SLAC TRANS - 88

STUDY OF THE FORMATION OF (e^+e^-) PAIRS BY 1.25-4 GeV ELECTRONS

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STANFORD LINEAR ACCELERATOR CENTER

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1) Introduction

The formation of electron-positron pairs by charged particles has been studied in a number of theoretical papers[1-8]. The cross-section of the process

$$e^- + Z \rightarrow e^- + e^+ + e^- + Z \qquad (1)$$

was first calculated by Bhabha[1] in the Weizsäcker-Williams approximation. The reaction was considered in greater detail in ref. 3. The formation of (e^+e^-) pairs by electrons in the field of atomic electrons was not calculated.

Reaction (1) was investigated experimentally in some tens of studies (reviewed in ref. 9). The results were nearly always compared with Bhabha's theory[1]. The main experimental difficulty in the determination of the cross-section of this reaction is isolation of the background events due to conversion of bremsstrahlung γ-quanta in the substance (pseudotridents)*:

* Translator's Note: Term uncertain.

$$e^- + Z \to e^- + \gamma + Z, \qquad (2)$$

$$\gamma + Z' \to e^- + e^+ + Z'. \qquad (3)$$

The bremsstrahlung cross-section is $\sim$ 100 times greater than the cross-section of the direct formation of (e^+e^-) pairs by electrons. The results of some experiments carried out by the electron method using < 1 GeV electrons agree with the theory[10,11].

For electron energies $E_0 \geq 1$ GeV the only data are those obtained by the method of nuclear emulsions irradiated with cosmic rays (e.g., ref. 12). The resulting cross-sections are 3-4 times those predicted by Bhabha's theory[1].

Weill[13] analyzed the nuclear-emulsions method of measuring the cross-section of reaction (1), and concluded that there is a discrepancy between the theory and the experimental results. On the other hand, in ref. 14 it is pointed out that the statistics in all these works are very limited (60 events of types (1), (2), and (3)); the background level is high (~ 80%), and the inaccuracies in the measurements of the primary-electron energy are large. The experimental results are thus uncertain.

It may be seen that the formation of (e^+e^-) pairs by electrons has so far been little studied experimentally and theoretically, and that further investigation of this process is of interest.

2) Experimental Method

The formation of (e^+e^-) pairs by electrons was studied with the aid of an LVE OIYaI [JINR] 24-1 propane bubble chamber in a magnetic field of 14.3 kgauss. The chamber was irradiated with a beam of π- mesons ($\sim$ 90%), μ- mesons ($\sim$ 8%), and electrons ($\sim$ 2%) with $pc = 4.00 \pm 0.06$ GeV (refs. 15-17).

The stereophotographs were scanned in such a way as to exclude the background of events due to the π- mesons. Cases satisfying the following requirements were finally selected:

1. The distance of the (e^+e^-) pair from the primary trace ($\sim$ 70 μ wide) on the left and right stereoframes should be $< 200\ \mu$.

2. The energy of the primary particle $E \geq 1250$ MeV. There is no break on the primary track at the point of the formation of the (e^+e^-) pair ($\theta \leq 1^\circ$).

3. The energy of the (e^+e^-) pair is $E_\gamma \geq$ MeV , and the electron and positron energies E_+ and $E_- \geq 2$ MeV.

4. The angle between the axis of the (e^+e^-) pair and the primary track is $\theta_{1,\gamma} < 5^\circ$.

In all, about 25,000 frames were scanned, collecting 451 events. The entire material was scanned twice, and the effectiveness of this double scanning proved to be $\epsilon = 96\%$.

In 80% of the events (e^+e^-) pairs were identified by ionization, energy discharge, δ-electrons, and the range-energy ratio[18]. The particle energy was determined with allowance for losses due to ionization and radiation[19]. The errors in the determination of the energies of e^+ and e^- amounted to 10-20%.

The main background process was electron bremsstrahlung accompanied by conversion of γ- quanta into (e^+e^-) pairs near the primary track. At moderate conversion lengths $(\ell \lesssim 9$ cm) we can neglect the angular distribution of the bremsstrahlung γ- quanta $(\bar{\alpha} = \frac{mc^2}{E} \approx 2 \times 10^{-4}$ rad) (ref. 20), multiple electron scattering in propane $(\sigma_S^2 \approx 10^7 \ \ell^3$ cm^2) (ref. 21), and their energy losses. In this approximation the electron after emission of a γ- quantum moves in a circle of radius $R = K (E - E_\gamma)$, where $K = 0.23$ cm/MeV for $H = 14.3$ kgauss.

