First observation of $\phi(1020) \rightarrow \pi^0\pi^0\gamma$ decay

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In the SND experiment at VEPP-2M $e^+e^-$ collider the $\phi(1020) \rightarrow \pi^0\pi^0\gamma$ decay was studied. Its branching ratio $B(\phi \rightarrow \pi^0\pi^0\gamma) = (1.14 \pm 0.10 \pm 0.12) \cdot 10^{-4}$ was measured. It was shown, that $f_0(980)\gamma$ mechanism dominates in this decay. Corresponding branching ratio $B(\phi \rightarrow f_0\gamma) = (3.42 \pm 0.30 \pm 0.36) \cdot 10^{-4}$ was obtained.

12.39.Mk, 13.40.Hq, 14.40.Cs

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I. INTRODUCTION

First search for $\phi \rightarrow \pi^0\pi^0\gamma$ decay was carried out with the ND detector at VEPP-2M $e^+e^-$ collider in 1987 [1,2]. In this early experiment the upper limit $B(\phi \rightarrow \pi^+\pi^-\gamma) < 10^{-3}$ was placed. As it was shown later by Achasov [3], study of this decay can provide a unique information on the structure of the light scalar $f_0(980)$ meson. Subsequent studies [4,5] proved this idea. In these works different models of the $f_0(980)$-meson structure were considered. The most popular were 2-quark model [10], 4-quark MIT-bag model [11], and $K\bar{K}$ molecular model [12].

In 1995 new Spherical Nonmagnetic Detector (SNDD), having better hermeticity, granularity, energy and spatial resolution than previous ND detector, started operation at VEPP-2M. First indications of the process

$$e^+e^- \rightarrow \phi \rightarrow \pi^0\pi^0\gamma \quad (1)$$

were seen by SND in 1997 [12]. This preliminary result was based on analysis of half of the $\phi$-meson data recorded in 1996 – 1997 [13]. Present work is based on the analysis of full data sample. The $\phi \rightarrow \pi^0\pi^0\gamma$ decay was observed for the first time and its branching ratio was measured.

II. DETECTOR AND EXPERIMENT

The SND detector [14] is designed for the study of $e^+e^-$-annihilation at center of mass energy about 1 $GeV$. Its main part is a three layer electromagnetic calorimeter, consisted of 1630 NaI(Tl) crystals [15]. The energy resolution of the calorimeter for photons can be described as $\sigma_E/E = 4.2\%/\sqrt{E [GeV]}$ [14,16], angular resolution is close to 1.5 degrees. The 1996 experiment consisted of 7 independent runs [13]. In each run the data were recorded at 14 different beam energies in the region $2E_0 = (980 - 1050)$ $MeV$ covering the peak and close vicinity of the $\phi$-resonance. The energy spread of the beam energy was equal to 0.2 $MeV$. The total integrated luminosity of 3.9 $pb^{-1}$ was collected, corresponding to about 8 $\cdot 10^6$ $\phi$ mesons produced. The luminosity determination was based on equations of Bhabha scattering and two-photon annihilation detected in the calorimeter. Accuracy of normalization is better than 3 %.

III. DATA ANALYSIS

Main resonant background to the decay [1] comes from the decay

$$e^+e^- \rightarrow \phi \rightarrow \eta\gamma \rightarrow 3\pi^0\gamma \quad (2)$$

due to the merging of photons and/or loss of photons through the openings in the calorimeter. The main source of non-resonant background is a process

$$e^+e^- \rightarrow \omega\pi^0 \rightarrow \pi^0\pi^0\gamma. \quad (3)$$

The background from the $\phi \rightarrow \rho\pi^0$ decay is small [18], nevertheless its amplitude was included into simulation of the process (3). The background from the QED $5\gamma$-annihilation process was estimated and found to be negligible.

In order to suppress the contribution of background the events were selected with 5 photons emitted at angles of more than 27 degrees with respect to the beam and without charged particles. Standard SND cuts on energy-momentum balance in an event and on photon identification function were used:

- $0.8 < E_{dep}/2E_0 < 1.1$, where $E_0$ is the beam energy, $E_{dep}$ - the total energy deposition in the calorimeter;
- $p/2E_0 < 0.15$, where $p$ – is a total momentum of all photons in the event;
- $\chi^2 < 20$ – event kinematics is consistent with $\pi^0\pi^0\gamma$ hypothesis;
- $\zeta < 0$;

The $\zeta$ parameter was constructed on the basis of the logarithmic likelihood function, describing the probability for observed transverse profile of electromagnetic shower in the calorimeter to be generated by a single photon [14,15]. This parameter facilitates efficient separation of events with well isolated photons from those with merged photons or with showers, produced by $K_L$ mesons.

