INTERACTION OF RELATIVISTIC PARTICLES WITH CRYSTALS AND MATTER

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EXPERIMENTAL STUDIES ON THE DELTA ELECTRON YIELD DURING THE INTERACTION OF HIGH-ENERGY ELECTRONS WITH THIN AMORPHIC FOILS

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The results of systematic experimental studies of the yield of δ-electrons during the interaction of an electron beam with energies of 10, 15, and 25 MeV with thin amorphous targets (Be, Al, Ni, Cu, Nb, Au) are presented. The studies were carried out in 2025 at the LPE-30 accelerator of the National Scientific Centre of "Kharkiv Institute of Physics and Technology" using a multi-target device. The key feature of the experiment was the unique selection of the target thickness, which provided close values of the parameter $T^{0.5}Z/A$ (in the range of 0.045…0.065), characterizing the collision statistics normalized to the specific electron density of the target. Thus, the thickness T for each target (with different Z/A ratios) was selected so that the total statistical effect of the interaction with electrons of the substance was close for all targets. It was found that under such conditions, the yield of δ-electrons weakly depends on the energy in the range of 10…25 MeV and is practically independent of the target serial number Z (deviation within 5…10%). This demonstrates that under the same beam scattering conditions, the yield of δ-electrons is determined mainly not by the type of material (Z), but by the collision statistics (thickness). A semi-automated measurement system based on the ADS1115 ADC and Arduino Nano has been developed and implemented for measuring the current-voltage characteristics of secondary emission.

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1. GENERAL METHODOLOGY FOR STUDYING DELTA ELECTRON YIELD

The study of the interaction of high-energy electrons with matter is a fundamental problem of radiation physics, which is of key importance for the development of accelerator technology, radiation materials science, and medical physics. In 2020, the NSC KPTI resumed a cycle of experimental research on the interaction of high-energy electrons with amorphous and single-crystal structures, which was reflected in the development of the concept for further advancement of this scientific direction [1].

Understanding the processes of secondary particle generation, particularly δ-electrons and bremsstrahlung, is crucial for accurately calculating absorbed doses during irradiation, designing radiation protection, developing new types of radiation sources, and understanding the interactions of high-energy electrons with matter. Experimental data obtained at the LPE-30 high-energy electron linear accelerator enable to verify theoretical models and enhance software complexes for modeling the passage of particles through matter [2], which is a crucial component of many scientific and technological applications.

The scientific novelty and relevance of this work lie in conducting a systematic experimental study of the secondary electron yield for a wide range of materials with different Z and primary beam energies. The special value of the study lies in its unique approach to selecting the target thickness, which enabled the isolation and study of the dependence of the delta electron yield on the atimic number (Z) of the target under nearly identical scattering conditions. To study the dependence of the secondary emission yield of thin amorphous foils, an experimental channel at the output of the LPE-30 linear electron accelerator was used, developed within the framework of the theme of the Institute of High Energy Physics and Nuclear Physics of the National Science Center "Kharkiv Institute of Physics and Technology" of the National Academy of Sciences of Ukraine: "Study of the interaction of electrons with amorphous and single-crystal structures and the influence of high radiation loads on scintillation measurement systems". A general description of the experimental channel is given in [3].

The use of a vacuum chamber with a multi-target device enables the study of the current-voltage characteristics of up to six targets in turn, without compromising the vacuum conditions during the research session. The previously presented analysis of experimental methods [4] for studying the yield of secondary electrons showed that it is the use of an electrostatic system with through collectors (the range of potential values on the collectors is from -80 to +80 V) that provides the integral characteristics of the yield of delta electrons and the low-energy component of the emission of secondary electrons from both surfaces of thin samples of amorphous targets [5].

When developing, testing, and improving the methodology for studying secondary emission, the main attention was paid to the study of secondary emission from thin aluminum foil samples [6-8], as a model material, which is characterized by relatively high purity of production and a wide range of samples with a thickness in the range from 8 to 100 μm. This approach made it possible to obtain new data on the yield of delta electrons [9] and low-energy electrons in the primary beam energy range from 2.5 to 30 MeV using electron accelerators of the NSC KIPT, to estimate the cross sections of delta electron production, and to investigate the main patterns, depending on the thickness of the aluminum foil.

Further use of a multi-target device made it possible to obtain experimental data on the delta electron yield depending not only on the target thickness, but also on Z. Based on the analysis of the obtained experimental data, generalized data on the delta electron yield dependence were obtained at the Institute of High Energy Physics and Nuclear Physics of the NSC KIPT, which showed that their yield primarily depends on the specific electron density of the experimental target [10-14].

