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INVESTIGATION OF IONIZATION LOSSES OF SHOWER ELECTRONS IN ELECTRON-PHOTON SHOWERS DEVELOPED IN LIQUID XENON BY GAMMA QUANTA IN THE ENERGY RANGE 1600-3400 MEV

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1. *Introduction*

In the present paper the results of the investigation of the longitudinal development of electron-photon showers produced by gamma-quanta of energies $E_\gamma = 1600 - 3400$ MeV in liquid xenon are given. The work was performed on the photographs from the xenon bubble chamber.

In the region of high energies of gamma quanta initiating the electron-photon shower, $E_\gamma \gg 2m_e c^2$, the principal importance is due, also from the methodical point of view, to the longitudinal development of showers. In Fig. 1 the typical picture of the electron-photon shower registered in 180 ℓ xenon bubble chamber of the Institute of Theoretical and Experimental Physics in Moscow is presented.

In order to get the characteristics of the longitudinal development of the shower, we recall firstly some notations. Let Σr be the observed total range, i.e., the total length of the tracks of shower with energies equal or larger than some minimal value E_0; by $\Delta \Sigma r$ we denote the total length of shower electrons with energy equal or larger than E_0 in the layer of matter of the assumed constant thickness Δt perpendicular to the axis of the shower on the depth t of the development of the shower. Δt should be chosen much smaller than the total depth of the shower. The useful quantity for the investigation of the longitudinal development of the shower is the function $\Delta \Sigma r / \Sigma r$ of the total range Σr.

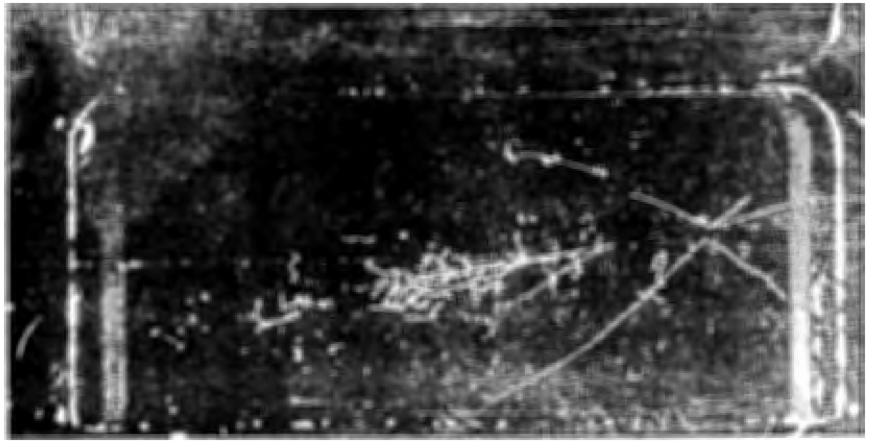

Fig. 1. A typical electron-photon shower registered in the 180 l xenon bubble chamber of JTEF.

The so defined quantity (depending on E_γ, E_0, t) appears to be a function of the same variables as the so-called one-dimensional cascade curve $Ne(E_\gamma, E_0, t)$ [2].

The total range of shower electrons * of energy $E_\gamma >> E_0$ is proportional to the energy spent by them on ionization [1]. The quantity $\Delta\Sigma r / \Sigma r$ is more convenient in the laboratory practice of the investigation of the processes with the participation of high energy gamma quanta than the cascade curve since in physical experiments we have mostly to measure either the total range of shower electrons or the ionisation or luminous effect.

The process of the longitudinal development of showers is accompanied by fluctuation which essentially restricts the precision of the determination of the energy of high energy gamma quanta. Let us define A as the fraction of the total range of shower electrons on the development length d_A, on which on the average the fraction $\bar{A}$ of the total range of shower electrons is realized. Then one can conveniently represent the fluctuations in the form of the dependence of the relative dispersion $\sigma_A / \bar{A}$ of the parameter A, on A.

This work is the continuation of the series of our experimental investigations of characteristics of electron-photon showers generated by gamma quanta in a wide energy interval [3-5].

2. *Description of the Experiment*

As a result of scanning of about 200.000 photographs from the 180 ℓ xenon bubble chamber of the Institute of Theoretical and Experimental Physics in Moscow irradiated by the 3.5 GeV/c π^--meson beam, 180 events of electron-photon showers were selected in which the values of total range Σr of the investigated shower electrons were contained in the interval Σr - 1740-4280 mm on the scale of reprojector. The mean linear enlargement, relative to the chamber, obtained on the reprojector on which the analysis of events was performed, was equal to 0.6821. The minimal length of the investigated electron tracks was assumed to be 5 mm in the chamber, which corresponds to the cut-off energy of electrons $E \sim 1.5$ MeV.

