FORWARD AND BACKWARD ELECTRON EMISSION INDUCED BY PROTONS FROM COPPER FOIL

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Forward and backward secondary electron emission induced by normal incidence of 1.5 MeV protons from 5 μm copper foil was experimentally studied. Measurements were carried out by means of two low-aperture retarding field energy analyzers, which were installed symmetrically on each side of the target at the angle of 53° with respect to the projectile beam. The relation of electron yields of forward and backward emission was obtained. Electron distribution functions were measured in 0…90 eV energy interval. The comparative analysis of electron distribution for forward and backward cases was performed and possible reasons for the differences observed were discussed.

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INTRODUCTION

It is well known that fast ions transfer kinetic energy mainly to electron subsystem of a solid. In this case energy transfer can occur by means of both close and distant collisions [1]. A part of projectile energy can goes into the excitation of plasmons [2].

In close collision primary particle produce fast δ-electrons. In further collisions these fast electrons produce slow electrons as a result of cascade process [3]. Moving ion can entrain some electrons of a substance, so called «convoy» electrons [3].

Part of arisen nonequilibrium electrons can overcome surface potencial barier and escape into vacuum. This process named secondary ion induced electron emission (SIEE) [1].

It is generally accepted that SIEE process is described by three-step model:

1) production of nonequilibrium 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 [1].

Fast electrons make a substantial energy contribution to SIEE. We have earlier studied forward-backward emission and showed that flux of energy (electrons) in the forward direction exceeds one in the backward direction (anisotropy) [4]. However, we left the question of energy distribution of SIEE electrons open.

It is proved for fast light ions theoretically and experimentally that SIEE coefficient (or electron yield) is directly proportional to the mean specific ionization loss *dE/dx* of ion in a matter [5, 6]. A high-energy ion propagating through a matter produces a large amount of nonequilibrium electrons, whose energy distribution can be approximated by a power law [7]:

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

where A is constant, s is power law index [7].

Both of the above mentioned mechanisms for energy transfer from the primary particle to the electrons in the matter (the collision and plasmon mechanisms) contribute to the electron energy distribution.

Study of the forward and backward energy spectra of SIEE will make it possible to obtain new data on the energy contribution of the fast electrons to the formation of the nonequilibrium distribution function.

The question is how this energy is distributed between different electron groups.

The paper deals with experimental study of forward and backward SIEE from copper foil bombarded by fast proton beam.

1. EXPERIMENTAL SETUP

Scheme of SIEE study experiment is showed on Fig. 1. 1.5 MeV proton beam from Van Graaf accelerator impinged on foil target perpendicularly to the surface. Ion beam was limited by diaphragm system, so diameter of the beam was equal 3 mm. The target was thin polycrystalline copper foil of high purity with 5 μm thickness and 15 mm diameter. Target foil was fixed and mounted on copper holder. Ion beam current registered by Faraday cup was equal I_{FC} = 0.8 μA. Residual gas pressure was lower than 10^{-4} Pa.

Because of target thickness was lower than path length of 1.5 MeV protons in a copper, there were possibility to measure both backward and forward emission. Emission electrons from both surfaces of the target (beam entrance surface – «backward», beam exit surface – «forward») were registered by means of two identical low aperture cylindrical energy analyzers based on retarding field principal.

