JOINT INSTITUTE FOR NUCLEAR RESEARCH
Dzhelepov Laboratory of Nuclear Problems

FINAL REPORT ON THE START PROGRAMME

Modeling the interaction of electrons with the nuclear field

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Participation period:
February 16 – Aprel 12,
Winter Session 2025

Dubna, 2025

ABSTRACT

This study modeled the interaction of electron beams with various materials (tungsten, tantalum, lead, bismuth, and carbon) using Monte Carlo simulations in the Geant4 toolbox. The study aimed to analyze the angular and energy distributions of secondary particles (electrons, photons, and neutrons) produced when electron beams with energies ranging from 10 to 800 MeV impinged on targets of different thicknesses (5 mm and 10 mm). The study provides insight into electron-material interactions with applications in radiation therapy, X-ray generation, and cosmic radiation protection.

INTRODUCTION

Bremsstrahlung is electromagnetic radiation emitted by a charged particle when it is scattered (braked) in an electric field. Sometimes the term "bremsstrahlung" also includes radiation from relativistic charged particles moving in macroscopic magnetic fields (in accelerators, in outer space), and it is called magnetobremsstrahlung; however, the term "synchrotron radiation" is more commonly used in this case. Interestingly, the German word Bremsstrahlung has become firmly established in the English language.

According to classical electrodynamics, which describes the basic laws of bremsstrahlung quite well, its intensity is proportional to the square of the acceleration of the charged particle. Since acceleration is inversely proportional to the mass m of the particle, then in the same field the bremsstrahlung of the lightest charged particle, the electron, will be, for example, millions of times more powerful than the proton radiation.

$$I \approx \alpha^2 \approx 1/m^2$$

Therefore, the bremsstrahlung that occurs when electrons are scattered in the electrostatic field of atomic nuclei and electrons is most often observed and used in practice; this is, in particular, the nature of X-rays in X-ray tubes and gamma radiation emitted by fast electrons passing through matter. [1]

The interaction of electron beams with solid materials is of great importance in radiation physics, medical technology, materials science, and accelerator technology. When electron beams of different energies strike high atomic number (Z) materials such as tungsten (W), tantalum (Ta), lead (Pb), and bismuth (Bi) and low-Z materials such as carbon (C), they undergo complex scattering processes. These processes produce electrons scattered at various angles, bremsstrahlung photons, and in some cases secondary neutrons.

In this study, we will consider:

Scattering of electrons and Bremsstrahlung photons and neutrons at different angles by the target and its dependence on the type of material.

Comparison of simulation results with theoretical calculations and experimental data.

The results obtained from this modelling work using Geant4 can be applied in the fields of X-ray generation, Electron microscopy, Cosmic radiation protection, Medical radiation therapy. The results of the study will help to better understand electron-material interactions and develop more efficient radiation technologies.

The main feature of the study is that the interaction of electron flow with various materials was modelled on the basis of Geant4. The energy and angular distribution of the secondary particles produced was analyzed. The dependence of the number of secondary particles produced when a stream of electrons of different energies hits high-Z and low-Z materials was compared as a function of angles, energies, and target thickness.

Modelling these phenomena using the Geant4 program allows for a precise analysis of the angular and energy distributions of the particles. Geant4 is a powerful Monte Carlo simulation platform that allows for detailed modelling of particle transport, electromagnetic interactions, and nuclear reactions. This study considers:

MONTE CARLO SIMULATIONS

In simulations using the Geant4 code, classes G4eBremsstrahlung, G4PenelopeBremsstrahlung and G4LivermoreBremsstrahlungModel calculate the energy loss of electrons and positrons due to the radiation of photons in the nuclear field.

The classes G4eBremsstrahlung, G4PenelopeBremsstrahlung andG4LivermoreBremsstrahlungModel are based on the Seltzer-Berger bremsstrahlung model, Penelope Model and Livermore Model, respectively. In the above models, below electron energies of 1 GeV, the cross section evaluation is based on a dedicated parameterization, above this limit an analytic cross section is used [2]. In our simulations we used the class G4eBremsstrahlung (default class).

The Seltzer-Berger bremsstrahlung model was developed based on interpolation of tables of differential cross sections [13,14], covering electron energies from 1 keV to 10 GeV. Single-differential cross section can be written as a sum of a contribution of bremsstrahlung produced in the field of the screened atomic nucleus $\frac{d\sigma_n}{dk}$, and the part $Z\frac{d\sigma_e}{dk}$ corresponding to bremsstrahlung produced in the field of the Z atomic electrons,

$$\frac{d\sigma}{dk}=\frac{d\sigma_n}{dk}+Z\frac{d\sigma_e}{dk}$$

The differential cross section depends on the energy k of the emitted photon, the kinetic energy of the incident electron and the atomic number Z of the target atom.

Geant4 is a toolkit to create simulations of the passage of particles or radiation through matter. Applications built on Geant4 can simulate any setup or detector and radiation source, and record chosen output of physical quantities due to source particles and secondaries interacting with the material of the setup. Geant4 provides complete functionality for all areas of the simulation of particle transport. It can be used to create a model of a geometry with shapes and materials, locate points and navigate tracks in that model, apply the effects of physics interactions and generate secondary particles, record selected information either as tallies or create hits (that are used to generate detector response), visualize a setup's geometry and the particle tracks passing through it, and interact with an application via an extensible terminal or graphical user interface. It includes a complete set of physics processes for electromagnetic, strong and weak interactions of particles in matter over an energy range that starts from milli-eV (for thermal neutrons), eV (electrons) or typically keV (hadrons), up to hundreds of GeV (or even in part up to 100 TeV). For each type of interaction, a complete set of physics model implementations is provided. Some choices of modelling approaches are available and ready to be used as coherent configurations (named physics lists).

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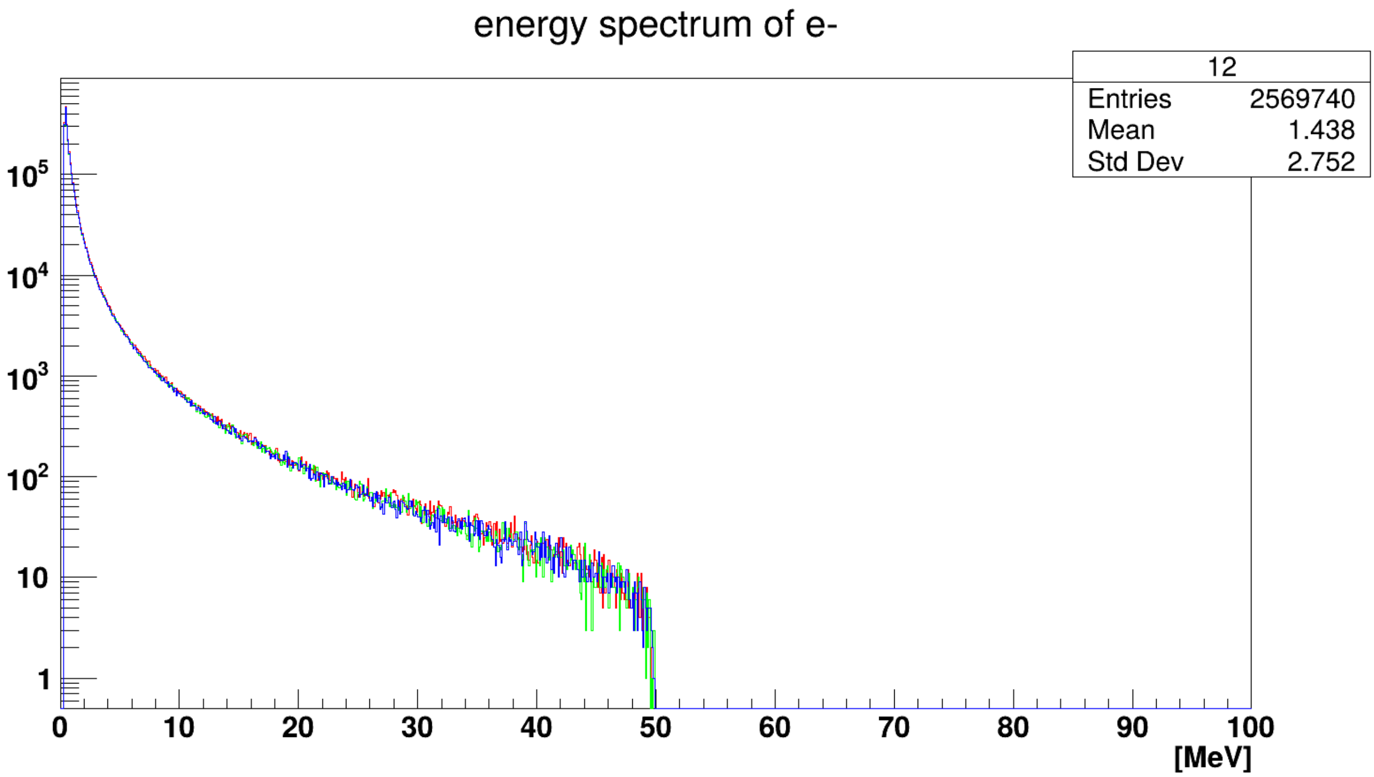
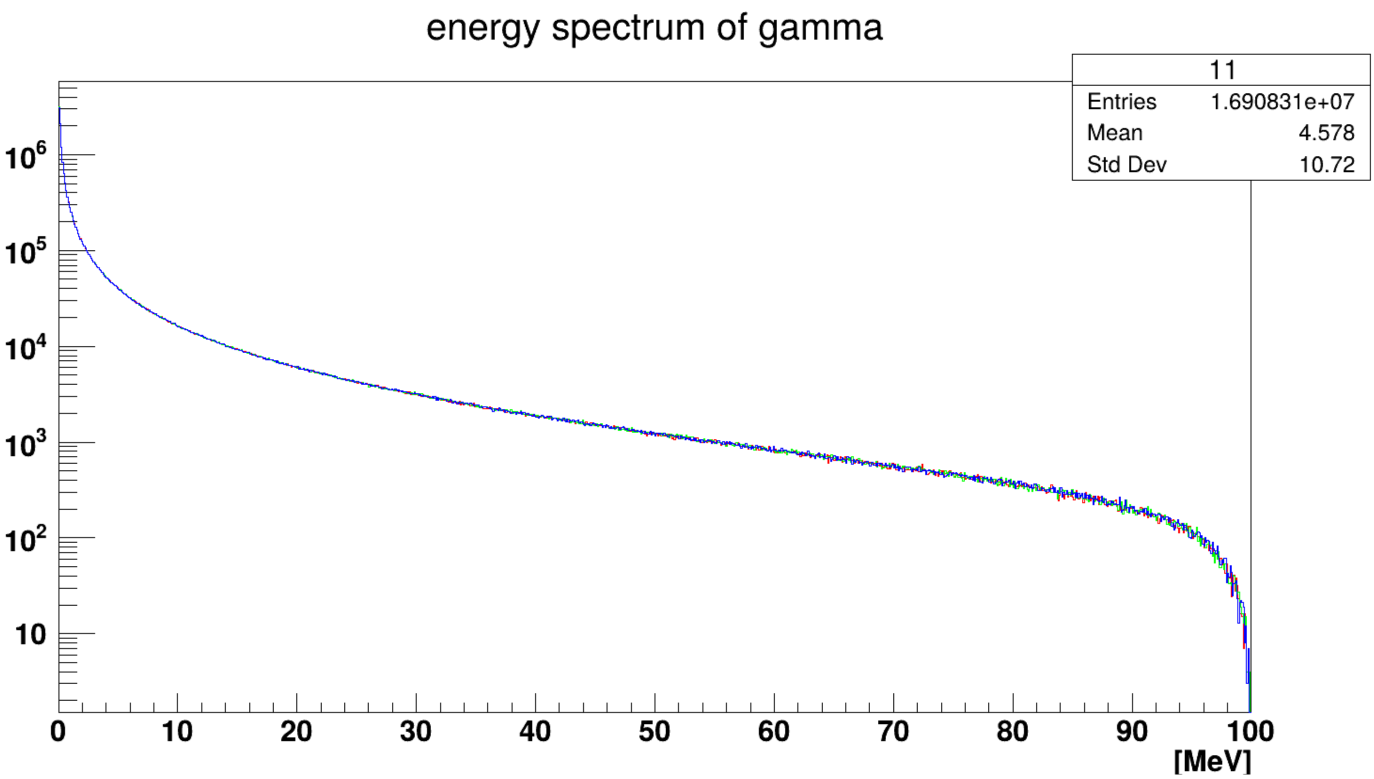
Geant4 source code is available under an open source license, and is written to be readable. The toolkit also includes example applications demonstrating several simpler setups and selected full applications from different domains. For some domains these applications have comprehensive capabilities, whereas others provide a starting point for building your own custom application.

It is also possible to use Geant4 indirectly through a program designed as a customised tool for an application domain, or to create a fully independent stand-alone application for a specific setup or detector.

RESULTS AND DISCUSSION





The graphs in Fig. 1-2 above show the energy spectra of electrons and photons in the three standard, Livermore, and Penelope models for a 100 MeV electron beam for tungsten. It can be seen that the results obtained in all three models are very close to each other. In both graphs, the y-axis indicates the number of electrons (Fig. 1.) and photons (Fig. 2.) scattered by the tungsten target. The x-axis indicates the energy of electrons and gamma rays scattered by the tungsten target.

The results presented below were obtained from tungsten, tantalum, lead, bismuth, and carbon elements with thicknesses of 5 mm and 10 mm. The graphs in **Fig. 1-12** show the angular distribution of the number of electrons, photons, and neutrons scattered by them when a particle stream consisting of 100 million electrons with energies of 10-800 MeV falls on tungsten, tantalum, lead, bismuth, and carbon targets with a thickness of 5 mm.

