New measurement of the rare decay $\phi \to \eta'\gamma$ with CMD-2

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Abstract

A new measurement of the rare decay $\phi \to \eta'\gamma$ performed with the CMD-2 detector at Novosibirsk is described. Of the data sample corresponding to the integrated luminosity of 14.5 pb^{-1}, twenty one events have been selected in the mode $\eta' \to \pi^+\pi^-\eta$, $\eta \to \gamma\gamma$. The following branching ratio was obtained:

$$\mathrm{B}(\phi \to \eta'\gamma) \;=\; (8.2^{+2.1}_{-1.9} \pm 1.1) \cdot 10^{-5}.$$

1 Introduction

Radiative decays of vector mesons have traditionally been a good laboratory for various tests of the quark model and SU(3) symmetry [1]. A recent discovery of the $\phi \to \eta'\gamma$ decay by the CMD-2 group [2] has been the last link in the otherwise complete picture of radiative magnetic dipole transitions between light vector and pseudoscalar mesons. This observation was later confirmed by the SND group [3]. Both experiments suffered from a low number of observed events, resulting in large uncertainties in the determined branching ratio and making comparison to theory difficult.

In this paper we report on the improved measurement of the rate of the $\phi \to \eta'\gamma$ decay based upon the total data sample accumulated with CMD-2 in the ϕ-meson energy range. It includes 3.1 pb^{-1} of data collected in 1992 – 1996 in our first measurement which used only photons observed in the CsI barrel calorimeter, and about 11.4 pb^{-1} collected in 1997 – 1998. In addition, this analysis uses photons detected in either the CsI barrel or the BGO endcap calorimeters for both data samples providing better detection efficiency than before.

The general purpose detector CMD-2 operating at the high luminosity e^+e^- collider VEPP-2M in Novosibirsk has been described in detail elsewhere [4, 5]. It consists of a drift chamber and proportional Z-chamber used for trigger, both inside a thin (0.4 X_0) superconducting solenoid with a field of 1 T.

The barrel calorimeter placed outside the solenoid consists of 892 CsI crystals of $6 \times 6 \times 15$ cm^3 size and covers polar angles from 46° to 132°. The energy resolution for photons is about 9% in the energy range from 50 to 600 MeV.

The end-cap calorimeter placed inside the solenoid consists of 680 BGO crystals of $2.5 \times 2.5 \times 15$ cm^3 size and covers forward-backward polar angles from 16° to 49° and from 131° to 164°. The energy and angular resolution are equal to $\sigma_E/E = 4.6\%/\sqrt{E(GeV)}$ and $\sigma_{\varphi,\theta} = 2 \cdot 10^{-2}/\sqrt{E(GeV)}$ radians respectively.

The luminosity was determined from the detected $e^+e^- \to e^+e^-$ events [6].

2 Decay kinematics and selection criteria

Since $\phi \to \eta'\gamma$ is a two-body decay and η' is a narrow state, the momentum of the recoil photon is fixed and approximately equals 60 MeV.

To study this decay we searched for the decay chain $\eta' \to \pi^+\pi^-\eta$, $\eta \to \gamma\gamma$. The photons are ordered by decreasing energy ($\omega_1 > \omega_2 > \omega_3$). In these events the softest photon must be a monochromatic recoil photon with the energy $\omega_3 \approx 60$ MeV at the ϕ meson peak, while the energies of the harder ones range from 170 to 440 MeV. The invariant mass of the two harder photons $M_{12} = M_\eta$.

The main source of background for this study is the decay mode $\phi \to \eta\gamma$ giving the same final state with two charged pions and three photons via the decay chain $\eta \to \pi^+\pi^-\pi^0$, $\pi^0 \to \gamma\gamma$. Here the hardest photon is monochromatic with $\omega_1 = 363$ MeV and the invariant mass of two others is $M_{23} = M_{\pi^0}$. This decay can be used as a monitoring process and the branching ratio $B(\phi \to \eta'\gamma)$ will be calculated relative to $B(\phi \to \eta\gamma)$. Due to similar kinematics and detection efficiency dependence on detector parameters some systematic errors will cancel in such a ratio.