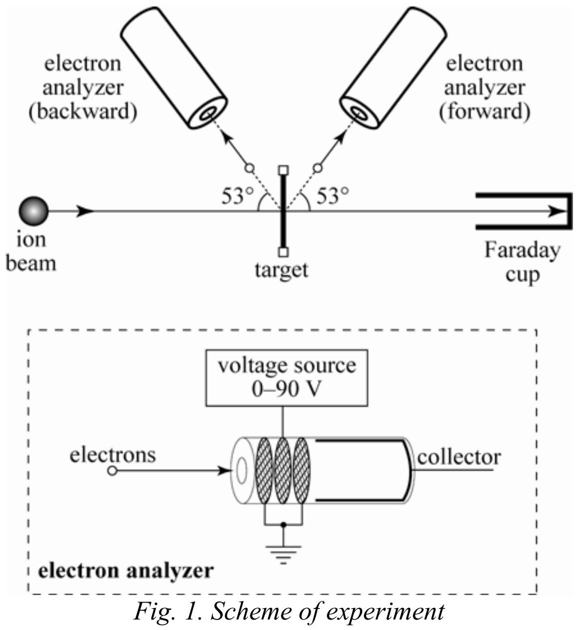

Fig. 1. Scheme of experiment

The analyzers were mounted symmetrically with respect to target surface (53° angle with respect to the beam direction) at the distance of 48 mm from emitting surfaces. Dimensions of the analyzer were the following: length – 65 mm, diameter – 19 mm, entrance aperture – 3 mm. It was consisted of metallic case with three high transparence (>90 %) grids and Faraday cup collector. The first and last grids were grounded, while middle grid was at retarding potential *U* (linear varying voltage of 0…90 V range with 1 V step). Emission currents of analyzer collectors were amplified by electrometric amplifiers. In the sequel, amplified signals were registered by controlling computer by means of analog-digital converter. Measuring complex enabled to perform averaging of 100 findings (7 second exposure) for each value of retarding voltage. Construction of energy analyzers and measuring channels satisfied electrometric circuit [8].

Relation of analyzer aperture to the distance from target was much lower than 1. Therefore, emission electrons were registered in narrow solid angle. Hence, such analyzer gave information about velocity vector magnitude. Consequently, it is possible to obtain energy distribution function of emission electrons by means of differentiation of retarding characteristics (dependence of emission current on retarding voltage) $I_{F/B}(U)$. Procedure of retarding characteristic treatment and obtaining of energy distribution functions one can find in our earlier papers (see, for example [9]).

It should be noted, in the case of power-law dependence of energy distribution functions it is convenient to use logarithmic scale. Then power-law dependence should be represented by straight line with slope, defined by power-law index *s* (see (1)).

Observation angle differential SIEE coefficient can be found by mean of energy analyzer at 0 retarding voltage mode:

$$\gamma_{F/B} = I_{F/B} / I_{FC}, \qquad (2)$$

2. RESULTS

2.1. MODELLING OF ION BEAM PASSAGE THROUGH THE TARGET

Passing through a target, ion losses part of its energy. Proton energy losses are described with high accuracy by Yu. Gott's empiric formula for projectile energy range of 10 keV…50 MeV [10]. Moreover, formula has simple compact form.

In our case ion energy at the exit of the foil target was calculated as a solution of integral equation with use of Yu. Gott's empiric formula for ion energy loss in a substance [10]. Numerical solution was obtained by means of our program in MathCad software. Calculated value of ion energy at the exit of the target was equal approximately 1.04 MeV.

We performed modeling for protons moving in copper target using SRIM2006 software [11]. There was significant scattering of ions at the end of tracks (Fig. 2).

It is accepted that dependence of SIEE coefficient on incident angle φ of ion (φ is measured from normal to the target plane) is defined as [12, 13]:

$$\gamma(\varphi) = \gamma(0) / \cos(\varphi), \qquad (3)$$

where $\gamma(0)$ is SIEE coefficient for normal incidence of ion on target.

Secondary electrons are emitted into vacuum from thin layer with thickness on the order of electron path length. Considerable ion scattering results in increase of average ion path in the emitting layer of the target. Therefore, the number of emission electrons is enlarged in forward direction. This ion scattering causes additional enlargement of ion energy losses in the emitting layer.

