ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ СО АН СССР

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# $e^+e^-$-PAIR PRODUCTION BY A SYNCHROTRON RADIATION PHOTON ON A COUNTER BEAM ELECTRON

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## ABSTRACT

The Bethe-Heitler process of $e^+e^-$-pair production was observed for the first time in the collision of a synchrotron radiation photon on the electron of the counter beam. The experiment was performed with the detector MD-1 at the storage ring VEPP-4 at the c.m. energy of 10.28 GeV. At this energy the counting rate is comparable with that of the reaction $e^+e^-\to e^+e^-e^+e^-$. The data are consistent with the QED expectations.

## 1. INTRODUCTION

Production of $e^+e^-$-pairs by high-energy photons in the field of an electron [1] refers to the reactions, studied by Bethe and Heitler as early as the beginning of 30's [2].

The process of $e^+e^-$-pair production by photons on atomic electrons was observed in cloud and bubble chambers [3], as well as in strimer chamber experiment [4]. The total cross section of this process was mainly measured in beam absorption experiments [3]. The accuracy of these experiments was about 10% [3].

This experiment was performed at the storage ring VEPP-4 with the MD-1 detector [5]. The distinctive feature of MD-1 is that its magnetic field is perpendicular to the orbit plane. As a result synchrotron radiation (SR) photons of beam electrons collide with the second beam in the interaction region. This peculiarity of the detector was used for the measurements of the beam polarization by the asymmetry in a scattering of SR photons on the colliding beam electrons [6] in the high precision measurements of the $\Upsilon$-meson masses [7—9].

Interaction of SR with colliding beam can also be due to the Bethe—Heitler process

$$\gamma e\to ee^+e^- , \qquad (1)$$

which is a subject of this work. Unlike the previous experiments, in our case photons interact with free electrons.

However another problem arises in such an experiment (see Fig. 1): a considerable part of SR photons is formed inside the «target»—a colliding electron bunch. In this case the photon can cause the Bethe—Heitler process when its formation has not been finished. This effect can also take place in a process of Compton scattering of SR photons on colliding beam. As far as we know, the problem of cross section calculation in such situation has not yet been solved. Naturally, the difference from the case of real photons depends on the relationship between the photon formation length (coherence length) and the effective distance to the colliding bunch electron. For the formation length of a photon with an energy of $\omega \lesssim \omega_c$ one can approximately write [10]

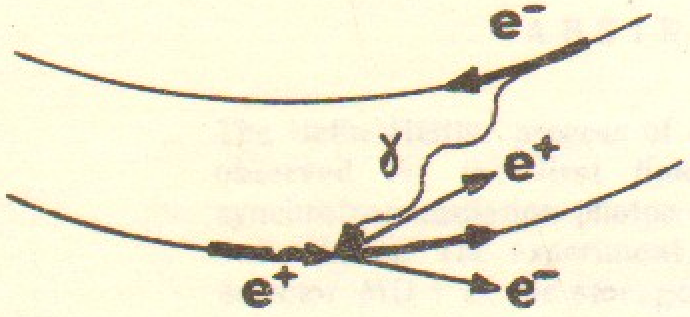

*Fig. 1.* Schematic view of the process $\gamma e \to e e^+ e^-$.

$$l_{coh} \approx \frac{R}{\gamma}\left(\frac{\omega_c}{\omega}\right)^{1/3},$$

where $R$ is the orbit radius, $\gamma$ is the electron gamma factor, $\omega_c(\mathrm{keV}) = 1.74 \cdot 10^{-8}\gamma^2 H(\mathrm{kG})$ is the critical SR photon energy, $H$ is the magnetic field in the detector. The effective distance to the colliding bunch electron can be estimated from the geometry of collision [11]

$$l_0 \approx \sqrt{2R\sigma_r},$$

where $\sigma_r$ is a rms radial beam size. For our experiment $l_{coh} \lesssim 0.4$ cm, $l_0 \approx 14$ cm. Hence, one can see that the fraction of interactions with the distance of the order of $l_{coh}$ is about several percent. At our experimental accuracy ($\sim 10\%$) it is not possible to observe the contribution of this effect.

