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ENERGY DISTRIBUTIONS OF ELECTRONS IN STAINLESS STEEL BOMBARDED BY FAST IONS

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The results of experimental investigations of secondary electron emission energy distributions and yields induced by 1÷2 MeV H^+ and He^+ ion impact on stainless steel are presented. The projectiles were obtained from Van de Graff accelerator. It is shown that for all projectiles the electron energy distribution functions measured have piecewise power-law dependences with different power indices on various electron energy intervals. The corresponding power indices and electron yields are presented.

KEY WORDS: fast ion, electron distribution function, electron emission, stainless steel, spherical analyzer, electron yield.

The interest to interactions of atomic particles with different materials is continuously grows. Especially, such effects gain in importance in connection with development of a controlled thermonuclear reactor. First vacuum wall of a controlled thermonuclear reactor will be exposed to high intensity flux of various kinds of radiation. Interactions of radiation with materials may cause changing of its physical and mechanical properties, contamination of plasma [1]. The most frequently occurring phenomena of particle-induced emission from the walls of a plasma device are a reduction of plasma temperature, altering of sheath potential and others. There is a number of papers devoted to particle induced electron emission from surfaces for situation relevant to a plasma device [see, for example, 7]. But there is little information on secondary emission properties of constructive materials widely used in high power plasma devices such as, for example, stainless steel.

Entry of an additional kinetic energy into plasma of a solid gives rise to ionizations of medium atoms and production of a plenty of free electrons, which have energies above an equilibrium level [3]. In such conditions it is possible to form of electron distributions differing from equilibrium ones [4, 5]. As it has been shown in a number of theoretical and experimental investigations, under bombardment of high energy ion beams a steady-state nonequilibrium power-law distribution function of electrons is formed in a solid-state plasma:

$$f(E)=A\cdot E^{s}, \qquad (1)$$

where A is a constant, s is a power index [5, 6]. Here E is a total energy of electrons in a solid: $E=\varphi+E_F+eU$, where φ is a work function, E_F is a Fermi level, and the energy eU is measured from a vacuum level. The principal condition for the existence of steady-state nonequilibrium distributions is the presence of a particle or energy flux formed by a source (ionization) and a sink (emission of electrons). Power-law distributions are characterized by presence of significant part of high energy electrons. For example, the fraction of electrons with energies higher than E_p=18,9 eV (where E_p is energy of a plasma oscillations in beryllium) in the electron distribution induced by 4,9 MeV α-particles in beryllium sample can exceed 37 % [7].

When velocity of an incident ion v essentially exceeds velocity of each electron of target atom, elastic losses are negligible small, and inelastic losses of energy usually referred to ionization losses or stopping power, are determined by the Bethe-Bloch formula [1]:

$$-dE/dx=(4\pi Z_1^2e^4/mv^2)Z_2N\ln(2mv^2/I), \qquad (2)$$

where m is the mass of an electron, Z_1 is the charge of the incident particle, Z_2 is the charge of the substance atoms, N is density of target atoms, and I is their mean excitation potential. As appears from the formula (2), in a high energy region ionization losses decrease as v^{-2}. Entry of an additional charge into the quasi-neutral equilibrated system of solid-state plasma results in excitation of electron plasma oscillations - plasmons [9]. Thus, the energy lost by an ion moving in a solid-state plasma, can be transferred to electrons of medium in two different ways: a fraction of the ion energy goes into excitation of plasmons, and the other fraction is converted into the energy of individual electrons in collisions (in particular, in ionizing collisions with atoms) [3].

The part of electrons produced in a solid, having the proper values and directions of momentum, can escape from the substance or, in other words, a kinetic secondary ion induced electron emission (SIEE) takes place. Process of an emission occurs in three stages:

1) production of secondary electrons;
2) transport of electrons (diffusion) to a surface of a solid and collisions;

3) overcoming potential barrier existing on a surface, and ejection into vacuum.

Since well-known Sternglass paper [9] such approach is considered to be most thorough representing the mechanisms of SIEE [10].

The fundamental integral of the kinetic emission is coefficient of SIEE γ frequently termed in the literature as an electronic yield [11]. Electronic yield γ is defined as a relation of a number of secondary electrons N_e emitted to a number of incoming ions N_i:

$$\gamma = N_e/N_i\,. \tag{3}$$

The value of electron yield essentially depends on energy of bombarding ions. Now it is considered theoretically and experimentally proved, that for light ion impact electronic yield γ is proportional to the stopping power (electronic energy loss per unit path lengths) in substance dE/dx [9, 11, 12].

Considerably more informative characteristics of SIEE are energy spectra of secondary electrons. The experimental study [13-16] has shown, that energy spectra of secondary electrons for different metals have power-law character.

In this paper we tried to obtain information about kinetic secondary electron emission properties of stainless steel bombarded by swift light ions.

EXPERIMENTAL SETUP

The investigations of energy spectra and electron yields of secondary electron emission induced by fast light ion beams were carried out on the experimental setup which schematic diagram is represented on fig. 1.