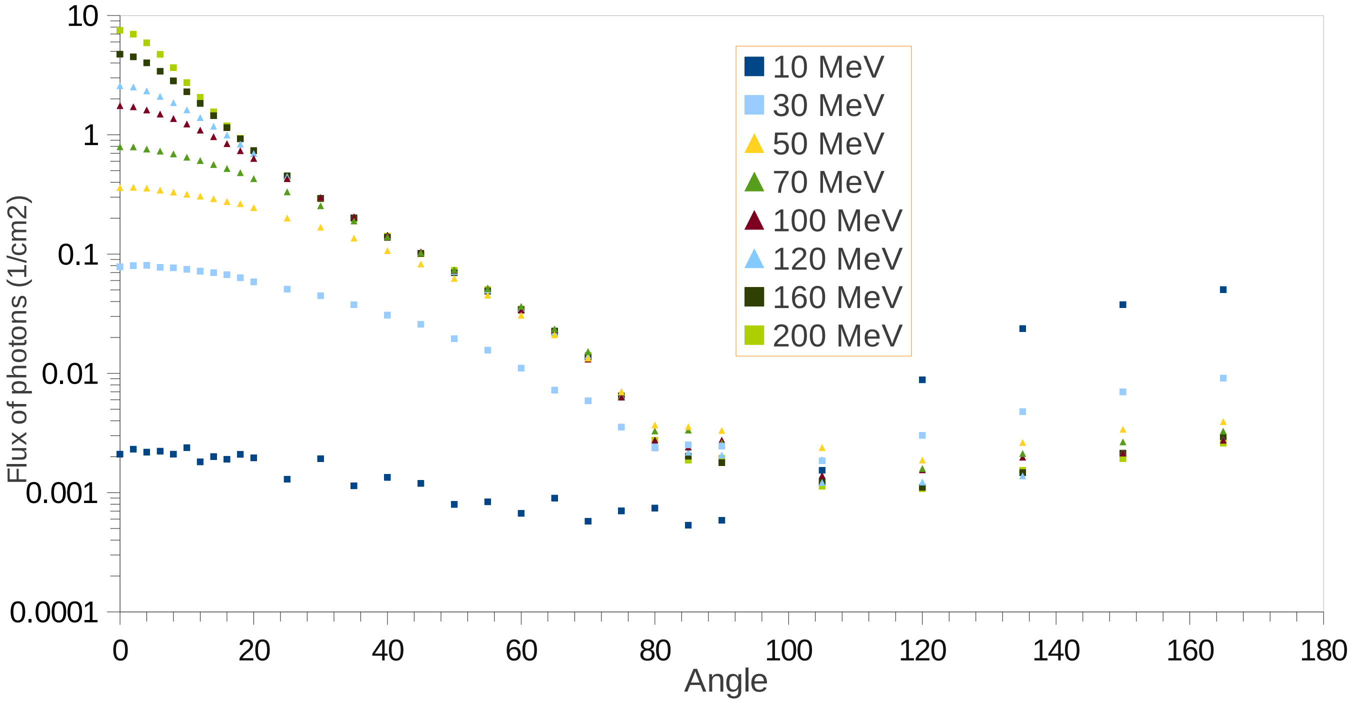


Fig. 3, Electrons scattering at angles from a tungsten target

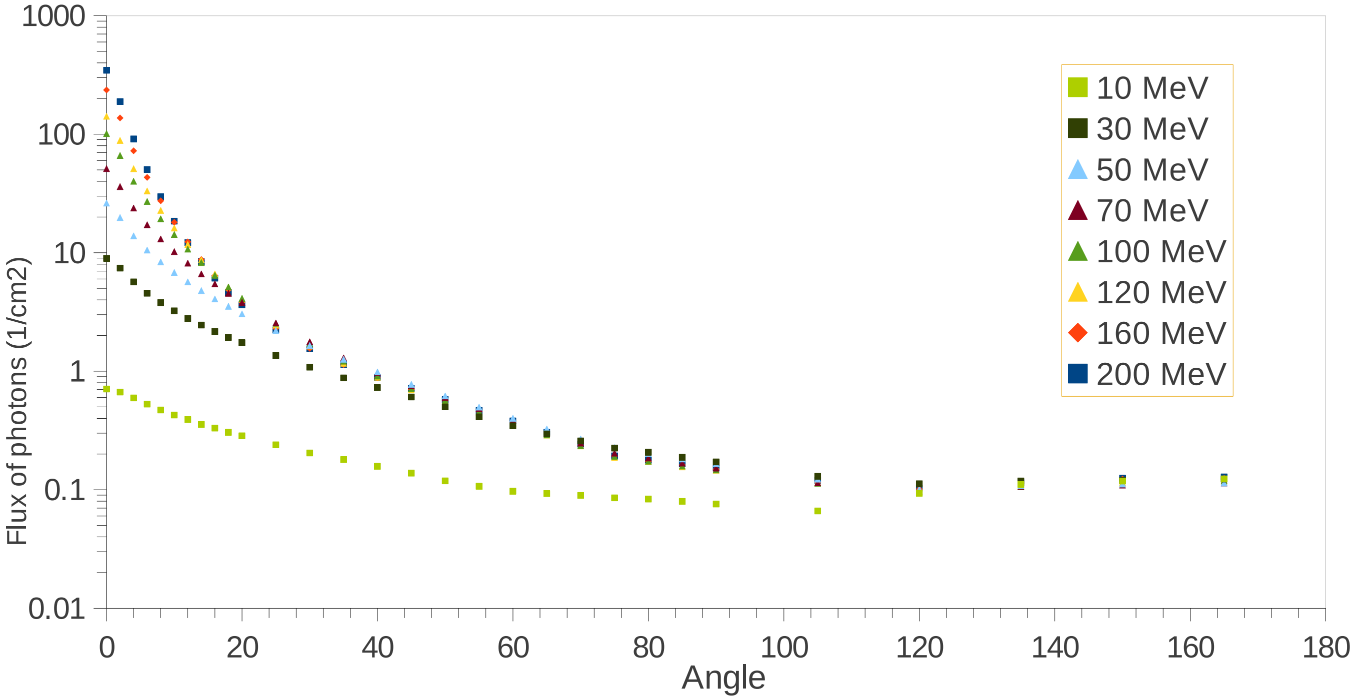


Fig. 4. Photons scattering at angles from a tungsten target

$\alpha > 90^0$ returned electrons $\alpha < 90^0$ passed electrons and photon

Tungsten (W) is a heavy material with a density of $\rho \approx 19.25$ g/cm^3. In dense materials, their atoms are very densely packed. The electron beam falling on tungsten is slowed down in the area of the nuclei of tungsten atoms. When a stream of low-energy electrons hits tungsten, fewer electrons pass through the target, and more return electrons. At higher energies, the opposite happens. We can also see this from the graph. (Fig. 3). When electrons with an energy of 10 MeV fall on tungsten, the number of electrons scattered along 1650 is ≈24 times greater than the number of electrons scattered along 00^0, and at an energy of 200 MeV, the number of electrons scattered along 0^0 is ≈ 2887 times greater than the number of electrons scattered along 165^0, and the electrons scattered along the sides of the target (90^{00}) are less than the number of electrons passing through and returning from both lower and higher energies. As we increase the energy, this relationship changes to the opposite for electrons. In a stream of high-energy particles, the number of electrons passing through tungsten and scattering along 0^0 is greater than the number of electrons scattering along 165^0. At an energy of 10 MeV, the number of electrons scattered at an angle of 0^0 is less than the number of electrons scattered at angles of 2^0, 4^0, 6^0, 8^0, 10^0. The number of electrons scattered at an angle of 165^0 is greater in the flow of high-energy electrons than in the flow of low-energy electrons. For example, when a beam of electrons with an energy of 200 MeV fell on tungsten, the number of electrons scattered at an angle of 165^0 was ≈ 19 times greater than at an energy of 10 MeV.

In the case of low (10 MeV) and high (E ≥ 30 MeV) energy electron streams, most of the photons generated inside the target are emitted in the direction of the incident electrons, and very little is scattered in the opposite direction. (Fig. 4). When a low-energy electron stream hits a tungsten target material, the number of electrons scattered at an angle of 0^0 is ≈ 5.7 times greater than the number of electrons scattered at an angle of 165^0, and at higher energies this figure is ≈ 2695. This means that photons are scattered more in the direction of the incident electron stream in both cases (at low and high energies). However, it can be seen that the number of electrons scattered at an angle of 165^0 is almost equal at all energies. If we look at the number of electrons and photons scattered at angles, the number of photons is always greater than the number of electrons. The ratio of the number of photons scattered at an angle of 165^0 to the number of electrons is ≈ 2.5 at an energy of 10 MeV, and ≈ 49 at an energy of 200 MeV. The ratio of the number of photons scattered at an angle of 0^0 to the number of electrons is ≈ 337 at an energy of 10 MeV, and ≈ 46 at an energy of 200 MeV.

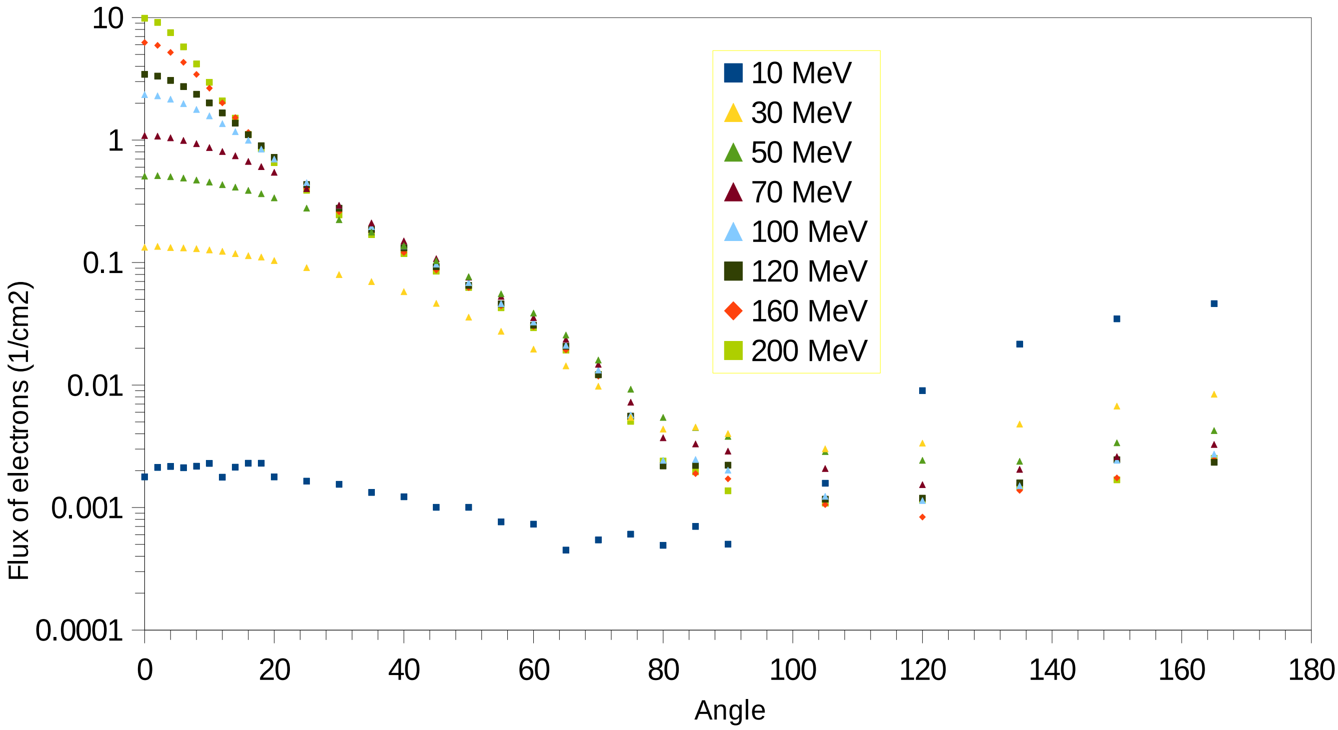


Fig. 5. Electrons scattering at angles from a tantalum target

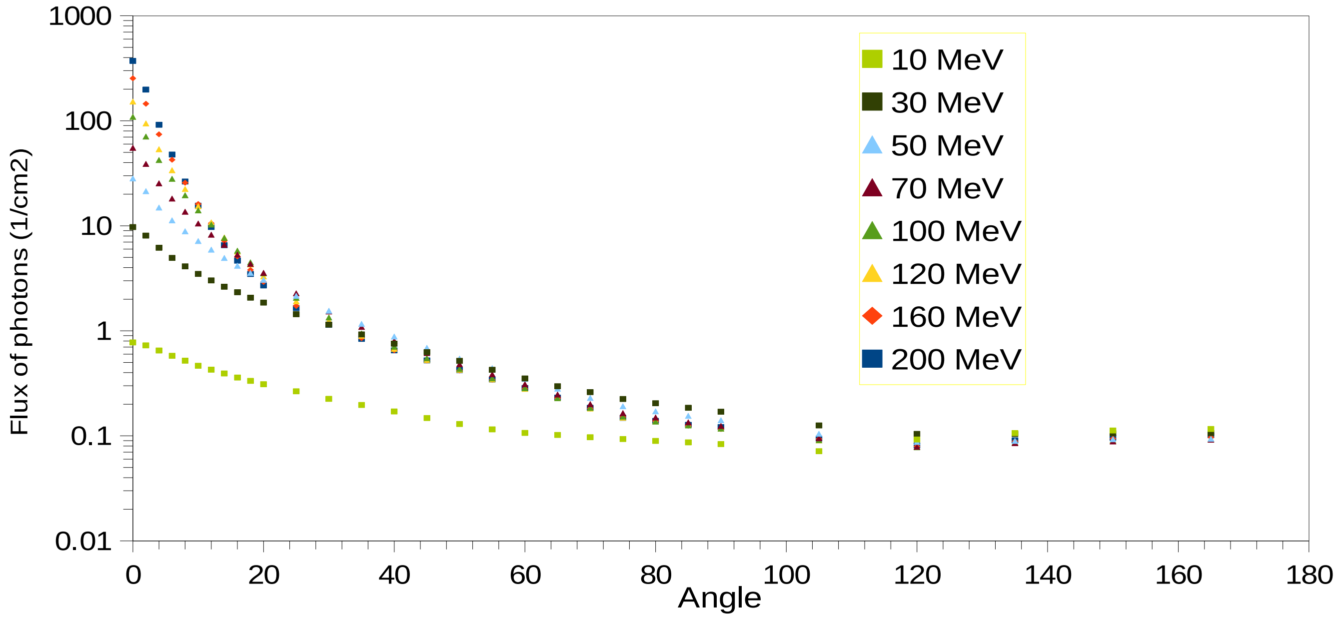


Fig. 6. Photons scattering at angles from a tungsten target

$\alpha > 90^0$ returned electrons $\qquad$ $\alpha < 90^0$ passed electrons and photon

Tantalum (Ta) is a heavy material with a density of $\rho \approx 16.65$ g/cm^3. Tantalum is the second densest of the materials we have selected after tungsten. Therefore, the processes in tantalum are very similar to those in tungsten (Fig. 5). As in tungsten, in tantalum, when a stream of electrons with an energy of 10 MeV hits the target, the number of electrons scattered at an angle of 165^0 is greater than the number of electrons scattered at an angle of 0^0, and the ratio between them is ≈ 26. At higher energies, the opposite is true. If we consider a stream of electrons with an energy of 200 MeV, the number of electrons scattered at an angle of 0^0 is ≈ 3916 times greater than the number of electrons scattered at an angle of 165^0. This means that the stream of electrons with higher energies passes through the Tantalum target material more than the number of electrons with lower energies. When a stream of electrons with an energy of 10 MeV hits tantalum, the number of electrons scattered at 0^0 differs slightly from the number of electrons scattered at angles of 2^0, 4^0, 6^0, 8^0, 10^0. For example, the number of electrons scattered at an angle of 4^0 is ≈ 1.2 times greater than the number of electrons scattered at an angle of 0^0. The number of electrons scattered at 0^0 is ≈ 5552 times greater at an energy of 200 MeV than at an energy of 10 MeV. The number of electrons scattered at an angle of 165^0 is in the opposite direction, that is, at an energy of 200 MeV than at an energy of 10 MeV, ≈ 18 times less.

When comparing tantalum with wolfram, the number of electrons and photons scattered at angles of lower energies is greater in tantalum than in wolfram. Only at an energy of 10 MeV is the number of electrons scattered at angles of 0^0 greater in wolfram than in tantalum. At an energy of 200 MeV, the ratio of the number of electrons and photons in tantalum scattered at an angle of 0^0 to that in tungsten is ≈ 1.3 and ≈ 1.07, respectively. At an energy of 10 MeV, the number of electrons scattered at an angle of 0^0 in tungsten is ≈ 1.2 times greater than in tantalum, and the number of photons in tantalum is ≈ 1.1 times greater than in tungsten.

If we consider photons, at each of the energies we measured, the number of photons scattered at an angle of 0^0 is always greater than the number of photons scattered at an angle of 165^0. (Fig. 6) At an energy of 10 MeV, the number of photons scattered at an angle of 0^0 is ≈ 6.7 times greater than the number of photons scattered at an angle of 165^0, and at an energy of 200 MeV, it is ≈ 3658 times greater. You can see from the graph that the number of photons scattered at an angle of 165^0 is almost the same at all energies. However, this difference is much larger for the number of photons scattered at an angle of 0^0, i.e. when a stream of high-energy electrons hits the target, the number of photons scattered at an angle of 0^0 is greater than at lower energies. For example, the number of photons scattered at an angle of 165^0 is ≈ 1.1 times greater at an energy of 10 MeV than at an energy of 200 MeV, and at an angle of 0^0, the number of photons scattered at an energy of 200 MeV is ≈ 478 times greater at an energy of 10 MeV than at an energy of 10 MeV.

