Statistics of ion-induced kinetic electron emission: A comparison between experimental and Monte Carlo–simulated results

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The statistics of kinetic electron emission from clean gold under impact of slow (< 1 a.u.) ions (H^+, Na^+, Xe^+) have been studied both experimentally and by means of Monte Carlo simulations. Experimentally observed deviations from the Poissonian distribution can be explained within the presented model calculations to result from large-angle-scattering events leading to backscattering of incident ions (for light projectiles) and/or recoiling of target atoms (for heavy projectiles). Good agreement is found between experimentally observed and simulated-emission statistics.

Ion-induced electron emission from an atomically clean, polycrystalline metal target surface can be formally ascribed to the two processes of potential emission (PE, i.e., emission taking place before the projectile hits the surface and arising from Auger-type processes) (Ref. 1) and kinetic emission (KE, i.e., contributions appearing after the projectile has hit the surface and connected to stopping of the projectile within the uppermost atomic layers of the solid).[2] The statistics of these processes is of special importance for registration of extremely small particle currents. From this statistics, i.e., the probabilities W_n for emission of a given number n of electrons due to a single impact event [henceforth called emission statistics/(ES)], the related total electron yield γ as the mean number of emitted electrons can be evaluated:

$$\gamma=\bar{n}=\sum_{n=1}^{\infty} nW_n, \quad \sum_{n=0}^{\infty} W_n=1 . \tag{1}$$

In a number of experiments,[3–16] ion-induced kinetic-electron-emission statistics have been investigated and considerable deviations from the Poissonian distribution $P_n(\gamma)$ with the mean value γ,

$$P_n(\gamma)=\frac{\gamma^n}{n!}e^{-\gamma} , \tag{2}$$

have been observed,[7,10,13,15,16] whereas such ES are quite often assumed to obey Poissonian distributions. The reason for these deviations has not yet, to the authors' knowledge, been investigated in detail.[17] The present work has been devoted to this question, by comparing experimental ES data with Monte Carlo calculations for the incident ion- and resulting recoil-atom transport, applying a semiempirical model for the kinetic emission process.

Our experimental methods to determine precise total yields and statistics for particle-induced electron emission have recently been described[15–18] and will thus only briefly be reviewed. A target surface (sputter-cleaned polycrystalline gold) is hit by projectile ions of interest with impact energies varied between 100 eV and several keV. An extraction geometry consisting of a negatively biased grid around the target and a number of cylindrical electrodes[18] serves for deflection and acceleration of all emitted electrons towards an energy-sensitive solid-state detector biased at 26 kV with respect to the target. Using quite low incident ion fluxes ($< 10^3$ ions/s), from the resulting electron-energy–pulse-height distributions, after correction for electrons backscattered from the detector,[17] the electron-emission statistics can be obtained.[15–18] As already shown in Ref. 16, a critical comparison of the measured ES with the related Poisson distribution for the actual electron yield γ can be made by plotting ratios of relative ES probabilities W_{n+1}/W_n versus the corresponding expressions of the related Poissonian distribution, which from Eq. (2) are given by

$$P_{n+1}/P_n=\gamma/(n+1) . \tag{3}$$

However, such a comparison can only be made for projectiles which cause a negligibly small PE contribution, because PE cannot be related to a statistical process like KE. For H^+ impact on clean gold the PE yield is below 0.02 at 100 eV, and decreases even further toward higher E.[18] Consequently, PE can be safely neglected for $E \geq 1$ keV in comparison with the KE. The also-applied heavier projectile ions Na^+ and Xe^+ do not carry enough potential energy to cause appreciable PE (Na^+, 5.1 eV; Xe^+, 12.1 eV), as was demonstrated in Ref. 19.

