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STUDY OF THE ϕ DECAYS INTO $\pi^0\pi^0\gamma$ AND $\eta\pi^0\gamma$ FINAL STATES

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Abstract

Radiative decays of the ϕ meson have been studied using a data sample of about 19 million ϕ decays collected by the CMD-2 detector at VEPP-2M collider in Novosibirsk. From selected $e^+e^- \to \pi^0\pi^0\gamma$ and $e^+e^- \to \eta\pi^0\gamma$ events the following model independent results have been obtained:

$Br(\phi \to \pi^0\pi^0\gamma) = (0.92 \pm 0.08 \pm 0.06) \times 10^{-4}$ for $M_{\pi^0\pi^0} > 700$ MeV,

$Br(\phi \to \eta\pi^0\gamma) = (0.90 \pm 0.24 \pm 0.10) \times 10^{-4}$.

It is shown that the intermediate mechanism $f_0(980)\gamma$ dominates in the $\phi \to \pi^0\pi^0\gamma$ decay and the corresponding branching ratio is

$Br(\phi \to f_0(980)\gamma) = (2.90 \pm 0.21 \pm 1.54) \times 10^{-4}$.

The systematic error is dominated by the possible model uncertainty.

Using the same data sample the upper limit has been obtained for the P- and CP-violating decay of η at 90% CL:

$Br(\eta \to \pi^0\pi^0) < 4.3 \times 10^{-4}$.

Introduction

In the preceding paper [1] we reported on the first observation of the $\phi \to \pi^+\pi^-\gamma$ decay with the CMD-2 detector. The present work provides complementary information on the electric dipole radiative transitions of the ϕ meson obtained from the $\pi^0\pi^0\gamma$ and $\eta\pi^0\gamma$ final states.

The purely neutral decay $\phi \to \pi^0\pi^0\gamma$ has no bremsstrahlung background as the $\phi \to \pi^+\pi^-\gamma$ decay and is the most efficient to study the two pion mass spectrum in the $\phi \to f_0(980)\gamma$ decay. With the CMD-2 detector this mode as well as another ϕ decay

with five photons in the final state $\phi \to \eta\pi^0\gamma$ have been studied and the first results [2] based on about 25% of the data confirmed those reported earlier by SND [3, 4].

The CMD-2 detector described in detail elsewhere [5] has been taking data since 1992. In addition to the barrel CsI calorimeter, the endcap calorimeter made of BGO crystals was installed in 1995 making the detector almost hermetic to the photons. The energy resolution for photons in the CsI calorimeter is about 8% independent of the energy and $\sigma_E/E = 4.6\%/\sqrt{E(GeV)}$ for the BGO calorimeter.

In total, the 14.2 pb^{-1} of data have been collected at 14 energy points around the ϕ mass. For the analysis of the $\phi \to \pi^0\pi^0\gamma$ and $\phi \to \eta\pi^0\gamma$ decays presented here 12.8 pb^{-1} were used corresponding to 18.8×10^6 ϕ decays.

$\phi \to \pi^0\pi^0\gamma$ channel

Selection of $\pi^0\pi^0\gamma$ Events

Candidates for this decay were selected from a sample of purely neutral events with the following criteria:

1. There are five or more photons in the CsI and BGO calorimeters with the total energy deposition $E_{tot} > 1.75 \cdot E_{beam}$. The Monte Carlo simulation of the $\pi^0\pi^0\gamma$ events well reproduces the resolution over E_{tot} and shows that 97% of signal events survive this cut. A requirement of minimum three photons in the CsI calorimeter gives a high trigger efficiency [6].

2. All photons have polar angles in the range 0.6-2.54 radians and have energy higher than 20 MeV.

3. To select $\pi^0\pi^0\gamma$ events a constrained fit requiring energy-momentum conservation was performed finding two best combinations of photon pairs with π^0 masses. The χ^2 distribution after the constrained fit is shown in Fig. 1a. Events with $\chi^2 < 6$ were taken for further analysis. This cut suppresses to the 10^{-3} level the background from the $\phi \to K^0_S K^0_L$ decay mode when K^0_S decays to $\pi^0\pi^0$ and K^0_L produces the fifth cluster in the calorimeter.

4. Photons from reconstructed π^0's in the BGO calorimeter have energy higher than 40 MeV. This cut removed incorrectly reconstructed events with photons from the beam background.

5. A selection cut $|(P^1_{\pi^0} - P^2_{\pi^0})/(P^1_{\pi^0} + P^2_{\pi^0})| < 0.8$, where $P^1_{\pi^0}, P^2_{\pi^0}$ were pion momenta, was applied to remove incorrect combinations in which a free photon of low energy was used as a part of a reconstructed π^0.