We denote the distance between the axis of the (e^+e^-) pair and the axis of the primary track by ξ, and put $\xi > 0$ if the apex of the (e^+e^-) pair lies outside the circle (R) but $\xi < 0$ if it is inside (R). With the above approximations we find:

$$\xi = \frac{\ell^2}{2R} . \tag{4}$$

Evidently for the background processes (2) and (3) the value of ξ has a wide distribution ($\xi \geq 0$), while for the process (1) $\xi = 0$ if we disregard errors in the measurements. The cross-sections of electron bremsstrahlung and photo-formation of (e^+e^-) pairs in the substance are well-known[22-27]. We can thus isolate quantitatively the direct formation of (e^+e^-) pairs in the region of $\xi \approx 0$.

A special method was developed for measuring the axes of single tracks and axes of (e^+e^-) pairs in bubble chambers[9]. The measurements were done using an MBI-9 microscope with an eyepiece-micrometer (15 X 6.3). One micrometer division corresponds to 1.83 μ on the film frame.

The magnification of the optical system of the camera* was $\varkappa = 10 \pm 0.4$.

* Translator's Note: Russian "kamera", earlier translated as "chamber". The above meaning seems, however, more logical in this context.

For each selected event we measured ξ on the left and right stereo-frames (ξ_ℓ and ξ_r). From two independent measurements on two different sections of the tracks of particles from the (e^+e^-) pair and of the primary electron we determined the error $\sigma_\xi = 2.1 \pm 0.2$ div. The track lengths used corresponded to 2-5 bubbles. The high accuracy of the ξ determinations was due to the small scatter of the bubble centers around the true particle trajectory[28] and to the fact that the growth of bubbles in the relatively small chamber volume occurs under the same conditions (σ_ξ is $\sim \frac{1}{15}$ of the track width).

The distribution of the collected events over the magnitude of $\Delta = \xi_\ell - \xi_r$ is illustrated in Figure 1. The events are found mainly in the interval $|\Delta| < 10$ div. (358 cases), with $\bar{\Delta} = 0.2 \pm 0.2$ div. and $\sigma_\Delta = 3.1$ div. On the other hand, for the background events (2) and (3) the magnitude of Δ has been calculated allowing for the angular distribution of the bremsstrahlung γ- quanta and the optical system of the camera.

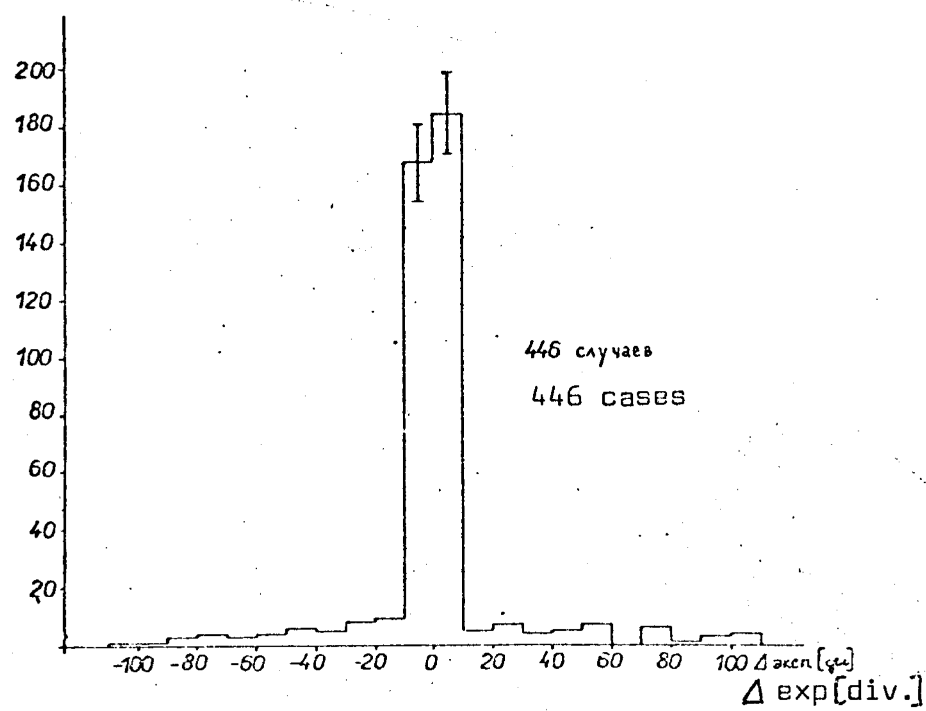

Figure 1: Histogram showing the distribution of the collected events over the magnitude of $\Delta = \xi_l - \xi_r$.

