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MEASUREMENT OF Φ-MESON RADIATIVE DECAYS AT THE STORAGE RING VEPP-2M WITH THE NEUTRAL DETECTOR

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НОВОСИБИРСК

Abstract

The results of the first experiments with the Neutral Detector at the electron-positron storage ring VEPP-2M are presented. Branching ratios of the Φ-meson radiative decays have been measured:

$$B(\Phi\to\eta\gamma) = (1.30\pm0.06)\,\%,$$
$$B(\Phi\to\pi^0\gamma) = (0.130\pm0.013)\,\%,$$

their accuracy being several times higher compared to the world-average ones. The width ratio is

$$\Gamma(\Phi\to\eta\gamma)\,/\,\Gamma(\Phi\to\pi^0\gamma) = (9.9\pm0.9)\,.$$

Basing upon the measured quantities, the ω-Φ mixing angle

$$\theta_v = (38.60\pm0.25)^\circ$$

as well as the ratio between the effective magnetic moments of the s- and u- quarks, $\mu_s/\mu_u = (0.60\pm0.04)$ have been calculated.

Previously, the Φ-meson radiative decays have been measured with the colliding electron-positron beams [1,2] and in the photoproduction experiments [3]. The work reported here has been done at the storage ring VEPP-2M with the Neutral Detector (ND). Our preliminary results are given in ref. [4].

Detector and experiment. The ND-detector [5] shown in fig.1 is an electromagnetic calorimeter based on 168 rectangular scintillation counters with NaI(Tl) crystals (total weight about 2.6 tons). Between the NaI(Tl) layers there are two layers of two-coordinate proportional chambers intended to measure photon angles (shower chambers). In the detector centre there is a coordinate system consisting of three layers of cylindrical proportional chambers. A total solid angle of the detector is about 65% of 4π. The energy resolution is determined by the amount of passive material between NaI(Tl) crystals and for photons in the energy range of 50—1000 MeV is 25—10% (FWHM). The energy calibration of the detector is performed by cosmic muons. The angular resolusion for photons constitutes 1.5° (RMS) in an azimuthal direction and 3.5° (RMS) for a polar angle.

The experiment has been carried out at the electron-positron storage ring VEPP-2M [6] at its average luminosity $0.7 \cdot 10^{30} \mathrm{sm}^{-2} \cdot \mathrm{s}^{-1}$ in the centre of mass energy range $2E_0 = 1000 \div 1050$ MeV. The cited energy range was scanned several times with a step of 0.5 MeV. The integrated luminosity in the experiment was 3 pb^{-1}, about $1.3 \cdot 10^7$ events were recorded, $3 \cdot 10^6$ of them being Φ-meson decays. The luminosity monitoring during the data taking was performed by the process of double bremsstrahlung, the final normalization was based on the events of Bhabha scattering and two-quantum annihilation at large angles and had a 2% accuracy. The energy scale of the storage ring has been calibrated using the table value of the Φ-meson mass and the excitation curve in the decay mode $\Phi \to K_S K_L \to$ neutrals containing four or more photons. As a result, the branching ratio $B(\Phi \to K_S K_L) = (31.0 \pm 2.4)\%$ has been obtained in agreement with the table value [7]. This error is mainly determined by an accuracy of the Monte-Carlo simulation of the nuclear interaction of the K_L-meson in the detector.

Analysis procedure. In the work reported here the Φ-meson radiative decays have been investigated in the reactions:

$$e^+e^- \to \Phi \to \eta\gamma \to \gamma\gamma\gamma \tag{1}$$

$$e^+e^- \to \Phi \to \pi^0\gamma \to \gamma\gamma\gamma \tag{2}$$

The recoil photons in these reactions are monochromatic. This allows a separation of these reactions between each other and from the following background processes:

$$e^+e^- \to \gamma\gamma\gamma \qquad \text{(QED)} \qquad (3)$$
$$e^+e^- \to K_S K_L \qquad \text{neutrals} \qquad (4)$$

For primary selection of three-photon events the following four conditions have been used: total energy deposition in the detector exceeds 550 MeV, there are no tracks in coordinate chambers, all the photons are detected in the fiducial volume, each photon triggers a shower chamber.