However a situation can arise, as for example at VLEPP [12], when $l_{coh}$ becomes of the order a bunch length (at $\omega < 10$ eV). Then in processes of interaction of SR photons with each other and with colliding beam electrons, representing the main source of QED background [14], the discussed effect would play a considerable role.

## 2. CROSS SECTION OF THE PROCESS

A counting rate of the Bethe—Heitler process can be written in terms of the luminosity of electron-photon beams and the cross section. But, to compare the counting rate due to this reaction with that of the processes in $e^+e^-$-collisions, it is convenient to introduce a cross section, connected with the luminosity of electron-positron beams by the relationship, usual for $e^+e^-$-colliding beams: $\dot{N} = \sigma_{obs} L$. This cross section will be called the «observable» cross section:

$$\sigma_{obs} = \int_{\omega_{min}}^{\omega_{max}} \frac{dN}{d\omega\, dt} \frac{l_{ef}(\omega)}{c} \sigma(E, \omega)\, d\omega, \qquad (2)$$

where $\frac{dN}{d\omega\, dt}$ is the SR spectrum; $\omega_{min}$, $\omega_{max}$ are the limits on the SR energy, determined by detection conditions; $l_{ef}(\omega)$ is the effective length of the beam trajectory, SR photons from which make a contribution to the counting rate; $\sigma(E, \omega)$ is the cross section of the process under consideration; $E$, $\omega$ are the beam and SR photon energy, respectively; $c$ is the speed of light.

With the vertical displacement of the beams $l_{ef}$ increases, causing an increase of the «observable» cross section (but not the counting rate). This effect was studied in the experiment.

For the beams separated by a distance $\Delta z$ one can derive the following formula for $l_{ef}(\omega)$:

$$l_{ef}(\omega) = l_0 \int_{-\infty}^{+\infty} \frac{dW}{d\psi}\, d\psi \int_0^{\infty} d\tau\, \frac{\exp\{-\tau^4/4 + g(\psi, \tau)\}}{\sqrt{h(\tau)}} \qquad (3)$$

where $\frac{dW}{d\psi}$ is the distribution of SR over $\psi$ — the emission angle of photon relative to the orbit plane [10]; $g(\psi, \tau) = 0.25\left[n^2 - \frac{(n + p\tau\psi)^2}{h(\tau)}\right]$; $h(\tau) = 0.5 p^2 \sigma_\beta^2 \tau^2 + 1$; $n = \Delta z/\sigma_z$; $p = l_0/\sigma_z$; $\sigma_\beta = \sigma_z/\beta_z$ is the rms vertical angle of beam particles; $\sigma_z$ is the rms vertical size of beam; $\beta_z$ is the vertical beta function of the storage ring. In the limit $\omega \to \infty$ for $\Delta z = 0$ one obtains $l_{ef} = 1.28 l_0$. When deriving formula (3) we assumed the beam density distribution to be

Gaussian and neglected the angular distribution of SR and the angular spread of beam particles in the orbit plane, since the width of these distributions is much less than a characteristic angle $l_0/R$, due to the collision geometry.

In Fig. 2 we show the result of the calculation of $l_{ef}(\omega)$ for several values of $\Delta z$.

