Applied Surface Science 47 (1991) 139–147
North-Holland

On the measurement of statistics for particle-induced electron emission from a clean metal surface

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Received 4 July 1990; accepted for publication 11 September 1990

Statistics of electron emission from clean gold under impact of slow (< 1 au) heavy particles have been measured by means of a surface barrier detector for collecting the ejected and subsequently accelerated electrons. Backscattering of these electrons from the detector surface causes a characteristic background between individual peaks of the pulse-height spectra, which must quantitatively be taken into account before evaluation of the measured statistics. From the latter, among other pieces of information the mean electron emission yield γ can be calculated. For γ values below and of the order of unity such determined emission statistics deviate clearly from a Poisson distribution, the reason of which is finally discussed.

1. Introduction

Impact of heavy particles such as atoms, molecules, positive or negative ions on solid surfaces gives rise to electron emission, which is of great importance for many applications, e.g. surface and space science, sensitive particle detection/counting, plasma wall interaction, electrical discharges, etc. This important class of processes, which is often incorrectly termed "secondary electron emission" (note that the latter terminology should be strictly reserved for electron-induced electron emission), has now been investigated for a century by common methods, measuring e.g. the involved total electron emission yield γ and the ejected-electron energy distribution $\mathrm{d}N(E_e)/\mathrm{d}E_e$. However, these properties are mainly of practical interest and in the majority of cases provide not much detailed insight into the mechanisms responsible for the electron emission. If we confine ourselves to atomically clean surfaces of polycrystalline metal targets (note that the surface conditions are of critical importance for all related experimental studies), the observed electron emission can be ascribed to the processes of potential emission [1] ("PE", i.e. emission taking place before the projectile hits the surface) and kinetic emission [2] ("KE", i.e. contributions which appear only after the projectile has hit the surface).

Particle-induced electron emission is of special importance for the registration of extremely small particle currents, for which the statistics of the electron emission plays a crucial role. This statistics, i.e. the probabilities W_n for emission of a given number n of electrons due to a single impact event (henceforth to be named emission statistics/"ES") immediately permits evaluation of the related total electron yield γ as the mean number of emitted electrons

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

It is commonly assumed that, as far as the KE process is concerned (i.e. if PE contributions are either essentially zero as for neutral ground-state particles or at least comparably small), such ES follow closely a Poisson distribution $P_n(\gamma)$ with the mean value γ

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

Under this assumption a measured ES can be fitted to a Poisson distribution, in particular to obtain the probability W_0 for emission of no electron, i.e. the counting loss

$$W_0 \approx P_0 = e^{-\gamma}. \tag{3}$$

For electron yields smaller than or of the order of unity, the counting loss will become relatively large and thus non-negligible, whereas for $\gamma \gg 1$ the precise shape of ES is of merely academic interest, since W_0 can be safely neglected. Various groups have investigated the exact shape of the ES and their possible deviations from a Poissonian or standard more-parameter statistical distributions.

In early work either proportional counters [3] or scintillator/photomultiplier set-ups [4] have been used for ES measurements, where individual peaks in the electron pulse height spectra could only be poorly resolved. Consequently, the evaluation of ES was subject to considerable ambiguity which therefore applied to the comparison of measured ES with Poisson statistics as well.

Much better resolved ES measurements could be achieved with solid-state electron detectors. In such measurements Delaney and Walton [5] demonstrated the influence of electron backscattering from the detector surface, which because of incomplete energy deposition gives rise to a characteristically structured background between individual peaks of the measured ES. A magnetic field along the detector surface provided rebending of the scattered electrons, by means of which the aforementioned background could be suppressed.

