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STATISTICS OF THE SECONDARY ELECTRON EMISSION BY THIN FOILS BOMBARDED WITH BEAMS OF ACCELERATED ATOMS

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A systematic study is reported of the statistics of secondary electron emission by a thin (~40 Å) carbon foil bombarded with H, He, O, and S atoms with energies between 10 and a few hundred keV. Two mechanisms were verified for the generation of secondary electrons.

Secondary electron emission produced when a solid target is bombarded with energetic atomic particles has been under investigation for many years [1]. However, existing phenomenological theories of the phenomenon (see [2,3]) have not been capable of predicting the differential (with respect to the number, energy, and angle of emission) probabilities of escape of electrons under bombardment by a beam of known composition and energy.

The unsatisfactory state of the theory and the practical need for data have acted as a stimulus for new studies capable of producing more detailed information about many-electron secondary emission (MESE). A reliable quantitative theory of the MESE mechanism can only be developed when such information becomes available. This, in turn, has led to considerable interest in MESE by thin foils in which the energy of the incident atomic particles can be controlled and is accurately known, and it is also possible to examine emission on either side of the foil.

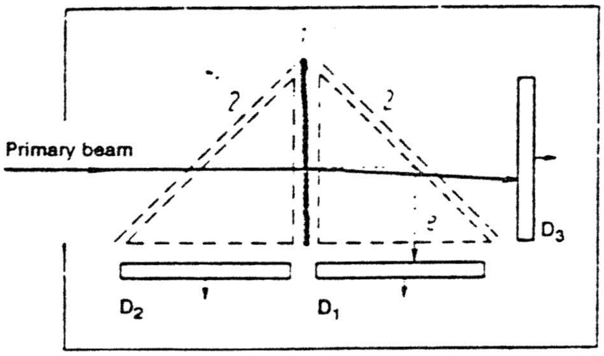
We have carried out a systematic study of the differential (with respect to the number k of escaping electrons, including k = 0) probabilities of MESE due to the bombardment of a thin carbon film (~40 Å thick) by H, He, O, and S beams with energies in the range between a few tens and a few hundred keV. We investigated $P_k(E)$, $P_{k'}(E)$, i.e., the probabilities of emission from the two sides of the foil and the probabilities $P_{kk'}(E)$ of simultaneous two-sided emission (the subscripts k, k' refer to emission by transmission and reflection, respectively). The probabilities P_k, $P_{k'}$, and $P_{kk'}$ are related by the following obvious expression:

$$P_k(E)=\sum_{k'} P_{kk'}(E).$$

The statistics can thus be investigated, at least in principle, by measuring only $P_{kk'}(E)$. However, in practice, it was found more convenient to measure all three quantities, which enabled us to perform a mutual verification and to increase the precision of the probabilities found in this way.

The method used in these measurements is described in detail in [4] and may be summarized as follows (Fig. 1). The beam of neutrals was obtained by using the neutral component of the ion beam of a linear accelerator (using charge transfers and deflection of charged ions). The carbon foil was mounted at right angles to the bombarded beam between two rotatable (by 90°) electrostatic mirrors consisting of high-transmission grids. The mirrors were used to accelerate secondary electrons to 1 keV. The electrons were then directed onto the detectors D_1 (transmission) and D_2 (reflection).

The detectors were specially constructed from microchannel plates [5] and were used as particle counters (the corresponding one-electron pulse-height distributions were found with a resolution of $\Delta A/A$ = 30-40%). This enabled us to distinguish reliably between different emission events in accordance with the number of arriving electrons, i.e., the pulse heights of the signals produced by D_1, D_2, which are proportional to the number of electrons. The beam atoms transmitted by the foil were detected by D_3, which was base on the VEU-7



many-electron secondary emission: 1) foil; 2) electrostatic mirror; D_1, D_2, D_3) detectors.

microchannel-plate detector. The recording system consisted of CAMAC modules and operated under microcomputer control. The three detectors D_1, D_2, and D_3 can work independently or as double and triple coincidence systems. Random coincidences were practically excluded and the correlation of MESE events could be investigated by recording D_1-D_2 coincidences.

Figure 2a shows typical MESE spectra (reflection) produced by bombarding the foil with S atoms of different energy. After numerical deconvolution, the recorded spectra can then be used to find the true distributions N_k for the electrons leaving the foil. If the primary beam intensity I_0 is known, these distributions, acquired over a time τ, can be used to find the absolute yields, i.e., the absolute probabilities of emission of k electrons $P_k(E)$ ($P_k = N_k/M$; $k = 1, 2, ...$; $M = I_0\tau$).