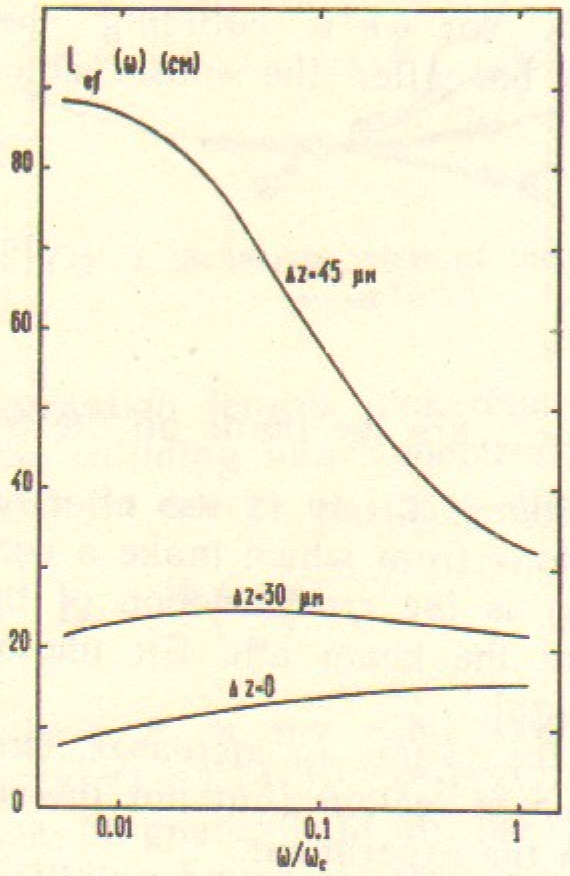

*Fig. 2.* Energy dependence of the effective length for $E_B = 5.14$ GeV, $H = 12.5$ kG, $\sigma_z = 12.5$ μm, $\sigma_r = 0.07$ cm.

During the experiment electron and positron beams were kept unpolarized. In the interaction of SR photons with an unpolarized beam, the linear polarization of SR photons does not change the cross section of the process (1), causing only an azimuthal asymmetry of reaction products [14] (the cross section does not depend on circular polarisation of photons). Nevertheless in our experiment this asymmetry does not play any role, since the emission angles of pair particles relative to the collision axis are very small — $\lesssim 10^{-2}$ rad. Therefore, calculations were carried out for the case of unpolarized initial particles.

For the Monte-Carlo generator of events we used the differential cross section, calculated with the help of main diagrams. We checked that in this case the cross section (2) differs less than by 1% from the calculation taking into account all diagrams of the third order in $\alpha$ [1]. The contribution of radiative corrections must also be small [3].

The main physical background, kinematically indistinguishable from the effect, comes from the process first calculated by Landau and Lifshitz [15]

$$e^+e^- \to e^+e^-e^+e^- \quad \text{(Landau—Lifshitz process)}. \qquad (4)$$

This process was for the first time observed at the VEPP-2 collider [16]. It is well studied theoretically [17] and was measured in many detectors [18], as well as in MD-1 [19].

In Fig. 3 we show the «observable» cross section of the process $\gamma e \to ee^+e^-$ as a function of the beam energy $E_B$ and the cross section for $e^+e^- \to e^+e^-e^+e^-$. One can see that at the energy about 5 GeV these cross sections are comparable.

In Fig. 4 we show the calculated cross sections for Bethe—Heitler and Landau—Lifshitz processes at $E_B = 5.14$ GeV for the effective mass of $e^+e^-$-pair greater than a certain value. The «observable» cross section for $\gamma e \to ee^+e^-$ quickly decreases, due to exponential decrease of the SR intensity at the energy above the critical one.

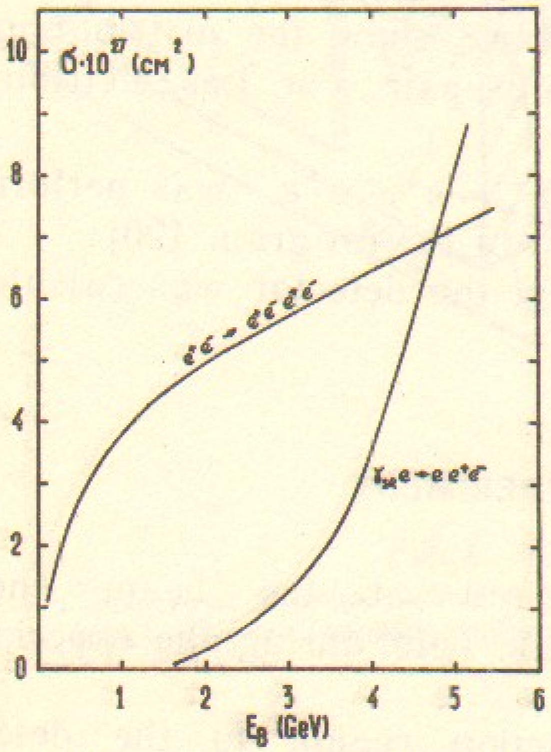

*Fig. 3.* Cross sections of the processes $\gamma e \to ee^+e^-$ and $e^+e^- \to e^+e^-e^+e^-$ vs beam energy.