In these measurements clear deviations from a Poisson distribution have been found, whereas other authors using similar methods [6] found good agreement. Beuhler and Friedman [7] stated clear deviations of very well resolved ES from Poissonians, whereas Hofer and co-workers [8] just assumed Poissonian behaviour of measured ES, to deduce W_0 and the corresponding absolute emission yields. More detailed considerations of the nature of the ES background have been made by van Asselt et al. [9]. These authors correctly took into account the possibility of 0, 1, 2,... up to n backscattered electrons from a group of n electrons impinging on the detector surface, and also the energy deposition of the scattered electrons, which has been experimentally determined for impact of single monoenergetic electrons on the detector. Unfortunately, these authors made the a-priori assumption of Poissionian behaviour of their experimentally determined ES, to fit the latter according to their model. However, for high n a deviation from the Poisson distribution became clearly apparent. Most recently, Moshammer and Matthäus [10] treated the ES background due to backscattered electrons, but assumed energy deposition of the latter in an oversimplified way.

We have applied ES measurements (for experimental methods, see ref. [11]) to study, among other things, again the question of whether measured ES can be approximated by standard statistical distributions, in particular a Poissonian. In a recent Letter [12] we have shown that considerable deviations from the Poissonian are found, and the present paper is devoted to a more elaborate discussion of the correct evaluation of measured ES, which is absolutely necessary before the above-described comparisons can be made. Our experimental technique is shortly recapitulated in section 2, and the methods for quantitative correction of measured ES for backscattering of electrons from the semiconductor detector surface will be explained in detail in section 3. Finally, we discuss our main result, i.e. the observed deviation of ES from the commonly assumed Poissonian behaviour.

2. Experimental set-up

Various projectile ion species of interest have been produced in a Duoplasmatron ion source, accelerated to 1–15 kV, focussed by a quadrupole doublet and charge-to-mass analysed by a magnetic sector field. After passing two differential pumping stages, the ions reached a main UHV chamber containing the target and detector set-up (base pressure below 2×10^{-10} mbar). The target consisted of a sputter-cleaned polycrystalline gold strip (for further details of cleaning procedure, etc., cf. ref. [11]).

For a primary ion Z^{q+} the total electron yield γ (mean number of electrons emitted per projectile) can be determined by measuring the currents of both the incoming projectiles I_i and the emitted electrons I_e, respectively (so-called current measurement/"CM").

$$\gamma = qI_e/I_i. \tag{4}$$

I_e was measured by applying +20 V to a highly transparent cage surrounding the target, while the primary ion current I_i was determined by directing the projectile ions into a deep Faraday cup (fig. 1).

In addition to measurements of the total yield γ, our apparatus has been specifically designed to investigate electron emission statistics. To this purpose the cage potential was set to −20 V, to ensure that all ejected electrons leave the cage exclusively via the extraction aperture (cf. fig. 1). Electrons were removed through this aperture by an electric field due to an extraction electrode set to +3.5 kV, and further accelerated towards a semiconductor detector (Canberra Passivated Implanted Planar Silicon detector PIPS 100-12-100) connected to +30 kV with respect to the target.

Ray trace calculations have been carried out to optimize the extraction geometry. As an example, fig. 1 shows calculated electron trajectories for ejection energies of 20 eV. It could be shown that all electrons ejected from the target surface with energies of $E_e \leqslant 20$ eV into a solid angle of 2π actually reach the active detector area. However, for higher ejection energies the acceptance angle would become gradually smaller.

The results of such calculations have been checked by careful experiments, replacing the detector by a "dummy" collector made of Al in the same geometry, and comparing the electron current measured on this collector with the electron current I_e emitted from the Au target. These measurements showed that apparently a 85% fraction of the electron current I_e arrived on the active area of the detector. This value could neither be

