Evidence of the $\phi \to \eta\pi^0\gamma$ decay

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Abstract

Signal of the rare radiative decay $\phi \to \eta\pi^0\gamma$ was observed in the SND experiment at VEPP-2M electron-positron collider. The result is based on the analysis of data, corresponding to a total integrated luminosity of $4pb^{-1}$, or $8 \cdot 10^6$ ϕ-mesons produced. The measured branching ratio of $\phi \to \eta\pi^0\gamma$ decay is equal to $(0.83 \pm 0.23) \cdot 10^{-4}$.

1 Introduction

Several mechanisms may contribute into $\phi(1020) \to \eta\pi^0\gamma$ decay rate including $\phi \to V\pi^0$ type transitions, where V is a vector meson, with a subsequent $V \to \eta\gamma$ radiative decay, and electric dipole radiative transition $\phi \to a_0(980)\gamma$ with a scalar $a_0(980)$ meson decaying into $\eta\pi^0$.

Theoretical predictions of the $\phi \to \eta\pi^0\gamma$ branching ratio, based on assumption of pure $\phi \to V\pi^0$ decay mechanism ([1], [2], [3]), are quite low, of the order of $5 \cdot 10^{-6}$. Situation with theoretical description of the $\phi \to a_0(980)\gamma$ decay is much more complicated, because the results strongly depend on the quark structure of the $a_0(980)$ meson. At present, its quark structure is not well established and several models exist including modifications of $q\bar{q}$ scheme [4], 4-quark model [5], and $K\overline{K}$ molecular model [6]. Theoretical estimations of $\phi \to a_0(980)\gamma$ branching ratios vary from about 10^{-5} in two-quark and $K\overline{K}$ molecular models up to 10^{-4} in the 4-quark model ([1],[7],[2]), making the $\phi \to a_0(980)\gamma$ decay a unique probe of the structure of $a_0(980)$ meson.

The first search for the $\phi \to \eta\pi^0\gamma$ decay was conducted in the ND experiment [8] at VEPP-2M e^+e^- collider in 1987, where an upper limit of $2.5 \cdot 10^{-3}$ was established. In 1995 the new SND detector having better hermeticity, granularity, energy and spatial resolution started operation at VEPP-2M. First indications of $\phi \to \eta\pi^0\gamma$ decay were seen by SND in 1997 [9]. The result was based on analysis of half of the ϕ-meson data recorded in 1996–1997. In this work analysis of full data sample was carried out. The $\phi \to \eta\pi^0\gamma$ decay was observed for the first time and its branching ratio was measured.

2 Detector and experiment

Experiment [10], [11] was carried out in 1996 at VEPP-2M e^+e^- collider with SND detector. The SND detector [12] is a universal nonmagnetic detector. Its main part is a 3-layer electromagnetic calorimeter consisted of 1630 NaI(Tl) crystals with a total thickness of 35 cm or 14 radiation lengths. The energy resolution for photons can be described as $4.2\%/\sqrt[4]{E(GeV)}$ [13], the angular resolution of the calorimeter is close to 1.5 degrees, and the solid angle coverage is 90% of 4π steradian.

The data, used for the study of $\phi \to \eta\pi^0\gamma$ decay was recorded in 1996-1997 in the energy range from 980 to 1040 MeV with the most of the data collected in the close vicinity of the ϕ-peak. Six successive scans of the energy range were performed with a total integrated luminosity of $4.0pb^{-1}$ and total number of ϕ-mesons produced of $8.2 \cdot 10^6$.

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3 Data analysis

The main background sources for the process under study

$$e^+e^- \to \phi \to \eta\pi^0\gamma \to 5\gamma \qquad (1)$$

are the following ϕ-meson decays:

$$e^+e^- \to \phi \to \eta\gamma \to 3\pi^0\gamma \qquad (2)$$

$$e^+e^- \to \phi \to K_S K_L \to neutrals \qquad (3)$$

$$e^+e^- \to \phi \to \pi^0\pi^0\gamma \qquad (4)$$

and nonresonant process

$$e^+e^- \to \omega\pi^0 \to \pi^0\pi^0\gamma. \qquad (5)$$

The expected number of events of the process (1) at a branching ratio of $\phi \to \eta\pi^0\gamma$ equal to 10^{-4} is about 300, while the number of background events (2) is $3 \cdot 10^4$. Although the process (2) does not produce 5γ events directly, it can fake the topology of the process (1) due to either merging of close photons or loss of soft photons through openings in the calorimeter. The process (3) produces $8 \cdot 10^5$ $K_S K_L$ events with $K_S \to \pi^0\pi^0$ decays. The K_L-s in ϕ-meson decays are slow and have a decay length of 3 m, while the nuclear interaction length in NaI(Tl) is about 30 cm. Characteristic feature of spurious 5γ events produced by $K_S K_L$ decays due to either nuclear interaction of K_L-s or their decays in flight is an energy-momentum imbalance and poor quality of at least one photon in the event.

