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Coincidence studies of electron emission statistics in ion surface interactions: a new experimental study

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Electron emission number statistics have been measured for 8 keV H^+ ions in collisions with clean polycrystalline copper at 80° and 67°. Also, in a new development, electron number statistics have been recorded for reflected particles using coincidences between the reflected particles and the emitted electrons. The results of both coincidence and non-coincidence measurements fitted Polya distributions, with a higher mean emission value in the coincidence case. A model has been developed to interpret the difference between the coincidence and non-coincidence electron number statistics.

Keywords: ion beams; surfaces; collisions; electron emission; coincidences

1. Ion surface interactions

Electron emission from a clean metal surface as a result of ion impact is currently a topic of considerable experimental interest. The methods used in this area fall into two distinct categories, each of which have had many variants. In the early experiments (cf. Hagstrum 1954*a*, *b*), the electron yields were determined either by simultaneously measuring the current to the target and a collector surrounding the target, or by measuring target currents with positive or negative target-bias voltages. In an alternative approach (cf. Aumayr & Winter 1994), the statistical distribution of the individual probabilities W_n for the ejection of n $(= 0, 1, 2, \dots)$ electrons was measured and the value of the secondary electron emission coefficient was calculated. The use of electron statistics (ES) had the advantages that (1) the inherently low incident ion flux reduced the contamination of the surface; and (2) additional information could be determined from the ES distribution. In the measurement of ES distributions, the electron groups were identified using a variety of energy detectors, e.g. electron proportional counters (Barrington & Anderson 1958), scintillation detectors (Collins & Stroud 1967), specially designed microchannel plate detectors (Kozochkina *et al*. 1991), and implanted silicon-barrier detectors (Dietz & Sheffield 1975; Lakits *et al*. 1989). The most successful of these detectors have been the silicon-barrier detectors, where there is good resolution between the electron groups. However, backscattering of a fraction of the electrons from the detector causes a characteristic

† Deceased 6 December 1998.

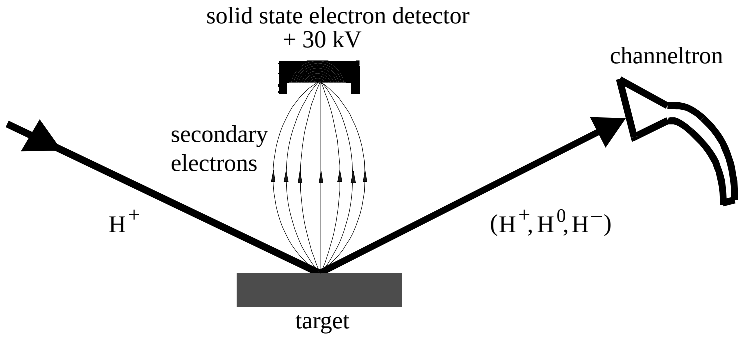

Figure 1. Schematic diagram of the experimental method.

background between individual peaks of the laboratory pulse-height spectrum, which must be taken into account when determining the measured statistics (cf. Aumayr *et al*. 1991). Morosov *et al*. (1996) have reported preliminary qualitative measurements of electron number distributions for electrons in coincidence with reflected ions. In their technique, a multi-detector arrangement was used to identify electron groups by recording coincidences between individual electron detectors.

Ions that impact on the target surface may be embedded in the bulk of the target material or reflected as charged and neutral particles with energies up to the elastic scattering limit. In this paper, we compare the ES distribution for all incident ions, whether embedded or reflected, with that obtained in coincidence with reflected particles. These distributions will be called non-coincidence and coincidence, respectively.