5140 events thus selected have been subjected to a kinematical reconstruction [8]. In this procedure, the energy-momentum conservations are used to improve the accuracy of particle energies and angles measured in the detector. As a result, a resolution in an effective mass of η and π^0 mesons was improved too (fig. 2). The events not satisfying the conservation laws have been rejected, thereby enabling a complete suppression of the background caused by the process (4). The Dalitz plot of selected 3509 events is demonstrated in fig.3d. This figure also shows the distributions of events for the processes (1), (2) and (3) obtained by the Monte-Carlo simulation [9]. The events of Φ-meson radiative decays are concentrated on the diagram around the lines corresponding to the energies of the recoil photons in these decays. It makes possible to define three regions in which the events of the reactions (1), (2) and (3) are dominating. For further processing all the events involved in the reaction (1) and reaction (3) region have been used (see fig.3a and fig.3c, respectively). A substantial number of the events due to the reaction (1) occurs in the region of the reaction (2) (fig.3b). From this region only the events which satisfy the condition $\ln(W_\pi/W_\eta) > 1$ have been used for further processing. Here W_η and W_π are the probabilities to belong to the reactions (1) and (2) for a given event. These probabilities have been obtained employing a kinematical reconstrustion [8] performed under the assumption that the invariant masses of photon pairs are equal to the masses of η or π^0 mesons. The detection efficiency for the processes (1) and (2) with the selection criteria cited above was found to be 10% and 7.5%, respectively, and the probability of occurence of the process (1) events among the process (2) events was 0.2%.

Results. For fitting the experimental data, the detection cross section for each of the processes (1), (2) and (3) has been written as follows:

$$\sigma_{viz}(E) = \sigma(E) \cdot \alpha(E) \cdot \varepsilon + \sigma_b(E)$$

where $\sigma(E)$ is a cross section in the first Born approximation, $\alpha(E)$ is a factor taking into account radiative corrections [10], $\sigma_b(E)$ is a detection cross section for background processes, and ε is the detection efficiency calculated by the Monte-Carlo method [9]. The following expression for the cross section has been used:

$$\sigma(E) = \sigma_0 \left(\frac{1 - m_p^2/4E^2}{1 - m_p^2/m_\Phi^2} \right)^3 \cdot \left(\frac{\Gamma_\Phi}{m_\Phi} \right)^2 \cdot \left| A + \frac{1}{(1 - 4E^2/m_\Phi^2 - i\Gamma_\Phi/m_\Phi)} \right|^2$$

where σ_0 is a cross section in the Φ-meson maximum, m_p are the masses of a η or π^0 meson, and A is a non-resonant interfering amplitude which can be expressed via the sum of Breit-Wigner amplitudes of ρ and ω mesons. Taking the table values of appropriate widths [7], we obtained $A = 4.7 - 0.3 \cdot i$ for the process (1) and $A = 37 - i$ for the process (2).

As a result of fitting (fig.4c), the measured cross section for the process (3) agrees with a calculated one [11]. This process determines completely the cross section $\sigma_b(E)$ for the reaction (1) and the larger part of this cross section for the reaction (2). The latter has been fitted with a small background of the reaction (1) taken into account. The contribution of the reaction (4) to all of the processes under study is negligibly small. After fitting the detection cross sections for the reactions (1) and (2) with a fixed mass and width of Φ-meson (figs.4a,4b) The following values of the cross sections have been obtained:

$$\sigma_0(e^+e^- \to \Phi \to \eta\gamma \to \gamma\gamma\gamma) = (22.3 \pm 0.7 \pm 0.9) \text{ nb} \qquad (5)$$
$$\sigma_0(e^+e^- \to \Phi \to \pi^0\gamma \to \gamma\gamma\gamma) = (5.6 \pm 0.5 \pm 0.3) \text{ nb}$$

