ISSN: 2582-4686 SJIF 2021-3.261,SJIF 2022-2.889, 2024-6.875 ResearchBib IF: 10.25 / 2025

THE MULTIDISCIPLINARY JOURNAL OF SCIENCE AND TECHNOLOGY

VOLUME-6, ISSUE-5

SATURATION THICKNESSES FOR SCATTERING BREMSSTRAHLUNG OF ELECTRONS WITH Ee = 13 AND 22 MeV FROM FLAT LEAD TARGETS AND THEIR STATISTICAL PROCESSING OF THE DATA DEPENDENCE

U.T. Asatov, N.Kh. Ulugmuradov, Sh.N. Buribaev
Tashkent Institute of Chemical Technology

Abstract. In the present work, the dependence of the saturation thickness of the scattered gamma radiation on the detection angles and the orientation of flat targets relative to the direction of the probing beam was observed for the first time.

Key words: spectra, scattering, gamma radiation, orientation, distribution, probing beam, least squares.

Introduction

In a large number of studies using radionuclide sources (in the early stages of research) and accelerated electron bremsstrahlung (BEB) with energies in the range of 10-900 MeV, the main patterns of formation of gamma-ray backscatter fields (GBF or gamma-ray albedo) from various targets with effective atomic numbers $Z_{eff.}$=5÷82 were established, the possibility of determining in which studies $Z_{eff.}$ the sizes, orientation, distribution of substance density by volume and other characteristics of probed targets, necessary for solving a number of important fundamental and applied problems (see, for example, [1-7] and references therein), was shown. Scattering of gamma radiation into the forward hemisphere in the direction of the probing beam (VRG), due to the high background level in this direction, has been practically studied only recently in our laboratory [8,9].

The conducted studies established the following:

- X-ray spectra include monochromatic isotropic (characteristic X-rays and annihilation) and continuous anisotropic (Compton scattering, bremsstrahlung of secondary electrons and positrons, background) radiation, the relative intensities of which are determined by Z_{eff} and the target thickness d;

- the ORGI method is applicable to studying targets with a thickness d smaller than the saturation thickness d_0, while the VRGI method has no such limitations (with increasing d in the region $d>d_0$, the ORGI yield does not change, since the ORGI generated here is absorbed upon exiting the object; the VRGI yield decreases, since the increase in absorption exceeds the increase in generation);

- the saturation thickness d_0 depends on Z_{eff} of the target material and the cutoff energy of the probing radiation Ee.

Obviously, the value of d, in addition to Z_{eff}, is important. The target material and the energy Ee of the probing beam radiation should also depend on the scattering (detection) angles θ_s and the target orientation φ relative to the Z - direction of the probing beam. This work is devoted to investigating these dependencies.

Numerical Characteristics of the Studied RGI Fluxes

The results of processing the experimental spectra of the studied RGI fluxes allowed us to determine the values of the corresponding numerical characteristics necessary for analyzing the patterns of RGI field formation. These characteristics are presented in Tables 2, 3, and 3.

Table. Numerical characteristics of RGI fluxes (θ_s =10^0, 25^0, 55^0 u 160^0 φ= 90^0), • -I_M (0,04-0,15 MeV), ×- I_K (0,15-0,43 MeV), ▲- I_a (0,43-0,57 MeV),O - $I_б$ (0,57-2,5 MeV), Pb(d=1-45 g/sm^2), Fe(d =4-45 g/sm^2), Al(d=1,5-20 g/sm^2) ,CT (d=0,7-15 g/sm^2) u ▽ - a$_n$, quantum /sm^2 E_e =22 MeV

	I_i (*MeV*)

ISSN: 2582-4686 SJIF 2021-3.261,SJIF 2022-2.889, 2024-6.875 ResearchBib IF: 10.25 / 2025

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Diffuser d (mm)	● - I_M	× - I_K	▲ - I_a	○ - I_B	▽ - a_n, **quantum /sm²**
1	2	3	4	5	6
Pb, θ_s=160°					
1	5,1	8,5	5,2	11,1	21,9
5	7,0	12,4	9,1	17,1	33,4
10	12,1	22,7	16,5	26,6	57,6
15	26,6	44,8	39,6	41,5	114,8
20	25,3	42,9	37,9	39,2	109,5
35	25,7	44,7	37,6	40,4	111,8
45	24,1	42,9	34,3	37,2	104,5

Below, we present a statistical analysis of two indicators that depend on the "saturation thickness of scattered gamma radiation from detection angles and the orientation of flat lead targets relative to the probe beam direction using the least-squares method":

1. Scattered gamma radiation intensity of the mesh (in MeV), $X_i(t)$;
2. Scattered gamma radiation intensity of the calemator (in MeV), $X_i(t)$.

