Observation of High Electron Emission Yields following Highly Charged Ion Impact (up to Th^{75+}) on Surfaces

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Doubly differential electron emission yields following the impact of fast (3.95×10^7 cm/sec) $Ar^{9,12,18+}$, Ne^{9+}, $Xe^{30,44+}$, and $Th^{70,75+}$ ions on Cu and Au targets have been measured. The electron emission is dominated by low-energy electrons (< 50 eV). It is found that the total yield, which rises to about 100 electrons per ion, is a nonlinear function of the total potential energy of the incident ion (up to about 200 keV).

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Ion-surface interaction studies by means of electron emission measurements have been of interest for many years [1] and are the subject of intense investigations at present. These studies address the fundamental question of how fast ions that carry up to about 200 keV of potential energy lose their energy in the neutralization process. Fast beams of highly charged ions are produced in sophisticated ion sources such as an electron cyclotron resonance source, an electron-beam ion source (EBIS), and a variant of the EBIS, the electron-beam ion trap (EBIT). In this Letter we report a first measurement of the electron emission yield as a function of total potential energy for extracted EBIT ions [2–4] ranging in Z from 10 to 90 and charges up to 75+ incident on Cu and Au targets.

It has been demonstrated that slow ions capture electrons efficiently into high-n states at relatively large distances depending on the ionic charge [5,6]. The ion is promoted into a multiply excited state as it approaches the surface with the electrons occupying high-n levels while the core is virtually empty. X-ray and electron spectroscopy are used to study the dynamics of the decay of these states via decay cascades. Total yield measurements [7,8] of the emitted electrons as a function of projectile velocity and charge as well as Auger electron spectroscopy have been performed so far using ions up to Ar^{q+} for $q \leq 12$ [9] and Ar^{16+} [8]. These data help to answer the question of to what extent the ion neutralization occurs prior to penetration of the surface and how much occurs after, as well as the energy loss mechanisms [10].

Previously the total electron emission yields were determined by measurements with ion velocities between 0.2×10^7 and 4.0×10^7 cm/sec and potential energies up to about 2.6 keV. Winter *et al.* [7] found that the emission yield rises linearly with the potential energy of the incident ion with one electron emitted for each 90 eV of potential energy. They furthermore showed that for Ar^{9+} the yield rises rapidly as the impact velocities are reduced below 10^7 cm/sec. Measurements of Auger electron emission from various groups [9,11,12] not only show the formation of "hollow" ions in slow highly charged ions incident on surfaces, but also suggest that much of the potential energy of the incident ions is not released in front of the surface. For example, Köhrbrük *et al.* [8] studied Ne^{9+} on copper under the conditions of incidence grazing and large angle of incidence. They found from an analysis of the Doppler-shifted spectra that the K-shell vacancy actually survives reflection from the surface; K-LL Auger electrons are emitted from the reflected ions with about three vacancies retained in the L shell.

In the experimental setup an ion beam is momentum analyzed and collimated onto the target such that the electron emission in the backward direction can be analyzed. A schematic representation of the experimental geometry is depicted in the inset of Fig. 1. The electrons are energy analyzed with a hemispherical electrostatic analyzer and detected with a channel-plate detector. Both the analyzer and the detector are enclosed within a magnetic shield to prevent perturbation of the low-energy electrons by stray magnetic fields. The geometric solid angle is 2.9×10^{-4} sr and the total detection efficiency is $\approx 30\%$. The targets consisted of evaporated self-supporting Cu and Au foils of about 200 $\mu g/cm^2$ thickness. The target was biased at negative 100 V to overcome space-charge effects and focus the electrons from

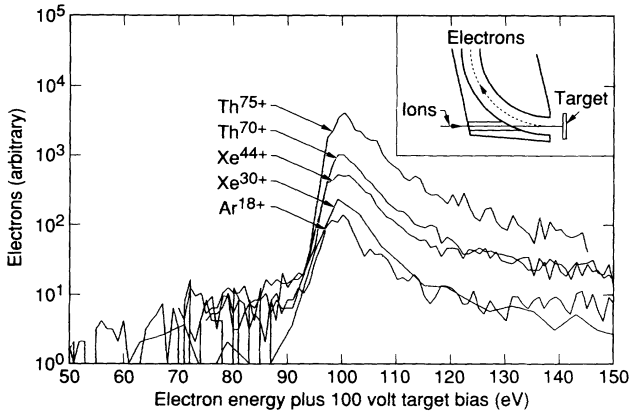

FIG. 1. Electron emission spectra following Ar^{18+}, Xe^{30+}, Xe^{44+}, Th^{70+}, and Th^{75+} impact at normal incidence on Au. Inset: Target-area geometry. The ions approach from the left to the target on the right; the electrons move to the left and up to the detector (not shown).