Primary event selection was based on simple criteria: the number of reconstructed photons is equal to five, there are no tracks in the central drift chambers, the total energy deposition ranges from 0.8 to 1.1 center of mass energy $2E_0$, and the total transverse momentum is less than $0.15E_0/c$. Such criteria greatly reduce background from the processes (2) and (3), not affecting the decays (1), (4), and (5). Also rejected were the events containing close photon pairs with spatial angle between photons less than 27 degrees, where energies could be poorly reconstructed.

Next step in the event selection was based on quality of photons and kinematic fit. Parameter ζ [14] was constructed describing the likelihood of a hypothesis, that given transverse energy deposition profile of a cluster of hit crystals in the calorimeter can be attributed to a single photon. The requirements were imposed that $\zeta < 0$, for all photons. Then kinematic fit was performed under the assumption, that selected events are $e^+e^- \to 5\gamma$ ones and corresponding parameter χ^2_e, describing the likelihood of this assumption was calculated. Events with $\chi^2_e > 10$ were also rejected. Study of simulated 5γ events of the processes (1), (4), and (5) showed, that the χ^2_e and ζ cuts reject less than 15% of true 5γ events, suppressing the process (2) by a factor of 3 and making the expected background due to the process (3) very small, of the order of 10 events. Although, in contrast with the other processes, the Monte Carlo simulation of the process (3) is much less accurate due to nuclear interaction of K_L, so the data analysis may not completely rely on this estimation.

Characteristic feature of the process (1) is that each event must contain two photon pairs with invariant masses of η and π^0 mesons. Simulation shows that if the photons in an event are enumerated in descending order in energy, the photons from $\eta \to \gamma\gamma$ decay have the numbers of either 1 and 2 or 1 and 3. Corresponding experimental and simulated distributions in m_{12} and m_{13} with an additional requirement, that rest of photons contains a pair with $|m_{ij} - m_{\pi^0}| < 20\ MeV/c^2$ and more stringent photon quality requirement $\zeta < -5$. are shown in Fig.1. Background estimations are based on PDG table value for $\phi \to \eta\gamma$ decay branching ratio [15], our measurements of $e^+e^- \to \omega\pi^0$ cross section [11] and $\phi \to \pi^0\pi^0\gamma$ decay branching ratio [16]. Distribution of experimental events in $m_{12} + m_{13}$ shows an enhancement centered at η-meson mass, while the sum of background processes is nearly flat in this region. The sum of all simulated background processes, where each one was normalized to the number of events expected at a given integrated luminosity and total number ϕ-meson decays, describes the spectrum outside the enhancement quite well. If this excess of events is due to the decay (1), it corresponds to a $\phi \to \eta\pi^0\gamma$ branching ratio of the order of $7 \cdot 10^{-5}$, but it is difficult to extract accurate result from these inclusive spectra, because of poor signal to background ratio and unknown decay dynamics.

Detailed study of the process (1) requires substantial suppression of background. It could be done using kinematic fit with intermediate η and π^0 mesons taken into account. For each event $\eta\pi^0\gamma$ and $\pi^0\pi^0\gamma$ hypotheses were tried and corresponding $\chi^2_{\eta\pi^0\gamma}$, and $\chi^2_{\pi^0\pi^0\gamma}$ parameters calculated. To suppress the processes (4) and (5) the following requirements were imposed: $\chi^2_{\eta\pi^0\gamma} < 20$, $\chi^2_{\pi^0\pi^0\gamma} > 20$, and for additional suppression the process (2): $\zeta < -4$. With these requirements the contribution from the processes (4) and (5), which are relatively rare themselves, becomes negligible.