A schematic diagram of the experimental method is shown in figure 1. H^+ ions at 8 keV from a new compact 10 GHz electron-cyclotron-resonance ion source (Schlapp *et al*. 1997) were incident upon a clean metal surface, and the reflected particles H^+, H^- and H^0 were detected by a channeltron placed at the specular angle of reflection with a half-angle of acceptance of 13°. Electrons emitted from the target were accelerated through 30 kV and focused onto a Canberra PIPS silicon-barrier detector. Ion and electron trajectory simulations showed that all electrons with an initial kinetic energy of less than 100 eV were collected without significantly influencing the incident or reflected ion paths. Pulse-height analysis of the output of the detector gave an ES spectrum where the pulse-height was proportional to the number of electrons, n, in each ejected group. Spectra were recorded for greater than 10^5 total counts, hence uncertainties arising from statistical fluctuations were small. Recorded spectra were corrected for the electrons that deposited part of their energy, and were backscattered from the solid-state detector.

The recorded non-coincidence signals, C_n were the total counts of pulses corresponding to a group of n electrons. Then the electron emission coefficient, γ, was given by

$$\gamma = \sum_{n=1}^{\infty} nW_n, \tag{1.1}$$

where

$$W_n = \frac{C_n}{F}, \qquad F = \sum_{n=0}^{\infty} C_n, \qquad \sum_{n=0}^{\infty} W_n = 1.$$

In these experiments, the incident ion flux, F, could not be measured directly, hence C_0, the count rate for zero electron emission, could not be determined. However, in this case, where γ is relatively large and C_0 is small, it can be estimated with sufficient accuracy as discussed later. Then the sum of the probabilities W_n was made equal to unity.

In the first coincidence measurements of their type, the coincidence counts $C_{\mathrm{r},n}$ between the emitted groups of n electrons and the specularly reflected ions and neutral particles, were recorded together with the total flux C_{r} of reflected particles. These coincidence measurements were used to determine the electron number statistics for the reflected particles, and their associated secondary emission coefficient γ_{r}, where

$$\gamma_{\mathrm{r}} = \sum_{n=1}^{\infty} nC_{\mathrm{r},n}/C_{\mathrm{r}}. \tag{1.2}$$

The target was mounted at the centre of a chamber of 800 mm diameter, and could be rotated to change the angle of incidence of the ion beam. The electron statistics detector and the channeltron were mounted on separate turntables. The preparation and characterization of the target surface were carried out in a small UHV chamber fitted with a heated target sample holder, argon-ion sputter gun and Auger electron spectrometer (AES). The prepared target was transported via load-locks to the UHV main experimental chamber. Background pressures, typically 2×10^{-10} Torr, were achieved, hence, there was negligible contamination of the target surface by the background gas during the measurements. This was confirmed by Auger analysis before and after each experimental run, and by the reproducibility of the measurement.

Figure 2 shows the ES pulse-height spectrum from the silicon solid-state detector in coincidence with reflected particles for 8 keV H^+ ions incident on clean polycrystalline copper at 80°, with respect to the normal to the surface. Also shown in figure 2 is a calculated least-squares fit to the data using the following procedure. Electrons that deposit their *full* energy, E, in the detector, give rise to a Gaussian distribution centre at $30\times n$ keV, with a half-width of ΔE_{f}. Electrons that are backscattered, and deposit only *part* of their energy, must be taken into account. Following the approach of Aumayr *et al*. (1991), we have assumed that 16% of the electrons are reflected and register as a Gaussian distribution centred at 12 keV (18 keV below the full energy peak) with FWHM (ΔE_{p}) of 16 keV. Then the experimental ES spectrum, $S(E)$, is made up of the sum of normalized functions, $F_n(E)$, which correspond to the emission of a group of n electrons, and

$$S(E) = \sum_{n} C_n F_n(E), \tag{1.3}$$

where the constant C_n gives the number of times a group of n electrons was created. $F_n(E)$ is a sum of individual peaks $f_n(E, E_m, \Delta E_m)$ corresponding to backscattering of $m = 0, 1, 2, \ldots,$ electrons from the detector:

$$F_n(E) = \sum_{m} P_n(m) f_n(E, E_m, \Delta E_m). \tag{1.4}$$

The $f_n(E, E_m, \Delta E_m)$ are normalized Gaussian functions centred around $E_m = 30n - 18\times m$ keV with a FWHM of $\Delta E_m = \sqrt{(\Delta E_{\mathrm{f}})^2 + m(\Delta E_{\mathrm{p}})^2}$.