Two time series were excluded from the indicator values, and for each row:

1. The main factors influencing the change in the series levels were identified.
2. To predict the series levels and subsequent time values, the series levels were calculated.

Statistical Analysis

Time Series and Its Characteristics.

The study of patterns in the evolution of events over time is one of the fundamental questions of statistics.

Such questions are primarily addressed by compiling and analyzing time series.

A sequence of statistical information values for a single point in time or for a specific period of time constitutes a time line.

The statistical information values that make up a time series are defined as a series of levels. Time series are most often presented in tables or graphs.

Time series analysis involves addressing the following questions:

1. Identifying the main factors influencing changes in series levels (series polishing);
2. Forecasting series levels and calculating series levels for subsequent time values.
3. Interpolation - finding an unknown series of levels for an intermediate time value based on specified adjacent levels.
4. Expressing the relationship between the levels of one or more time series;
5. Interpretation and analysis of periodic changes in a number of levels.

We limit ourselves to considering the solution to questions 1 and 2, which are the main ones [4].

I. Determination of the main factors influencing the change in row levels (row polishing):

Table 2. Numerical characteristics of RGI flows (θ_s =10⁰, 25⁰, 55⁰ u 160⁰ φ = 90⁰), • -I_M (0,04-0,15 MeV), ×- I_K (0,15-0,43 MeV), ▲- I_a (0,43-0,57 MeV),O - $I_в$ (0,57-2,5 MeV), Pb(d=1-45 g/sm²), Fe(d =4-45 g/sm²), Al(d=1,5-20 g/sm²) ,CT (d=0,7-15 g/sm²) u ▽ - **a_n, quantum /sm²** ***E_e =22 MeV*** $X_i(t)$ is given in the form:

Table 2.

(i) d (mm)	1	5	10	15	20	35	45

ISSN: 2582-4686 SJIF 2021-3.261,SJIF 2022-2.889, 2024-6.875 ResearchBib IF: 10.25 / 2025

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X_i (t) (•) (-Im)	5,1	7,0	12,1	26,6	25,3	25,7	24,1

The type and parameters of the empirical function of this relationship $\overline{X}(t_i') = a + b(t_i')$ is a linear model. To do this, we create auxiliary computational table №3 and find the parameters of the empirical function a and b:

$\bar{t} = (1/n)\sum_{i=1}^{n} t_i = 131/7 = 18{,}7 \approx 19.$

$t_1' = t_1 - \bar{t} = 1-19 = -18$; $t_2' = t_2 - \bar{t} = 5-19 = -14$; $t_3' = t_3 - \bar{t} = 10-19 = -9$;

$t_4' = t_4 - \bar{t} = 15-19 = -4$; $t_5' = t_5 - \bar{t} = 20-19 = 1$; $t_6' = t_6 - \bar{t} = 35-19 = 16$;

$t_7' = t_7 - \bar{t} = 45-19 = 26$;

Table 3.

(i)d(mm)	X_i (-Im)	t_i'	$X_i \cdot t_i'$	$(t_i')^2$	$X_i \cdot (t_i')^2$	$(t_i')^4$
1	5,1	- 18	- 91,8	324	1652,1	104976
5	7,0	- 14	- 98	196	1372	38416
10	12,1	- 9	- 108,9	81	980,1	6561
15	26,6	- 4	- 106,4	16	425,6	256
20	25,3	1	25,3	1	25,3	1
35	25,7	16	411,2	256	6579,2	65536
45	24,1	26	626,6	676	16291,6	456976
Σ	125,9	- 2	658	1550	27325,9	672722

$a = \overline{X} = (1/n)\sum_{i=1}^{n} X_i = 125{,}9/7 = 17{,}99.$

$b = \frac{\sum_{i=1}^{n} X_i \cdot t_i'}{\sum_{i=1}^{n} (t_i')^2}$; $\quad b = \frac{\sum_{i=1}^{n} X_i \cdot t_i'}{\sum_{i=1}^{n} (t_i')^2} = \frac{658}{1550} \approx 0{,}43.$