Events with two tracks and three photons were selected using the following criteria:

- One vertex is found in the event
- Two tracks with opposite charges are reconstructed from this vertex and there are no other tracks
- The angles of both tracks with respect to the beam are limited by $40° < \theta < 140°$ to match the optimal drift chamber coverage
- The number of photons detected in the CsI and BGO calorimeters is three. The cluster in the calorimeter is accepted as a photon when it does not match any charged track and its energy is more than 30 MeV in the CsI calorimeter or more than 40 MeV in the BGO calorimeter.

- The distance from each track to the beam $R_{min} < 0.2$ cm
- The distance from the vertex to the interaction point along the beam direction $|Z_{vert}| < 10$ cm
- The space angle between the tracks $\Delta\psi < 143°$
- The angle between the tracks in the R-φ plane $\Delta\varphi < 172°$
- The total energy of the charged particles (assuming that both particles are charged pions) $\varepsilon_{\pi^+\pi^-} < 520$ MeV.

The events thus selected were subject to the kinematical reconstruction assuming energy-momentum conservation. Events with good quality of the reconstruction were selected by the following criteria:

- $\chi^2/d.f. < 3$
- The ratio of the photon energy measured in the calorimeter ω_{cal} to that from the constrained fit ω is $\omega_{cal}/\omega < 1.5$
- $\omega_3 > 10$ MeV

3 Analysis

Events surviving after all above criteria mostly come from the process $\phi \to \eta\gamma$, $\eta \to \pi^+\pi^-\pi^0$ and $e^+e^- \to \omega\pi^0 \to \pi^+\pi^-\pi^0\pi^0$, as illustrated by Fig. 1 showing the scatter plot of the invariant mass M_{23} versus the hardest photon energy ω_1. The data are shown in Fig. 1d. The region around $M_{23} = 135$ MeV and $\omega_1 = 363$ MeV is densely populated with $\phi \to \eta\gamma$, $\eta \to \pi^+\pi^-\pi^0$ events. Simulated events of this process are presented in Fig. 1a. To determine the number of $\phi \to \eta\gamma$ events we count the number of events inside the ellipse-like region:

$$\frac{(\omega_1 + 0.45 \cdot (M_{23} - m_{\pi^0}) - \omega_{\eta\gamma})^2}{22\ MeV} + \frac{(M_{23} - m_{\pi^0})^2}{60\ MeV} < 1.$$

For our data this number is $N_{\eta\gamma} = 7357$. Determination of the number of $\eta\gamma$ events for simulation gives the detection efficiency $\varepsilon_{\eta\gamma} = (15.5 \pm 0.3)\%$.