It was found that events with $\xi \leq 100$ div. should have $\Delta \lesssim 2.8$ div, so that the cases with $|\Delta| \geq 10$ div. may be regarded as random superpositions of (e^+e^-) pairs on tracks of the primary particles, mainly π- mesons. Such (e^+e^-) pairs arise as a result of the conversion of γ- quanta formed in the entry window of the chamber, which comprises ~ 0.3 rad unit of length. Scanning revealed 8(10) secondary nuclear interactions on the primary track past the apex of the (e^+e^-) pair for events with $|\Delta| > 10$ div. and 3(40) interactions for cases with $|\Delta| \leq 10$ div. [The values in parentheses indicate the expected number of nuclear interactions if the primary particles are π- mesons].

Histograms of the distribution of the observed events over the values of ξ_ℓ and ξ_r (Figure 2) show that the events with $|\Delta| \geq 10$ div. have a uniform distribution over ξ (the cases with $|\Delta| \geq 10$ div. are hatched in Figure 2).

Further below we shall confine ourselves to the events with $\xi \leq 30$ div., since in the region of $\xi > 30$ div. there are cases where the γ- quantum was formed in the entry window of the chamber, which complicates considerably analysis of the experimental material.

Analysis of the possible background events showed that the admixture of random superpositions of (e^+e^-) pairs, bremsstrahlung of π- and μ- mesons, and inelastic nuclear interactions of π- mesons amounts to $\sim 3\%$ of the events of types (1), (2), and (3) with $|\Delta| \leq 10$ div. and $\xi \leq 30$ div.

The admixture of secondary electrons with $E \geq 1.25$ GeV is $1.1 \pm 0.6\%$ of the number of electrons in the beam.