$\overline{X}(t_i') = a + b(t_i') = 17{,}99 + 0{,}43 t_i'.$

$t_1' = -18$; $\overline{X}(-18) = 17{,}99 + 0{,}43(-18) = 17{,}99 - 7{,}74 = 10{,}25.$

$t_2' = -14$; $\overline{X}(-14) = 17{,}99 + 0{,}43(-14) = 17{,}99 - 6{,}02 = 11{,}97.$

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$t'_3 = -9;\ \overline{X}(-9) = 17{,}99 + 0{,}43(-9) = 17{,}99 - 3{,}87 = 14{,}12.$

$t'_4 = -4;\ \overline{X}(-4) = 17{,}99 + 0{,}43(-4) = 17{,}99 - 1{,}72 = 16{,}27.$

$t'_5 = 1;\ \overline{X}(1) = 17{,}99 + 0{,}43(1) = 17{,}99 + 0{,}43 = 18{,}42.$

$t'_6 = 16;\ \overline{X}(16) = 17{,}99 + 0{,}43(16) = 17{,}99 + 6{,}88 = 24{,}87.$

$t'_7 = 26;\ \overline{X}(26) = 17{,}99 + 0{,}43(26) = 17{,}99 + 11{,}18 = 29{,}17.$

The results are entered into Table No. 4.

a) $\overline{X}(t_i) = a+b(t_i-\bar{t})+c(t_i-\bar{t})^2$, $\overline{X}(t'_i) = a+b(t'_i)+c(t'_i)^2$ - in the linear quadratic model.

$$b = \frac{\sum_{i=1}^{n} X_i \cdot t'_i}{\sum_{i=1}^{n}(t'_i)^2} = \frac{658}{1550} \approx 0{,}43.$$

$$c = \frac{n\sum_{i=1}^{n} X_i\cdot(t'_i)^2 - \sum_{i=1}^{n} X_i \cdot \sum_{i=1}^{n}(t'_i)^2}{n\sum_{i=1}^{n}(t'_i)^4 - (\sum_{i=1}^{n}(t'_i)^2)^2} = \frac{7\cdot 27325{,}9 - 125{,}9\cdot 1550}{7\cdot 672722 - (1550)^2} =$$

$$= \frac{191281{,}3 - 195145}{4709054 - 2402500} = \frac{-3863{,}7}{2306554} \approx -0{,}0017.$$

$$a = \frac{\sum_{i=1}^{n} X_i - c\cdot\sum_{i=1}^{n}(t'_i)^2}{n} = \frac{125{,}9 + 0{,}0017\cdot 1550}{7} = \frac{125{,}9 + 2{,}60}{7} = \frac{123{,}3}{7} \approx 17{,}61.$$

$\overline{X}(t'_i) = a + b(t'_i) + c(t'_i)^2 = 17{,}61 + 0{,}43(t'_i) - 0{,}0017(t'_i)^2$.

$t'_1 = -18;\ \overline{X}(-18) = 17{,}61 + 0{,}43(-18) + 0{,}0017(-18)^2 = 17{,}61 - 7{,}74 + 0{,}55 = 10{,}42.$

$t'_2 = -14;\ \overline{X}(-14) = 17{,}61 + 0{,}43(-14) + 0{,}0017(-14)^2 = 17{,}61 - 6{,}02 + 0{,}33 = 11{,}92.$

$t'_3 = -9;\ \overline{X}(-9) = 17{,}61 + 0{,}43(-9) + 0{,}0017(-9)^2 = 17{,}61 - 3{,}87 + 0{,}14 = 13{,}88.$

$t'_4 = -4;\ \overline{X}(-4) = 17{,}61 + 0{,}43(-4) + 0{,}0017(-4)^2 = 17{,}61 - 1{,}72 + 0{,}027 = 15{,}92.$

$t'_5 = 1;\ \overline{X}(1) = 17{,}61 + 0{,}43(1) + 0{,}0017(1)^2 = 17{,}61 + 0{,}43 + 0{,}0017 = 18{,}04.$

$t'_6 = 16;\ \overline{X}(16) = 17{,}61 + 0{,}43(16) + 0{,}0017(16)^2 = 17{,}61 + 6{,}88 + 0{,}44 = 24{,}93.$