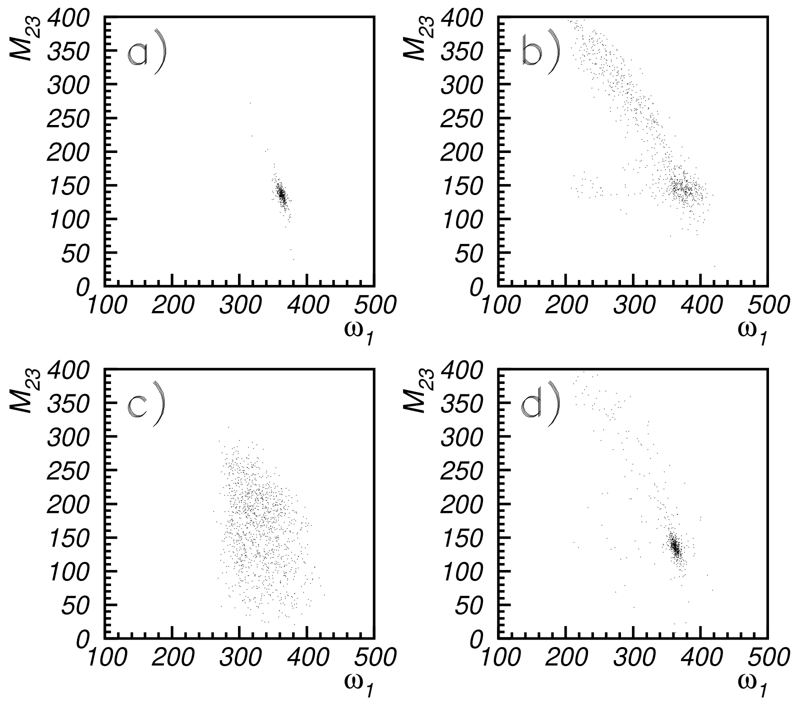

Figure 1: Invariant mass of two soft photons M_{23} vs hardest photon energy ω_1. a) — simulation of $\phi \to \eta\gamma, \eta \to \pi^+\pi^-\pi^0$; b) — simulation of $e^+e^- \to \omega\pi^0 \to \pi^+\pi^-\pi^0\pi^0$ at the ϕ-meson energy; c) — simulation of $\phi \to \eta'\gamma, \eta' \to \pi^+\pi^-\eta, \eta \to \gamma\gamma$; d) — experimental data.

Figure 1b presents the simulation of $e^+e^- \to \omega\pi^0 \to \pi^+\pi^-\pi^0\pi^0$, where a densely populated region is also observed at large values of ω_1. Comparison of these distributions with that for the data (Fig. 1d) confirms that the dominant contribution to selected events comes from these two processes. The same distribution for the simulation of the process under study is shown in Fig. 1c.

To search for the rare decay $\phi \to \eta'\gamma$ we need to suppress the events from $\phi \to \eta\gamma$ and $\omega\pi^0 \to \pi^+\pi^-\pi^0\pi^0$. To this end a cut on the energy of the hardest photon is applied:

$$\omega_1 < 350 \text{ MeV}.$$

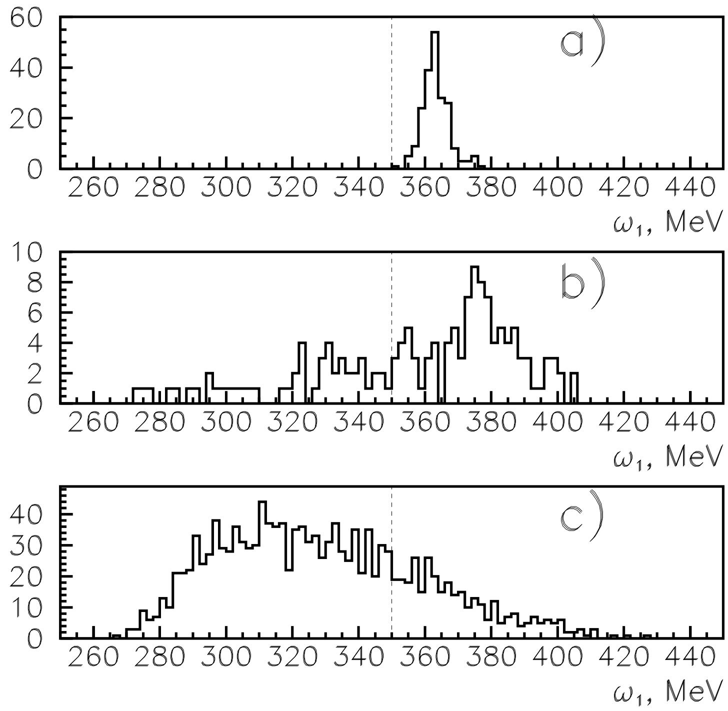

Figure 2: The hardest photon energy ω_1 for a) — simulation of $\phi \to \eta\gamma, \eta \to \pi^+\pi^-\pi^0$; b) — simulation of $e^+e^- \to \omega\pi^0 \to \pi^+\pi^-\pi^0\pi^0$ at the ϕ-meson energy; c) — simulation of $\phi \to \eta'\gamma, \eta' \to \pi^+\pi^-\eta, \eta \to \gamma\gamma$.

The ω_1 distributions for the simulation of $\phi \to \eta'\gamma$ and background processes are shown in Fig. 2.