In each event the energy of the primary gamma quantum was determined from the known range-energy dependence for shower electrons [1]. The total range on the lengths intervals Δt = 20 mm in the reprojector plane along the axis of the development of the shower, beginning from the point of conversion of the primary gamma quantumtum was also measured. The numbers of the selected showers corresponding to the different values of energy of primary gamma quanta are shown in Table 1. Methodical problems concerning the analysis of events of electron-photon showers registered on photographs from xenon bubble chambers were treated in our earlier publications [3-5].

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* Electrons are ment as both negatons and positions, whole traces in our experiments were undistinguishable.

Table 1

Numbers N_{γ} of electron-photon showers produced by gamma quanta of energies E_{γ}

E_{γ} (MeV)	1625 ±125	1875 ±125	2125 ±125	2375 ±125	2625 ±125	2875 ±125	3125 ±125	3375 ±125
N_{γ}	10	17	23	27	30	27	12	34

Table 2

The values of the fractions of total ranges of shower electrons $\Delta \Sigma r / \Sigma r$ observed in the layer of thickness $\Delta d = 1$ perpendicular to the axis of the shower on the depth of the development of the shower d, in showers produced by gamma quanta of energy E_{γ} in liquid xenon. The depth d is expresses in units equal to 0.3368 t_{Xe} radiational units for liquid xenon.

E_{γ} (MeV) \ d	1	2	3	4	5	6	7	8	9	10	12	14	16	20	25
1625	0.028 ±0,002	0.071 ±0.008	0.122 ± 0,012	0.190 ±0.018	0.282 0.017	0.374 ±0.021	0.454 ± 0.027	0.542 ±0.034	0.614 ±0.036	0.671 ±0.041	0.792 ±0,041	0.883 ±0,026	0.928 0.079	0.981 ±0,006	–
1875	0,025 ±0.002	0,072 ±0.005	0.140 ±0.008	0.225 ±0.013	0.322 ±0.018	0.426 ±0.022	0.522 ±0.025	0.610 ±0.026	0.693 ±0.024	0.763 ±0.022	0.864 ±0.020	0.926 ±0.014	0.961 0.012	0.990 ±0.006	0.999 ±0.001
2175	0.029 ± 0.006	0.074 ±0.008	0.138 ±0.010	0.220 ±0.013	0.312 ±0,016	0.405 ±0.018	0.492 ±0.022	0.573 ±0.022	0.646 ±0.021	0.714 ±0.020	0.827 ±0.020	0.895 ±0.160	0.943 0.011	0.988 ±0.038	0.997 ±0.013
2375	0.019 ±0.001	0.055 ±0.003	0.106 ±0.006	0.171 ±0.010	0.252 ±0.014	0.334 ±0.017	0.420 ±0.020	0.507 ±0.023	0.591 ±0.025	0.669 ±0.024	0.791 ±0.023	0.870 ±0.020	0.928 0.014	0.983 ±0.007	0.996 ±0.002
2675	0.020 ±0.001	0.055 ±0.004	0.101 ±0.006	0.162 0.009	0.242 ±0.012	0.328 ±0.014	0.423 ±0.017	0.515 ±0.018	0.602 ± 0.018	0.671 ±0.019	0.786 ±0.017	0.873 ±0.014	0.930 0.010	0.981 ±0.004	0.998 ±0.001
2875	0.016 ±0.001	0.043 ±0.002	0.086 ±0.004	0.150 ±0.007	0.224 ±0.010	0.309 ±0.014	0.401 ±0.016	0.492 ±0.016	0.573 ±0.016	0.640 ±0.016	0.767 ±0.012	0.861 ±0.009	0.924 0.007	0.982 ±0.004	0.999 ±0.001
3175	0.016 ±0.002	0.046 ±0.005	0.0087 ±0.008	0.142 ±0.012	0.215 ±0.016	0.281 ±0.020	0,365 ±0.024	0.459 ±0.029	0.548 ±0.031	0.628 ±0.030	0.743 ±0.030	0.838 ±0.028	0.896 0.024	0.965 ±0.013	0.993 ±0.006
3375	0.018 ±0.006	0.042 ±0.007	0.082 ±0.009	0.138 ±0.010	0.205 ±0.013	0.275 ±0.015	0.348 ±0.017	0.424 ±0.018	0.496 ±0.020	0.558 ±0.021	0.680 ±0.020	0.780 ±0.018	0.857 0.016	0.951 ±0.013	0.989 ±0.004

3. *Experimental Results*

Differential distributions of ionization losses of shower electrons in liquid xenon and also the corresponding fluctuations of the fraction A of the total range of shower electrons in showers produced by gamma quanta of energies contained in the interval E_γ = 1600-3400 MeV are given below.