$t'_7 = 26;\ \overline{X}(26) = 17{,}61 + 0{,}43(26) + 0{,}0017(26)^2 = 17{,}61 + 11{,}18 + 1{,}15 = 29{,}94.$

The results are entered into Table No. 4.
Table 4.

t/t №	$X_i(t)$	$\overline{X}_i(t'_i)$	$X_i - \overline{X}_i$	$(X_i - \overline{X}_i)^2$	$\overline{X}_i(t'_i)$	$X_i - \overline{X}_i$	$(X_i - \overline{X}_i)^2$
1	5,1	10,25	- 5,57	31,03	10,42	- 5,32	28,30
5	7,0	11,97	- 6,97	48,58	11,92	- 4,92	24,21
10	12,1	14,12	- 2,02	4,08	13,88	- 1,78	3,17

ISSN: 2582-4686 SJIF 2021-3.261,SJIF 2022-2.889, 2024-6.875 ResearchBib IF: 10.25 / 2025

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15	26,6	16,27	10,33	106,71	15,92	10,68	114,06
20	25,3	18,42	6,88	47,33	18,04	7,26	52,71
35	25,7	24,87	0,83	0,69	24,93	0,77	0,59
45	24,1	29,17	- 5,07	25,71	29,94	- 5,84	34,11
Σ	125,9	125,07	- 1,59	264,13	125,05	0,85	257,15

The residual dispersion value is considered to be the sum of the identified values of the coefficients of each relationship:

$$S_{01}^2 = \left(\frac{1}{n-1}\right)\cdot\sum_{i=1}^{n}(X_i - \overline{X}_i)^2 - ((1/n)\cdot\sum_{i=1}^{n}(X_i - \overline{X}_i))^2 = (1/(7-1))\cdot(264{,}13) - ((1/7)\cdot(-1{,}59))^2$$

$==264{,}13/6 - (-0{,}23)^2 = 44{,}02 - 0{,}05 = 43{,}97$.

$$S_{02}^2 = \left(\frac{1}{n-1}\right)\cdot\sum_{i=1}^{n}(X_i - \overline{X}_i)^2 - ((1/n)\cdot\sum_{i=1}^{n}(X_i - \overline{X}_i))^2 = 1/(7-1).(257{,}15) - ((1/7).(0{,}85))^2 =$$

$=257{,}15/6 - (0{,}12)^2 = 42{,}86- 0{,}014 = 42{,}85$.

The residual variance value best reflects the change in the time series levels.

The relationship with the smallest residual variance best reflects the change in the time series levels.

$43{,}97 > 42{,}85$; $S_{01}^2 > S_{02}^2$; for finding

$\overline{X}(t_i') = a + b(t_i') + c(t_i')^2 = 17{,}61 + 0{,}43(t_i') - 0{,}0017(t_i')^2$ linear quadratic model best reflects.

I. Table 5. Numerical characteristics of RGI flows (θ** $\theta_s = 10^0, 25^0, 55^0$ **u** 160^0 $\varphi = 90^0$**),** • **-**$I_м$ **(0,04-0,15 MeV), ×-** $I_к$ **(0,15-0,43 MeV), ▲-** I_a **(0,43-0,57 MeV),O -** $I_в$ **(0,57-2,5 MeV), Pb(d=1-45 g/sm²), Fe(d =4-45 g/sm²), Al(d=1,5-20 g/sm²) ,CT (d=0,7-15 g/sm²) u ▽ - aₙ, quantum /sm²** E_e ***=22 MeV $X_i(t)$ is given in the form:

Table 5.

(i) d (mm)	1	5	10	15	20	35	45
X_i *(t)* × - I_K	8,5	12,4	22,7	44,8	42,9	44,7	42,9

The type and parameters of the empirical function of this relationship $\overline{X}(t_i') = a + b(t_i')$ is a linear model. To do this, we create auxiliary computational table №6 and find the parameters of the empirical function a and b:

$\bar{t} = (1/n)\sum_{i=1}^{n} t_i = 131/7 = 18{,}7 \approx 19$.

