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Dissipation of the Energy of a Fast Charged Particle in a Solid-State Plasma

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Abstract—Results are presented from experimental investigations of mechanisms for the dissipation of the energy of light ions in metal plasmas by using the method of secondary electron emission. It is shown that the coefficient of anisotropy of energy transfer from fast light ions is about 1.7. It is also shown that plasma oscillations excited by an ion significantly influence the production and emission of low-energy electrons, especially in the case of projectile molecular ions. © *2003 MAIK "Nauka/Interperiodica"*.

1. INTRODUCTION

Because of the wide use of high-energy sources in science and engineering, increased attention is being given to the processes of interaction of charged particle flows with matter, in particular, to mechanisms for the transfer of energy from the particles to the medium. These mechanisms can be investigated by measuring the secondary effects that occur during the passage of a charged particle through a solid. A fast nonrelativistic particle moving in a solid-state plasma excites weakly damped collective oscillations of the electron density (electron wake waves), or so-called plasmons [1]. A particle moving with a velocity such that $v \gg v_0$ (where v_0 is the Bohr orbital velocity of an electron in a hydrogen atom in the ground state) transfers the main portion of its energy to the electron subsystem [2, 3]. The transfer occurs in two different ways: a fraction of the particle energy goes into the excitation of plasmons, and the remaining fraction is converted into the energy of individual electrons in collisions (in particular, in ionizing collisions with atoms). The ionization process that may also come into play when the energy transferred to an atomic electron is sufficiently large is an avalanche ionization (by collision cascades) [2]. In turn, plasmons propagating in the medium can give rise to the ionization of atoms in the fields of plasma oscillations, thereby producing new free electrons. The mean energy of the electrons produced by this mechanism is higher than the electron thermal energy (some of the electrons may be even far more energetic). These nonequilibrium electrons are capable of overcoming the potential barrier and thus escaping from the medium. The electrons emitted from the matter carry information about the processes that have occurred in the ionization track of an ion. Hence, by studying electron effects during the passage of a charged particle in a solid, it may be possible to estimate the role of different mechanisms in energy dissipation.

The main features of the mechanism for electron production through ionization by plasma oscillations are associated with a relatively long lifetime of the wake waves and with the continuous excitation of these waves along the entire ionization track. Because of the large lifetime of the wake wave, the secondary ionization inside the track proceeds over a long period of time after the passage of a charged particle. The amount of slow electrons produced in cascade ionization is large when the cascade is initiated by a fast electron. A consequence of the long mean free path of a fast electron in the medium is that, in the cascade ionization, most of the slow electrons are produced over a distance of about its mean free path. Consequently, the distribution function of the ionization-produced electrons near the axis of the particle track is dominated by ionization by the wake field, while the distribution at distances from the track axis that are about the mean free path of a fast electron is dominated by cascade ionization [2]. Since the impact ionization is induced only during the propagation of a particle through the medium and since the wake waves play the role of a linear source of secondary electrons, which operates for a long period of time after the passage of a charged particle, the temporal behavior of the ionization processes is governed completely by the wake waves.

Theoretically, it is estimated that a fast particle moving with velocity v expends a comparatively large fraction of its energy on the excitation of collective oscillations [2]:

$$\Delta E_k/\Delta E = \ln(v/10v_0)/2\ln(v/v_0), \qquad (1)$$

where ΔE_k is the fraction of energy that has gone into the excitation of collective oscillations, ΔE is the total energy loss of a fast charged particle in a solid-state

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plasma, and v_0 is the Bohr orbital velocity of an electron in a hydrogen atom in the ground state. Since the energy of the wake waves is comparable in order of magnitude to the total energy that the particle transfers to the matter, the energy loss to wake waves can be regarded as an important aspect of the process of dissipation of the energy of a fast particle.

