Many-electron secondary emission of thin foils bombarded by accelerated atomic beams

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The secondary electron emission statistics of a thin (~ 40 Å) carbon foil bombarded with H, He, O, and S atoms with energies from ten to several hundred keV has been systematically studied. The manifestation of two mechanisms of production of secondary emission electrons has been detected experimentally.

The secondary electron emission (SE), produced by bombarding a solid target with high-energy atomic particles, has been studied for many years.[1] However, the phenomenological theories developed to account for this effect[2–3] are unable to predict the differential (with respect to the number, energy, and exit angle) probabilities of escape of electrons under bombardment of the target with a beam of known composition and energy, and this stimulates new studies of many-electron secondary emission (MSE).

The object of the present work was a systematic study of the differential (with respect to the number $k = 0, 1...$ escaping electrons) probabilities of MSE caused by bombardment of a thin carbon foil (~ 40 Å thick) by atomic beams. We studied the $P_k(E)$, $P_{k'}(E)$ probabilities of escape from both sides of the foil and the probability $P_{kk'}(E)$ of simultaneous two-sided escapes (subscripts k and k' correspond to escapes by penetration and by reflection). The probabilities are related by an equation of the form $P_k(E) = \Sigma_{k'} P_{kk'}(E)$.

In principle, the study of the statistics is ensured by the measurement of only $P_{kk'}(E)$. However, methodologically it was found convenient to carry out the measurements of all three quantities, making it possible to independently obtain two files of data that permitted cross-checking and a more accurate determination of the P_k values. The measurements were conducted during bombardment of the foil with ^1H, ^4He, ^{16}O, and ^{32}S atoms with energies ranging from ten to several hundred keV.

The measuring technique was described in detail in Ref. 4 and can be summarized as follows. The beams were obtained by using the neutral component of the ion beam (background charge exchange; ions which have not undergone charge exchange are deflected) of a linear accelerator. The carbon foil was mounted perpendicular to the bombarding beam between two deflecting (by 90°) electrostatic mirrors. The mirrors were used to accelerate the secondary electrons to ~ 1 keV and to direct them at specially designed detectors D_1 (shoot through) and D_2 (reflection).[5] The detectors operated in the counting mode and made it possible to distinguish reliably between emission events according to the number of incoming electrons–the signal amplitudes of D_1 and D_2 were proportional to the number of electrons arriving at their input. A detector D_3 was used to detect the beam atoms which passed through the foil.

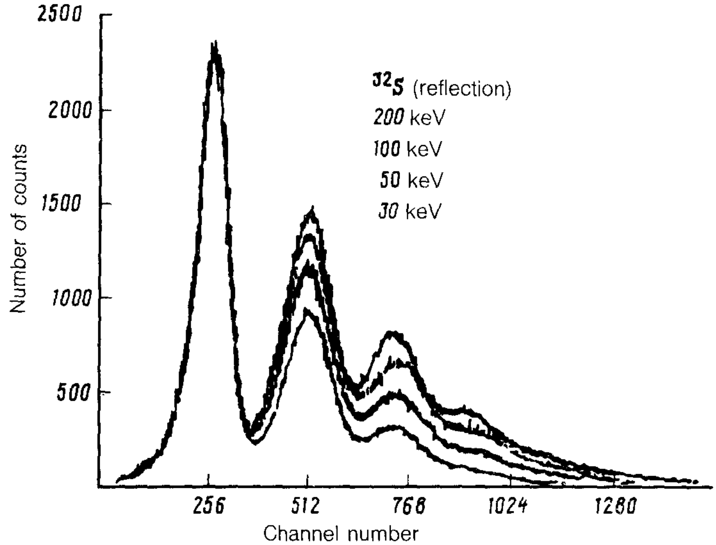

FIG. 1. Amplitude spectra of output pulses of detector D_2, obtained by bombarding a foil with ^{32}S atoms of different energies. The distribution peaks correspond to simultaneous detection of 1, 2, etc. emission electrons, and the peak widths are determined by the statistical character of the multiplication in the detector.

Figure 1 shows typical spectra of MSE yield, from which, after numerical deconvolution, one can extract the true distributions of N_k over the number of electrons that escape from the foil. For a known primary beam intensity I_0 (which can be determined from the counting rate and coincidence counting rate of the detector[6]), from these distributions, accumulated in time T, one can find the absolute yields, i.e., determine the absolute probabilities P_k $(P_k = N_k/M,\ k = 0,1,2,...;\ M = I_0 T)$ of emission of k electrons.

Figure 2a shows results of the analysis of the measurements (Fig. 1): The bar graphs show the distributions of P_k and the nature of the changes in emission probabilities with energy S of the atoms (similar bar graphs were obtained for H, He, and O).

