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In Pursuit of the f_0

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Abstract

In 1996, the Frascati ϕ–factory DAΦNE will begin delivering of the order of 500 ϕ-mesons/sec. This provides a unique opportunity to study the $f_0(975)$ in ϕ radiative decays, even for branching ratios which in some estimates could be as low as 1×10^{-6}. This unique, lightest scalar meson state is poorly described by current models, and more information is essential. By Monte Carlo studies in KLOE, the particle physics detector to be installed at DAΦNE, we show that the smallest expected branching ratio can easily be measured in the decay $f_0\to\pi^0\pi^0$. In decays to $\pi^+\pi^-$, there are backgrounds from continuum processes. Interference between one of these processes and the f_0 amplitude leads to very interesting and complex patterns. A complete study of the photon spectrum from $e^+e^-\to\pi^+\pi^-\gamma$ at the ϕ peak, after suppression of continuum contributions by suitable kinematics and angular cuts, can determine the sign of the $\phi f_0\gamma$ coupling even for the smallest branching ratio, thus providing a totally new piece of information for the investigation of the nature of the f_0. A similar study of the decay $\phi\to\eta'\gamma$ shows that its branching ratio can be measured with very good accuracy, therefore measuring the gluon contents of light pseudoscalar mesons to high accuracy.

1. INTRODUCTION

DAΦNE,[1] scheduled to be operational in 1996, should deliver a initial luminosity $\mathcal{L}\sim 10^{32}$ cm^{-2} s^{-1}, giving some 5 billion ϕ's in four months of machine-on time. In this paper we assume that 5×10^9 ϕ mesons are collected in the first year, while DAΦNE is tuned to reach maximum $\mathcal{L}$. While the main goal of this high luminosity e^+e^- collider is the study of CP violation, an important complementary goal is spectroscopy, given the enormous sample of ϕ's, previously unavailable. We will have the possibility of detecting rare ϕ decays, especially rare radiative decays which typically are predicted to have branching ratio's (BR) of the order of 10^{-4} to 10^{-7}.[2] There are few existing experimental measurements. The most common radiative mode is $\phi\to\eta^0\gamma$ with BR($\phi\to\eta^0\gamma$)=0.0128 ± 0.0006; the next most frequent mode $\phi\to\pi^0\gamma$ is measured to an accuracy of only 30%: BR($\phi\to\pi^0\gamma$)=$(0.31\pm 0.13)\times 10^{-3}$.[3] Many modes which are not forbidden by symmetry arguments, but are very interesting from a spectroscopic point of view, such as $\phi\to\eta'\gamma$, $\to f_0\gamma$, $\to a_0\gamma$, $\to\pi^+\pi^-\gamma$, $\to\pi^0\pi^0\gamma$, $\to\pi^0\eta\gamma$, have not been observed at all and upper limits are only at the 10^{-3} level. About the C violating decays $\phi\to\omega\gamma$, $\to\rho\gamma$, $\to\eta\pi^0$ we know nothing; upper limits are at the 10^{-2} level.[3] We discuss in the following detector issues associated with measuring rare radiative decays amidst prolific background events arising from $\phi\to X+\pi^0(\to 2\gamma)$ decays, by considering the specific examples $\phi\to f_0\gamma$ and $\phi\to\eta'\gamma$. We show that background processes, though they might be much larger than the signal, can be well controlled by appropriate kinematical cuts.

The $f_0(975)$,[2] the lightest scalar ($I^G J^{PC}=0^+0^{++}$) meson, has been a puzzle since the 1970's. If it is assumed to be a $q\bar{q}$ bound state, many predictions fail, such as the total width (500 MeV rather than the measured 30 MeV), two photon couplings and so on. Other structures, such as four-quark bound states or $K\bar{K}$ "molecules," have been proposed for the f_0. The current predictions[2] for the branching ratio of $\phi\to f_0\gamma$ (BR$_{\phi f_0\gamma}$) vary from $\mathcal{O}(10^{-4})$ for various four quark states, to $\mathcal{O}(10^{-5})$ for $s\bar{s}$ states, to $<\mathcal{O}(10^{-5})$ for diffuse $K\bar{K}$ systems. The experimental upper bound is currently 2×10^{-3} at 90% c.l. In this paper we will consider BR$_{\phi f_0\gamma}$'s ranging from 1×10^{-6} to 2.5×10^{-4}.

One observes f_0's through their decay to pions, a 78% branching ratio. We will first consider the decay to neutral pions, which is simpler than the charged pion case. The signal is then five photons, with one low energy photon of about 50 MeV, and the other photons reconstructing to two nearly back-to-back pions. The primary background process (A_1) is $\phi\to\pi^0\pi^0\gamma$ via an intermediate ρ. Even pessimistically taking the rate at the experimental upper limit (1×10^{-3}) rather than the theoretical estimate which is two orders of magnitude smaller, this background is easily controlled. Smaller backgrounds come from processes such as $\phi \to \pi\rho, \rho \to \eta\gamma, \eta \to \gamma\gamma$, yielding five photons but with different kinematics; or events such as $\phi \to \gamma\eta, \eta \to \pi\pi\pi$, which is a background when two photons are missing.

Our simulations have been done in KLOE,[4] a large general purpose detector with a magnetic field. The detector, surrounding a thin, 10 cm radius beam pipe, consists of a drift chamber with a helium-based gas mixture, of 2 m radius and 4 m length, providing a momentum resolution of ~0.45%, at the range of interest. The chamber is surrounded by a hermetic (solid angle coverage greater than 98%) electromagnetic calorimeter with three-dimensional readout, resulting in a geometrical acceptance for five photons of 0.92. The EM calorimeter consists of sandwiches of very thin (0.5mm), grooved, lead foils and 1 mm diameter scintillating fibers. Its energy resolution is $5\%/\sqrt{(E/1\mathrm{GeV})}$, with full efficiency for 20 MeV photons, and has exceptional timing performance, 300 $\mathrm{ps}/\sqrt{(E/20\mathrm{MeV})}$. The angular resolution for photons is excellent, ~±5 mrad.

For the case of $f_0 \to \pi^+\pi^-$, additional backgrounds come from continuum processes such as coupling of the initial e^+e^- state to the tail of the ρ, an *initial state radiation process*, which we shall call A_2, and $e^+e^- \to \mu^+\mu^-\gamma$ if muons are mistaken for pions. Furthermore, the ϕ can produce a pair of pions through off-shell ρ production with one of the pions radiating a γ, a *final state radiation process*. We shall call A_{ρ^*} the amplitude for this process and A_{f_0} the amplitude for $\phi \to f_0\gamma \to \pi^+\pi^-\gamma$.