the surface into the analyzer. The residual gas pressure in the ion transport system was 2×10^{-8} Torr which caused a charge exchange of the ions of less than 20%. The vacuum in the target chamber was 2×10^{-7} Torr which implies undefined surface conditions for both the Cu and the Au target. The vacuum is sufficient to prevent changes of the unprepared surfaces during the measurements and the relative yields should not be affected. The incident ion flux is low such that target alterations from projectile ion impact are negligible. It is assumed that the surface of the Cu target has more oxygen layers built up on it than the Au target. This is reflected in the different work functions of the targets. The work functions of Cu and Au are 4.65 and 5.1 eV, respectively [13], or a difference of 0.45 eV, while the measured difference is ≈ 0.2 eV.

A series of low-energy electron spectra are presented in Fig. 1 for several ions incident on the Au target; the relative doubly differential yield is plotted as a function of the electron energy. The spectra are shifted by the target bias of negative 100 V. From the integrated yields the absolute number of electrons per ion has been deduced by applying the above quoted solid angle and detector efficiencies. Figure 2 shows a spectrum obtained from Ne^{9+} incident on a Cu target; it shows the lower-energy electron distribution and structure due to Ne L- and K-shell Auger electron emission. The contribution of Auger electrons to the total emission yield is less than 20%. Space-charge and focusing effects were examined by measuring the ratio of the L- and K-shell Auger emission as a function of target bias as shown in Fig. 2. Our results compare favorably with those presented by Folkerts and Morgenstern [12]. Our measurements show that the electron emission is dominated by low-energy electrons with a mean energy of less than 20 eV which agrees well with predictions from the Bardsley model [14], which is based on classical field-emission theory and the dynamics of the electron plasma. The absolute yields have been plotted as a function of total potential energy in Fig. 3. Data published by Delaunay *et al.* [7] for $Ar^{4,9,11,12+}$ and Kr^{11+} are plotted for comparison. These data from Delaunay *et al.* were taken at an incident ion velocity of 2.0×10^{7} cm/sec on a W target. Our data were taken with an incident ion velocity of 3.95×10^{7} cm/sec on Au and Cu targets. Justification for comparing the different incident velocities is given in Ref. [7], where it is shown that the electron yield changes by less than 10% when the velocity is changed from 2.0×10^{7} to 3.5×10^{7} cm/sec, and there is similarity of the various targets. It was noted by deZwart [15] that there seems to be a rather weak dependence of the electron yield per incident ion on the angle at which the incident ion approaches the target. Auger electron emission is weakly observed ($<10\%$ of the total yield) at higher electron energies for the cases of incident $Ar^{9,18+}$ ions. Energy scans up to 900 eV for Xe^{44+} and Th^{70+} ions did not show Auger emission. The fact that essentially no Auger electron intensity is observed for $Z>18$ indicates that there is no significant filling of shells with $n<10$ via direct Auger cascades for high-Z ions. An ion velocity of 3.95×10^{7} cm/sec implies that the ion reaches the surface from about 25 Å ($\approx 6.3\times10^{-15}$ sec) much faster than the assumed filling times for low-lying states (10^{-12} to 10^{-13} sec [16]).

Recently an analysis and comparison of model calculations and measurements of the velocity dependence of Auger electron emission for N^{6+} ion impact on Au surfaces has been reported [17,18]. The calculations are based on the classical over-the-barrier model where image charge, screening effects, and a so-called "peeling off" of electrons in high-n states or loss to the conduction band were taken into account or discussed. The data from N^{6+} incident on Au targets demonstrate the appearance of an "above the surface" component in the Auger structure at sufficiently low ion velocities [17,18].

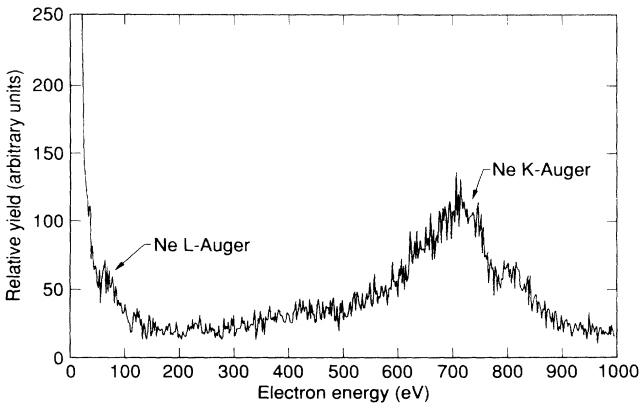

FIG. 2. Ne L- and K-shell Auger emission spectra following 32-keV Ne^{9+} normally incident on a Cu target. The energy spectrum has been corrected for the target bias.