The first error indicated above is statistical, while a second one is systematical. The latter is determined by the accuracy in the detection efficiency calculation and by the accuracy of the absolute luminosity determination. The cross sections obtained are slightly dependent on the model assumptions. For example, if we assume that $A = 0$ the values of cross sections (5) will change only by 0.1 nb. Using the table values [7]:

$$B(\eta \to \gamma\gamma) = (39.1 \pm 0.8)\,\%$$
$$B(\pi^0 \to \gamma\gamma) = 98.8\%$$
$$B(\Phi \to e^+e^-) = (3.11 \pm 0.10) \cdot 10^{-4}$$
$$\Gamma_\Phi = (4.21 \pm 0.13) \text{ MeV}$$

one can obtain from (5):

$$\sigma_0(e^+e^- \to \Phi \to \eta\gamma) = (57.0 \pm 2.8) \text{ nb}$$
$$\sigma_0(e^+e^- \to \pi^0\gamma) = (5.7 \pm 0.6) \text{ nb}$$

$$\begin{aligned} B(\Phi\to\eta\gamma) &= (1.30\pm0.06)\,\% \\ B(\Phi\to\pi^0\gamma) &= (0.130\pm0.013)\,\% \\ \Gamma(\Phi\to\eta\gamma) &= (55\pm3)\ \text{keV} \\ \Gamma(\Phi\to\pi^0\gamma) &= (5.5\pm0.6)\ \text{keV} \end{aligned} \tag{6}$$

It is worth noting that the systematical errors in the reactions being investigated are the same and, therefore, the error in the ratio of the widths is mainly a statistical one:

$$\Gamma(\Phi\to\eta\gamma)/\Gamma(\Phi\to\pi^0\gamma) = (9.9\pm0.9)$$

The events with larger than 6 photons have been analysed as well. These events are due to the reactions $e^+e^-\to\Phi\gamma\to\pi^0\pi^0\pi^0\gamma$, and (4). With the use of the monochromaticity of the recoil photon (fig.5), it is possible to separate the events of this reaction and obtain $B(\Phi\to\eta\gamma) = (1.4\pm0.2)\,\%$. This value is consistent with (6) but has a large error.

Discussion. The values found for the branching ratios of the Φ-meson radiative decays are in agreement with the world-average ones but have smaller errors.

Within the framework of a non-relativistic quark model (see refs.[12,13]), one can derive the following relation:

$\Gamma(\Phi\to\pi^0\gamma)/\Gamma(\omega\to\pi^0\gamma) = \mathrm{tg}^2\,(\theta_v-35.3^\circ)\cdot(k_\Phi/k_\omega)^3$, where θ_v is a ω-Φ mixing angle in the nonet of vector mesons, and k_Φ, k_ω are the momenta of the pions in the radiative decays. Using our result for $\Gamma(\Phi\to\pi^0\gamma)$ and the quantity $\Gamma(\omega\to\pi^0\gamma) = (0.79\pm0.09)$ MeV [12], which is somewhat different from the table value [7], one can obtain the mixing angle $\theta_v = (38.60\pm0.25)^\circ$. This coincides with the value of $\theta_v = (38.6\pm0.4)^\circ$ [7] obtained from the quadratic mass formula.

Using the expressions for the radiative decay widths presented in refs. [12,13], we derived the relation:

$$\frac{\Gamma(\Phi\to\eta\gamma)}{\Gamma(\omega\to\pi^0\gamma)} = \left|\frac{2\mu_s\cos(\theta_p-35.3^\circ)}{2\mu_u+\mu_d} - \frac{2\mu_u-\mu_d}{2\mu_u+\mu_d}\,\mathrm{tg}\,(\theta_v-35.3^\circ)\sin(\theta_p-35.3^\circ)\right|^2\cdot\left|\frac{I_{\Phi\eta}}{I_{\omega\pi}}\right|^2\left(\frac{k'_\eta}{k_\omega}\right)^3$$

where μ_u, μ_d and μ_s are the magnetic moments of u-, d- and s- quarks, k_η is a momentum of the η-meson in the reaction (1), θ_p is a mixing angle for pseudoscalar mesons, $I_{\Phi\eta}/I_{\omega\pi}$ is a ratio of the overlap integrals in radiative decays. Following refs. [12-14], it is posssible to put the latter equal to unity. Taking use of $\mu_d/\mu_u = 1.05$ [13,14] and $\theta_p = (-11.1\pm0.2)^\circ$ [7] coupled with our result for $\Gamma(\Phi\to\eta\gamma)$, we obtain $\mu_s/\mu_u = (0.60\pm0.04)$. A similar calculation [13,14] with the use of the well known values of the baryon magnetic moments gives $\mu_s/\mu_u = (0.663\pm0.005)$.

