INTERACTION OF RELATIVISTIC PARTICLES WITH CRYSTALS AND MATTER

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SPECTRA OF LOW-ENERGY SECONDARY ELECTRONS IN THE INTERACTION OF RELATIVISTIC ELECTRONS WITH ALUMINUM FOIL

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The integral yields of secondary low-energy electrons (with energies up to 50 eV) in the interaction of primary electrons 10…30 MeV with 50 μm aluminum foil have been studied. It is shown that the proposed method for approximating the spectra of low-energy electron emission in the measured part of the spectrum (E > 4.2 eV) makes it possible to obtain data on the absolute values of the spectra of electrons emitted from the target. It has been established that the spectra of secondary low-energy electrons, depending on the energy of primary electrons, have a maximum in the range of 1.3…1.6 eV, and the FWHM values are in the range of 2.7…3.8 eV.

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INTRODUCTION

One of the important directions in the experimental study of the interaction of high-energy electrons with thin foils (amorphous, single-crystal, single-layer, and multilayer ...) is directly related to obtaining absolute and relative data on secondary electron emission [1]. Of particular interest in such studies is the comparison of the integral and spectral yields of secondary electrons from the first and second surfaces of the samples during research. Since this approach makes it possible to establish the regularities of the interaction of precisely relativistic and ultra-relativistic particles with matter.

The spectrum of secondary electron emission can be conditionally divided into two parts: more than 50 eV and less than 50 eV. The first group is high-energy inelastically scattered electrons (including Auger electrons), and the second group is low-energy secondary electrons [2].

The theory of secondary electron emission describes the spectra of high-energy secondary electrons quite well but is not yet able to satisfactorily explain even some simple experimental patterns associated with the low-energy part of the spectra, not to mention the effects associated with the specific characteristics of the matter [3].

Low-energy electrons emit from the target surface from a depth of about 100 A [4]. The energy spectrum of the emitted electrons depends on the physical and chemical properties of the target surface. Studying the yields of secondary electrons and their energy spectra makes it possible to obtain information about the emission properties of the surface as a whole. This is of particular interest for studying new materials, thin coatings, and multilayer structures and evaluating the effect of various types of surface treatment to obtain predictable secondary electron fluxes (for example, to enhance or weaken the effect of secondary emission).

1. SECONDARY ELECTRONS SPECTRA INDUCED IN THE METAL

Using an experimental facility designed for research the interaction of high-energy electron beams with amorphous and single-crystal structures, based on 30 MeV *Electron Linac of IHPNP NSC KIPT NASU* [5], the yields of low-energy (E < 50 eV) secondary electron emission of 50 μm aluminum foil (target) produced by primary electron beam with energies 10, 15, 20, 25, and 30 MeV had studied.

The dependence of the secondary electron yield from 50 μm aluminum foil for 10 MeV electron beam is shown in Fig. 1. The retarding voltage operation range from -80 to 0 V on the gridded electrodes C1 and C2 placed before and after the target were used for measurement. The details of the experiment are presented in [6].

By retarding potential variation, the current-voltage characteristic (CVC) of the secondary electron yields were obtained, after normalized to the primary electron beam current. Experimental data in Fig. 1 are shown by dots.

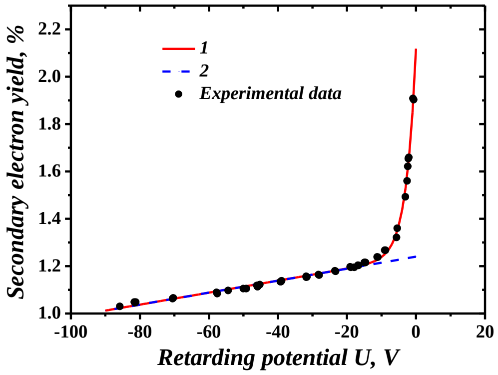

Fig. 1. Current-voltage characteristic (CVC) of the integral secondary electron emission yield from two target surfaces, retarding potential is applied to gridded electrodes C1 and C2, the potential value was varied from -80 to 0 V

It should be noted that all data represent the dependence of the number of secondary electrons in percent concerning the number of incident high-energy primary beam electrons. The result of differentiation of the presented dependence will be the energy spectra of secondary electrons within the indicated limits of retarding potential values. For electrons, when the retarding potential value decreases by 1 V, the maximum energy of the electron yield spectrum increases by 1 eV, so a change in voltage by 1 V corresponds to a change in energy by 1 eV.

