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ABOUT EARLIER HISTORY OF TWO-PHOTON PHYSICS*

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The earlier history of two-photon physics is reviewed.

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The term **two-photon processes** is used now for the reactions in which some system of particles is produced in the collision of two photons, either real or virtual. In the study of these processes the principal goal is to describe main features of proper two-photon process separating it from mechanism which is responsible for the production of incident photons.

• An early interest in the two-photon physics has arisen after the discovery of the positron by Anderson (1932). There appeared a necessity to find out the process in which positrons are generated. In 1934, while studying e^+e^- pair production in collision of ultrarelativistic charged particles Landau and Lifshitz [1] have ascertained that the two photon channel of Fig. 1 is dominated here.

They calculated the cross section of the process $Z_1Z_2 \to Z_1Z_2e^+e^-$ in the leading logarithmic approximation. Almost simultaneously Bethe and Heitler [2] considered e^+e^- pair production by a photon in the field of a nucleus. This process contains subprocess $\gamma\gamma \to e^+e^-$, such as shown in Fig. 1.

The leading log result of [1] was improved by Racah [3] who has calculated the corresponding cross section with a high accuracy $\sim (M/E)^2$, where E and M are energy and mass of incident nuclei. The process $\gamma A \to e^+e^- A$ was included in the theory of wide atmospheric showers in cosmic rays [4] and in the description of the energy losses of fast muons in matter [5].

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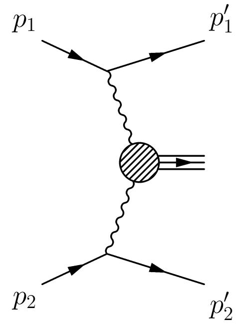

Fig. 1. Two-photon particle production in collision of two fast particles.

The two-photon hadron production was considered for the first time by Primakoff [6] who suggested in 1951 to measure the π^0 life-time in the reaction $\gamma Z \to \pi^0 Z$. The new interest in such processes appeared when the construction of e^+e^- colliders became close to a reality. In 1960 Low [7] paid attention to the fact that the π^0 life-time can be measured also in e^+e^- collisions. Simultaneously the two-photon reaction $e^+e^- \to e^+e^- \pi^+\pi^-$ (for point-like pions) was considered [8]. However, the rates involved seemed unmeasurable at that time and no further work was done.

In 1969–1970 a new generation of papers appeared with the goal to cover possible set of final states of e^+e^- colliders as completely as possible. The authors considered the two-photon production of π^0, η and point-like pion and kaon pairs [9]. Some of these processes and purely QED processes $e^+e^- \to e^+e^- \pi^+\pi^-$, $e^+e^- \to e^+e^- \mu^+\mu^-$ were considered in more detail by Paris [10] and the Novosibirsk BINP [11] groups. These papers did not provoke high interest in particle physics community since they were in line with numerous calculations of various processes at e^+e^- colliders with small cross section (at the contemporary energies) and did not pretend to obtaine new information except for new tests of QED.

• To the end of 1969, the results in the study of deep inelastic *ep* scattering were a hot point in particle physics. Besides, a preliminary information about the experimental discovery of $e^+e^- \to e^+e^- e^+e^-$ process in Novosibirsk BINP [14] became known. Under the influence of these two facts the Novosibirsk IM group wrote a paper which was submitted to Russian Pis'ma ZhETF at May 4 and appeared there at June 5, 1970 [12], Fig. 2 (it was translated soon into English).

It was shown in that paper that the experiments at e^+e^- colliders *open new experimental field of particle physics* — the opportunity to extract from the data information about fundamental process, $\gamma^*\gamma^* \to$ *hadrons (or some other particles)*. The paper contains also an estimate of high energy total

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ВОЗМОЖНОСТЬ ЭКСПЕРИМЕНТА ПО РОЖДЕНИЮ АДРОНОВ ДВУМЯ ФОТОНАМИ ОТ ПОРОГА ДО ПРЕДЕЛЬНО БОЛЬШИХ ЭНЕРГИЙ

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Fig. 2. V.E. Balakin, V.M. Budnev, I.F. Ginzburg, *The Possibility of Experiment with Production of Hadrons by Two Photons from Threshold to the Extremely High Energies*, published June 5, 1970, submitted May 4, 1970, *Russian Pis'ma ZhETF*.

