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STUDY OF Φ-MESON DECAYS WITH THE NEUTRAL DETECTOR AT THE VEPP-2M COLLIDER

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ABSTRACT

Results of experiments with the Neutral Detector at the electron-positron collider VEPP-2M are presented. The branching ratios of Φ-meson decays are measured:

$$B(\Phi\to\pi^+\pi^-) = (0.56^{+0.33}_{-0.25})\cdot 10^{-4},$$

$$B(\Phi\to\pi^+\pi^-\pi^0) = (14.3\pm1.7)\,\%,$$

$$B(\Phi\to K_S K_L) = (32.6\pm3.5)\,\%.$$

where X-boson with a mass less than 200 MeV is not detected. An upper limit is given for the decay of the K_S-meson into two photons:

$$B(K_S\to 2\gamma) < 8\cdot 10^{-4}.$$

A limit for the nonresonant cross section of reaction $e^+e^-\to\pi^0\pi^0\gamma$ is obtained:

$$\sigma(e^+e^-\to\pi^0\pi^0\gamma) < 0.4 \text{ nb},$$

as well as the limit for polarizability of the neutral pion α_{π^0}, related with it:

$$|\alpha_{\pi^0}| < 60\cdot 10^{-43}\ \text{cm}^3.$$

The phase of $\omega-\Phi$ interference in the channel $\pi^+\pi^-\pi^0$: $\alpha=(155\pm14)^\circ$ is determined. Upper limits for the following decays of the Φ-meson are placed at 90% confidence level:

$$B(\Phi\to S^*\gamma) < 4\cdot 10^{-3},$$

$$B(\Phi\to\delta\gamma) < 6\cdot 10^{-3},$$

$$B(\Phi\to\eta'\gamma) < 2\cdot 10^{-4},$$

$$B(\Phi\to X\gamma) < 7\cdot 10^{-6},$$

In 1983 the experiment was performed at the electron-positron collider VEPP-2M [1] with the Neutral Detector [2] (Fig.1) in the center of mass energy range $2E_0=1000\div1050$ MeV with 2.8 pb^{-1} integrated luminosity. As a result of this experiment radiative decays of Φ-meson $\Phi\to\eta\gamma$, $\Phi\to\pi^0\gamma$ were measured [3], the test of quantum electrodynamics in Compton scattering of quasireal photons on electrons and positrons was done [4], the rare Φ-meson decay $\Phi\to\eta e^+e^-$ was observed [5] and some other processes were studied [6, 7]. In this paper the results of further analysis of experimental data are presented.

DECAY MODE $\Phi\to\pi^+\pi^-$

The decay $\Phi\to\pi^+\pi^-$ reveals itself as an interference in the energy dependence of the cross section of the reaction $e^+e^-\to\pi^+\pi^-$ near the Φ-meson. This decay has been earlier observed for the first time at VEPP-2M [8]. Our preliminary result was presented in Ref. [7].

For the analysis events with two collinear charged particles were selected:

$$|\Delta\varphi| < 3^\circ, \qquad |\Delta\theta| < 15^\circ, \tag{1}$$

where $\Delta\varphi$, $\Delta\theta$ are the acollinearity angles in the azimuthal and polar directions respectively. Besides the reaction studied the following processes can meet these criteria:

$$e^+e^-\to e^+e^-, \tag{2}$$

$$e^+e^-\to\mu^+\mu^-, \tag{3}$$

$$e^+e^-\to\Phi\to K_S K_L,\ K_S\to\pi^+\pi^-, \tag{4}$$

$$e^+e^-\to\Phi\to\pi^+\pi^-\pi^0. \tag{5}$$

Charged kaons from the decay $\Phi\to K^+K^-$ do not punch through the tracking system, thereby not resulting in two collinear tracks.

For further event selection the multilayer structure of the calorimeter is used. One of the particles in an event has to satisfy the following conditions:

— energy depositions in the first two NaI(Tl) layers are these of the minimum ionizing particle (25—30 MeV);
— both shower chambers are fired;
— the energy deposition in the fourth layer is greater than 20 MeV.

These criteria almost completely remove the background process (2), in which electron showers result in large energy depositions in the first and second NaI(Tl) layers (about 100 MeV). Also suppressed are the events of the reaction (4), in which pions have an energy less than 300 MeV and as a rule do not reach the fourth layer. The greater part of the muons from the reaction (3) fires the anticoincidence counters and does not give trigger. For additional suppression of this process events were rejected in which both particles had an energy deposition greater than 20 MeV in the fourth NaI(Tl) layer.

The detector acceptance for the reaction $e^+e^-\to\pi^+\pi^-$ was calculated, whereas the detection efficiency within the acceptance was determined from observed events. For that purpose among all collinear events the $\pi^+\pi^-$-events were selected by the condition that one of particles must be definite π-meson: it must stop in the third NaI(Tl) layer and give energy depositions characteristic to minimum ionising particle in first two layers. The second particle was used to obtain all necessary distributions to determine the detection efficiency. The total detection efficiency obtained is $(16.7\pm1.3)\%$. The values of the visible cross sections of the reaction $e^+e^-\to\pi^+\pi^-$ as well as of the background processes under selection criteria described above are shown in Table 1. The remaining background does not exceed 8% of the visible cross section of the reaction $e^+e^-\to\pi^+\pi^-$ and was statistically subtracted. To this end the cross section of the reaction (3) was calculated taking into account the interference with the decay $\Phi\to\mu^+\mu^-$. Since processes (4) and (5) do not give a peaking at $\Delta\varphi=0$, their contribution was determined using quasicollinear events with

$$3^\circ<|\Delta\varphi|<6^\circ, \qquad |\Delta\theta|<15^\circ. \tag{6}$$

The ratio of the visible cross sections of the reactions (4) and (5)

for collinear (1) and quasicollinear (6) events was determined by a Monte-Carlo simulation.

Table 1

process	$e^+e^-\to\pi^+\pi^-$	$e^+e^-\to e^+e^-$	$e^+e^-\to\mu^+\mu^-$	$\Phi\to K_SK_L$ $\Phi\to\pi^+\pi^-\pi^0$
σ_{viz}, nb	9.0	<0.11	0.38	0.26

For parametrization of experimental data the following formula [8] was used:

$$\sigma_{vis}(E)=\frac{\pi\alpha^2}{12E^2}\left(\frac{\beta}{\beta_\Phi}\right)^3|F_\pi|^2\left(1+A\left(E-\frac{m_\Phi}{2}\right)\right)\times$$
$$\times\left|1+\frac{Qe^{i\psi}m_\Phi\Gamma_\Phi}{4E^2-m_\Phi^2+im_\Phi\Gamma_\Phi}\right|^2(1+\delta)\varepsilon+\sigma_B(E),$$

$$\beta=(1-m_\pi^2/E^2)^{1/2}, \quad \beta_\Phi=(1-4m_\pi^2/m_\Phi^2)^{1/2},$$

where Q and ψ are the interference amplitude and phase, $|F_\pi|^2$ and A are the pion formfactor and its slope at the Φ-meson peak, ε is a detection efficiency, δ is a radiative correction [9, 10], σ_B is a background cross section. Interference amplitude Q depends on Φ-meson branching ratios:

$$Q=\sqrt{\frac{36B(\Phi\to e^+e^-)B(\Phi\to\pi^+\pi^-)}{\alpha^2\beta_\Phi^3|F_\pi|^2}}.$$

The measured values of the visible cross section and the optimal curve are shown in Fig.2. χ^2 for the curve is equal to 22 at 19 degrees of freedom, whereas the fit with a zero interference amplitude resulted in χ^2 value of 44 at 21 degrees of freedom ($P(\chi^2)<0.03$). The following optimal parameters were obtained:

$$|F_\pi|^2=2.6\pm0.2,$$
$$Q=0.071\pm0.018,$$
$$\psi=(-20\pm13)^\circ,$$
$$B(\Phi\to\pi^+\pi^-)=(0.56^{+0.33}_{-0.25})\cdot10^{-4}.$$

The value of the formfactor found is consistent with the result of Ref. [11]. The value of branching ratio obtained is close to our preliminary result [7]. The results of the only previous experiment [8] were: $|F_\pi|^2=3.0\pm0.3$, $Q=0.12\pm0.03$, $\psi=(40\pm13)°$, $B(\Phi\to\pi^+\pi^-)=(1.9^{+1.0}_{-0.8})\cdot10^{-4}$.

