Scientific session of the Division of General Physics and Astronomy of the Academy of Sciences of the USSR (28 November 1990)

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A scientific session of the Division of General Physics and Astronomy of the Academy of Sciences of the USSR was held on November 28, 1990 at the S. I. Vavilov Institute of Physics Problems, Academy of Sciences of the USSR, Moscow. The following papers were heard at the session: 1) *Prospects of Cosmology*, **I. D. Novikov.** 2) *Multi-Electron Emission Induced by Fast Atoms Passing Through a Thin Foil*, **A. A. Kozochkina and V. B. Leonas.** Brief contents of the second report are given below.

The method[1,2] and results[3–6] of an experimental investigation of the statistics of secondary electron emission, caused by the bombardment of a carbon foil with fast atoms, were presented in the report, and a quantitative description of the results was also shown to be possible on the basis of modeling by the Monte Carlo method using data on the cross sections of atomic and electron collisions. Secondary electron emission is a fundamental process of interaction of a plasma with a solid. Secondary electron emission from the surface of a solid has been known for a long time, the first publication having appeared in the past century. A vast amount of experimental data has been accumulated up to the present time,[7,8] but the data from investigations of the past 10–15 years have priority and reliability. Several phenomenological and semiempirical theories of the phenomenon have been developed (see appropriate citations in Ref. 8).

Traditional objects of secondary emission studies are the yield γ—the average number of secondary electrons per bombarding particle and the energy spectrum of the secondaries–$d\gamma/dE_e$. Recently, however, in addition to the above-mentioned integrated characteristics of secondary emission, studies of the differential characteristics have begun-the statistics of multi-electron secondary emission (the distribution in terms of the number of secondary electrons leaving the surface), symmetry of the forward/backward yield (with respect to the direction of the bombarding beam), and the angular and energy distributions of the secondaries. The term multi-electron emphasizes that the quantity γ is the statistical average for events of different emission multiplicity in individual events.

Investigations of kinetic secondary emission have led to a consideration of an emission event as the result of three successive stages (Fig. 1): 1) primary ionization by a high-energy particle passing through a material (secondary ionization processes involving high-energy internal electrons and recoil atoms are also possible), 2) the migration of the resulting internal electrons to the material-vacuum interface, 3) escape of emission electrons into vacuum after surmounting the surface potential barrier.

These conclusions are arrived at on the basis of measurements of the integrated characteristics, leaving considerable arbitrariness for understanding the actual physical mechanisms underlying the phenomenon. The transition to measurements of the emission statistics and twofold differential outputs (with respect to angle and energy) will make it possible to "narrow the tolerances" on the process mechanisms used in the theories and to bring us closer to a quantitative understanding of multi-electron secondary emission.

Figure 1, which shows a qualitative picture of the passage of a high-energy atomic particle through a thin target, provides a context in which to discuss the principal collision processes associated with secondary electron emissions. The heavy particle, after traversing a path x_k ($k = 1, 2, 3, \ldots$), determined by the characteristic ionization mean free path λ_i, produces an internal secondary electron e_k. The escape of this electron is characterized by certain angular and energy distributions. Given the lack of a nonempirical theory for describing the distribution, an extension of the results of studies of the distributions for electrons, ejected during collisions of protons in gas targets,[9] can be an excellent model. The migration of internal secondary electrons in the target is accompanied by individual and collective interaction processes. Individual collisions lead to elastic scattering—a change in trajectory, and to inelastic collisions—a slowing of the electrons and direct ionization leads to a cascade multiplication (the appearance of the electrons e'_k; see Fig. 1). Collective interactions are accompanied by slowing.

An important feature of investigations of recent years is the use of thin targets—foils, which provide a number of advantages over massive targets.

Figure 2 shows a diagram of an apparatus used by us to measure the secondary emission statistics of a thin (~ 50 Å) foil,[2] providing for the ability to record the secondary yield from both sides both independently and also in coincidence. The principal elements of the apparatus are two identical electrostatic mirrors, transporting electrons to the detectors (D_1, D_2). The specially constructed[1] detectors D_1, D_2 employing microchannel plates makes it possible to distinguish

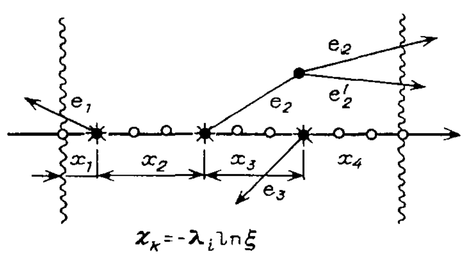

FIG. 1. Qualitative picture of the passage of a fast particle through target material. x_k is path traversed by particle between successive ionization events–production of the electrons e_k, e'_k–cascade electron, ξ is an arbitrary number from 0 to 1.

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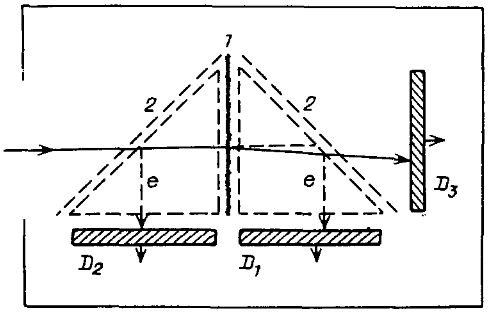

FIG. 2. Apparatus for investigating statistics of two-sided emission of a thin target.[2] 1–foil, 2–electrostatic mirror for acceleration and deflection of electrons from path of primary beam, D_1, D_2–detectors (employing microchannel plates) of the electrons leaving by transmission and by reflection, D_3 is primary beam detector. D_1, D_2, D_3 can operate independently and in coincidence. The secondary electron trajectory is indicated by the dashed line.

emission events in terms of the number of electrons involved. The beam particles are detected by D_3.