Theoretically, the ES for KE are regarded as the result of statistical collision processes of both the projectile ion and the excited electrons, and, for heavy projectiles, also of the recoiling target atoms which are generated from elastic collisions of the projectile inside the target. For the simulation of KE-related ES, a semiempirical model[20] was applied in a Monte Carlo simulation of the slowing down along nonlinear trajectories of the projectile and the recoiling target atoms in the target. The TRIM Monte Carlo program[21] was modified to follow also the trajectories of recoiling atoms in the same manner as the projectile.[22] In the semiempirical model, depending on the inelastic stopping power $(-dE/ds)$, electrons are excited along the trajectories, viz., $N=(-dE/ds)/J$, where J is the average energy to be deposited for excitation of an electron. Transport of the excited electrons to the surface is described by an exponential attenuation function $\exp(-x/L)$, where x is the excitation depth and L the mean electron attenuation length. With P as the probability for an electron to overcome the surface potential barrier, we obtain for the total electron emission yield the sum of $(P/J)(-dE/ds)\exp(-x/L)$ along trajectories of both the projectile and recoil atoms.[22] For L we adopt a value of 13.7 Å.[23] The statistical fluctuation in the transport of excited electrons is taken into account by a Poissonian distribution. The factor P/J was evaluated by fitting the mean electron yield calculated with 10^4 incident ions to the corresponding experimentally obtained electron yield.

In Figs. 1, 2, and 3, we show relation (3) between the total yield and the ratios of subsequent ES probabilities for impact of H^+, Na^+, and Xe^+ ions, respectively, on clean gold. The above-stated deviations of the experimental ES from the Poissonian distribution can be clearly recognized. For low electron yield the experimental ES are apparently wider than the related Poissonian distributions, whereas an opposite trend takes over toward higher electron yield. The simulated ES (with 10^4 ions of each ion energy and species) clearly reproduce these deviations of the experimental ES. This agreement between simulation and experiment leads us to the important insight that the deviations from the Poissonian ES result from the particular collision processes of incident ions and recoil atoms in the target.

Some of the ions incident on the surface are backscattered in large-angle scatterings from the target atoms, while the remaining ones experience a few small-angle scatterings during penetration of the target and ultimately become trapped inside the target. Therefore, two types of KE may be distinguished, leading to different ES. Figure 4 for H^+ impact shows simulated ES for KE due to backscattered and trapped ions (for H^+, recoiling effects can be neglected). We find that deviation of the ES from the Poissonian distribution is primarily caused by the ES of the backscattered ions, although at low impact energy (also for oblique incidence) the ES due to the trapped ions also deviate from the Poissonian distribution, because of the pronounced localization of the ion trajectory near the surface.

For heavy-ion impact the large-angle scattering in elastic collisions with the target atoms not only results in

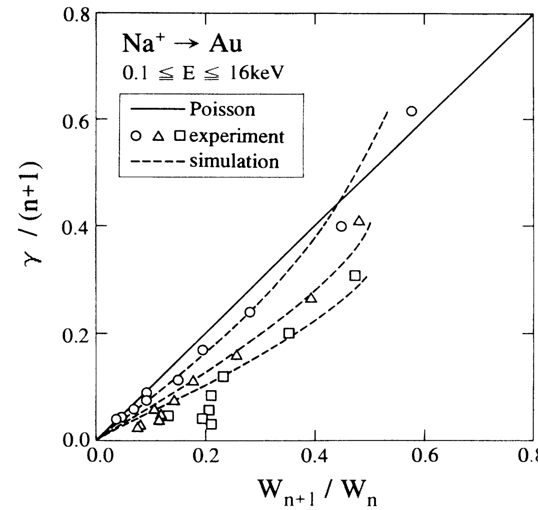

FIG. 2. Relations between $\gamma/(n+1)$ and W_{n+1}/W_n for impact of 0.1–16-keV Na^+ on clean gold. The circles, triangles, and squares represent $n=1$, $n=2$, and $n=3$, respectively.