STUDY OF THE PROCESS $e^+e^-\to\pi^+\pi^-\pi^0$

The energy dependence of the cross section of the reaction $e^+e^-\to\pi^+\pi^-\pi^0$ near the Φ-meson is mainly determined by $\omega-\Phi$ interference [12]. To separate events of this process from those due to the decay $\Phi\to K_SK_L$, $K_S\to\pi^+\pi^-$ the simple kinematical criterion is usually applied: $\omega<135°$, where ω is a spatial angle between two charged pions. In our analysis the process $e^+e^-\to\pi^+\pi^-\pi^0$ is also studied at $\omega>135°$. Such angles correspond to larger values of the $\pi^+\pi^-$-pair invariant mass.

To investigate the process $e^+e^-\to\pi^+\pi^-\pi^0$ events with two charged particles and two photons were selected. In the region $\omega>130°$ we additionally required that at least one of the two charged pions fired all four NaI(Tl) layers. This condition removes the background caused by the decay $\Phi\to K_SK_L$, $K_S\to\pi^+\pi^-$ in which maximum energy of the pions is less than 300 MeV and they do not reach the fourth NaI(Tl) layer. The detection efficiency calculated by a Monte-Carlo simulation was $(8.4\pm0.4)\%$. Its uncertainty is due to the simulation inaccuracy and estimated to be 10%. The relative fraction of the background processes $\Phi\to K_SK_L$, K^+K^- is $(1.0\pm0.7)\%$, whereas that of the process $\Phi\to\eta\gamma$, $\eta\to\pi^+\pi^-\pi^0$ equals $(3.4\pm0.3)\%$.

To parametrize the energy dependence of the cross section the following formula is used:

$$\sigma_{viz}=\sigma_{3\pi}\cdot\varepsilon\,(1+\delta)\,\lambda+\sigma_B\ ,$$

$$\sigma_{3\pi}=|A_\omega+e^{i\alpha}A_\Phi|^2F(S),\quad A_V=\sqrt{\frac{\sigma_V^{max}}{F(m_V^2)}}\cdot\frac{m_V\Gamma_V}{S-m^2-i\sqrt{S}\,\Gamma_V(S)},$$

where σ_{viz} is a visible cross section, σ_B is a cross section of the background processes, A_V is a Breit-Wigner amplitude of ω, Φ-mesons, σ_V^{max} is the cross section in the peak, $F(S)$ is a factor allowing for account the transition $\omega,\ \Phi\to\varrho\pi\to3\pi$ [13], δ is a radiative correction, λ is a correction for the beam energy spread,α is a relative phase of $\omega-\Phi$ interference, ε is a detection efficiency. The calibration of the Φ-meson position was performed using the events of the process $\Phi\to K_SK_L$. The values of σ_Φ^{max}, σ_B, and α were optimized. For other parameters their table values were used [14]. The ratio of the vizible cross sections for regions with $\omega<130°$ and $\omega>130°$ equals 3.0 ± 0.2 and agrees with estimated value for $\varrho\pi$ intermediate state: 3.2 ± 0.5. The following values of the cross section of $e^+e^-\to\pi^+\pi^-\pi^0$ in the Φ-meson peak and $\omega-\Phi$ interference phase have been obtained:

$$\sigma_\Phi^{max}=(620\pm30\pm70)\text{ nb},$$

$$\alpha=(155\pm14)°.$$

The first error indicated is statistical, while the second one is systematical. Experimental points and optimal excitation curves are shown in Fig.3. Using the table value of $B(\Phi\to e^+e^-)$, the branching ratio of $\Phi\to\pi^+\pi^-\pi^0$ decay was obtained:

$$B(\Phi\to\pi^+\pi^-\pi^0)=(14.3\pm1.7)\%.$$

The value obtained for the cross section of $e^+e^-\to\pi^+\pi^-\pi^0$ reaction, and $\omega-\Phi$ interference phase are consistent with the result of Ref. [13].

DECAY MODE $\Phi\to K_SK_L$

To measure the branching ratio of the decay $\Phi\to K_SK_L$, $K_S\to\pi^+\pi^-$ events with two charged particles and no more than one neutral particle were selected. By requiring that a spatial angle between charged pions is greater than 130°, about 60% of the main background process $e^+e^-\to\pi^+\pi^-\pi^0$ was removed, while the efficiency for the process under study redused very little, since the minimum spatial angle for this process is equal to 140°. To eliminate the background of the processes $e^+e^-\to e^+e^-$, $\mu^+\mu^-$, $\pi^+\pi^-$ we required $|\Delta\varphi|>10°$, where $\Delta\varphi$ is an azimuthal acollinearity angle. The background due to the process $e^+e^-\to\varrho\gamma$ was suppressed by requiring that no one charged pion in the event fires four layers of NaI(Tl). Also the condition that the energy deposition $E_{dep}/E_0<0.6$ was imposed. This cut removed much of contribution of $e^+e^-\to e^+e^-\gamma$. The detection efficiency calculated by a Monte-Carlo simulation was $(8.5\pm0.3)\%$. A systematical uncertainty associated with the inaccuracy of simulation of K_L-meson interaction with detector material was determined using those events of the decay in which the K_S decay point was at a distance 0.7–2 cm from the beam axis and was found to be less than 10%. The relative contribution of the background events due to the reaction $e^+e^-\to\pi^+\pi^-\pi^0$ was (9.0 ± 0.9)%, while that of the process $e^+e^-\to\varrho\gamma$ was estimated to be 1.7%. The contribution of the background due to the processes $e^+e^-\to e^+e^-\gamma$, $\eta\gamma$, K^+K^- did not exceed 0.2%.

The energy dependence of the experimental cross section was parametrized using the formula:

$$\sigma_{viz}=\sigma_{viz}^{K_SK_L}+\sigma_{viz}^{3\pi}+\sigma_B\ ,$$

where σ_{viz} is a visible cross section, σ_B is a cross section of nonresonant background processes. The following values of the cross section in the Φ-meson peak and the branching ratio have been obtained:

$$\sigma_{K_SK_L}^{max}=(1.43\pm0.03\pm0.14)\ \mu b,$$

$$B(\Phi\to K_SK_L)=(32.6\pm3.5)\ \%.$$

The visible cross section and the optimal curve are shown in Fig.4. The obtained value $\sigma_B=(2.0\pm0.2)$ nb does not contradict to the estimated one. The branching ratio $B(\Phi\to K_SK_L)$ is in agreement with the table value.

SEARCH FOR DECAYS $\Phi\to S^*\gamma$ AND $\Phi\to\delta\gamma$

Electromagnetic calorimeters are especially suitable for investigations of the radiative transitions. Earlier we have measured the branching ratios of the decay modes $\Phi\to\eta\gamma$ and $\Phi\to\pi^0\gamma$ [3] with an accuracy several times higher than the table one. In this work an attempt is made to look for rare decay modes $\Phi\to S^*\gamma$ and $\Phi\to\delta\gamma$. According to Ref. [15] their branching ratios must be of the order of 10^{-5}. It should be noted that a quark structure of S^*- and δ-mesons is not yet clear. Although in the standard classification they are two-quark states with an orbital moment equal to 1 [14], some models consider these mesons as low-lying four-quark states (see the review paper [16]). This explains the importance of the study of the reactions involving these mesons.

In the radiative decays under study the recoil photon is not monochromatic because its energy (~50 Mev) is comparable with the widths of S^*- and δ-mesons. This makes a search for these decays in the inclusive photon spectrum rather complicated. Therefore in our study we have used an exclusive decay modes with five photons in final state. Such events can be due to the following reactions:

$$\Phi\to S^*\to\pi^0\pi^0\gamma\ , \qquad (7)$$

$$\Phi\to\delta\gamma\to\pi^0\eta\gamma\ . \qquad (8)$$

The decay $\Phi\to K_SK_L$ and $\Phi\to\eta\gamma$ with a large number of final photons can also result in five-photon events, since some of the photons can merge or escape through the open ends of the detector. For selection of events due to the processes (7) and (8) a kinematical fit [2] has been used, with the additional requirement that each event had two independent pairs of photons with an invariant mass equal to that of π^0- or η-meson. A considerable part of recoil photons in reactions (7) and (8) has the energy less than 150 MeV. Selecting events satisfying this condition and taking into account radiative corrections, one obtains the following values for the visible cross sections in the Φ-meson peak:

$$\sigma(\Phi\to\pi^0\pi^0\gamma\to5\gamma)=(0.020\pm0.007)\ \text{nb}\ ,$$

$$\sigma(\Phi\to\pi^0\eta\gamma\to5\gamma)=(0.10\pm0.02)\ \text{nb}\ .$$

The contribution of the reaction $\Phi\to\eta\gamma\to\pi^0\pi^0\pi^0\gamma$ to these cross sections calculated by a Monte-Carlo simulation was (0.018 ± 0.008) nb and (0.09 ± 0.02) nb respectively, thus the experimental spectra observed are well accounted for by the events of the reaction $\Phi\to\eta\gamma$, so only upper limits may be placed for those decay modes. Using the detection efficiencies for the processes $\Phi\to\pi^0\pi^0\gamma$ and $\Phi\to\pi^0\eta\gamma$ equal to 0.8% and 1% respectively and the table values for the branching ratios $B(S^*\to\pi^0\pi^0)=25\%$ and $B(\delta\to\pi^0\eta)=50\%$ one obtains the following upper limits for the branching ratios at 90% C.L.:

$$B(\Phi\to S^*\gamma)<0.4\%\ ,$$

$$B(\Phi\to\delta\gamma)<0.6\%\ .$$

The upper limits for these decays are established for the first time. The values obtained are so far greater than those predicted by theory. Further decrease of the upper limits requires a study of the other final states.