Although this cut causes a decrease of efficiency for the $\phi \to \eta'\gamma$ decay (see Fig. 2c), the suppression of the background processes is rather good.

One more cut suppressing the background from the $\phi \to K_S K_L$ and $\phi \to \pi^+\pi^-\pi^0$ decays is:

$$\varepsilon_{\pi^+\pi^-} < 420 \text{ MeV}.$$

After all the cuts the scatter plot of the invariant masses for two hardest photons M_{12} versus the weakest photon energy ω_3 was studied. Figure 3 presents the data (black triangles) together with simulation of $\phi \to \eta'\gamma$ (points). The simulation points show the region of the plot which should be populated by

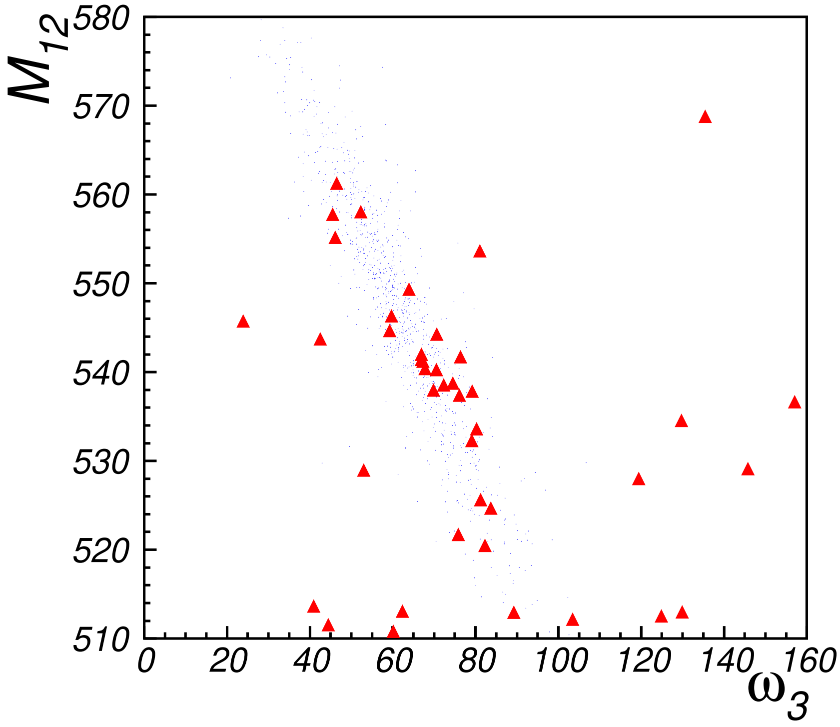

Figure 3: Invariant mass of two hard photons M_{12} vs softest photon energy ω_3. Points present the simulation of $\phi \to \eta'\gamma, \eta' \to \pi^+\pi^-\eta, \eta \to \gamma\gamma$, triangles — data after all the selections.

the events of $\phi \to \eta'\gamma$ and experimental points are densely covering this region. The lower part of the Figure contains obvious background events which can be suppressed by imposing the additional cut $M_{12} > 515$ MeV.

To determine the number of events the one-dimensional distribution of $\omega_3 + M_{12} - M_\eta$ (projection of the plot in Fig. 3 to the axis perpendicular to the correlation line) was studied. Such projection is shown in Fig. 4c for the data. The same projection for 10000 simulated events of $\phi \to \eta'\gamma$, $\eta' \to \pi^+\pi^-\eta$, $\eta \to \gamma\gamma$ is shown in Fig. 4b, and the fit of this distribution fixes the signal shape and gives the detection efficiency $\varepsilon_{\eta'\gamma} = (9.1 \pm 0.3)\%$. The background distribution in this parameter determined from the data before applying the last two cuts ($\omega_1 < 350$ MeV and $\varepsilon_{\pi^+\pi^-} < 420$ MeV) is shown in

Fig. 4a. The fit of this distribution fixes the background shape. Finally, the data were fit using the background shape fixed from Fig. 4a together with that of the signal from simulation in Fig. 4b.