The resulting spectra of the $E_{\gamma max}/E_0$, energy of the most energetic photon, are shown in Fig.2. Since the recoil photon in the process (2) has a narrow spectrum peaked at 360 MeV, $E_{\gamma max}/E_0$ must be more than 0.7 in this process. The spectrum in Fig.2b, where true 5γ events are suppressed by an order of magnitude, is well reproduced by simulation of the process (2) alone, while the spectrum in Fig.2a shows excess of experimental events with $\zeta < -4$ over the simulation of (2). The background (2) still dominates at $E_{\gamma max}/E_0 > 0.7$, so events with $E_{\gamma max}/E_0 > 0.7$ were rejected. From Fig.2a one can see, that this roughly halves the detection efficiency for the process (1). This also enhances dependence of the detection efficiency on the invariant mass of $\eta\pi^0$ system, which varies from 1% at $M_{\eta\pi^0} = 970\ MeV/c^2$ up to 5% at $M_{\eta\pi^0} = 700\ MeV/c^2$.

The distributions of the events over photon quality parameter ζ are shown in Fig.3. Selection criteria here were the same as described above, except loosened requirement on photon quality: $\zeta < 10$. It can be seen, that simulation well describes the background from the process (2), while the excess of events in Fig.3a at low ζ is compatible with existence of the decay (1) with BR of the order of 10^{-4}. Also was checked the distribution in $\chi^2_{\eta\pi^0\gamma}$. While the distributions of experimental events with $0 < \zeta < 10$ is in a good agreement with simulation of the process (2), the distribution of the events with $\zeta < -4$ agrees with the simulation of the process (1) with a small contribution of the process (2). The total number of selected events satisfying the selection criteria is 25, from which 5 were estimated to be a background from the process (2). The corresponding branching ratio was calculated using the $\eta\pi^0$ invariant mass distribution of the selected events and detection efficiencies, obtained from simulation. The resulting value is $(0.83 \pm 0.23) \cdot 10^{-4}$, where error is a statistical one. For such stringent selection criteria the systematic error in detection efficiency could be as high as 15%, but at present level of experimental statistics the statistical error dominates.

In order to study the $\eta\pi^0$ mass spectrum the $E_{\gamma max}$ cut was dropped. This increased the background from the $\phi \to \eta\gamma$ decay, but made detection efficiency twice higher and less dependent on $\eta\pi^0$ mass. The $\eta\gamma$ background was subtracted using events with $M_{\gamma\gamma}$ outside η peak. The result is shown in Fig.4. The invariant mass spectrum was fitted using formulae from Ref.[1] and assuming that the decay is a pure $\phi \to a_0(980)\gamma$ transition. The result is also shown in Fig.4. It is seen, that although the errors are very large, the observed mass spectrum is consistent with $a_0\gamma$ decay mechanism. Constraint fit with $g_{a\eta\pi} = 0.85 g_{aK^+K^-}$ [5] gives the following values of $a_0(980)$ meson parameters:
$M_{a_0} = 986^{+23}_{-10}\ MeV/c^2$,
$g^2_{aK^+K^-}/4\pi = (1.5 \pm 0.5)\ GeV^2$.

4 Conclusion

In this work evidence of the new decay $\phi \to \eta\pi^0\gamma$ with a branching ratio of $(0.83 \pm 0.23) \cdot 10^{-4}$ is presented. The observed enhancement in the $\eta\pi^0$ invariant mass spectrum at large $m_{\eta\pi^0}$ is consistent with domination of $a_0\gamma$ decay mechanism, while relatively high decay rate agrees with the theoretical predictions based on 4-quark model of $a_0(980)$-meson [1], [2].

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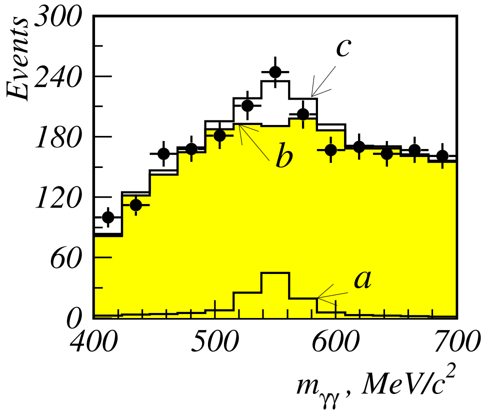