The CVC shape of the measured secondary electrons consists of: an almost constant substrate of high-energy elastically reflected primary electrons, which is practically independent of the retarding voltage (straight line 2 in blue – dependence of the type $f_1(U)=p_3+p_4\cdot U$), and a sharply increasing yield of low-energy secondary emission when the retarding potential decreases to zero (curve 1 – type dependence $f_2(U)=p_1\cdot e^{p_2\cdot U}$). In Fig. 1 shows red general dependence such type

$$f(U)=p_1\cdot e^{p_2\cdot U}+p_3+p_4\cdot U. \qquad (1)$$

The coefficients p_1, p_2, p_3, p_4 in equation (1) are determined using the least squares method.

For zero potential on the grid electrodes *C1* and *C2*, all ionized secondary electrons, whose energy is higher than the value of the work function for metal (4.2 eV for aluminum) [3] – the so-called over-barrier electrons, emit from the sample.

In this case $p_1 = 0.88$, $p_2 = 0.36$, $p_3 = 1.24$, $p_4 = 0.0025$. For further analysis, the coefficient p_3 is important, which gives the value of the yield of primary elastically reflected electrons at zero potential on *C1* and *C2*, and the coefficient p_1, which indicates the yield of over-barrier electrons. The p_4 coefficient shows that the background of the high-energy emission component slightly increases as the voltage on the grid electrodes *C1* and *C2* approaches zero.

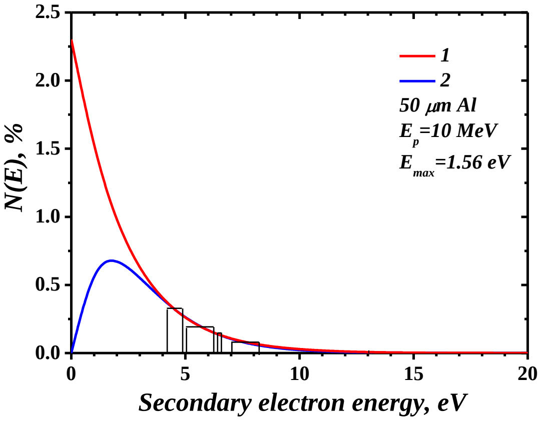

Fig. 2. The spectrum of low-energy secondary electrons generated in the metal (curve 1) and the spectrum of electrons emitted from the metal (curve 2). The histogram is the measured spectrum of over-barrier electrons with energies greater than the work function

By counting the number of electrons emitted in a certain energy range (see Fig. 1), one can construct a spectrum of secondary low-energy electrons in a metal. Mathematically, the spectrum is the derivative of the output value. Such a spectrum (shifted by the work function value from aluminum – 4.2 eV) is presented like a histogram in Fig. 2.

This histogram shows the form of the spectrum of low-energy electrons emitted from the metal with energies over the height of the existing barrier (work function) – the spectrum of over-barrier electrons.

The shape of the calculated spectrum of generated electrons is close to the exponential dependence. We approximated the measured spectrum using the least squares method with an exponential dependence and extrapolate to low energy range. New data were obtained for the part of the spectrum inaccessible for measurement (below the value of the work function). Curve 1 in Fig. 2 shows a view of the low-energy part of the spectrum of secondary electrons in a metal. Part of the energy spectrum is obtained from experimental data (from 4.2 to 20 eV) and the low energy part is obtained by extrapolation to the unmeasured part of the spectrum (from 0 to 4.2 eV). The presented dependence has the form $p_1\cdot e^{p_2\cdot E}$, where the values $p_1 = 1.51$ and $p_2 = -0.36$ are determined by the least squares' method.

Thus, based on the results of experimental measurements and the proposed approximation to the unmeasured part of the energy spectrum, we assume that the spectrum of secondary electrons in metal has a decreasing exponential dependence in the energy range from zero to ~ 20 eV.