SEARCH FOR DECAY $\Phi\to X\gamma$

This work continues a search for an exotic decay $\Phi\to X\gamma$ started earlier [6]. X-boson may be one of large number of light bosons discussed in literature [17, 18, 19] (axion, supersymmetric particle, mirror particle etc.). It is assumed that neither X-boson, nor its decay products are detected. For analysis events were selected with one photon coming from the interaction region and recorded by two layers of shower chambers. The photon must be detected by three NaI(Tl) layers with the 5 MeV threshold. To look for an X-boson with the mass less than 200 MeV, events were selected, in which photons had an energy from $0.95E_0$ to $1.15E_0$, where E_0 is a beam energy. The detection efficiency for such photons was calculated by a Monte-Carlo simulation assuming an angular distribution $dN=(1+\cos^2\theta)d\Omega$ and was found to be $(19\pm1)\%$. The energy dependence of the visible cross section for the selected events is shown in Fig.5. The background to the process under study is due to the processes of bremsstrahlung in electron-positron collisions, three-photon annihilation, bremsstrahlung on the residual gas and cosmic rays. No peak in the cross section was observed in the region of the Φ-meson. Therefore the following upper limit was placed for the branching ratio of the decay $\Phi\to X\gamma$:

$$B(\Phi\to X\gamma)<7\cdot10^{-6}\quad(90\%\ \text{C.L.}).$$

Our preliminary result was $2\cdot10^{-5}$ [6]. An increase in accuracy by a factor of 3 is mainly due to the increase of statistics.

SEARCH FOR DECAY $K_S\to2\gamma$

The Neutral Detector allows to study some rare decays of neutral K-mesons. One of them is the $K_S\to2\gamma$ decay. Theoretical estimations give for this branching ratio values from $2\cdot10^{-6}$ to $2\cdot10^{-5}$ [20]. The existing upper limit is $4\cdot10^{-4}$ [21].

To search for this decay the two-photon events were selected, which were supposed to be from the reaction $e^+e^-\to\Phi\to K_SK_L$ with K_S-meson decaying into two photons and K_L-meson passing through the detector without interaction or decay. The probability of this for K_L-meson is about 20%. The following selection criteria were used:

$-100<E_{\gamma1}$, $E_{\gamma2}<600$ MeV, where $E_{\gamma1}$, $E_{\gamma2}$ are the photon energies;

$-420<E_{\gamma1}+E_{\gamma1}<570$ MeV;

$-410<M_{2\gamma}<560$ MeV, where $M_{2\gamma}$ is the two-photon invariant mass.

Fig. 6 gives energy dependence of the visible cross section for 134 events thus selected. The main contribution to this sample comes from the Φ-meson decays. However the measured two-photon invariant mass spectrum is not consistent with the expected one for $K_S\to2\gamma$ decay (Fig.7). This spectrum is due to background from other neutral decays of the Φ-meson with different distribution over $M_{2\gamma}$. This difference was used to obtain the upper limit for the $K_S\to2\gamma$ decay. Assuming the linear dependence of the background as a function of $M_{2\gamma}$, the upper limit for the visible cross section of the process $\Phi\to K_SK_L$, $K_S\to2\gamma$ was established:

$$\sigma(K_S\to2\gamma)<4\cdot10^{-2}\ \text{nb},$$

taking into account the detection efficiency equal to 3.4%, one obtains the following upper limit:

$$B(K_S\to2\gamma)<0.8\cdot10^{-3}\quad(90\%\ \text{C.L.}).$$

This value is by a factor of 2 worse than the best existing limit [21]. Further improvement of the accuracy requires higher statistics and suppression of the background. The latter is possible if besides two photons a K_L-meson is detected as well.

PROCESS $e^+e^-\to\pi^0\pi^0\gamma$

Study of the reaction

$$e^+e^-\to\pi^0\pi^0\gamma \qquad (9)$$

is of interest, since it allows to measure the neutral pion polarizability α_{π^0} [22]. From the simplest gauge invariant matrix element the following expression for the total cross section can be obtained [23]:

$$\sigma=\frac{4\alpha}{3m_\pi^2}(\alpha_{\pi^0}Em_\pi^2)^2I(S), \qquad (10)$$

where $I(S)=0.14$ at $E_0=0.5$ GeV. The cross section value is about $0.2\cdot10^{-36}$ cm^2 if $\alpha_{\pi^0}=-0.7\cdot10^{-43}$ cm^3 as predicted by the chiral model [24].

To investigate the reaction (9) events were selected with five photons satisfying energy-momentum balance with two π^0-mesons and a photon in final state. In Fig.8,*a* we show a spectrum of $\pi^0\gamma$ invariant masses $M(\pi^0\gamma)$ for the part of selected events at the beam energy range outside the Φ-meson resonance region. For comparison in Figs. 8,*b*, 8,*c* similar spectra for the process under study and for the reaction

$$e^+e^-\to\omega\pi^0\to\pi^0\pi^0\gamma \qquad (11)$$

are presented. All selected events were further divided into two classes with different $M(\pi^0\gamma)$:

— $M(\pi^0\gamma)>730$ MeV (assigned to the reaction (11));

— $M(\pi^0\gamma)<730$ MeV (assigned to the reaction (9)).

The energy dependence of the visible cross section was parametrized by the following expression:

$$\sigma_{viz}(E)=\sigma_1(E)+\sigma_2\ ,$$

where $\sigma_1(E)$ is a Φ-meson Breit-Wigner contribution, σ_2 is a constant nonresonant cross section. Optimization gave the following values for the visible nonresonant cross sections:

$$\sigma_2(e^+e^-\to\omega\pi^0\to\pi^0\pi^0\gamma)=(13\pm5)\ \text{pb}\ , \qquad (12)$$

$$\sigma_2(e^+e^-\to\pi^0\pi^0\gamma)<6.5\ \text{pb} \quad (90\%\ \text{C.L.}). \qquad (13)$$

The detection efficiencies for the processes (11) and (9) calculated by a Monte-Carlo simulation were (1.8±0.2)% and (1.6±0.3)% respectively. Taking into account the branching ratio $B(\omega\to\pi^0\gamma)=(8.8\pm0.8)\%$, one obtains from (12), (13) the total cross sections:

$$\sigma(e^+e^-\to\omega\pi^0)=(8\pm3)\ \text{nb}\ , \qquad (14)$$

$$\sigma(e^+e^-\to\pi^0\pi^0\gamma)<0.4\ \text{nb} \quad (90\%\ \text{C.L.}). \qquad (15)$$

The measured value of the cross section (14) is close to the expected one [25]. From (10) and (15) the following upper limit is obtained:

$$|\alpha_{\pi^0}|<60\cdot10^{-43}\ \text{cm}^3.$$

The result obtaned and some theoretical prediction [24, 26, 27, 28] are listed in Table 2.

Table 2

Theoretical and Experimental Data on Neutral Pion Polarizability

Authors	$\alpha_{\pi^0}\cdot10^{43}$ cm³	Method
M.K. Volkov, V.N. Pervushin [23]	−0.7	Chiral model
A.I. Lvov, V.A. Petrunkin [26]	0.9	Dispersion relations
G.V. Efimov, V.A. Okhlopkova [27]	−1.2	Non-local quark model
E. Llanta, R. Tarrach [25]	−7	Quark model
This work	<60	Experiment

Our upper limit is still much higher than theoretical predictions. To increase the sensitivity one should increase the integrated luminosity and measure reaction (9) below a threshold of (11), i.e. at $2E_0<900$ MeV.