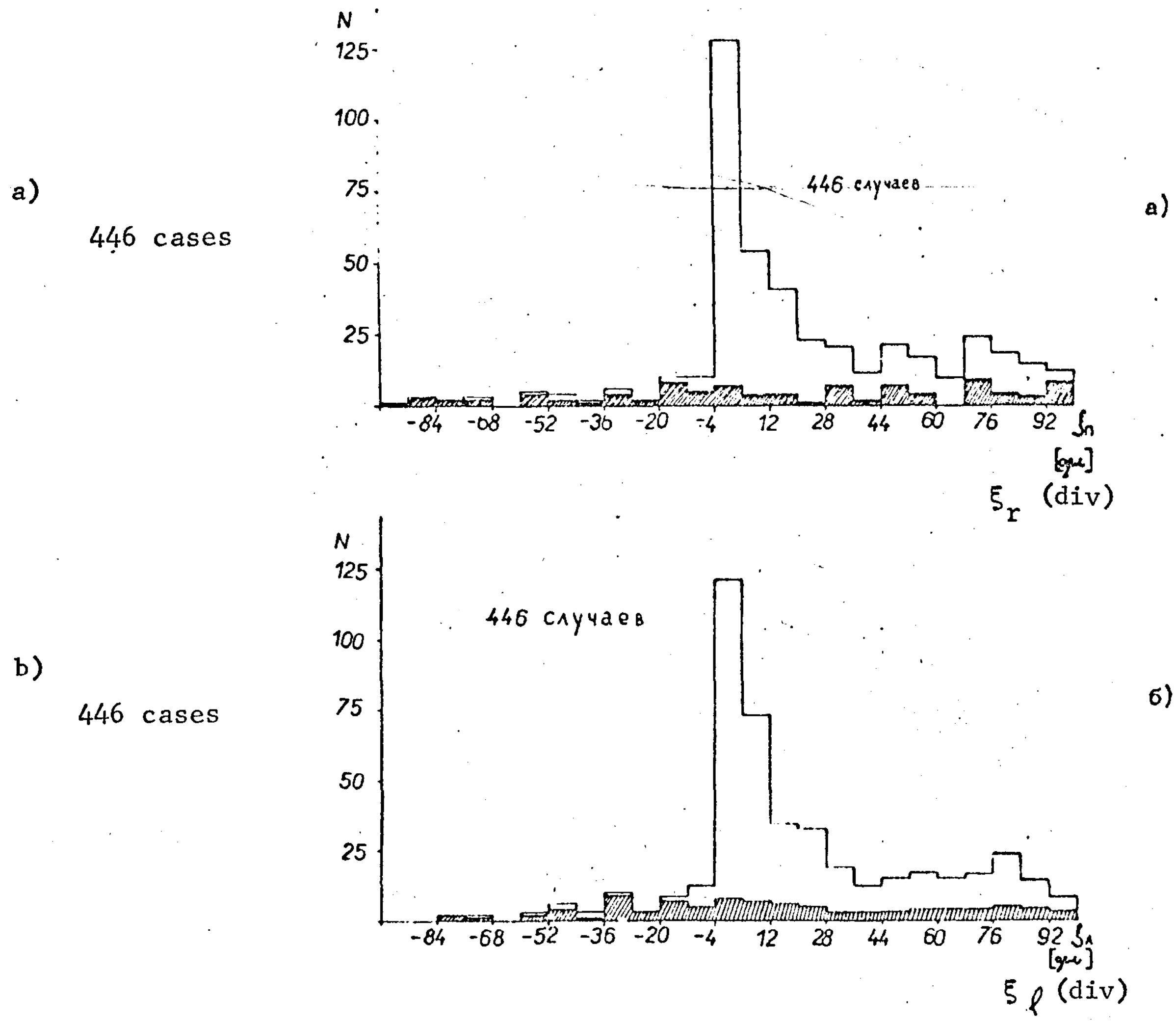

Figure 2*: Histograms of the distribution of the collected events, over the values of ξ_ℓ (a) and ξ_r (b).

Translator's Note: Diagrams (a) and (b) have probably been interchanged; cf. caption.

3) Results

The distributions $\frac{dN}{d\xi}$ and $\frac{dN}{dE_\gamma}$ for processes (2) and (3) were calculated from the Bethe-Heitler formulae[22] with allowance for screening of the nuclei by atomic electrons and for corrections to the Born approximation[23]. The cross-sections of electron bremsstrahlung and the photo-formation of (e^+e^-) pairs in the field of atomic electrons were calculated from the Wheeler-Lamb theory[24], introducing corrections for the difference between the distributions of momenta transferred to the electron and the proton[25]. The distributions $\frac{dN}{d\xi}$ and $\frac{dN}{dE_\gamma}$ were averaged over the theoretical energy spectrum of the electrons at various points of the effective volume of the chamber[29]. The energy spectrum of the electrons was calculated with an allowance for their energy losses in the entry window of the chamber, monitor counters, etc. (the total thickness of matter is $t = 0.4$ rad. units). The corrections introduced into the distributions $\frac{dN}{d\xi}$ and $\frac{dN}{dE_\gamma}$ in connection with the various approximations and the error in the measurement of ξ were $\sim 3\%$ in region I $(|\xi| \lessapprox 3\,\sigma_\xi = 6$ div.) and $\sim 1\%$ in region II $(6 \le \xi \le 30$ div.). All the calculations were performed on a computer, and the total error in the calculation of the background distributions $\frac{dN}{d\xi}$ and $\frac{dN}{dE_\gamma}$ due to inaccuracies in the theoretical cross-sections of (2) and (3) did not exceed 5%.

The calculated curve of $\frac{dN}{d\xi}$ was normalized to the number of experimentally observed events in region II, where there were only background events. A histogram of the distribution of the collected cases with $10 \leq E_\gamma \leq 810$ MeV and $1.25 \leq E \leq 4$ GeV is given in Figure 3. The broken line shows the theoretical histogram. It may be seen that the theoretical distribution describes quite well the experimental data in region II. On the other hand, in region I ($|\xi| \leq 6$ div.) above the background curve there are 64 events due to direct formation of (e^+e^-) pairs.

The histogram of the distribution of cases from region II over the energy of (e^+e^-) pairs agrees well with the calculated distribution $\frac{dN}{dE_\gamma}$ (Figure 4).