Figure 3 shows typical multi-electron secondary yield spectra (by reflection) when a carbon foil is bombarded by beams of H, He, or O atoms. The absolute probabilities P_k and $P_{k'}$ for a yield of k, k' (0, 1, 2,...) electrons by transmission and by reflection, respectively, can be found from spectra of this type after a numerical deconvolution. Two-dimensional spectra, measured in coincidence for transmission and reflection yields of different multiplicity, give values for the probabilities $P_{kk'}$. Measurements of P_k, $P_{k'}$, $P_{kk'}$ have been made for H, He, O, and S atom beams in the energy interval from tens to hundreds of keV.

The data obtained for P_k, $P_{k'}$, $P_{kk'}$, when separated into the individual probabilities, characterize quantitatively the asymmetry between the transmission and reflection secondary yields. The results indicate without any doubt that the angular dependence of internal secondary electrons is asymmetric.

Data on the probabilities P_k and $P_{k'}$ make it possible to analyze the type of multi-electron secondary emission statistics. The main result of this analysis is that the experimentally found distributions of P_k and $P_{k'}$ are not Poisson distributions. The deviations observed must be related to mechanisms other than ionization by heavy particles for the production of internal secondary electrons.

Data on P_k, $P_{k'}$, $P_{kk'}$ make it possible to perform a correlation analysis of the probabilities. The absence of yield correlations has been established, meaning that the events producing the individual internal secondary electrons are mutually independent. From known values of P_k and $P_{k'}$ one can find the average yields $\bar{k}(E)$, $\bar{k}'(E)$ ($\bar{k} = \Sigma k P_k$), which agree with the γ values known from the literature.

The multistage nature of secondary electron emission makes it difficult to develop a closed quantitative nonempirical theory. The introduction of models is unavoidable in this situation. It appears that the collision model of secondary emission, discussed quantitatively in conjunction with Fig. 1, has the greatest physical clarity. On the basis of a formalization[10] of this model a set of computer programs has been developed, providing for a numerical modeling (on the basis of the Monte Carlo method) of the transport process of atoms and electrons in the target material. Data on the angular and energy distributions of electrons from Ref. 9 were used for calculations with H atoms, and an excellent reconstruction of the measured P_k, $P_{k'}$, $P_{kk'}$ has been obtained.

Essentially all characteristics of multi-electron accessible to measurement—statistical, angular and energy-related—can be obtained in calculations using this set of programs, and, thus, the agreement of the calculations with measurements will make it possible to determine more precisely the input parameters of the calculation. The inverse problem of determining the key characteristics of the collision processes responsible for electron emission is solved, in essence, in this manner. Moreover, quantities that are inaccessible to measurement, such as the cascade contribution, escape depth of secondary electrons, etc., can also be obtained.

The first successful results of modeling foster the expectation that by following this path it will be possible to arrive at a reliable quantitative description of multi-electron secondary emission.

The prospects for expanding experimental studies of multi-electron secondary emission involve the simultaneous

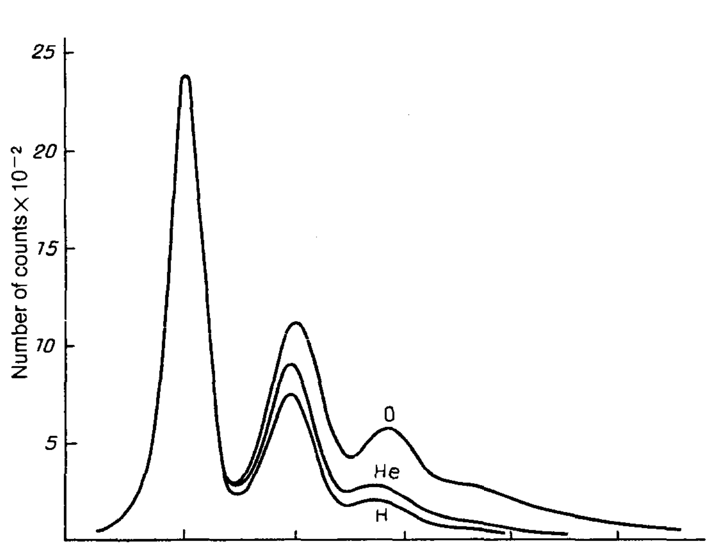

FIG. 3. Smoothed amplitude spectrum of secondary electron detector (H:$E = 20$ keV; He:$E = 50$ keV; O:$E = 200$ keV, emission by reflection). The peaks refer to arrival at detector of 1, 2, 3, etc., electrons simultaneously. Width of single-electron (and other) peaks is caused by the multiplication statistics of the channel plate assembly. A numerical deconvolution of the spectrum is carried out to separate the peaks.

recording of statistical, angular and energy characteristics, a changeover to studies of thin metal targets, the use of multiply charged ion beams in the experiments and an investigation of isotope effects for H and D beams, the use of targets of different thickness for the controlled "turn-on" of different collisional processes and the control of the charge state of the particles passing through the target.

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Translated by Eugene R. Heath