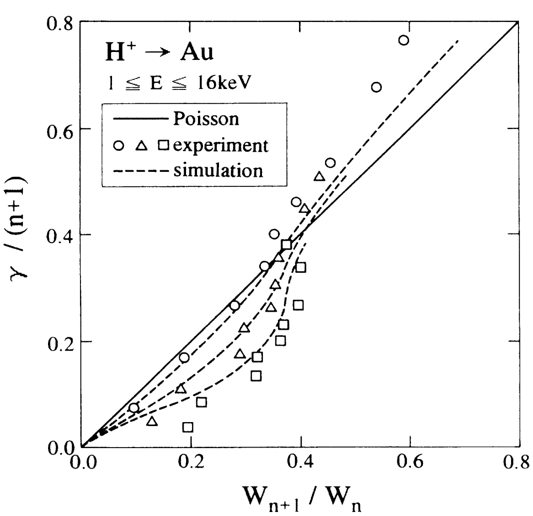

FIG. 1. Relations between $\gamma/(n+1)$ and W_{n+1}/W_n for impact of 1–16-keV H^+ on clean gold. The circles, triangles, and squares represent $n=1$, $n=2$, and $n=3$, respectively.

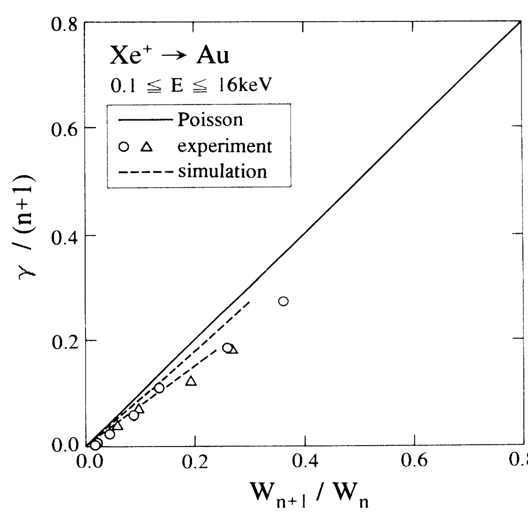

FIG. 3. Relations between $\gamma/(n+1)$ and W_{n+1}/W_n for impact of 0.1–16-keV Xe^+ on clean gold. The circles and triangles represent $n=1$ and $n=2$, respectively.

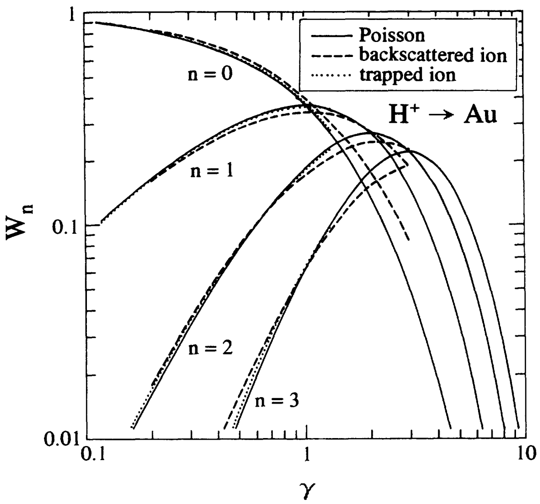

FIG. 4. Relations of W_n ($n=0,1,2,3$) for backscattered and trapped H^+ ions with their mean electron yields.

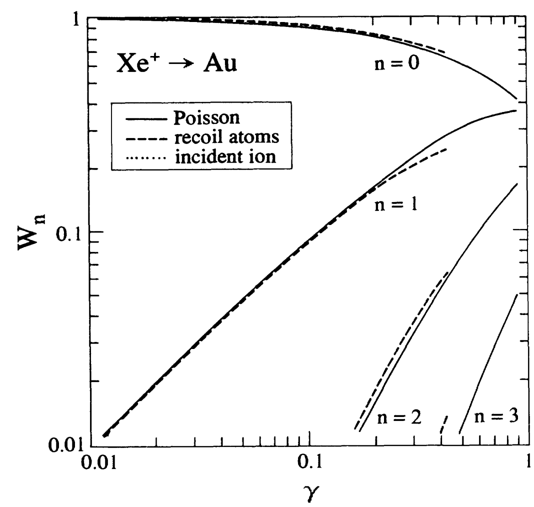

FIG. 6. Relations of W_n ($n=0,1,2,3$) for an incident Xe^+ ion and recoiling Au atoms with their mean electron yields.