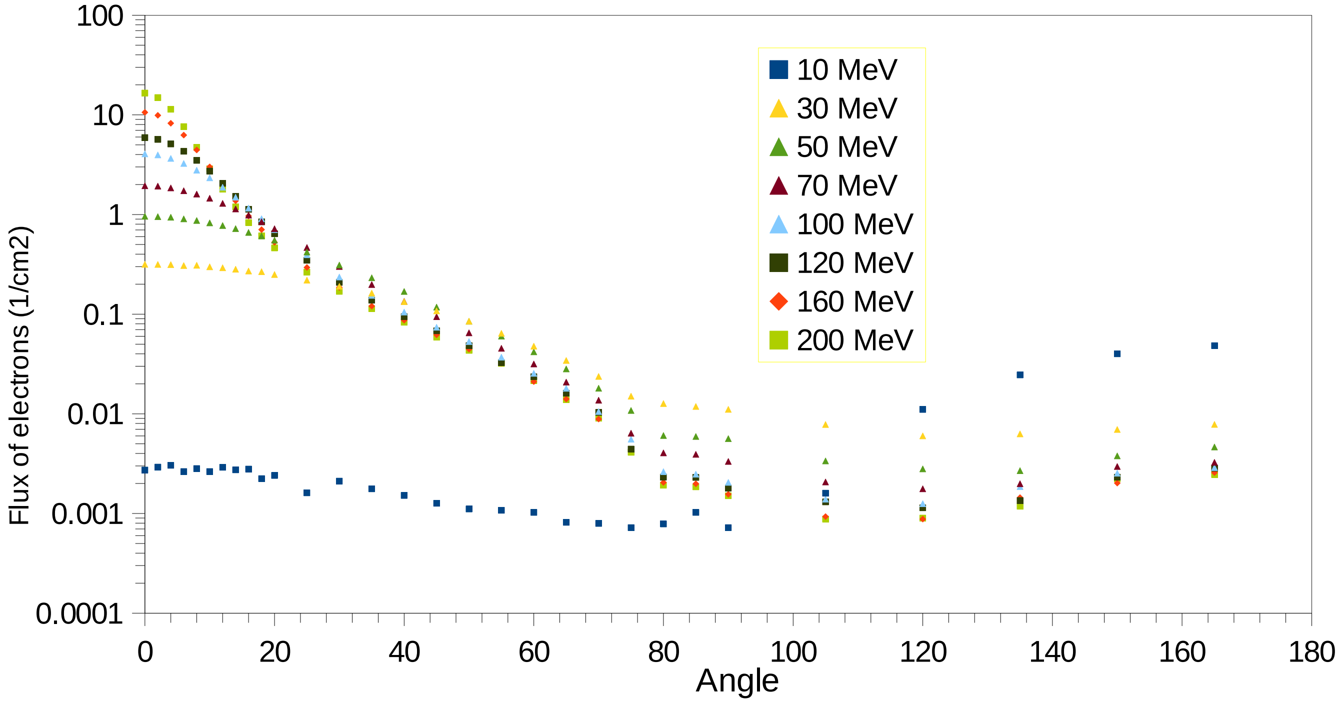


Fig. 7. Electrons scattering at angles from a lead target

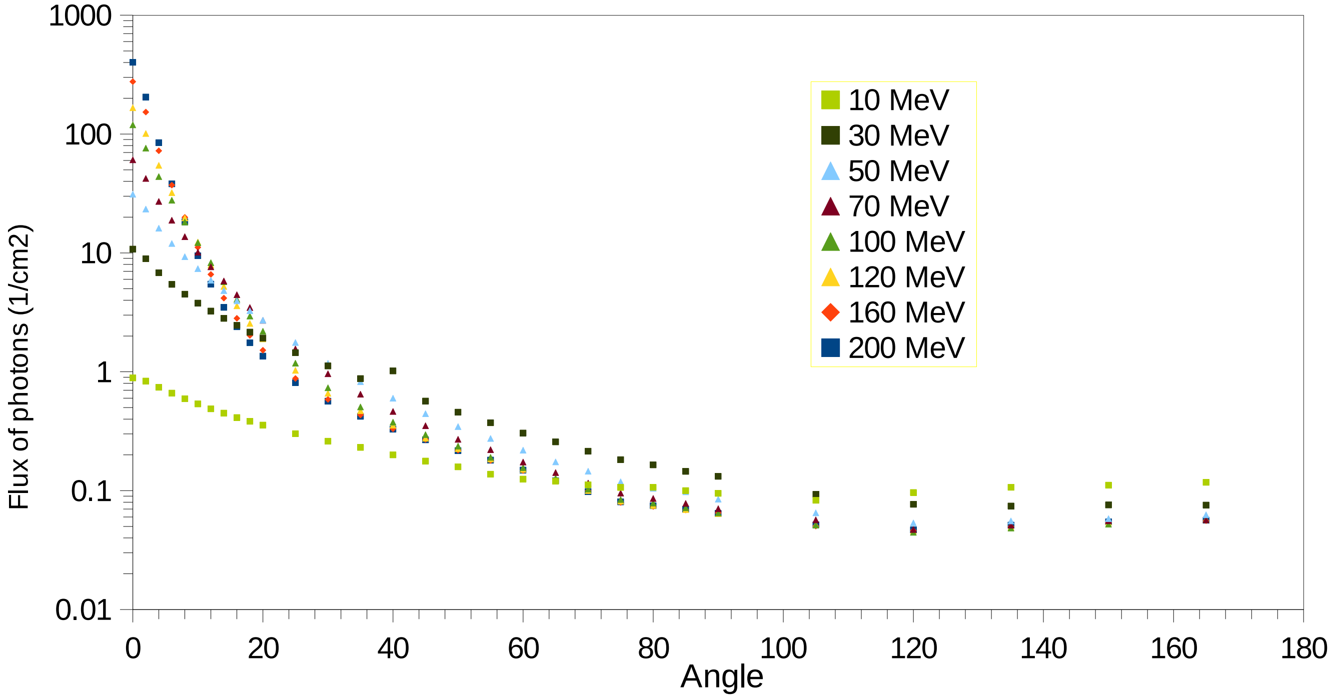


Fig. 8. Photons scattering at angles from a lead target

$\alpha > 90^0$ returned electrons $\alpha < 90^0$ passed electrons and photon

Lead (Pb) is a heavy material with a density of $\rho \approx 11.34$ g/cm^3. The graph for lead is almost identical to the results obtained with the above elements. At high energies, the number of electrons scattered at an angle of 0^0 is greater than at lower energies (Fig. 7), and when a stream of electrons with an energy of 200 MeV strikes the target, the number of electrons scattered in the direction of this incident electron stream is ≈ 6073 times greater than when a stream of electrons with an energy of 10 MeV strikes. However, the number of electrons scattered at an angle of 165^0 degrees is ≈ 20 times greater at energies below 10 MeV than at 200 MeV. This means that when a stream of electrons at lower energies hits lead, more electrons are returned than at higher energies, that is, there are more electrons scattered at an angle of 165^0. When a stream of electrons with an energy of 10 MeV hits lead, the number of electrons scattered at an angle of 0^0 is 2^0, 4^0, etc. For example, the number of electrons scattered at an angle of 4^0 is ≈ 1.1 times greater than the number of electrons scattered at an angle of 0^0. In lead, as in tungsten and tantalum, when a stream of low-energy electrons hits the target, the number of electrons scattered in the direction of the electron flow is less than the number of electrons scattered in the direction opposite to the direction of the electron flow. In the process with high-energy electrons, the opposite is true (Fig. 7). At an energy of 10 MeV, the number of electrons scattered at an angle of 0^0 is ≈ 17.7 times greater than the number of electrons scattered at an angle of 165^0. At an energy of 200 MeV, the number of electrons scattered at an angle of 165^0 is ≈ 6745 times greater than the number of electrons scattered at an angle of 0^0.

As with the other elements, the photons produced by the electron beam incident perpendicularly on the lead target material are scattered more at both low and high energies at the 0^0 angle than at the 165^0 angle (Fig. 8). If we compare these, the number of photons scattered at the 0^0 angle as a result of the electron beam with an energy of 10 MeV hitting the target was ≈ 7.5 times greater than the number of photons scattered at the 165^0 angle. At an energy of 200 MeV, it was ≈ 7107 times greater. If we compare the number of photons scattered at the same energies and at the same angles. The number of photons generated in the target and scattered at an angle of 0^0 as a result of a stream of electrons with an energy of 10 MeV hitting the lead is ≈ 453 times greater than the number of photons generated in the target and scattered at an angle of 0^0 when a stream of electrons with an energy of 200 MeV hits the lead, while the number of photons scattered at an angle of 165^0 is the opposite, that is, at an energy of 10 MeV it is ≈ 2 times greater than at an energy of 200 MeV.

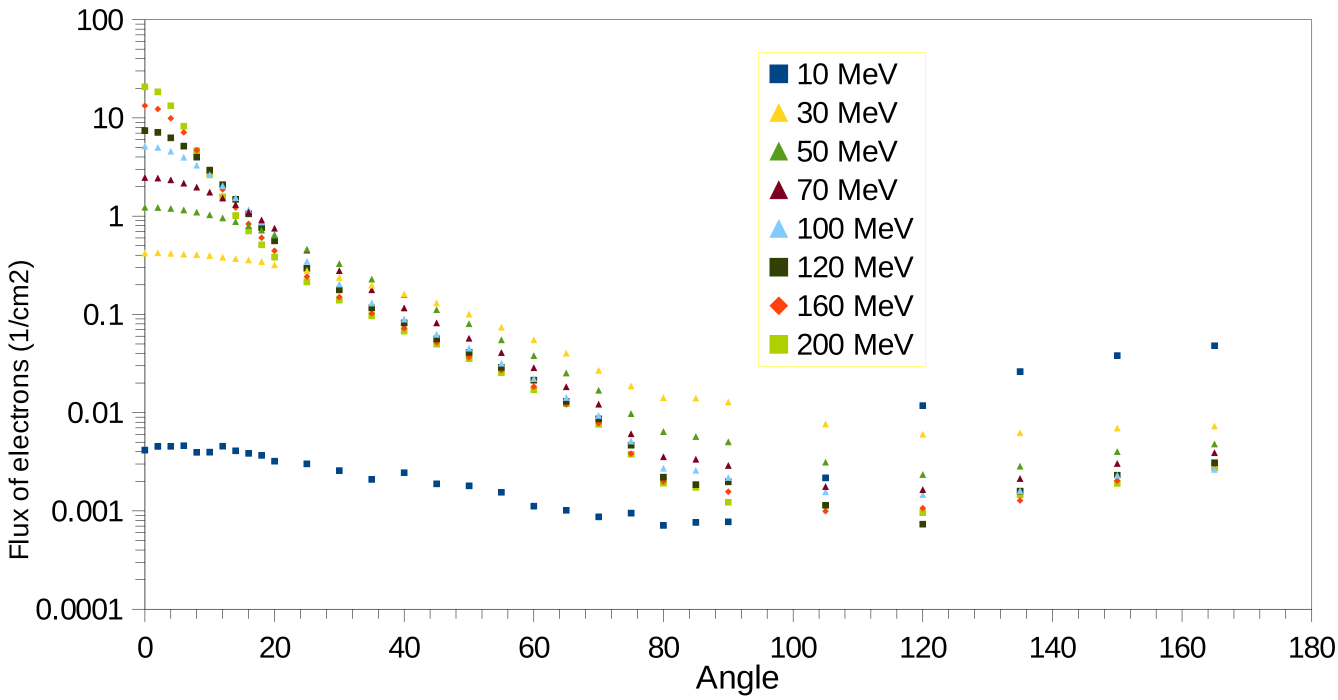


Fig. 9. Electrons scattering at angles from a bismuth target

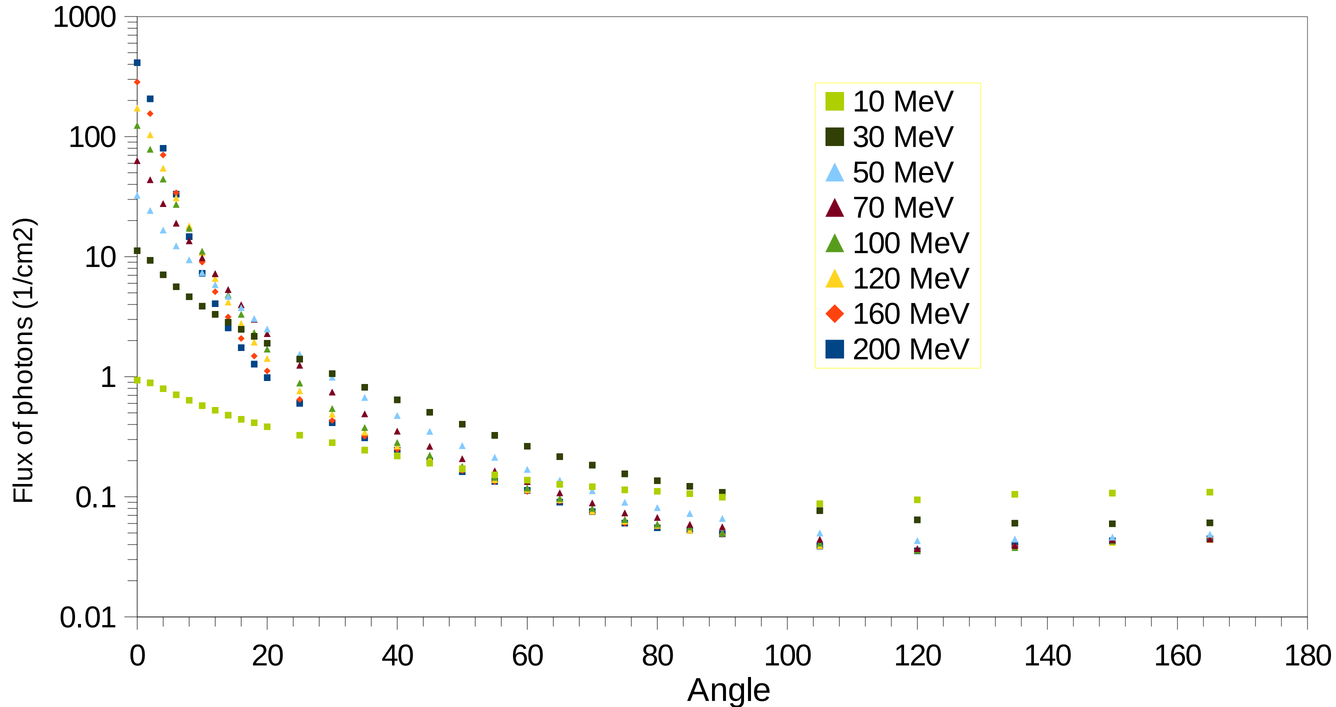


Fig. 10. Photons scattering at angles from a bismuth target

$\alpha > 90^0$ returned electrons $\alpha < 90^0$ passed electrons and photon

Bismuth (Bi) is a heavy element with a density of $\rho \approx 9.78$ g/cm^3. Since the density of bismuth is very close to that of lead, the processes in bismuth are more similar to those in lead than in tungsten and tantalum. In lead, as in bismuth, when a stream of low-energy electrons hits the target, the number of electrons scattered at an angle of 0^0 is less than the number of electrons scattered at an angle of 165^0 (Fig. 9). When a stream of high-energy electrons hits the target, the number of electrons scattered at an angle of 0^0 is greater than the number of electrons scattered at an angle of 165^0. For example, at an energy of 10 MeV, the number of electrons scattered at an angle of 165^0 is ≈ 11.5 times greater than the number of electrons scattered at an angle of 0^0, while at an energy of 200 MeV, the number of electrons scattered at an angle of 0^0 is ≈ 7515 times greater than the number of electrons scattered at an angle of 165^0. This means that at lower energies, like the substances above, electrons are reflected more than at higher energies, and at higher energies, they are transmitted more. We can see this in another way. For example, when a beam of electrons with an energy of 200 MeV hits a target, the number of electrons scattered from the target at an angle of 0^0 is ≈ 4966 times greater than the number of electrons scattered at an angle of 0^0 when a beam of electrons with an energy of 10 MeV hits the target, while the number of electrons scattered at an angle of 165^0 is in the inverse proportion, that is, at an energy of 10 MeV it is ≈ 17 times greater than at an energy of 200 MeV. Since bismuth is a heavy substance, as a result of a flow of electrons with an energy of 10 MeV hitting the target, like the materials we measured above, the number of electrons scattered at an angle of 0^0 is less than the number of electrons scattered at angles of 2^0, 4^0, 6^0. For comparison, the number of electrons scattering at an angle of 4^0 is ≈ 1.1 times greater than the number of electrons scattering at an angle of 0^0.