While A_2 only contributes an incoherent background, as it is the only $\phi \to \pi\pi\gamma$ process antisymmetric under pion exchange ($C(\pi^+\pi^-)=-1$), the amplitudes A_{ρ^*} and A_{f_0} interfere, because the pions from ρ decay with final state radiation are in a C–even state, as are those from f_0 decay.[5,6] The sign of the interference term (i.e., the sign of the $\phi f_0\gamma$ -coupling) is one of the unknown features of the f_0. While the magnitude of $|A_{\rho^*}|^2$ is approximately one tenth of that of $|A_2|^2$, $|A_{f_0}|^2$ is comparable to or smaller than $|A_{\rho^*}|^2$, by as much as a factor of ten to one hundred. The interference term can drastically alter the f_0 signal in ϕ decays, both in shape and in magnitude. For the case of destructive interference, the f_0 signal becomes very small, and was expected to essentially disappear in Ref. 6. However, since the shape of the interference term and its angular distribution[7] are different from those from $|A_{f_0}|^2$, the presence of an f_0 signal can always be recognized, even when cancellation is maximal. We only lose sensitivity to the presence of f_0's in ϕ decays when the branching ratio for $\phi \to f_0\gamma$ ($\mathrm{BR}_{\phi f_0\gamma}$)

becomes smaller than about 3×10^{-7}. In addition, the shape of the signal allows in general to determine the sign of the interference term. The $\mu^+\mu^-\gamma$ background, while much larger than the signal, can be easily removed in a detector such as KLOE by appropriate kinematical cuts. The initial state radiation contribution can be strongly suppressed by angular cuts. Thus we find the conclusions of ref. 6 more pessimistic than necessary.

2. $\phi\to f_0\gamma$

2.1 $f_0\to\pi^0\pi^0$

We chose for our MC studies the reaction $\phi\to f_0\gamma$, where the f_0 decays into a $\pi^+\pi^-$ pair or into two π^0's. The branching ratio for this reaction is interesting because of:

1. the implications it has for the measurement of $\Re(\epsilon'/\epsilon)$ and $\Im(\epsilon'/\epsilon)$,
2. the value it has in its own right from a spectroscopic point of view (see the discussion of Brown and Close).[2]

This decay has not been observed yet. The experimental limit is of the order of 2×10^{-3}, which is much higher than the most optimistic theoretical expectation of 2.5×10^{-4}.[8] Partial wave analysis suggests that 78% of the f_0's decay to two pions (1/3 neutral, 2/3 charged), 22% to a pair of K's.

The signature for the decay $\phi\to f_0\gamma$, $f_0\to\pi^0\pi^0$ is five photons, with one of the photons having ~50 MeV and four of the photons reconstructing to a pair of nearly collinear π^0's, whose invariant mass sums up to that of the f_0. The possible background events are from:

1. $\phi\to\pi^0\pi^0\gamma$, experimentally not yet detected, with an upper limit of $BR<1\times10^{-3}$. Measured values in this paper are taken from the Particle Data Book[3] unless otherwise specified. Predicted values for this process via a virtual ρ vary from 1.2×10^{-5},[7,9] to 3.62×10^{-5}.[10]
2. $\phi\to\pi^0\rho^0$ with $\rho\to\pi^0\gamma$. The product branching ratio of these two observed processes is $BR=(3.4\pm0.88)\times10^{-5}$.
3. $\phi\to\pi^0\rho^0$ with $\rho\to\eta\gamma$, $\eta\to2\gamma$, with the product BR from the three observed processes, $BR=(6.4\pm1.2)\times10^{-6}$, all of which yield five photons.
4. $\phi\to\gamma\eta$ with $\eta\to3\pi^0$, with product BR from the observed two processes: $BR=(4.1\pm2.0)\times10^{-3}$, and two of the photons are not detected in the calorimeter.

There is no background arising from $\phi \to K_S K_L$ where the K_S decays into $2\pi^0$'s and the K_L decays into $3\pi^0$'s and five photons are missed. The (acceptance$\times K_L$ decay probability)$\times$BR, $\mathcal{A}$, is 3.1×10^{-10} in KLOE. This is before applying any energy-momentum constraint.

To be on the conservative side, we have considered background (1) both at the estimated level found theoretically in Refs. 7 and 9, and at the much larger level allowed by the current experimental bound. We have treated background (2) separately from background (1) because it can be best dealt with experimentally using the constraint of a physical ρ. Moreover, we suspect that the theoretical estimate of background (1) in Refs. 7 and 9 might be low by a factor of two or three since the estimates in the same model for the $\phi \to \pi^0 \rho^0$ and $\rho \to \pi^0 \gamma$ branching ratios are also low. $\phi \to \pi\rho \to \pi\eta\gamma$ can also be treated similarly as background (1). If we use the theoretical estimate via a virtual ρ,[9] (3) is negligible; if we use the experimental value, it is a similar exercise to that of considering background (1).

For the $\phi \to \pi^0\pi^0\gamma$ process we have used the matrix elements with angular distributions from reference 7. Photon spectra and acceptance×detection efficiencies (ϵ) for each process were obtained after applying the following selection criteria: five and only five photons are present in the detector; four of the photons are paired into two π^0's whose reconstructed mass must be within 50 MeV of the π^0 mass; the reconstructed f_0 mass from the two pions must be within 50 MeV of the expected mass peak at 975 MeV; the energy of the leftover photon is to be less than 95 MeV, and, finally, the invariant mass of all the decay products must be within 50 MeV of the known ϕ mass. The geometrical acceptance for five photons is 0.92. The application of kinematical cuts, reconstruction of pions, and f_0, etc., decreases the overall efficiency to 84%. Table I summarizes the BR's and efficiencies for the various relevant processes.