A particle propagating through a medium produces free electrons, some of which, with the proper values and directions of momentum, can escape from the medium. This process is called secondary electron emission (SEE). At present, it is proved theoretically and experimentally that the SEE coefficient in the case of light ions is directly proportional to the mean specific ionization loss dE/dx of an ion in a medium [4, 5]. Consequently, the investigation of SEE makes it possible to derive information about the energy lost by an ion as it moved through a solid-state plasma and about how this energy is distributed between different electron groups. The mean specific ionization loss dE/dx of an ion at each point in a medium can be represented as a sum of the losses associated with energy transfer to the electrons that move in the same direction as the primary ion, $(dE/dx)_F$, and with the energy transfer to the electrons that move in the opposite direction, $(dE/dx)_B$: $dE/dx = (dE/dx)_F + (dE/dx)_B$. In our opinion, it is quite natural that the quantities $(dE/dx)_F$ and $(dE/dx)_B$ are, respectively, proportional to the coefficients of SEE in the propagation direction of a fast light ion (in the forward direction), γ_F, and in the opposite (backward) direction, γ_B. Hence, by investigating the kinetic ion–electron emission from a thin film in the forward and backward directions, it is possible to study the anisotropy of energy transfer from a primary ionizing charged particle.

A high-energy ion propagating through a medium produces a large amount of nonequilibrium electrons (see above), whose energy distribution can be approximated by a power law [6]. Both of the above mechanisms for energy transfer from the primary particle to the electrons in the medium (the collisional and plasmon mechanisms) contribute to the electron energy distribution. A study of the energy spectra of the electrons that are produced from the SEE induced by fast ions will make it possible to obtain new data on the energy contribution of the wake field to the formation of the nonequilibrium electron distribution function.

The excitation of plasma oscillations is more intense in the case of projectile molecular ions [7–9]. This indicates that an investigation of the kinetic electron emission induced by atomic and molecular ions also provides a promising way of studying the effect of plasma oscillations in a medium on the electron distribution function.

In this paper, we present the results of measurements of the SEE coefficients and electron energy distributions in the forward and backward directions. Generalizing the results obtained in three different experiments makes it possible to determine the mechanisms for energy losses of a fast ion propagating in a solid-state plasma.

2. ANISOTROPY OF THE ENERGY TRANSFER FROM AN ION

In direct (head-on) collisions, a fast primary particle produces the so-called δ electrons. The velocity of the δ electrons that corresponds to the maximum possible momentum transfer can be defined as $v_\delta = 2v_P\cos\theta$, where v_P is the velocity of a bombarding ion and the angle θ is measured from its propagation direction [10]. In further collisions, these fast electrons produce slow electrons as a result of a cascade process [4]. In the medium, the motion of slow electrons produced in the avalanche and in the ionization by a wake field is isotropic, while fast δ electrons move predominantly in the propagation direction of the primary ion. Also, a moving ion entrains some of the free and ionization-produced electrons within the substance. The velocity of these entrained electrons, which are called “accompanying” or “convoy” electrons [11], coincides in magnitude with the velocity of the ion, $v_e = v_P$, and has the same direction [12]. Consequently, in the energy spectrum of the electrons produced from the SEE, we can distinguish between three electron groups: (i) slow electrons with energies $E < E_p$ (where E_p is the energy of the plasma oscillations), which are produced from the ionization by plasma oscillations and from direct collisions with large impact parameters, accompanied by small momentum transfers; (ii) moderate-energy electrons, which are produced exclusively in direct collisions accompanied by small momentum transfers; and (iii) fast electrons, which move preferentially in the propagation direction of the ion and can be regarded as being represented by convoy electrons and by δ electrons produced from direct collisions with small impact parameters, accompanied by large momentum transfers.

Since a fast primary ion transfers a substantial fraction of its energy to the electrons that move in its propagation direction (convoy electrons and δ electrons), we can speak of the anisotropic energy transfer from an ion.

Experiments aimed at investigating the anisotropy of the energy transfer from a fast ion were carried out on a device whose schematic diagram is shown in Fig. 1. Vacuum chamber (*1*) was equipped with primary particle source (*2*), target (*3*), and collector (*5*). The pressure of the residual gases in the chamber was no higher than 10^{-6} torr. A 5.15-MeV α-particle flow with the intensity $I_{\alpha 0} = 4.64 \times 10^6$ particles per second was emitted into a half-space by an MIR3-A Pu^{239} radioisotope source. An α-particle flow penetrated target (*3*) and reached massive collector (*5*), made of the same material as the target. The experiments were carried out with aluminum, copper, and nickel collector–target pairs.