The photons produced inside the target, however, are more scattered at 0^0 than at 165^0 at all measured energies (Fig. 10). As evidence, when a beam of electrons with an energy of 10 MeV hits the bismuth material, the number of photons scattered at 0^0 is ≈ 8.6 times greater than the number of photons scattered at 165^0. In the case of a stream of electrons with an energy of 200 MeV, it is ≈ 9276 times greater. And another aspect similar to the results obtained for the remaining heavy elements is that photons at lower energies are scattered more at 0^0 than at higher energies. And when a stream of high-energy electrons hits the target, they are scattered more at 165^0 than at lower energies. For example, when a stream of electrons with an energy of 200 MeV hits a target, the number of photons scattered at an angle of 0^0 is ≈ 441 times greater than that of a stream of electrons with an energy of 10 MeV. The number of photons scattered at an angle of 165^0 is ≈ 2.5 times greater at an energy of 10 MeV than at an energy of 200 MeV.

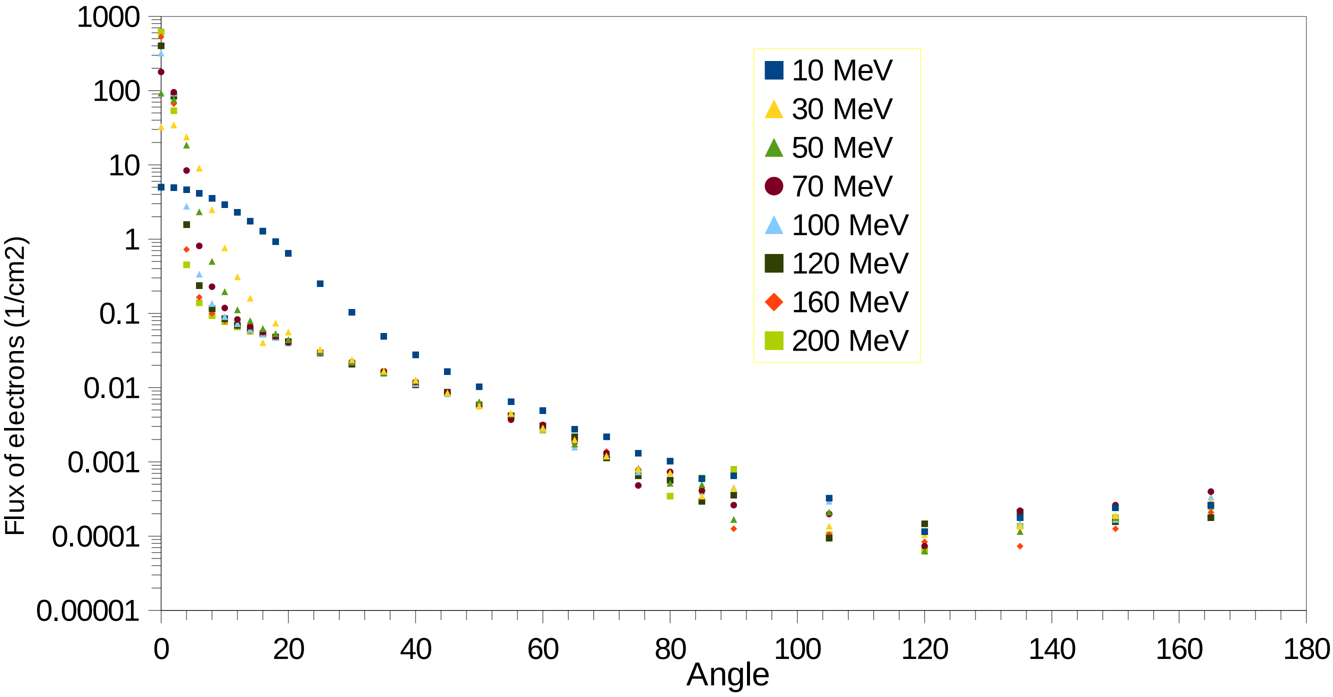


Fig. 11. Electrons scattering at angles from a carbon target

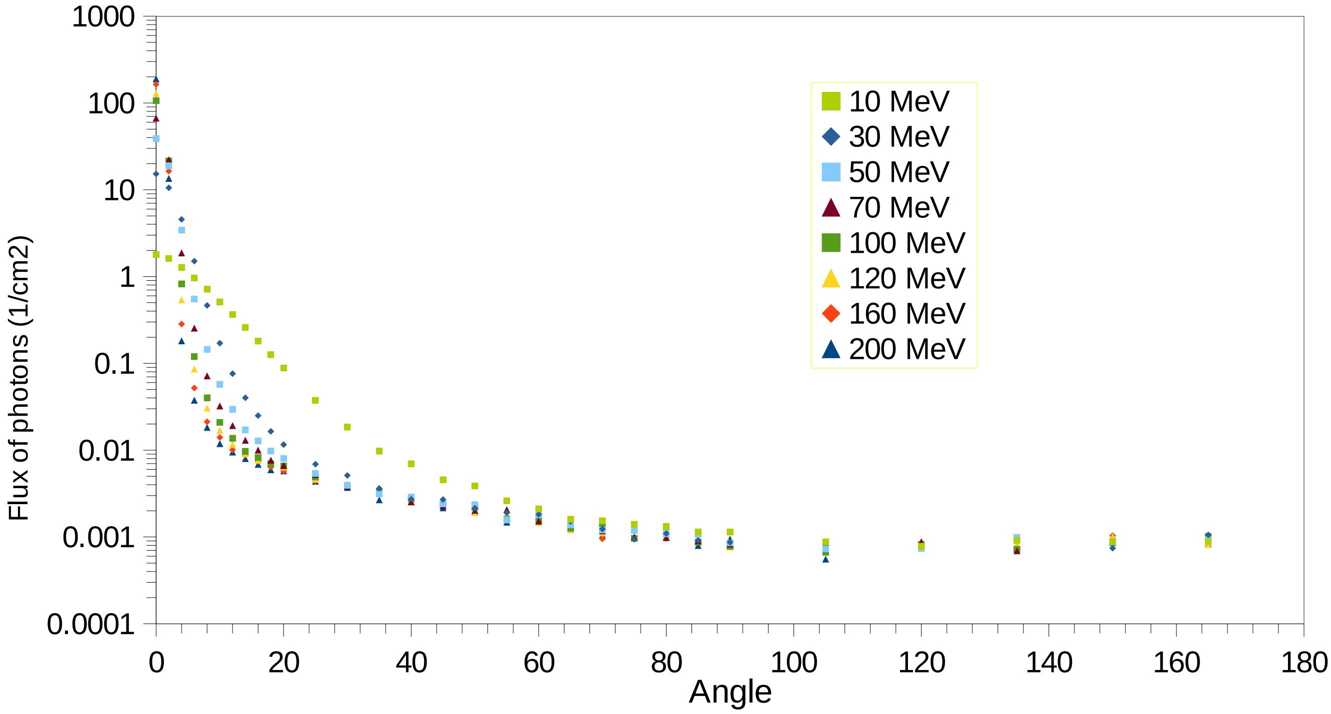


Fig. 12. Photons scattering at angles from a carbon target

$\alpha > 90^0$ returned electrons $\alpha < 90^0$ passed electrons and photon

Carbon (C) is a light element, its density is $\rho \approx 2.26$ g/cm^3, which is much lower than that of Bi, Ta, Pb, W, and so the results obtained for carbon are quite different from those for other materials. Carbon molecules are very sparsely packed, so even at low energies, when a beam of electrons hits the carbon material, most of the electrons pass through (Fig. 11). In contrast to the results obtained for heavy elements, at an energy of 10 MeV the number of electrons scattered at an angle of 0^0 is ≈19185 times greater than the number of electrons scattered at an angle of 165^0. This difference increases further when we increase the energy of the electron beam hitting carbon, becoming ≈3479588 times greater. Thus, at all energies we measured, the majority of the scattered electrons are scattered in the direction of the incoming electron beam at an angle of 0^0. If we compare carbon with other heavy elements, at an energy of 10 MeV the number of electrons scattered at the 0^0 angle in carbon is ≈ 2386 times more than in tungsten, ≈ 2821 times more than in tantalum, ≈ 1838 times more than in lead, and ≈ 1205 times more than in bismuth. At an energy of 200 MeV the number of electrons scattered at the 0^0 angle in carbon is ≈ 82.5 times more than in tungsten, ≈ 62.7 times more than in tantalum, ≈ 37 times more than in lead, and ≈ 30 times more than in bismuth.

Photons generated in the carbon target material, like electrons, are scattered more in the direction of the electron flow incident on the target (Fig. 12). At an energy of 10 MeV, the number of electrons scattered at an angle of 0^0 is ≈ 2010 times greater than the number of electrons scattered at an angle of 165^0, and at an energy of 200 MeV it is ≈ 225622 times greater. The number of photons scattered in the direction of the incident electron flow increases with increasing energy. The number of photons scattered at an angle of 0^0 when electrons with an energy of 200 MeV hit the target is ≈ 105 times greater than when electrons with an energy of 10 MeV hit the target. In this case, it is known that the scattered photons are scattered more at an angle of 0^0. At an energy of 10 MeV, the number of photons scattered at an angle of 0^0 is ≈ 1.1 times greater than the number of photons scattered at an angle of 4^0, and at an energy of 200 MeV, it is ≈ 1042 times greater. This means that at both lower and higher energies, photons are scattered more at small angles and less at large angles. When electrons with an energy of 10 MeV hit the target, the number of photons scattered at an angle of 0^0 is ≈ 2010 times greater than the number of photons scattered at an angle of 165^0. At an energy of 200 MeV, this value is ≈ 225622 times greater.

Table 1. The number of electrons and photons scattered from the target at angles 0^0 and 165^0 when a stream of electrons with energies of 10 and 200 MeV is incident perpendicularly on targets made of various elements.

Materials	Energies (MeV)	Electrons	Neutrons	Angle(x^0)
W	10	201	67736	0
		4819	11817	165
	200	718938	33104800	0
		249	12283	165
Ta	10	170	74176	0
		4413	11121	165
	200	943851	35486600	0
		241	9702	165
Pb	10	261	84819	0
		4614	11235	165
	200	1585010	38415000	0
		235	5405	165
Bi	10	398	89634	0
		4587	10451	165
	200	1976320	39533900	0
		263	4262	165
C	10	479628	170904	0
		25	85	165
	200	59153000	18049800	0
		17	80	165

As can be seen from the table, the results obtained from Wolfram (W), Tantalum (Ta), Lead (Pb), and Bismuth (Bi) are very similar to each other. In carbon, these results are completely opposite. Because, as we said above, carbon is a light substance, and the other measured elements are heavy substances, and for comparison, you can see their densities in Table-3. As can be seen from the table, both at energies of 10 MeV and 200 MeV, the amount of electrons and photons scattered at the 0^0 angle is the highest in the carbon material compared to the other materials (Table-1). This amount decreases inversely with the density. That is, in materials with the highest density, electrons and photons are scattered less at the 0^0 angle, and in materials with the lowest density, they are scattered more. Tungsten has the highest density among these elements, and when an electron beam hits a tungsten target, the number of electrons and photons scattered at an angle of 0^0 is less than the number of electrons and photons scattered at an angle of 0^0 when the electron beam hits the other elements. At an energy of 10 MeV, the number of electrons and photons scattered at an angle of 165^0 is greater in substances with higher density. At an energy of 10 MeV, the most electrons and photons scattered at an angle of 165^0 are scattered in tungsten (W), while the least electrons and photons are scattered in carbon (C). Another important point is that at energies of 10 MeV and 200 MeV, when an electron beam hits heavy target elements, more photons are scattered than electrons in these targets, while in carbon, which is a light element, electrons scatter more than photons. When a stream of electrons with an energy of 10 MeV hits tungsten, the number of photons scattered at an angle of 0^0 is ≈ 337 times greater than the number of electrons. At an energy of 200 MeV, the number of photons scattered at an angle of 0^0 is ≈ 46 times greater than the number of electrons. When a stream of electrons with an energy of 10 MeV hits carbon, the number of electrons scattered at an angle of 0^0 is ≈ 2.8 times greater than the number of photons, and at an energy of 200 MeV, it is ≈ 3.3 times greater.

Table 2. The total number of electrons, photons, and neutrons scattered in these elements when a stream of electrons with energies of 10 and 200 MeV hits tungsten (W), tantalum (Ta), lead (Pb), bismuth (Bi), and carbon (C) targets with a thickness of 5 mm and 10 mm, respectively.

E	Materials	Electrons		Photons		Neutrons	
		5 mm	10 mm	5 mm	10 mm	5 mm	10 mm
10 MeV	W	1.57E+09	1.6126e+09	2.93E+08	3.06269e+08	182	304
	Ta	1.62E+09	1.66E+09	2.89E+08	3.01409e+08	327	520
	Pb	1.79E+09	1.84E+09	2.89E+08	2.95964e+08	65	111
	Bi	1.85E+09	1.90E+09	2.88E+08	2.93406e+08	200	366
	C	6.39E+08	1.03E+09	2.05E+07	4.23149e+07	-	-
200 MeV	W	3.59E+09	8.56E+09	1.71E+09	4.00045e+09	891324	2.64216e+06
	Ta	3.02E+09	7.53E+09	1.40E+09	3.38001e+09	717363	2.25382e+06
	Pb	2.19E+09	5.73E+09	9.20E+08	2.23375e+09	388492	1.2986e+06
	Bi	1.90E+09	4.92E+09	7.76E+08	1.85807e+09	266329	900312
	C	4.11E+08	5.44E+08	3.20E+07	6.62849e+07	159	558

According to the table above, for the elements tungsten (W), tantalum (Ta), lead (Pb), bismuth (Bi), and carbon (C), the total number of electrons scattered from the mesh at energies of 10 MeV and 200 MeV at both 5 mm and 10 mm thicknesses is greater for elements with higher densities. (Table 2). The same relationship is observed for photons. You can see that the largest number of scattered electrons and photons corresponds to tungsten. The smallest number of scattered electrons and photons corresponds to carbon. The density of tungsten is the largest among these elements, and the density of carbon is the smallest. (Table 3).

Table 3. Densities of elements.

Materials	W	Ta	Pb	Bi	C
Density (kg/m^3)	19250	16650	11340	9780	2260

Figures 13-27 below show a graph of the total number of electrons, photons, and neutrons scattered by 10 mm thick tungsten, tantalum, lead, bismuth, and carbon targets when a particle stream consisting of 100 million electrons at energies of 10-800 MeV strikes these targets.