2. LOW ENERGY SPECTRA OF SECONDARY ELECTRONS EMITTED FROM THE TARGET

The energy distribution of low-energy secondary electrons emerging from the sample differs from the distribution of secondary electrons formed in the metal since the initial electron spectrum is deformed due to absorption on the way out of the metal.

Let the energy spectrum of electrons emerging from a metal layer of thickness *t* is represented as:

$$f_{yield}(E)=\int_0^t f_0(E,x)\,dx. \qquad (2)$$

Assuming that the energy loss is proportional to the path length in the region of the studied energies of several eV $(dE/dx=const)$, then the initial spectrum of ionized electrons ($e^{p_2\cdot E}$, see Fig. 2), when passing through a certain layer of matter, must be multiplied by its thickness, which is proportional to the energy value $f_1=p_1\cdot E$, and the spectrum of outgoing electrons can be represented as:

$$f_{yield}(E)=p_1\cdot E\cdot e^{p_2\cdot E}. \qquad (3)$$

Here p_1, p_2 are the coefficients that are found by the least squares method from the measured data (see histogram in Fig. 2). In this case: $p_1 = 1.168$ and $p_2 = -0.615$. The maximum of the spectrum is at the energy $-1/p_2$ and is equal to 1.56 eV. When determining the fitting parameters by the least-squares method of dependence (3), an additional condition was used, namely, the total integrated yield for the spectrum determined by curve

(3) should be equal to the total yield of the low-energy emission component.

Approximation of a part of the measured yield spectrum by dependence (3) is shown in Fig. 2 Curve 2. It can be seen that electrons with very low energy can escape from a thin near-surface layer, and their fraction is small. With increasing energy, the thickness with which electrons can escape increases, and their fraction increases until a maximum occurs. With a further increase in energy, the fraction of electrons in the initial spectrum falls, and therefore their total yield also decreases.

Thus, the spectrum of generated secondary electrons of an exponential type upon exit is transformed into a spectrum with a characteristic maximum. This is confirmed both in the simulation of secondary emission by the Monte Carlo method [7] and in experimental studies [8].

3. EXPERIMENTAL RESEARCH OF THE LOW-ENERGY COMPONENT YIELD OF THE SECONDARY ELECTRON EMISSION

The secondary electron emission yields were studied for the primary electron beam energies 10, 15, 20, 25, and 30 MeV [6].

During experimental studies, several important parameters necessary for the quantitative presentation of the results were recorded: the primary beam current, the voltage on gridded electrodes *C1* and *C2*, and the current from the emitter – 50 µm aluminum foil. The yields of low-energy electrons from the first and second target surfaces, as well as the total yield from the two target surfaces, were directly measured.

The total output from the two target surfaces should, with good accuracy, be equal to the sum of the outputs from the first and second surfaces, which was observed in our measurements. Note that the measurements of the yields of secondary electrons from the 1st, and 2nd surfaces and the total were carried out in a series of independent measurements.

As an example, Fig. 3 shows the *CVC* of the yield of low-energy secondary electrons as a function of the equal voltage on gridded electrodes *C1* and *C2* in the range from -80 to +80 V.

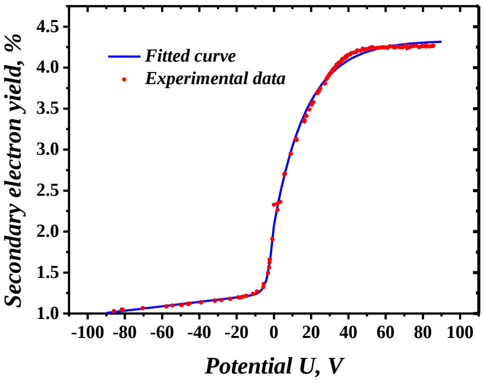

Fig. 3. The dependence of the yield of low-energy secondary electrons from two target surfaces on the voltage on the grids (C1+C2) placed before and after the target. The dots are the measured values; the blue fitted curve is the least squares approximation of the measured values

The energy of incident high-energy electrons is 10 MeV. The measured values are shown in Fig. 3 by red dots. All results are given as the ratio of target emitted electrons to incident primary electrons and are given as a percentage.