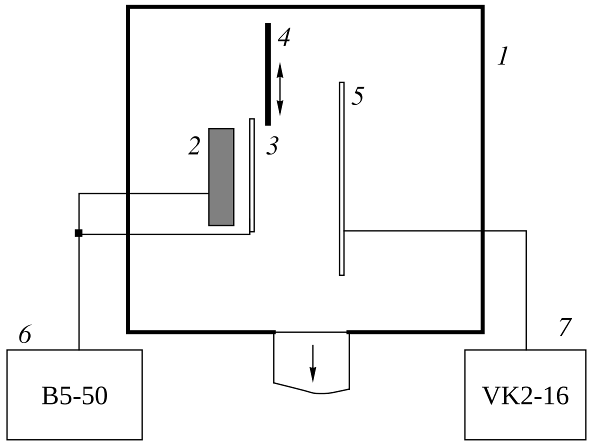

Fig. 1. Schematic of the experimental device: (*1*) vacuum chamber, (*2*) Pu^{239} radioisotope source of α-particles, (*3*) target, (*4*) movable diaphragm, (*5*) collector, (*6*) B5-50 dc source, and (*7*) electrometric voltmeter.

The targets were in the form of foils of thicknesses 5.6 μm (Al), 2.01 μm (Cu), and 0.27 μm (Ni). The target thickness was chosen to be less than the mean free path of α-particles with the above energy in a given substance. After passage through the target, α-particles had energies no larger than E_{max} (the energy corresponding to the penetration in a direction perpendicular to the target plane). The radioisotope source was connected electrically to the target. A voltage of 300 V of either polarity was applied between the collector and the target by means of B5-50 dc source (*6*). In the case of a voltage of positive polarity, the SEE coefficient γ_B was measured from the collector (backward emission), and, in the case of a voltage of negative polarity, the SEE coefficient γ_F was measured from the outer target surface (forward emission). The SEE current I_c was measured in the collector circuit by VK2-16 electrometric voltmeter (*7*). The measurement system was adjusted by using movable diaphragm (*4*), which was placed between the collector and the target and cut off the particle flow.

The coefficient γ was determined from the formula

$$\gamma_F = 2\frac{k_F I_{\alpha 0} + I_c}{k_F I_{\alpha 0}}, \quad \gamma_B = 2\frac{I_c - k_F I_{\alpha 0}}{k_F I_{\alpha 0}}, \tag{2}$$

where $I_{\alpha 0}$ is the current of α-particles from a radioisotope source and k_F is the fraction of α-particles that have passed through the target. The ratio R of the forward SEE coefficient γ_F to the backward one γ_B,

$$R = \gamma_F/\gamma_B \tag{3}$$

was measured to be 1.57 for aluminum, 1.69 for copper, and 1.82 for nickel. According to these data, the ratios R for different substances differ insignificantly, by no more than 10% of the mean value.

Rothard and his colleagues [13] carried out a series of measurements of the coefficient γ of SEE induced in a thin carbon film by the ions with different charge numbers. Measurements on both sides of the film showed a considerable difference between the coefficients of SEE from the front surface irradiated by the ions (backward emission) and from the rear surface (forward emission) [13].

An analysis of the above results from our measurements and of the data from experiments [13], carried out with a carbon target and with Li^{2+} ions, which are close in mass, energy ($0.86 \le E \le 1.15$ MeV/amu), and charge state to α-particles used in our experiments, allows us to suggest that the ratios of the fractions of energy that are transferred from a light ion to the electrons moving in the propagation direction of the ion and in the opposite direction are fairly close to each other for different target substances. In the case in question, the energy loss of a light ion (He^{2+}, Li^{2+}) to the electrons moving in its propagation direction is larger than the loss to the electrons moving in the opposite direction by a factor of approximately 1.7.

