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R E P O R T   No. 39/VI

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Submitted for publication in "Il Nuovo Cimento"

W A R S A W

November, 1958

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Summary

Four high energy ($\sim 10^{12}$ eV) electron-photon cascades have been investigated at the first stage of their development. The number and the energy of the electron pairs of the first generation produced on the first radiation length were estimated and compared with the theoretical values calculated on the basis of the theory of Bethe and Heitler. On the other hand the same was calculated according to theories of Landau, Pomeranchuk and Ter-Mikaelyan which take into account the influence of medium on the bremsstrahlung of electrons of very high energy. The experimental results are in better agreement with the predictions of Landau, Pomeranchuk and Ter-Mikaelyan than with that of Bethe and Heitler. This fact confirms the results obtained earlier in our laboratory and given in a previous paper (Mięsowicz et al. 1957 [1]).

Introduction

Up to the present time there were very few experiments investigating the problem of the influence of the dense medium on the probability of emission of bremsstrahlung photons by electrons of very high energies. The point in question is an effect first predicted by Landau [2], Pomeranchuk and Ter-Mikaelyan [3,4] and followed up in papers by Migdal [5,6,7]. According to theories developed by these authors we ought to expect that for very high energies ($\gtrsim 10^{12}$ eV in nuclear emulsions) the spectrum of bremsstrahlung photons is strongly cut down for low energy photons as compared with the Bethe and Heitler spectrum.

Landau, Pomeranchuk and Ter-Mikaelyan have put into question the validity of Bethe and Heitler formulas for very high electron energy and for photons for which $W/E \ll 1$, where W denotes the energy of the emitted photon and E the energy of the radiating electron. According to Landau, Pomeranchuk and Ter-Mikaelyan theory which will be further denoted by L-P-T the reason for this is as follows. If W/E is sufficiently small, the change of the momentum of an electron in consequence of an emission of photon is so small that the uncertainty of the localization of the event due to the Heisenberg's principle is much greater than the distances between the scattering centres. If so, in Landau's opinion, the effects due to the particular centres can not be treated additively as in Bethe and Heitler [8] (B-H) calculations. If this uncertainty range is large enough, the L-P-T theory predicts that multiple coulomb scattering of the electron on the distance can destroy the coherence between electron and photon waves. It is thus expected that the bremsstrahlung cross section at high energy will decrease below B-H value. The polarization of medium leads also to analogical "decoherence effect". The quantitative estimations of these phenomena were made firstly by Landau and Pomeranchuk (multiple scattering effect) and Ter-Mikaelyan (polarization effect). The more rigorous calculations based on the quantum theoretical treatment were given by Migdal.

The existence of the effect mentioned above was reported in a previous paper from our laboratory (Międsowicz et al.[1]). For studying the quantitative agreement of the observed effect with the theory, more events of very high energy electron-photon cascades were needed, for increasing the statistical significance of the obtained results.

The aim of this paper is to present an analysis performed on four electromagnetic cascades with primary energies $\simeq 10^{12}$ eV. The results obtained, were compared with the theoretical predictions of B-H and L-P-T theories.

Just before sending our work to print we received a paper by Varfolomeev et al.[9)*] in which the discrepancy between the observed development of electron-photon cascades and the development predicted by cascade theory, has been also interpreted on the basis of L-P-T theory.

Experimental method

The present analysis concerns four electron-photon cascades. Three of them (cascade A,B,C in Table 1.) have been generated in a nucleon-nucleon interaction of the type $0 + 14\alpha$ and energy 3.3×10^{14} eV/nucleon (Ciok et al.[10]). The fourth isolated cascade (cascade D in Table 1.) was described in the paper of Międsowicz et al.[1]. The energy of the primary photon of cascade D was found to be $(7.0^{+3.4}_{-2.6}) \times 10^{11}$ eV.