In conclusion, we would like to note that the accuracy of the results obtained is several times higher in comparison with the world-average one. The mixing angle found by means of our results confirms once more the validity of the quadratic mass formula for vector mesons. The calculated value for the ratio of magnetic moments indicates to the universal nature of the magnetic moments of light quarks in baryons and mesons.

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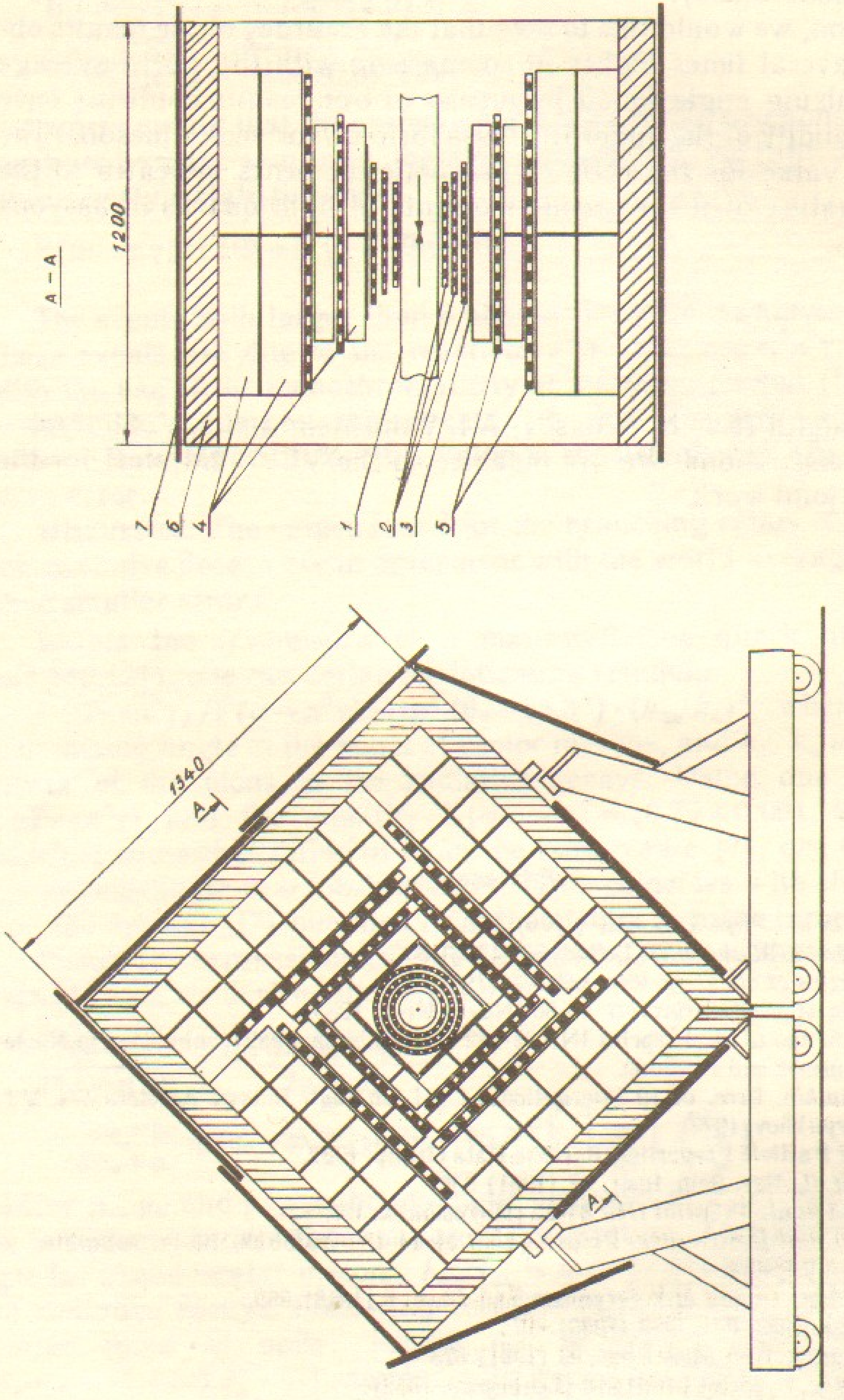

Fig.1. Lay-out of the Neutral Detector: 1—vacuum chamber of the storage ring, 2—coordinate proportional chambers, 3—scintillation counters, 4—NaI(Tl) counters, 5—shower chambers, 6—absorber (10 cm iron), 7— anticoincidence counters.

