii) Auger emission from reflected ions is observed for solids of (heavy) Cu but not for solids of (light) C, and (iii) the Ne K Auger spectra are nearly free of solid-state effects suggesting that the electrons are emitted from ions which have already left the solid. Furthermore, it should be recalled that indications for Auger processes in scattered ions have previously been observed by de Zwart *et al.* [13].

On the other hand, Auger emission from reflected ions was not observed for Ar^{9+} impact. In this case it is expected that, during the deflection event, the L-shell vacancy of Ar^{9+} is filled by an electron-exchange process inhibiting further L Auger transitions. Hence, the survival of an inner-shell vacancy in a reflection event appears to be a specific feature for the K shell of N^{6+}, O^{7+}, and Ne^{9+}. It is anticipated that the inner-shell vacancy survival is particularly important for future studies where highly charge ions are applied as probes to gather information about surface properties.

Another significant result is concerned with the observation that for Ne^{9+} impact the L shell of the reflected ions is only partially neutralized. About three L-shell electrons are missing when the major part of the K Auger transitions takes place. This phenomenon can be seen even more clearly for Ar^{16+} impact. The Ar L shell is nearly empty during the emission of the observable L Auger electrons. This finding indicates that the projectiles enter into the surface as highly charged ions where only the first part of the L-shell filling is observed via the method of Auger-electron detection. Hence, the ions arrive at the solid as hollow atoms whose effects on the surface are anticipated to be a novel subject for further studies.

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