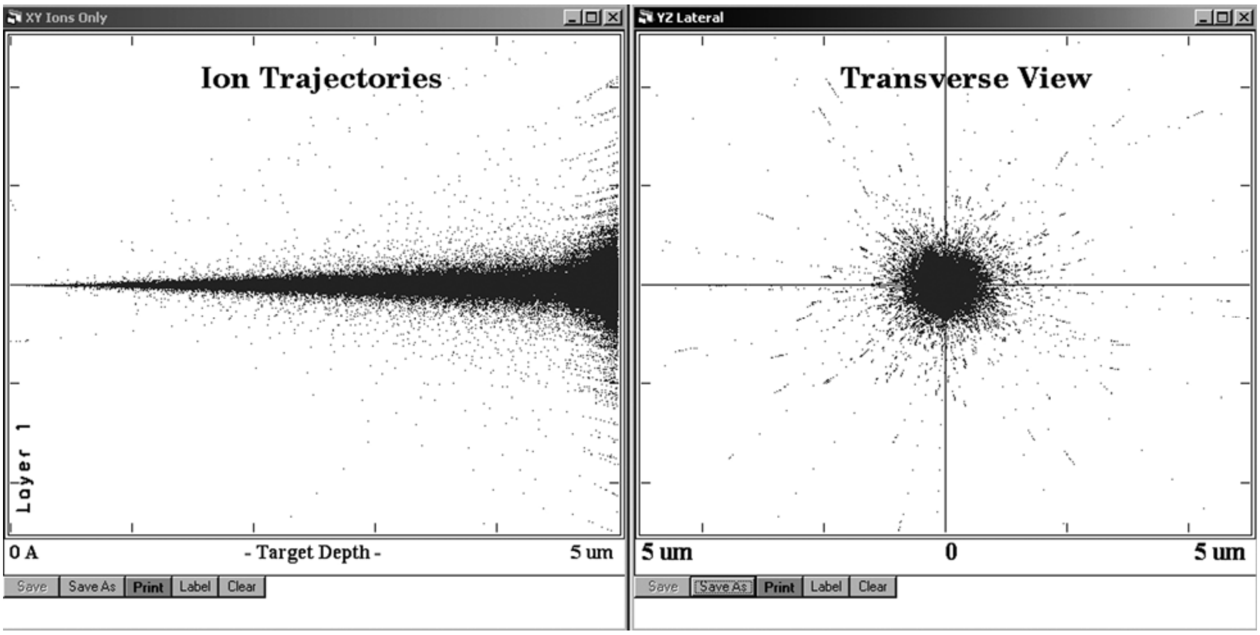

Fig. 2. 1.5 MeV proton trajectories in copper target (SRIM2006 software)

2.2. EXPERIMENTAL RESULTS

The experiments showed that intensity of forward emission induced by proton from copper foil was more than one of backward emission at the same observation angle.

SIEE coefficient for protons with energy under study is well known to be proportional to the specific ionization energy losses of ion in a substance [5]:

$$\gamma = \Lambda \, dE/dx \, , \qquad (4)$$

In our case, in order to appreciate the effect of emission direction (forward-backward) we defined *k* coefficient as a relation between specific ionization energy losses of protons *dE/dx* at the beam entrance $(dE/dx)_B$ and exit $(dE/dx)_F$ in the target. Value for *k* coefficient calculated by SRIM2006 was approximately equal 0.8 [11].

Thus,

$$R = k{\cdot}\gamma_F/\gamma_B \approx 1{,}8. \qquad (5)$$

This *R* relation is usually called as Meckbach factor [14].

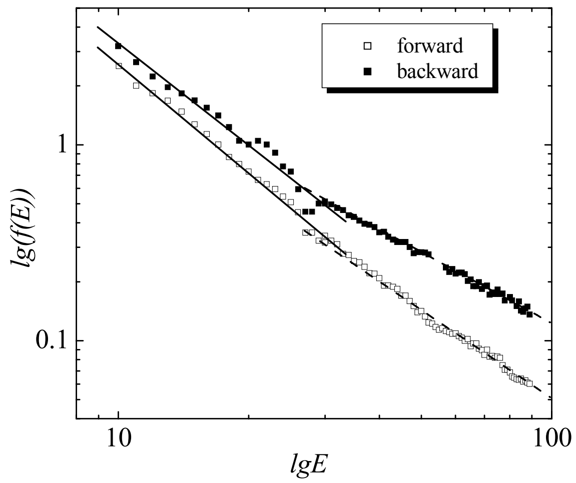

Fig. 3. Double logarithmic scale energy distribution function of electrons

It should be noted that obtained value of *R* relation for copper is close to one observed for other species of light ions with energy from some hundred keV to some MeV and others targets, particularly, carbon (see, for example [15]). Thus, for normal incidence of 250 keV proton beam on thin carbon foil [12] it was obtained the relation of forward and backward SIEE coefficients (output angle integral coefficient) was close to 1.55. For 4 MeV Li^+ ions and carbon target R was approximately 1.72 [14].