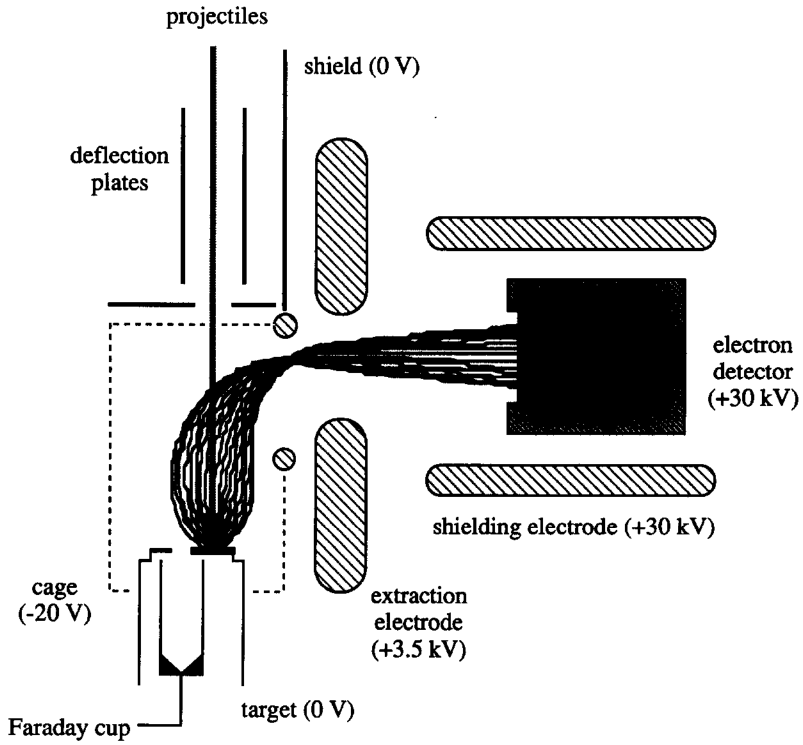

Fig. 1. Experimental set-up for measuring electron emission statistics. Typical calculated trajectories of ejected and subsequently extracted electrons (starting energy 20 eV) have been added.

increased by enlarging the detector area nor by varying the applied extraction voltages. The missing 15% could be attributed to electrons backscattered from the detector surface, because this fraction is in perfect agreement with published data on electron backscattering from Al and Si, i.e. reflection coefficients of 15% and 17% respectively, for 30 keV electrons [13]. We therefore can safely assume that practically all electrons ejected from the target reach the detector, which is absolutely mandatory for a correct ES measurement.

PE processes last no longer than typically 10^{-13} s [1], and subsequent KE events are terminated within 10^{-12}–10^{-11} s [14]. Therefore, all electrons emitted due to the impact of a particular projectile reach the detector within its resolution time. Consequently, the total energy of each group of electrons ejected by a single particle impact corresponds to the number n of these electrons. The pulses produced by the detector were amplified by a preamplifier (Ortec 142A) and a spectroscopy amplifier (Ortec 471), transformed to ground potential, base-line restored and pulse-height analyzed by a multichannel analyzer (Nuclear Data ND 62), from which ES spectra were obtained.

To avoid pulse pile-up when measuring ES spectra, the incident ion flux had to be reduced to $\leqslant 10^4$ ions/s, to ensure sufficient time between subsequent ion impacts with respect to the detector resolution time. A quick reduction of the ion beam intensity by a factor of 10^6 as compared to CM requirements was achieved by defocussing the magnetic quadrupole doublet in the primary ion beam line.

3. Evaluation of electron emission spectra

In fig. 2 we show a typical uncorrected ES spectrum as measured for the case of 12 keV H_3^+ impact on clean Au. To a first approximation the peak areas of the ES spectrum are proportional to the probabilities W_n. However, between the main peaks (the typical energy resolution was $\Delta E_{\mathrm{Det}} = 6$ keV FWHM, resulting mainly from detector noise) we recognize a structured "background" (cf. fig. 2), which we in accordance with other authors attribute to electrons backscattered from the detector surface [5,6,9,10]. These reflected electrons deposit only a fraction of their energy into the detector [15]. Usually, this effect is claimed to be compensable by applying a magnetic field along the detector surface, to force back the backscattered electrons. Because this method requires a rather large detector area, it would deteriorate the energy resolution of the detector. We overcame this problem by considering quantitatively the