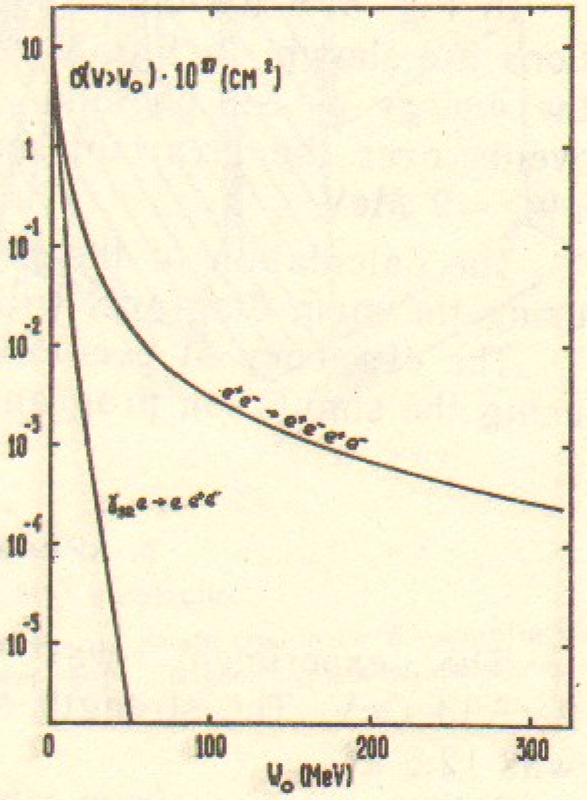

*Fig. 4.* Cross sections of the processes $\gamma e \to ee^+e^-$, $e^+e^- \to e^+e^-e^+e^-$ for the effective mass of a produced $e^+e^-$-pair greater than a certain value. $E_B = 5.14$ GeV.

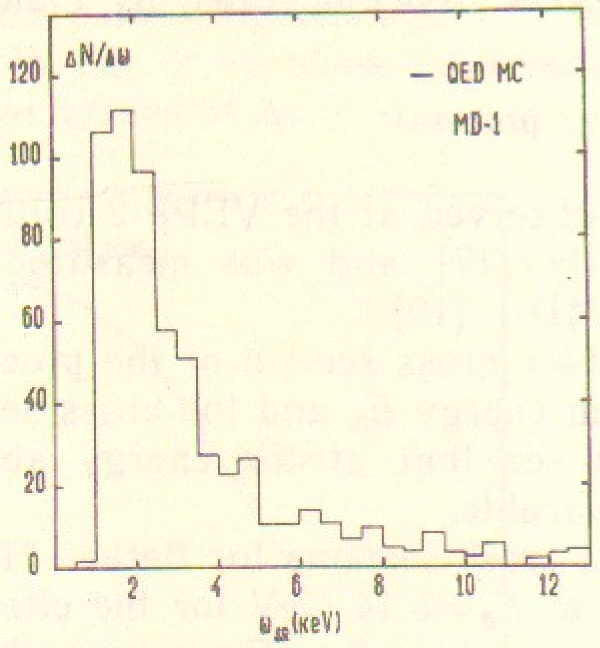

*Fig. 5.* Distribution over the SR photon energy for detected events.

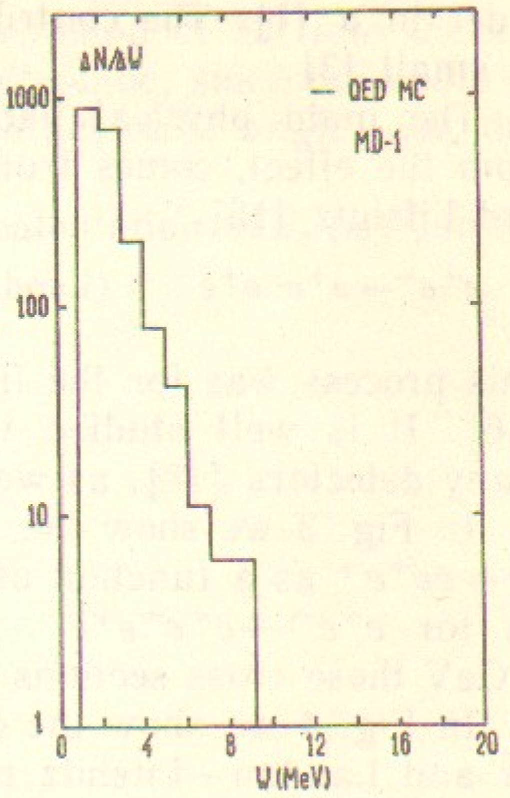

*Fig. 6.* Distribution over the mass of $e^+e^-$-pair for detected events.