Since cascades A,B,C originate from the decays of π^0 generated in the same nuclear interaction, the mutual radial distances between them are small. In consequence, electron tracks belonging to the different cascades are crossing each other at greater depths than about one radiation length from the point of origin of each primary pair. Therefore there was no possibility to evaluate the energy of each cascade separately. For this reason we have evalua-

* We are much indebted to Professor Gurevich for sending us the preprint before publication.

ted the mean energy of each cascade under the assumption that there is energy equipartition between primary photons and electrons of the primary pairs. This mean energy has been evaluated from the longitudinal development of the cascades taking into account the correction for lateral distribution according to Pinkau [11]. From the number of electrons with energies greater than 1×10^9 eV and 4×10^8 eV within two different radii (these values of energies have been received from scattering measurements) at the depth 2.76 rad. lengths from the point of interaction we have obtained for the mean energy of the cascade the values $(1.1 {}^{+0.4}_{-0.4}) \times 10^{12}$ eV, $(1.3 {}^{+0.8}_{-0.5}) \times 10^{12}$ eV respectively. In these calculations we used the cascade tables of Janossy [12] as well as Janossy's [13] standard deviation. In the following we have accepted the value 1.2×10^{12} eV for the mean energy of each cascade.

The mean energy of π^0 meson (assuming the equipartition of energy between the two photons) equal to 2.4×10^{12} eV is in good agreement with the energy values of two charged mesons which are contained within the same angle as the cascades. Their energies obtained from the secondary interactions are equal to 1×10^{12} eV and 2×10^{12} eV respectively.

Now we investigated the energy spectrum of pairs of the first generation only, generated on a given length from the point of origin of the cascade, and not the energy spectrum of all secondary electrons at a given depth as in cascade theory. By first generation pairs we understand pairs produced by the conversion processes of bremsstrahlung photons emitted by electrons of the primary pair.

We succeeded in evaluating the energy of almost all electron pairs of first generation for each cascade separately. It is obvious that the distance from the point of origin of the primary pair up to the end point where the scanning for electron pairs is stopped, ought to be as long as possible (in our case about one radiation length from the point of origin of each primary pair).

The restriction to electron pairs coming from the first generation only, was imposed by conditions of our measurements. As it was mentioned above, the small radial distances between the separate cascades A, B, C do not allow to correlate with the particular cascade any electron pair generated in a rather great distance from the tracks of the primary electron pair. On the other hand, it is known that all the electron pairs of the first generation, in consequence of great energy of the primary electrons, must originate in close proximity to the parent track as apparent tridents. Since the losing of such pairs is rather improbable, our procedure releases us from the scanning bias. In our opinion, investigation performed on electron pairs of the first generation is more sensitive for detecting the L-P-T effect than the investigation of the development of the whole cascade. The L-P-T effect is rather diminished by the degradation of energy, whereas in our procedure such a degradation does not take place.

We have used two criteria, energy and geometry criteria, whether a pair is a first generation one. Such a procedure was successful in all cases except in the case of three electron pairs where there was no possibility to establish the order of generation i.e. in which successive generation the pair was produced. The energy measurements have been performed by scattering, especially the differential one. In cases in which the application of scattering was not possible, we have based on the data derived from the measurements of the angle of divergence.

In Table 1 there are given the results of our measurements performed on four cascades. The energy spectrum of electron pairs of the first generation created on the first radiation length has been done on the basis of the data given in Table 1 (Fig.1). The histograms represent the experimental spectrum taking into account the uncertainty of the order of generation of the three electron pairs (histogram a and b). For energies greater than about 10^9 eV (the point with an arrow on Fig.1) the shapes of the histograms are unknown because of the impossibility of evaluating the upper limit of such high energies. Curves I and II represent the B-H and L-P-T spectra respectively for the primary electron energy equal to 5×10^{11} eV at the depth of one radiation length. This energy value corresponds to the mean energy of eight primary electrons of our cascades under consideration (six primary electrons each of energy of 6×10^{11} eV and two primary electrons each of energy of 3.5×10^{11} eV). The dashed curves represent the Poisson's deviation from the theoretical curves of B-H and L-P-T.