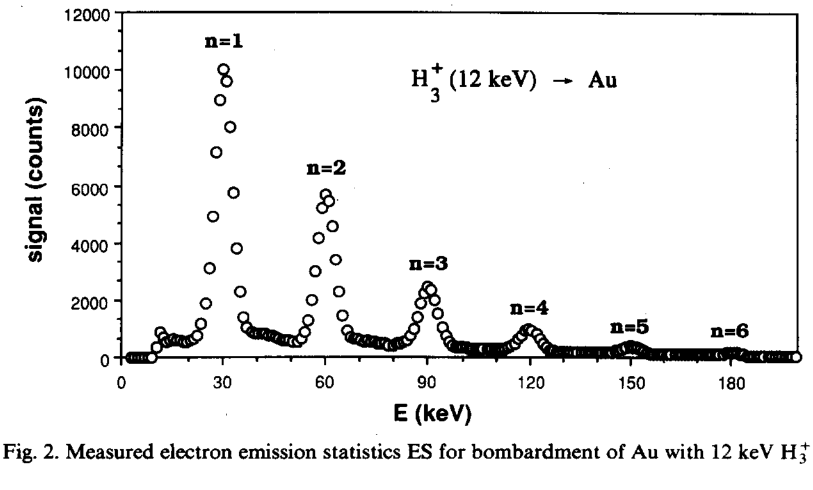

Fig. 2. Measured electron emission statistics ES for bombardment of Au with 12 keV H_3^+.

contributions of backscattered electrons within an evaluation procedure for the measured ES spectrum.

This evaluation relies on the following measured data for electron backscattering:

- The probability for backscattering of electrons with 30 keV impact energy from bulk silicon p_{Si} = 17% [13]. PIPS detectors are made of Si, but covered with a thin Al layer (< 500 Å Si equivalent), which also contributes to backscattering with $p_{Al} \approx 15\%$ [13].
- To a good approximation, the backscattered electrons assume a Gaussian energy distribution with a mean energy at 60% of $E_0 \approx 18$ keV and $\Delta E \approx 12$ keV FWHM [15].

To verify these findings for our detector configuration we measured pulse-height distributions for single electrons impinging onto the detector with 30 keV, as already performed by others [9]. These single electrons were produced simply by field emission from the extraction electrode vis-a-vis the detector. If the detector was set to +30 kV and all surrounding elements including the extraction electrode were grounded, field-emitted electrons could be registered with typical count rates of 20–50 electrons per second. Fig. 3 shows the resulting single-electron pulse-height distribution. Because of electronic noise, the discriminator level of our multichannel analyzer had to be set to 13 keV.

Electrons having deposited only a part of their initial energy are registered at the low energy side of the main peak, showing a broad Gaussian-like energy distribution. While the half width (FWHM = 14 keV, i.e. 12 keV folded with the detector resolution of 6 keV) and the maximum of this peak are in perfect agreement with the data given above, its area (shaded part in fig. 3) is only 14% of the total area (= integral including the main peak at 30 keV). We have therefore performed Monte Carlo calculations of backscattered electron trajectories in our geometry, to determine the fraction of electrons which after being reflected return back to the active detector area due to the influence of the electric field (cf. fig. 4). For the ejected electrons their starting points were chosen randomly with a Gaussian distribution along the detector surface, centred in the middle of the detector. The angular distribution of the backscattered electrons was assumed to obey a cos(|ϑ|) law (ϑ being the ejection angle with respect to the surface normal). For the energy