In Fig. 5, 6 the distributions obtained under the detection conditions are shown. In Fig. 5 we present the distribution of events over the energy of SR photons. In Fig. 6 we show the distribution of events over the invariant mass of $e^+e^-$-pair. For this distribution $\langle W\rangle \approx 2$ MeV.

The calculation of the process $e^+e^- \to e^+e^-e^+e^-$ was performed using the main diagrams with the help of the program [20].

The efficiency of event detection in the detector was calculated using the simulation program [21].

### 3. APPARATUS. EXPERIMENT

The experiment was carried out at the beam energy $2\times5.14$ GeV. The strength of magnetic field during the experiment was 12.5 kG.

While moving from the interaction region to the detector (Fig. 7) particles cross the vacuum chamber of $0.085X_0$ thickness. For the detection of charged particles and the measurement of their momenta the system of 38 proportional chambers with a maximum size of $0.9\times0.9$ m was used. Wire spacing of momentum measuring

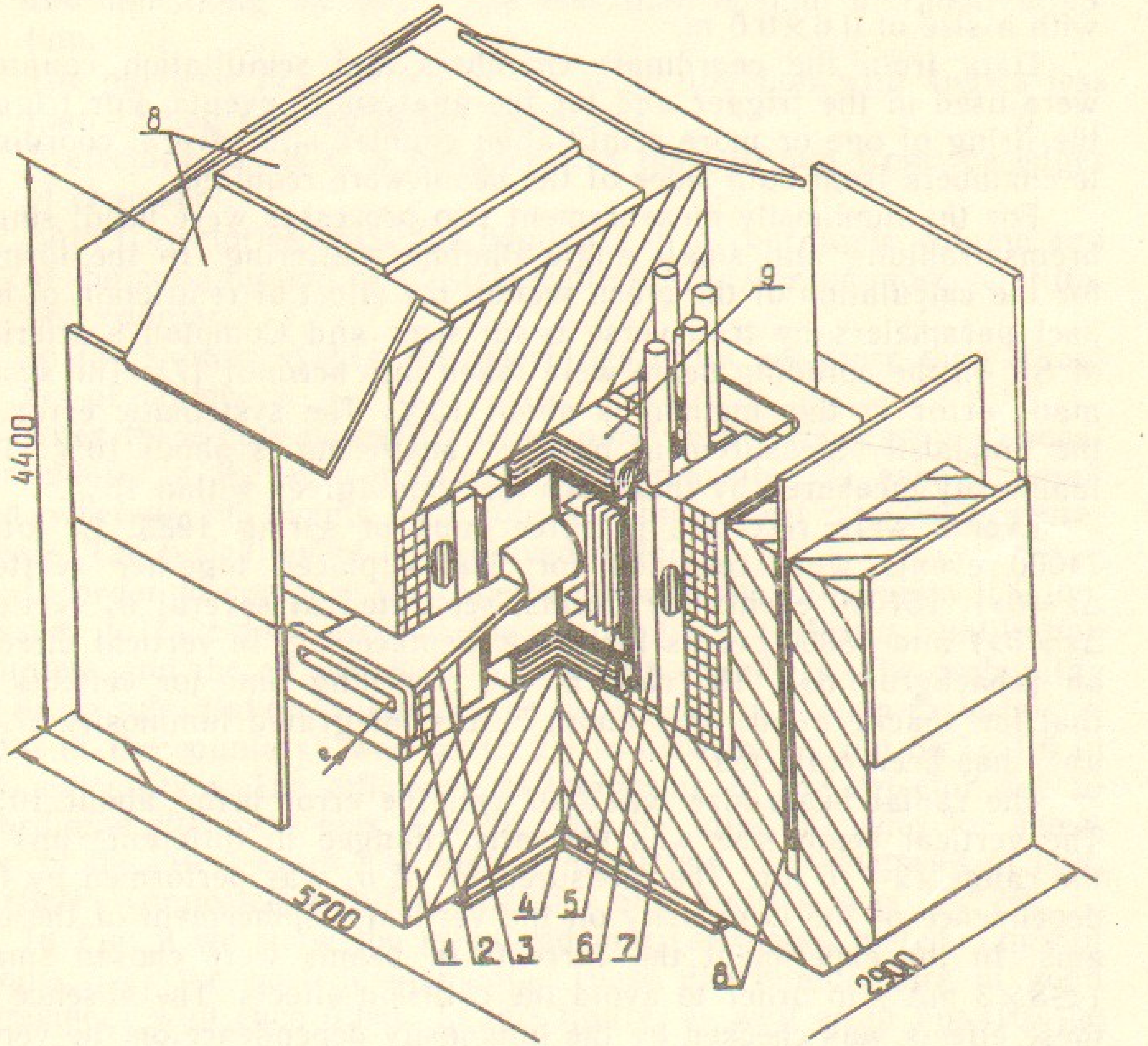

*Fig. 7.* Layout of the MD-1 detector:

*1*— magnet yoke; *2*—copper winding; *3*—beam pipe; *4*—coordinate chambers; *5*—scintillation counters; *6*—gas Cherenkov counters; *7, 9*—shower-range chambers; *8*—muon chambers.

chambers is 2 mm and that of measuring vertical coordinate—4 mm. The total number of electronics channels is 12000. The coordinate chambers are surrounded by 24 scintillation counters, placed on sides of a cube of 1.2 m. Each side contains 4 counters with a size of $0.6\times0.6$ m.

Data from the coordinate chambers and scintillation counters were used in the trigger and for the analysis of events. For trigger the firing of one or more scintillation counter and several coordinate chambers from both sides of the beam were required.

For the luminosity measurement two processes were used: single bremsstrahlung and small angle Bhabha scattering. In the former for the calculation of the cross section the effect of restriction of impact parameters by transverse beam sizes and Compton scattering of SR on the colliding beam were taken into account [7]. The systematic error in this method is about 15%. The systematic error in the luminosity measurement by $e^+e^-$ scattering is about 10%. The luminosity measured by these two methods agrees within 15%.

Events were recorded in three runs in spring 1983. In total, 74000 events were recorded for beams placed together («effect $\Delta z=0$»), 151000 events for beams, separated at several $\sigma_z$ («effect $\Delta z\neq0$») and 15000 events for large displacement in vertical direction («background»). The ratio of the recording time for «effect» to that for «background» was about 7. The integrated luminosity of 46 $\mu b^{-1}$ has been collected.