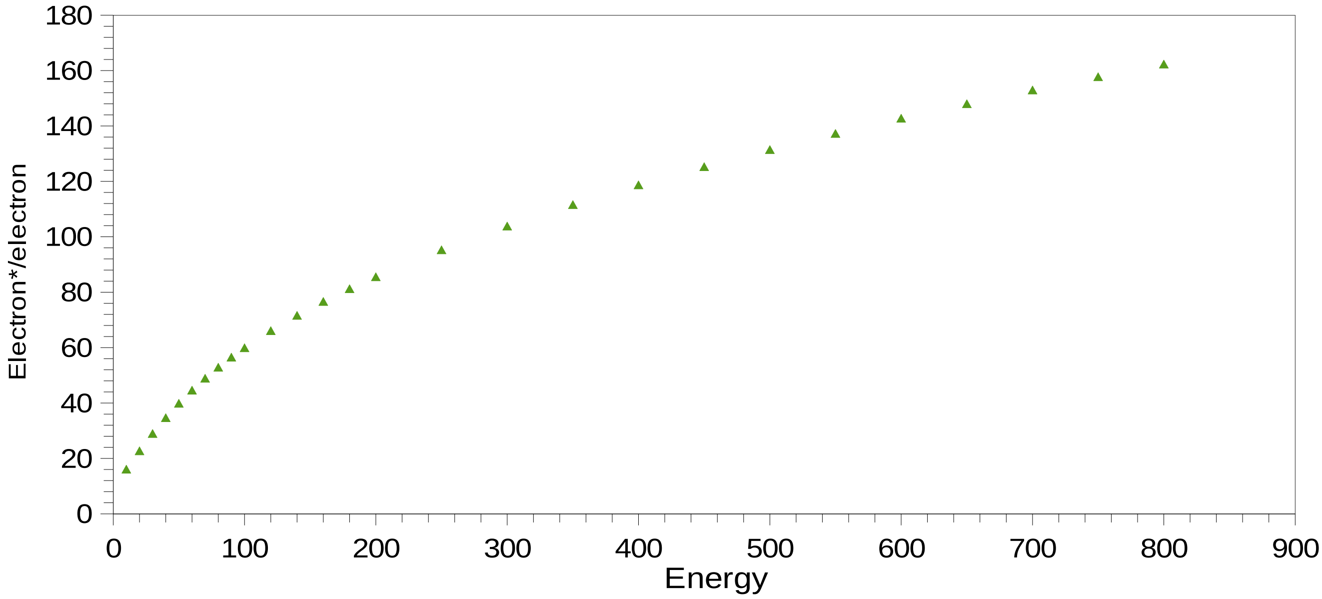


Fig. 13. The dependence of the number of electrons emitted from a tungsten on the energy of the electrons incident on the tungsten.

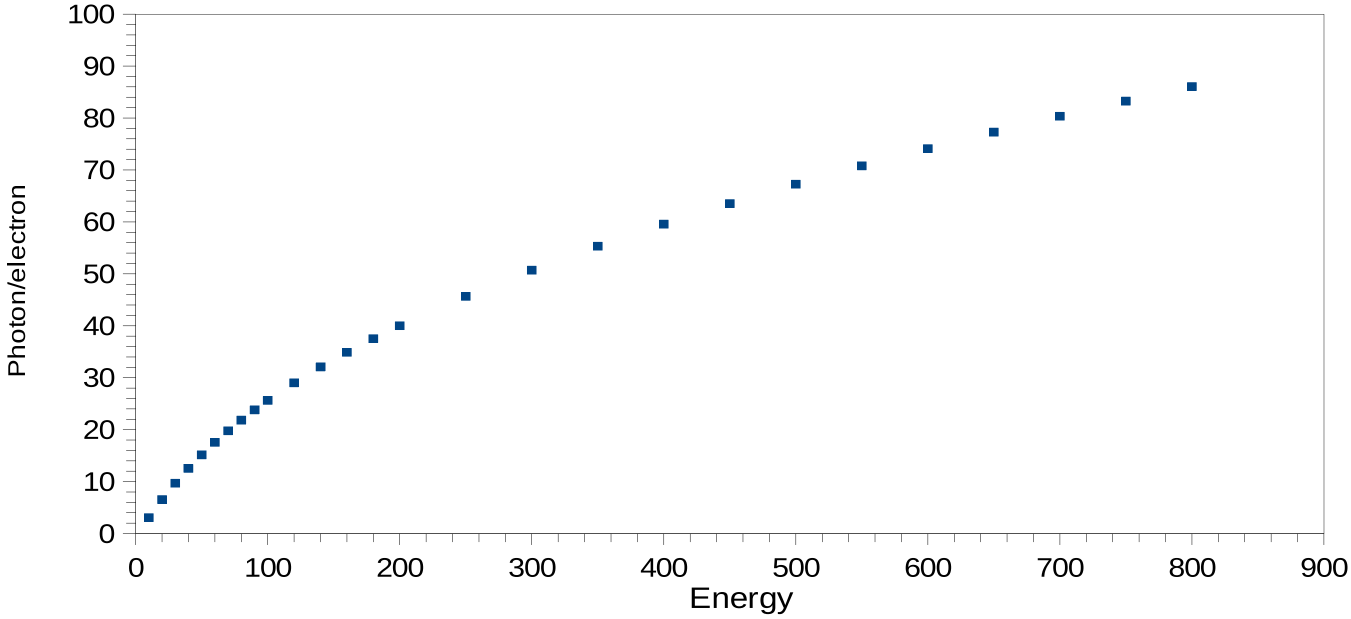


Fig. 14. The dependence of the number of photons emitted from a tungsten on the energy of the electrons incident on the tungsten.

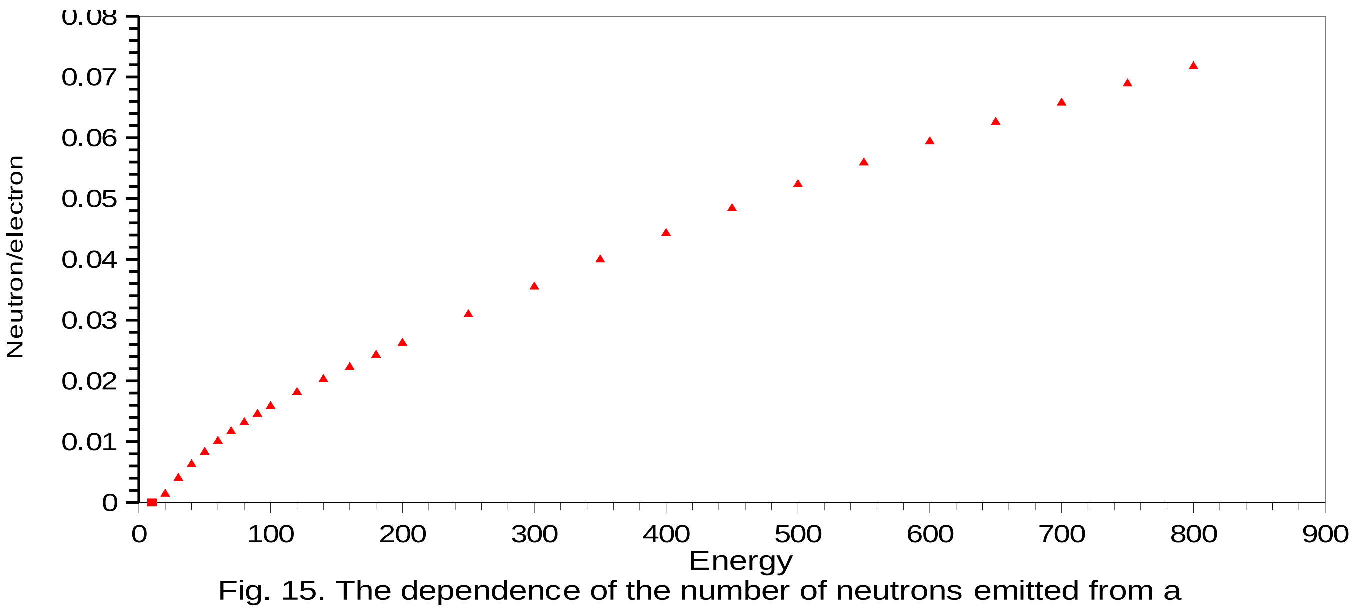


Fig. 15. The dependence of the number of neutrons emitted from a tungsten on the energy of the electrons incident on the tungsten.

From the graphs in **Fig. 13-15** above, it is clear that when any electron beam with energies of 10-800 MeV is incident on 10 mm tungsten, the number of electrons scattered from the tungsten target is always greater than the number of photons and neutrons scattered from the tungsten. This quantity can be compared at any energies in the range of 10-800 MeV. For example, when an electron beam with energy of 800 MeV is incident on tungsten, the total number of electrons scattered from tungsten is ≈ 1886 times the total number of photons and ≈ 2256 times the total number of neutrons. When an electron beam with energy of 10 MeV falls on tungsten, the total number of these electrons is ≈ 5 times greater than the total number of photons, and ≈ ≈ 5304605 times greater than the total number of neutrons. And another important point is that as the energy of the electron stream hitting the target increases, the total amount of electrons, photons, and neutrons emitted from the target also increases.

If we look at these comparisons in terms of target thicknesses, we get the following results (by **Fig 13-15** and **Table 4**). When a stream of electrons with an energy of 10 MeV falls on a 10 mm thick tungsten, the number of electrons scattered from it is ≈ 1.025 times greater than the number of electrons scattered from it when the same energy stream of electrons falls on a 5 mm thick tungsten. The number of photons in a stream of electrons with an energy of 10 MeV is ≈ 1.045 times greater in a 10 mm thick tungsten than in a 5 mm thick tungsten, and the number of neutrons in a 10 mm thick tungsten at the same energy is ≈ 1.67 times greater in a 10 mm thick tungsten than in a 5 mm thick tungsten. The total number of electrons emitted in a stream of electrons with an energy of 800 MeV is ≈ 3.4 times greater in 10 mm tungsten than in 5 mm tungsten, while the total number of photons and neutrons is both ≈ 3.3 times greater in 10 mm tungsten than in 5 mm tungsten.

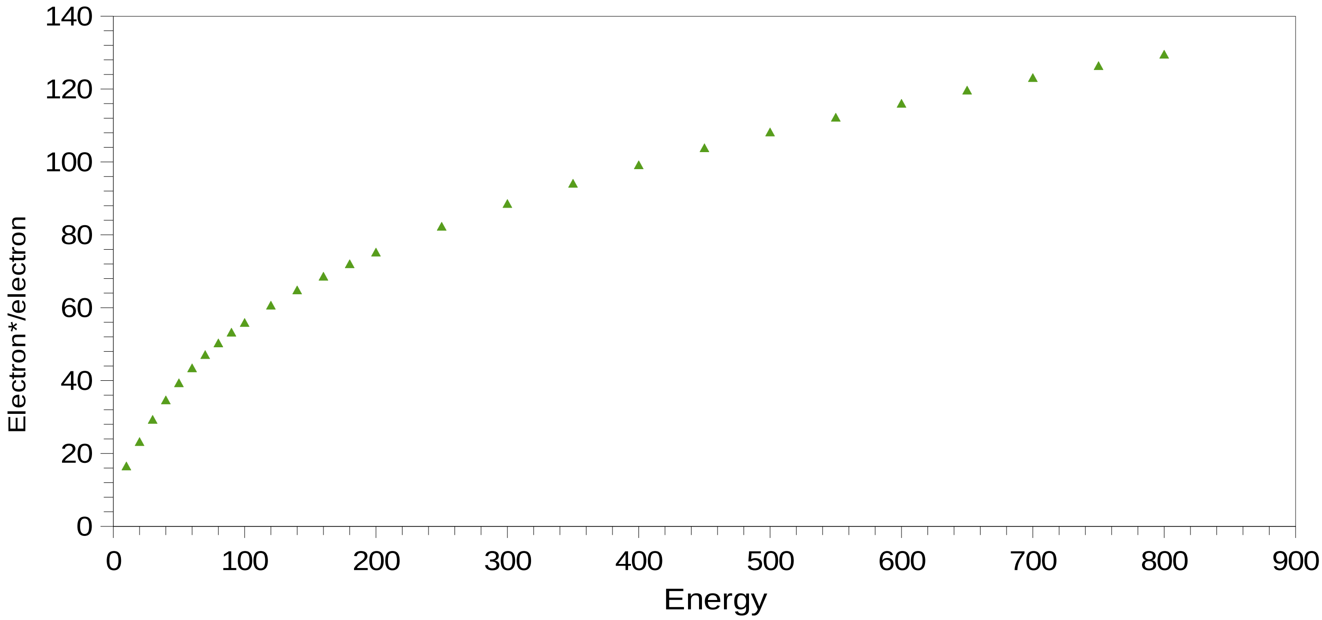


Fig. 16. The dependence of the number of electrons emitted from a tantalum on the energy of the electrons incident on the tantalum.

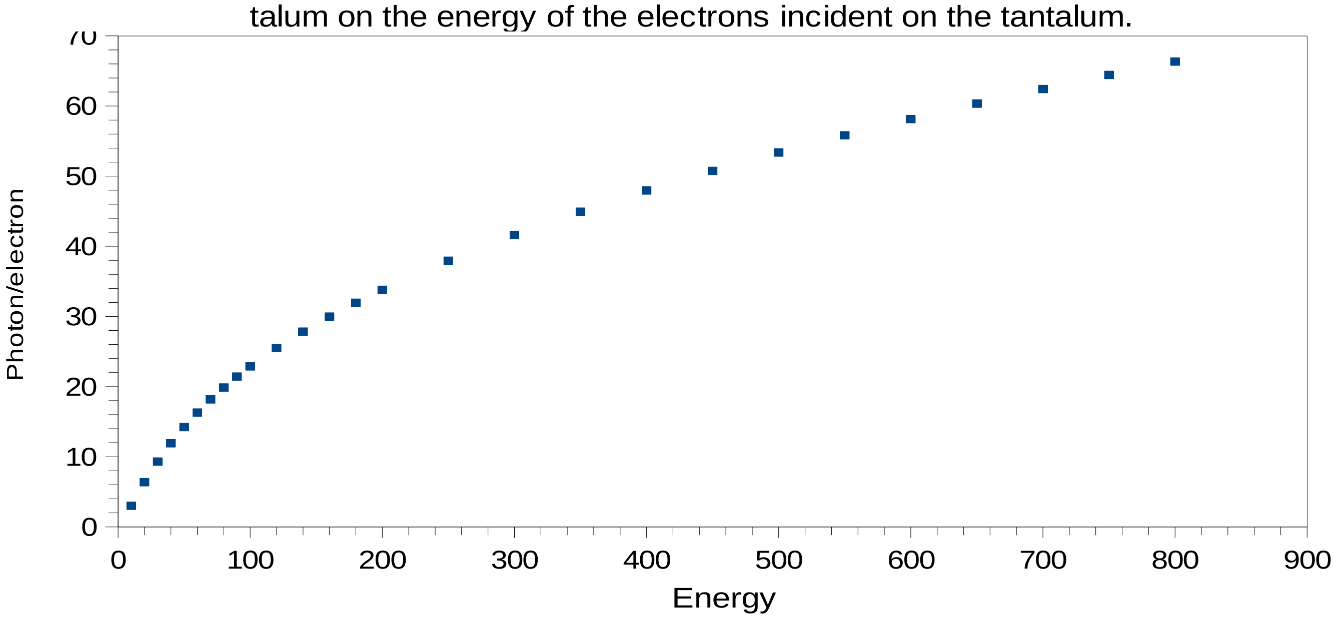


Fig. 17. The dependence of the number of photons emitted from a tantalum on the energy of the electrons incident on the tantalum.

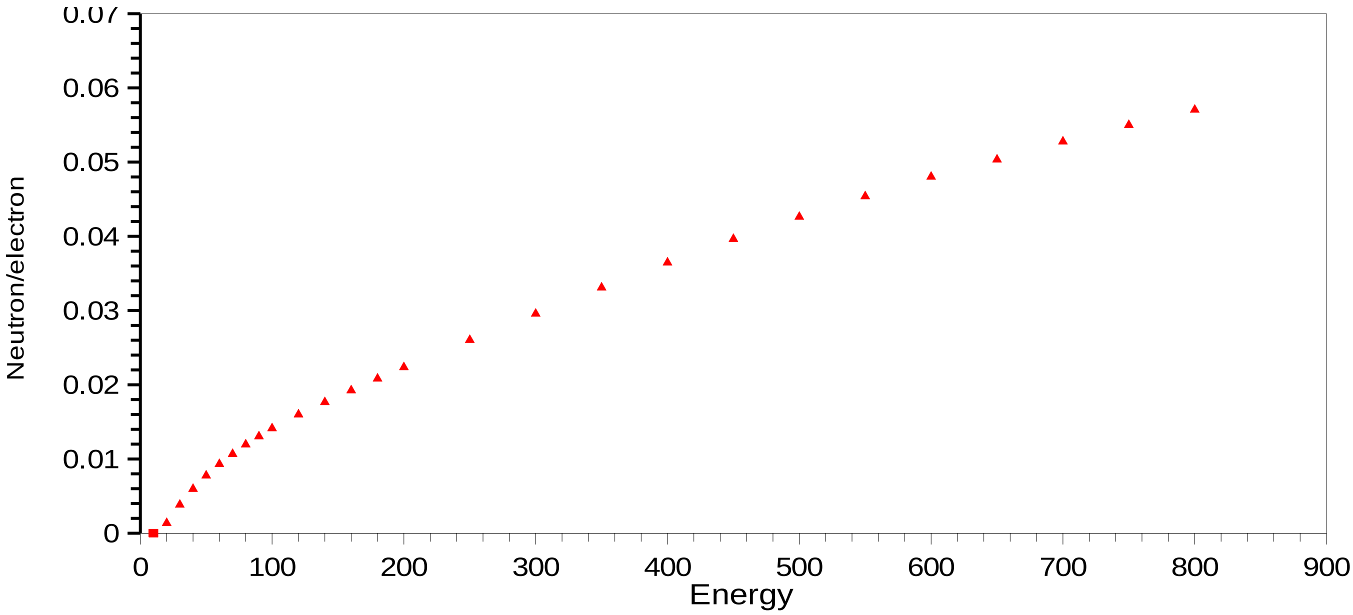


Fig. 18. The dependence of the number of neutrons emitted from a tantalum on the energy of the electrons incident on the tantalum.