With an increase in the potential from -80 V on grids *C1* and *C2*, the yield of secondary emission increases and, upon reaching approximately +50 V, reaches a maximum and then remains constant, independent of voltage in the range from 50 to 80 V.

The measured secondary electron emission yield is approximated by two dependencies – one in the area of negative voltages (-80…0 V), the other in the area of positive voltages (0…+80 V). Approximation of the measured values using the least squares method makes it possible to obtain quantitative data characterizing the yield values from the obtained approximation coefficients.

In the region of negative voltages, the measured dependence of the yield is approximated by a curve of the type (1). The value of the coefficient p_1 indicates the yield of above-barrier electrons, which can also be approximately determined from the data in Fig. 3. Those in the absence of voltage on grids *C1* and *C2* (U=0 V, see in Fig. 3) and the presence of primary electron beam, secondary electrons emitted of the target, the energy of which in the target exceeds the work function, and which have a movement direction away from the target, the so-called over-barrier electrons.

In the region of positive voltages, the measured dependence of the yield of secondary electron emission is approximated by a curve of the type:

$$f\left(U\right)=c_1+c_2\cdot e^{c_3\cdot U}. \qquad (4)$$

The value of the coefficient c_1, represents the total yield of the secondary low-energy emission plus the high-energy background. By subtracting the background value p_3, see (1), from c_1, we obtain the value of the total yield of secondary low-energy electron emission, which can also be approximately estimated from the data shown in Fig. 3. In this case: c_1 = 4.33, c_2 = - 2.26, c_3 = - 0.056.

The proposed measured data approximation made it possible to obtain the dependence of the parameters of secondary low-energy emission on the energy of primary electrons.

4. PARAMETERS OF THE LOW-ENERGY ELECTRONS SPECTRA

All of the measured parameters of the low-energy spectra for the initial energy of primary electrons of 10, 15, 20, 25, and 30 MeV are used below. It must be taken into account that all spectra are similar to each other. Small differences are due to measurement errors. Also, all energy spectra are normalized to the total yield of the low-energy emission component.

High energy background. The high-energy background is the calculated value of the background at zero voltage on the grids *C1* and *C2*, see line 1 in Fig 1. This value is numerically equal to the coefficient p_3 from curve (1).

As follows from the data presented, the high-energy background is approximately 1 % of the total current of incident electrons on the target.

The magnitude of the high-energy background at the same energy as the initial particles is approximately the same when measuring the emission yield from different target surfaces in different measurement sessions. Insignificant fluctuations in the background value (Fig. 4) at different values of the primary electron beam energy are due to different background conditions during its formation and transportation.

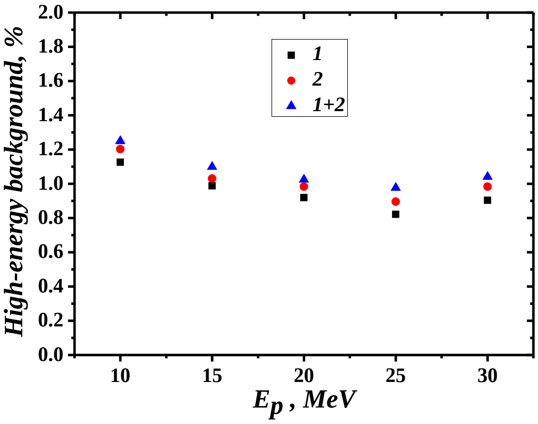

Fig. 4. Dependence of the high-energy background versus the primary electron energy E_p. (1), (2) and (1+2) are related to the 1st, 2nd, and the sum of two surfaces of the aluminum target

The total yield of the low-energy emission component. The total yield of the low-energy emission component at a maximum extracting voltage of +80 V is numerically equal to the difference between the approximating coefficients c_1 of dependence (4) obtained by approximation at positive voltage values and p_3 of dependence (1) obtained by approximation for negative voltage values.