SEARCH FOR DECAY $\Phi\to\eta'\gamma$

The following reaction was used to search for $\Phi\to\eta'\gamma$ decay:

$$\Phi\to\eta'\gamma\to\pi^+\pi^-\eta\gamma\to\pi^+\pi^-\gamma\gamma\gamma\ . \qquad (16)$$

In this case the charged pions have an energy of about 200 MeV and stop in the first NaI(Tl) layer. Two photons have invariant mass equal to η-mass, while the remaining recoil photon has an energy of 60 MeV. These characteristics of the reaction (16) were used to suppress other Φ-meson decays: $\Phi\to K_SK_L$, $\pi^+\pi^-\pi^0$, $\eta\gamma$.

The following cuts have been imposed for selection of events (16):

—charged pions stop in the first NaI(Tl) layer;

—the energy and momentum are balanced;

—$938<M_R<978$ MeV, where M_R is a recoil mass against the lowest energy photon;

—$450<M_{\gamma\gamma}<650$ MeV, where $M_{\gamma\gamma}$ is an invariant mass of two other photons.

The two-photon invariant mass spectrum for 62 selected events, satisfying to the criteria described above is shown in Fig.10. The solid line represents the expected distribution for reaction (16). One can see, that obtained distribution over $M_{\gamma\gamma}$ is not consistent with the expected one and determined by other Φ-meson decays, hence only upper limit on $\Phi\to\eta'\gamma$ decay can be obtained. Assuming the linear dependence of background as a function of $M_{\gamma\gamma}$ the limit on the visible cross section of reaction (16) was placed at 90% C.L.:

$$\sigma_{viz}(\Phi\to\pi^+\pi^-\gamma\gamma\gamma) < 5 \text{ pb} .$$

Taking into account the detection efficiency $\varepsilon = 4\%$ for reaction (16) as well as branching ratios $B(\eta'\to\pi^+\pi^-\eta) = 44\%$, $B(\eta\to\gamma\gamma) = 40\%$ and the value of Φ-meson production cross section in e^+e^--collisions $\sigma_\Phi = 4.4$ μb one obtains the upper limit for decay under study:

$$B(\Phi\to\eta'\gamma) < \sigma_{viz}(\Phi\to\pi^+\pi^-\gamma\gamma\gamma) / (\varepsilon\,\sigma_\Phi\, B(\eta'\to\pi^+\pi^-\eta)\, B(\eta\to\gamma\gamma)) = 2\cdot 10^{-4}.$$

The expected branching ratio for decay $\Phi\to\eta'\gamma$ in the framework of nonrelativistic quark model [29] is equal to $0.7\cdot 10^{-4}$.

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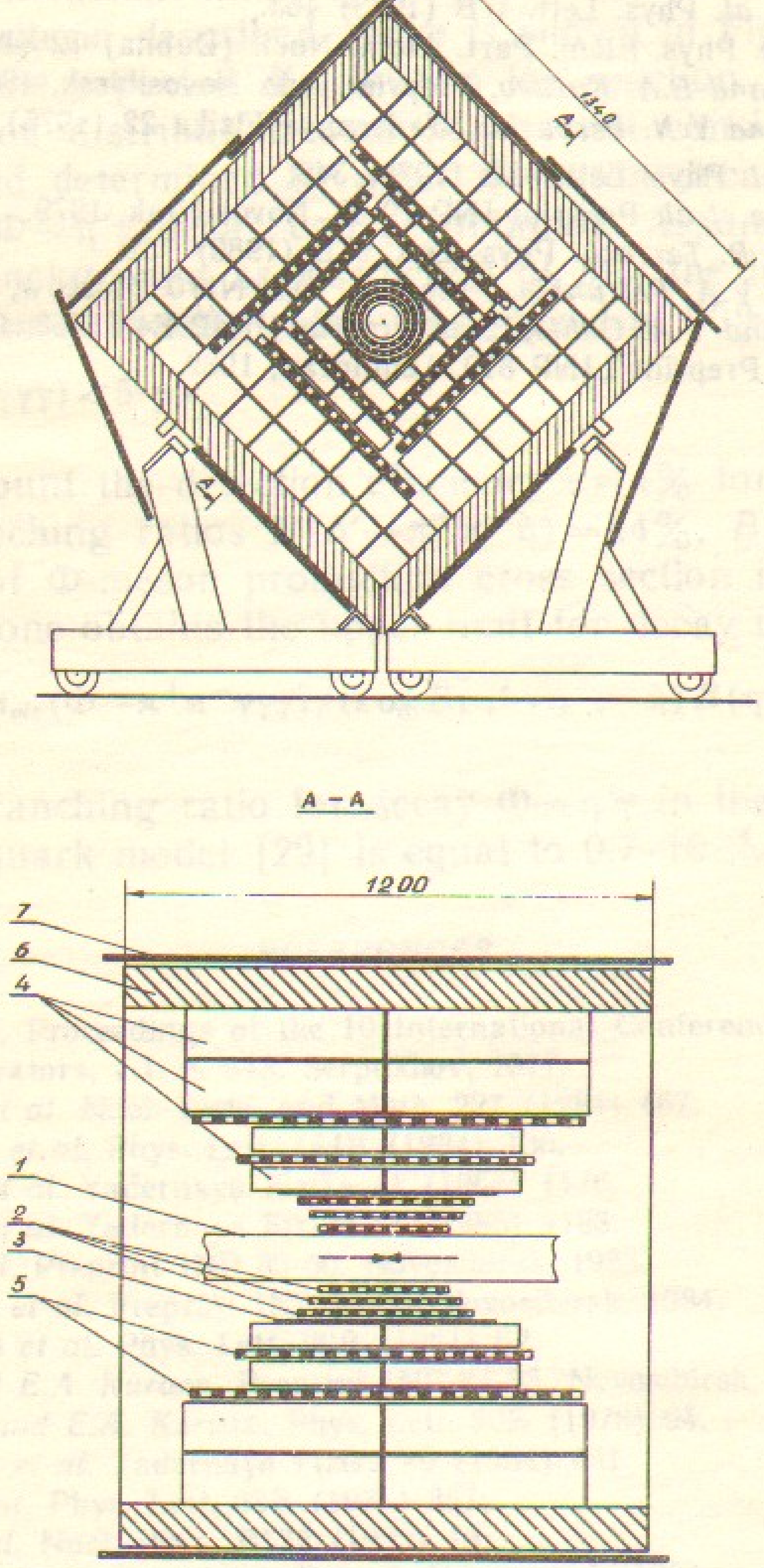

Fig.1. Lay-out of the Neutral Detector:
1—beam pipe of the storage ring, *2*—coordinate proportional chambers, *3*—scintillation counters, *4*—NaI(Tl) counters, *5*—shower chambers, *6*—absorber (10 cm of iron), *7*—anticoincidence counter.