Table I. BR and ϵ for neutral final states in KLOE

PROCESS	BR	ϵ
$\phi \to f_0+\gamma \to \pi^0\pi^0+\gamma$	$(0.26\text{–}65)\times10^{-6}$	8.4×10^{-1}
$\phi \to \pi^0\pi^0\gamma$	$(1.2\text{–}100)\times10^{-5}$	1.3×10^{-3}
$\phi \to \pi^0+\rho^0 \to \pi^0 + \pi^0\gamma$	3.4×10^{-5}	8.4×10^{-4}
$\phi \to \pi^0+\rho^0 \to \pi^0 + \eta\gamma$	6.4×10^{-6}	8.4×10^{-4}
$\phi \to \gamma+\eta \to 3\pi^0 + \gamma$	4.1×10^{-3}	$<1\times10^{-7}$

All spectra of background photon surviving the cuts were fitted to polynomials, $g(k)$

where k is the photon energy. The signal can be fitted to a Breit-Wigner form, $s(k)$. Using the *a priori* error estimate,[11] the fractional accuracy of the signal BR is given by:

$$\frac{\delta(\mathrm{BR})}{\mathrm{BR}} = \frac{1}{\mathrm{BR}}\frac{1}{\sqrt{N}}\Big(\int \frac{1}{f(k)}\Big(\frac{\partial f(k;\mathrm{BR})}{\partial \mathrm{BR}}\Big)^2 \mathrm{d}k\Big)^{-\frac{1}{2}} \qquad (2.1)$$

where

$$f(k) = \sum_1^4 \epsilon_{bcknd,i} \times \mathrm{BR}_{bcknd,i} \times g_i(k) + \epsilon_{signal} \times \mathrm{BR}_{signal} \times s(k).$$

Thus, in a year's run at DAΦNE ($\sim 5\times 10^9$ ϕ's), we can measure BR($\phi \to f_0\gamma$) using the two $\pi^0\pi^0$ decay mode from 0.2% to 2.5% accuracy over the expected range of theoretical predictions if the BR for direct $\phi \to \pi^0\pi^0\gamma$ is the one expected theoretically (1.2×10^{-5}). If the direct $\phi \to \pi^0\pi^0\gamma$ BR is at the experimental limit (1×10^{-3}) KLOE's range becomes 0.2% to 4.4%.

2.2 $f_0 \to \pi^+\pi^-$

2.2.1 Backgrounds from misidentified ϕ decays

The signature for $\phi \to f_0\gamma$, $f_0 \to \pi^+\pi^-$ is a pair of nearly collinear charged pions, whose invariant mass equals that of the f_0, and one low energy photon. The possible backgrounds from misidentified ϕ decays are

1. $\phi \to \pi^+\pi^-\pi^0$, BR=$(1.9\pm 1.1)\times 10^{-2}$.
2. $\phi \to \pi^0\rho^0 \to \pi^0\pi^+\pi^-$, product BR= $(4.3\pm 0.2)\times 10^{-2}$.
3. $\phi \to \pi^\pm\rho^\mp \to \pi^0\pi^+\pi^-$, product BR=$(8.6\pm 0.5)\times 10^{-2}$.

These reactions yield two oppositely charged pions and one neutral pion, so contribute to the background if one photon is not detected.

There is no background arising from $\phi \to K_S K_L$ where the $K_S \to \pi^+\pi^-$and $K_L \to 3\pi^0$'s and five photons are not detected. $\mathcal{A}$ is about 1.7×10^{-11}. Nor is there any background from $\phi \to K_S K_L$ where $K_S \to \pi^0\pi^0$ and $K_L \to \pi^+\pi^-\pi^0$ or $\pi^\pm\mu^\mp\nu$, and five or three photons are undetected. $\mathcal{A}$ for the two processes are about 4.5×10^{-12} and 5.4×10^{-8}. Finally, there is also no background arising from $\phi \to K_S K_L$ where the $K_S \to \pi^+\pi^-$and $K_L \to \gamma\gamma$ and one photon is not detected. $\mathcal{A}$ is about 1×10^{-6}. All these numbers are obtained before applying the energy-momentum conservation constraint.

We used the following selection criteria: two tracks and one photon are present in the detector; the opening angle between the two tracks is within 2° of 175°; the energy of the photon is within 10 MeV of 53 MeV. Table II summarizes the BR's and ϵ's for the background processes and the signal. We get a fractional error on BR($\phi\to f_0\gamma$) (using only backgrounds with one lost γ) of 0.1% if this BR is 2.5×10^{-4}, 0.8% if it is 1.0×10^{-5}, and 3.3% if it is 1.0×10^{-6}.

Table II BR and ϵ for $\pi^+\pi^-\gamma$: $\phi\to f_0\gamma$ signal, and backgrounds with one lost γ

PROCESS	BR	ϵ
$\phi\to f_0\gamma\to\pi^+\pi^-\gamma$	$0.52\text{–}130\times10^{-6}$	7.4×10^{-1}
$\phi\to\pi^0\rho^0\to\pi^+\pi^-\gamma(\gamma)$	4.3×10^{-2}	$<3\times10^{-6}$
$\phi\to\pi^\pm\rho^\mp\to\pi^+\pi^-\gamma(\gamma)$	8.6×10^{-2}	$<3\times10^{-6}$
$\phi\to\pi^+\pi^-\pi^0\to\pi^+\pi^-\gamma(\gamma)$	1.9×10^{-2}	$<3\times10^{-6}$

However, because of KLOE's hermeticity, and the fact that one measures the charged particles' momenta, applying kinematical constraints and cuts around the ρ mass make background processes (1), (2) and (3) practically negligible despite their larger BR's. We have used KLOE's geometry and assumed 0.45% momentum resolution. The fractional accuracy achievable has been increased by a factor two, to roughly account for various uncertainties not yet fully evaluated. The complete KLOE simulation confirms our results.[12] So, in conclusion, if these were the only backgrounds, using general purpose detectors, the photon contamination from the background in the signal region disappears, and one could expect a very good BR determination over the whole range of signal and background BR examined. However, we shall see in the next sections that other backgrounds (notably from initial and final state radiation) are by far dominant.

2.2.2 Backgrounds from $e^+e^-\to\mu^+\mu^-\gamma$

The cross section at 1020 MeV for $e^+e^-\to\mu^+\mu^-\gamma$, where the photon energy is between 10 and 120 MeV, is 4.8 nb, equivalent to a BR of 1×10^{-3}, orders of magnitude larger than the signal from $f_0\to\pi^+\pi^-\gamma$ whose BR is at most 1.3×10^{-4}.[13] The large background contribution from $e^+e^-\to\mu^+\mu^-\gamma$ can however be fully controlled in KLOE because of its good momentum resolution.