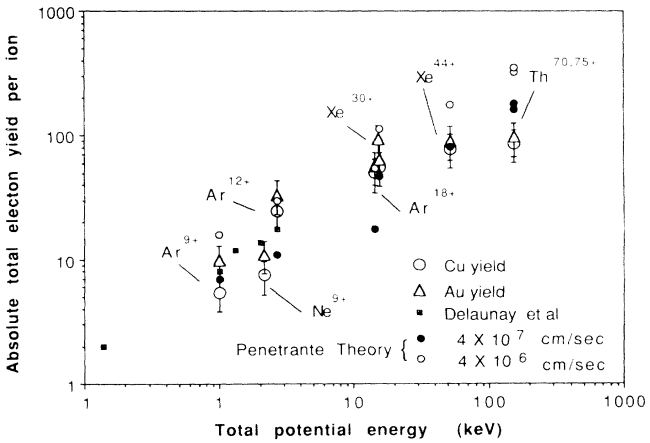

FIG. 3. Absolute total electron emission yield as a function of total ion potential energy. Previous data from Ref. [7] and theoretical data from Penetrante [21] are superimposed.

It can be inferred from these studies that the electron emission observed in the present case stems predominantly from the neutralization processes below the surface. That can also be assumed from the broad Auger electron emission spectra observed from Ne^{9+} incident on Cu. It has been reported [19,20] that the electron yield increases drastically with decreasing incident ion velocity due to the wider time window available for the neutralization processes to take place above the surface. The measured electron yield in the present work is representative of electrons that escape from the surface or below and they do not reflect the total yield due to the neutralization processes below the surface. The attenuation of the electron emission is difficult to estimate due to the unknown depth profile of the neutralizing ions. For the case of Ne^{9+} incident on Cu it can be assumed that the ratio of low-energy electrons to high-energy Auger electrons is much higher than indicated because of the difference in escape depth for the Auger electrons at different energies. A rough estimate for the fraction of electrons produced via neutralization below the surface compared to those above the surface can be deduced from a comparison of the measured yield curve to calculated values for slower ion impact using the Bardsley model. The yield increase for the ion species studied here averages to about a factor of 2 when the velocity changes from 4×10^7 to 4×10^6 cm/sec as shown in Fig. 3. It should be noted that this is a crude comparison since the calculation is incomplete and since the effect of the image-charge acceleration, for example, is untested. The fluorescence yields for the various inner shells $(K,L,M,N,O,\ldots)$ from highly charged ions, which are assumed to neutralize in the surface and below, might increase up to at least 60% with increasing Z. This strong increase suggests that the major decay of the inner shells occurs via x-ray emission and may therefore account for the saturation of the total electron emission yield. A velocity-dependent measurement of the fluorescence yield could clarify this question.

The total electron emission yield in Fig. 3 increases from about 10 electrons per ion for Ne^{9+} to about 100 electrons per ion for Th^{75+} incident. The increase of the measured yields with increasing total potential energy of the ions is found to be nonlinear at an ion velocity of 3.95×10^7 cm/sec. This observation is in agreement with both Winter's and deZwart's [9,15] discussion of the predicted proportionality of electron yield with total potential energy being valid only up to certain q limits, above which the electron yield increases more slowly with potential energy than for lower q. The existing experimental data presented previously [7] indicate a linear rise in electron emission with increasing ion potential energy for velocities up to 0.4×10^7 cm/sec. Extrapolation of these linear results yields ≈ 1600 electrons per incident ion for Th^{75+}. The present results for a higher velocity are considerably lower. Since the high-Z highly charged ions carry inner-shell vacancies, it can be assumed that the emission of much more energetic Auger electrons or x rays occurs which causes the loss of a substantial fraction of the available potential energy. For the case of Th^{75+} only about 2 of the available 152 keV potential energy would be released via low-energy electrons.

The data presented show that even for fast very highly charged ions incident on metal surfaces the total electron emission is dominated by low-energy electron emission (< 20 eV). The increased total electron yield shows a nonlinear dependence from the total potential energy in the range from 1 to about 200 keV. The number of emitted electrons per ion indicates that much of the potential energy is maintained until the ion actually reaches the surface. The total energy of the ions penetrating the surface cannot be deduced since the yield for high-energy Auger electrons and x rays is unknown at present.

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