We presented earlier the experimental results on anisotropy of energy losses of fast α-particles in some metals (forward and backward), which were obtained by means of measurements of output angle integral SIEE coefficient γ_F и γ_B [4]. It is was shown, that $R \approx 1.7$, therefore ionization losses associated with energy transfer to the electrons that move in the same direction as the primary ion approximately 1.7 times greater than one in the opposite direction [4].

R value for copper under study showed that in the case of light ions with energy of some MeV the relation between γ_F and γ_B is slightly changed both for integral and differential on output angles values.

Typical energy distribution function of SIEE is curve with maximum at low energy of some eV and subsequent power-law decrease [5, 16, 17]. Energy distribution functions had the same structure in our case.

Fig. 3 shows double logarithmic scale typical energy distribution functions of electrons emitted from copper for both forward and backward emission (start plot of the distribution up to 10 eV (maximum) is not presented on the graph).

One can see that the distributions are well approximated by linear functions with different slope angles (solid and dotted line). It means that the distributions have power-law dependences with *s* power index varying from –2 to –3. Junction point of the distributions (intersections of approximating solid and dotted lines), where power index changes its value, is located at 25…30 eV energy interval both for forward and backward case. Peacewise power-law dependence of SIEE energy distribution functions was also observed for some other metals [5 - 7, 16, 17].

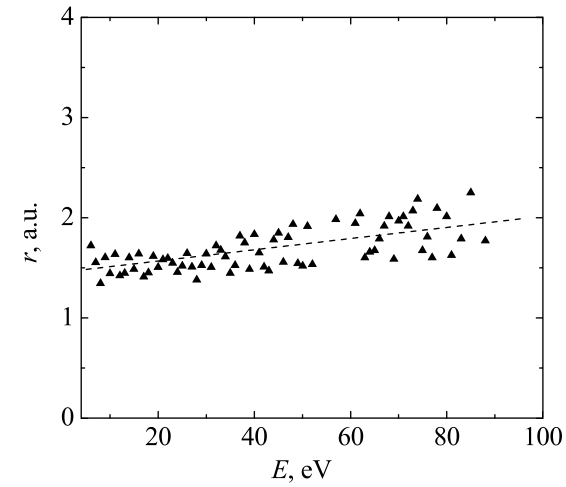

Fig. 4. Relation of forward-backward energy distribution functions of electrons

In order to reveal differences in energy distribution functions for forward and backward emissions we found relation $r = f_F(E)/f_B(E)$ (Fig. 4). *R* value is more than 1 for energy intervals under study. This fact is well conformed by other forward-backward experiments. For example, experiments with normal incidence of atomic and molecular hydrogen beam with 0.8 MeV/a.m.u. energy on thin Au foil showed that intensity of forward spectrum (0° observation angle) was approximately double greater than one for backward spectrum (180° observation angle) [18]. The intensity of the 65° forward spectra was much lower than the intensity of the 0° spectra [18].

Let's consider features of *r(E)* dependence. For electrons with energies more than 10 eV we found slow growth of *r* curve. To guide the eye we presented by dotted curve the results of linear approximation of *r* dependence in 10…90 eV energy interval on Fig. 4 (equation of straight line: $y = 1.455{+}0.006{\cdot}x$). As it can be seen, the part of fast electrons is increased with growth of energy. Authors of paper [12] observed similar behavior *r* dependence, though they found stronger increase of fast electron part in forward spectra in comparison with backward one.