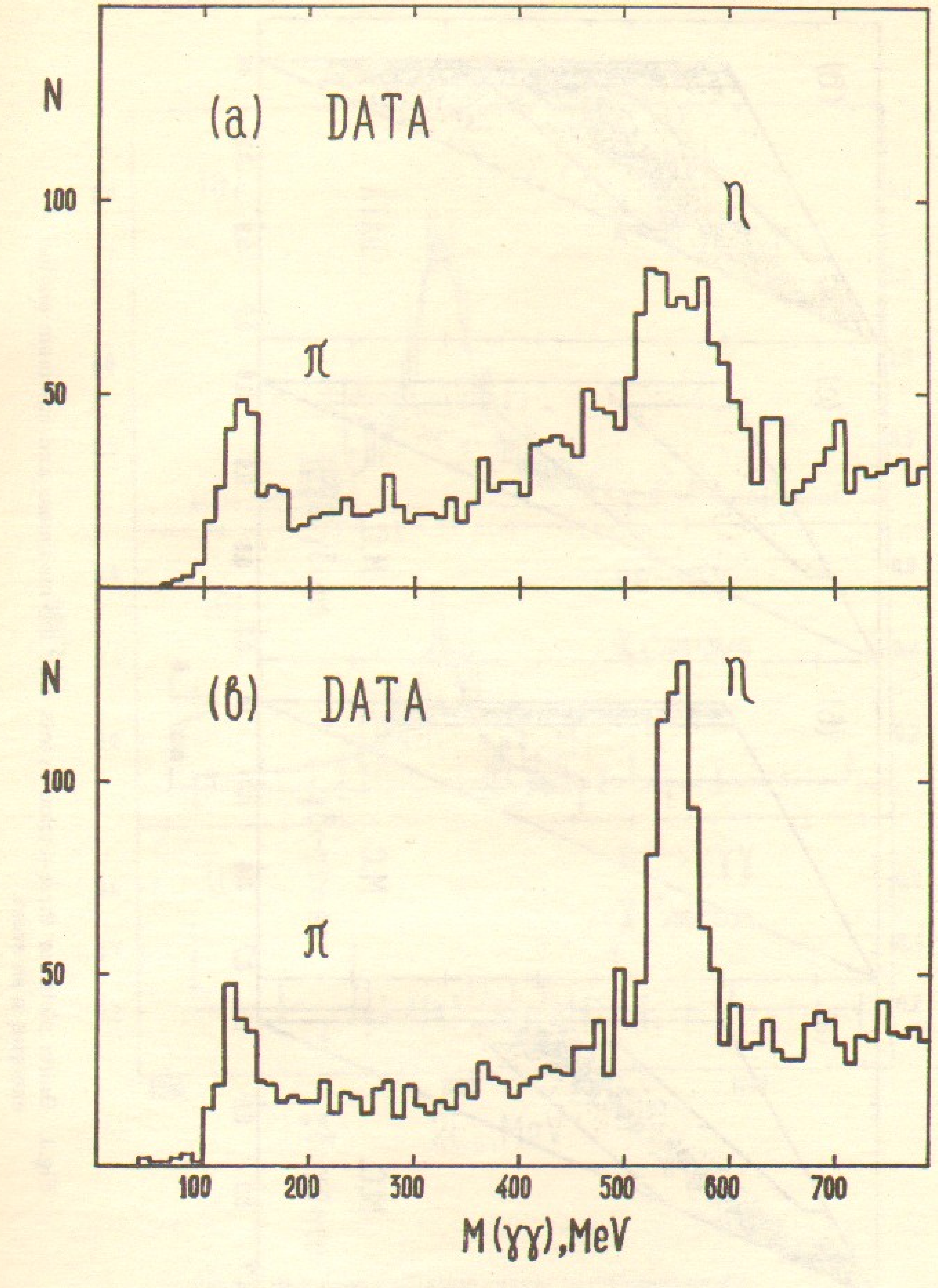

Fig.2. Spectra of effective masses of photon pairs in three-photon events before (a) and after (b) kinematical reconstruction.