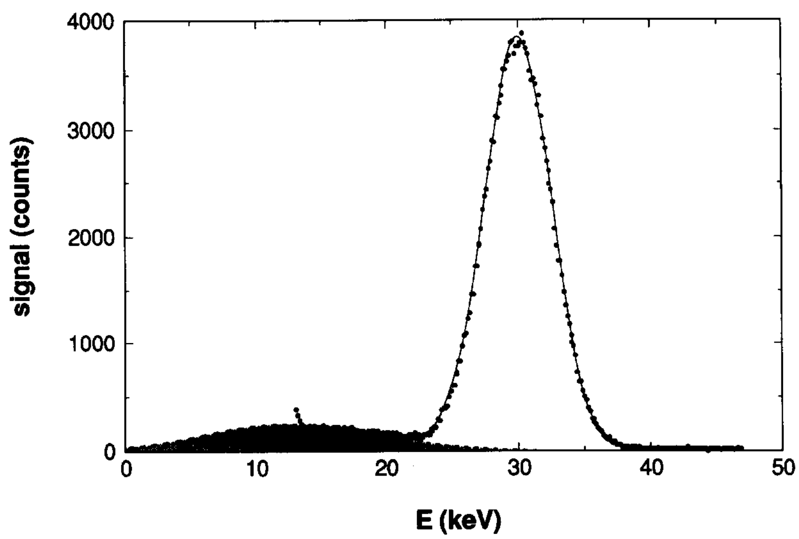

Fig. 3. Measured pulse-height distribution for single electron impact (dots) in comparison with our model calculations (solid and dashed lines). Primary electrons with 30 keV incident energy have been produced by field emission and impinged onto the detector surface to produce the shown energy distribution.

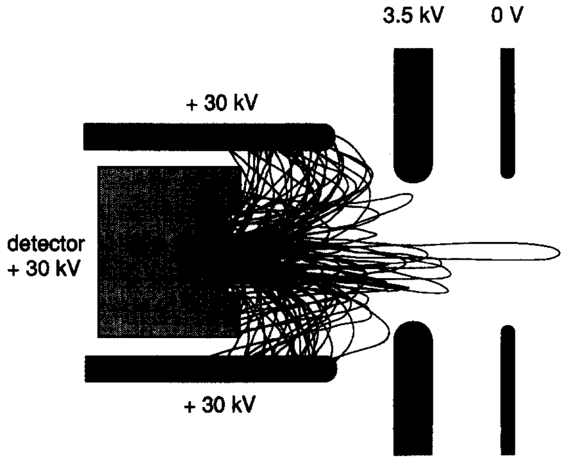

Fig. 4. Trajectories of electrons backscattered from the detector surface, as derived from Monte Carlo simulation (for details see text).

distribution of backscattered electrons, the above-mentioned data from ref. [15] have been used.

The paths of 10^4 electrons have been followed (fig. 4 shows only 100 trajectories), leading to the result that about 17%–18% of the backscattered electrons are returning to the active detector area. This explains quantitatively ($0.17 \times (1-0.17) = 0.14$) why we find only 14% (effectively) backscattered electrons in our measured pulse-height distribution (fig. 3).

For an evaluation of the measured ES spectra the following procedure was now adopted:

The experimental ES spectrum $S(E)$ (E being the energy deposited by electrons inside the active detector volume) was fitted by a linear combination of normalized functions $F_n(E)$, which correspond to the respective events of emission of n electrons per incident projectile,

$$S(E) = \sum_{n=0}^{n_{\max}} C_n\, F_n(E). \tag{5}$$

Without electron reflection from the detector surface the functions $F_n(E)$ would be of Gaussian shape centred around $n \times 30$ keV with a halfwidth of ΔE_{Det} (note that energy loss straggling in the inactive detector region actually causes a slight increase of ΔE_{Det} for increasing number of incident electrons n).