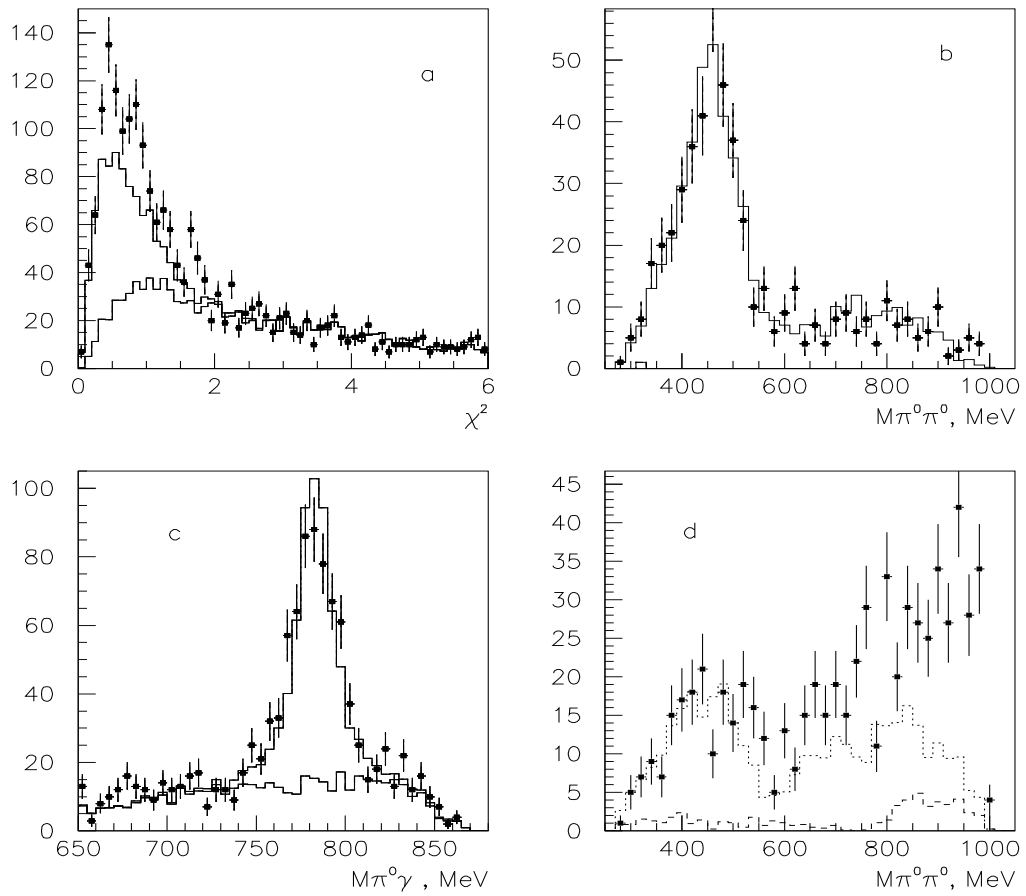

Figure 1: Study of the $\phi \to \pi^0\pi^0\gamma$ events: a. χ^2 distribution for a five photon sample after the constrained fit. Histograms present the normalized simulated contribution from $\eta\gamma$ events (lower) and a sum of this distribution with that for $\omega\pi^0$ events (upper); b. $\pi^0\pi^0$ invariant mass for events with $2.4 < \chi^2 < 6$. The histogram is simulation of $\eta\gamma$ events ; c. $\pi^0\gamma$ invariant mass. Histograms are as in "a"; d. $\pi^0\pi^0$ invariant mass for events with $\chi^2 < 2.4$. Histograms show a contribution from $\omega\pi^0$ events after the "anti-ω" cut (dashed) and a sum of this contribution with $\eta\gamma$ background (dotted).

Background Subtraction

The main background to events of interest comes from the processes $\phi \to \eta\gamma$, $\eta \to \pi^0\pi^0\pi^0$ with two lost photons and from $e^+e^- \to \omega\pi^0$ with the $\omega \to \pi^0\gamma$ decay.

The subtraction of the background from $\eta\gamma$ events was performed according to the simulation. The invariant mass of the $\pi^0\pi^0$ system for $2.4 < \chi^2 < 6$ is shown in Fig. 1b and demonstrates good agreement of the observed background spectrum with simulation. The normalization of observed background events to the collected integrated luminosity gives $N_\phi = (20.6 \pm 1.0)$ millions of ϕ decays in agreement with the (18.8 ± 0.9) millions obtained from the analysis of seven photon events from the $\phi \to \eta\gamma \to \pi^0\pi^0\pi^0\gamma$ decay [7]. The latter number was used for the normalization of

signal events.

The invariant mass of the $\pi^0\gamma$ system for selected events is shown in Fig. 1c and demonstrates the presence of events from $e^+e^- \to \omega\pi^0$ process. The number of $\omega\pi^0$ events was found to be 506 ± 28 with the $\pi^0\gamma$ mass of (782.0 ± 0.9) MeV close to the world average value of the ω meson mass [8]. These events were used to check the above cut efficiencies and event selection criteria. By looking for the $\omega\pi^0$ signal in a sample of six and seven photon events it was confirmed that 92% of signal events had exactly five photons. This was used for the efficiency correction. The simulated detection efficiency for $e^+e^- \to \omega\pi^0$ events was found to be $(14.4 \pm 0.1)\%$.