The radial beam size was 0.07 cm, the error being about 10%. The vertical beam size was specially changed in different runs in the range 12—16 μm. The measurement of $\sigma_z$ was performed by the dependence of the luminosity on the vertical displacement of the beams. In the experiment the currents of beams were chosen small ($\lesssim 3\times3$ mA$^2$) in order to avoid the collision effects. The absence of these effects was checked by the luminosity dependence on the vertical displacement of beams that was close to Gaussian.

## 4. DATA PROCESSING. COMPARISON WITH QED EXPECTATIONS

Selection of the effect events was performed using the following criteria based mainly on the geometrical characteristics of events.

— There is one reconstructed particle trajectory from each side of the interaction point.

— Trajectories lie nearby the orbit plane in the layer of 140 mm. For each particle the point of the trajectory closest to the beam has a distance from the center of interaction region less then 100 mm along the beam and less than 60 mm in radial direction.

— The particles are emitted in the same direction with angles less than 12 deg relative to the beam axis.

— Trajectories pass in a distance less than 10 mm from the edges of chambers.

— Both trajectories cross the boundary of a coordinate volume and at the continuation of the trajectories fired one or more scintillation counter.

— In the shower system the trjectories cross not more than 4 layers of chambers.

After these cuts no events were found in the «background» measurements, in the «effect $\Delta z=0$» measurements 324 events remained, whereas 206 events were found in the «effect $\Delta z\neq0$» measurements. The typical event is displayed in Fig. 8.

In order to compare the experiment with the calculation it is necessary to take into account the probabilities of firing scintillation counters and the efficiencies of coordinate chambers. The probability of firing scintillation counters (the inefficiency is due to materials in front of the counters) was $55.3\pm2.0$ in experiment and $56.7\pm1.6$ in MC calculation. The efficiency of triggering of the detector due to coordinate chambers was $90\pm2\%$, and the total efficiency for detection of the effect event and for reconstruction of trajectories of both particles, connected with the efficiency of chambers, was $77\pm2\%$.