Inclusion of backscattered electrons changes each function $F_n(E)$ to a sum of individual peaks $f_n(E, E_m, \Delta E_m)$ corresponding to backscattering of $m = 0, 1, 2, \ldots, n$ electrons from the detector

$$F_n(E) = \sum_{m=0}^{n} P_n(m)\, f_n(E, E_m, \Delta E_m). \tag{6}$$

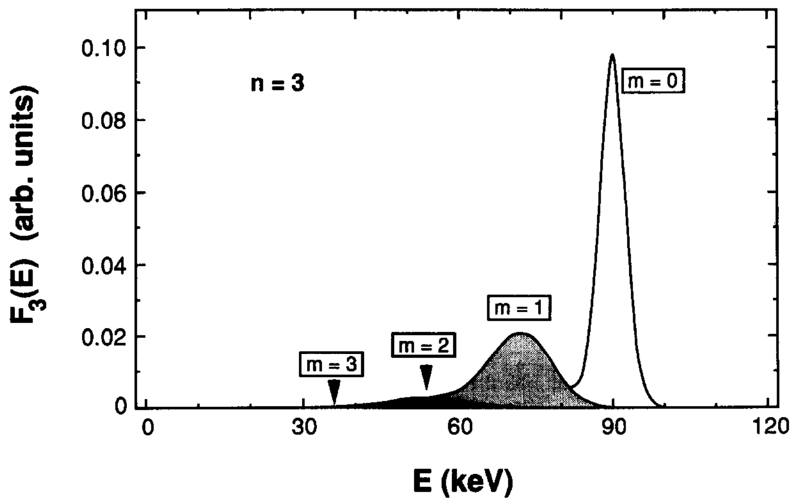

Fig. 5. Pulse-height distribution simulated for a case with $n = 3$ electrons (30 keV impact energy each) simultaneously impinging onto the detector. Contributions for backscattering of $m = 0, 1, 2$ and 3 electrons, respectively, are individually marked.

The $f_n(E, E_m, \Delta E_m)$ are normalized Gauss functions centred around

$$E_m = n \times 30 \text{ keV} - m \times 18 \text{ keV} \quad (7a)$$

with a FWHM of

$$\Delta E_m = \sqrt{(\Delta E_{\mathrm{Det}})^2 + m(\Delta E)^2}. \quad (7b)$$

These f_n are weighted with the probabilities $P_n(m)$ for backscattering of m electrons out of a group of n electrons arriving at the detector surface, which obey the binomial statistics

$$P_n(m) = \binom{n}{m} p^m (1-p)^{n-m}. \quad (8)$$

As an example $F_3(E)$ ($n = 3$ ejected electrons incident on the detector) is plotted in fig. 5, showing the contributions of $m = 0$, 1, 2 and 3 backscattered electrons $P_n(m) f_n(m)$.

The measured ES spectrum (open circles) in fig. 2 was fitted by following the above-described method. The result of such a fit (solid line) is compared to the measured ES spectrum in fig. 6a, with some individual contributions being plotted in fig. 6b. The experimentally obtained ES spectrum is excellently reproduced by this fitting procedure, in particular yielding a quantitative ap-