While the calorimeter resolution at low energies is relatively poor, events with two charged particles and a photon are four times overconstrained. For ϕ production at rest, momentum conservation gives $E_\gamma=|\mathbf{p}^+ + \mathbf{p}^-|$. From energy conservation, assuming that the positive and negative particles are pions, we get $E'_\gamma = M_\phi - E^+ - E^-$. For $\phi\to\pi^+\pi^-\gamma$ we expect $E_\gamma = E'_\gamma$, while for $e^+e^-\to\mu^+\mu^-\gamma$, the two energies differ by about 17.5 MeV, having used the pion mass for the muons. We have generated by Monte Carlo

(MC) simulations the difference $\Delta E_\gamma = E_\gamma - E'_\gamma$, using the expected KLOE momentum resolution.[4] For $\phi\to\pi^+\pi^-\gamma$ decays we find that the rms spread of ΔE_γ is 2 MeV and for $e^+e^-\to\mu^+\mu^-\gamma$, ΔE_γ=17.5 MeV, also with a spread of 2 MeV. Therefore, a cut at in ΔE_γ at 8 MeV gives us a rejection factor of ~2400 against the muon background, which in fact makes it negligible with respect to any other processes with pions in the final states. Note that we have not used the well measured photon direction (±5 mrad) for additional help.

2.2.3 Backgrounds from $e^+e^-\to\pi^+\pi^-\gamma$

As we have seen in the previous sections, the background from misidentified events can be completely controlled in KLOE if we select f_0 candidates by requiring that only a pair of nearly collinear, oppositely charged tracks and one low energy photon, $20< E_\gamma <100$ MeV, are present in the detector; that the visible energy equals W, the total energy, and that $\Delta E_\gamma <8$ MeV, in order to eliminate the $\mu^+\mu^-\gamma$ background.

In the remainder of this chapter, we discuss the various contributions to the final physical state $\pi^+\pi^-\gamma$ from e^+e^- annihilation at the ϕ peak. Four amplitudes, A_1, A_2, A_{ρ^*} and A_{f_0}, contribute. The corresponding intensities, $|A_1|^2$, $|A_2|^2$ and $|A_{\rho^*}|^2$ are background contributions and the f_0 signal is contained in $|A_{f_0}|^2$ and $2\Re(A_{\rho^*}A^*_{f_0})$, as discussed below.

- $A_1=A(\phi\to\pi_1\rho^*\to\pi_1\pi_2\gamma)$. This is the amplitude for $\phi\to\pi^+\pi^-\gamma$ via $\pi\rho^*$ with the ρ^* coupling to $\gamma\pi$. ρ^* here stands for an internal line, virtual ρ in the corresponding Feynman amplitude. The Feynman diagram for this process is shown in Fig. 1a. We have already discussed the analogous process for neutral pions in Sec. 3.1. Its contribution to the background is small compared to the other sources, see Fig. 2a. In this figure we have taken A_1 at its theoretically estimated level,[7,9] but we have checked[14] that even if we take it at the experimental upper limit, the changes in our results are negligible. The interference of this background with other processes is also negligible.

- $A_2 = A(e^+e^-\to\gamma\gamma\to\rho^*\gamma\to\pi^+\pi^-\gamma)$. The Feynman diagram for this process is shown in Fig. 1b. This amplitude from *initial state radiation* is the largest incoherent source of background. However, since, as expected for a radiative process, $|A_2|^2$ is peaked very sharply at small angles between the photon and the beam, $\theta_{\gamma,\ \mathrm{beam}}$, we reduce its contribution by a factor of ~7 by a cut $|\cos\theta_{\gamma,\ \mathrm{beam}}| < 0.9$, see Fig. 2b.

- $A_{\rho^*} = A(\phi\to\rho^*\to\pi^+\pi^-\gamma)$, the γ being radiated from one of the pions. The Feynman diagram for this process is shown in Fig. 1c. This process contributes approximately

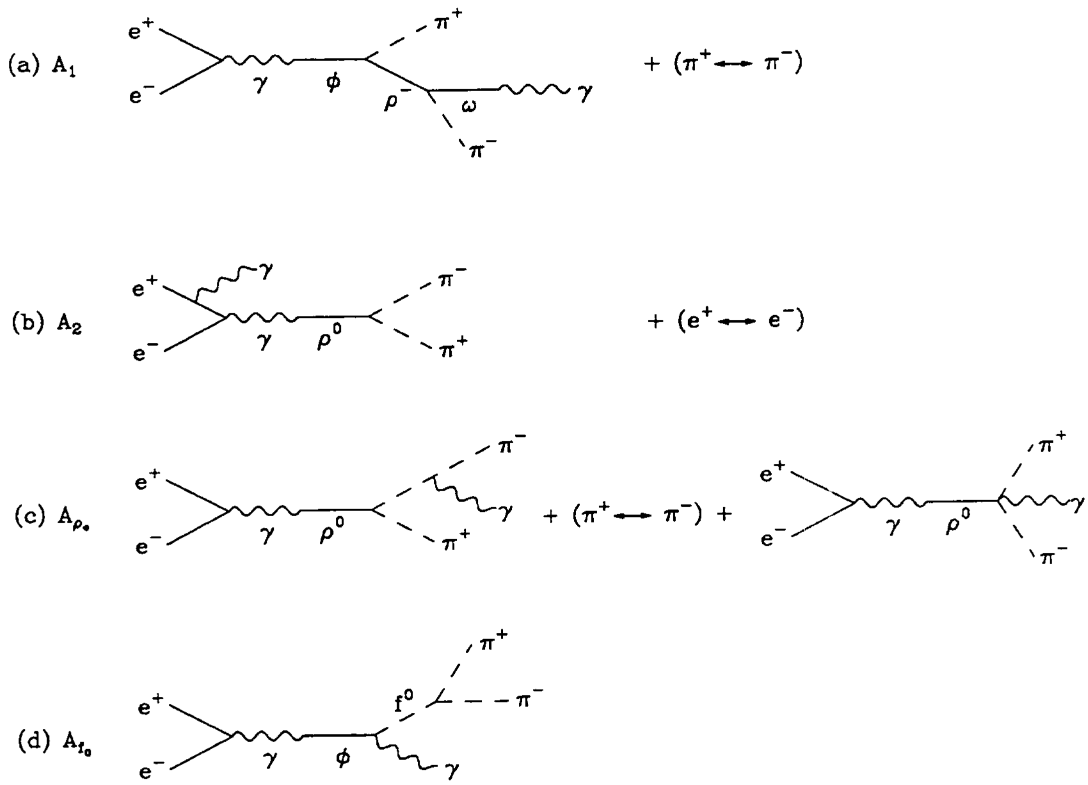

Figure 1. The Feynman diagrams of the processes discussed in the text.

one tenth of the A_2 background. However, as expected for a radiative process, $|A_{\rho^*}|^2$ is peaked at small values of the angle between the pions and the photon in the dipion rest frame, $\theta_{\pi\gamma}$. We therefore restrict $|\cos\theta_{\pi\gamma}|$ to be less than 0.9, see Fig. 2c. The sum of these three sources of background is shown in Fig. 2d, the solid line being without angular cuts, the dashed line with the two angular cuts of $|\cos\theta|$ less than 0.9. With these cuts combined, we retain 80% of the signal and improve the signal to background ratio, S/B, by a factor of $5-6$, see Figs. 7 and 8.