2. EXPERIMENTAL STUDY OF DELTA ELECTRON YIELD AS A FUNCTION OF *Z* AND TARGET THICKNESS *T*

To supplement the generalized data on the yield of delta electrons from thin targets presented in the review [14], an experimental study was conducted using the methodology described in [9]. Using an accelerated electron beam with energies of 10, 15, and 25 MeV with an average electron current of ~1 μA, the current-voltage characteristics (I/V) of the yield of secondary electrons from thin targets were obtained, the characteristics of which are presented in Table 1, which shows: Z – atomic number; T – thickness in μm; ρ – reference density values in g/cm^3 and the calculated value of the surface density in g/cm^2; A – atomic weight; $T^{0.5}$ – square root of the surface thickness, which is proportional to the square root of the number of collisions.

Table 1

Characteristics of experimental targets that were installed in a multi-target device at the direct output of the LPE-30 accelerator

Z	T, μm	ρ,g/cm^3	T, g/cm^2	Z	A
Au	7	19.3	0.01351	79	196.9
Be	74	1.848	0.013675	4	9.012
Nb	25	8.57	0.021425	41	92.96
Al	58	2.69	0.015602	13	26.98
Cu	15	8.96	0.01792	29	63.54
Ni	10	8.9	0.0089	28	58.69

The use of a three-electrode electrostatic system enabled the investigation of the I–V characteristic of the secondary electron yield in the scanning mode, within a potential range of -80 to 80 V, for both cases of total emission from both surfaces and from each surface separately.

In order to improve the I-V characteristic measurement system and automate the process of research on the interaction of high-energy electrons with amorphous and single-crystal structures based on the LPE-30 linear electron accelerator of the Institute of High Energy Physics and Nuclear Physics of the NSC KIPT, a measuring complex was developed, tested and implemented in the Department of Radiation Physics and Multichannel Track Detectors, which includes channels for measuring the current of secondary electrons emitted from the target, scanning potentials on collector electrodes, electron beam current channels on the Faraday cylinder and a magnetoinduction (flight) sensor. The structure and circuit solutions of the measuring complex are considered in more detail in the work [15]. Such channels were developed and manufactured in the form of a functionally complete block connected to a computer via a USB port. The structural diagram of the complex is presented in Fig. 1.

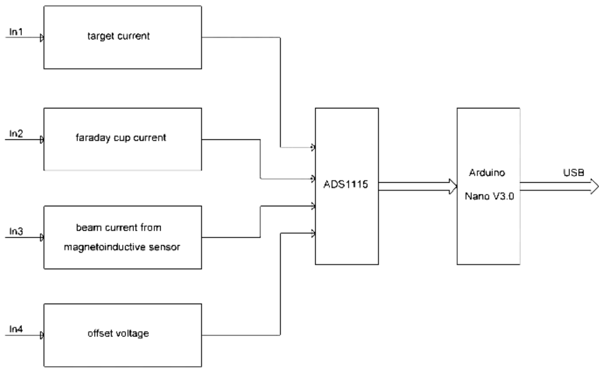

Fig. 1. Structural diagram of the secondary electron emission yield measuring complex

According to the block diagram, the outputs of the normalizing converters are connected to the ADS1115 analog-to-digital converter (ADC) module. The module, based on the ADS1115 chip [16], is a four-channel 16-bit ADC capable of obtaining up to 860 voltage measurements per second. Control and data acquisition are carried out via the I2C bus. The Atmega328, which is part of the Arduino Nano V3.0 module, was selected as the control microprocessor.

To measure the secondary emission current of the target (channel ln1), a gated integrating current-voltage converter was used [17]. The converter has four measurement limits with conversion coefficients of 1, and 0.1 μA/V; 10 and 1 nA/V. During the experiments, the value of the primary beam current of high-energy electrons per Faraday cup was about 1 μA. The developed channel (channel ln2) allows measuring the beam current value in the range from 0.5 to 50 μA. Since the FC is installed in front of the experimental chamber with a multi-target device, a magnetic induction (flight) sensor (channel ln3) was additionally used to control the change in the primary electron beam current during the experiment. The range of measured electron beam currents is 0.5…20 μA.

During the I-V characteristic measurement in manual mode, the value and polarity of the potential on the collectors were changed according to the operator's choice. Its value was automatically recorded by the ln4 channel simultaneously with the current measurement, which ensured the correct construction of the I-V characteristic. The maximum permissible scanning range can vary from -200 V to +200 V.