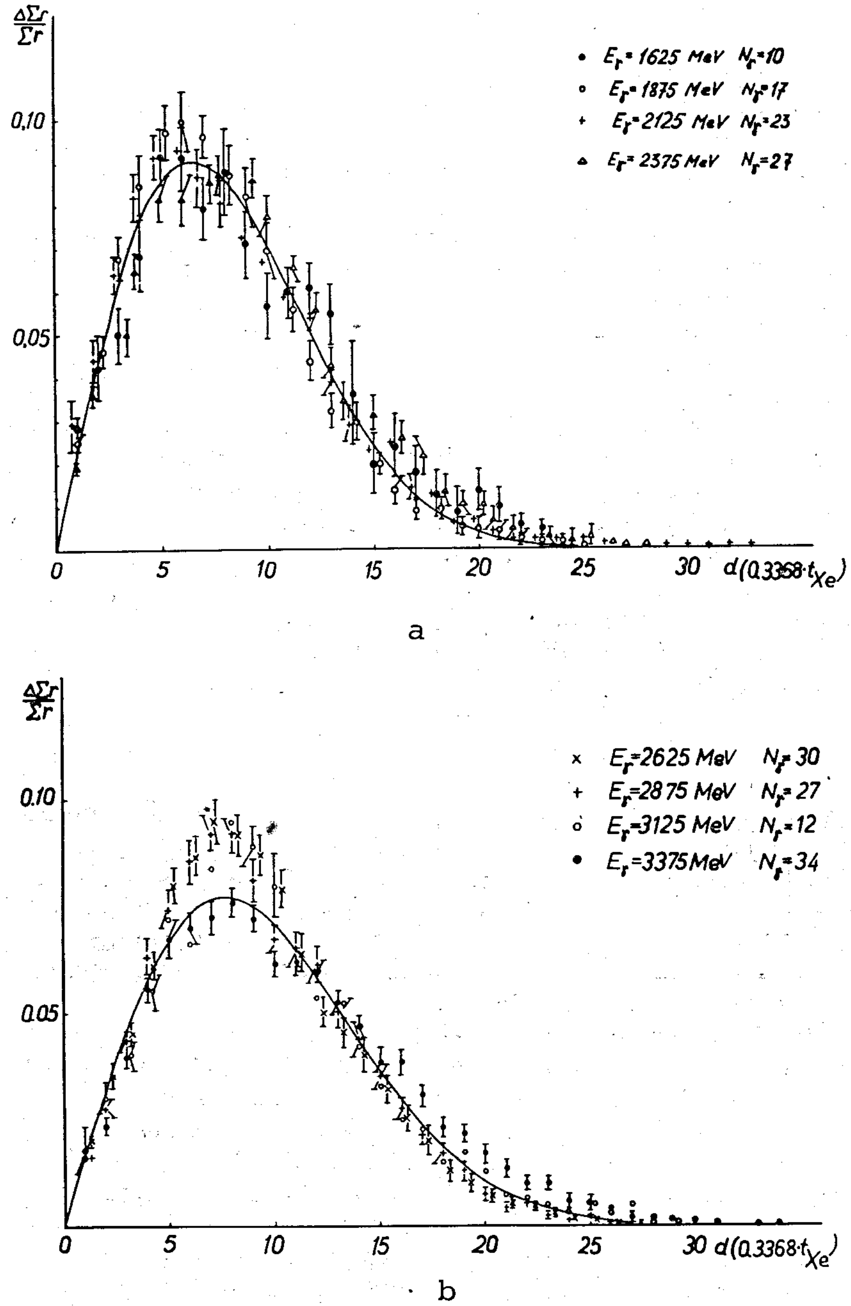
3.1. Distribution of ionization losses of shower electrons

In Fig. 2 differential distributions of ionization losses of shower electrons in showers produced by gamma quanta for eight values of the energy E_γ are presented. The corresponding numerical values are given in Table 2. We see that the maximum of the distributions of $\Delta\Sigma r/\Sigma r$ slowly moves towards larger values of the depths of the development of showers with the increase of the energy of primary gamma quanta.