In Fig. 9 we show the measured and calculated distributions of events over the particle momenta. These distributions are in good agreement with each other. In this figure, as well as in Fig. 10, the number of MC events is plotted at the vertical axis. For the experimental points the statistical errors are shown.

In Fig. 10 the distribution over the «visible» effective mass of produced pair is presented. The experiment and the MC calculation are in agreement with each other.

The effect of increase of «observable» cross section with the vertical displacement of the beams was measured in all experimental runs. In Fig. 11 we show the measured and calculated dependences of visible cross section $\sigma^{vis}(\Delta z)=\sigma_{B-H}(\Delta z)+\sigma_{L-L}$ on the displacement $\Delta z$ for one of the experimental runs. In the experimental error bars we have included errors due to statistics, an uncertainty of the

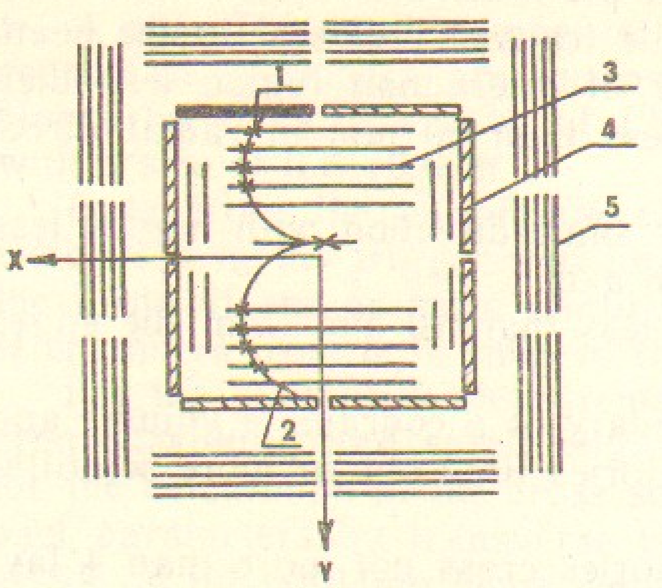

*Fig. 8.* View of an event in the MD-1 detector from above:
*1, 2*—a detected $e^+e^-$-pair; *3*—coordinate chambers: *4*—scintillation counters; *5*—shower-range chambers.

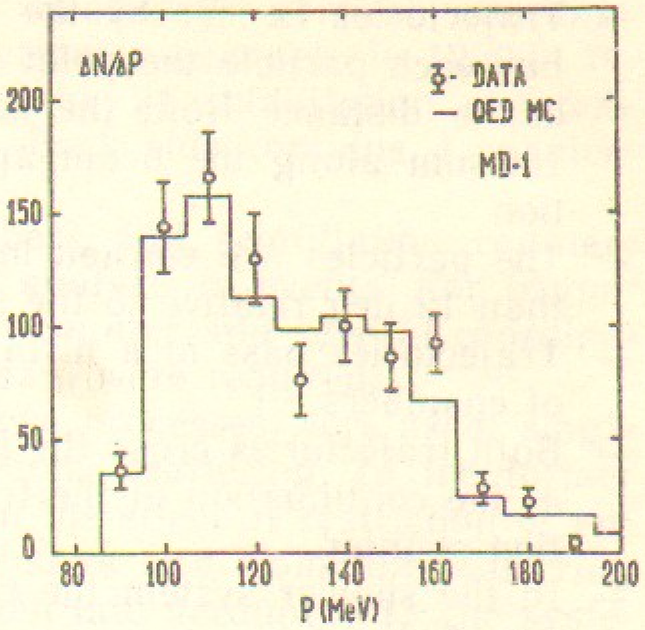

*Fig. 9.* Distribution over particle momenta.