In total, more than 54 experimental I-V characteristics were obtained during one week experimental session in 2025, of which three were obtained for each target for a fixed primary beam energy (total secondary electron yield from both surfaces, separately from the frontal (first) surface in relation to the primary beam, and at the yield (second) from the thin target). The general form of the I-V characteristic (Fig. 2,a-f) is presented for the case when the energy of the primary beam E_e of electrons was 25 MeV, and its average current was 1 μA.

Since the energy of delta electrons significantly exceeds the value of the stopping potentials (-80 V), to determine the yield of low-energy electrons from the first or second surface, it is necessary to subtract the part corresponding to the yield of delta electrons δ (see Fig. 2). Thus, the yield of low-energy electrons for a gold foil (see Fig. 2,a) for the first surface is 0.172, and for the second, 0.138; the total emission from both surfaces is 0.315≈0.172+0.138+Δ, difference is Δ=0.005, and for a beryllium foil (see Fig. 2,b), for the first – 0.144, for the second – 0.114, from both surfaces – 0.267≈0.144+0.114+Δ, Δ=0.009.

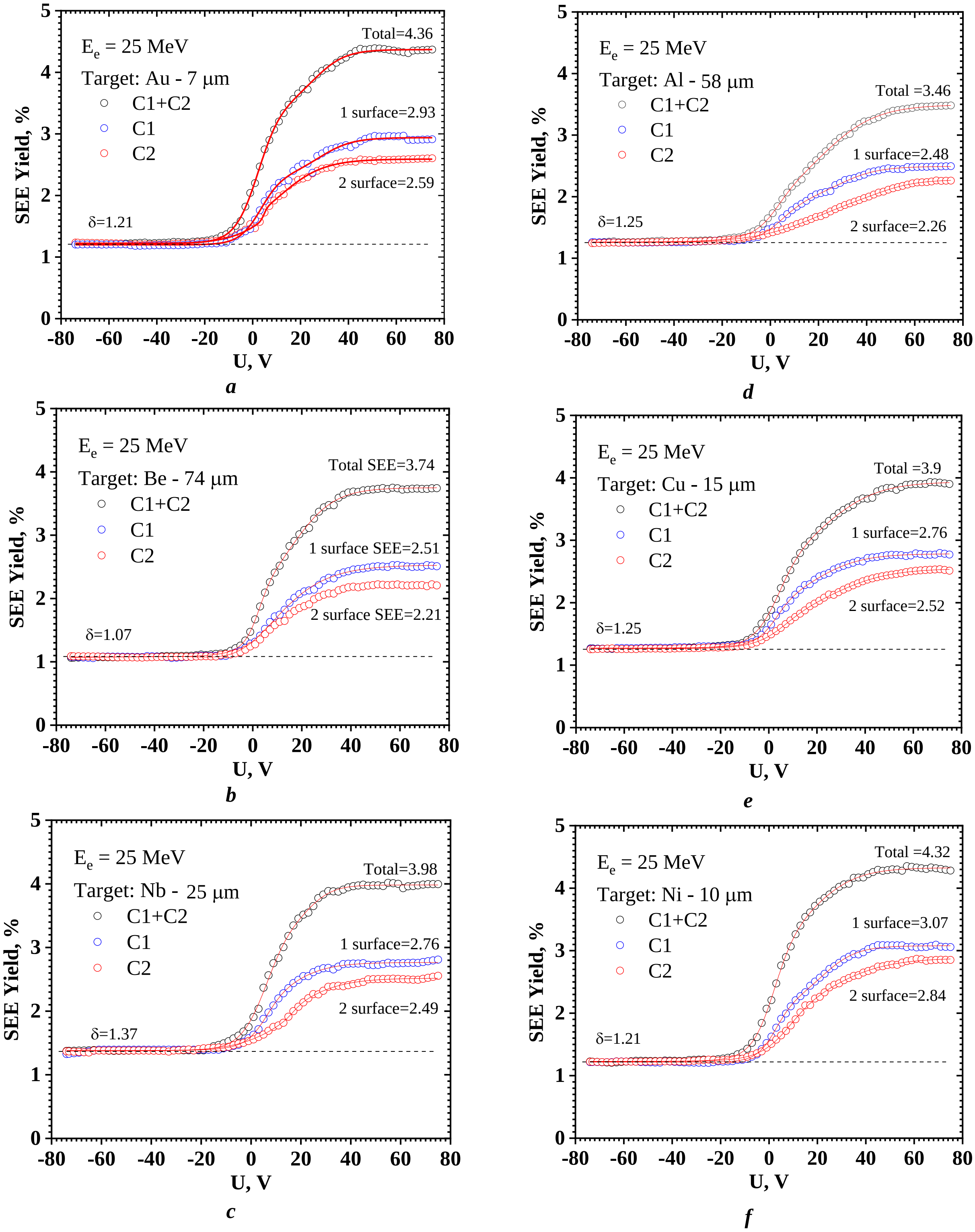

Fig. 2. Experimental dependences of the yield of secondary electrons when high-energy electrons with an energy of 25 MeV pass through thin films: a – Au (7 μm); b – Be (74 μm); c – Nb (25 μm); d – Al (58 μm); e – Cu (15 μm); f – Ni (10 μm)

The results of the analysis of the I-V characteristics for all 6 targets when irradiated with high-energy electrons with energies: 10, 15, and 25 MeV are presented in Table 2. The analysis revealed that the change in energy within this range does not significantly