Presumably, the above difference in the forward and backward SEE coefficients at the same energy of the bombarding ions stems from the presence of convoy and δ electrons, which are emitted predominantly in the propagation direction of the ions. For the targets investigated in our experiments, the energy E_{max} of α-particles varied from 0.8 to 1 MeV/amu; consequently, the maximum energies of the emitted convoy electrons and δ electrons are about 0.5 and 2 keV, respectively. The relative amount γ_δ of these electrons can be determined from the difference between the forward and backward SEE coefficients, $\gamma_\delta = \gamma_F - \gamma_B$. Recall that, for light ions, the SEE coefficient is proportional to the mean specific ionization loss dE/dx of an ion in a medium. Therefore, the ratio R_δ of the energy going into the production of convoy electrons and δ electrons to the total energy losses of an ion in a medium can be defined as $R_\delta = \gamma_\delta/\gamma$, where $\gamma = \gamma_F + \gamma_B$ is the total coefficient of the forward and backward SEE. In the case under consideration, with allowance for the experimentally measured values of R, the ratio R_δ is from 0.22 to 0.29. Hence, the δ and convoy electrons can carry away approximately 22–29% of the energy that the ion transfers to the electrons in different substances.

3. ENERGY DISTRIBUTION AMONG DIFFERENT ELECTRON GROUPS

In a number of papers, it was shown theoretically and experimentally that, when the ion-induced SEE takes place in a medium, the presence of a flux generated in momentum space by a source (ionization) and a sink (electron emission) results in the formation of a steady-state nonequilibrium power-law electron distribution function in a solid-state plasma:

$$N(E) = AE^{-s}, \quad (4)$$

where s is the power index and A is a constant [6, 14]. Also, in formula (4), E is the total electron energy in a solid body, $E = \varphi + E_F + eU$, where φ is the work function, E_F is the Fermi energy, and the energy eU is measured from the vacuum energy. The experimentally measured energy distribution functions of the electrons produced from the ion-induced SEE are piecewise power functions with different power indices s for different energy intervals [6, 15].

An important role in the production of free electrons (and, accordingly, in the emission process) is played by the wake-field oscillations. The energy loss to these oscillations can be estimated from formula (1). The energy $E_p = \hbar\omega_p$ of the plasma oscillations, which is usually lower than 25 eV, is nonetheless sufficiently high in comparison with the energy required to excite an electron from its valence band to the conduction band where they are freely mobile. The energy of the electrons produced in ionization by the wake-field oscillations cannot exceed E_p. Consequently, slow electrons produced in this ionization process are distributed in the emission spectrum over its low-energy part bounded from above by the plasmon energy.

Under conditions close to those mentioned above, we experimentally measured the energy spectra of the electrons produced from the backward SEE induced in a beryllium foil by 4.9-MeV α-particles [15]. The measurements were carried out in the energy range from 0 to $E^* = 100$ eV. The experimentally obtained power-law energy spectrum may be divided into two parts, the boundary between which is determined by the energy $E_p = 18.9$ eV of a plasmon within the beryllium target. One part of the spectrum is represented by the slow electrons of the first group (see Section 2), and the other, by the moderate-energy electrons of the second group. Since the number of emitted electrons is proportional to the specific energy loss of the primary ion, we can estimate the fractions of the energy lost by the ion to the slow electrons from the first group and to the electrons from the second group. We separately integrate these two parts of the experimental emission spectrum $N(E)$ over energy and determine the number N_1 of electrons from the first group and the number N_2 of electrons from the second group for beryllium:

$$N_1 = \int_{\varphi + E_F + eU}^{E_p} N(E)\sqrt{E}dE,$$
$$N_2 = \int_{E_p}^{\varphi + E_F + E^*} N(E)\sqrt{E}dE. \quad (5)$$

The fractions of the energy lost by the ion to the electrons from the first and the second group can be estimated as the ratios of N_1 and N_2 to the total number $N_0 = N_1 + N_2$ of the emitted electrons:

$$K_1 = N_1/N_0 = 0.63 \text{ and } K_2 = N_2/N_0 = 0.37, \quad (6)$$

In other words, the energy transferred from the ion to the slow electrons from the first group is about twice as large as the fraction of the ion energy that is lost to the electrons from the second group.