The result of the fit is $N_{\eta'\gamma} = 21.0^{+5.5}_{-4.9}$.

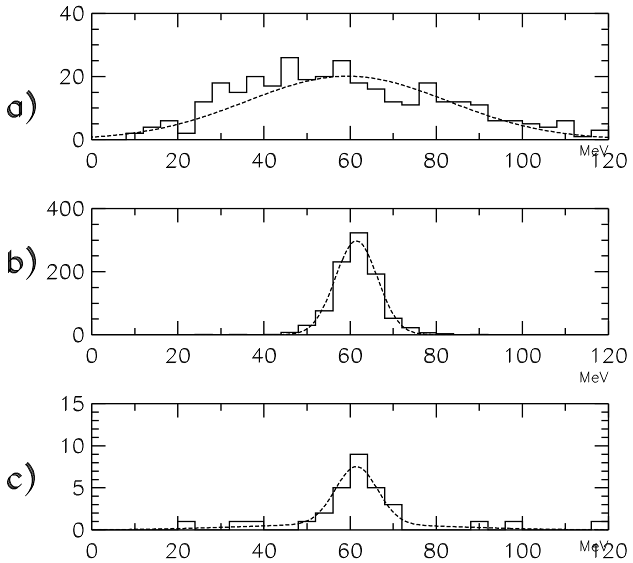

Figure 4: Distribution in $\omega_3 + M_{12} - M_\eta$ together with the fit function (dashed line): a) — background from $\phi \to \eta\gamma, \eta \to \pi^+\pi^-\pi^0$ events; b) — simulation of $\phi \to \eta'\gamma,\ \eta' \to \pi^+\pi^-\eta,\ \eta \to \gamma\gamma$; c) — data.

Using the number of events from the fit, one can calculate the relative branching ratio:

$$\frac{B(\phi\to\eta'\gamma)}{B(\phi\to\eta\gamma)} = \frac{N_{\eta'\gamma}}{N_{\eta\gamma}} \cdot \frac{B(\eta\to\pi^+\pi^-\pi^0)}{B(\eta'\to\pi^+\pi^-\eta)} \cdot \frac{B(\pi^0\to\gamma\gamma)}{B(\eta\to\gamma\gamma)} \cdot \frac{\varepsilon_{\eta\gamma}}{\varepsilon_{\eta'\gamma}} = (6.5^{+1.7}_{-1.5}) \cdot 10^{-3}$$

where the values of the branching ratios of η', η and π^0 were taken from [7].

A separate analysis of the normalizing decay $\phi \to \eta\gamma$ has recently been published [8], with a branching ratio of $(1.18 \pm 0.03 \pm 0.06)\%$ consistent with previous measurements [7] and thus giving confidence in the analysis presented here.

In the above calculation of the relative branching ratio common systematic errors such as luminosity determination cancel exactly, while others such as detector inefficiency and evaluation of radiative corrections cancel approximately.

Finally, using the value of $B(\phi \to \eta\gamma) = (1.26 \pm 0.06)\%$ from [7], one obtains:

$$B(\phi \to \eta'\gamma) \ = \ (8.2^{+2.1}_{-1.9} \pm 1.1) \cdot 10^{-5}.$$

The last error is our estimate of the systematic uncertainty. The sources of systematic errors are the following:

- Uncertainties in the ratio $\frac{\varepsilon_{\eta\gamma}}{\varepsilon_{\eta'\gamma}}$ caused by different energy spectra for final photons and pions - 10%;
- Uncertainties in the branching ratios $B(\eta \to \pi^+\pi^-\pi^0)$, $B(\eta' \to \pi^+\pi^-\eta)$, $B(\eta \to \gamma\gamma)$ and $B(\phi \to \eta\gamma)$ - 6.3%;
- Determination of the background shape – 5%;
- Different resonance shape caused by different energy dependence of the phase space - 2%;

The total systematic error obtained by adding separate contributions quadratically is 13%.