impact the delta electron yield, which remains in the range of 0.011 to 0.0142. Based on the obtained values, it follows that the thickness of the samples and the serial number of the elements provide a sufficiently close value of $T^{0.5}$ Z/A, which is in the range of 0.045…0.065.

Table 2

Experimental values of delta electron yield depending on the energy of primary electrons obtained from the I-V characteristic

Z	δ-electron yield			Average values
	10 MeV	15 MeV	25 MeV	
Au	0.0117	0.012	0.0121	0.0119
Be	0.0107	0.0107	0.0108	0.0107
Nb	0.0142	0.0147	0.0138	0.0142
Al	0.0119	0.0116	0.0126	0.0120
Cu	0.0131	0.0123	0.0126	0.0126
Ni	0.01	0.0105	0.0122	0.0109

In previous works [11-14], the authors indicated the presence of a linear dependence of the delta electron yield, taking into account target characteristics such as Z, A, and $T^{0.5}$ Z/A. Fig. 3 shows the dependence of the delta electron yield on the parameter T0.5·Z/A.

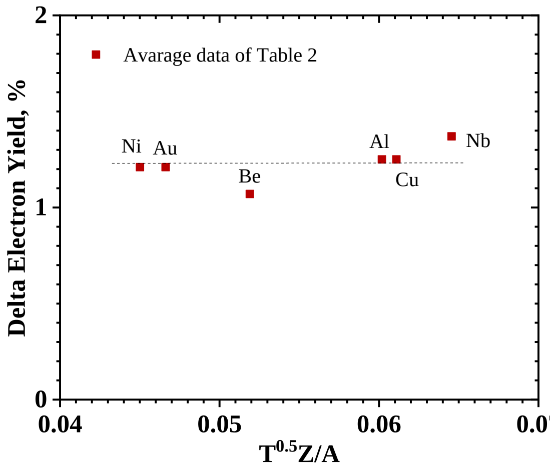

Fig. 3. Dependence of the average delta electron yield on $T^{0.5}$·Z/A

As shown (see Fig. 3), the δ-electron yield demonstrates a clear correlation with the parameter $T^{0.5}$·Z/A. The new data within the error range of <10% correspond to the given dependence. At the same time, the key process that accompanies the passage of particles through the foil and affects the trajectories of secondary electrons is multiple Coulomb scattering. This process is characterized by the root-mean-square scattering angle, which is proportional to the ratio $T^{0.5}$Z/A0.5 (see calculated values are presented in Table 1). Fig. 4 presents the results of the averaged data on the delta-electron yield of thin films (see Fig. 3) as a function of $T^{0.5}Z/A^{0.5}$.