3.2. Fluctuations of total ranges of shower electrons

In Fig. 3 the dependence of the relative dispersion $\sigma_A/\bar{A}$ on the parameter A is presented. The experimental distributions $\sigma_A/\bar{A}$ refer to the eight energy value E_γ of gamma quanta producing the showers. Let us remark that the kind of dependence of $\sigma_A/\bar{A}$ on A does not change at the achieved experimental accuracy, with the change of the energy E_γ for the entire considered interval of energy values E_γ.

Fig. 2. (a,b). Distributions of ionization losses of shower electrons in showers produced by gamma quanta of energy E_γ in liquid xenon. Functions (1) for E_γ = = 2125 MeV (Fig. 2a) and E_γ = 3125 MeV (Fig. 2b) are represented by solid lines. Notations on the Figures.



4. *Discussion of Experimental Results and Conclusions*

The presently existing theoretical calculations of cascade curves, based on the one-dimensional equations of the diffusion type [2] do not describe correctly the experimentally observed process of the development of electron-photon showers produced by gamma quanta of high energies [3–5]. More satisfying agreement with experimental results can be attained with the help of the Monte-Carlo method [6], but the application of this method is connected usually with considerable technical difficulties.

Therefore it will be of great interest to generalize the existing experimental materials in a form of simple, and convenient from the methodical point of view approximate rules describing the longitudinal development of showers.

It turned out, that the obtained experimental distributions of ionization losses of shower electrons in electron-photon showers produced by gamma quanta of energy E_γ = 1600-3400 MeV in liquid xenons are well approximated by the two parameter function of the form

$$\frac{\Delta \Sigma r}{\Sigma r} = \alpha t \cdot \exp(-\beta t^2). \qquad (1)$$

Numerical values of the parameters α and β depending on the energy E_γ are presented in Table 3. In Figure 2 curves calculated from (1) for two cases $E_\gamma = 2125$ MeV and $E_\gamma = 3125$ MeV are plotted. The dependence of the parameters α and β of the function (1) on the energy E_γ of gamma quanta producing showers in liquid xenon is also represented in Fig. 4.

It should be stressed that the quantity $\Delta\Sigma r/\Sigma r$ used by us is proportional to the number $N_e(E_\gamma, E_0, t)$ of electrons with the energy $E_e \geq E_0$ on the depth t of the development of the shower and the corresponding proportionally coefficient inessentially depends on the cut-off energy E_0 in a wide interval of the E_0 values [4].

It can be concluded on the basis of the results obtained by us that the relative dispersion $\sigma_A/\bar{A}$ of the fraction of the total range of shower electrons does not

Table 3
The values of the parameters α and β of the function (1), approximating the distributions of ionization losses of shower electrons in showers produced by gamma quanta of energy E_γ in liquid xenon; n - number of degrees of freedom, P - probability concerning the given value of χ^2.

E_γ (MeV)	α	β	n	χ^2	P /%/
1625	0.0656±0.0026	0.0965±0.0039	20	37,4	~1,5
1875	0.0765±0.0024	0.1148±0.0028	24	10,7	99
2125	0.0675±0.0020	0.1025±0.0024	32	26,7	65
2375	0.0584±0.0015	0.0873±0.0018	30	16,4	98
2625	0.0576±0.0013	0.08625±0.0016	26	28,0	30
2875	0.0531±0.0010	0.0808±0.0012	26	57,1	≲ 1
3125	0.0496±0.0016	0.0754±0.0021	28	32,1	30
3375	0.0413±0.0008	0.0620±0.0010	34	38,7	15