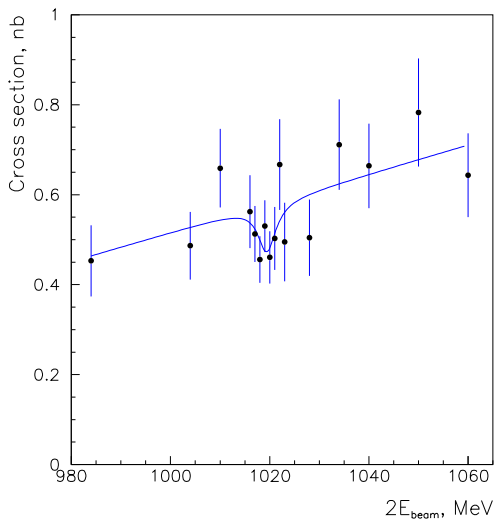

Figure 2: The cross section vs. energy for selected $\omega\pi^0$ events.

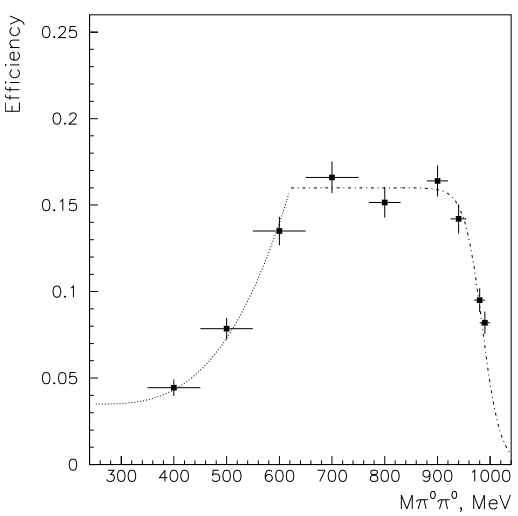

Figure 3: The simulated efficiency vs. $\pi^0\pi^0$ invariant mass. The line is an approximation used for calculations.

The energy dependence of the cross section of the process $e^+e^- \to \omega\pi^0 \to \pi^0\pi^0\gamma$ is presented in Fig. 2. It was fit taking into account the interference of the non-resonant process with the ϕ decay. The values of the parameters of the $\phi \to \omega\pi^0$ decay were taken from [9]. The non-resonant cross section obtained at $2E_{beam} = m_\phi$ is $\sigma_0 = (0.58 \pm 0.02 \pm 0.04)$ nb consistent with that measured by SND [9]. The second error represents the systematic uncertainty caused by background subtraction.

The "anti-ω" cut $M_{inv}(\pi^0\gamma) < 750$ MeV reduces the admixture of $\omega\pi^0$ events to the level of about 5% (see the dashed histogram in Fig. 1d). However, it does not completely remove $\omega\pi^0$ events mostly because of some incorrectly reconstructed events in which a free photon is used as a part of a reconstructed π^0. These incorrect combinations were studied using simulated $\omega\pi^0$ events and experimental events from the "off-ϕ" region where the process $e^+e^- \to \omega\pi^0$ dominates. The ratio of the number of

incorrectly reconstructed events to the total number of $\omega\pi^0$ events was found to be 0.060 ± 0.003 for simulation and 0.09 ± 0.02 for experimental data. The difference was used to estimate a systematic error so that the final admixture of $\omega\pi^0$ events in the $\pi^0\pi^0\gamma$ sample was $(5.0\pm1.5)\%$.

Branching Ratio Calculation

The invariant mass distribution of the $\pi^0\pi^0$ system for $\chi^2 < 2.4$ is shown in Fig. 1d with the expected backgrounds from $\omega\pi^0$ after the "anti-ω" cut and from $\eta\gamma$ events. The distribution demonstrates the increase in the number of events with a high invariant mass (a free photon of low energy). In total, 268 ± 27 of $\pi^0\pi^0\gamma$ events have been found after all cuts and background subtraction.

The detection efficiency as a function of the $\pi^0\pi^0$ invariant mass was obtained using simulation of the process $e^+e^- \to X(M)\gamma$ where X(M) was a particle with a small width and variable mass M decaying into $\pi^0\pi^0$.

The angular distribution of the free photon was taken as $dN/d\theta_\gamma \approx (1 + cos^2(\theta_\gamma))$. The detection efficiency obtained is presented in Fig. 3 as a function of the $\pi^0\pi^0$ invariant mass.