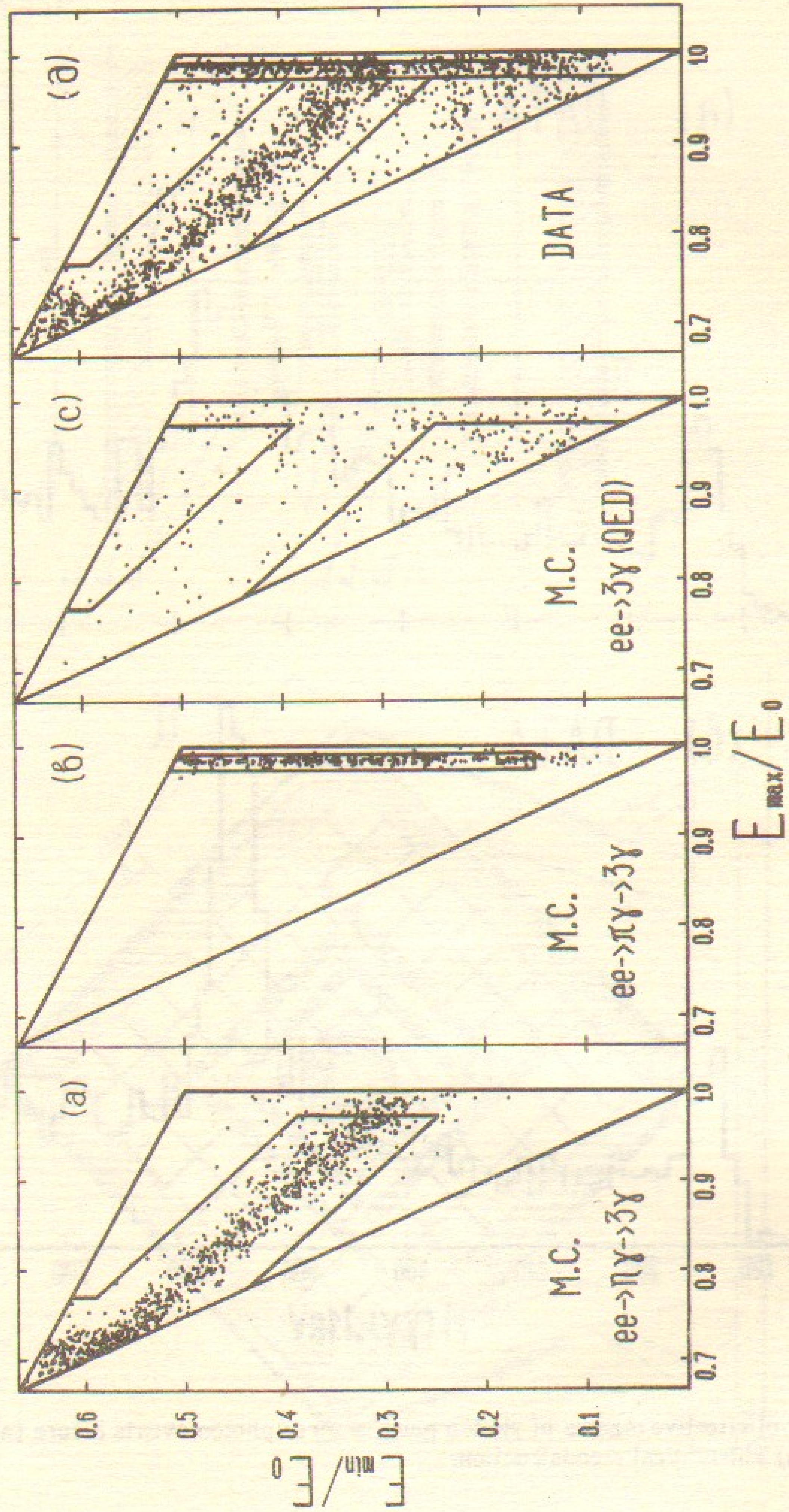

Fig.3. Dalitz plots for three-photon events over the maximum and minimum photon energies in an event.