As we said earlier, tantalum is a heavy element like tungsten, but their densities are close to each other. Therefore, the results in them are similar to each other. According to the graphs in **Fig. 16-18** above, when an electron beam at energies of 10-800 MeV falls on a 10 mm tantalum, the number of electrons scattered from the tantalum target is always greater than the number of photons and protons scattered from tungsten. If we look at this relationship at any energies in the range of 10-800 MeV. When an electron beam with an energy of 800 MeV falls on tantalum, the total number of electrons scattered from tantalum is ≈ 2 times the total number of photons, and ≈ 2263 times the total number of neutrons. When a stream of electrons with an energy of 10 MeV falls on tantalum of the same thickness, the total number of electrons scattered is ≈ 5.5 times greater than the total number of photons, and the total number of neutrons is ≈ 3189057 times greater than the total number of neutrons.

Now let's see these comparisons in terms of the thickness of the tantalum targets.(by **Fig 16-18** and **Table 5**). When a stream of electrons with an energy of 5 MeV falls on tantalum of 10 mm thickness, the number of electrons scattered from it is the same as in tungsten ≈ 1.025 times greater than the number of electrons scattered from it when the same energy stream falls on tantalum of 10 mm thickness. And the number of photons in a stream of electrons with an energy of 10 MeV is ≈ 1.043 times greater in tantalum of 10 mm thickness than in tantalum of 5 mm thickness. The number of neutrons in a 10 mm thick tantalum is ≈ 1.6 times greater than in a 5 mm thick tantalum at the same energy. The total number of electrons emitted in a stream of electrons with an energy of 800 MeV is ≈ 3.4 times greater in a 10 mm tantalum than in a 5 mm tantalum, and this ratio is the same as in tungsten. The total numbers of photons and neutrons in a 10 mm tantalum are ≈ 3.3 times and ≈ 3.4 times greater, respectively, than in a 5 mm tantalum.

In conclusion, the ratios obtained from the comparisons in tantalum are almost the same as in tungsten.

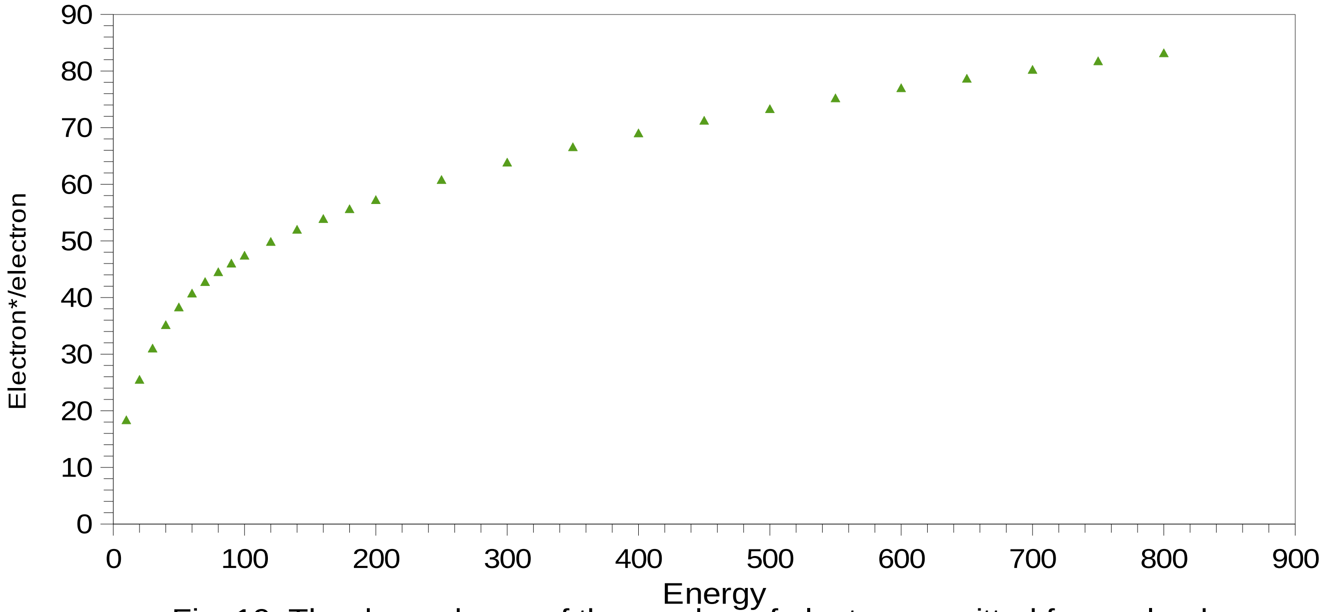


Fig. 19. The dependence of the number of electrons emitted from a lead on the energy of the electrons incident on the lead.

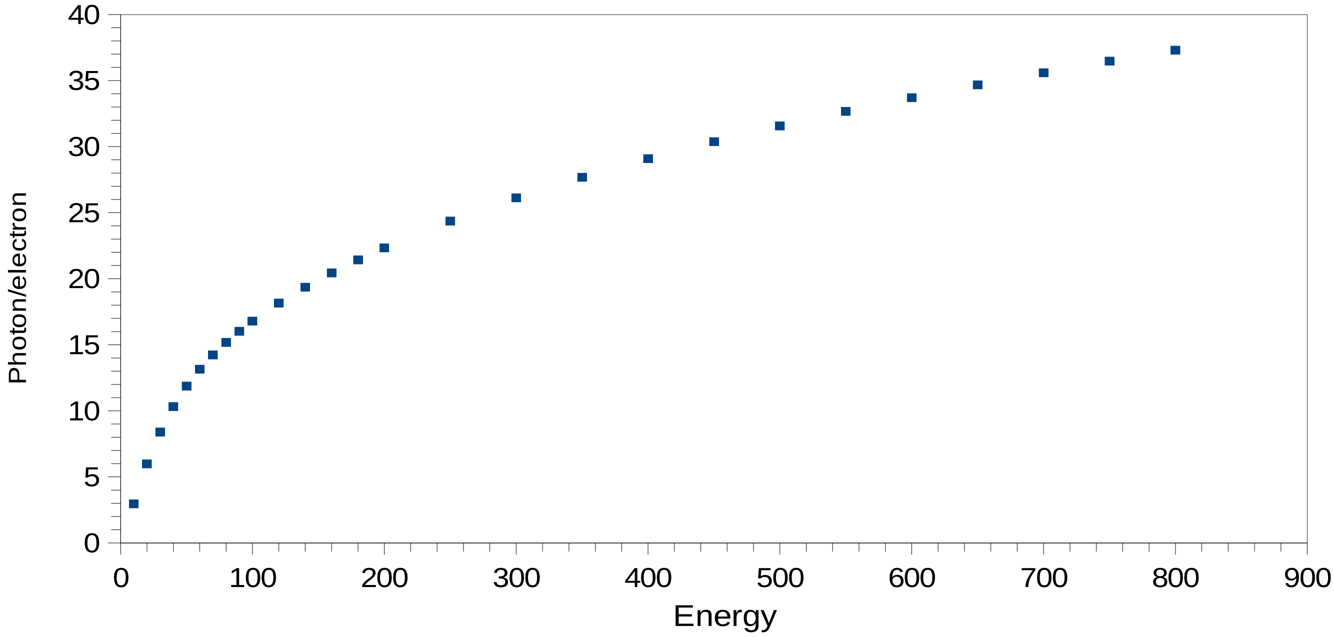


Fig. 20. The dependence of the number of photons emitted from a lead on the energy of the electrons incident on the lead.

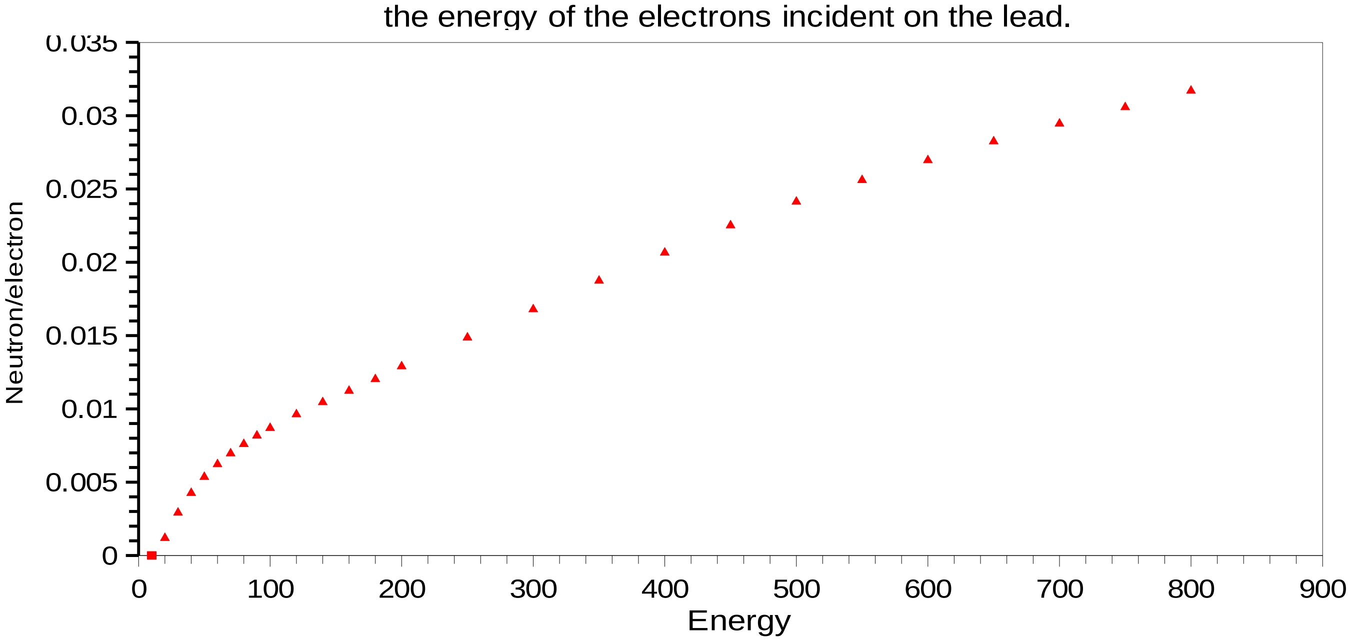


Fig. 21. The dependence of the number of neutrons emitted from a lead on the energy of the electrons incident on the lead.

Lead is also a heavy element like tungsten and tantalum. Therefore, the results in them are similar to each other. According to the graphs in **Fig. 19-21** above, when an electron beam at energies of 10-800 MeV falls on a 10 mm thick lead, the number of electrons scattered from the lead target is always greater than the number of photons and protons scattered from the lead target. This relationship can be seen at any energies in the range of 10-800 MeV. When an electron beam with an energy of 10 MeV falls on a 10 mm thick lead, the total number of electrons scattered is ≈ 6.2 times the total number of photons, and ≈ 16572792.8 times the total number of neutrons. When an electron beam with an energy of 800 MeV hits lead, the total number of electrons scattered by lead is ≈ 2.2 times the total number of photons, and ≈ 2617 times the total number of neutrons.

When we compare these comparisons with 5 mm and 10 mm lead targets, we get the following results.(by **Fig 19-21** and **Table 6**). When an electron beam with an energy of 10 MeV hits 10 mm thick lead, the number of electrons scattered from it is ≈ 1.028 times greater than the number of electrons scattered from it when the same electron beam with the same energy hits 5 mm thick lead. The number of photons in a 10 MeV electron beam is ≈ 1.025 times greater than in a 5 mm thick lead. It was found that the number of neutrons at this energy in 10 mm thick lead is ≈ 1.7 times greater than in 5 mm thick lead. The total number of electrons emitted in a stream of electrons with an energy of 800 MeV is ≈ 3.26 times greater in 10 mm tantalum than in 5 mm tantalum. The total number of photons in 10 mm lead is ≈ 3.05 times greater than in 5 mm lead. The number of neutrons when an electron stream with an energy of 800 MeV hits 10 mm thick lead is ≈ 3.47 times greater than in 5 mm thick lead.

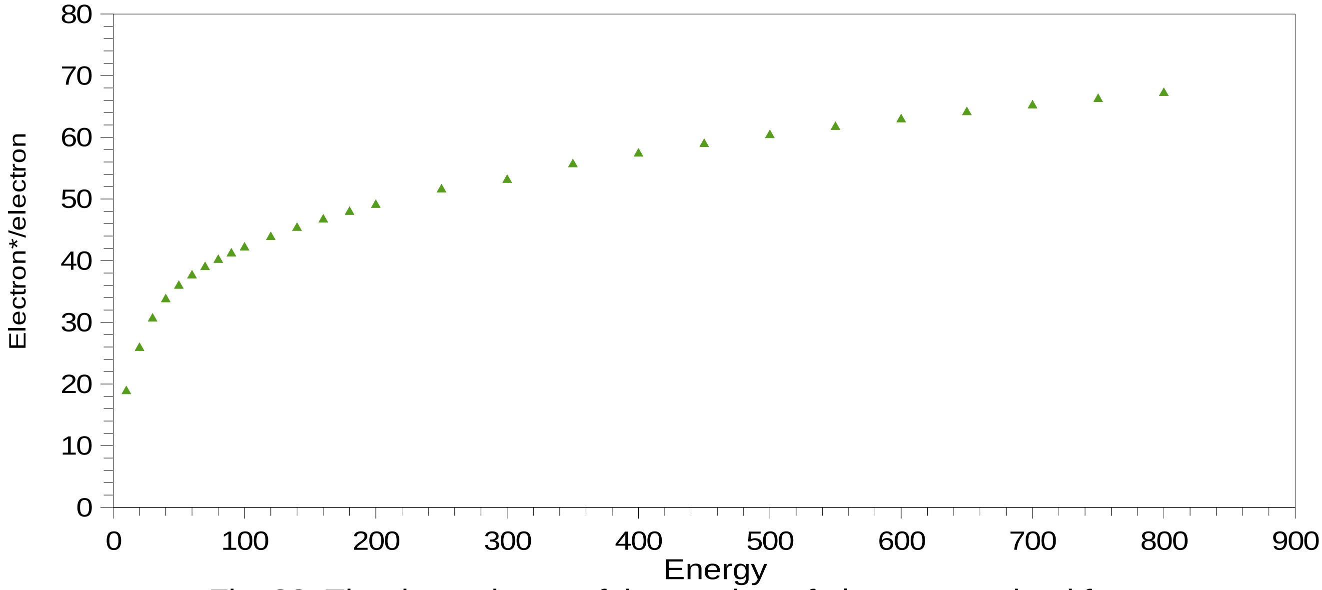


Fig. 22. The dependence of the number of electrons emitted from a bismuth on the energy of the electrons incident on the bismuth.