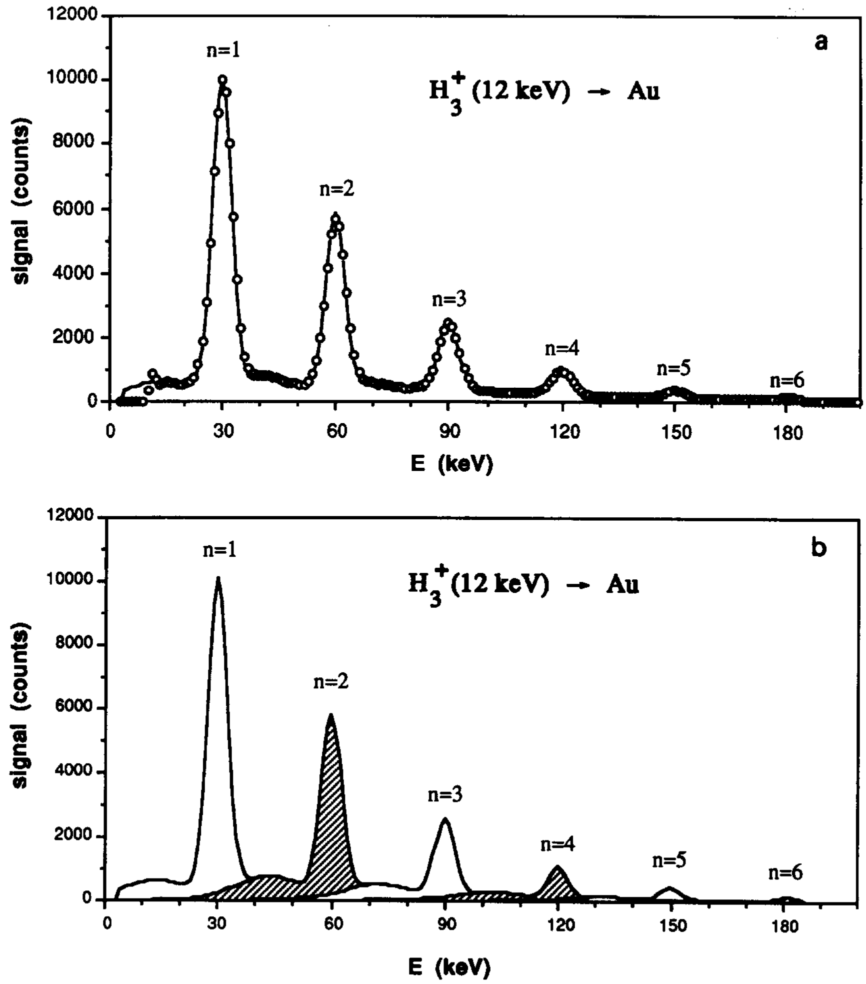

Fig. 6. (a) Comparison between a measured electron emission statistics (open circles) and results of the fit (solid line). (b) Individual contributions to the fitted spectrum including electron backscattering (contributions to even numbered peaks have been shaded).

proximation of the structures observed between the main peaks.

Since the functions $F_n(E)$ are normalized, i.e.

$$\int_0^\infty F_n(E)\,\mathrm{d}E \equiv 1 \tag{9}$$

the fitting parameters C_n of eq. (4) correspond to the peak areas of the individual contributions in fig. 6b and therefore also to the probabilities W_n:

$$W_n = kC_n, \quad k = \text{const.} \tag{10}$$

At too high count rates the shape of the measured ES spectrum will become subject to severe changes due to pulse pile-up [16]. At count rates $> 5 \times 10^4$ electrons/s we have observed the onset of both "peak pile-up" (which results in a high energy shoulder) and "tail pile-up" (resulting in an asymmetric broadening of the peaks at the low energy side).

Although the above-discussed work clearly identified the physical origin of the commonly observed background in ES spectra measured with semiconductor detectors, some authors are still disagreeing with this interpretation. Recently it has been argued [17] that such an ES background is not caused by electron backscattering and can be avoided by proper choice of the bias voltage of the surface barrier detector used for registration of the ES. However, a decrease of this bias voltage just lowers the detector collection efficiency, resulting in a poorer energy resolution (in ref. [17] the FWHM of ES peaks increased from 9 keV at 50 V bias voltage up to 25 keV at 10 V bias, with a peak separation of 32 keV). Obviously a poor energy resolution just masks the presence of a structured background, which can easily be demonstrated by calculating ES spectra with our above-described method under the assumption of different values for ΔE_{Det}.

4. Summary and final remarks

We have found that electron emission statistics for particle impact on a clean metal surface do not obey a Poisson distribution as regularly assumed in the literature on particle-induced electron emission.