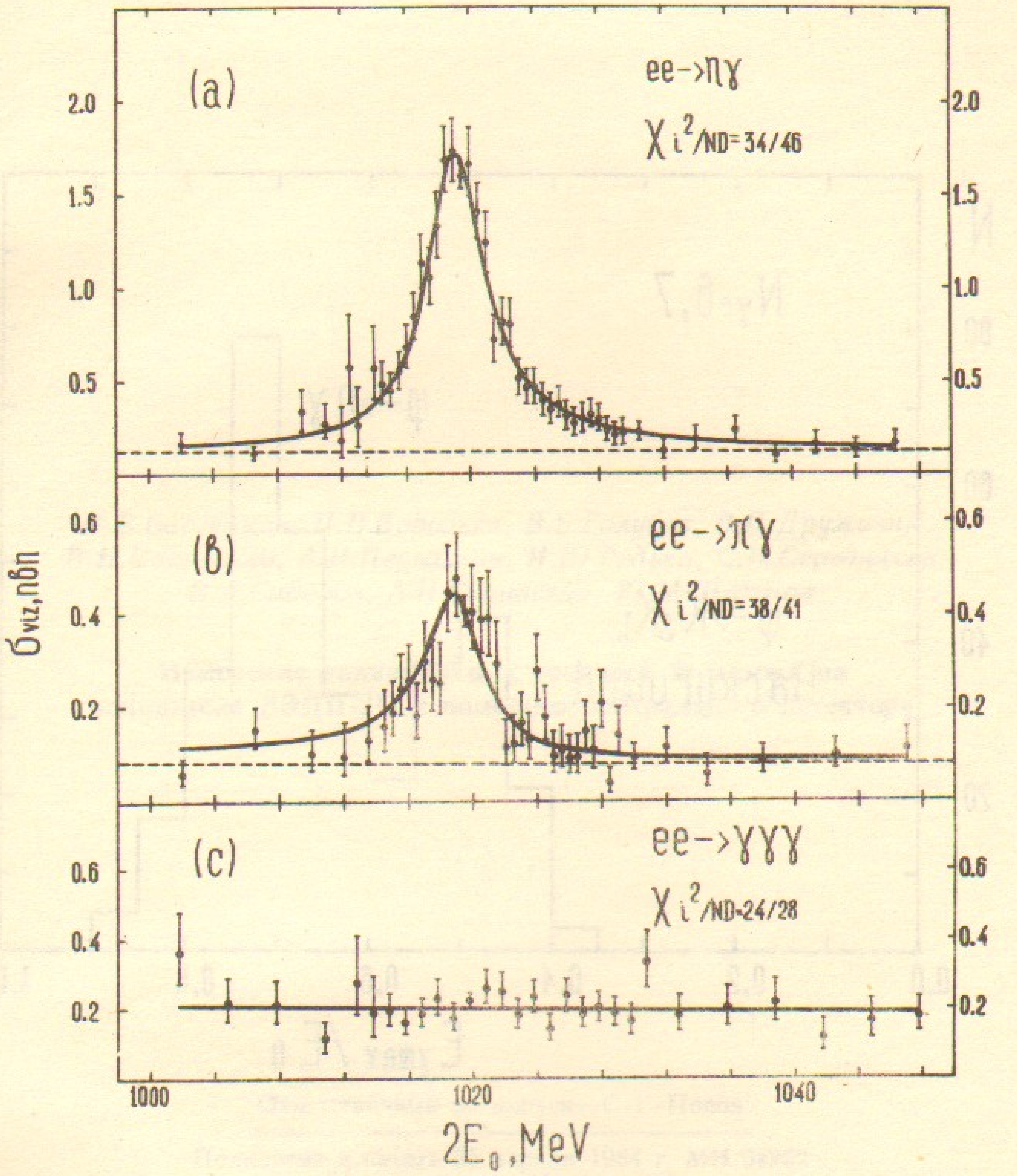

Fig.4. Φ-meson excitation curves in different modes.