The number of primary electrons in region II was determined as $N_0 = 1.8 \pm 0.3$ % of all particles in the beam, which coincides with the results of other experiments: $N_0 = 2.3 \pm 0.4$ % (ref. 17) and

N_0 = 2.2 ± 0.6 % (ref. 16). The values of N_0 for various limiting values of E_γ and E agree between themselves within the framework of a single error.

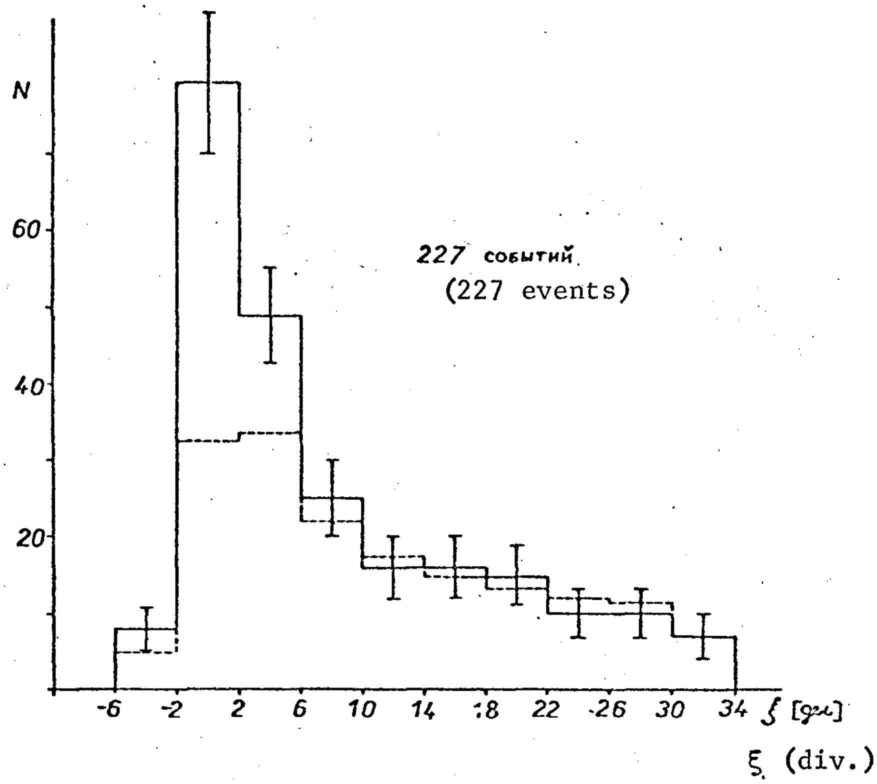

Figure 3: Histogram of the distribution of collected events over the value of ξ . The broken line shows the theoretical distribution $\frac{dN}{d\xi}$ for processes (2) and (3).

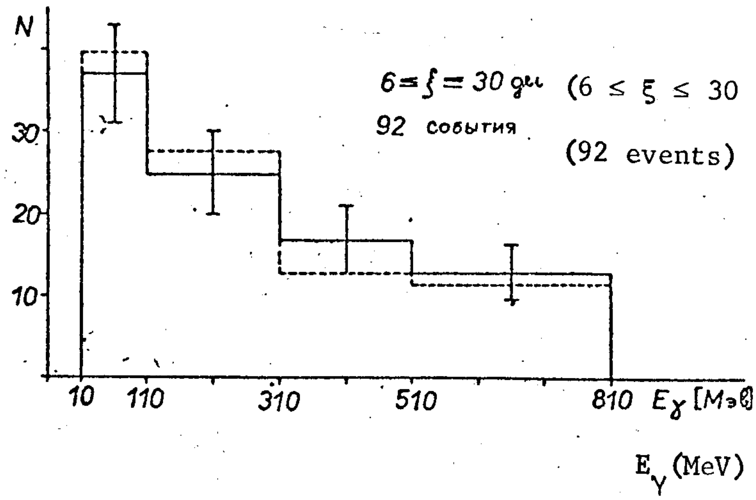

Figure 4: Histogram of the distribution of events in the region $6 \leq \xi \leq 30$ div. over the energy of the (e^+e^-) pairs. The broken line shows the theoretical distribution $\frac{dN}{dE_\gamma}$ for processes (2) and (3).