The $\chi^2$ is a kinematic fit parameter, describing the degree of energy-momentum conservation in the event with additional requirement that two $\pi^0$ mesons are present. During this fit all possible combinations of photons (Fig.4) in the event were checked in a search for invariant masses $m_1$ and $m_2$, satisfying the condition:

$$\sqrt{(m_1 - m_\pi)^2 + (m_2 - m_\pi)^2} < 25 \ MeV/c^2.$$  

The $\phi \rightarrow K_S\bar{K}_L \rightarrow \pi^0\pi^0K_L$ decay can contribute due to nuclear interactions of $K_L$ mesons in the material of the calorimeter but after described cuts it is not seen at present level of statistics.

In the energy region of this experiment the invariant mass of the pion pair in the process (3) is less than 700 $MeV$. In the events satisfying this condition clear $\omega(782)$ peak is seen in $m_{\pi\gamma}$ distribution (Fig.2), proving the domination of the process (3) in this kinematic region. The $m_{\pi\gamma}$ parameter was defined as an invariant mass of the recoil photon and one of $\pi^0$ mesons, closest to the $\omega$-meson mass. 499 found events with 750 $MeV < m_{\pi\gamma} < 815$ $MeV$ were assigned to $\omega\pi^0$ class, while 189 events with $m_{\pi\gamma}$ outside this interval and $m_{\pi\pi} > 700$ $MeV$ were assigned to $\pi^0\pi^0\gamma$ class. Subtracting calculated contribution of the process (3) and using estimated probabilities of events misidentification for the processes (1) and (3) the number of the events of
the process (3) in the ωπ^0 class was estimated to be equal to 449. The corresponding number of events of the decay (4) in the π^0π^0γ class is 164. The background from the process (3) was estimated using events of the ωπ^0 class. No additional knowledge of the actual production cross section of this process was necessary.

Then, for the events of the π^0π^0γ and ωπ^0 classes the comparison of experimental and simulated distributions in ψ and θ angles was done. Here ψ is an angle of the recoil photon with respect to pion direction in the π^0π^0 center of mass reference frame, θ is an angle between recoil photon and the beam. The distribution in θ for π^0π^0γ events with pion pair in a scalar state must be proportional to 1 + cos^2θ and uniform in cosψ. The comparison (Fig.3b,c) shows, that in π^0π^0γ class of events pions are actually produced in scalar state. On the contrary, the experimental events of the ωπ^0 class (Fig.3d) well match the hypothesis of the intermediate ωπ^0 state with quite different ψ distribution.

The π^0π^0 invariant mass distribution for the events with m_ππ outside the 750 MeV < m_ππ < 815 MeV interval (Fig.4a) shows significant excess over background at large m_ππ. At m_ππ < 600 MeV the efficiency was used in the fitting of the π^0π^0 mass spectrum. In the systematic error estimation the first error is statistical and the second is systematic, which was estimated to be close to 12 %. The systematic error is mainly determined by the following contributions:

- the background subtraction error, which decreases almost linearly with the increase of invariant mass m_ππ and is 5 % on average;
- error in the detection efficiency estimation, which increases with m_ππ and is equal to 8 % on average;
- systematic error in B(φ → ηγ) is equal to 5 %.

The m_ππ invariant mass spectrum (Fig.2) was fitted according to Refs. [3] and further used for simulation of the decay (3). As a result the detection efficiency of the process (2) was estimated (14.72 %) for invariant masses within the (600 – 1000) MeV interval (Fig.4a). This efficiency was used in the fitting of the φ-resonance excitation curve. The visible cross section in each energy point was described as a sum of the processes (1), (2), and (3) with efficiency and radiative corrections taken into account for each process. The background cross section due to the process (3) was estimated by fitting the visible cross section of the events of the ωπ^0 type with linear function. The background from the process (3) was obtained from simulation. The only free parameter of the fit was the φ → π^0π^0γ branching ratio, all other φ–meson parameters were taken from the PDG data [21]. As a result (Fig.4b), the following value was obtained:

$$B(\phi \rightarrow \pi^0\pi^0\gamma) = (1.14 \pm 0.10 \pm 0.12) \cdot 10^{-4},$$

which, in contrast with (1) and (3), is valid for the whole mass spectrum. In the systematic error estimation the following considerations were taken into account. In comparison with the results (1) and (3) the accuracy of normalization 3 % and efficiency estimation 5 % are higher here, the background subtraction error 5 % is the same, but an additional systematic error 6 % exists, due to uncertainty in extrapolation of the invariant mass spectrum into the region m_ππ < 600 MeV. Smaller systematic uncertainty has a ratio of branching ratios:

$$\frac{B(\phi \rightarrow \pi^0\pi^0\gamma)}{B(\phi \rightarrow \eta\gamma)} = (0.90 \pm 0.08 \pm 0.07) \cdot 10^{-2},$$
Assuming that the process (1) is fully determined by $f_0\gamma$ mechanism, using the relation $B(f_0 \to \pi^+\pi^-) = 2B(f_0 \to \pi^0\pi^0)$, and neglecting the decay $\phi \to KK\gamma$ [3], we can obtain from (6)

$$B(\phi \to f_0(980)\gamma) = (3.42 \pm 0.30 \pm 0.36) \cdot 10^{-4}.$$ (8)

To monitor stability of experimental results, the number of $\pi^0\pi^0\gamma$ events was checked separately in all 7 experimental runs. The results for all runs agree well within statistical uncertainty. Another important proof of validity of the results is the study of the process (4) [24], which properties are very close to the decay under study. The methods of analysis are also very close, and the measured value of the decay branching ratio (4) agrees with the PDG table value [21].

V. DISCUSSION

We would like to emphasize that all results presented in the previous section are not based on model assumptions about $f_0$ structure. The enhancement at large $m_{\pi\pi}$ (Fig. 5) is compatible only with large $f_0\gamma$ contribution. Further analysis is carried out under assumption that the decay mechanism is a pure $f_0\gamma$ and the mass spectrum can be described by the following expression [3,18]:

$$\frac{dBr(\phi \to \pi^0\pi^0\gamma)}{dm_{\pi\pi}} = \frac{2m^2\Gamma(f_0 \to \pi^0\pi^0)\Gamma(\phi \to f_0\gamma)}{\pi|D_f(m_{\pi\pi})|^2},$$ (9)

where $D_f(m_{\pi\pi})$ is an $f_0$ propagator, partial widths $\Gamma(f_0 \to \pi^0\pi^0)$ and $\Gamma(\phi \to f_0\gamma)$ are functions of $m_{\pi\pi}$. In the “narrow resonance” approximation [22] the results of the fit of the spectrum are the following:

$$m_f = (984 \pm 12) \text{ MeV}, \quad \Gamma_f = (74 \pm 12) \text{ MeV}$$

in agreement with PDG data [21]. The coupling constant of $f_0$ with pions is found to be $g_{f0\pi\pi}^2/4\pi = (0.20 \pm 0.03) \text{ GeV}^2$.

On the other hand this simple approximation seems inadequate for $f_0$ meson. In this case width corrections might be very large [24]. Instead of calculating such corrections we used complete formulas from Refs. [3,18] for the “broad resonance” fit. The formulas take into account final width of $f_0$ and strong coupling with $KK$. The results of this fit are the following:

$$m_f = (971 \pm 6) \text{ MeV}, \quad \Gamma_f(m_f) = (188^{+48}_{-33}) \text{ MeV},$$

$$g_{f0KK}^2/4\pi = 2.10^{+0.86}_{-0.56} \text{ GeV}^2, \quad g_{f0\pi\pi}^2/4\pi = 0.51^{+0.13}_{-0.09} \text{ GeV}^2,$$

$$g_{f0KK}^2/g_{f0\pi\pi}^2 = 4.1 \pm 0.9.$$

Comparison of the results of the fits shows strong model dependence of $f_0$-meson parameters. Both fitting curves in Fig. 5 practically coincide, although the “broad resonance” parameterization looks more realistic. In the latter case the value of the coupling constant $g_{f0KK}^2/4\pi$ obtained from the fit agrees with the predictions of 4-quark MIT-bag model (2.3 GeV$^2$ [44]) as well as the value of the branching ratio [3]. The corresponding predictions of the $KK$ molecular model [3,18] and the 2-quark model [2] are about 5 times lower.

Of course, besides $f_0$ other intermediate states may contribute to the decay under study, and most probably the heavy and broad $\sigma$-state [15]. This contribution can decrease values of $f_0$ coupling constants, but in any case such a state must produce nearly flat $\pi^0\pi^0$ invariant mass spectrum, not masking $f_0$-meson signal in the mass region $m_{\pi\pi} > 900$ MeV. Theoretical estimations of branching ratios are also imprecise depending on a set of not well defined coupling constants and may vary within a factor of two [18]. Thus, measured $\phi \to f_0\gamma$ branching ratio, which is 5 times higher than 2-quark and $KK$ model predictions can be considered as another indication of significant 4-quark MIT-bag part in the $f_0$ meson not excluding participation of other quark configurations. To determine contributions of all possible transition mechanisms and all quark configurations in $f_0$ one has to perform simultaneous analysis of all $f_0$ data.