- $|A_{f_0}|^2$ and $2\Re(A_{\rho^*}A^*_{f_0})$. The Feynman diagram for the signal process $\phi \to f_0\gamma$ is shown in Fig. 1d. The angular dependence of $|A_{f_0}|^2$ is $(1+\cos^2\theta_{\gamma,\,\mathrm{beam}})$. The amplitude given in Ref. 6 ignores the bound quark pair wave function of the corresponding mesons, without which the amplitude blows up because of the k^3 factor characteristic of the emission of a photon of momentum k. We damp the amplitude following De Rújula, Georgi and Glashow,[15] with an exponential $Ae^{-x/\Gamma}$, where $x = s - M^2_{\pi\pi} = 2m_\phi E_\gamma$, Γ=300 MeV, and A=2.65 normalizes the damping factor to 1 at the f_0 peak (42.7 MeV). The signal size depends on $\mathrm{BR}_{\phi f_0\gamma}$. We illustrate it for the two extremes of the range of interest, in Figs. 3a and 4a. We use 52% for $\mathrm{BR}(f_0 \to \pi^+\pi^-)$.

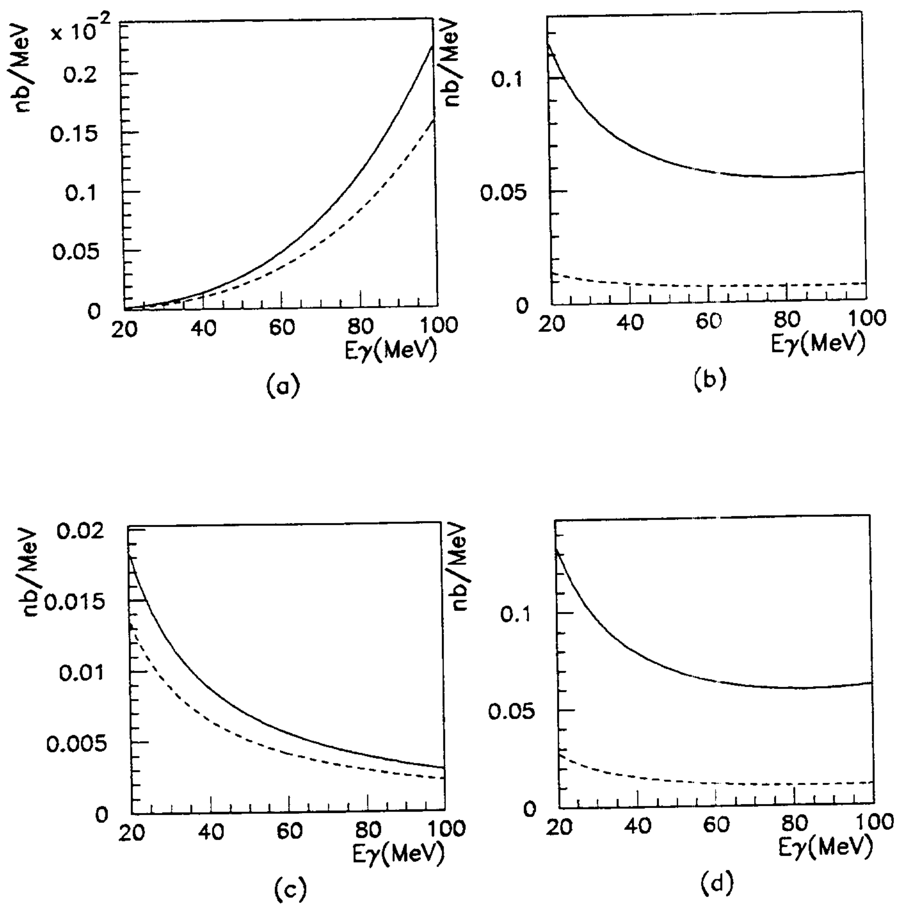

Figure 2. **a.** $|A_1|^2$ contribution; **b.** $|A_2|^2$ contribution; **c.** $|A_{\rho^*}|^2$contribution; **d.** Total incoherent background. Solid lines are without angular cuts, dotted lines are for $|\cos\theta_{\gamma,\ \text{beam}}| < 0.9$ and $|\cos\theta_{\pi\gamma}| < 0.9$.

The interference term $2\Re(A_{\rho^*}A^*_{f_0})$ is slightly peaked along the beam direction and slightly suppressed along the pions. Its integrated magnitude is shown for the two extreme cases of the $\mathrm{BR}_{\phi f_0\gamma}$ in Figs. 3b and 4b. For small $\mathrm{BR}_{\phi f_0\gamma}$ the interference term dominates in absolute value over the f_0 term, while the reverse is true for the largest $\mathrm{BR}_{\phi f_0\gamma}$. This interesting cross over is because $|A_{f_0}|^2$ is proportional to $\mathrm{BR}_{\phi f_0\gamma}$, whereas the interference term varies as $\sqrt{\mathrm{BR}_{\phi f_0\gamma}}$. Thus, even for destructive interference, the contribution of $|A_{f_0}|^2+2\Re(A_{\rho^*}A^*_{f_0})$ to the total cross section is not always negative. Figs. 3c,d and 4c,d show $|A_{f_0}|^2\pm2\Re(A_{\rho^*}A^*_{f_0})$ for the two extremes of the range of interest. For $\mathrm{BR}_{\phi f_0\gamma}$ $\sim1.75\times10^{-4}$, the integrated contribution to the $\pi^+\pi^-\gamma$ cross section vanishes; however, a dip appears at low γ energies and an enhancement at high γ energies, allowing detection of the f_0 signal.