Figure 1: Invariant masses of pairs of most energetic photons: circles with error bars – experimental data, a – simulated signal from $\phi \to \eta\pi^0\gamma$ decay corresponding to a branching ratio of $0.7 \cdot 10^{-4}$, b – estimated background from the $e^+e^- \to \omega\pi^0$ and $\phi \to \eta\gamma, f_0(980)\gamma$ events, c – sum of a and b

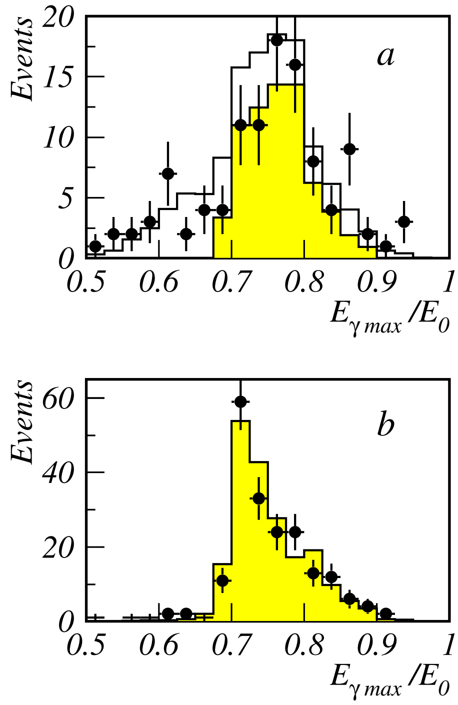

Figure 2: Spectra of the most energetic photon in the event: a – photons quality $\zeta < -4$, b – $0 < \zeta < 10$. Circles with error bars depict experimental data, shaded histogram – simulation of the process (2) and clear histogram – simulated sum of (2) and (1) with a $BR = 10^{-4}$.

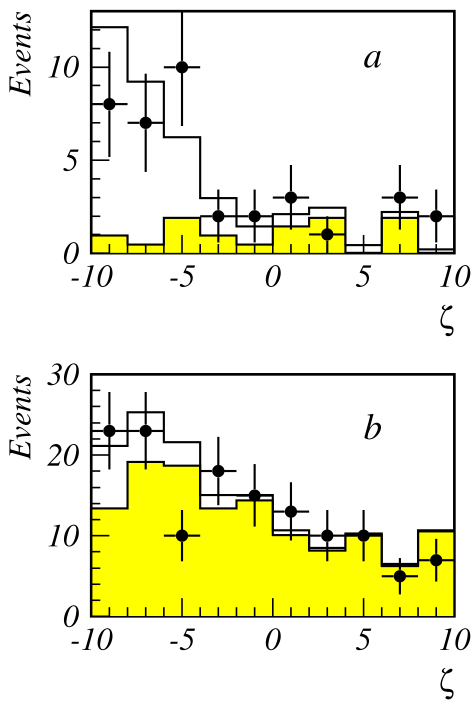

Figure 3: Distribution of events over ζ: a – events with $E_{\gamma max}/E_0 < 0.7$, b – events with $0.7 < E_{\gamma max}/E_0 < 0.8$ circles with error bars – experimental data, shaded histogram depicts simulation of the process (2) and clear histogram – simulated sum of (2) and (1) with a $BR = 10^{-4}$.

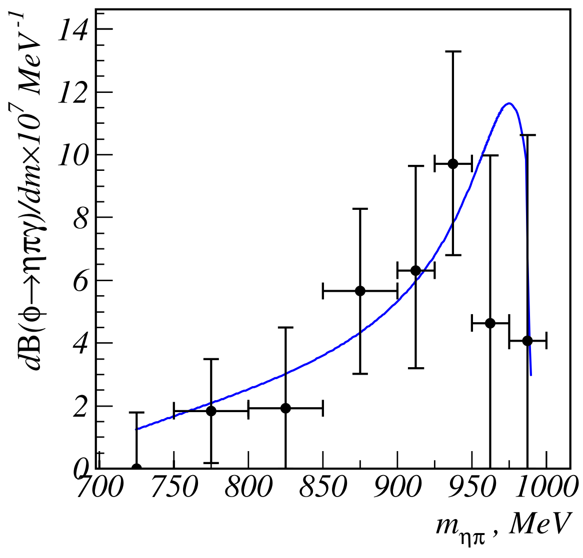

Figure 4: $\eta\pi^0$ invariant mass spectrum: points – experimental data, curve – optimal fit according to Ref. [1].