ISSN: 2582-4686 SJIF 2021-3.261,SJIF 2022-2.889, 2024-6.875 ResearchBib IF: 10.25 / 2025

t_1'=t_1- $\bar{t}$ = 1-19 = -18; t_2' = t_2- $\bar{t}$ = 5-19 = -14; t_3' = t_3- $\bar{t}$ =10-19 = -9;

t_4' = t_4- $\bar{t}$ = 15-19= -4; t_5' = t_5- $\bar{t}$ = 20-19 =1; t_6' = t_6- $\bar{t}$ =35-19=16;

t_7' = t_7- $\bar{t}$ = 45- 19 = 26;

Table 6.

(i)d(mm)	X_i(-Im)	t_i'	$X_i \cdot t_i'$	$(t_i')^2$	X_i·$(t_i')^2$	$(t_i')^4$
1	8,5	- 18	- 153,0	324	2754,0	104976
5	12,4	- 14	- 173,6	196	2430,4	38416
10	22,7	- 9	- 204,3	81	1838,7	6561
15	44,8	- 4	- 179,2	16	716,8	256
20	42,9	1	42,9	1	42,9	1
35	44,7	16	715,2	256	11443,2	65536
45	42,9	26	1115,4	676	29000,4	456976
Σ	218,9	- 2	1163,4	1550	48226,4	672722

a = $\overline{X}$ = (1/n) $\sum_{i=1}^{n} X_i$= 218,9/7 = 31,27.

b = $\frac{\sum_{i=1}^{n} X_i \cdot t_i'}{\sum_{i=1}^{n} (t_i')^2}$; b = $\frac{\sum_{i=1}^{n} X_i \cdot t_i'}{\sum_{i=1}^{n} (t_i')^2} = \frac{1163,4}{1550} \approx 0,75$.

$\overline{X}(t_i') = a + b(t_i') = 31,27 + 0,75 t_i'$.

t_1' = - 18; $\overline{X}(-18) = 31,27 + 0,75(-18) = 31,27 - 13,5 = 17,77$.
t_2' = - 14; $\overline{X}(-14) = 31,27 + 0,75(-14) = 31,27 - 10,5 = 20,77$.
t_3' = - 9; $\overline{X}(-9) = 31,27 + 0,75(-9) = 31,27 - 6,75 = 24,52$.
t_4' = - 4; $\overline{X}(-4) = 31,27 + 0,75(-4) = 31,27 - 3,0 = 28,27$.
t_5' = 1; $\overline{X}(1) = 31,27 + 0,75(1) = 31,27 + 0,75 = 32,02$.
t_6' = 16; $\overline{X}(16) = 31,27 + 0,75(16) = 31,27 + 12,00 = 43,27$.
t_7' = 26; $\overline{X}(26) = 31,27 + 0,75(26) = 31,27 + 19,5 = 50,77$.

The results are entered into Table No. 7.

b) $\overline{X}(t_i) = a+b(t_i-\bar{t})+c(t_i-\bar{t})^2$, $\overline{X}(t_i') = a+b(t_i')+c(t_i')^2$ the linear quadratic model.

$$b = \frac{\sum_{i=1}^{n} X_i \cdot t_i'}{\sum_{i=1}^{n} (t_i')^2} = \frac{1163,4}{1550} \approx 0,75.$$

$$c = \frac{n\sum_{i=1}^{n} X_i \cdot (t_i')^2 - \sum_{i=1}^{n} X_i \cdot \sum_{i=1}^{n} (t_i')^2}{n\sum_{i=1}^{n} (t_i')^4 - (\sum_{i=1}^{n} (t_i')^2)^2} = \frac{7 \cdot 48226,4 - 218,9 \cdot 1550}{7 \cdot 672722 - (1550)^2} =$$

$$= \frac{337584,8 - 339295}{4709054 - 2402500} = \frac{-1710,2}{2306554} \approx -0,00074.$$

$$a = \frac{\sum_{i=1}^{n} X_i - c \cdot \sum_{i=1}^{n} (t_i')^2}{n} = \frac{218,9 + 0,00074 \cdot 1550}{7} = \frac{218,9 + 1,15}{7} =$$

$$= \frac{220,05}{7} \approx 31,44.$$

$$\overline{X}(t_i') = a + b(t_i') + c(t_i')^2 = 31,44 + 0,75\,(t_i') - 0,00074\,(t_i')^2 .$$

$t_1' = -18$; $\overline{X}(-18) = 31,44 + 0,75(-18) - 0,00074(-18)^2 = 31,44 - 13,5 - 0,24 = 17,70.$