The $\pi^0\pi^0$ mass spectrum was obtained from the experimental distribution (Fig. 1d) after background subtraction and taking into account the detection efficiency for each histogram bin. The spectrum was normalized to the number of ϕ decays obtained from the $\phi \to \eta\gamma \to \pi^0\pi^0\pi^0\gamma$ analysis [7]. The resulting differential cross section vs. invariant mass is presented in Fig. 4a showing a resonance increase at high masses. Figure 4b presents the angular distribution for free photons for signal events with $M_{\pi^0\pi^0} > 800$ MeV. The line shows the distribution expected for a scalar intermediate resonance: $dN/d\theta_\gamma \approx (1 + cos^2(\theta_\gamma))$. Open points show the angular distribution of the subtracted background. The branching ratio calculated from the integral over the differential spectrum was found to be:

$Br(\phi \to \pi^0\pi^0\gamma) = (1.08 \pm 0.17 \pm 0.09) \times 10^{-4}$

for the whole invariant mass range. The systematic error comes from the uncertainty of the background subtraction (about 5%) and from the uncertainty of the number of ϕ mesons (about 5%). The main contribution to the statistical error comes from the region $M_{\pi^0\pi^0} < 550$ MeV because of the big uncertainty of the background subtraction.

This result can also be presented as:

$Br(\phi \to \pi^0\pi^0\gamma) = (1.06 \pm 0.09 \pm 0.06) \times 10^{-4}$ for $M_{\pi^0\pi^0} > 550$ MeV;

$Br(\phi \to \pi^0\pi^0\gamma) = (0.92 \pm 0.08 \pm 0.06) \times 10^{-4}$ for $M_{\pi^0\pi^0} > 700$ MeV;

$Br(\phi \to \pi^0\pi^0\gamma) = (0.57 \pm 0.06 \pm 0.04) \times 10^{-4}$ for $M_{\pi^0\pi^0} > 900$ MeV.

The results above are consistent with those presented by SND [9, 4].

It should be mentioned that only results for $M_{\pi^0\pi^0} > 700$ MeV can be considered

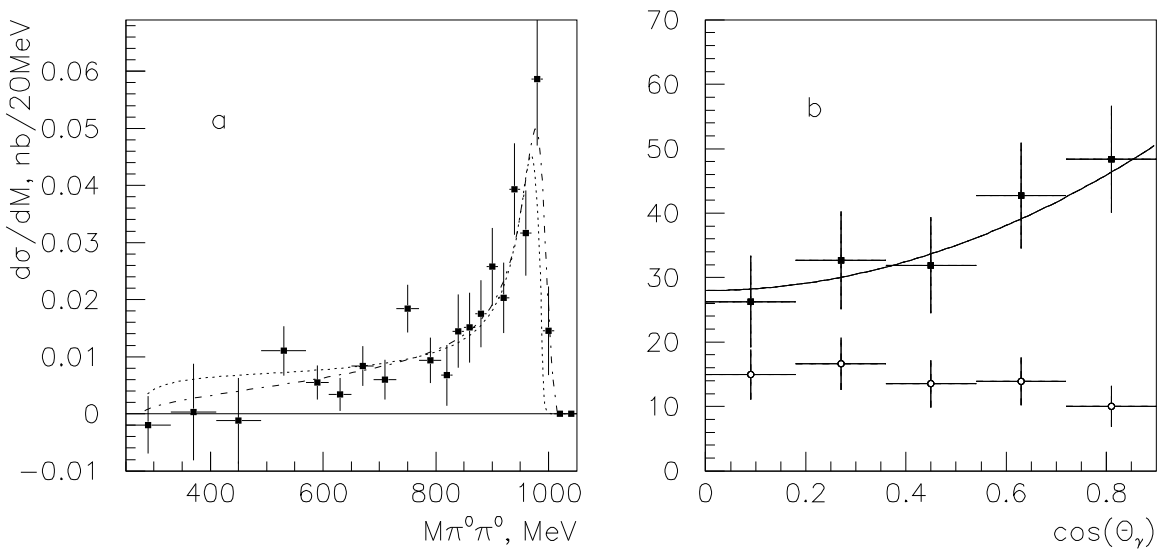

Figure 4: a. Differential cross section vs invariant mass. The dotted line is the four quark model fit with the branching ratio of 3.11×10^{-4}. The dashed line is the narrow pole fit; b. Angular distribution for signal events and background (open points). The line is $dN/d\theta_\gamma \approx (1 + cos^2(\theta_\gamma))$

as model independent. For lower masses the interference with the nonresonant ($\omega\pi^0 \to \pi^0\pi^0\gamma$) and resonant ($\phi \to \rho\pi^0 \to \pi^0\pi^0\gamma$) backgrounds can change the branching ratio. To extract these contributions a much better measurement at lower masses is needed.

About half of the signal events have the free photon energy below 100 MeV pointing to the presence of the $f_0(980)$ intermediate state in the $\pi^0\pi^0$ system.

Data Interpretation

For data interpretation, similarly to our analysis of the $\phi \to\to \pi^+\pi^-\gamma$ decay [1], the model suggested in [10, 11] was used. The model considers the $\phi \to f_0(980)\gamma$ decay under different assumptions about the f_0 meson structure (a two-quark or four-quark state or $K\bar{K}$ molecule depending on the values of the coupling constants $g^2_{K\bar{K}}/4\pi$, $g^2_{\pi\pi}/4\pi$) and calculates the differential cross section over the invariant mass of two pions $M_{\pi\pi}$. Also considered are effects of other possible intermediate states like $\sigma\gamma$ and $\rho\pi^0 \to \pi^0\pi^0\gamma$ with the total contribution of about 15%.