The angular dependence of $|A_{f_0}|^2+2\Re(A_{\rho^*}A^*_{f_0})$ also depends on the relative strength

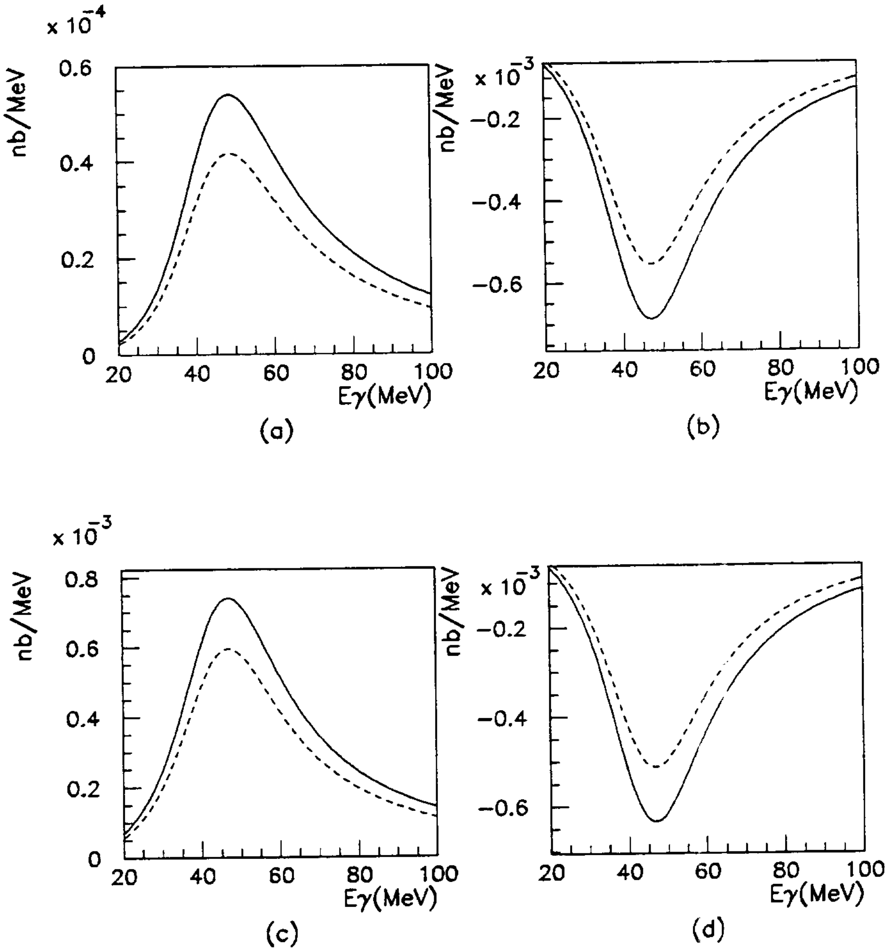

Figure 3. **a.** γ spectrum: $f_0 \rightarrow \pi^+\pi^-\gamma$; **b.** $2\Re(A_{\rho^\bullet} A^*_{f_0})$; **c.** $|A_{\rho^\bullet}|^2 - 2\Re(A_{\rho^\bullet} A^*_{f_0})$; **d.** $|A_{\rho^\bullet}|^2 + 2\Re(A_{\rho^\bullet} A^*_{f_0})$. $\mathrm{BR}_{\phi f_0 \gamma} = 1 \times 10^{-6}$. Solid lines are without angular cuts, dotted lines are for $|\cos\theta_{\gamma,\ \mathrm{beam}}| < 0.9$ and $|\cos\theta_{\pi\gamma}| < 0.9$.

of each term, of course reflecting that of the dominant one. To illustrate the complexity of the situation, we chose $\mathrm{BR}_{\phi f_0 \gamma} = 1.5 \times 10^{-4}$, where the two terms have about equal strength, and show $\mathrm{d}^2\sigma/\mathrm{d}E_\gamma \mathrm{d}\cos\theta_{\gamma,beam}$ vs E_γ, $\cos\theta_{\gamma,beam}$, and $\mathrm{d}^2\sigma/\mathrm{d}E_\gamma \mathrm{d}\cos\theta_{\pi\gamma}$ vs E_γ, $\cos\theta_{\pi\gamma}$ for constructive interference in Figs. 5a and b respectively. The same quantities in the case of destructive interference are shown in Figs. 6a and b respectively, where dips and enhancements are clearly visible. We also note that the relative strength of $|A_{f_0}|^2$ and $2\Re(A_{\rho^\bullet} A^*_{f_0})$ are modulated by the γ–π angle, upon which $A_{\rho^\bullet}$ depends strongly.

For $\mathrm{BR}_{\phi f_0 \gamma} = 1 \times 10^{-6}$, the signal over the background cannot be shown directly. In order to demonstrate the effectiveness of the cuts we show the signal to background (S/B) ratio for the two cases of constructive and destructive interference, Figs. 7a,b. Note that in both cases we enhanced this ratio by about a factor of five, for a net