According to the above results on the anisotropy of the energy transfer, approximately one-quarter of the energy lost by a charged particle is converted into the energy of the electrons in direct collisions accompanied by large momentum transfers (δ electrons) and also into the energy of the convoy electrons. The remaining fraction of the energy of a charged particle moving in a solid-state plasma is lost through the following two dissipation mechanisms: first, in direct collisions accompanied by small momentum transfers and, second, by the excitation of plasmons. The fraction of energy that goes into the production of slow electrons ($E < \hbar\omega_p$) can be defined as $\Delta E_{slow}/\Delta E = K_1(1 - R_\delta)$. In the case at hand, this fraction, which is transferred to electrons by the above two mechanisms, is from 45 to 49% of the total energy lost by an ion in the substance. In our opinion, theoretical formula (1) somewhat overestimates the fraction of the energy $\Delta E_k/\Delta E$ lost to the wake waves: $\Delta E_k/\Delta E \approx 40\%$.

Earlier, it was established that the experimentally measured energy distribution functions of the electrons produced from the ion-induced SEE are piecewise power functions with different power indices s for different energy intervals [6, 15]. Such distribution functions of the electrons that were produced in silver, copper, and nickel thin films from both forward and backward SEE induced by He^+ ions with energies from 1 to 3 MeV were measured in our experiments. Analyzing the experimental SEE spectra, we determined how the power index s_1 for the first energy interval (corresponding to slow electrons with energies $E < 35$ eV) depends on the specific ionization losses of an ion in the medium. Our experimental data show that, over this energy interval, the power index decreases with increasing the energy losses of a fast ion [16].

According to the Bethe–Bloch formula [3]

$$-dE/dx = (4\pi Z_1^2 e^4/mv^2)Z_2 N\ln(2mv^2/I), \quad (7)$$

(where m is the mass of an electron, Z_1 is the charge of the incident particle, Z_2 is the charge of the atoms of the decelerated medium, and I is their mean excitation potential), the energy lost by a fast ion decreases with increasing its velocity. Consequently, the higher the velocity (energy) of a fast ion, the larger is the relative amount of fast electrons with energies above E_P. This tendency was also pointed out by Hasselcamp *et al.* [17]. In other words, as the velocity of a fast ion increases, the plasmon mechanism for slow electron production becomes less efficient. This result, however, does not follow from formula (1), which implies that the energy $\Delta E_k/\Delta E$ lost by an ion to wake waves depends only weakly on its velocity.

4. MOLECULAR IONS

A great deal of information on the wake-field oscillations in a medium penetrated by a fast ion can be obtained by studying the kinetic SEE from metal surfaces bombarded by molecular ions. Such experiments were carried out in a number of papers [7–9]. Hasselcamp and Scharmann [7] studied the energy spectra of the secondary electrons knocked out of a massive copper target by H_1^+, H_2^+, and H_3^+ ions with an energy of 200 keV/amu. According to the results reported in that paper, measurements in the energy interval $E \le 35$ eV gave power-law spectra of the secondary electrons produced by both atomic and molecular ions. The yields γ of secondary electrons produced from the emission induced by H_1^+, H_2^+, and H_3^+ bombarding ions are in the ratio 1 : 2 : 3. This ratio fails to hold for the differential electron yield $\gamma(E)$, where E is the energy of the secondary electrons. As was shown by Hasselcamp and Hippler [8], the coefficient $R_\gamma(E)$, defined as

$$R_\gamma(E) = \gamma_{H_2}(E)/2\gamma_{H_1}(E), \tag{8}$$

changes substantially within the energy range 0–200 eV of the secondary electrons. The data published in [8] show that, for a golden target bombarded by primary ions with energies from 75 to 300 keV/amu, the curve $R_\gamma(E)$ has two maxima. For low-energy secondary electrons, the coefficient is $R_\gamma(E) < 1$. It should be noted that, with increasing the energy of the primary ions, the first maximum and the intersection point with the straight line $R_\gamma = 1$ both shift toward lower energies, while the second maximum shifts toward higher energies. Hasselcamp and Hippler [8] pointed out that the electron velocity corresponding to the second maximum is equal to the velocity of the bombarding ions.

As a molecular ion enters the medium, it breaks into fragments, each of which excites plasma oscillations. In studying kinetic electron emission induced by CO^+, C^+, and O^+ ions, Frischkorn *et al.* [9] showed that the interference between the plasma oscillations excited by different fragments of a molecular ion influence the total electron yield.