Discussion on experimental procedure

We have calculated the average number of electron pairs of first generation with energy greater than W, created by the primary electron of initial energy E_0 on the length t, where t is the distance from the beginning of the electron trajectory. The calculations were made, first on the basis of the L-P-T B-H formulas and then also performed by means of the formulas.

Fig.2 shows the integral energy spectrum of electron pairs of first generation obtained from these two theories. Theoretical curves I and II on Fig.1 have been obtained on the same way as the curves on Fig.2.

We have taken into account the energy loss of the primary electron resulting from the radiation. The energy losses from ionization (about 2×10^{7} eV on one radiation length) are in our case negligible in comparison with the energy of about 10^{12} eV.

In our problem we must take into consideration the cross sections of the following processes which are decisive in forming the energy spectrum of electron pairs.

1. Pair production by photons,
2. Compton effect,
3. Photonuclear reactions,
4. Production of tridents.

Processes 1, 2 and 3 are competitive. From the geometry of the experiment, namely the fact that we observe the number of pairs on the first radiation length follows that the diminishment of the number of pairs caused by 2 and 3 is negligible. The number of pairs of energy $W \geqslant 10^7$ eV is diminished by about 2 - 3 %. The number of pairs of energy $W \geqslant 10^8$ eV practicaly rests unchanged, because in this energy region the cross sections of the processes 2 and 3 are very small in comparison with the cross section of 1.

The increasing of mean free path for pair production with the decreasing energy of photon ($\sim 10^7$ eV) results in the same direction. Although this effect and the effects 2 and 3 act in the same direction as the modification of L-P-T nevertheless they are much smaller than this modification. We have estimated that the whole cumulative influence amounts only some per cent and so, is negligible in comparison with L-P-T modification.

So we see that the number of electron pairs of first generation is a sensitive detector of the character of the bremsstrahlung spectrum and quite insensitive to competitive effects, in comparison with the process of pair production.

The number of pairs is of course increased by the trident production, however, this last one does not privilage the production of pairs of small energies. Accepting for $E_o =$ $= 5 \times 10^{11}$ eV the mean free path for trident production about 3.5 rad.lengths, we obtain a contribution of about 6 % of the whole number of pairs produced by the first process. Finally we see that the effects 2, 3 and 4 are of no importance in our problem.

On Fig.2, representing the results of both theories (B-H and L-P-T), it is interesting to remark that in B-H energy spectrum we have the dependence of the number of pairs on E_o/W only, while in the analogical curves of L-P-T there is a dependence on both E_o and W.

Although there is a possibility of great error in estimating E_o - the primary energy of the electron, it is important to stress that the change of E_o even of the order of magnitude, does not change the character of L-P-T spectrum. From Fig.2 we see also that the L-P-T spectrum curves have a plateau beginning from a certain $\mathcal{E}$, which feature is not shown by the B-H spectrum curve. This is the main consequence of L-P-T theory which just expresses the lack of small energy pairs.

Conclusions

1. The experimental energy spectrum of the electron pairs of the first generation, produced on the first radiation length, shows a statistically significant deviation from the Bethe and Heitler energy spectrum curve.
2. There is rather a good agreement between the experimental results and the curve which represents the energy spectrum of Landau, Pomeranchuk and Ter-Mikaelyan.
3. The method of investigation of electron pairs of the first generation only, is in authors opinion a sensitive tool in detecting the difference between the energy spectrum of Bethe and Heitler and that of Landau, Pomeranchuk and Ter-Mikaelyan, since in cascade development there is a degradation of energy of the emitting electron.

We wish to express our gratitude to Professor M.Męsowicz for suggesting these investigations, his permanent interest in our work and many valuable ideas and hints during the progress of this work.