The energy dependences of the yield of the low-energy emission component from the 1st, 2nd, and sum of surfaces are shown in Fig. 5.

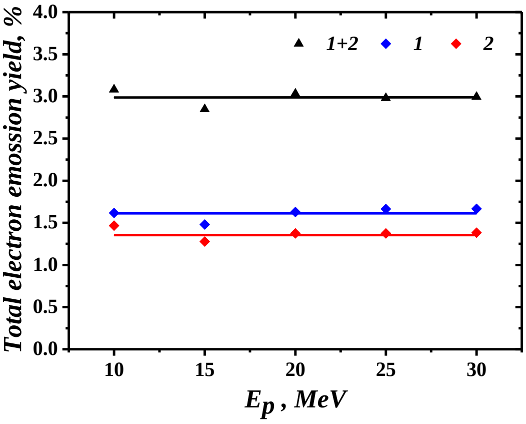

Fig. 5. Total low-energy secondary electron emission yield for the maximum extracting voltage of +80 V versus the energy of the primary electron beam. (1), (2) and (1+2) are values related to the 1st, 2nd, and the sum of two Al foil surfaces. The solid curves show the mean values

As follows from the given data, the total yields of the low-energy emission component do not depend on the energy of primary electrons in the range of 10...30 MeV. The average values for the total secondary electron emission yield from the 1st surface, 2nd surface, and their sum are 1.61, 1.35, and 2.98 % respectively.

The total yield of secondary emission from the 1st surface at an extracting voltage of + 80 V exceeds the yield from the second surface. This is explained by the influence of the medium polarization on the value of the transverse component of the electromagnetic field of an incident relativistic particle at the entrance to the target and its exit. When passing through the target, the transverse component of the incident particle field decreases in size due to the polarization of the target medium, so the total ionization of the target electrons at the exit is smaller. And, therefore, the exit from the second target surface will be less than from the first. The output of secondary electrons with low energies of less than 10 eV (see Fig. 2) comes from a thin surface layer of the target since the momentum of these low-energy ionized electrons is directed mainly perpendicular to the momentum of the incident primary electron.

Spectra of the low-energy emission component. The shape of the spectrum of the low-energy emission component was calculated using formula (3). Using the least squares method, the curve was fitted to the measured part of the spectrum at energies above 4.2 eV (see the histogram in Fig. 2) under the condition that the total area of the spectrum is equal to the total yield of the low energy component of the secondary emission.

For example, the calculated spectra of the low-energy emission component at an initial energy of 10 MeV incident electrons emitted from the 1st target surface, from the 2nd target surface, and the total spectrum from both surfaces shown in Fig. 6. Similar spectra were also calculated for other energies of primary electrons.

As follows from the data shown in the figure, the spectra of low-energy electrons emerging from different surfaces of the target and the total of the two surfaces (curves 1, 2, 3 in Fig. 6) are almost identical in shape. The maxima position is in the range of 1.2…1.6 eV, the areas under the spectra are equal to the total emission yield, and the FWHM is approximate ~4 eV.

For comparison, the spectrum of secondary low-energy emission from aluminum at the primary electron energy in the range of 0.3…1.6 MeV, taken from [8] and shown in Fig. 6.

The spectra obtained by us are normalized to the number of incident initial particles and the representation in percent, and the spectrum from [8] is normalized to the maximum experimental value of the spectrum for the total yield of emission from two surfaces in our case. As follows from a comparison of curves 3 and 4 in Fig. 6 spectra are similar in shape. There is a slight difference in the position of the maxima. The full width value at half maximum agrees enough and is equal to ~ 4 eV. There is only a slight difference in the energy range of secondary electrons > 5 eV, but it has be taken into account that in [8] the initial energy of primary particles E_p does not exceed 1.6 MeV, in contrast to our case, when E_p = 10…30 MeV. It is possible that at lower energies the spectrum broadens more than at high energies. In [9], for even lower initial particle energy value (< 1 keV), the FWHM is in the range of 8…14 eV.