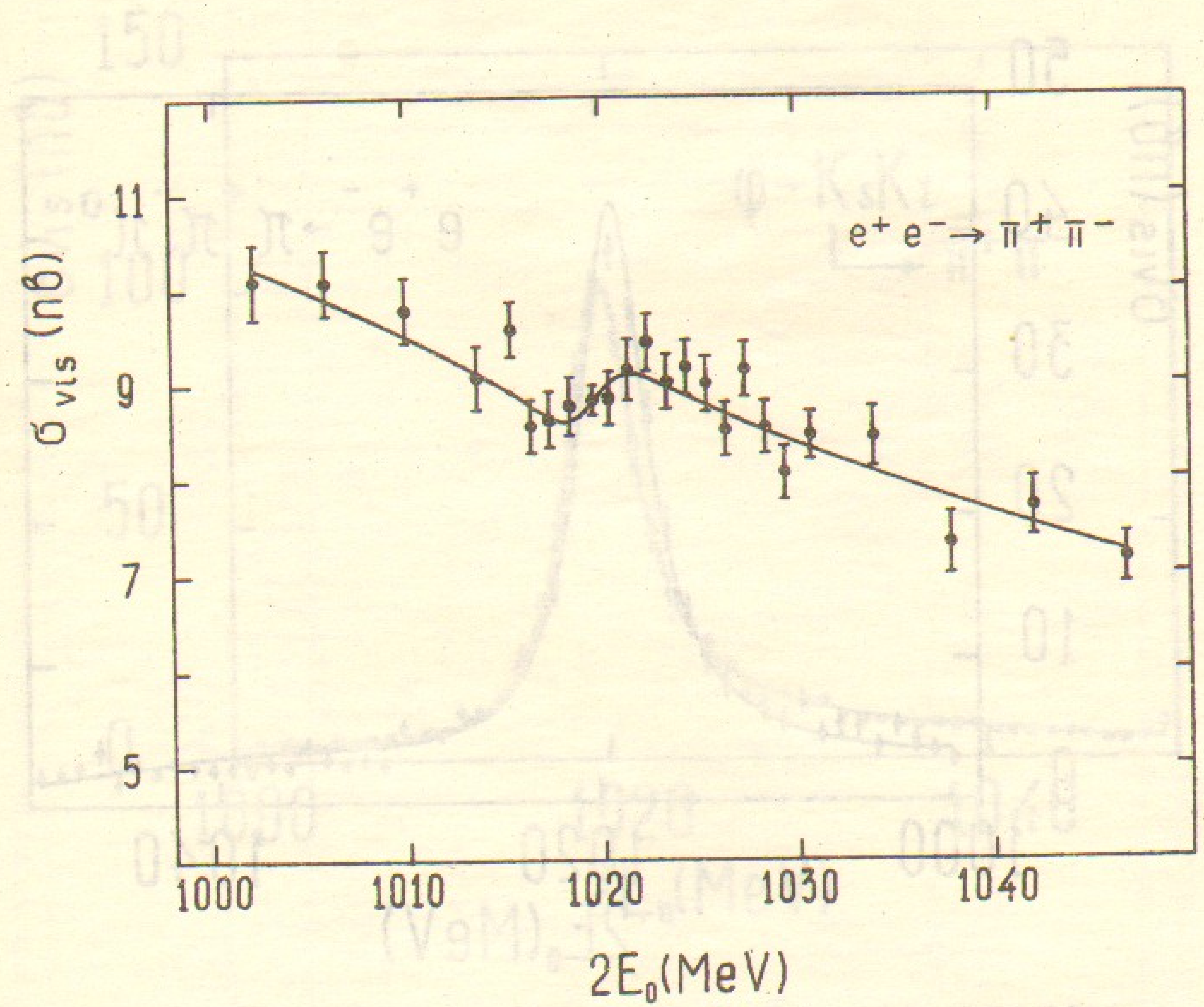

Fig.2. Visible cross section of the process $e^+e^-\to\pi^+\pi^-$. The solid curve is a result of optimization.

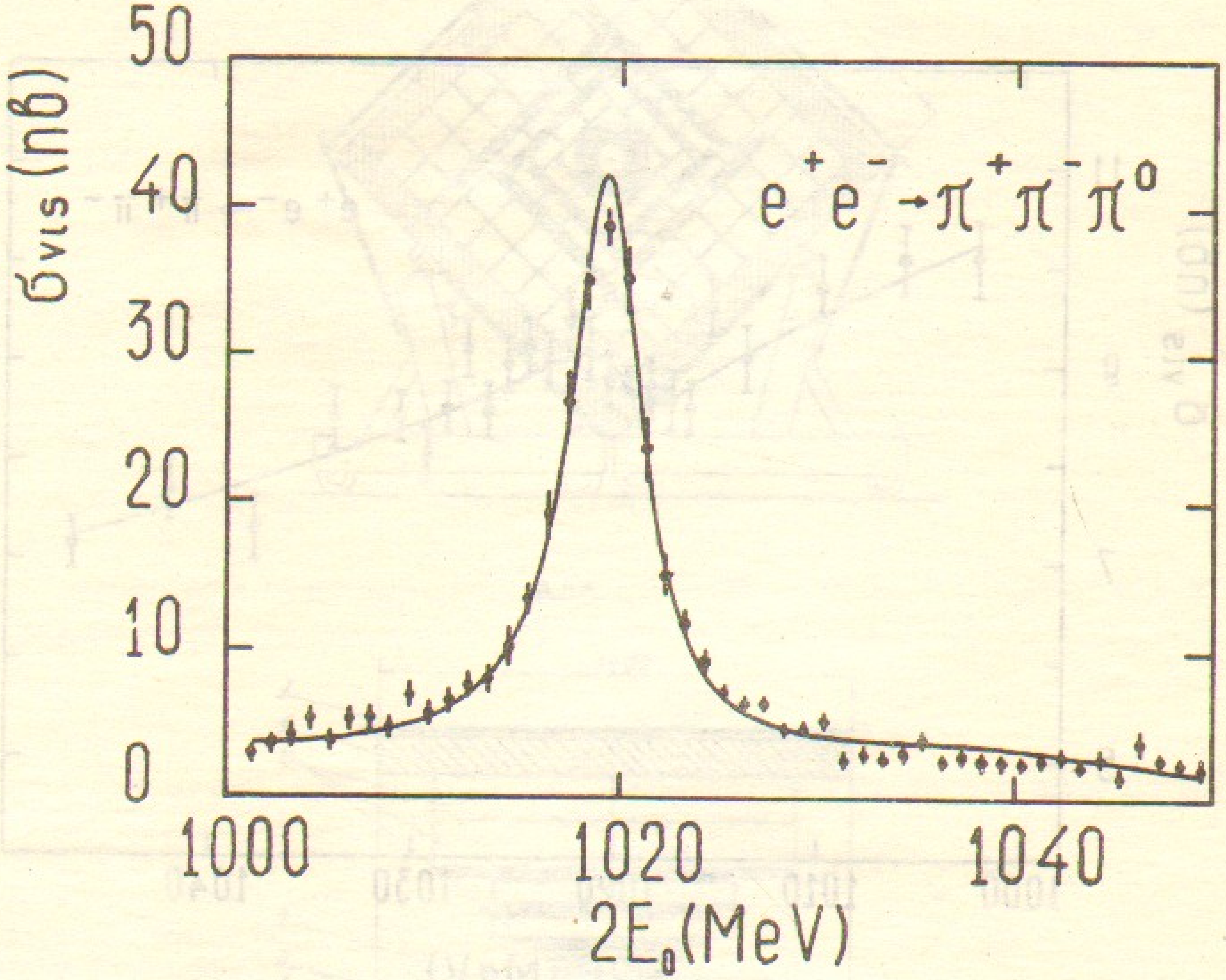

Fig.3. Visible cross section of the process $e^+e^- \to \pi^+\pi^-\pi^0$ and the optimal curve.