The experimental spectrum Fig. 4a was fit using the differential cross section from [10, 11] assuming that the $\phi \to \pi^0\pi^0\gamma$ decay is completely dominated by the $f_0(980)\gamma$ mechanism. The following model parameters have been obtained: $m_{f_0} = (977 \pm 3 \pm 6)$ MeV, $g^2_{K\bar{K}}/4\pi = (2.44 \pm 0.73)$ GeV ^{2}, $g^2_{\pi\pi}/4\pi = (0.40 \pm 0.06)$ GeV^2, $Br(\phi \to f_0(980)\gamma) = (3.05 \pm 0.25 \pm 0.72) \cdot 10^{-4}$.

The second error includes experimental uncertainties at high $\pi^0\pi^0$ masses and the 15%

effect of other processes. The parameters obtained are in good agreement with those presented by the SND group [4] and can be compared to the values obtained from our analysis of the $\phi \to \pi^+\pi^-\gamma$ channel [1]: $m_{f_0} = (976 \pm 5 \pm 6)$ MeV, $Br(\phi \to f_0(980)\gamma) = (1.93 \pm 0.46 \pm 0.50) \cdot 10^{-4}$.

The results for the m_{f_0} and $Br(\phi \to f_0(980)\gamma)$ obtained from the $\pi^0\pi^0\gamma$ and $\pi^+\pi^-\gamma$ final states are consistent within the errors. Therefore, we can perform their combined analysis. A simultaneous fit of the photon spectra using the formulae from [11, 12, 13] allowed to determine the model parameters with a better statistical accuracy:
$m_{f_0} = (975 \pm 4 \pm 6)$ MeV, $g^2_{K\bar{K}}/4\pi = (1.48 \pm 0.32)$ GeV ^{2}, $g^2_{\pi\pi}/4\pi = (0.41 \pm 0.06)$ GeV^2, $Br(\phi \to f_0(980)\gamma) = (2.90 \pm 0.21 \pm 0.65) \cdot 10^{-4}$, and $\Psi = (1.47 \pm 0.19)$ radians. The χ^2/d.f.=1.5 has been obtained. The results of the fit are shown in Fig. 4a by the dotted line. According to the model, the obtained values of the coupling constants (or the branching ratio) could only be explained if f_0 is a four quark state. The ratio R=$g^2_{K\bar{K}}/g^2_{\pi\pi}$ had weak dependence on the f_0 structure and was found to be R=3.61$\pm$0.62.

In the above interpretation the whole visible signal was due to the $\phi \to f_0\gamma$ decay whereas the influence of other possible mechanisms ($\rho\pi, \sigma\gamma$) was estimated to be about 15% and included into the systematic error.

To understand the sensitivity of the branching ratio of the $\phi \to f_0(980)\gamma$ decay to the particular model, we used another approach and performed the narrow pole fit. The $\pi^0\pi^0$ mass spectrum was fit with the function:

$$\frac{d\sigma}{dM_{\pi\pi}} \sim 2M_{\pi\pi} \cdot (1 - \frac{M^2_{\pi\pi}}{4E^2_{beam}}) \cdot \sqrt{1 - \frac{4m^2_\pi}{M^2_{\pi\pi}}} \cdot |\frac{m_{f(980)}\Gamma_{f(980)}}{\Delta_{f(980)}} + \frac{Ae^{i\psi}m_{f(1200)}\Gamma_{f(1200)}}{\Delta_{f(1200)}}|^2,$$

where $\Delta_f = M^2_{\pi\pi} - m^2_f + iM_{\pi\pi}\Gamma(M_{\pi\pi})$. The parameters of the $f_0(1200)$ (or σ) resonance could not be extracted from our data and were fixed at $m_{f(1200)} = 1200$ MeV and $\Gamma_{f(1200)} = 600$ MeV. These parameters have very small influence on the result and instead of the $f_0(1200)$ Breit-Wigner the constant background amplitude $Ae^{i\psi}$ can be used. The relative phase ψ was found to be close to zero and fixed at that value.

The following parameters have been obtained:
$m_{f_0} = (987 \pm 7)$ MeV/c^2, $\Gamma_{f_0} = (56 \pm 20)$ MeV, the relative amplitude A=0.22$\pm$0.09 (or A=0.08$\pm$0.03 in case of constant background), and χ^2/d.f.=0.96. The result of the fit is shown in Fig. 4a by the dashed-dotted line.

The corresponding branching ratio (assuming that only 1/3 is seen in the $\pi^0\pi^0$ mode) $Br(\phi \to f_0(980)\gamma) = (1.5 \pm 0.5) \cdot 10^{-4}$ has been found.

The discussion above shows that the data obtained cannot be interpreted without a resonance in the two pion mass spectrum at about 980 MeV both in charged and neutral modes and the $\phi \to f_0\gamma$ branching ratio cannot be lower than about $1.0 \cdot 10^{-4}$. As many

authors agreed [14], a value that high can hardly be explained in the frame of the two quark model of the $f_0(980)$ which predicts the branching ratio at the level of $0.5 \cdot 10^{-4}$. To study the influence of other intermediate mechanisms, better measurements of the $\pi\pi$ mass spectra are needed.