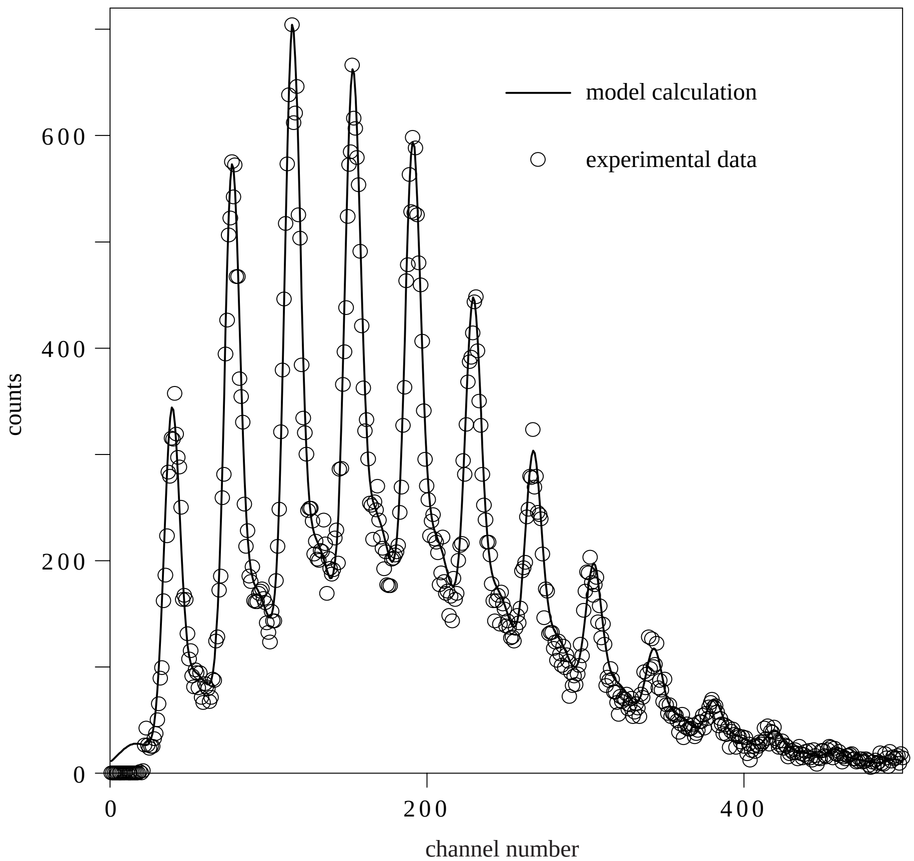

Figure 2. Coincidence pulse-height spectrum for 8 keV H^+ incident on Cu at 80°.

The expression $P_n(m)$ gives the probabilities for backscattering m electrons out of a group of n electrons arriving at the detector, and obeys binomial statistics:

$$P_n(m) = \binom{n}{m} p^m (1-p)^{n-m}, \qquad (1.5)$$

where $p = 0.16$ is the probability of reflection of a single electron.

In figure 3, the coincidence and non-coincidence electron emission probability distributions, W_n (deduced from the fitting procedure described above), are shown for 8 keV H^+ incident on polycrystalline copper at 80°. Figure 4 shows a similar plot for 8 keV ions, incident at 67°. The values of C_0 (and $C_{r,0}$) have been deduced by assuming a Poisson ES distribution and using the relationship

$$\frac{C_0}{C_2} = \frac{2}{9}\left(\frac{C_2}{C_3}\right)^2.$$

Values of C_1 could have a component due to field emission, hence, they were not used in this procedure. Since C_0 is small, the percentage error in its value can be large without introducing a serious error in the overall value of γ or the interpretation of the ES distributions. In the case of the coincidence measurements, $C_{r,0}$ can also be