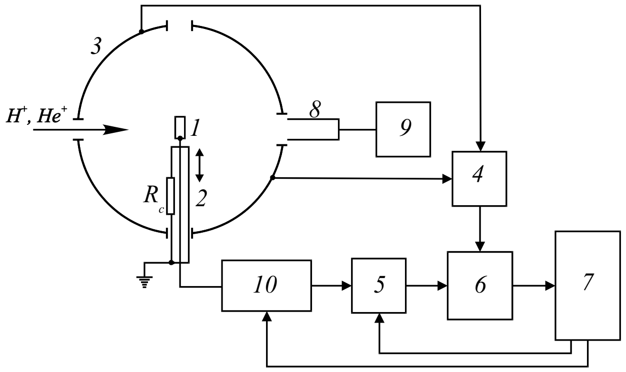

Fig. 1. Schematic diagram of the experimental setup: 1 - target, 2 - holder of a target, 3 - half-spheres, 4,5 - electrometric amplifiers, 6 - the analog-digital converter, 7 - IBM PC computer, 8 – Faraday cup, 9 - current device F303, 10 - source of sawtooth voltage.

The electrostatic ion Van de Graff accelerator, used as a source of primary particles, permitted to produce hydrogen H^+ and helium He^+ ion beams with energies from 1 up to 2 MeV.

The target under study 1 had 10 mm diameter and were fixed in copper workholder fastened on holder 2. The ion beam, collimated by means of diaphragm system, impinged on the target and caused backward secondary electron emission from its surface. Plane of the target was perpendicular to beam axis. The diameter of the beam spot on the target was 3 mm. The ion current density was not higher, than 30 μA/cm^2. Experiments were carried out with thick target prepared of stainless steel (12C18N10T).

The chamber was pumped out with a NMD-0,4-1 magnetic-discharge pump and an NVPR-16D fore vacuum pump with a liquid nitrogen trap. In all experiments vacuum system has allowed to provide residual gas pressure in the chamber no more than 10^{-6} Torr.

The experimental setup and procedure for energy distribution and electron yield measurements have been described in [17]. Electron yield was determined by the formula:

$$\gamma = |I_C| / (I_T - |I_C|), \tag{4}$$

where I_C is collector current, I_T is target current.

Studying energy spectrum of SIEE electrons by means of the spherical analyzer designed for a point source of emission, it is possible to find an explicit shape of the distribution function of electrons inside a solid [18]. When the electron distribution is the power-law function the derivative of emission currents on electron energy dI/dU can be represented as:

$$dI/dU = B\cdot(E_F+\varphi+eU)^{-s+1}, \tag{5}$$

where B is a constant, E_F is Fermi level, φ is work function, eU is the energy of electrons in vacuum. Hence, the dependence (5) in double logarithmic scale represents straight line, which slope ratio is equal to (-s+1). The energy distributions of secondary emission electrons were measured by means of the spherical collector in a retarding field energy analyzer mode. The dependences of the collector current on retarding voltage (5) (retarding curves) allowed to obtain the energy spectrum of SIEE electrons by differentiation of these dependences, and then restored the distribution function. Calculation procedure of the power index s values of electron distribution functions included some operations. At the beginning the "fitting" of electron emission current and differentiation of the retarding curves were carried out.

Then the linear approximation of the dI/dU dependences on a total energy of electrons inside a solid (E_F+φ+eU) plotted in logarithmic scale was performed. According to (5), the slope ratio of the straight lines is equal to (-s+1).

EXPERIMENTAL RESULTS AND DISCUSSIONS

The experimental research of an energy distribution of SIEE electrons has shown, that for all energies of H^+ and He^+ ions the electron distribution function formed in stainless steel has piecewise power-law dependence. These distributions are characterized by presence of two sections with different power indices. The typical distribution function of electrons induced by He^+ ions with energy 1,25 MeV is presented on fig. 2. The experimental curve is approximated by two straight lines with different power indices on energy intervals (counted from vacuum level) of 5-30 eV and 30-100 eV. As a result of experimental data processing the corresponding power indices were obtained. The values of power indices s_1 and s_2 for two sections of the distribution, which correspond to the above-mentioned energy intervals, are presented in the table.

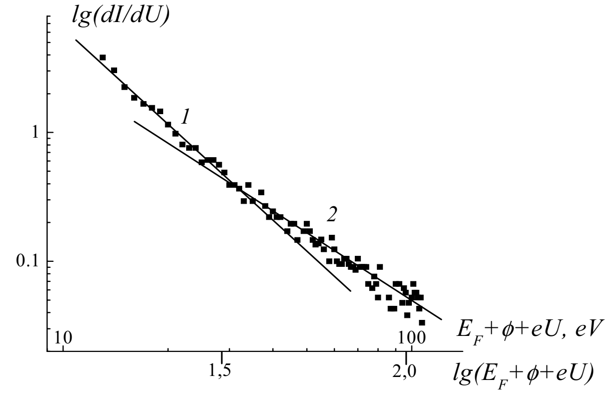

Fig.2. Typical lg(dI/dU) dependence on lg(E_F+φ+eU) for stainless steel bombarded by He^+ ions with energy 1,25 MeV. The power indices s_1=3,5 and s_2=2,7 correspond to sections 1 (energy interval 5-30 eV) and 2 (30-100 eV) of the distribution function.