Search for $\phi \to \eta\pi^0\gamma$ Decay

Using the five photon final state, one can also look for the decay mode $\phi \to \eta\pi^0\gamma$ appearing when η decays into two photons. This analysis was based on the same event sample as in the study of the $\phi \to \pi^0\pi^0\gamma$ decay mode with the selection criteria described above.

A fit finding the best combination of photon pairs with the π^0 mass constrained and reconstructed pion momentum less than 350 MeV/c was used. An additional requirement is that the difference in the energy of the photons from the found π^0 is less than 80%. It rejects background from low energy photons and increases the efficiency for events with a low energy free photon because of a smaller probability of wrong combinations.

The invariant masses of the remaining most energetic photon pairs are shown in Fig. 5a.

The main source of background to observed events is the decay $\phi \to \eta\gamma \to 3\pi^0\gamma$ with two photons lost. The cut $760 < M_{\pi^0\gamma} < 805$ MeV from the $\pi^0\pi^0\gamma$ reconstruction almost removes the background from $\omega\pi^0$. The $\omega\pi^0$ events remaining after the "anti-ω" cut are shown by the dotted histogram.

Over the broad background distribution the excess of 80 ± 22 events is observed at (545 ± 4) MeV compatible with the mass of the η meson. The solid histogram shows the sum of the simulated background from $\phi \to \eta\gamma \to 3\pi^0\gamma$ and remaining $\omega\pi^0$ events normalized to the number of ϕ decays. These simulated events were used for background subtraction. The dashed histogram at 550 MeV shows a simulated signal from the $\phi \to \eta\pi^0\gamma$ decay at the 1×10^{-4} level.

The distributions over $cos\theta_\gamma$ and invariant mass $M_{\eta\pi^0}$ are shown in Figs. 5b,c for events with $510 < M_{\gamma\gamma} < 590$ MeV after background subtraction and taking into account the detection efficiency obtained by simulation (Fig. 5d). The following branching ratio:

$Br(\phi \to \eta\pi^0\gamma) = (0.90 \pm 0.24 \pm 0.10) \times 10^{-4}$

has been obtained. The systematic error comes from the uncertainty of the background subtraction and of the number of ϕ's taken for normalization.

To check the stability of the result these distributions were also obtained in the case of "strong" cuts when the additional requirement for the reconstructed photon