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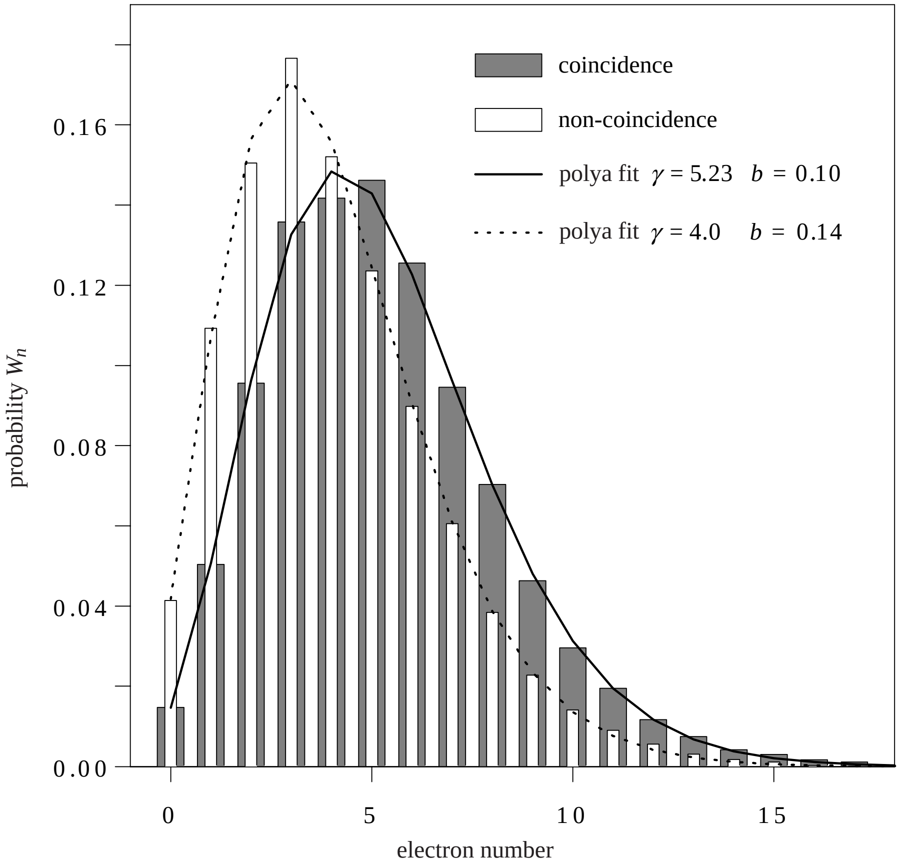

Figure 3. Experimental electron statistics probabilities W_n fitted to Polya distributions for 8 keV H^+ ions incident on polycrystalline Cu at 80°.

determined directly from the experimental data using the relationship

$$C_{r,0} = C_r - \sum_{n=1}^{\infty} C_{r,n}. \tag{1.6}$$

The best fit to the experimental data is a Polya distribution, given by

$$W_n(\gamma, b) = \frac{\gamma^n}{n!}(1 + b\gamma)^{-(n+1/b)} \prod_{i=1}^{n} [1 + (i - 1)b], \tag{1.7}$$

where b is a constant. For $b = 0$ the Polya distribution degenerates into a Poisson distribution.

Table 1 gives those values of γ that have been determined using equations (1.1) and (1.2), and those from best fits to a Polya distribution for coincidence and non-coincidence distributions at 67° and 80°.

Electron emission results from potential and kinetic processes. In this experiment the potential mechanism is expected to yield values of $\gamma \ll 1$ because the excess energy in an Auger neutralization event (Hagstrum 1954*a*, *b*), for electrons below the Fermi limit, is $(I - 2\phi)$, where I is the ionization energy and ϕ the work function.