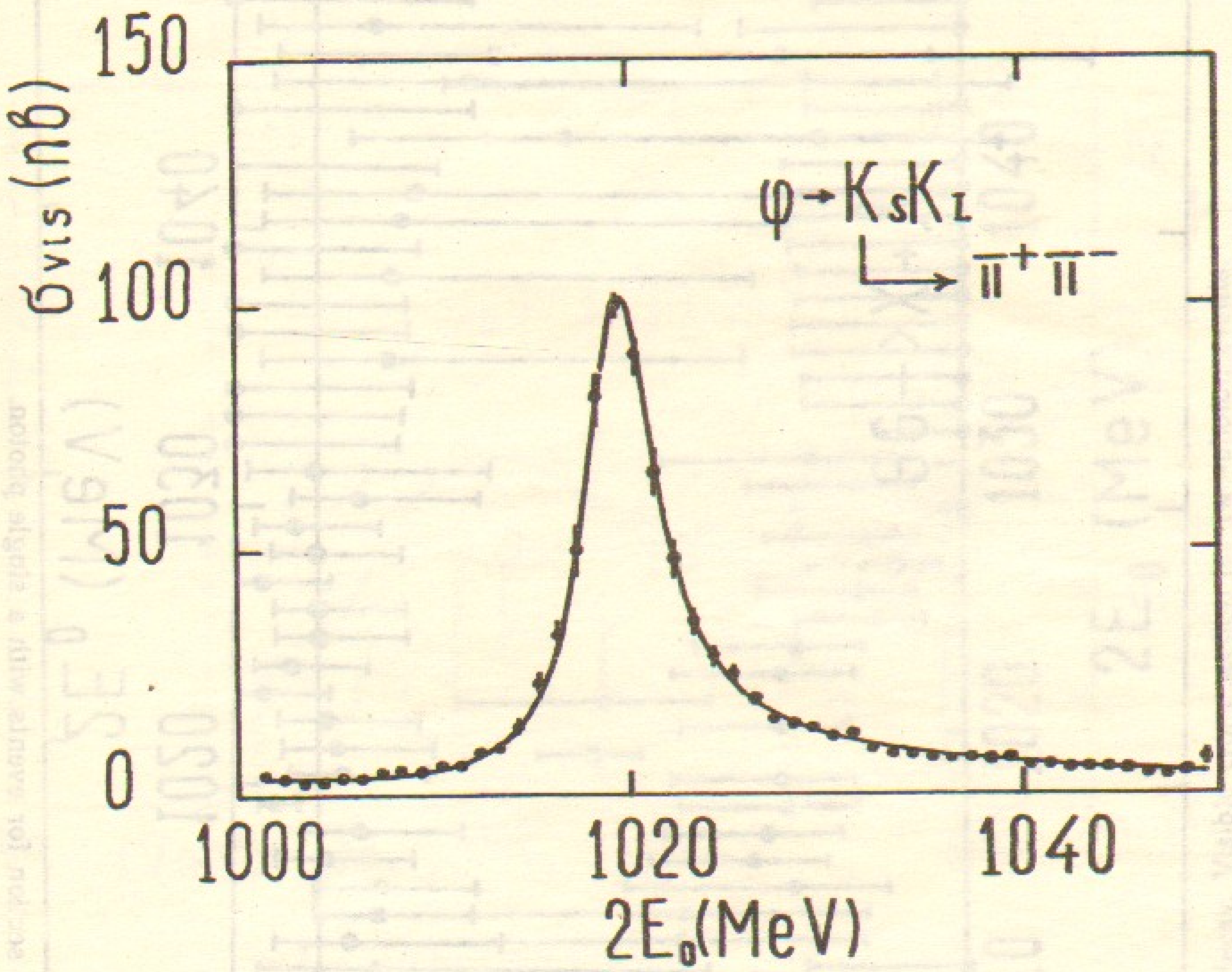

Fig.4. **Visible cross section of the process $\Phi \to K_S K_L$ and the optimal fit.**

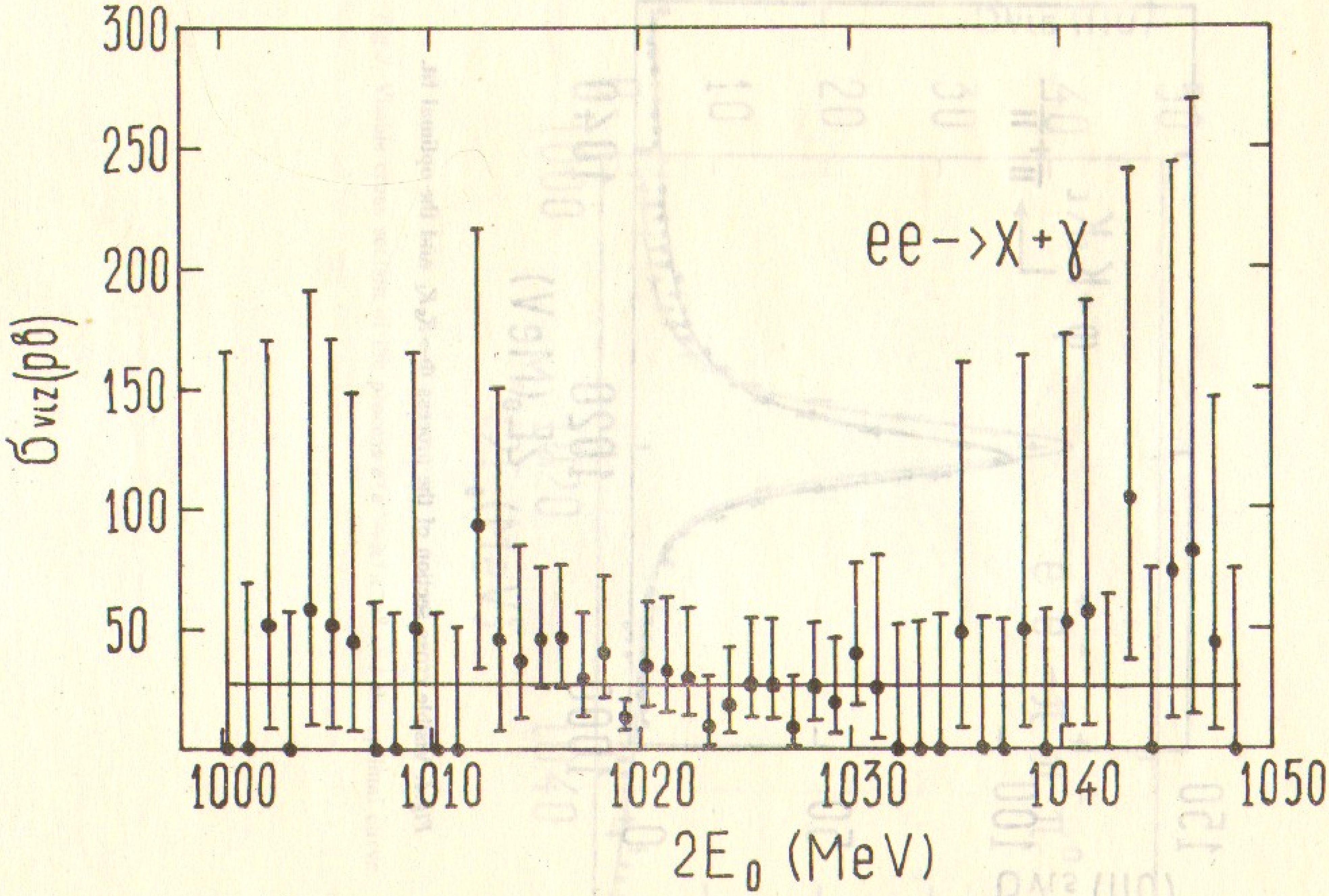

Fig.5. Visible cross section for events with a single photon.

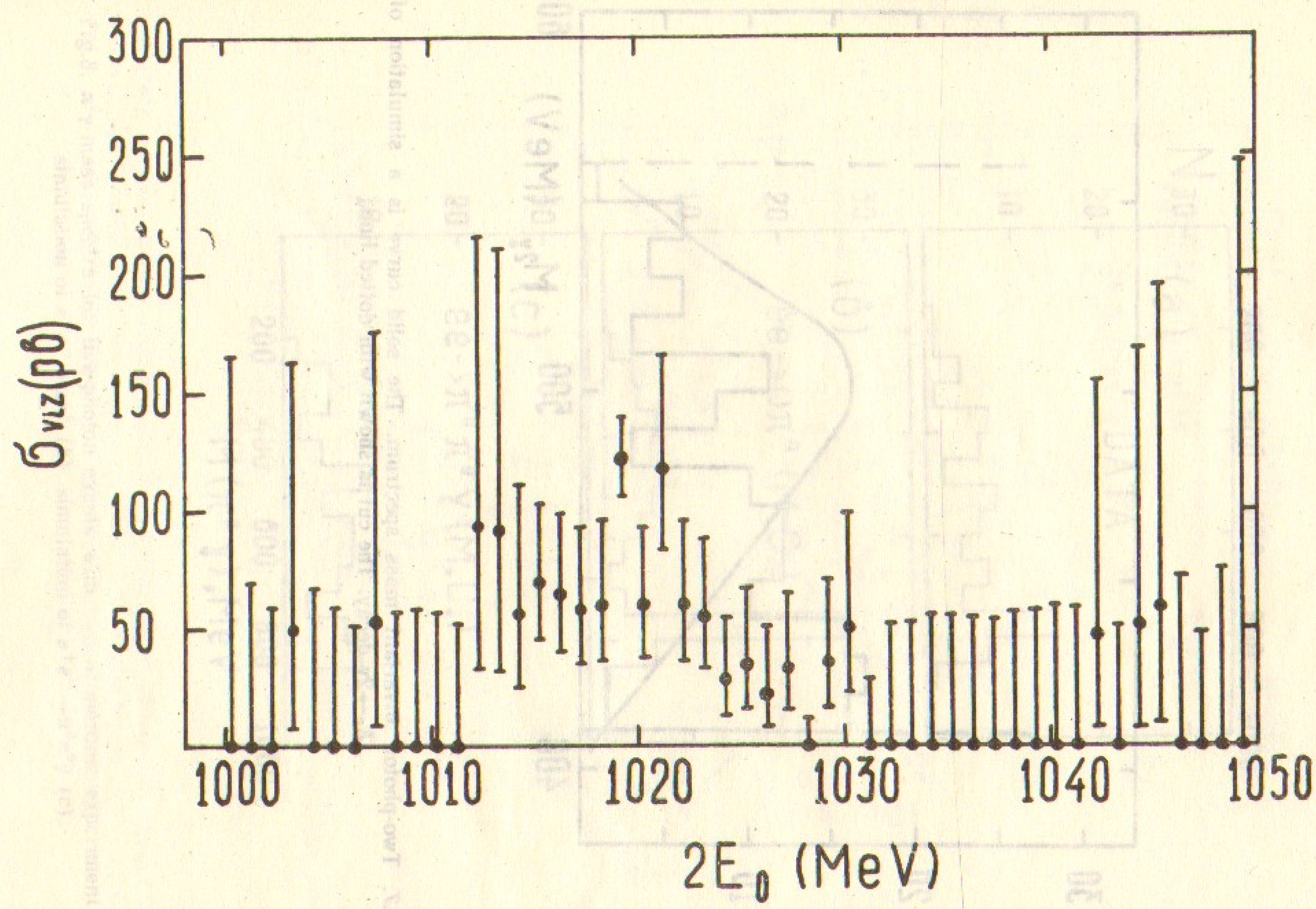

Fig.6. Search for $K_S \to 2\gamma$ decay. Visible cross section for two-photon events.