VI. CONCLUSION

In the SND experiment the $\phi \to \pi^0\pi^0\gamma$ radiative decay was observed for the first time and its branching ratio was measured. Observed enhancement at high $m_{\pi\pi}$ in the invariant mass spectrum together with angular distributions agreeing with scalar intermediate $\pi^0\pi^0$ state show, that $f_0(980)\gamma$ transition mechanism dominates in this decay.

Measured $f_0$ parameters are strongly model dependent due to the fact that $f_0$ meson is broad and its mass is close to $K\bar{K}$ threshold, making simple Breit-Wigner description of the resonance inadequate.

Observed high decay probability $\sim 10^{-4}$ gives evidence, that $f_0$ meson contains significant 4-quark component but does not exclude participation of other quark configurations.

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FIG. 1. Invariant mass spectrum of photon pairs for selected 5-gamma events.

![Graph](image1.png)

FIG. 2. Distribution over $\pi^0\gamma$ invariant mass for $m_{\pi\pi} < 700$ MeV. Points – data, histogram – simulation, shaded histogram – sum of simulated contributions from $\phi \rightarrow \eta\gamma$ and $\phi \rightarrow \pi^0\pi^0\gamma$ decays, arrows – selection of the $\omega\pi^0$ class.

![Graph](image2.png)

FIG. 3. a, b – cosine of $\psi$, the angle between directions of $\pi^0$ and recoil $\gamma$ in the rest frame of $\pi^0\pi^0$ system; c, d – distributions in $\theta$, angle of the recoil $\gamma$ with respect to the beam. Points – data, histogram – simulation.

![Graph](image3.png)
FIG. 4. a – invariant mass distribution of $\pi^0\pi^0$ pairs for selected $\pi^0\pi^0\gamma$ events without acceptance corrections. Histogram – data, shaded histogram – estimated background contribution from $e^+e^- \rightarrow \omega\pi^0$ and $\phi \rightarrow \eta\gamma$; b – detection efficiency for $\pi^0\pi^0\gamma$ events.

FIG. 5. The measured $\pi^0\pi^0$ invariant mass spectrum. Background is subtracted and efficiency corrections applied. Points – data, solid line – the result of the “broad resonance” fit, dashed line – the result of the “narrow resonance” fit.

FIG. 6. Energy dependence of the visible $e^+e^- \rightarrow \pi^0\pi^0\gamma$ cross section. Points – data, solid line – fit, dotted line – estimated background contribution from $e^+e^- \rightarrow \omega\pi^0$ and $\phi \rightarrow \eta\gamma$.

TABLE I. The experimental mass spectrum for the $\phi \rightarrow \pi^0\pi^0\gamma$ decay after background subtraction and acceptance corrections. Only statistical error are shown.

| $m_{\pi\pi}$ (MeV) | $\frac{d\text{Br}(\phi \rightarrow \pi^0\pi^0\gamma)}{d\text{m}_{\pi\pi}} \times 10^7$ (MeV$^{-1}$) |
|---------------------|-----------------------------------------------|
| 600-620             | 0.61 ± 0.84                                  |
| 620-640             | 1.26 ± 0.89                                  |
| 640-660             | 0.59 ± 0.68                                  |
| 660-680             | 1.66 ± 0.84                                  |
| 680-700             | 1.62 ± 0.78                                  |
| 700-720             | 0.81 ± 0.61                                  |
| 720-740             | 2.86 ± 0.94                                  |
| 740-760             | 1.63 ± 0.76                                  |
| 760-780             | 1.73 ± 0.80                                  |
| 780-800             | 2.69 ± 0.96                                  |
| 800-820             | 2.50 ± 0.94                                  |
| 820-840             | 2.25 ± 0.90                                  |
| 840-860             | 4.58 ± 1.21                                  |
| 860-880             | 2.32 ± 0.91                                  |
| 880-900             | 3.80 ± 1.11                                  |
| 900-920             | 3.59 ± 1.14                                  |
| 920-940             | 3.74 ± 1.17                                  |
| 940-950             | 8.41 ± 2.47                                  |
| 950-960             | 8.93 ± 2.62                                  |
| 960-970             | 6.50 ± 2.34                                  |
| 970-980             | 3.74 ± 1.93                                  |
| 980-990             | 6.20 ± 2.57                                  |
| 990-1000            | 1.60 ± 1.60                                  |