The experimental energy spectrum of the primary electrons is well described by the theoretical distribution (see Figure 5)[22,24,29].

In the collected events there are cases due to the process:

$$\pi^-(\mu^-) + Z \rightarrow \pi^-(\mu^-) + Z + e^+ + e^- . \qquad (5)$$

In connection with this the theoretical histogram of Figure 5 was normalized for the range $1.25 \leq E \leq 3.25$ GeV .

The agreement of theoretical and experimental distributions for

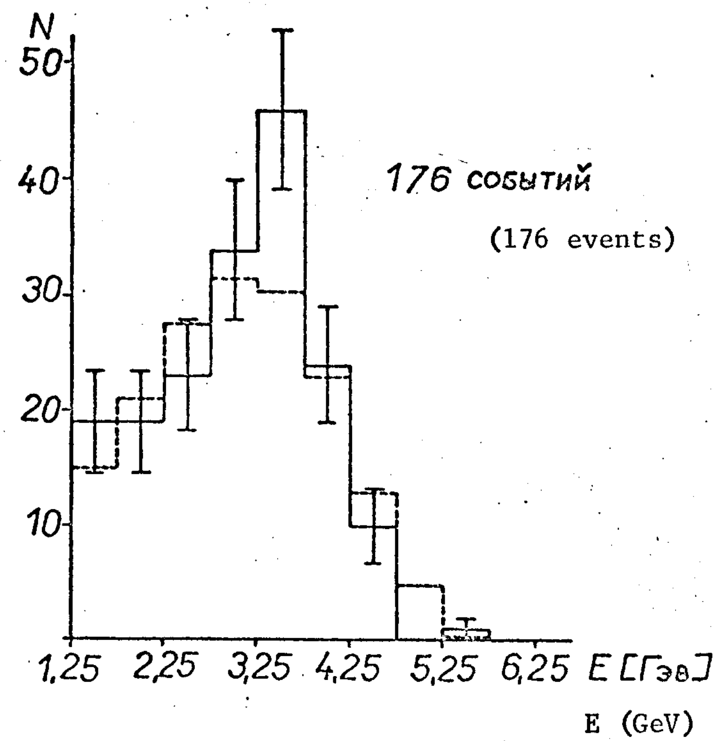

Figure 5: Histogram of the distribution of the collected events over the primary electron energy. The broken line shows the theoretical histogram, normalized for the number of events in the range $1.25 \le E \le 3.25$ GeV .

the background processes (2) and (3) and N_0 with other experiments thus serves as an additional confirmation of our method.

We shall now pass to the determination of the cross-section for the direct formation of (e^+e^-) pairs. For a comparison of the experimental results with theory it is convenient to use a quantity σ^T_{exp} , proportional to the sum of the cross-sections of reactions (1) and (5).

The values of σ^{T}_{exp} for various energy ranges $E_{\gamma min} \leq E_{\gamma} \leq 810$ MeV and $1.25 \leq E \leq E_{max}$ are given in Table 1.

(TABLE 1) Таблица I

	I,25 ≤ E ≤ 4 Гэв (1.25 ≤ E ≤ 4 GeV)					I,25 ≤ E ≤ 3,2 Гэв (1.25 ≤ E ≤ 3.2 GeV)
$E_{\gamma min}$ /Мэв/ (MeV)	I0	30	60	90	I60	I0
a) $\sigma^{T}_{экс}$ /мб/	22.7 ± 4	I7.3±5.7	II.8±4.8	8.7±4.2	4.9±3.3	7.8±5.4
b) $\sigma^{T}_{\pi,\mu}$ /мб/	5.3 ± 0.8	I.7±0.3	0.53±0.08	0.25±0.04	0.06±0.0I	-
c) σ^{T}_{e} /мб/ (Баба)	I3.2	I0.0	7.6	6.2	4.2	6.8
d) σ^{T}_{e} /мб/ (Мурота) $\alpha \approx 1,7$	I4.8	I2.5	I0.2	8.7	6.4	-

Key: a) - σ^{T}_{exp} (mb)

b) - $\sigma^{T}_{\pi,\mu}$ (mb)

c) - σ^{T}_{e} (mb) (Bhabha)

d) - σ^{T}_{e} (mb) (Murota)

$\alpha \approx 1.7$

The results were compared with Bhabha's[1] theoretical cross-sections of electrons and Kel'ner's[8] for π- and μ- mesons*. In the calculations of the corresponding values σ^{T}_{e} and $\sigma^{T}_{\pi,\mu}$ screening was neglected and the formation of $(e^{+}e^{-})$ pairs in the field of atomic electrons was considered by the replacement of Z^{2} with $Z(Z + 1)$ in the

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* Bhabha's[1] formulae depend on two constants usually put equal to unity.

expressions for the cross-sections of reactions (1) and (5) (Z is the atomic number of the nucleus). The results of the calculations are given in Table 1.