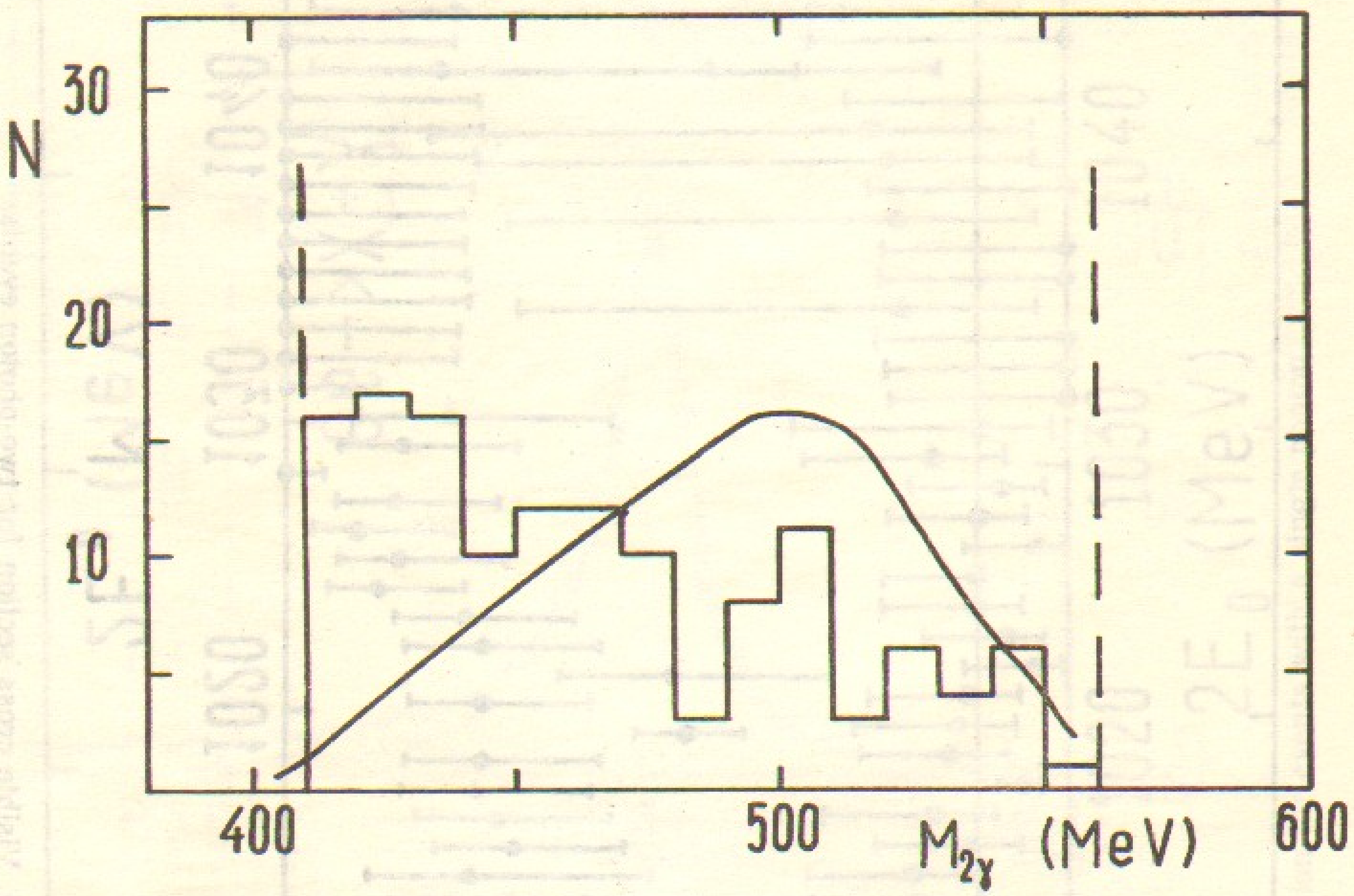

Fig.7. Two-photon invariant mass spectrum. The solid curve is a simulation of $K_S \to 2\gamma$ decay. The cut is shown with dotted line.

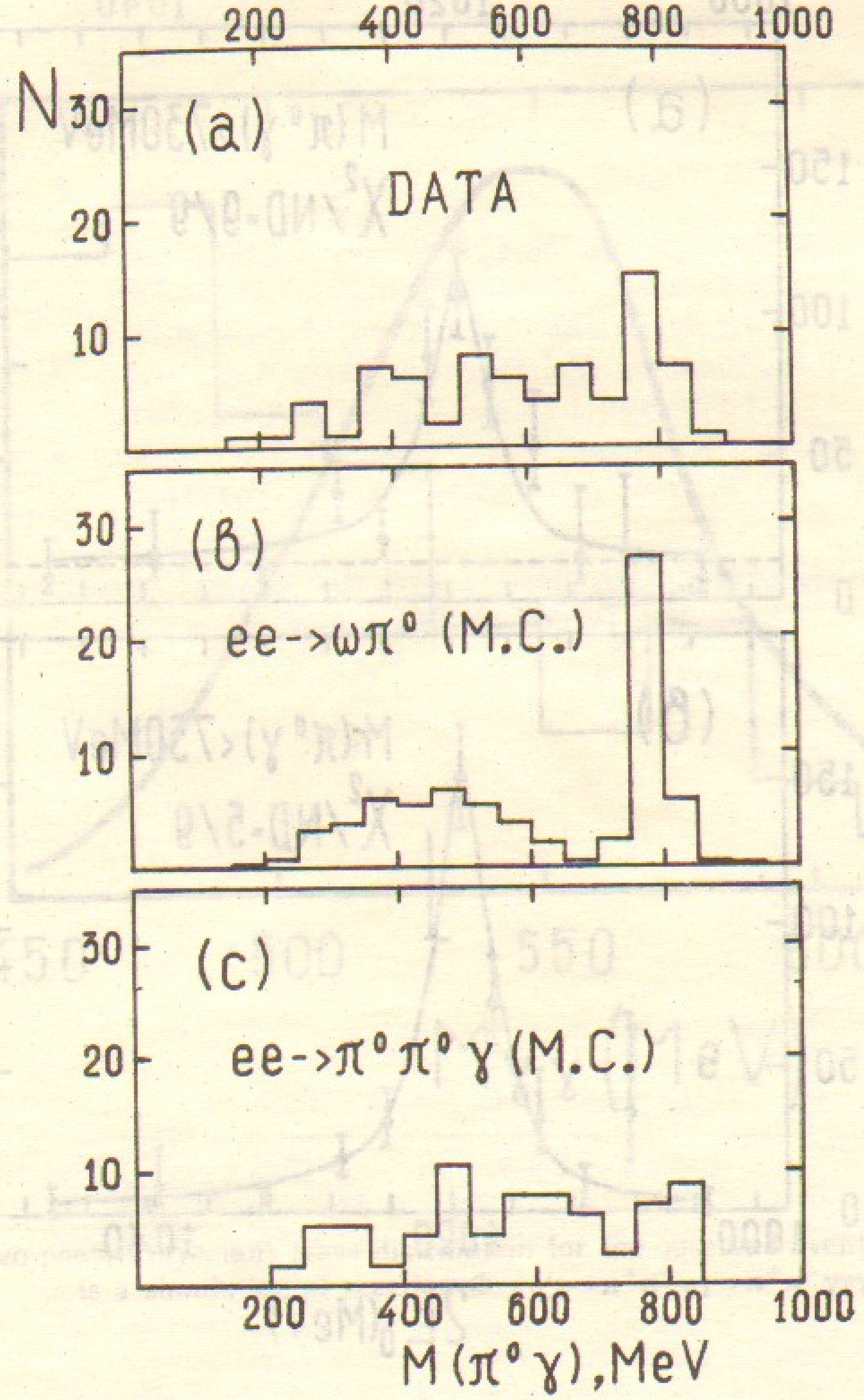

Fig.8. $\pi^0\gamma$-mass spectra for five-photon events with two π^0-mesons: experiment (*a*), simulation of $e^+e^- \to \omega\pi^0$ (*b*), simulation of $e^+e^- \to \pi^0\pi^0\gamma$ (*c*).