When a medium is penetrated by a diatomic molecule (rather than by an atom or ion), the processes of the trapping and loss of electrons by the molecule become important at velocities close to those of the bound electrons of the atoms in the medium, as is the case with a bombarding atom. Because of ionization, the ions composing the molecule experience Coulomb repulsion. This repulsion becomes strong so rapidly that it is possible to speak of a Coulomb explosion. As a result, a diatomic molecule moving in the medium breaks into two ions [18]. As a fast hydrogen molecular ion moves through the target substance, it is completely ionized and breaks into fragments—atomic ions—which propagate over distances that only slightly exceed the radius r of their Coulomb screening. For metals, we have $r \sim 10^{-8}$ cm. The diameter of the ionization track is determined by the length of a collision cascade and is approximately equal to 10^{-6} cm; this indicates that both fragments of a molecular ion move in the same track.

A molecule with an energy of $E \ge 100$ keV per nucleon starts to be stripped of electrons as it propagates through just the first several outer monolayers of the target; i.e., the constituent ions of the molecule begin to experience Coulomb repulsive forces immediately after the molecule enters the target and, as a result, the distance between the ions begins to increase with time. An experimental analysis showed that the ions fly away from their mutual center of mass in an asymmetric fashion [19]. The observed asymmetry can be explained as being due to the effect of plasma oscillations excited by the ion fragments and indicates that, as the fragments fly apart, they undergo an additional interaction with matter.

The interaction of atomic and molecular ions with target substances was investigated in the experimental device described in detail in [16]. We studied secondary electron emissions from silver, copper, and nickel thin foils in the forward direction, i.e., in the propagation direction of the primary ion. As in the experiments reported above, the thicknesses of the targets were less than the mean free paths of ions with given energies in the corresponding substances and were chosen to be 2.0 μm for silver, 2.1 μm for copper, and 1.1 μm for nickel. The targets were produced by chemical means. In most experiments, the beam current density at the target was no greater than 0.1 μA/cm^2. A small-aperture retarding-potential spectrometer was oriented at an angle of 40° to the ion beam. Earlier, it was shown that the functional dependence of the emission spectra is insensitive to the measurement direction. As a recording and storage terminal system, we used an AI-1024-95 pulse analyzer connected to a computer. The energy width of each of the analyzer channels was 0.044 eV, the number of channels being 1024. The measured data were processed by a computer.

Figure 2 shows representative energy spectra of the SEE induced in a silver target by 1-MeV H_1^+ ions and by 2-MeV H_2^+ ions. According to our experimental results, the distribution functions of the nonequilibrium electrons emitted from all kinds of targets are power-law functions with power indices close to those given in [6]. In order to reveal the differences between the energy spectra from SEE induced by molecular and atomic hydrogen ions, we calculated the differential coefficient $R_\gamma(E)$, defined in formula (8). Figure 3 illustrates the coefficient $R_\gamma(E)$ as a function of the energy of the secondary electrons for the three kinds of targets

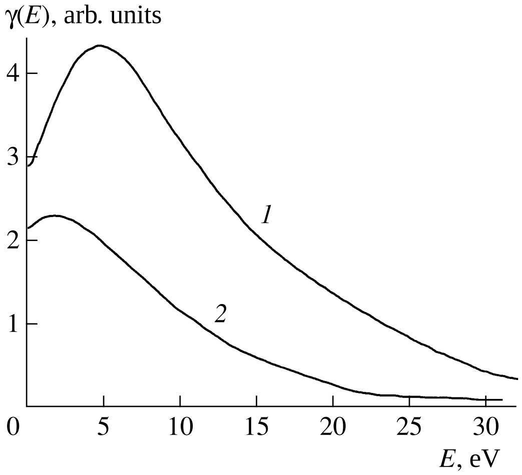

Fig. 2. Energy spectra of the secondary electrons produced from a silver target by (*1*) H_2^+ ions with an energy of 2 MeV and by (*2*) H_1^+ ions with an energy of 1 MeV.