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TABLE 1

Pair	Distance from the point of origin of the primary pair (rad. length)	Received from the scattering measurements			Received from the angle of divergence	Remarks
		E_1 (eV)	E_2 (eV)	$W=E_1+E_2$ (eV)		
			Cascade	A		
1	0	----	----	----	----	Primary pair $E_1+E_2 \simeq 1.2 \times 10^{12}$ *
2	0.26	7.7×10^8	1.2×10^9	2.0×10^9	----	First generation
3	0.42	1.3×10^8	6.6×10^8	7.9×10^8	----	The order of generation is unknown
4	0.50	$>2.4 \times 10^9$	$>2.5 \times 10^9$	$>4.9 \times 10^9$	----	First generation
5	0.64	----	----	----	$>1 \times 10^9$	First generation
6	0.81	$(3.0^{+2.5}_{-0.9}) \times 10^8$	$(3.5^{+4.0}_{-1.2}) \times 10^8$	$(6.5^{+6.5}_{-2.1}) \times 10^8$	----	The order of generation is unknown
7	0.92	----	----	----	$>4.6 \times 10^9$	First generation
8	0.96	----	----	----	$>3.5 \times 10^9$	First generation
			Cascade	B		
1	0	----	----	----	----	Primary pair $E_1+E_2 \simeq 1.2 \times 10^{12}$ *
2	0.02	$>1 \times 10^{10}$	$(7.8^{+10.7}_{-2.7}) \times 10^8$	$>1 \times 10^{10}$	$>1 \times 10^{10}$	First generation
3	0.18	$>3.8 \times 10^9$	$>3.4 \times 10^9$	$>7.2 \times 10^9$	$>1 \times 10^{10}$	First generation
4	0.52	$>3.5 \times 10^9$	----	$>3.6 \times 10^9$	$>1 \times 10^9$	First generation
5	0.93	----	----	----	$>1 \times 10^{10}$	First generation
6	0.94	----	----	----	$>7 \times 10^9$	First generation

* $E_1 + E_2 = 2E_0$ according to the assumption of the equipartition of energy

TABLE 1 (Continued)

Pair	Distance from the point of origin of the primary pair (rad. length)	Received from the scattering measurements			Received from the angle of divergence	Remarks
		E_1 (eV)	E_2 (eV)	$W=E_1+E_2$ (eV)		
			Cascade C			
1	0	----	----	----	----	Primary pair* $E_1+E_2 \simeq 1.2\times10^{12}$
2	0.27	$(1.1^{+0.6}_{-0.3})\times10^8$	$(1.3^{+2.6}_{-0.5})\times10^9$	$(1.4^{+2.7}_{-0.5})\times10^9$	$>5\times10^8$ $<1\times10^9$	First generation
3	0.57	$>3.2\times10^9$	$>4.8\times10^9$	$>8.0\times10^9$	$>1\times10^{10}$	First generation
4	0.57	$(1.3^{+0.5}_{-0.3})\times10^8$	$(3.0^{+3.6}_{-2.0})\times10^8$	$(4.3^{+4.1}_{-2.3})\times10^8$	$<1\times10^8$	First generation
5	0.89	$(2.2^{+2.5}_{-0.7})\times10^8$	$(2.7^{+2.2}_{-0.8})\times10^8$	$(4.9^{+4.7}_{-1.5})\times10^8$	----	The order of generation is unknown
			Cascade D			
1	0	----	----	----	----	Primary pair* $E_1+E_2 \simeq 7.0\times10^{11}$
2	0.32	2.0×10^8	1.0×10^8	3.0×10^8	----	First generation
3	0.57	1.3×10^8	1.0×10^7	1.4×10^8	----	First generation
4	0.60	6.0×10^8	$\geqslant7.0\times10^8$	$\geqslant1.3\times10^9$	----	First generation
5	0.82	1.3×10^8	8.0×10^7	2.1×10^8	----	First generation
6	0.96	$\geqslant1.0\times10^9$	7.5×10^8	$\geqslant1.8\times10^9$	----	First generation