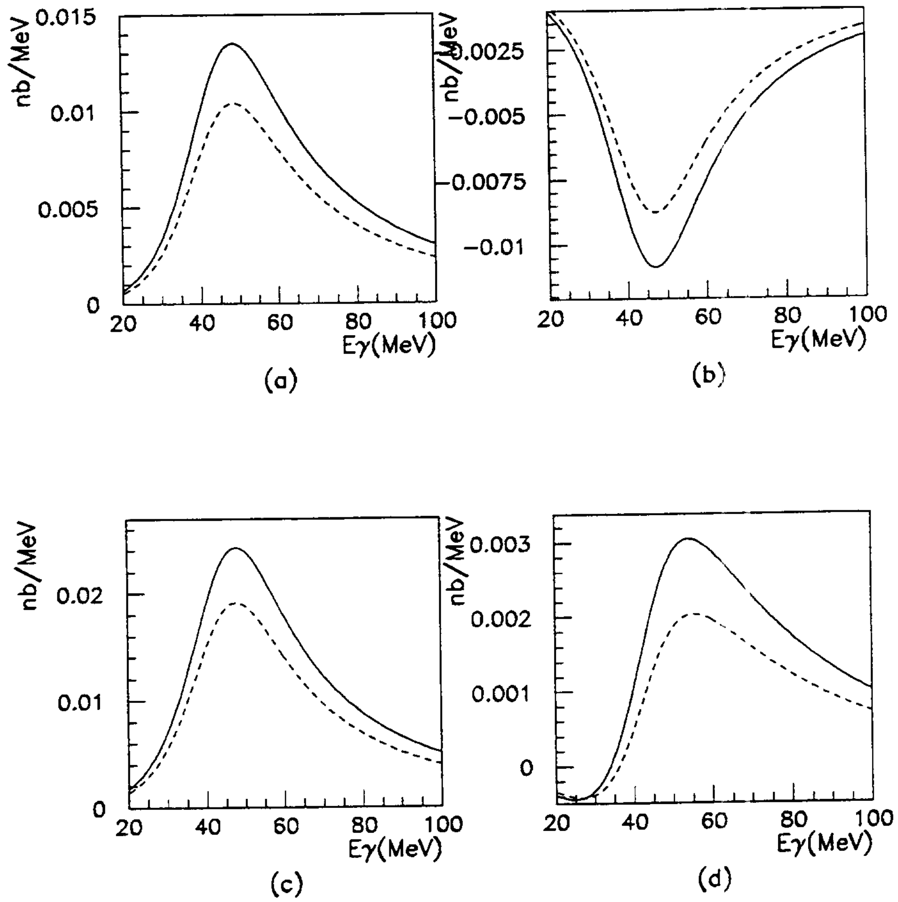

Figure 4. **a.** γ spectrum: $f_0 \to \pi^+\pi^-\gamma$; **b.** $2\Re(A_{\rho}\cdot A^*_{f_0})$; **c.** $|A_{\rho}\cdot|^2 - 2\Re(A_{\rho}\cdot A^*_{f_0})$; **d.** $|A_{\rho}\cdot|^2 + 2\Re(A_{\rho}\cdot A^*_{f_0})$. $\mathrm{BR}_{\phi f_0 \gamma} = 2.5\times10^{-4}$. Solid lines are without angular cuts, dotted lines are for $|\cos\theta_{\gamma,\ \mathrm{beam}}| < 0.9$ and $|\cos\theta_{\pi\gamma}| < 0.9$.

effect of a few %, for either destructive or constructive interference. With the expected DAΦNE luminosity the signal is quite measurable. In Figs. 7c,d we show the S/B for $\mathrm{BR}_{\phi f_0 \gamma} = 2.5\times10^{-4}$. The signal is certainly much larger and should be much easier to measure.

Fig. 8 shows the MC simulated photon spectrum which would be observed in KLOE (after cuts) for $\phi \to f_0\gamma \to \pi^+\pi^-\gamma$ for the two cases, constructive and destructive interference, for $\mathrm{BR}_{\phi f_0 \gamma} = 2.5\times10^{-4}$ and assuming $5\times10^{+9}$ ϕ's are produced in the first year of DAΦNE's operations. The incoherent background contribution is also shown. In Fig. 9 we show the resultant estimate of the fractional accuracy that KLOE can achieve in one year's running at DAΦNE, which gives pleasant reassurance that even at the smallest $\mathrm{BR}_{\phi f_0 \gamma}$ considered and with destructive interference, the fractional accuracy in the measurement of BR is ten percent. In addition we note that the differential

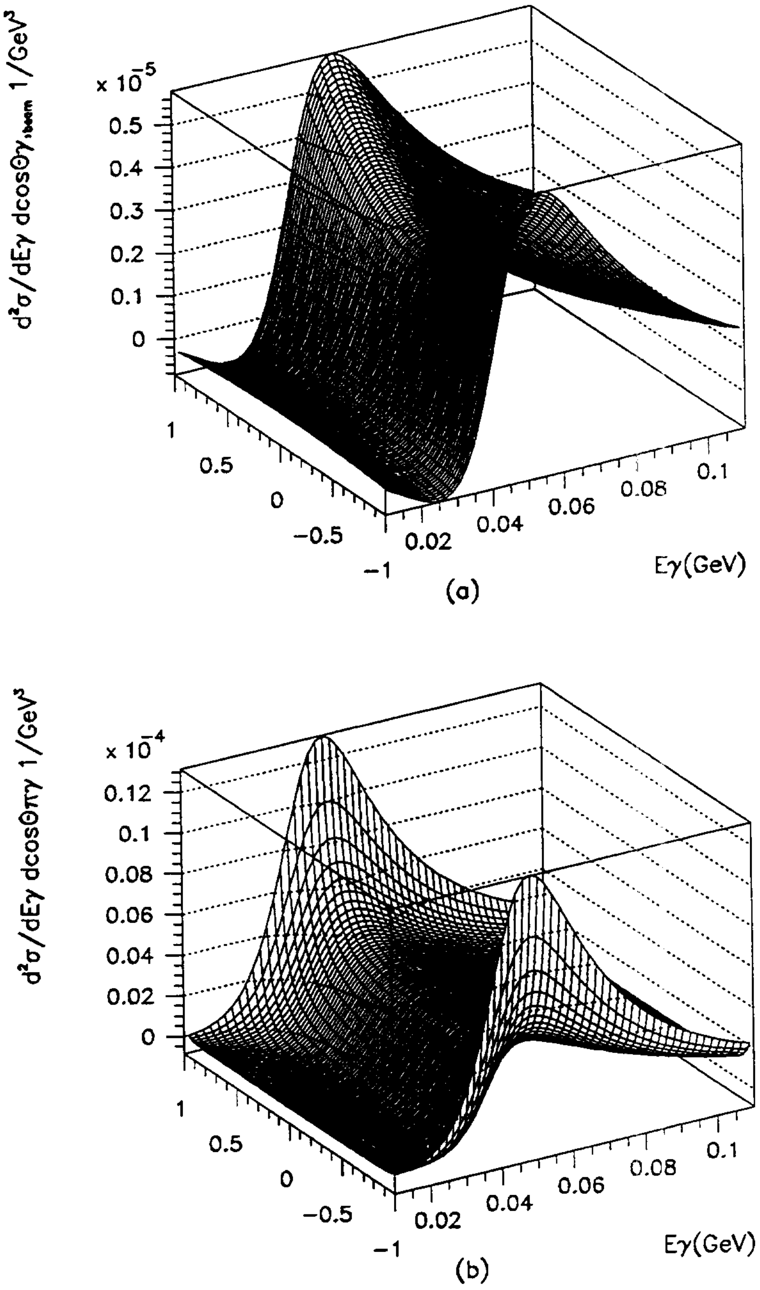

Figure 5. **a.** $d^2\sigma/dE_\gamma d\cos\theta_{\gamma,beam}$ *vs* E_γ, $\cos\theta_{\gamma,beam}$; **b.** $d^2\sigma/dE_\gamma d\cos\theta_{\pi\gamma}$ *vs* E_γ, $\cos\theta_{\pi\gamma}$ for constructive interference, $BR=1.5\times10^{-4}$