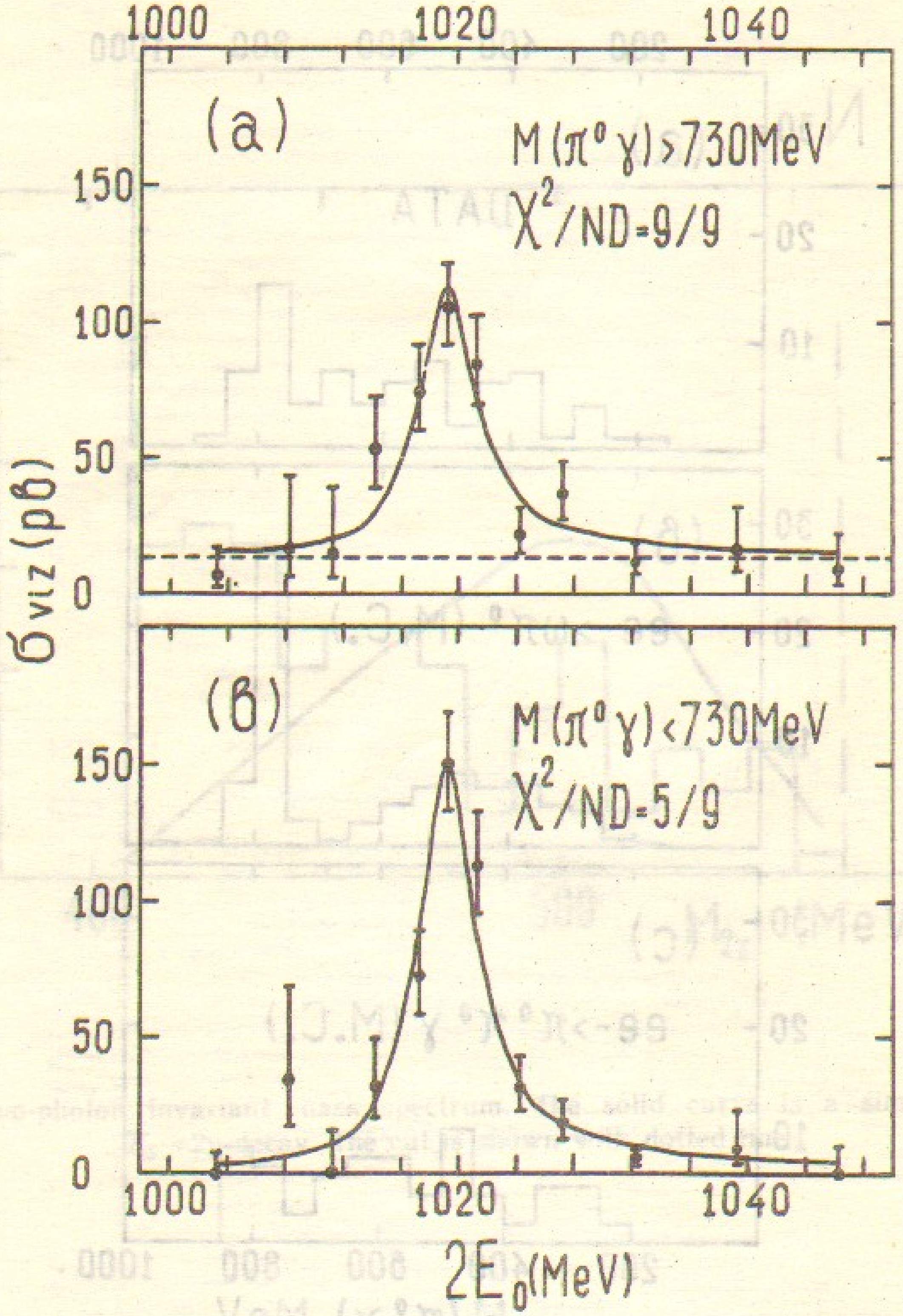

Fig.9. Energy dependence of the visible cross section for events of the type $\pi^0\pi^0\gamma$: the region in which the reaction $e^+e^-\to\omega\pi^0$ dominates (a), the region of the reaction $e^+e^-\to\pi^0\pi^0\gamma$ with $\pi^0\gamma$ invariant mass less than 730 MeV.

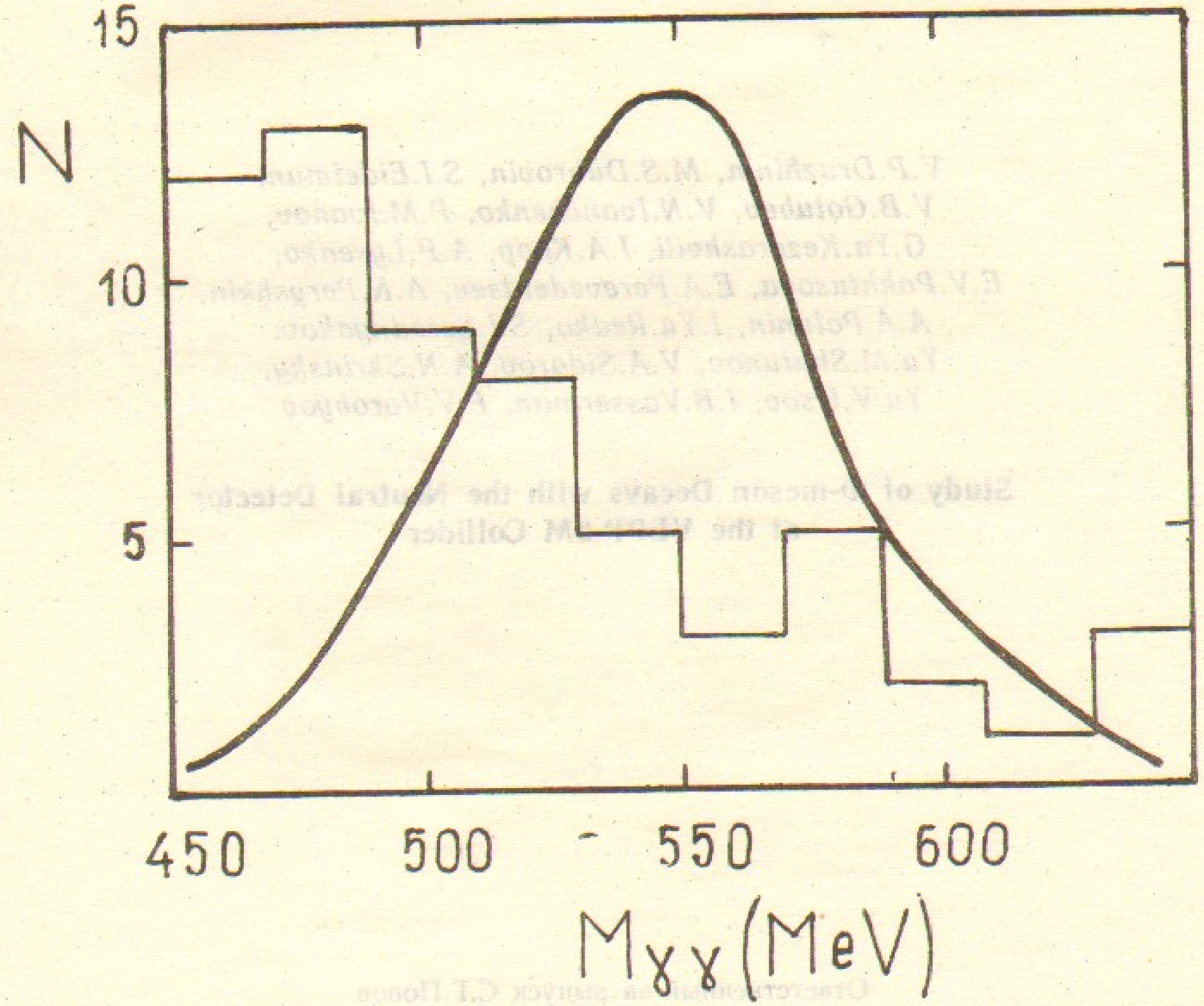

Fig.10. Two-photon invariant mass distribution for the observed events. The solid line is a simulation of reaction $\Phi\to\eta'\gamma\to\pi^+\pi^-\eta\gamma\to\pi^+\pi^-\gamma\gamma\gamma$.

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