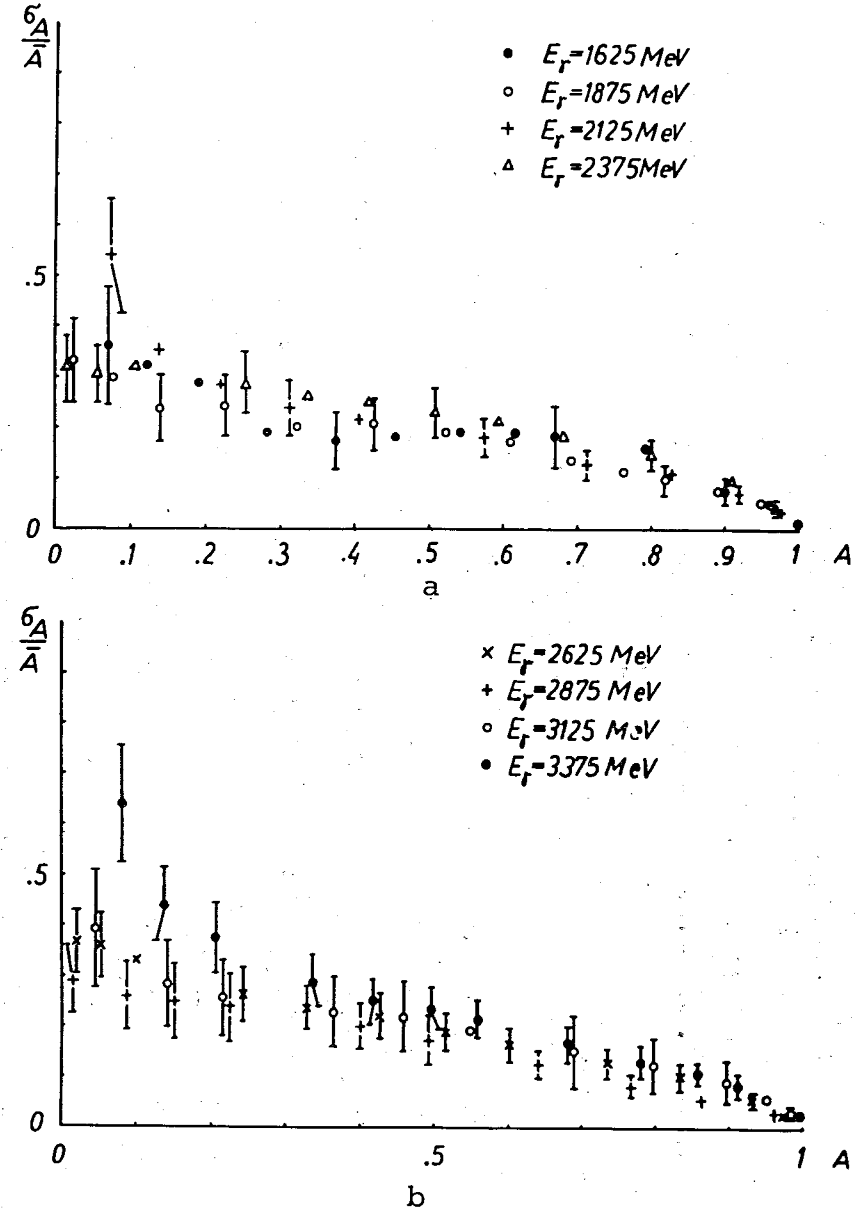


Fig. 3 (a,b). The dependence on A *of relative dispersions* $\sigma_A / \bar{A}$ *of the function* A *of the total ranges of shower electrons at different energy values* E_γ *of gamma quanta producing showers.*

depend, within the limits of experimental errors, on the energy E_γ of gamma quanta producing showers in the considered interval of E values. The analogical result was obtained by us in the interval E_γ=30-120 *MeV* /5/ and E_γ = 100-1600 MeV /3,4/. But the tendency of the decrease of the value of σ_A / A with the increase of the gamma quanta energies by one order of magnitude, i.e., from 30 MeV to 3400 MeV, can be observed.

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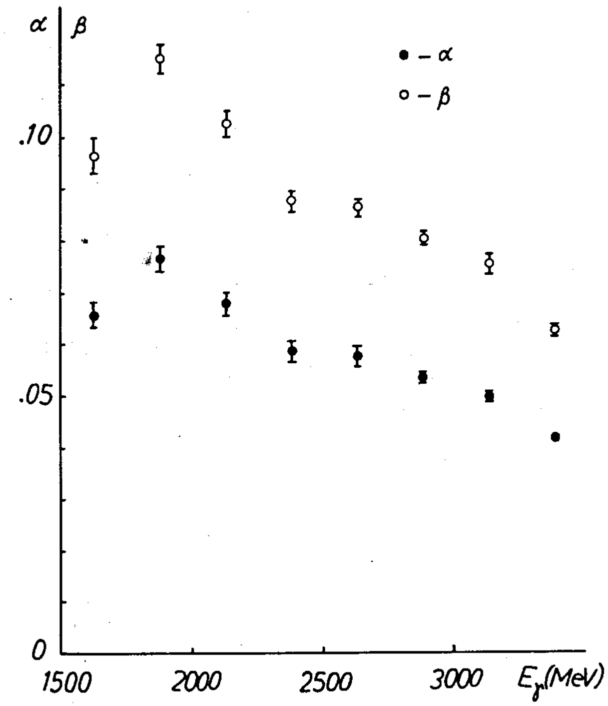

Fig. 4. The dependence on E_γ *of parameters* α *and* β *on the function (1) approximating ionization losses of shower electrons.*

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