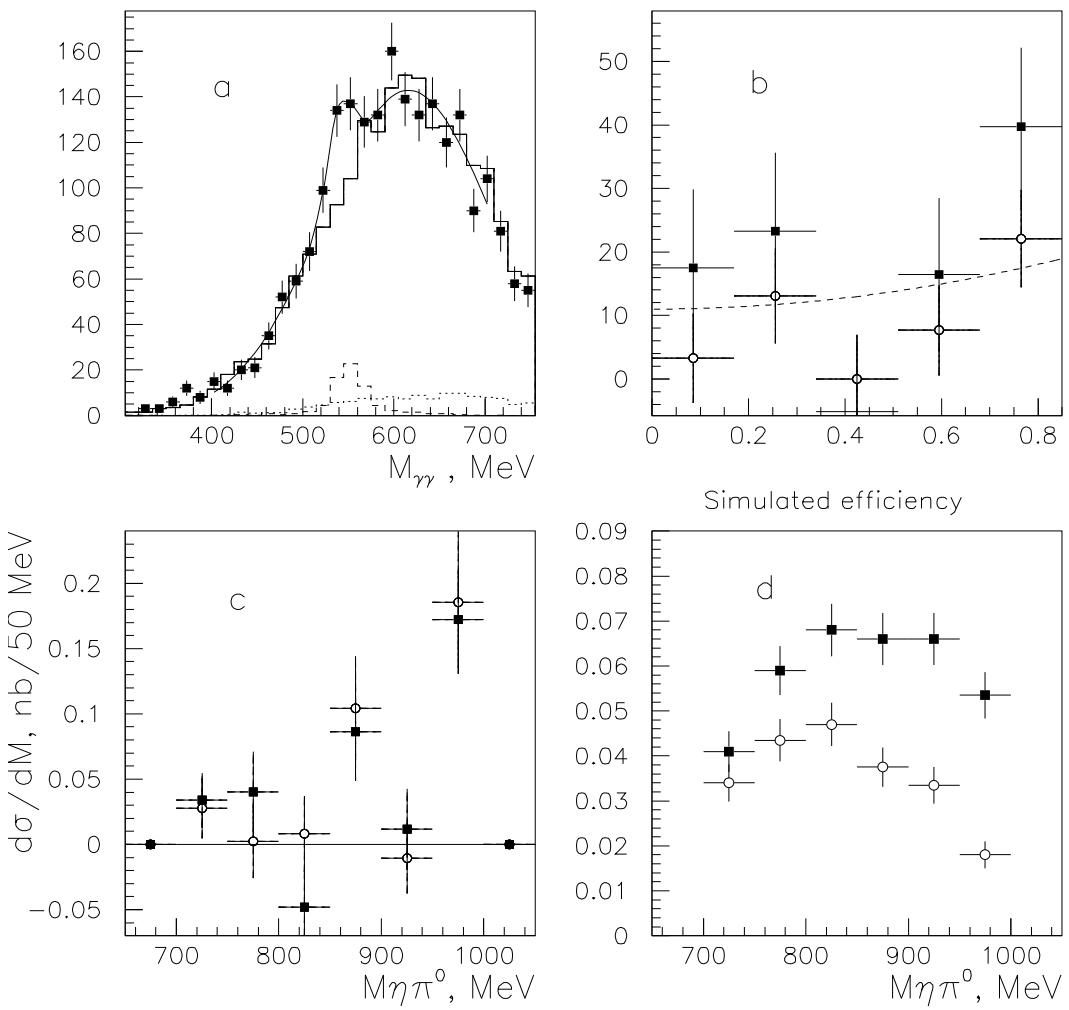

Figure 5: The $\phi \to \eta\pi^0\gamma$ study. Open points correspond to the "strong" cuts: a. Invariant masses of two photons with the highest energy for data (points) and simulation (histograms); b. $cos\theta_\gamma$ distribution for events around the η mass after background subtraction. The line corresponds to the expected distribution $dN/d\theta_\gamma \approx (1 + cos^2(\theta_\gamma))$; c. $\eta\pi^0$ mass distribution; d. Simulated detection efficiency vs. invariant mass.

with the highest energy was applied: $E_{\gamma max}/E_{beam} < 0.75$. This cut reduced the main background from $\phi \to \eta\gamma \to 3\pi^0\gamma$ by a factor of 4, but at the same time considerably reduced the detection efficiency at higher $\eta\pi^0$ invariant masses (open points in Fig. 5d). The number of observed signal events dropped to 37 ± 12 and the obtained branching ratio was the same within statistical errors.

The obtained invariant mass distribution shows the growth of the cross section to higher masses supporting the hypothesis about the $a_0(980)$ intermediate state. The obtained value of the branching ratio can be explained in the four quark model suggested in [10, 11].

Search for $\eta \to \pi\pi$ Decays

The selected $\pi^0\pi^0\gamma$ events can be used to search for the P- and CP-violating decay $\eta \to \pi^0\pi^0$, where the η comes from the radiative $\phi \to \eta\gamma$ decay. From 18.8 million ϕ decays used for the analysis of the $\pi^0\pi^0\gamma$ channel one could expect about 236,000 events decayed via the $\eta\gamma$ channel. Such a P- and CP-violating decay should be observed as a peak in the invariant mass of two pions at $M_{\pi\pi} = m_\eta$. Figure 6 shows the experimental

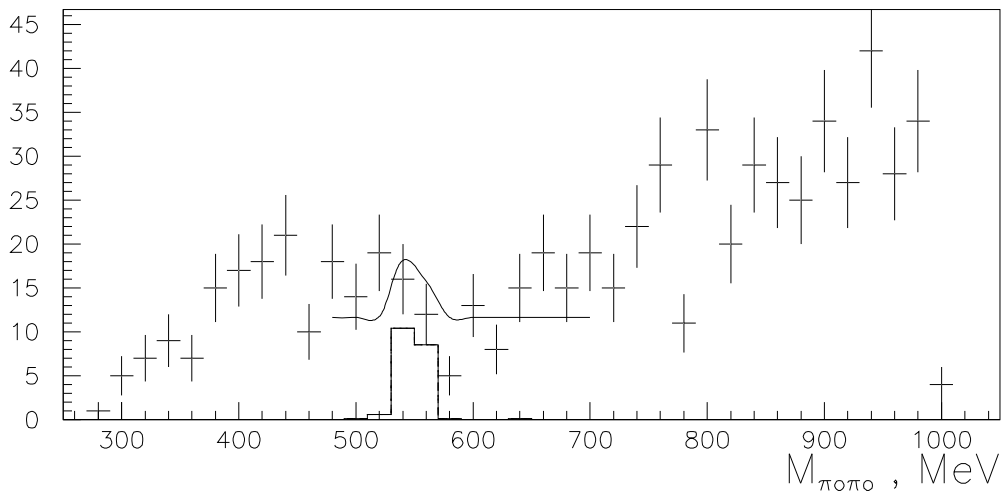

Figure 6: Search for $\eta \to \pi^0\pi^0$ decay. The histogram is simulation. The line shows a possible signal at 90% CL.

$\pi^0\pi^0$ mass distribution from selected $\pi^0\pi^0\gamma$ events. The line corresponds to a fit with a linear function and gaussian distribution representing a possible signal at 90% CL. It was found that a possible signal does not exceed 11 events for neutral decay mode. The histogram shows a simulated signal from the $\eta \to \pi^0\pi^0$ decay at 90% CL. The detection efficiency found by simulation was 0.108. The following result has been obtained:

$\mathrm{Br}(\eta \to \pi^0\pi^0) < 4.3 \times 10^{-4}$,

which should be compared to the best previous limit 7×10^{-4} for the neutral decay mode [15].