* $E_1 + E_2 = 2E_0$ according to the assumption of the equipartition of energy

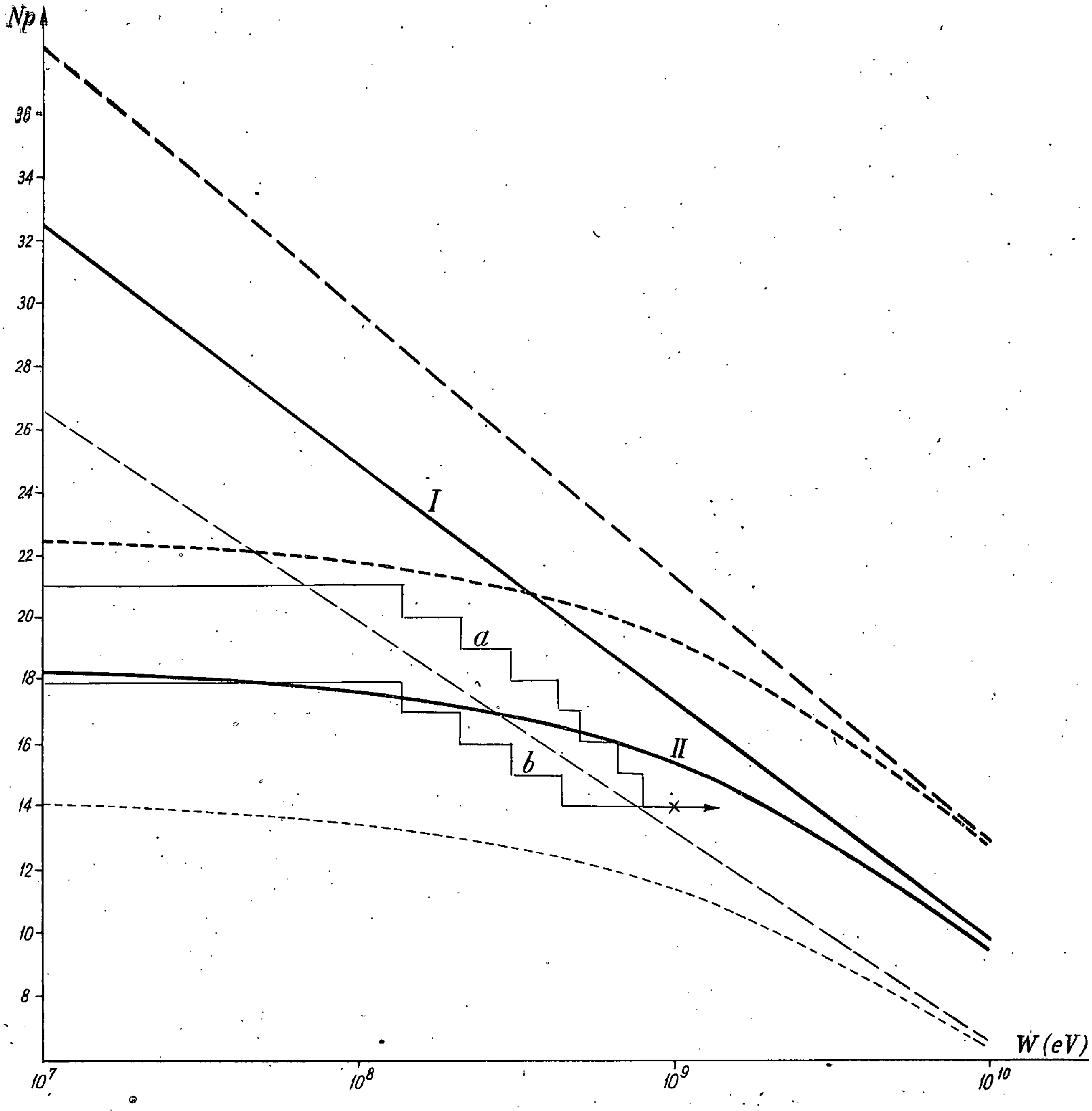

Fig. 1. Integral energy spectrum of electron pairs of the first generation created on the first rad.length.

N_p - number of pairs of energy greater than the given value W

a, b- experimental histograms

I, II - Bethe-Heitler and Landau, Pomeranchuk, Ter-Mikaelyan curves respectively (primary electron energy 5×10^{11} eV)

Curves I and II are given with their standard deviations.

