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EXPERIMENTS ON ELECTROPRODUCTION OF $e^+ e^-$ PAIRS WITH COLLIDING BEAMS AT NOVOSIBIRSK

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Résumé. — Nous présentons les résultats de deux expériences réalisées en 1969 et 1970 sur l'anneau de collision VEPP-2, concernant la réaction $e^- e^+ \rightarrow e^- e^+ e^- e^+$; nous donnons également les résultats des calculs correspondants de Baier et Fadin. Nous évoquons brièvement les perspectives d'avenir, plus particulièrement en ce qui concerne l'anneau de collision VEPP-4 (7 GeV par faisceau), actuellement en construction à Novosibirsk, et le détecteur magnétique MD-1 qui fonctionnera avec cet anneau.

Abstract. — We present the data of two experiments performed in 1969 and 1970 with VEPP-2, concerning the reaction $e^- e^+ \rightarrow e^- e^+ e^- e^+$, and of the corresponding analysis performed by Baier and Fadin. We also give an outlook on the future, in particular on the storage ring VEPP-4 (7 GeV per beam) now under construction at Novosibirsk, and on the magnetic detector MD-1 to be used with that machine.

Real photon-photon collisions have up to now been available only to theorists; however, considerable experimental data had been collected in this field long before the term « photon-photon collisions » became fashionable. During recent years, this term was applied to processes generated by virtual photons; in the case of a collision of a virtual photon with a real one it corresponds to photoproduction (e. g. Bethe-Heitler process, Primakoff effect), while in the case of the collision of two virtual photons it corresponds to electroproduction. The Novosibirsk group of physicists calls this type of electroproduction, in which the produced system of particles is kinematically symmetric with respect to both colliding particles (Fig. 1a), *symmetric electroproduction* in order to distinguish it from bremsstrahlung electroproduction (Fig. 1b).

FIG. 1. — Diagrams of electroproduction processes : a) symmetric electroproduction ; b) bremsstrahlung electroproduction.

During the last three years our group did not perform any measurements and so we have no new results at present. Therefore I will speak only about the past and the future, in accordance with the subject of the session.

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1. **The past.** — The process of electroproduction of $e^+ e^-$ pairs in the interaction of two relativistic particles was considered theoretically by Landau and Lifshitz in 1934 [1]. They calculated the cross-section of this process in the highest order logarithmic approximation, being essentially the equivalent photon approximation. A year later the same result was obtained by Williams [2]; then a number of theoretical and experimental papers appeared which studied electroproduction (or direct production) of electron-positron pairs when fast charged particles penetrated matter. A similar process of μ -meson pair production has also been observed [3].

The second wave of interest in electroproduction (to be more specific, in symmetric electroproduction) appeared 35 years after the basic paper by Landau and Lifshitz. It is connected with the development of the colliding beam method. We have every reason to suppose that the new generation of $e^+ e^-$ colliding beam machines will make symmetric electroproduction an important tool of particle physics. The high energy of the colliding particles and high luminosity allow production of « colliding beams » of virtual photons which, without any doubt, will be used for many interesting experiments. Perhaps the $\pi^+ \pi^-$ system in the 0^+ state will be one of the first to be investigated.

Physicists working with the colliding beam machines did pay attention to these possibilities but with some delay, and the initial experimental programs for $e^+ e^-$ storage rings did not envisage investigation of symmetric electroproduction. However, in 1960 two important works in this field appeared: Low [4] considered production of π^0 mesons, while the paper

of Calogero and Zemach [5] was devoted to $\pi^+ \pi^-$ pair production. The cross-sections obtained were too small for the first electron storage rings being discussed at that time.

Only the production of $e^+ e^-$ pairs having, according to Landau and Lifshitz, at that energy range, a cross-section of the order of 10^{-26} cm^2 could be observed with any storage ring of the first generation. The quantitative measurement of this purely electrodynamical process is of interest because it makes it possible to test the correctness of the methods of calculation, which are also used in more complicated cases. However, even the paper of Baier [6], who obtained the result of Landau and Lifshitz from more general considerations, was left unnoticed.

Theoretical papers concerning electroproduction on colliding beams attracted general attention during the Kiev Conference in 1970; the results of Novosibirsk theorists and of Brodsky and Kinoshita were widely discussed there. Since 1969 this problem has been considered also by Kessler and collaborators at the Collège de France.