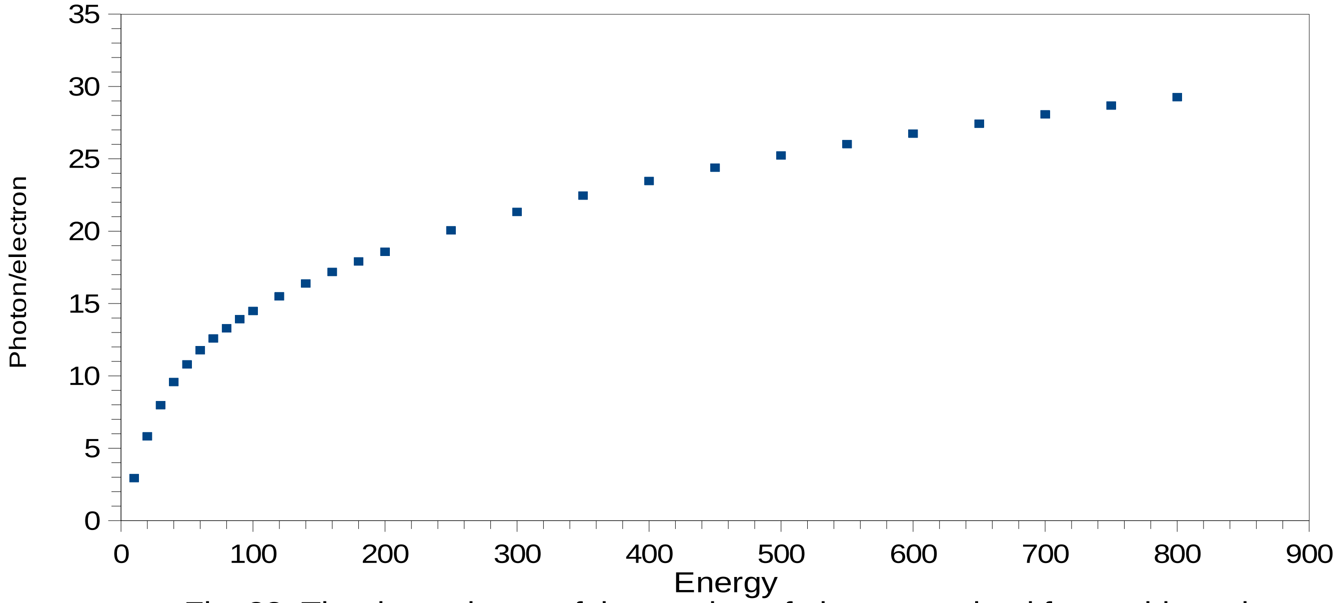


Fig. 23. The dependence of the number of photons emitted from a bismuth on the energy of the electrons incident on the bismuth.

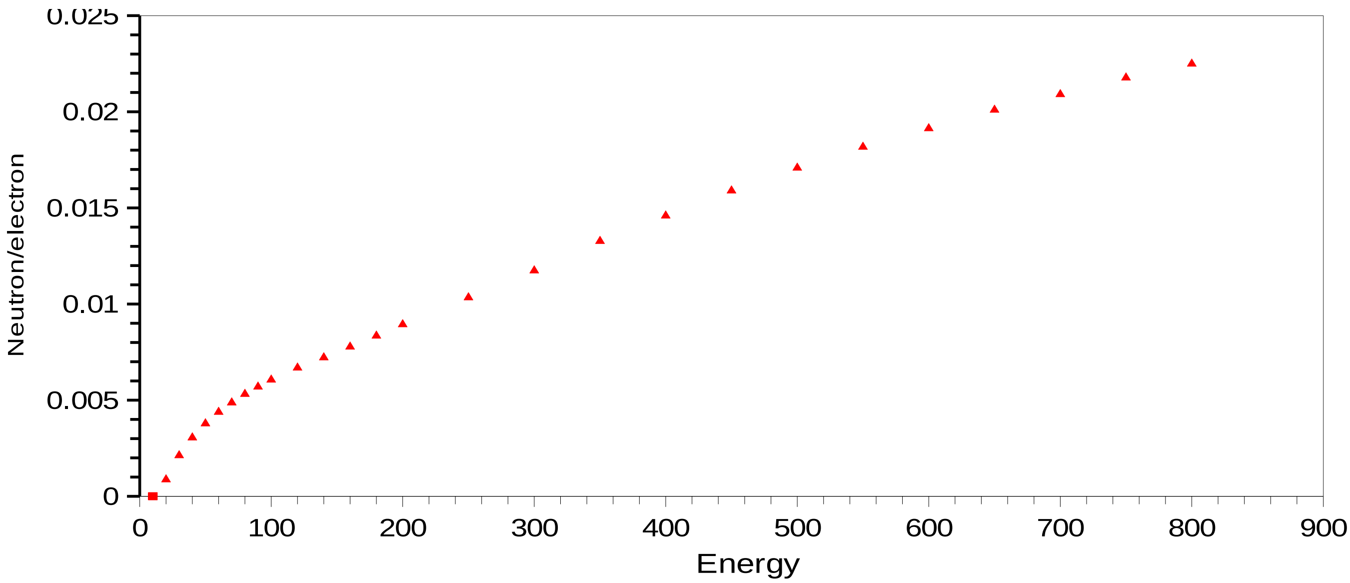


Fig. 24. The dependence of the number of protons emitted from a bismuth on the energy of the electrons incident on the bismuth.

Bismuth is also a heavy element like tungsten and tantalum. Therefore, the results in them are similar to each other. According to the graphs in **Fig. 22-24** above, when a stream of electrons at energies of 10-800 MeV falls on a 10 mm thick bismuth, the number of electrons scattered from the bismuth target is always greater than the number of photons and protons scattered from the bismuth target. This relationship can be seen at any energies in the range of 10-800 MeV. When a stream of electrons with an energy of 10 MeV falls on a 10 mm thick bismuth, the total number of electrons scattered is ≈ 6.5 times the total number of photons, and ≈ 5199945 times the total number of neutrons. When a stream of electrons with an energy of 800 MeV falls on bismuth, the total number of electrons scattered from bismuth is ≈ 2.3 times more than the total number of photons, and ≈ 2987.6 times more than the total number of neutrons.

When we compare these comparisons with 5 mm and 10 mm bismuth targets, we get the following results.(by **Fig 22-24** and **Table 7**). When a stream of electrons with an energy of 10 MeV falls on 10 mm of bismuth, the number of electrons scattered from it is ≈ 1.028 times more than the number of electrons scattered from it when the same energy stream falls on 5 mm of bismuth, and this result is the same as for lead. And the number of photons in a stream of electrons with an energy of 10 MeV is ≈ 1.02 times more in 10 mm of bismuth than in 5 mm of bismuth. It turned out that the number of neutrons at this energy in 10 mm thick bismuth is ≈ 1.83 times more than in 5 mm thick bismuth. The total number of electrons scattered in a stream of electrons with an energy of 800 MeV is ≈ 3.13 times more in 10 mm tantalum than in 5 mm tantalum. The total number of photons in 10 mm bismuth is ≈ 2.9 times more than in 5 mm bismuth. It turned out that the number of neutrons when a stream of electrons with an energy of 800 MeV falls on 10 mm thick bismuth is ≈ 3.44 times more than in 5 mm thick bismuth.

To summarize, the ratios obtained from these results are the same as for lead.

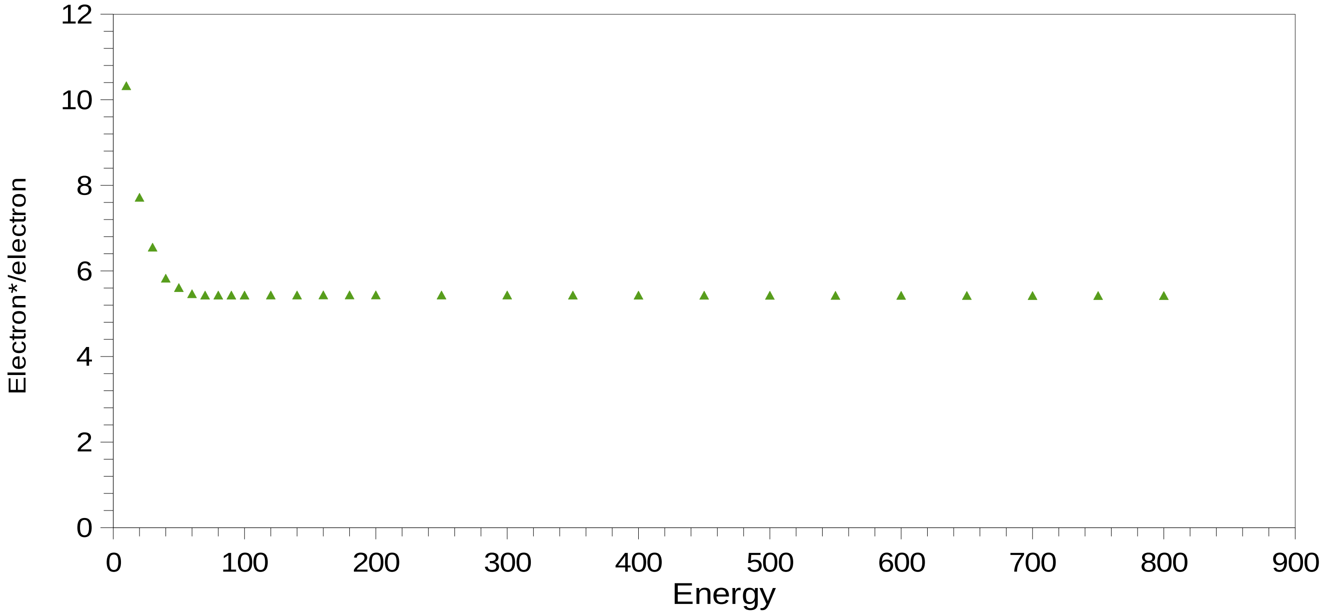


Fig. 25. The dependence of the number of electrons emitted from a carbon on the energy of the electrons incident on the carbon.

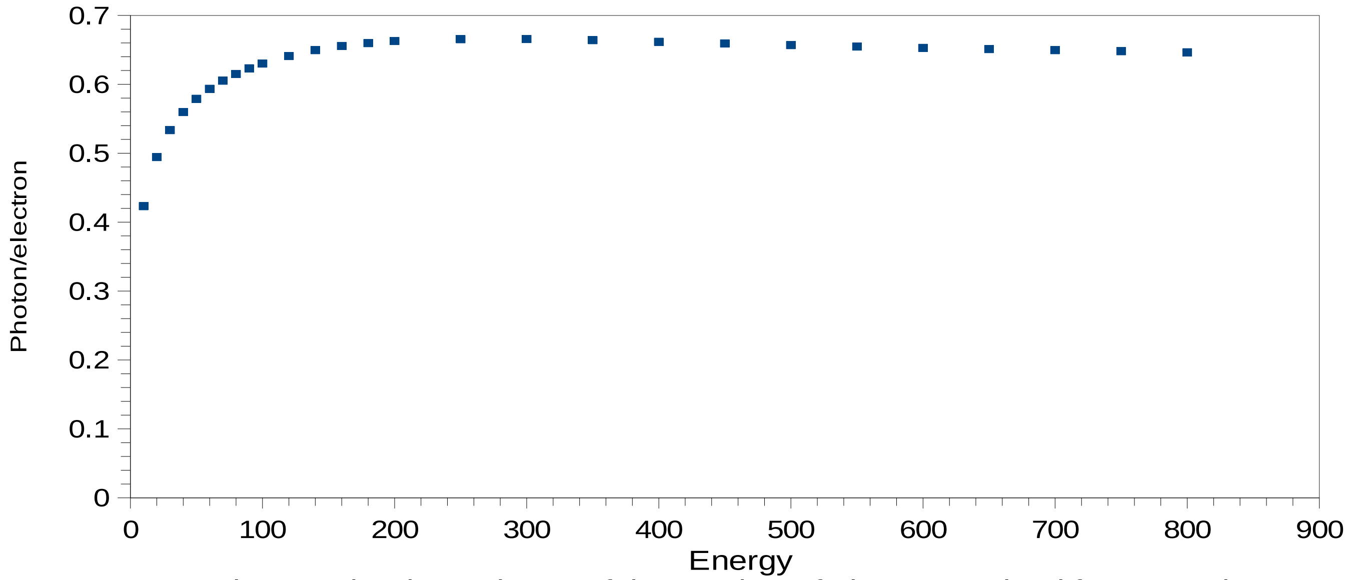


Fig. 26. The dependence of the number of photons emitted from a carbon on the energy of the electrons incident on the carbon.

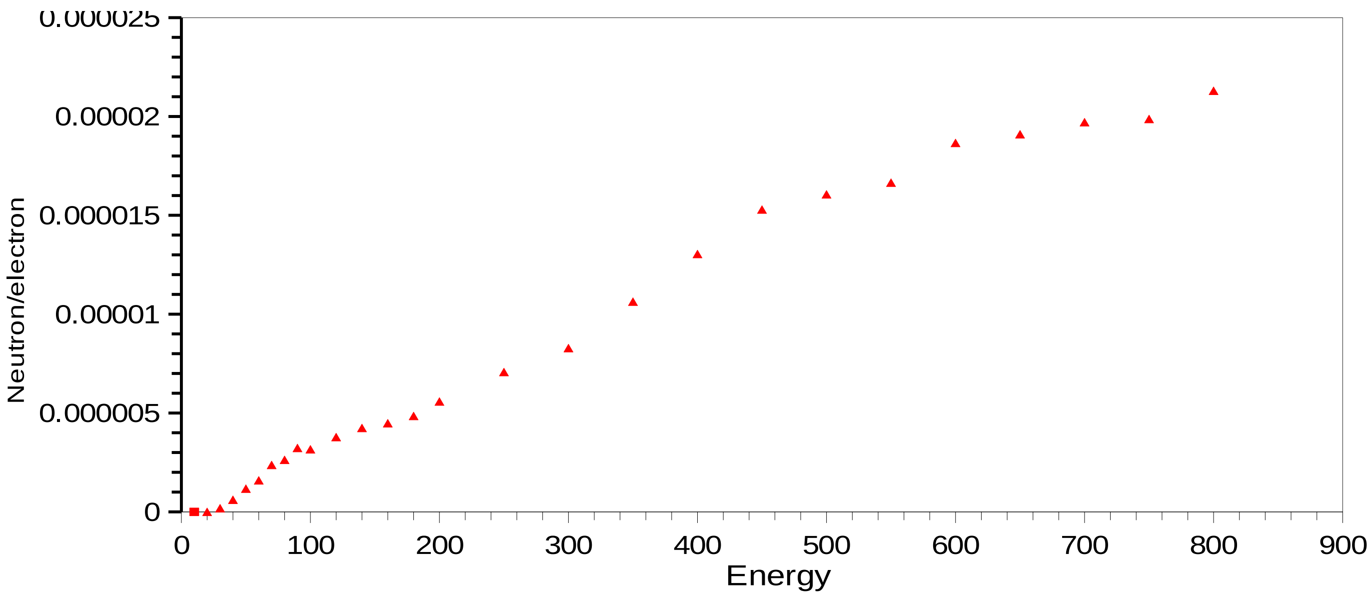


Fig. 27. The dependence of the number of neutrons emitted from a carbon on the energy of the electrons incident on the carbon.

Unlike the other materials measured, carbon is a light element, so the results are quite different from those for tungsten, tantalum, lead, and bismuth. From the graphs in **Figures 25-27**, it can be seen that when any electron beam with energies of 10-800 MeV is incident on 10 mm of carbon, the number of electrons scattered from the carbon target is always greater than the number of photons and neutrons scattered by the carbon target. This amount can be compared at any energy in the range 10-800 MeV. For example, when an electron beam with energy of 800 MeV is incident on carbon, the total number of electrons scattered from the carbon is ≈ 8.4 times the total number of photons and ≈ 254624 times the total number of neutrons scattered from the target. When a stream of electrons with an energy of 10 MeV hits carbon, the total number of electrons scattered from the target is ≈ 24 times greater than the total number of photons. Another important point is that as the energy of the stream of electrons hitting the target increases, the total number of electrons, photons, and neutrons scattered from the target also increases.