It was found that the ratio of the cross-section for the formation of (e^+e^-) pairs by electrons and π- and μ- mesons to the theoretical cross-section is

$$\frac{\sigma^T_{exp}}{\sigma^T_e + \sigma^T_{\pi,\mu}} = 1{,}2 \pm 0{,}3 . \qquad (6)$$

The differential cross-sections of processes (1) and (5) in dependence on the energy of (e^+e^-) pairs agree with the theoretical ones (Figure 6).

The ratio of the obtained cross-section for the formation of (e^+e^-) pairs by electrons to the cross-section calculated theoretically for $1.25 \leq E \leq 4$ GeV is:

$$\frac{\sigma^T_{exp} - \sigma^T_{\pi,\mu}}{\sigma^T_e} = 1{,}3 \pm 0{,}5 . \qquad (7)$$

The obtained results also do not contradict the theory of Murota et al.[3] if the integration parameter α used in the derivation of the formulae is taken as ~ 1.7 .

Thus the obtained cross-sections for the direct formation of

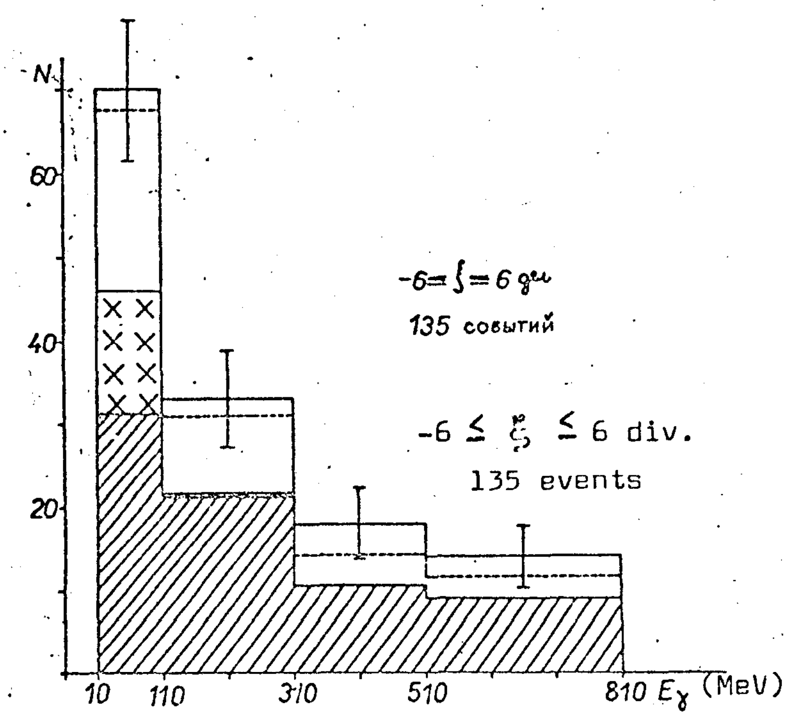

Figure 6: Histogram of the distribution of events from the region $|\xi| \leq 6$ div over energies of (e^+e^-) pairs. The broken line denotes the total theoretical spectrum $\frac{dN}{dE_\gamma}$ for processes (1), (2), (3) and (5). The contribution of reaction (5) is denoted by crosses, and the contribution of reactions (2) and (3) is hatched.

(e^+e^-) pairs by electrons agree with those calculated theoretically within the framework of a single error, which contradicts the results obtained with the aid of nuclear emulsions[12].

The method used in this experiment makes it possible to investigate successfully the formation of (e^+e^-) pairs by electrons with the aid of a hydrogen bubble chamber, since the background from processes (2) and (3) will then be about 10 times smaller (L_{rad} (H) = 10 m; $L_{rad}(C_3H_8)$ = 1 m).

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