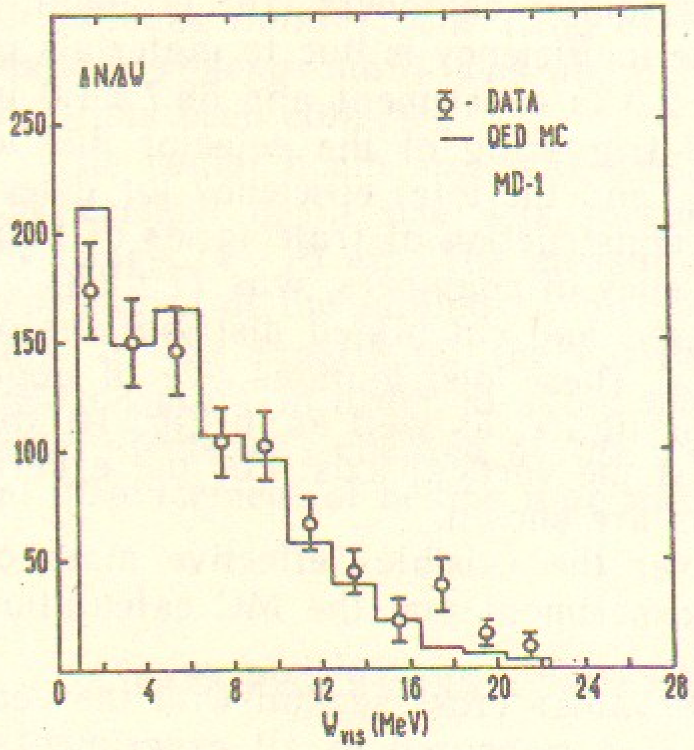

*Fig. 10.* Distribution over the visible invariant mass of the detected pair.

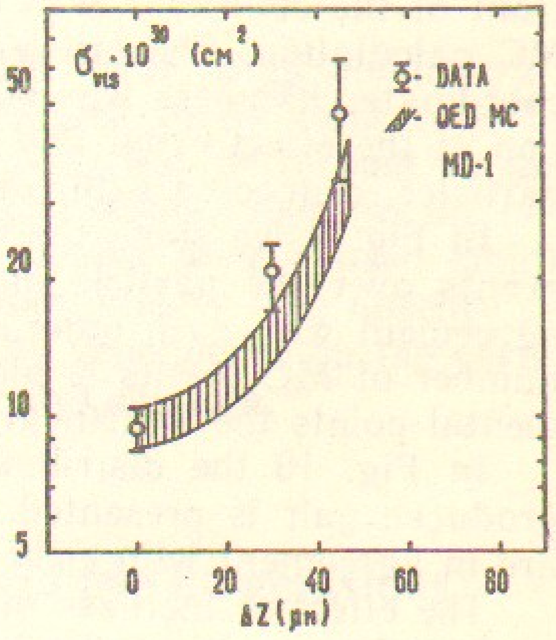

*Fig. 11.* Dependence of the visible cross section on the vertical displacement of beams for one of the experimental runs: $\sigma_z = 12.5$ μm; $\bar{\phi}$—experiment; dashed band—calculation ±rms error.

luminosity measurements and errors, due to uncertainties in the vertical beam size. The dashed area is the result of calculation, the width of the strip (two rms errors) is due to statistics and uncertainty of determination of the cross section for a limited phase space.

Calculation for $\Delta z = 0$ showed, that the cross section of the process depends weakly on the vertical beam size. This allowed us to sum the statistics of all runs. The obtained experimental cross section, corrected for the chamber inefficiencies, is equal to

$$\sigma^{vis} = 9.1 \pm 1.0\ \mu b,$$

where the error includs the statistical error, the uncertainty of the luminosity measurements and the error in determination of the chamber efficencies. The errors are added quadratically.

The calculated cross section of the Bethe—Heitler process is equal to $\sigma^{MC}_{B-H} = 7.1 \pm 0.7\ \mu b$ and of the Landau—Lifshitz process $\sigma^{MC}_{L-L} = 2.5 \pm 0.4\ \mu b$. The errors are due to the statistical uncertanties and errors of the determination of the cross sections for the limited phase space, which are added in quadrature. The total MC cross section is equal to

$$\sigma^{MC} = 9.6 \pm 0.8\ \mu b.$$

The result of the calculation is in agreement with the measured value.

In conclusion the authors express their gratitude to VEPP-4 and MD-1 staff, as well as to many other people, whose labor provided the performance of the present experiment.

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## Рождение $e^+e^-$-пары фотоном синхротронного излучения на электроне встречного пучка

Ответственный за выпуск С.Г.Попов

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