cross section $\sigma(\gamma\gamma \to \text{hadrons}) \sim \sigma^2(\gamma p)/\sigma(pp) \sim (0.3 \div 1)\mu\text{b}$, which is in accord with modern measurements, and the equations for extraction of two-photon cross sections from the data at small electron scattering angles in the form which is used for this aim up to now,

$$\begin{aligned}
\frac{d\sigma}{dE_1 dE_2 d\Omega_1 d\Omega_2} &= \left(\frac{\alpha}{2\pi^2}\right)^2 \frac{1}{q_1^2 q_2^2} \frac{E_1 E_2}{E^2} \frac{(E^2+E_1^2)(E^2+E_2^2)}{(E-E_1)(E-E_2)} \sigma_{\text{exp}}^{\gamma\gamma}\,,\\
\sigma_{\text{exp}}^{\gamma\gamma} &= \sigma_{\text{TT}}^{\gamma\gamma} + \varepsilon_1 \sigma_{\text{ST}}^{\gamma\gamma} + \varepsilon_2 \sigma_{\text{TS}}^{\gamma\gamma}\\
&\quad + \varepsilon_1\varepsilon_2 \left(\sigma_{\text{SS}}^{\gamma\gamma} + \tau_{\text{TT}}^{\text{ex}} \cos 2\phi/2\right) + \varepsilon_3 \tau_{\text{TS}}^{\text{ex}}\,,\\
\varepsilon_1 &= \frac{2EE_1}{E^2+E_1^2}\,, \quad \varepsilon_2 = \frac{2EE_2}{E^2+E_2^2}\,,\\
\varepsilon_3 &= \varepsilon_1\varepsilon_2 \frac{(E+E_1)(E+E_2)}{32E\sqrt{E_1E_2}} \cos\phi\,. \qquad (1)
\end{aligned}$$

(E and E_i are the energies of initial and scattered electrons, ϕ is the angle between their scattering planes, other notation was not changed practically during 35 years.) The numerical estimates of anticipated cross sections were done and it was found that the cross section grows fast with the beam energy. Besides, the sketch of experimental program was formulated. In July this paper was reported at the Kiev Rochester conference (a preliminary version of paper [13] was also reported there) — see *abstracts of Kiev–Rochester, 1970.*

Three month later after [12], S. Brodsky, T. Kinoshita, S. Terazawa have submitted to Physical Review Letters their paper [13] (Fig. 3). They considered two-photon production of π^0, η, point-like $\pi^+\pi^-$ in e^+e^- and e^-e^- colliding beams. They found that these cross sections grow fast with the beam energy and described some features of the angular distributions of produced pions (in point-like QED approximation). Analogously to [12], these results had shown that two-photon physics provides a large field for theoretical studies and experimentation. They obtained results with the aid of Weizsacker–Williams method with incorrect spectra of equivalent photons (about twice as large as the correct ones). Many authors of subsequent papers reproduced this inaccuracy.

In 1971 VEPP-2 (BINP, Novosibirsk [14]), and in 1972 ADONE (Frascati, Italy) [15] reported about the observation of $e^+e^- \to e^+e^- e^+e^-$ process.

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DOMINANT COLLIDING-BEAM CROSS SECTIONS AT HIGH ENERGIES*

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Fig. 3. S.J. Brodsky, T. Kinoshita, H. Terazawa, *Dominant Colliding Beam Cross Sections at High Energies*, published October 5, 1970, submitted August 11, 1970, Physical Review Letters.

• The papers [12–14] open window for stream of publications devoted two-photon physics. The theoretical publications considered different problems related to the details of data extraction, backgrounds, QED processes and problems of hadron physics in $\gamma\gamma$ collisions. The first stage of these studies was summarized in a review [16] containing all necessary equations for data preparation and the set of equations useful for different estimates. This review contains also detailed description of the equivalent photon (Weizsacker–Williams) method, including estimate of its accuracy in different situations. In 1974 the authors of [21] could not imagine opportunity of longitudinal electron polarization at e^+e^- storage rings and did not describe this case in basic equations. This lacuna in [16] was closed in [17].

Most of the (theoretical) papers of the 1970-ties devoted to hadron physics in $\gamma\gamma$ collisions were reproductions of results and ideas considered earlier for other hadronic systems. However it was found by Witten that the structure function of the photon is an unique quantity in particle physics which can be found from QCD at large enough Q^2 and s completely without phenomenological parameters [18]. The verification of this result in future experiments is necessary to verify that the QCD is indeed a theory of strong interactions.

The real experimental activity in this field started, in fact, in 1979, by the SLAC experiment in which it was demonstrated that two-photon processes can be successfully studied at the modern detectors without recording of the scattered electrons and positrons — via the separation of events with the small total transverse momentum of produced system [19]. Beginning from this work, the investigation of two-photon processes became an essential component of physical studies at each e^+e^- collider. A number of results obtained are summarized for example in Particle Data Review [20].

• Very new opportunities for two-photon physics were found in 1981. It was shown that the construction of very high energy linear $e^\pm e$ colliders will allow to transform them into the $\gamma\gamma$ and γe colliders with luminosity and energy close to those for the basic $e^\pm e$ colliders (the Photon Collider), with relatively small additional equipment [21].

In contrast with the photon collisions at e^+e^- colliders, having relatively small effective $\gamma\gamma$ luminosity, Photon Colliders will be competitive with other machines in the discovery of New Physics effects. But that is quite another story.

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