The achievements of experimentalists are much more modest. The $e^+ e^-$ pair electroproduction ($e^+ e^- \rightarrow e^+ e^- + e^+ e^-$) was first observed with the colliding beams of VEPP-2 in Novosibirsk in 1969 [7], [8]. This observation was not planned. The aim of the experiment was to investigate the ϕ -meson resonance. Discussion of the origin of the unexpectedly observed events stimulated the first papers of Novosibirsk theorists devoted to « photon-photon collisions » [9]. In our paper [7] submitted to the Kiev Conference and having widespread distribution among the participants it was said :

« During the analysis about 100 non-collinear events were selected which did not belong to any of the six reaction channels considered. These events have zero ranges in shower chambers. The detection threshold for the fourfold coincidence circuit was 13 MeV for electrons and 35 MeV for pions. The rms angle of multiple scattering in foil is $\sim 5^\circ$ for these events. Therefore we may assume that in this process the electrons of $\sim 15 \text{ MeV}$ are detected. The distribution of these events as a function of beam energy shows that they are not connected with the ϕ -resonance.

The possible source of these events is the process of $e^+ e^-$ pair production

$$e^+ e^- \rightarrow e^+ e^- + e^+ e^-.$$

The total cross-section of this process is very large [1]. Unfortunately today we have no calculations of its energy and angular distribution. »

Soon after the Kiev Conference these calculations were performed by Baier and Fadin [10]. An excellent agreement of their results with experimental data [8] removed all the doubts that the observed events were due to the $e^+ e^- \rightarrow e^+ e^- + e^+ e^-$ process.

In 1970 one more experiment, in which the same process was observed, was performed with VEPP-2 at the total energy of 1.18-1.34 GeV [11]-[13]. In the same year as special experiment to observe $e^+ e^-$ pair electroproduction was performed in Frascati [14]-[16].

Before these experiments the electroproduction processes were not observed with the colliding beams in spite of a very large cross-section for the case of $e^+ e^-$ pair production. The fact is that the angular distribution of produced particles is sharply peaked in the direction of initial particles, while all the detection systems are placed at large angles. Also, the energy spectrum of produced particles is rather soft — the detection cross-section is inversely proportional to the square of the detection threshold of electrons. Thick plates of matter are usually placed in front of the scintillation counters to exclude the large background of soft particles; therefore the probability of detection of the $e^+ e^-$ pair electroproduction becomes negligibly small. The detection system of VEPP-2 had the lowest detection threshold.

The detection system used in the 1969 experiment (the first experiment) is shown in figure 2. It consisted

FIG. 2. — Detection system of the ϕ -meson experiment : 1) anticoincidence scintillation counter ; 2) lead absorber, 200 mm thick ; 3) range spark chamber ; 4) shower spark chamber ; 5) scintillation counters ; 6) duraluminium absorber, 20 mm thick ; 7) scintillation counters ; 8) thin plate spark chambers ; 9) γ -quantum removable converter ; 10) thin plate spark chambers ; 11) interaction region ; 12), 13) inner and outer vacuum chambers ; 14) storage ring magnet.

of two identical groups of optical spark chambers covering the solid angle of 2×0.9 sr near the vertical direction. Each group included coordinate, shower, and range chambers. The spark chambers were triggered by four coincidence scintillation counters. The detection threshold was 15 MeV for electrons and 35 MeV for pions.

Before the 1970 experiment (the second experiment) the detection system was somewhat modernized. The coordinate optical spark chambers were replaced by wire chambers, and threshold water Čerenkov counters were placed between the scintillation counters instead of aluminium filters. Owing to the Čerenkov counters, the detection threshold became 25 MeV for electrons and 50 MeV for pions.

In both experiments the selection of the $e^+ e^-$ pair electroproduction events was made using particle ranges. In the first experiment those events were selected where both particles had a range from 6.4 up to 16 g/cm²; in the second one the corresponding range interval was 10.5 to 20 g/cm².

In the second experiment the requirement of Čerenkov counter triggering was also imposed. Then the detection efficiency of the electron pair measured using the elastic scattering events was 72 %. The calculated value of the detection efficiency for a pair of pions have the ranges mentioned was less than 1 %.