$t_2' = -14$; $\overline{X}(-14) = 31,44 + 0,75(-14) - 0,00074(-14)^2 = 31,44 - 10,5 - 0,15 = 20,79.$

$t_3' = -9$; $\overline{X}(-9) = 31,44 + 0,75(-9) - 0,00074(-9)^2 = 31,44 - 6,75 - 0,06 = 24,63.$

$t_4' = -4$; $\overline{X}(-4) = 31,44 + 0,75(-4) - 0,00074(-4)^2 = 31,44 - 3,0 - 0,012 = 28,43.$

$t_5' = 1$; $\overline{X}(1) = 31,44 + 0,75(1) - 0,00074(1)^2 = 31,44 + 0,75 - 0,00074 = 32,19.$

$t_6' = 16$; $\overline{X}(16) = 31,44 + 0,75(16) - 0,00074(16)^2 = 31,44 + 12,0 - 0,19 = 43,25.$

$t_7' = 26$; $\overline{X}(26) = 31,44 + 0,75(26) - 0,00074(26)^2 = 31,44 + 19,5 - 0,5 = 50,44.$

The results are entered into Table No. 7.

Table 7.

t/t №	$X_i(t)$	$\overline{X}_i(t_i')$	$X_i - \overline{X}_i$	$(X_i - \overline{X}_i)^2$	$\overline{X}_i(t_i')$	$X_i - \overline{X}_i$	$(X_i - \overline{X}_i)^2$
1	8,5	17,77	- 9,27	85,93	17,7	- 9,2	84,64
5	12,4	20,77	- 8,37	70,06	20,79	- 8,39	70,39
10	22,7	24,52	- 1,82	3,31	24,63	- 1,93	3,73
15	44,8	28,27	16,53	273,24	28,43	16,37	268,0
20	42,9	32,02	10,88	118,37	32,19	10,71	114,7
35	44,7	43,27	1,43	2,05	43,25	1,45	2,1

ISSN: 2582-4686 SJIF 2021-3.261,SJIF 2022-2.889, 2024-6.875 ResearchBib IF: 10.25 / 2025

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45	42,9	50,77	- 7,87	61,94	50,44	- 7,54	56,85
Σ	218,9	125,07	- 1,51	614,90	217,43	1,47	600,41

The residual dispersion value is considered to be the sum of the identified values of the coefficients of each relationship:

$$S_{01}^2 = (\frac{1}{n-1})\cdot\sum_{i=1}^{n}(X_i - \overline{X}_i)^2 - ((1/n)\cdot\sum_{i=1}^{n}(X_i - \overline{X}_i))^2 = (1/(7\text{-}1))\cdot(614{,}9) - ((1/7)\cdot(\text{-}1{,}51))^2 =$$

$614{,}9/6 - (\text{-}0{,}22)^2 = 102{,}48 - 0{,}05 = 102{,}43.$

$$S_{02}^2 = (\frac{1}{n-1})\cdot\sum_{i=1}^{n}(X_i - \overline{X}_i)^2 - ((1/n)\cdot\sum_{i=1}^{n}(X_i - \overline{X}_i))^2 = 1/(7\text{-}1).(600{,}41) - ((1/7).(1{,}47))^2 =$$

$=600{,}41/6 - (0{,}21)^2 = 100{,}07 - 0{,}044 = 100{,}03.$

The residual variance value best reflects the change in the time series levels.

The relationship with the smallest residual variance best reflects the change in the time series levels.

102,43> 100,03; $S_{01}^2 > S_{02}^2$; for finding,

$\overline{X}(t_i') = a + b(t_i') + c(t_i')^2 = 31{,}44 + 0{,}75\,(t_i') - 0{,}00074\,(t_i')^2$ linear quadratic model best reflects.

Conclusion.

Thus, the conducted studies allow us to conclude:

- changing the probe beam radiation energy within the range of 13-22 MeV affects the absolute value of I_A without changing its dependence on the thickness *d*. The linear-quadratic model best reflects the dependence of the absolute value of I_A on the thickness *d*.

- changing the probe beam radiation energy within the range of 13-22 MeV affects the absolute value of I_K without changing its dependence on the thickness *d*. The linear-quadratic model best reflects the dependence of the absolute value of I_K on the thickness *d*.

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