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Table 1. *Values of γ for coincidence and non-coincidence measurements*

	non-coincidence		coincidence	
angle	equation (1.1)	Polya	equation (1.2)	Polya
67°	2.01	1.97	3.73	3.7
80°	4.04	4.00	5.25	5.23

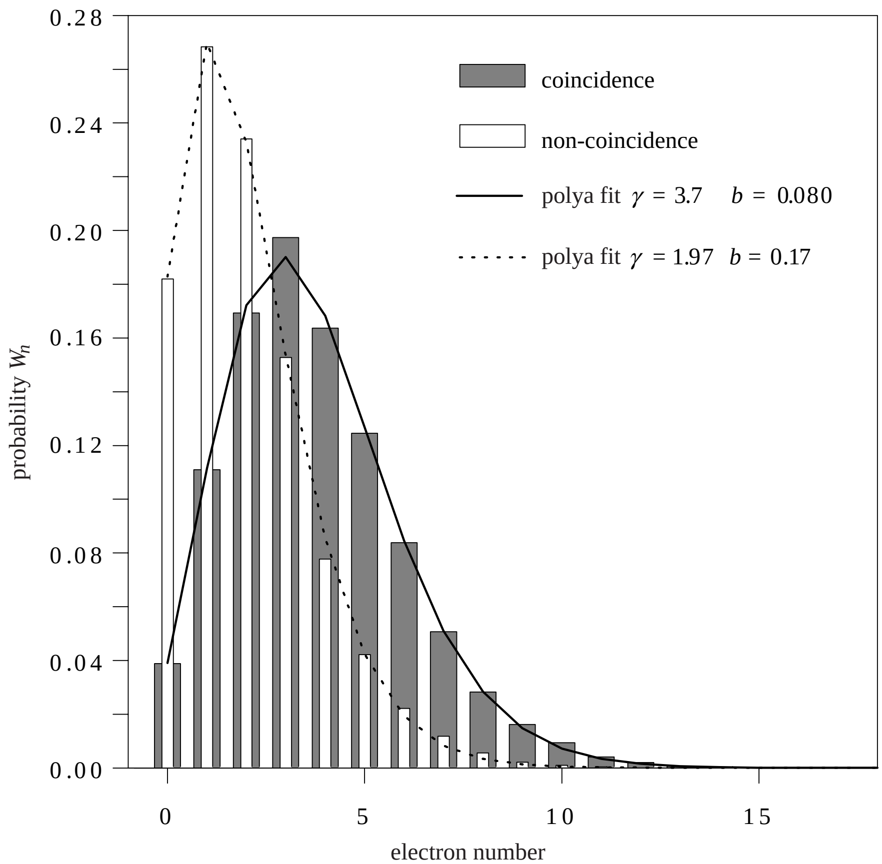

Figure 4. Experimental electron statistics probabilities W_n fitted to Polya distributions for 8 keV H^+ ions incident on polycrystalline Cu at 67°.

For H^+ on Cu, $(I - 2\phi)$ is 4.3 eV and there is not sufficient energy for the ejection of more than one secondary electron. Hence, the relatively large measured values of γ must arise through kinetic emission. The results of Lakits *et al*. (1990) for H^+ on Au also confirm that kinetic emission dominates at energies above 1 keV.

A Polya distribution arises from a sum of Poisson distributions, where the γ values have a gamma distribution (Dietz & Sheffield 1975). Physically, variation in γ is a realistic assumption for kinetic emission, in that secondary electrons formed at different sites on and below the surface can have different secondary emission probabilities for a variety of reasons, including different electron-escape probabilities.