Conclusions

Using 12.8 pb^{-1} of data collected around the ϕ meson (about 19 million ϕ decays) events with five photons were selected. The reconstruction of the $\pi^0\pi^0\gamma$ and $\eta\pi^0\gamma$ final states gives the following model independent results:

$Br(\phi \to \pi^0\pi^0\gamma) = (0.92 \pm 0.08 \pm 0.06) \times 10^{-4}$ for $\mathrm{M}_{\pi^0\pi^0} > 700$ MeV,

$Br(\phi \to \eta\pi^0\gamma) = (0.90 \pm 0.24 \pm 0.10) \times 10^{-4}$,
in agreement with those reported by the SND group [4, 3]. A resonance at 980 MeV is observed in the $\pi^0\pi^0$ mass spectrum.

For the $\pi^0\pi^0\gamma$ channel the branching ratio obtained by integration over the whole mass spectrum was found to be

$Br(\phi \to \pi^0\pi^0\gamma) = (1.08 \pm 0.17 \pm 0.09) \times 10^{-4}$,
but this result can be affected by the possible interference with $\omega\pi^0 \to \pi^0\pi^0\gamma$ or $\rho\pi^0 \to \pi^0\pi^0\gamma$ intermediate states at $M_{\pi^0\pi^0} < 700$ MeV.

In the $\pi\pi\gamma$ channel the $\phi \to f_0(980)\gamma$ mechanism dominates and the most consistent description for both charged and neutral modes can be obtained in the four quark model with the branching ratio

$Br(\phi \to f_0(980)\gamma) = (2.90 \pm 0.21 \pm 0.65) \times 10^{-4}$.
However, this result is model dependent and it is shown that in another approach the branching ratio can decrease to about 1.5×10^{-4}, still higher than the prediction of the two quark model. The difference between two approaches can be used as an estimate of the additional systematic uncertainty because of the model so that

$Br(\phi \to f_0(980)\gamma) = (2.90 \pm 0.21 \pm 1.54) \times 10^{-4}$.

From the discussed models the following $f_0(980)$ parameters can be obtained:

$m_{f_0} = (978 \pm 4 \pm 8)$ MeV, $\Gamma_{f_0} = (56 \pm 20 \pm 10)$ MeV,
where the second error represents a model dependent uncertainty.

In the $\eta\pi^0\gamma$ final state events with the high $\eta\pi^0$ invariant mass dominate. This supports the hypothesis about the $a_0(980)$ intermediate state. The obtained branching ratio is also higher than the prediction of the two quark model.

For the P- and CP-violating decay of $\eta \to \pi^0\pi^0$ the following upper limit at 90% CL has been obtained:

$Br(\eta \to \pi^0\pi^0) \ < \ 4.3 \times 10^{-4}$.
This result is the most stringent upper limit today.

The values of the branching ratios $Br(\phi \to f_0(980)\gamma)$ and $Br(\phi \to a_0(980)\gamma)$ obtained in this work are rather high and according to theoretical predictions favour the four-quark structure of these states [10, 14]. However, predictions for the branching ratios significantly differ from one work to another and can hardly be considered as very accurate. Moreover, recently there were successful attempts to explain the observed distributions in radiative decays $\phi \to \pi\pi\gamma$ as well as their branching ratios without assumptions about the exotic structure of the $f_0(980)$ meson [16, 17].

In general, the situation with the identification of the members of the lowest scalar nonet and the related problem of the $f_0(980)$ and $a_0(980)$ structure remains to be unclear and controversial. While Ref. [18] presents many arguments in favour of the four-quark structure of these states, other possibilities are widely discussed. Ref. [19]

advocates the idea that the $f_0(980)$ meson doesn't belong to the $q\bar{q}$ family and originates from the $K\bar{K}$ molecule embedded in the $\pi\pi$ continuum. However, in [20] the idea of the loosely bound $K\bar{K}$ molecule is strongly disfavoured and the possibility is discussed that both $f_0(980)$ and $a_0(980)$ are conventional $q\bar{q}$ states with properties strongly distorted by coupling to the nearby $K\bar{K}$ threshold. The small value of the two-photon width of these states which traditionally used to be one of the strong arguments in favour of their exotic structure seems to be well accounted for in different theoretical models assuming the conventional $q\bar{q}$ structure of $f_0(980)$ and $a_0(980)$ mesons [16, 21, 22]. Note also the results of OPAL [23] and DELPHI [24] who studied the inclusive production of $f_0(980)$ and $a_0(980)$ mesons in hadronic Z^0 decays and found that their properties are consistent with the normal $q\bar{q}$ mesons.

One can conclude that the problem of the $f_0(980)$ and $a_0(980)$ structure is far from being solved and requires both new theoretical approaches and reliable, model independent experimental results.

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