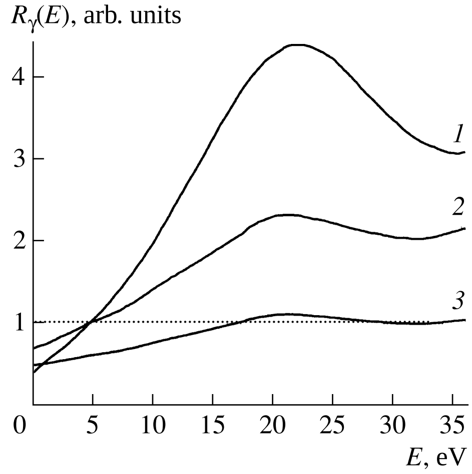

Fig. 3. Experimental dependences of the coefficient $R_\gamma(E)$ on the energy of the secondary electrons for (*1*) Cu, (*2*) Ni, and (*3*) Ag.

used in our experiments. We can see that the plots obtained for different targets have the same shape and differ exclusively in amplitude. It is worth noting that the positions at which the coefficient $R_\gamma(E)$ is maximum are different for different targets. The larger the specific energy loss dE/dx of an ion, the lower the energy of the secondary electrons at the maximum in the curve $R_\gamma(E)$ and the larger the amplitude of the curves. The curves $R_\gamma(E)$ obtained in [8] for a massive gold target are similar to those shown in Fig. 3. Analogous curves were also derived from experiments with primary ions of lower energies.

In analyzing the experimental curves presented in Fig. 3, it is important to take into account that each of them has a maximum and that, for secondary-electron energies lower than 10 eV, the differential coefficient is smaller than unity, $R_\gamma(E) < 1$. Presumably, the presence of the maxima can be explained as follows. When propagating through the medium, a diatomic molecule loses a larger fraction of energy than do two atomic ions [2]; moreover, the fraction of the energy that goes into the excitation of the wake waves is substantially larger. The energy of the plasma oscillations is fixed for a given substance [1]; consequently, the energy loss to plasma oscillations is associated with a certain part of the electron energy spectrum, specifically, with electrons whose energy is no greater than the plasmon energy. These considerations indicate that the maxima in the curves $R_\gamma(E)$ may be of plasmon origin.

The fact that, in the SEE spectra, there are energy intervals over which molecular ions (diatomic molecules) produce low-energy electrons less efficiently than do their constituents can possibly be explained as follows. In the low-energy range over which $R_\gamma(E) < 1$, the electrons are produced not only by the plasmon mechanism but also in direct collisions of a moving ion with the atoms of the target substance. In this case, the fore ion of a diatomic molecule prevents its rear ion from colliding with the atoms. The rear ion can thus be shadowed by the fore ion; as a result, the yield of the low-energy electrons (in the range $R_\gamma(E) < 1$) in the case of an H_2^+ ion is smaller than that in the case of two H^+ ions. Moreover, in a hydrogen molecule moving through a medium, the rear ion is in the wake of the fore ion; hence, the rear ion may be additionally screened by the electrons of the medium. Since slow electrons are produced in distant collisions, their number can be much smaller than that in the case of two individual protons. Consequently, the presence of the spectral interval over which $R_\gamma(E) < 1$ in the spectra of the secondary electrons can also be explained as being due to the additional screening of the rear ion in a diatomic molecule by the electrons of the medium.

The above two possible causes of the smaller efficiency of the production of low-energy electrons by molecular ions imply that the collisional mechanism for producing slow secondary electrons is hindered by the correlated motion of the molecule fragments in the medium.

Our experiments show that, when a fast charged particle passes through a substance, the mechanism for producing free electrons in the ionization by plasma oscillations appears to be more efficient in the case of projectile molecular (rather than atomic) ions.

5. CONCLUSION

According to the above analysis of the results obtained, the observed anisotropy of the ion-induced SEE is presumably associated with the fraction of energy that is carried away from the medium by both convoy electrons and δ electrons. An increase in the energy (velocity) of the bombarding ions leads to an increase in the relative number of electrons with energies higher than the energy of plasmons in the substance. In addition, it has been noted that plasma oscillations excited by an ion have a substantial impact on the production and emission of electrons, especially in the case of projectile molecular ions.

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