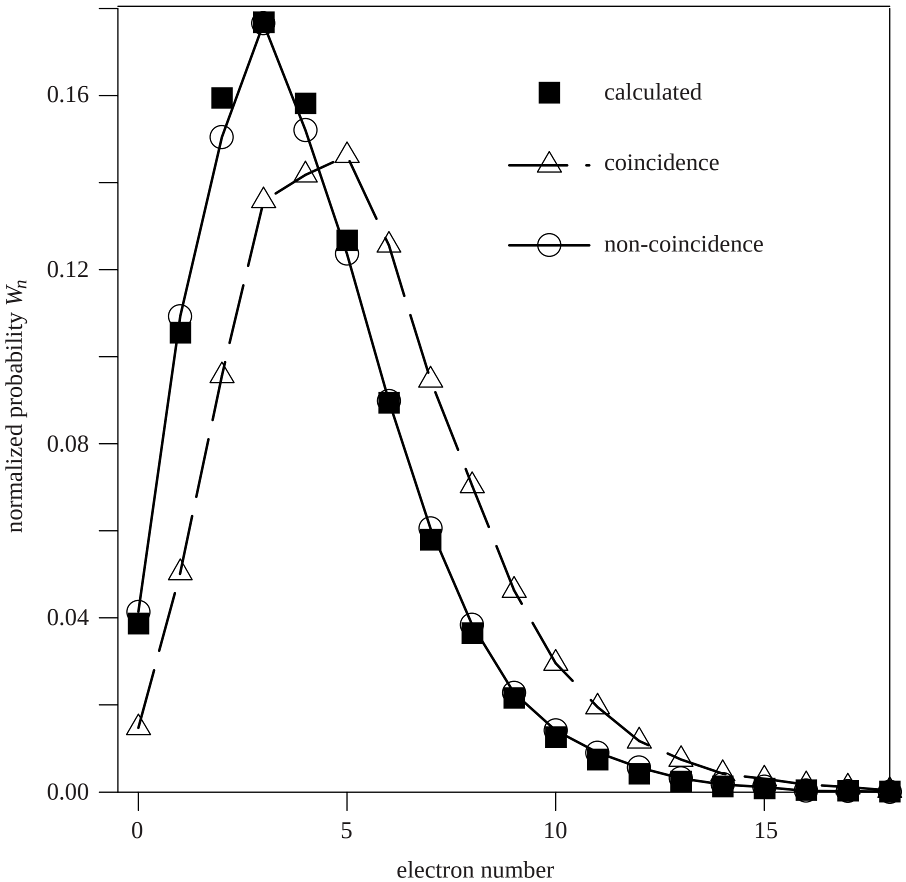

Figure 5. Electron statistics distributions for coincidence and non-coincidence cases, and the predictions of model 1 (see text) for 8 keV H^+ ions at 80° incidence.

In figures 3 and 4, the mean value of γ decreases with decreasing incident angle. At the lower incident angle, the velocity of the ion perpendicular to the surface will be higher, and it will penetrate deeper below the surface where secondary electrons will be liberated. This release of secondary electrons at greater penetration depths will result in a lower secondary emission yield, due to a reduction in the probability of the escape of the electron caused by the increased distance it has to travel through a sea of electrons.

At a fixed angle, the value of γ is lower for the non-coincidence than for the coincidence data. We have developed two models that can be used to interpret the difference in the shape of the distributions. Both models are based on the same physical interpretation: that electrons formed below the surface have a reduced probability of escape.

In model 1, it is assumed that the ions, which are reflected or embedded within the material, produce electrons with identical ES distributions. The electrons, which escape from the surface and are recorded, give the ES distributions for electron production modified by electron-escape probabilities. Since the trajectories of the