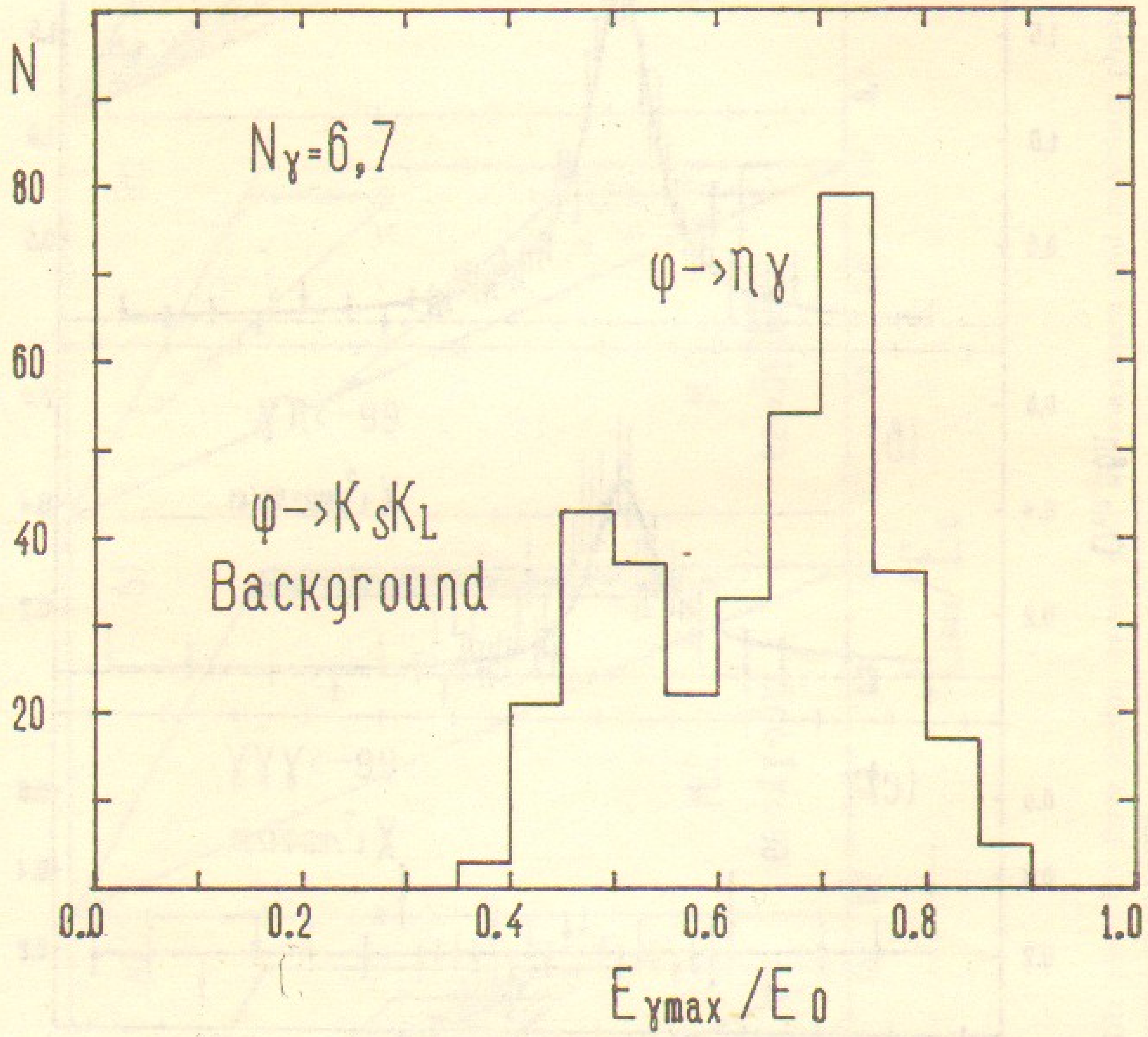

Fig.5. Energy spectrum of photons with a maximum energy for the many-photon events.

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Измерение радиационных распадов Ф-мезона на накопителе ВЭПП-2М с помощью нейтрального детектора

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