projectile backscattering, but is also accompanied by recoiling of target atoms with sufficient energy to excite many electrons. A large number of electrons emitted from the surface is produced by the recoil atoms.[22,24,25] In Figs. 5 and 6 simulated ES for KE by recoiling Au atoms are distinguished from ES by the incident Na^+ and Xe^+ ions, respectively. For Na^+ impact, deviation of the ES due to incident ions from the Poissonian distribution again shows the effect of backscattering. Also the recoil atoms cause a deviation of the ES from a Poissonian distribution. For impact of heavy ions such as Xe^+ such deviations are also observed, although here the influence—from backscattering—of the incident ion on the ES can be neglected.

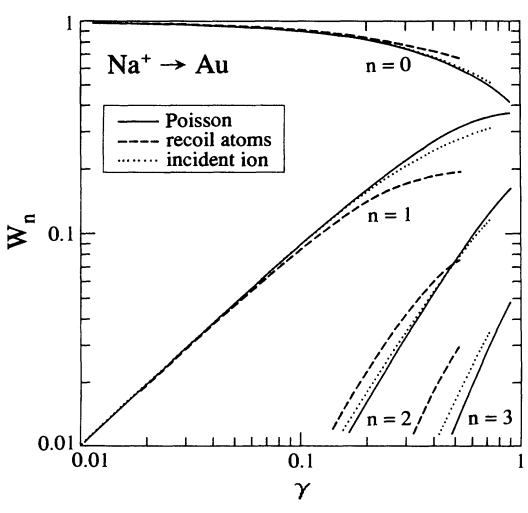

FIG. 5. Relations of W_n ($n=0,1,2,3$) for an incident Na^+ ion and recoiling Au atoms with their mean electron yields.

From our simulation studies, the experimentally observed deviations of ES from Poissonian distributions can be explained as follows. Backscattering of the incident ion has both an enhancing and suppressing effect on the KE. The enhancing effect is due to additional excitation of electrons near the surface by backscattered projectiles on their way out, while the suppressing effect is due to ions backscattered from the uppermost surface layers without excitation of electrons. This results in larger and smaller widths of the ES for low and high electron yields, respectively, than expected for the related Poissonian distribution (Fig. 4). On the other hand, fast recoil atoms impose the same effect on ES as backscattered incident ions, which also causes a deviation of the ES from the Poissonian distribution.

In summary, electron-emission statistics from clean gold have been investigated for impact of H^+, Na^+, and Xe^+ ions, both experimentally and by means of Monte Carlo simulations with a semiempirical model for the kinetic emission. The measured ES apparently deviate from the related Poissonian distributions, and the simulations can reproduce these deviations. Furthermore, simulations of the ES for kinetic emission by backscattered ions and recoiling target atoms, which can be distinguished from trapped incident ions, demonstrate the dominant effect of large-angle scattering events on the observed deviations of the ES from Poissonian behavior.

We are well aware of the fact that, in our model, the transport of electrons to the surface has been described in an oversimplified way by just assuming an exponential attenuation factor and not taking into account the electron-energy-dependent exit probability of excited electrons transported towards the surface. Cascade generation of (true) secondary electrons by the primary electrons is not taken into account either, but might cause a deviation from the Poissonian statistics in a similar way as backscattered ions and recoiling heavy particles.[26] A more realistic modeling should therefore also include a Monte Carlo treatment of the internal electron transport, taking into account elastic scattering (electron-nucleus interaction), ionizing collisions with both inner-shell and valence electrons of the target atoms, and maybe also collective interaction with the electron gas (plasmon excitation).

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