The coincidence system was used to record the simultaneous yields of electrons in transmission and reflection. A typical spectrum of these simultaneous yields is shown in Fig. 2b.

The intensity I_0 of the primary bombarding beam was determined by the method described in [6], using the relation $I_0 = I_1I_3/I_{1-3}$ or $I_0 = I_2I_3/I_{2-3}$ (where I_1, I_2, I_3 are the count rates in detectors D_1, D_2, D_3, respectively, and I_{1-3} and I_{2-3} are the rates of coincidences between D_1 or D_2 and D_3). The intensity I_0 was also monitored with a semiconductor detector.

The MESE yield distributions on the two sides of the foil are not identical. There is an asymmetry between the count rates ($I_1 > I_2$) and coincidence rates ($I_{1-3}/I_{2-3} \geq 1.2$ in all measurements).

Figure 3a shows the results of an analysis of these measurements for S atoms bombarding the carbon foil: the histograms show the P_k, $P_{k'}$, $P_{kk'}$ distributions and the energy dependence of the emission probabilities (similar results were obtained for H, He, and O).

It is clear from Fig. 3a that the MESE yield exhibits an asymmetry that has certain specific properties that we have established for the first time. Thus, the energy dependence of the probabilities P_k and $P_{k'}$ is not the same, and these probabilities do not reproduce the form of the energy dependence of the corresponding specific loss S_e (the two agree approximately only in the case of the mean electron yield $\bar{k}=\sum_k kP_k$). The asymmetry $\Delta P_k = (P_{k'}-P_k)/(P_{k'}+P_k)$ changes sign for different k ($\Delta P_k(k=0,1)>0$; $\Delta P_k(k>1)<0$).

The data obtained in this way enabled us to analyze the MESE statistics, and this showed that the experimental probabilities P_k, $P_{k'}$ do not follow Poisson statistics and $\bar{k} \neq -\ln P_0$. This fact is probably an indication that the number of electrons produced by a particle inside the foil deviates from the Poisson distribution.

By analyzing the coincidence data, we were able to find the values of $P_{kk'}(E)$, and Fig. 3b shows an example of a two-dimensional histogram that plots the probabilities of simultaneous yields of different multiplicity, both by reflection and transmission. The values of P_k, $P_{k'}$, $P_{kk'}$ found in this way can be used to calculate the probability correlation coefficients

$$\rho_{kk'} = \frac{P_{kk'}-P_kP_{k'}}{\sqrt{P_k(1-P_k)P_{k'}(1-P_{k'})}}$$

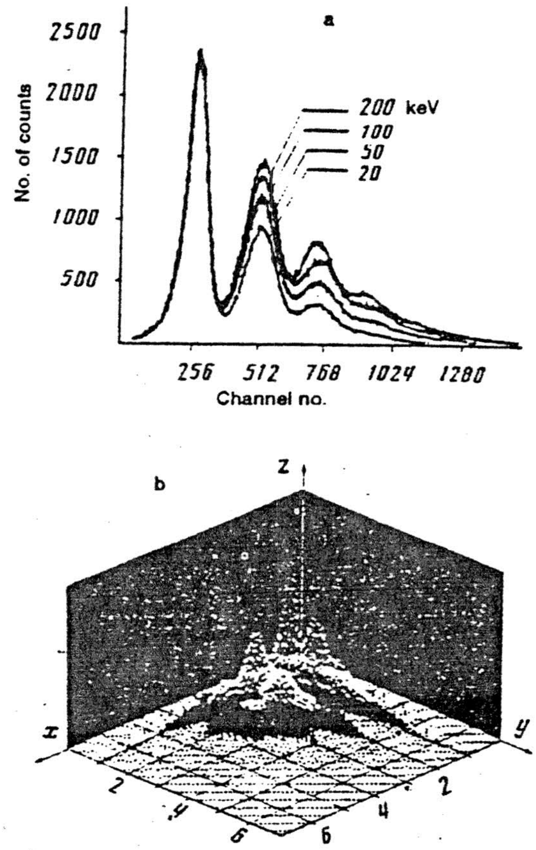


Fig. 2. Pulse-height spectra of output pulses from detectors, obtained by bombarding a foil with ^{32}S atoms of different energy: a) reflection (D_2); b) D_1, D_2 coincidences (100 keV). The distribution peaks correspond to the yields of a different number of electrons, and the peak broadening is due to the statistical character of multiplication in the detectors.