As already shown in ref. [12], a critical check for agreement of measured ES with Poisson distributions can be made by comparing ratios of relative ES probabilities W_{n+1}/W_n with the corresponding expressions of a Poissonian for the involved γ, which from eq. (2) are related to the total yield as

$$P_{n+1}/P_n = \gamma/(n+1). \tag{11}$$

However, such a comparison should only be made for collision systems giving negligibly small PE contribution, because PE cannot be described in terms of a statistical process like KE. As we have recently shown, for H^+ impact on clean gold the PE yield is $\leqslant 0.02$ at 100 eV and decreases further toward higher E. It can thus be safely neglected in comparison to the KE yield for $E \geqslant 1$ keV [18].

In fig. 7 we show for H^+–Au relation (11) between independently measured total yields and the ratios of relative subsequent ES probabilities for impact energies $E = 1$–16 keV. The above-stated deviations from a Poisson distribution can be clearly recognized.

Our measurements have been quantitatively corrected for the structured background in the ES spectra, which have been measured by means of a semiconductor electron detector. This background is evidently produced by electron backscattering

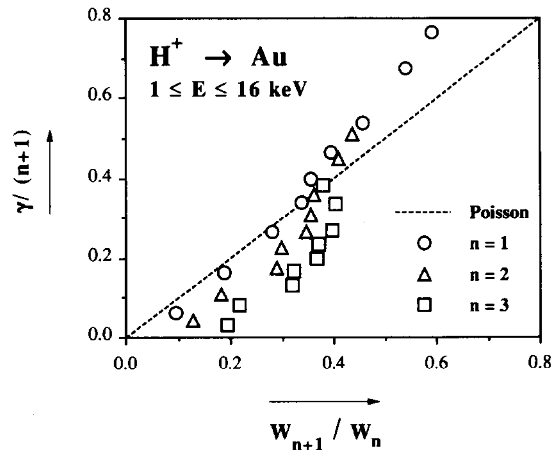

Fig. 7. Comparison of $\gamma/n+1$ and W_{n+1}/W_n ($n = 1, 2, 3$) for impact of $1-16$ keV W^+ on clean gold, showing the deviation of measured ES from Poisson distribution (further details cf. text).

from the detector surface. Apparently such corrections without a-priori assumptions on the shape of ES and/or the backscattered electron energy distribution have been made for the first time.

In the following we offer an explanation for deviations of experimental ES from the Poissonian shape as shown in fig. 7 (note that quite often two or even more-parameter statistical distributions are invoked to fit measured ES, since it is argued that originally Poisson-distributed electrons excited inside the solid are affected by secondary processes as e.g. energy loss straggling). Obviously, the common "statistical" concept of particle-induced electron emission considers ejection of a relatively small number n of mutually independent electrons out of a large ensemble of N electrons, which are excited inside the solid in a collision cascade initiated by the particle impact. If the probability for single electron ejection is p, the resulting ES will be given by a binomial distribution

$$P(n) = \binom{N}{n} p^n (1-p)^{N-n}. \tag{11}$$

For $p \ll 1$ and $n \ll N$ this binomial distribution converges to a Poissonian (eq. (2)).

Our observation that for small γ deviations from the Poissonian shape become clearly apparent, shows that there the above-explained concept for particle-induced electron emission becomes incorrect. Rather, for impact of slow heavy particles the resulting collision cascades seem not to involve a sufficiently large number of electrons inside the solid and, moreover, these electrons cannot be assumed as mutually independent. The excitation process does not correspond to a sufficiently large ensemble to justify the statistical description, which however gradually might change for higher impact energies and consequently larger γ, where the collision cascades will involve rapidly increasing numbers of electrons. Only in such cases a Poissonian ES should be expected, as for thermionic emission of very small currents, where the shot noise behaviour is well described by a Poisson-distributed electron escape from the emitting surface into free space.

Acknowledgments

This work has been supported by Fonds zur Förderung der wissenschaftlichen Forschung (Projekt Nr. 6381) and Kommission zur Koordination der Kernfusionsforschung at the Austrian Academy of Sciences.

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