Visible here is the asymmetry of SE yield—it has specific features that have been detected for the first time. Thus, the energy dependences of the probabilities P_k and $P_{k'}$ turn out to be different, i.e., they do not reproduce the shape of the corresponding curves of specific losses S_e as a function of energy. [An approximate reproduction of this shape was noted only for average electron yields $\tilde{q}(E) = \Sigma_k P_k k$]. The latter fact may be related to the establishment of the equilibrium charge of the particle in the foil—the characteristic length of the required range is comparable to the foil thickness. The degree of asymmetry $\Delta P_k = (P_{k'} - P_k)/(P_k + P_k)$ changes sign for different $k(\Delta P_{0,1} > 0; \Delta P_{k>1} < 0)$.

The data obtained made it possible to carry out an analysis of the nature of the MSE statistics; the probabilities, P_k and $P_{k'}$, do not follow a Poissonian distribution, in particular, $\tilde{q} \neq -\ln P_0$.

Analysis of the amplitude measurements in the coincidence mode made it possible

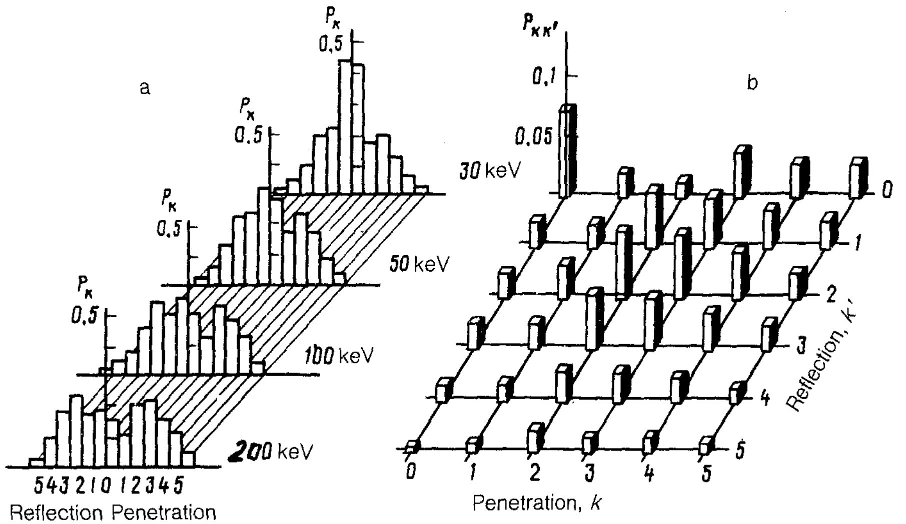

FIG. 2. Secondary-electron emission probabilities upon bombardment with ^{32}S atoms. (a) Independent emission at different energies, (b) emission in coincidences at E = 200 keV.

to find $P_{kk'}(E)$. The independently determined probabilities P_k, $P_{k'}$, and $P_{kk'}$, (random errors do not exceed 1%) were found to be in good quantitative agreement. An example of the bar diagram of the probabilities of simultaneous onset of reflection and transmission is shown in Fig. 2b. From $P_k(E)$,$P_{k'}(E)$,$P_{kk'}(E)$ one can calculate the correlation coefficients of the probabilities $\rho_{kk'}(E)$ and the so-called sampling correlation coefficient $\hat{\rho}(E)$. It turns out that for all systems, $\hat{\rho} \lesssim 0.2$. Since the main contribution to $\hat{\rho}$ is related to the probability P_{00}, it may be concluded that there is no appreciable correlation of the charges that emerge on both sides.

The correlations of the probabilities $\rho_{kk'}$, also have significant values ($\lesssim 0.4$) only for $k = k' = 0$, i.e., for "blank" shots through the foil.

Absence of correlations, differences in behavior of the energy dependences of specific losses S_e and probabilities P_k, deviations of P_k from Poissonian behavior, specific asymmetries of probabilities P_k and $P_{k'}$, asymmetries of probabilities P_{ij} and P_{ji}—all these observations can find an explanation only on the basis of an examination of the two mechanisms of production of *SE* electrons. These mechanisms correspond to collisional ionization of the atoms of the substance and to cascade multiplication of the inner secondary electrons that are formed. The relative contributions of the mechanisms change with the energy and kind of bombarding atoms. Numerical Monte Carlo simulation of the transfer of inner secondary electrons with a known[7] energy spectrum, produced as a result of ionizing collisions with *H* atoms, made it possible to reproduce many observed characteristics of the $P_k(E)$, $P_{k'}(E)$, $P_{kk'}(E)$ curves. The first positive results lead to the conclusion that the outlook is promising for such an approach to the numerical solution of the inverse problem—determination of quantitative contributions of direct (collisional ionization) and secondary (electron cascade) processes during MSE caused by high-energy atomic particles that pass through the substance.

Let us note in conclusion that the characteristics of many-electron secondary emission have been systematically studied in the present work over a wide energy range (10–200 keV) and mass range ($z = 1-16$) for the first time. The body of the data obtained provides a reliable basis for testing the quantitative theory of the effect.

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