The agreement between the experimental and calculated values of the multiple scattering angle confirms that the selected particles are electrons. For the first experiment the angle of multiple scattering in foil (0.1 g/cm² of iron and 0.05 g/cm² of aluminium) was 5.5°, and for the second one (0.5 g/cm² of iron) it was 9°. Note that these values of multiple scattering angles correspond for pions to the energy of 8 MeV and 13 MeV in the first and second experiments, respectively, i. e. much less than the detection threshold.

The data of the two experiments are presented in table I. The luminosity integral was determined using the process of elastic $e^+ e^-$ scattering detected by the same apparatus. The background measurements were performed with two beams vertically displaced from each other by 2 mm and they took about 30 % of the total time of the experiments. For the second experiment only summary results at three energy values are given, due to low statistics.

In the first experiment, because of the different background conditions, it proved convenient to divide the whole observation region into two parts with respect to the discolinearity angle $|\Delta\theta|$ between the particle tracks, where θ is the angle of a particle track to the beam direction.

In the second experiment, the admixture of other multiparticle events [17] could be made negligible providing that the information from Čerenkov counters was used. In the first experiment the admixture

TABLE I

Experiments	First 1969	Second 1970
Energy $2E$, GeV	1.02	1.18-1.34
Luminosity integral 10^{33} cm^{-2}	8.5 ± 0.4	13.5 ± 0.6
Range interval, g/cm ²	6.4-16	10.5-20
$ \Delta\theta $ region, degrees	0-40	40-90
Effect	150	71
Background (normalized)	53	70
Admixture of other processes	13 ± 5	0.2
Pure effect	84 ± 19	1 ± 18
Calculation	65 ± 13	22 ± 5
		15 ± 3

was calculated for the known channels of the ϕ -meson decay and pion pair production.

The expected number of events was calculated by the Monte Carlo method according to the paper of Baier and Fadin [10]. One of the peculiar features of the process considered is the peaking of the distribution with respect to the azimuth discolinearity angle between the produced particles. Figure 3 shows this distribution for the first and the second experiments. A solid curve corresponds to the calculation of Baier and Fadin, taking into account geometrical experimental conditions and multiple scattering. For comparison the dashed curve shows the calculated distribution for the process with an independent and isotropic particle distribution.

FIG. 3. — Distribution of events with respect to $|\Delta\phi|$ for the first and the second experiment.

The quantitative criteria of agreement between experimental data and two types of the calculated distributions have been obtained by mathematical simulation of statistical scattering of the points. This method is the natural generalization of the well known χ^2 -criterion for the case of low statistics [18]. During the calculations the background was assumed to be composed of two components — an isotropic and a peaked one with $\Delta\phi = 0$.

For the first experiment the confidence value P thus obtained is equal to 35 % for the Baier and Fadin curve, and 0.1 % for the isotropic distribution.

In the second experiment the insufficient number of events does not allow the exclusion of the isotropic distribution. To increase the sensitivity to the type of calculated distribution, the first two intervals were combined as well as all the remaining intervals. However, even in this case, $P = 11\%$ for the isotropic distribution and $P = 62\%$ for the Baier and Fadin distribution.

2. The future. — The best possibilities for studying processes of symmetric electroproduction can be provided by a machine with two colliding beams of electrons. In this case the interpretation of results is considerably simplified owing to the absence of the annihilation channel. This fact provides great advantages for physicists working at DESY who will soon have the only accelerator with two magnetic rings (DORIS).

To select electroproduction processes when only electron-positron collisions are available one must use the characteristic feature of these processes — conservation of the initial particles in the final state. After collision these particles continue to move in the same directions, changing only their energy. The magnetic field of the storage ring extracts these particles from the beam to the internal side of a magnetic path. Thus the part of the magnetic path adjacent to the region of colliding beams must be designed to allow the detection of the particles of interest and their energy analysis. To simplify the analysing properties of the system, it is desirable that this part of the magnetic path and the straight section do not have focusing lenses.

Detection of the electron and positron in the narrow solid angle near the beams allows the exclusion of a considerable part of the background of bremsstrahlung electroproduction (Fig. 1b). This mechanism is characterized by wider angular distribution for the radiating electron than that in the symmetric electroproduction [19].