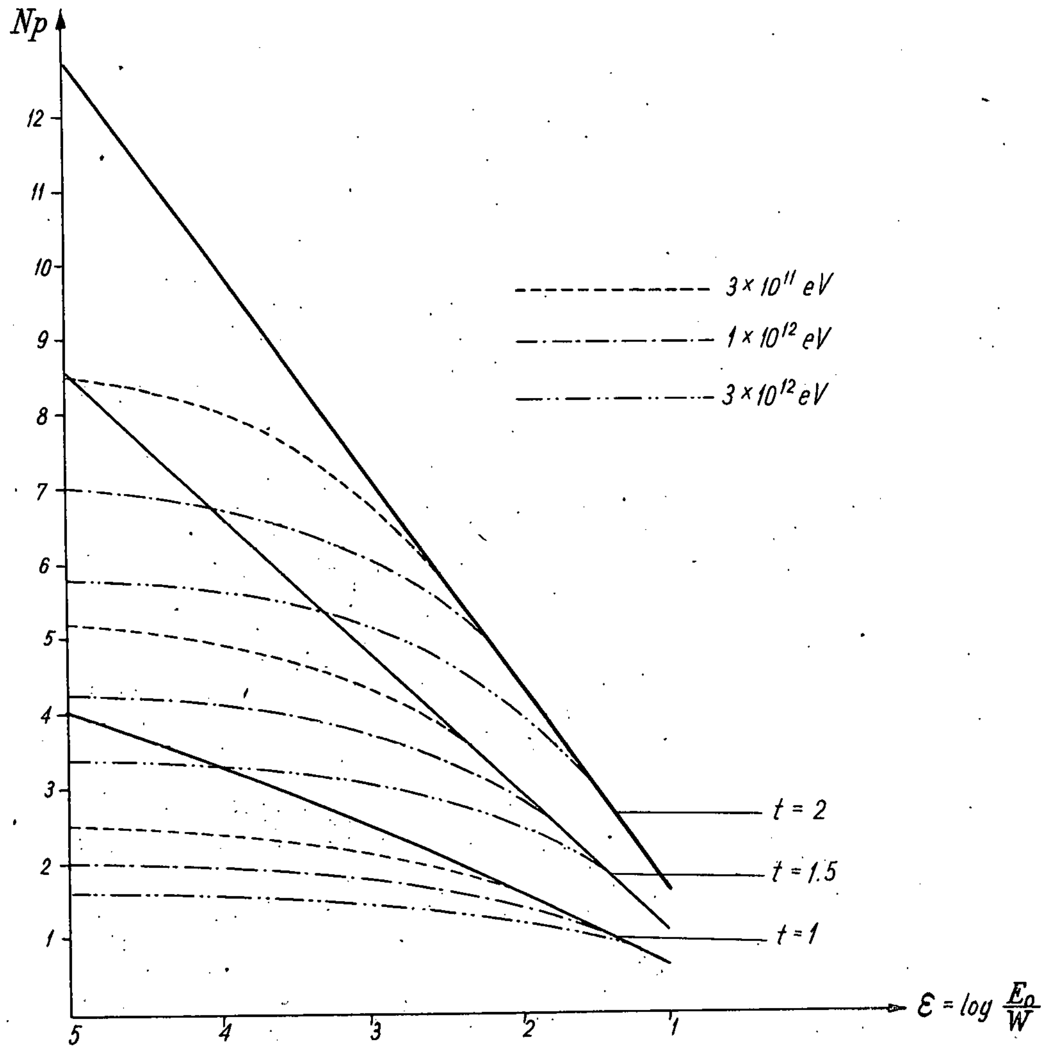

Fig. 2. Integral energy spectrum of electron pairs of the first generation.

N_p - number of pairs of energy greater than that corresponding to the value $\mathcal{E}$.

Full curves - Bethe-Heitler curves for three different depths (1.0 , 1,5 , 2.0 rad.lengths).

Dotted and dotted-dashed curves - Landau, Pomeranchuk, Ter-Mikaelyan curves for the depths (1.0 , 1.5 , 2.0 rad.lengths) and the primary electron energy $E_o = 3 \times 10^{11}$ eV, 1×10^{12} eV and 3×10^{12} eV.