If we consider these comparisons for carbon targets with thicknesses of 5 mm and 10 mm, we obtain the following results (**according to Fig. 25-27 and Table 8**). When a stream of electrons with an energy of 10 MeV hits carbon with a thickness of 10 mm, the number of electrons scattered from it is ≈ 1.6 times greater than when the same energy stream of electrons hits carbon with a thickness of 5 mm. It was found that when a stream of electrons with an energy of 10 MeV hits a carbon target, the number of photons emitted from the target is ≈ 2 times greater in a 10 mm thick carbon target than in a 5 mm thick carbon target. When a stream of electrons with an energy of 800 MeV hits a 10 mm carbon target, the total number of electrons emitted from the target is ≈ 2 times greater than in a 5 mm carbon target, and at the same energy, the total number of photons and neutrons is ≈ 4.37 times greater in a 10 mm carbon target than in a 5 mm carbon target.

Table 4. The total number of electrons, photons, and neutrons scattered from a target when a beam of electrons with energies of 10-800 MeV strikes a 5 mm thick tungsten.

Energy (MeV)	Tungsten (W)		
	electrons	photons	neutrons
10	1.57E+09	2.93E+08	182
20	2.11E+09	5.96E+08	98717
30	2.51E+09	8.24E+08	239728
40	2.73E+09	9.74E+08	337116
50	2.80E+09	1.08E+09	408741
60	2.90E+09	1.15E+09	462445
70	2.99E+09	1.22E+09	508904
80	3.02E+09	1.27E+09	551383
90	3.07E+09	1.32E+09	586244
100	3.16E+09	1.37E+09	619905
120	3.26E+09	1.45E+09	677843
140	3.35E+09	1.53E+09	728643
160	3.44E+09	1.59E+09	780671
180	3.52E+09	1.65E+09	834984
200	3.59E+09	1.71E+09	891324
250	3.76E+09	1.83E+09	1.02E+06
300	3.90E+09	1.94E+09	1.15E+06
350	4.03E+09	2.03E+09	1.30E+06
400	4.14E+09	2.12E+09	1.43E+06
450	4.24E+09	2.19E+09	1.56E+06
500	4.34E+09	2.26E+09	1.67E+06
550	4.42E+09	2.33E+09	1.77E+06
600	4.51E+09	2.39E+09	1.85E+06
650	4.58E+09	2.44E+09	1.94E+06
700	4.65E+09	2.50E+09	2.02E+06
750	4.72E+09	2.55E+09	2.09E+06
800	4.78E+09	2.59E+09	2.17E+06

Table 5. The total number of electrons, photons, and neutrons scattered from a target when a beam of electrons with energies of 10-800 MeV strikes a 5 mm thick tantalum.

Energy (MeV)	Tantalum(Ta)		
	electrons	photons	neutrons
10	1.62E+09	2.89E+08	327
20	2.15E+09	5.80E+08	91972
30	2.46E+09	7.73E+08	215514
40	2.56E+09	8.80E+08	295940
50	2.59E+09	9.48E+08	350158
60	2.62E+09	1.00E+09	392107
70	2.64E+09	1.04E+09	426142
80	2.67E+09	1.08E+09	457855
90	2.70E+09	1.12E+09	485521
100	2.73E+09	1.15E+09	511857
120	2.80E+09	1.21E+09	555425
140	2.86E+09	1.27E+09	593048
160	2.92E+09	1.31E+09	633088
180	2.97E+09	1.36E+09	674707
200	3.02E+09	1.40E+09	717363
250	3.13E+09	1.49E+09	820060
300	3.23E+09	1.56E+09	921453
350	3.31E+09	1.63E+09	1.03E+06
400	3.39E+09	1.69E+09	1.13E+06
450	3.46E+09	1.74E+09	1.22E+06
500	3.52E+09	1.79E+09	1.31E+06
550	3.58E+09	1.83E+09	1.38E+06
600	3.63E+09	1.87E+09	1.44E+06
650	3.68E+09	1.91E+09	1.50E+06
700	3.73E+09	1.95E+09	1.57E+06
750	3.78E+09	1.98E+09	1.62E+06
800	3.82E+09	2.01E+09	1.67E+06

Table 6. The total number of electrons, photons, and neutrons scattered from a target when a beam of electrons with energies of 10-800 MeV strikes a 5 mm thick lead.

Energy (MeV)	Lead (Pb)		
	electrons	photons	neutrons
10	1.79E+09	2.89E+08	65
20	2.25E+09	5.34E+08	70554
30	2.22E+09	6.25E+08	140314
40	2.13E+09	6.62E+08	177101
50	2.07E+09	6.89E+08	201646
60	2.21E+05	7.12E+08	220532
70	2.04E+09	7.34E+08	238601
80	2.05E+09	7.54E+08	253281
90	2.06E+09	7.73E+08	264880
100	2.07E+09	7.91E+08	277620
120	2.10E+09	8.23E+08	300695
140	2.12E+09	8.51E+08	319389
160	2.15E+09	8.76E+08	339877
180	2.17E+09	8.99E+08	361939
200	2.19E+09	9.20E+08	388492
250	2.24E+09	9.66E+08	444038
300	2.29E+09	1.00E+09	502912
350	2.33E+09	1.04E+09	563340
400	2.36E+09	1.07E+09	624174
450	2.39E+09	1.09E+09	676766
500	2.42E+09	1.12E+09	723662
550	2.44E+09	1.14E+09	764627
600	2.47E+09	1.16E+09	804688
650	2.49E+09	1.17E+09	833229
700	2.51E+09	1.19E+09	862946
750	2.53E+09	1.21E+09	888328
800	2.55E+09	1.22E+09	915469

Table 7. The total number of electrons, photons, and neutrons scattered from a target when a beam of electrons with energies of 10-800 MeV strikes a 5 mm thick bismuth.

Energy (MeV)	Bismuth(Bi)		
	electrons	photons	neutrons
10	1.85E+09	2.88E+08	200
20	2.18E+09	4.99E+08	49427
30	2.02E+09	5.53E+08	94645
40	1.90E+09	5.76E+08	117992
50	1.83E+09	5.95E+08	134457
60	1.81E+09	6.13E+08	147436
70	1.80E+09	6.30E+08	158686
80	1.80E+09	6.46E+08	169875
90	1.81E+09	6.61E+08	179307
100	1.82E+09	6.75E+08	188079
120	1.83E+09	7.00E+08	202625
140	1.85E+09	7.22E+08	215853
160	1.87E+09	7.42E+08	231468
180	1.89E+09	7.60E+08	246331
200	1.90E+09	7.76E+08	266329
250	1.94E+09	8.11E+00	309485
300	1.97E+09	8.41E+08	351829
350	1.99E+09	8.66E+08	394559
400	2.02E+09	8.88E+08	436714
450	2.04E+09	9.07E+08	47745
500	2.06E+09	9.25E+08	512842
550	2.08E+09	9.41E+08	540670
600	2.09E+09	9.56E+08	568661
650	2.11E+09	9.70E+08	594655
700	2.12E+09	9.82E+08	616304
750	2.14E+09	9.94E+08	636046
800	2.15E+09	1.00E+09	655214

Table 8. The total number of electrons, photons, and neutrons scattered from a target when a beam of electrons with energies of 10-800 MeV strikes a 5 mm thick carbon.

Energy (MeV)	Carbon (C)		
	electrons	photons	neutrons
10	6.39E+08	2.05E+07	-
20	4.42E+08	2.39E+07	-
30	4.13E+08	2.58E+07	8
40	4.10E+08	2.70E+07	21
50	4.10E+08	2.79E+07	45
60	4.10E+08	2.86E+07	49
70	4.10E+08	2.92E+07	67
80	4.10E+08	2.97E+07	65
90	4.10E+08	3.01E+07	72
100	4.10E+08	3.04E+07	86
120	4.11E+08	3.09E+07	94
140	4.11E+08	3.13E+07	115
160	4.11E+08	3.16E+07	111
180	4.11E+08	3.18E+07	118
200	4.11E+08	3.20E+07	159
250	4.11E+08	3.21E+07	170
300	4.11E+08	3.21E+07	245
350	4.10E+08	3.20E+07	274
400	4.10E+08	3.19E+07	352
450	4.10E+08	3.18E+07	370
500	4.10E+08	3.17E+07	378
550	4.10E+08	3.16E+07	443
600	4.10E+08	3.15E+07	484
650	4.10E+08	3.14E+07	457
700	4.10E+08	3.13E+07	471
750	4.10E+08	3.13E+07	444
800	4.10E+08	3.12E+07	487

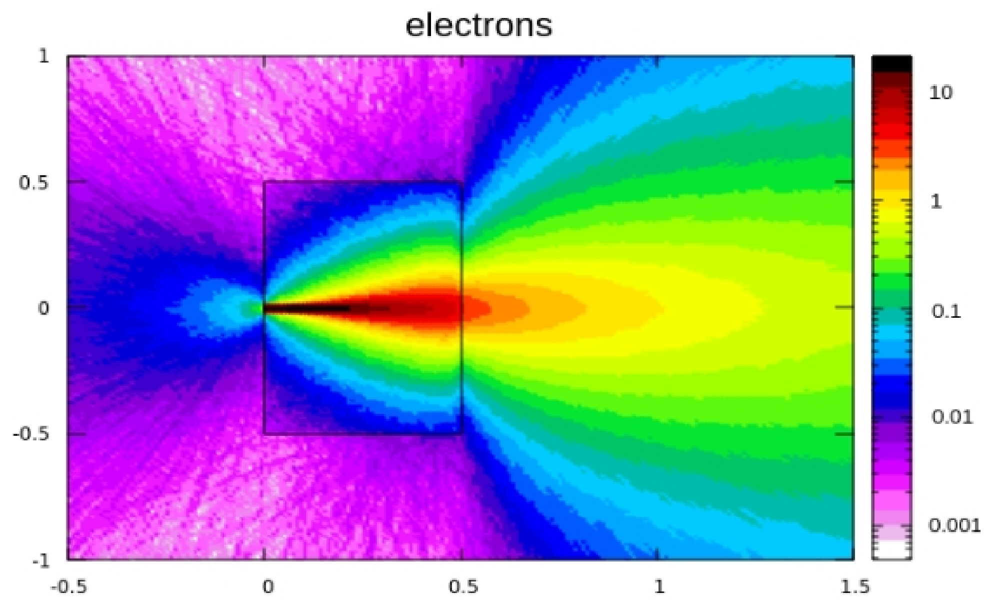


Fig. 28.

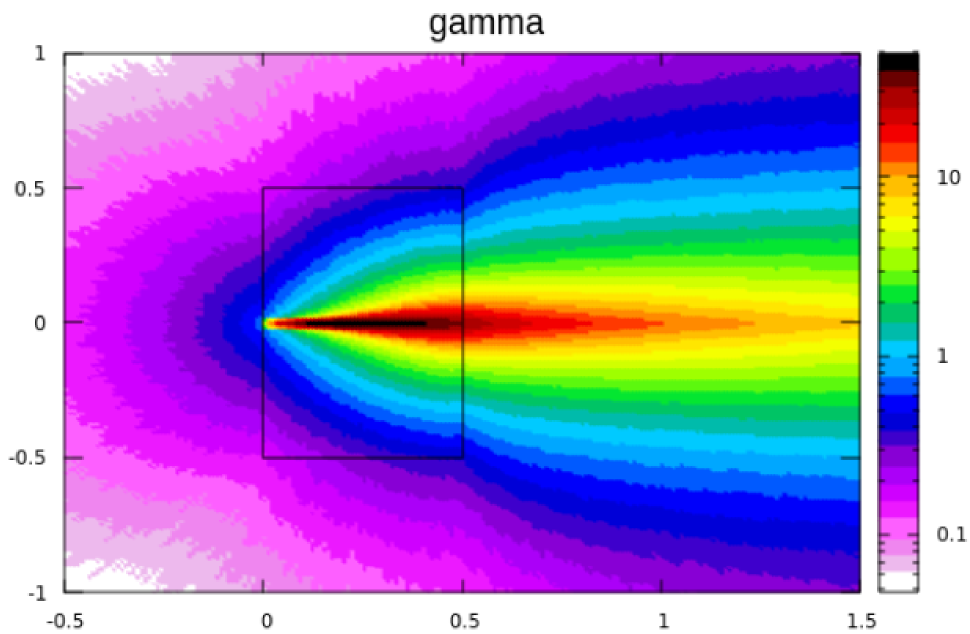


Fig. 29.

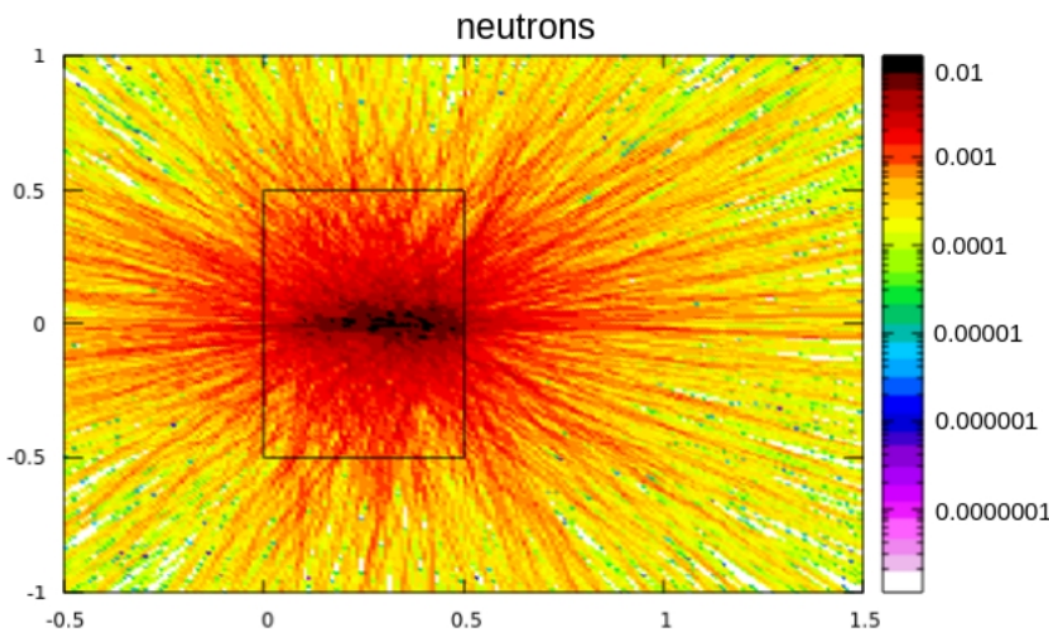


Fig. 30.

In these **Fig. 28-30**, the scattering of electrons, photons, and neutrons from a 100 MeV electron beam incident on tungsten is modeled in the Fluka program.[3] The x and y axes of the target are shown in cm. On the right, you can see the amount of scattered electrons, photons, and neutrons in color ($1/cm^2$). And these graphs confirm the results we obtained in Geant4. (**Fig. 13-15**).

References

1. https://en.wikipedia.org/wiki/Bremsstrahlung

2. J. Allison, et al., Recent developments in Geant4, Nucl. Instrum. Methods Phys. Res. A 835 (2016) 186–225, http://dx.doi.org/10.1016/j.nima.2016.06.125

3. http://www.fluka.org/fluka.php

Acknowledgement

I take this opportunity to express my profound gratitude and kind regards to my supervisor Khushvaktov J.H. for his exemplary guidance, monitoring and constant encouragement throughout the course of this project. I was able to work with modern equipment and programs in this project. I learned new knowledge from the mentors at JINR that will be useful for my future studies. Also I would like to thank a committee of Summer Student Program for the opportunity to visit Joint Institute for Nuclear Research and for financial support.