Maximum in the spectrum of the low-energy emission component. The measured part of the spectrum of the low-energy emission component in the energy range above 4.2 eV was approximated by dependence (3) and normalized to the total yield of low-energy emission (for example, curve 2 in Fig. 2). Thus, the maxima were determined in the spectrum of low-energy emission from the 1st, 2nd, and sum surfaces at energies of the primary electron beam of 10, 15, 20, 25, and 30 MeV.

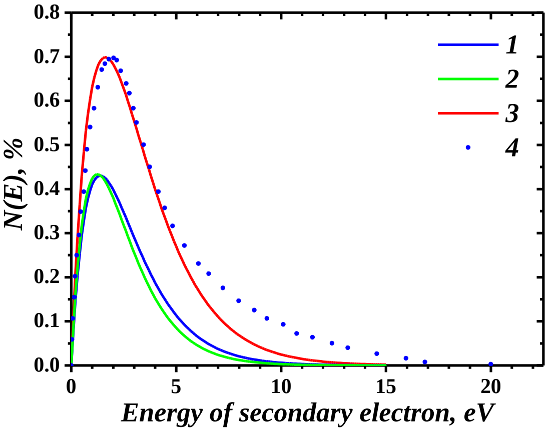

Fig. 6. Calculated spectra of secondary low-energy electron emission at energy of 10 MeV primary electron beam. (1), (2), (3), and (4) are spectra from the 1st, the 2nd, the total spectrum from two surfaces, and the spectrum from the Al target [8], respectively

The maximum values in the spectra of low-energy secondary electrons emitted from the 1st surface of the target, from the 2nd, and the sum of the surfaces are shown in Fig. 7.

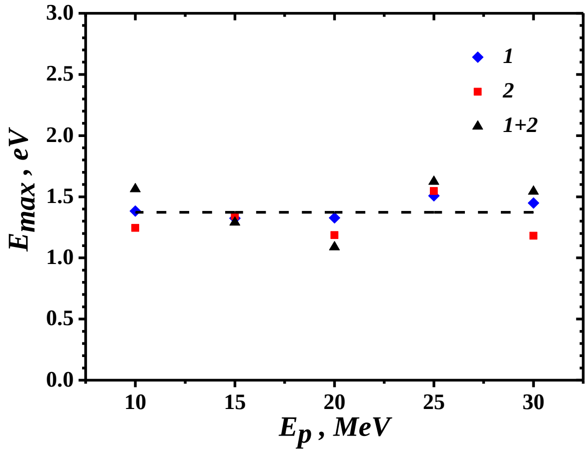

Fig. 7. Maxima in the spectra of the low-energy secondary electron emission component versus primary electron beam energy. (1), (2) and (1+2) are dependences for the 1st, 2nd, and the sum of two surfaces of Al foil. The dashed line is the average value for all measurements

No noticeable differences in the values of the maximum yield of secondary electron emission from one or another surface and at different initial energies of primary electrons were found. All maxima are located in the energy range of 1.1…1.6 eV. The average value equals to 1.4 eV in Fig. 7 is marked with a dashed curve.

According to [9], in the studies of electron microscopy and microanalysis, determining the position of the maximum in the secondary electron emission spectrum is a difficult task. In our case, this maximum was found by fitting the given curve to the measured portion of the spectrum. Therefore, in our measurements, there is a relatively large scatter in the position of the maximum for different initial energies and even for emission at the same energy, but from different surfaces (see the data in Fig. 7). In [10], an approximate energy range of the location of the maximum is presented. For metals, the maximum locates in the range of 1.3…2.5 eV, which agrees well with our data. But necessary to take into account that the data from [9] refer to emission at the primary electron energy E_p < 1 keV, while in our case the primary electron energies are relativistic E_p = 10…30 MeV.

In [8], the spectrum of the low-energy emission component for initial electron energies of 0.3…1.6 MeV is presented. It follows from the data presented in this work that the maximum in the spectrum for aluminum locates at energy of about 2 eV, which is close to our data.

Spectrum width of the low-energy emission component. Knowing the value of the full width at half maximum of the spectrum (FWHM) of the low-energy component of electron emission is necessary for applied studies of the properties of material surfaces. The measured FWHM values of the low-energy emission spectrum, as well as the position of the maximum in the spectrum, depend on the target material surface.