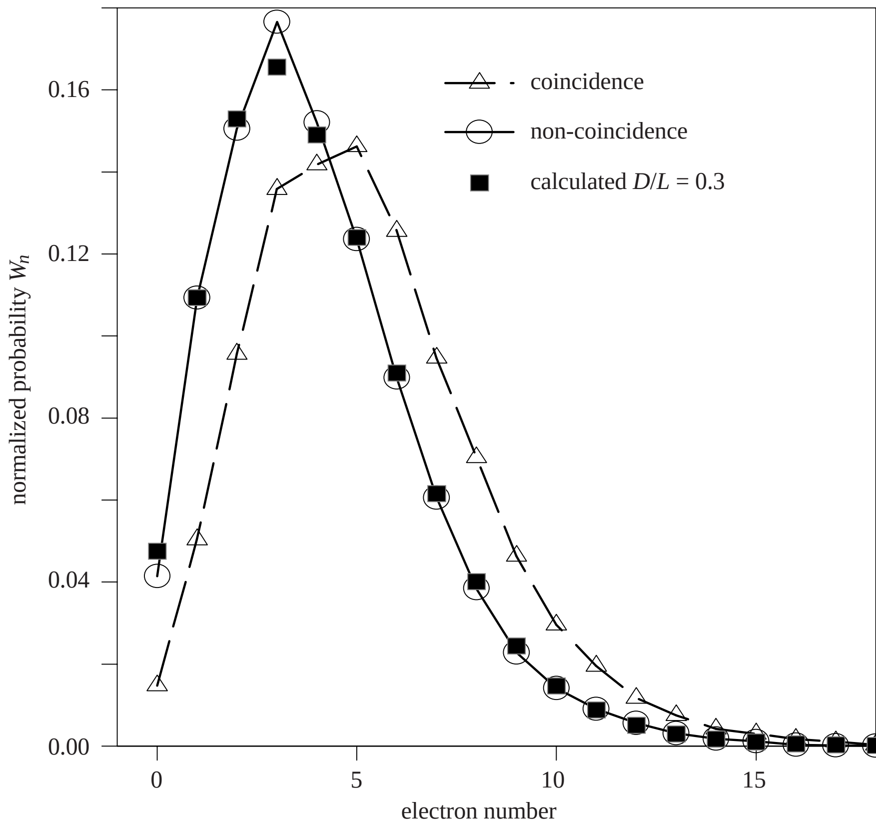

Figure 6. Electron statistics distributions for coincidence and non-coincidence cases, and the predictions of model 2 (see text) for 8 keV H^+ ions at 80° incidence.

majority of reflected particles remain close to the surface, the electrons ejected in the direction of the surface have a very high probability of escape. Hence, the coincidence ES distribution can be taken as the electron production ES distribution. However, the secondary electrons from the non-reflected ions that interact deeper in the material have a reduced probability of escape due to collisions with target electrons. If the average escape probability is p_e for a single electron, then for groups of n electrons, the probability that r electrons escape is

$$\binom{n}{r} p_e^r (1 - p_e)^{n-r}.$$

An ES distribution has been calculated using the above model. The best fit to the non-coincidence distribution (see figure 5 for 80° incidence) was obtained under the conditions where 22% of the ions gave rise to the ES distribution for coincidence. The other 78% of ions, which were not reflected, gave rise to the ES coincidence distribution modified by an escape probability $p_e = 0.69$ for each electron. The reflection coefficient measured under the experimental conditions was 18%. The results at 67° incidence could also be fitted, but a lower value of p_e was required. At this lower angle of incidence the velocity normal to the surface is higher. Then the ion penetrates to a greater depth and the emitted electrons have a lower probability of escape.

In model 2, we assume that the incident ions, on average, cause secondary electron formation, which has an exponential distribution $\exp(-z/D)$, at a depth z in the direction normal to the surface, where D is the mean range of the incident ion for secondary electron formation. The distribution of secondary electrons is assumed to be that given by the coincidence measurements. The transport of an electron to the surface is described by an exponential attenuation function $\exp(-z/L)$, where L is the mean electron attenuation length. Then, when we integrate over all ion penetration depths and take into account the escape probability of electron groups, the probability, P_n, of obtaining a group of n electrons at the surface is given by

$$P_n = \sum_{m=0}^{\infty} W_{n+m} \frac{(m+n)!}{n!} \sum_{i=0}^{n} \frac{(-1)^i}{(m-i)!i![D(n+i)/L+1]}, \tag{1.8}$$

where W_{n+m} is the electron emission probability for $(n+m)$ electrons in the coincidence measurements. The values of P_n were fitted to the non-coincidence results by varying the ratio D/L. The results are shown in figure 6 for 8 keV H^+ ions incident at 80°. It can be seen that for $D/L = 0.3$, the agreement is quite good. In the case of 8 keV ions incident at 67°, the best fit occurred with $D/L = 0.7$. This change in the ratio D/L is physically acceptable. At the lower incidence angle, where the velocity normal to the surface increases, the value of D would be expected to increase while L should remain constant.

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