Greater emission observed in forward direction (beam exit side of target foil) in comparison with backward one can be explained by asymmetric angular distribution of electrons produced by ion in a solid. In our case the major source of electron production in a solid is ionization energy losses of moving fast ion, therefore asymmetry of electron distribution points out on anisotropy of energy losses of moving ion. It is well known (see, for example, [19]) that for forward emission case there is group of fast convoy and δ-electrons, which possess of significant part of energy transferred from moving ion to slow electrons of a solid. Having quite large energy these electrons can result in production of new nonequilibrium electrons and cause appearance of collision cascades. Directed motion of convoy and δ-electrons apparently causes anisotropy of ion energy losses in a matter. This anisotropy causes difference in electron emission from thin foil in forward and backward directions.

It should be noted that besides anisotropy effect the differences in energy spectra can be explained by energy losses of ion in a target matter. As it was mentioned above, non-equilibrium power-law distribution function (NPDF) can be formed in a fast ion track [20]. Moreover, so-called «universal» distribution function of electrons can be realized under certain conditions. Thus papers [21, 22] presented conditions under which distribution function became universal with power-law index $s = -5/4$. Formation of such NPDF depends first of all on density of non-equilibrium electrons. Density of non-equilibrium electrons is in direct proportion to dE/dx. Density of non-equilibrium electrons in forward emission case is larger than in backward one. Therefore, power index of NPDF should be approached to –5/4, which results in increase of relative part of fast electrons.

Similar results (increase of fast electron relative part in energy spectra) were observed with atomic and molecular hydrogen ions [23]. It is well-known, that energy losses of molecular hydrogen ions is greater than energy losses of two protons, so-called «molecular effect» [23].

CONCLUSIONS

Experimental study of secondary electron emission induced by fast protons from thin copper foil at small solid angle showed differences in emission characteristics in forward and backward directions. The differences can be explained by anisotropy of ion energy losses in a matter (directed motion of convoy and δ-electrons, which have quite large energy). The results obtained are in good agreement with earlier emission experiments performed for fast light ions with integral measurements on output angles of electrons.

An enlargement of part of fast electrons in forward distribution function can be explained for the following reasons:

- anisotropy of ion energy loss in a matter;
- greater specific energy loss of ion at the exit of a target;
- considerable ion scattering at the exit of the foil target.

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ЭЛЕКТРОННАЯ ЭМИССИЯ, ИНДУЦИРОВАННАЯ ПРОТОНАМИ ИЗ МЕДНОЙ ФОЛЬГИ НА ПРОСТРЕЛ И НА ОТРАЖЕНИЕ

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Экспериментально исследована вторичная эмиссия электронов из медной фольги 5 мкм на прострел и на отражение при нормальном падении пучка протонов с энергией 1,5 МэВ. Измерения были проведены при помощи двух малоапертурных энергоанализаторов с тормозящим полем, установленных симметрично с обеих сторон мишени под углами 53° по отношению к пучку бомбардирующих частиц. Получено отношение коэффициентов вторичной ионно-электронной эмиссии на прострел и на отражение. Измерены функции распределения электронов по энергиям в интервале 0…90 эВ. Проведен сравнительный анализ распределений электронов по энергиям на прострел и на отражение и обсуждаются возможные причины наблюдаемых различий.

ЕЛЕКТРОННА ЕМІСІЯ, СПРИЧИНЕНА ПРОТОНАМИ З МІДНОЇ ФОЛЬГИ НА ПРОСТРІЛ І НА ВІДБИТТЯ

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Експериментально досліджена вторинна емісія електронів з мідної фольги 5 мкм на простріл і на відбиття для нормального падіння пучка протонів з енергією 1,5 МеВ. Вимірювання були проведені за допомогою двох малоапертурних енергоаналізаторів з гальмуючим полем, які було розміщено симетрично по обидва боки мішені під кутами 53° до пучка частинок, що бомбардують. Отримано відношення коефіцієнтів вторинної іонно-електронної емісії на простріл і на відбиття. Виміряні функції розподілу електронів за енергіями в інтервалі 0…90 еВ. Проведено порівняльний аналіз розподілів електронів за енергіями на простріл і на відбиття та обговорюються можливі причини різниць, що спостерігаються.