Unfortunately any apparatus to detect particles moving near the beams but having smaller energy will detect not only the electrons and positrons of interest, i. e. responsible for electroproduction, but also the particles having lost their energy in ordinary bremsstrahlung as well. Therefore random coincidences impose restrictions on the luminosity integral obtained during one collision of the particle bunches (the luminosity pulse whose duration is less than the resolution time of the coincidence circuits).

The bremsstrahlung cross-section with 5 to 50 % energy loss is about 300 mb; hence the integral of the luminosity pulse must be much smaller than $3 \times 10^{24} \text{ cm}^{-2}$, the value corresponding to detection of one electron (positron) by a conceivable system suited to the detection of the particles in the energy range of 50 to 95 % of the initial energy. Under these conditions, in order to increase luminosity one can only increase the frequency of bunch collisions,

i. e. increase the RF of the storage ring supply and fill uniformly all the separatrices with the particles. DORIS also has some advantages in this respect.

We plan to study symmetric electroproduction processes with VEPP-4 now being constructed in Novosibirsk. It is an electron-positron colliding beam machine with an energy of up to 7 GeV per beam [20]. Figure 4 shows the main intersection region of the storage ring; it is clear that it is not straight — the collision region is in the magnetic field. The central magnet bending the initial beams by 7° has a large aperture ($1.7 \times 2.0 \text{ m}^2$) and will be used as a spectrometer of produced particles, MD-1 (*). The magnetic field is perpendicular to the orbit plane of the storage ring. The strength of magnetic field in MD-1 will vary with the storage ring energy, the magnet being part of the magnetic system of the ring. This magnetic configuration is well suited to the analysis of the particles produced at small angles with respect to the beams (the characteristic feature of electroproduction). Two side magnets increase the system resolution for electrons and positrons moving in the initial direction.

FIG. 4. — Main intersection region of VEPP-4: 1) magnetic detector MD-1; 2) additional analysing magnets; 3) focusing lenses; 4) detection system for electrons and positrons.

Figure 5 shows the magnetic detector MD-1. It is a closed rectangular solenoid with a useful magnetic volume of 9.5 m^3 . To determine particle trajectories and their type, coordinate, shower-range and muon proportional chambers will be used in MD-1, as well as gas Čerenkov counters and scintillation counters. Geometrical characteristics of the trajectories and the particle momenta will be measured with the help of 30 coordinate proportional chambers with the dimensions of $1.0 \times 0.9 \text{ m}^2$, wire spacing in the signal plane being 2 mm. To determine particle range and detect γ -quanta, shower-range chambers with stainless steel plates are used. Muon chambers placed beyond the magnet winding and its yoke help to select particles having large range. To select electrons with momentum greater than 700 MeV/c, shower-range chambers are used; at lower momenta gas Čerenkov counters are used. The main parameters of MD-1 are presented in table II.

(*) The main contribution to the project was done by A. P. Onuchin.

FIG. 5. — Magnetic detector MD-1 : 1) magnet yoke ; 2) copper winding ; 3) vacuum chamber ; 4) cylindrical scintillation counter ; 5) coordinate proportional chambers ; 6) scintillation counters ; 7) gas Čerenkov counters ; 8), 9) shower-range chambers ; 10) muon chambers ; 11) monitoring system detecting small angle scattering ; 12) electron-positron colliding beams.

The preparation of the magnets and the vacuum chamber of VEPP-4 is now finished. Assembly work is in progress. The MD-1 magnet will be constructed in 1974. The trial units of the detection system are under test.

TABLE II

Magnet

Magnetic volume	9.5 m
Maximum strength	16 kG
Weight of the copper winding	40 t
Weight of steel	400 t
Power at $H = 16$ kG	3.8 MW

Proportional chambers

Coordinate measurement 1.0×0.9 m ²	30 planes
Shower and range 1.7×0.7 m ²	100 planes
Muon 1.6×1.3 m ²	40 planes
Electronics channels	20,000

Gas Čerenkov counters

Dimensions	1.6×1.7 m ²
Ethylene pressure	25 atm
Threshold for pions ($n = 1.02$)	700 MeV
Number	8

Scintillation counters

Cylindrical	2
Flat 1.0×0.5 m ²	12

Momentum resolution

at $H = 16$ kG, $pc = 1$ GeV	0.05
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Solid angle

Particle detection	$0.85 \times 4\pi$
With Čerenkov analysis	$0.58 \times 4\pi$

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