Table. Power indices for two sections of the electron distributions.

Ion	Energy, MeV	s_1	s_2
He^+	1,00	3,7	2,8
	1,25	3,5	2,7
	1,50	3,3	2,7
	1,75	3,2	2,7
	2,00	3,1	2,5
H^+	1,00	3,8	2,5
	1,25	3,5	2,5
	1,50	3,5	2,2
	1,75	3,4	2,4
	2,00	3,2	2,1

In our opinion, the presence of piecewise character, namely two sections on the distribution function, perhaps, is connected with the action of two different mechanisms of energy transfer from the moving fast ion to the electron subsystem of the solid: plasma oscillation excitation with subsequent electron production by plasmon ionization and inelastic collisions with substance atoms, leading to direct ionization.

An electron yield is considered to be basic characteristic of secondary ion induced electron emission. The results of experimental measurements of the electron yield values for H^+ and He^+ projectiles depending on stopping power of the ions are presented on fig. 3.The assumption of proportionality between the electron yield of SIEE and the stopping power is demonstrated on these figures. As evident, the experimental points of electron yield dependence on the stopping power dE/dx for H^+ and He^+ projectiles are seen to fit well in straight lines.

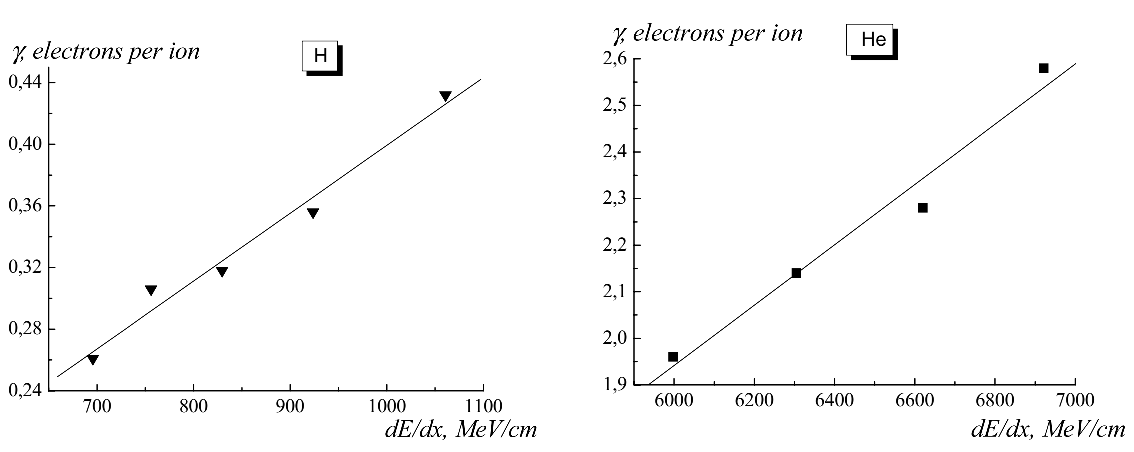

Fig.3. Electron yields from stainless steel as functions of the stopping power dE/dx for H^+ and He^+ projectiles.

CONCLUSIONS

As a result of the experiments performed it is shown, that the electron distribution functions induced by fast hydrogen and helium ions in stainless steel under study have piecewise power-law dependence with different power indices on electron energy intervals of 5-30 eV and 30-100 eV. Presumably, the presence of two parts on the distribution function is connected with two channels of dissipation of the energy of fast ions in solid-state plasma. The first one is plasma oscillation excitation and next plasmon decay with the production of nonequilibrium electrons. The second one is transfer of ion kinetic energy to individual electrons in collision processes.

The values of electron yield measured are in good agreement with assumption of proportionality between electron yield of secondary emission and the electronic energy loss per unit path length of the ion bombarded.

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ЭНЕРГЕТИЧЕСКИЕ РАСПРЕДЕЛЕНИЯ ЭЛЕКТРОНОВ В НЕРЖАВЕЮЩЕЙ СТАЛИ ПРИ БОМБАРДИРОВКЕ БЫСТРЫМИ ИОНАМИ

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Представлены результаты экспериментальных исследований электронных выходов и энергетических распределений вторичной электронной эмиссии, индуцированной ионами H^+ и He^+ с энергией 1÷2 МэВ из нержавеющей стали. Эксперименты проводились на ускорителе ионов Ван де Граафа. Показано, что для всех ионов измеренные функции распределения электронов по энергиям имеют кусочно-степенной характер с различными показателями степени на различных энергетических интервалах. Представлены соответствующие показатели степени и электронные выходы.

КЛЮЧЕВЫЕ СЛОВА: быстрый ион, функция распределения электронов, электронная эмиссия, нержавеющая сталь, сферический анализатор, электронный выход.