and the so-called correlation sampling coefficient $\hat{\rho}$ for the charges leaving the foil

$$\hat{\rho} = \frac{\sum_{kk'} P_{kk'}(k-\bar{k})(k'-\bar{k}')}{\left[\sum_{k} P_k (k-\bar{k})^2\right]^{1/2} \left[\sum_{k'} P_{k'}(k'-\bar{k}')^2\right]^{1/2}}.$$

It is found that, for all systems, $\hat{\rho} \sim 0.4$. Since the main contribution to $\hat{\rho}$ is due to the probability P_{00}, we may conclude that there is no appreciable correlation between the charges escaping on the two sides of the foil. The probability correlations $\rho_{kk'}$ have significant values ($\leqslant 0{,}2$) only for $k = k' = 0$.

The differences that we have found in the dependence of the specific loss and P_k, $P_{k'}$ on the energy, the deviation from the Poisson behavior, the specific asymmetries of yields of different multiplicity, and the asymmetry in the two-sided yields with interchanged multiplicity (for example, P_{12} and P_{21}) should be regarded as evidence for the presence of two mechanisms controlling the generation of MESE electrons. These mechanisms correspond to collisional ionization and cascade multiplication of internal secondary electrons. The relative contribution of these mechanisms depends on the energy and the type of bombarding atom. Actually, numerical Monte Carlo

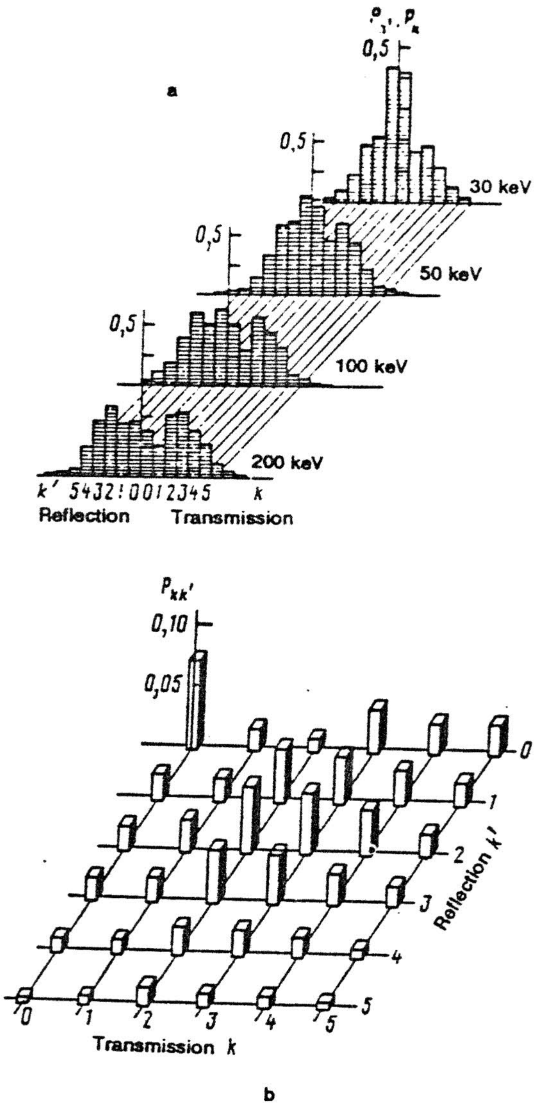


Fig. 3. Yield distribution for secondary electrons produced under bombardment with ^{32}S atoms: a) independent yield at different energies; b) coincidence yields for E = 200 keV.

simulation of the transfer of internal secondary electrons produced as a result of ionizing collisions has enabled us to reproduce many of the observed properties of the functions $P_k(E)$, $P_{k'}(E)$, $P_{kk'}(E)$. The case of bombardment with H atoms was simulated using the known [7] energy spectrum of MESE electrons. Preliminary evidence suggests that this approach can be used to obtain a numerical solution of the inverse problem, namely, the determination of the quantitative contribution of direct (ionization by impact) and secondary (electron cascade) processes in MESE due to the passage of energetic atomic particles through the medium.

We note in conclusion that this has been the first systematic investigation of many-electron secondary emission in wide energy (10-200 keV) and mass (Z = 1-16) ranges. The data obtained so far provide a reliable basis for further tests of the quantitative theory of the phenomenon.

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