4 Discussion

The results of our analysis have higher statistical significance than before since they are based on a data sample of 21 selected events compared to 6 events in our previous work [2] and 5 events observed by SND [3]. The obtained value of the branching ratio $B(\phi \to \eta'\gamma)$

$$(8.2^{+2.1}_{-1.9} \pm 1.1) \cdot 10^{-5}.$$

agrees with our previous result based on part of the whole data sample [2]

$$(12.0^{+7.0}_{-5.0} \pm 1.8) \cdot 10^{-5}$$

as well as with the result of the SND group [3]

$$(6.7^{+3.4}_{-2.9} \pm 1.0) \cdot 10^{-5}$$

and is more precise. Within experimental accuracy it is also consistent with the preliminary result of CMD-2 based on other decay modes of the η meson ($\eta \to \pi^+\pi^-\pi^0, \pi^+\pi^-\gamma$) with four charged pions and two or more photons in the final state [6]:

$$(5.8 \pm 1.8 \pm 1.5) \cdot 10^{-5}.$$

Analysis of the available data sample of the produced ϕ mesons by both CMD-2 and SND and full use of other decay modes of the η' and η mesons will further improve the statistical error. Much larger increase can be expected from the DAΦNE ϕ-factory where one plans to accumulate the number of ϕ mesons by at least two orders of magnitude higher than ours.

Let us briefly discuss theoretical predictions for the decay under study. Usual methods of the description of radiative decays are based on the non-relativistic quark model [1]. Various ways of incorporating effects of SU(3) breaking have been suggested leading to the values of $B(\phi \to \eta'\gamma)$ in the range $(5-20) \cdot 10^{-5}$ [9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20].

The value of the branching ratio studied in our work is also of interest for the problem of $\eta - \eta'$ mixing which has been a subject of intense investigation for a long time [21, 22, 23, 24, 25, 26, 27, 28]. It is sensitive to the structure of the η' wave function or, in other words, to the contribution of various $q\bar{q}$ states as well as the possible admixture of glue in it [29, 22, 30]. According to [29], a branching ratio $B(\phi \to \eta'\gamma) < 2 \cdot 10^{-5}$ would indicate a substantial glue component in the η', while the expected branching ratio is less than $3 \cdot 10^{-6}$ for a pure gluonium. Even smaller values were obtained in [13] assuming a specific model of QCD violation.

The revival of interest to the problem of the η' structure and possible contents of glue in it (see [30] and references therein) was partially due to two recent observations by CLEO involving the η' meson: in [31] it was shown that the transition form factor of the η' studied in the two photon processes strongly differs from those for the π^0 and η mesons and in [32] the unexpectedly high magnitude of the rate of $B \to \eta' K$ was observed. However, in a recent paper [20] it is claimed that it is impossible to disentangle the effects of the nonet symmetry breaking and those of glue inside the η'.

Most of the models mentioned above are able to describe the data reasonably well in terms of some number of free parameters which, unfortunately, can not be determined from first principles. An attempt to overcome this drawback was made in [33] where radiative decays of light vector mesons are considered in the approach based on QCD sum rules [34] and the value $15 \cdot 10^{-5}$ is obtained for the branching ratio of $\phi \to \eta'\gamma$ decay.

One can summarize that the variety of theoretical approaches to the problem of the description of the ϕ meson radiative decay to $\eta'\gamma$ is rather broad and more theoretical insight into the problem is needed.

5 Conclusions

Using an almost five times bigger data sample than in the first measurement the CMD-2 group confirmed the observation of the rare radiative decay $\phi \to \eta'\gamma$. The measured branching ratio is:

$$B(\phi \to \eta'\gamma) \ = \ (8.2^{+2.1}_{-1.9} \pm 1.1) \cdot 10^{-5}.$$

Its value is consistent with most of the theoretical predictions based on the quark model and assuming a standard quark structure of the η'. It rules out exotic models suggesting a high glue admixture [29] or strong QCD violation [13].

Further progress in this field can be expected after the dramatic increase of the number of produced ϕ mesons expected at the DAΦNE ϕ-factory and refinement of theoretical models of radiative decays.

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