According to the data of [9], for metals, the total width of the spectrum is in the range of 8…14 eV. Measurements on very clean metal surfaces show that the spectral width can locate in the range of 6…30 eV [10].

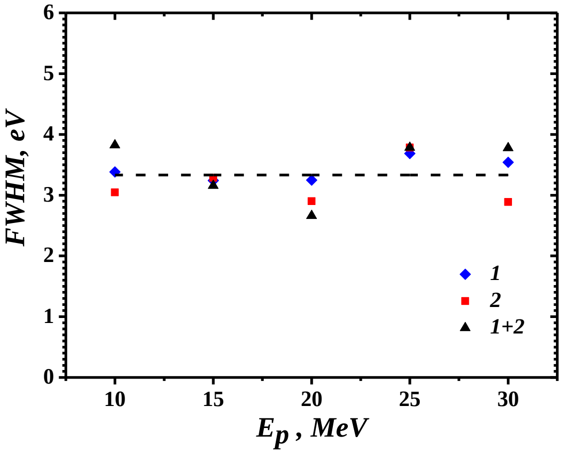

Fig. 8. FWHM values of the spectra of the low energy component of the secondary electron emission versus primary electron beam energy. (1), (2) and (1+2) are the 1st, 2nd, and the sum of two surfaces of the Al foil. The dashed line is the average value for all measurements

When analyzing the obtained experimental data, the total widths of the spectra of the low-energy component of electron emission from the 1st, 2nd, and sum of surfaces were determined at initial electron beam energies of 10, 15, 20, 25, and 30 MeV.

The obtained data are in the range of 2.7…3.8 eV and the results of the analysis are shown in Fig. 8. The average value of the measured FWHM is 3.3 eV, which is less than the lower limit of the range given in [11], but in our case, the initial particle energies are much higher and are in the relativistic energy region.

CONCLUSIONS

Using the developed experimental facility at the direct electron beam line of 30 MeV Electron Linac IHEPNP NSC KIPT, the yields of low-energy ($E < 50$ eV) secondary electron emission from 50 µm aluminum target were measured at the initial energy of the primary electron beam of 10, 15, 20, 25, and 30 MeV.

The absolute yields of low-energy emissions in the energy range of 0…50 eV have been studied and analyzed. It is shown that the absolute yield of the low-energy emission component from the 1st, 2nd, and the sum of two surfaces does not depend on the initial energy of primary electrons in the range of 10…30 MeV within an error of 10 %.

The measurements showed that the yield of low-energy electrons from the 1st target surface is higher than from the 2nd one for the energy of the primary electron beam in the range from 10 to 30 MeV. Approximation of the spectra of low-energy electron emission in the measured part of the spectrum ($E > 4.2$ eV) made it possible to obtain the absolute values of the spectra of electrons emitting from the target in the region of the spectrum up to 20 eV.

Measurements and calculations showed that the maximum in the yield spectrum of low-energy electrons is in the range of 1.3…1.6 eV. The width at half maximum (FWHM) is very small and is in the range of 2.7…3.8 eV.

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СПЕКТРИ НИЗЬКОЕНЕРГЕТИЧНИХ ВТОРИННИХ ЕЛЕКТРОНІВ ПРИ ВЗАЄМОДІЇ РЕЛЯТИВІСТСЬКИХ ЕЛЕКТРОНІВ З АЛЮМІНІЄВОЮ ФОЛЬГОЮ

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Досліджено інтегральні виходи вторинних низькоенергетичних електронів (з енергією до 50 еВ) при взаємодії первинних електронів 10…30 МеВ з алюмінієвою фольгою товщиною 50 мкм. Показано, що запропонована методика апроксимації спектрів низькоенергетичної емісії електронів у вимірюваній частині спектру ($E > 4{,}2$ еВ) дозволяє отримати дані про абсолютні значення спектрів електронів, які вийшли з мішені. Встановлено, що спектри вторинних низькоенергетичних електронів залежно від енергії первинних електронів мають максимум у діапазоні 1,3…1,6 еВ, а значення ширини на половині висоти знаходяться у діапазоні 2,7…3,8 еВ.