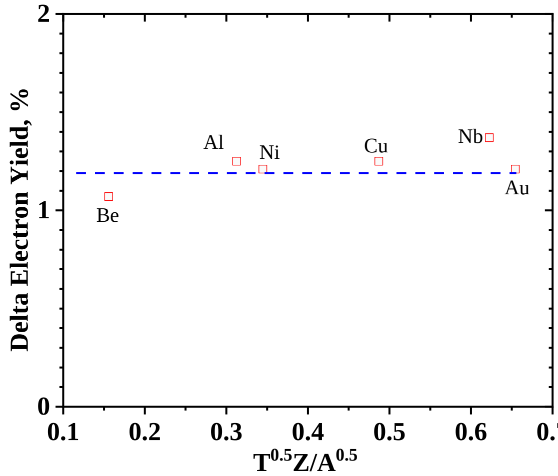

Fig. 4. Dependence of the average yield of delta electrons on $T^{0.5}Z/A^{0.5}$

The dependence presented in Fig. 4 complements the result presented in Fig. 3, separating two phenomena: the generation of δ-electrons and their exit from the target. Result Fig. 3 (yield constancy at $T^{0.5}$Z/A=const) shows that the total number of generated δ-electrons is determined mainly by collision statistics. Instead, Fig. 4 demonstrates that the probability of these electrons leaving the sample is directly affected by the angle of multiple Coulomb scattering, which is proportional to $T^{0.5}Z/A^{0.5}$.

The systematic data obtained in the work and established regularities have both fundamental and applied significance. They are an experimental basis for verification and adjustment of modeling software complexes (such as Geant4, MCNP, FLUKA) that describe the transport of particles through matter. The independence of the yield of δ-electrons from Z under the condition $T^{0.5}$Z/A=const is important for radiation materials science, which allows, for example, when designing output windows of accelerators or protective coatings, to choose the material according to its mechanical or thermal properties while maintaining the predicted radiation load. At the same time, data over a wide Z range (from Be to Au) are critical for dosimetry and medical physics, particularly for refining calculations of absorbed doses at the boundaries of media separation (e.g., biological tissue-metal implant).

The established regularities of the δ-electron yield are the basis for the correct selection and systematic study of the yield of "real" low-energy electrons (LEE), which will allow to separately investigate the dependence of the LEE yield on Z and scattering conditions, separating the contributions to their generation from the primary beam and from the cascade of δ-electrons. The obtained data enable the development of a generalized semi-empirical model that combines both parameters identified in this research ($T^{0.5}$Z/A and $T^{0.5}Z/A^{0.5}$) to predict the yield of secondary emission over a wider range of conditions. In addition, the application of the developed technique to single-crystal targets will enable the study of the influence of orientation effects on the processes of secondary particle generation and release.

CONCLUSIONS

1. Two measuring complexes based on an Arduino Nano microcontroller and a 16-bit ADS1115 ADC were developed and implemented for precise recording of current-current characteristics of secondary electronic emission.

2. Systematic measurements of δ-electron output from six amorphous targets (Be, Al, Ni, Cu, Nb, Au) were carried out at primary electron energies of 10, 15, and 25 MeV.

3. Due to the unique selection of targets with close values of the parameter $T^{0.5}Z/A \approx 0.045…0.065$, it was experimentally shown that the yield of δ-electrons in the investigated energy range is a practically constant value, independent of the serial number of the target Z.

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ЕКСПЕРИМЕНТАЛЬНІ ДОСЛІДЖЕННЯ ВИХОДУ ДЕЛЬТА-ЕЛЕКТРОНІВ ПРИ ВЗАЄМОДІЇ ВИСОКОЕНЕРГЕТИЧНИХ ЕЛЕКТРОНІВ ІЗ ТОНКИМИ АМОРФНИМИ ПЛІВКАМИ

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Представлено результати систематичних експериментальних досліджень виходу δ-електронів при взаємодії електронного пучка з енергіями 10, 15 та 25 МеВ із тонкими аморфними мішенями (Be, Al, Ni, Cu, Nb, Au). Дослідження проводились на прискорювачі ЛПЕ-30 ННЦ ХФТІ з використанням багатомішенного пристрою у 2025 році. Ключовою особливістю експерименту був унікальний підбір товщини мішеней, що забезпечував близькі значення параметра $T^{0.5}Z/A$ (в інтервалі 0.045…0.065), який характеризує статистику зіткнень, нормовану на питому електронну густину мішені. Таким чином, товщина *T* для кожної мішені (з різним відношенням Z/A) підібрано так, щоб сумарний статистичний ефект взаємодії з електронами речовини був близьким для всіх мішеней. Встановлено, що за таких умов вихід δ-електронів слабо залежить від енергії в діапазоні 10…25 МеВ і є практично незалежним від порядкового номера мішені Z (відхилення в межах 5…10%). Це демонструє, що за однакових умов розсіяння пучка вихід δ-електронів визначається переважно не типом матеріалу (Z), а саме статистикою зіткнень (товщиною). Розроблено та впроваджено напівавтоматизований вимірювальний комплекс на базі АЦП ADS1115 та Arduino Nano для вимірювань вольт-амперних характеристик вторинної емісії.