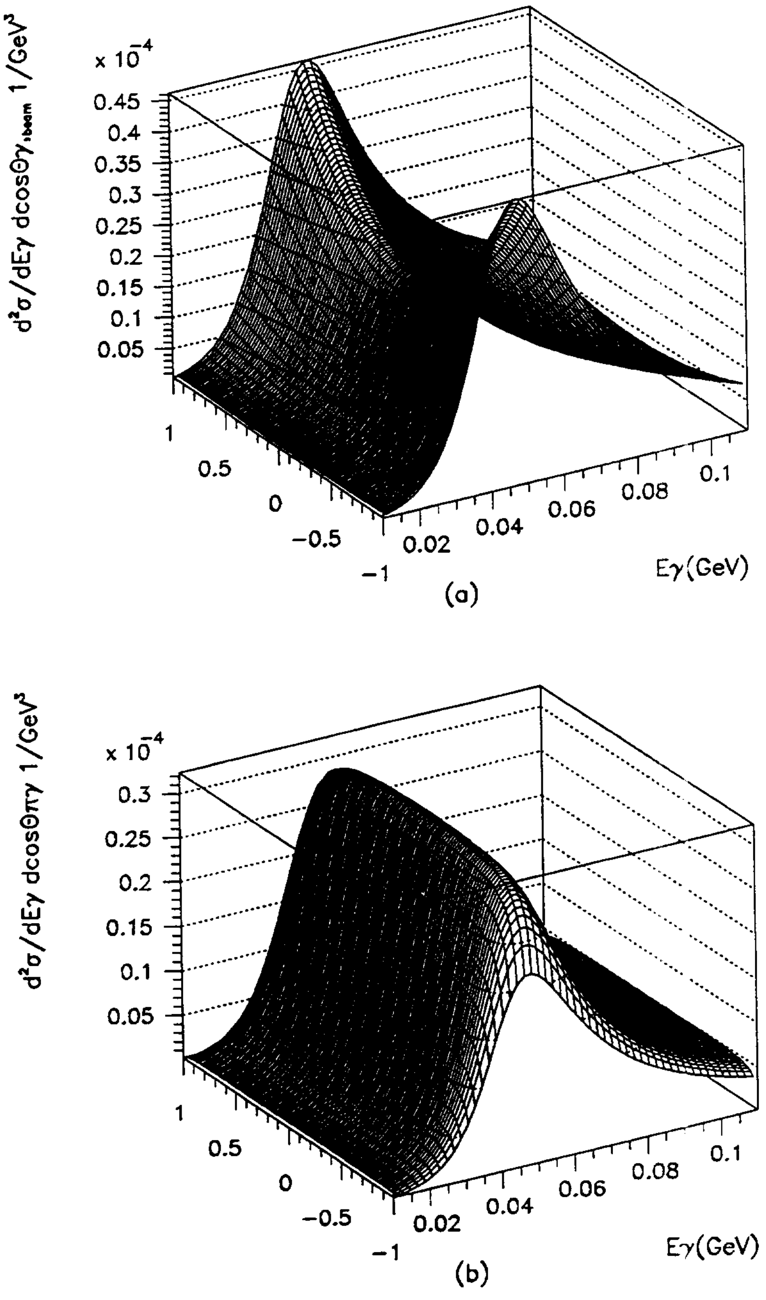

Figure 6. **a.** $d^2\sigma/dE_\gamma d\cos\theta_{\gamma,beam}$ *vs* E_γ, $\cos\theta_{\gamma,beam}$; **b.** $d^2\sigma/dE_\gamma d\cos\theta_{\pi\gamma}$ *vs* E_γ, $\cos\theta_{\pi\gamma}$ for destructive interference, BR=1.5×10^{-4}

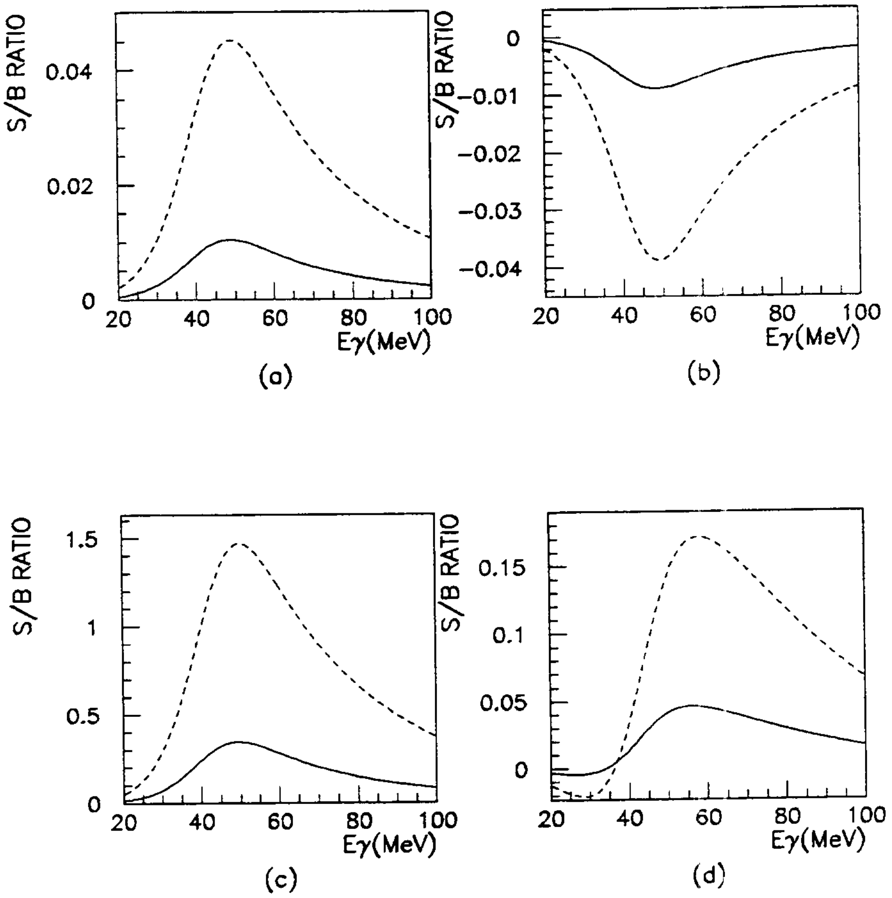

Figure 7. S/B ratio for **a.** constructive **b.** destructive interference, BR=1×10^{-6}; **c.** constructive **d.** destructive interference, BR=2.5×10^{-4}. Solid lines are without angular cuts, dotted lines are for $|\cos\theta_{\gamma,\ \mathrm{beam}}| < 0.9$ and $|\cos\theta_{\pi\gamma}| < 0.9$.

rate $\mathrm{d}^3\Gamma/\mathrm{d}E_\gamma \mathrm{d}\cos\theta_{\gamma,beam}\mathrm{d}\cos\theta_{\pi\gamma}$ clearly contains more information than the integrated cross section, thus it is possible to improve on the results presented. The study of $\phi\to f_0\gamma\to\pi^0\pi^0\gamma$ provides an independent measure of the strength of the $\phi f_0\gamma$ coupling and therefore a check on the determination of its sign in the $\pi^+\pi^-$case, thus completing the picture of the f_0.

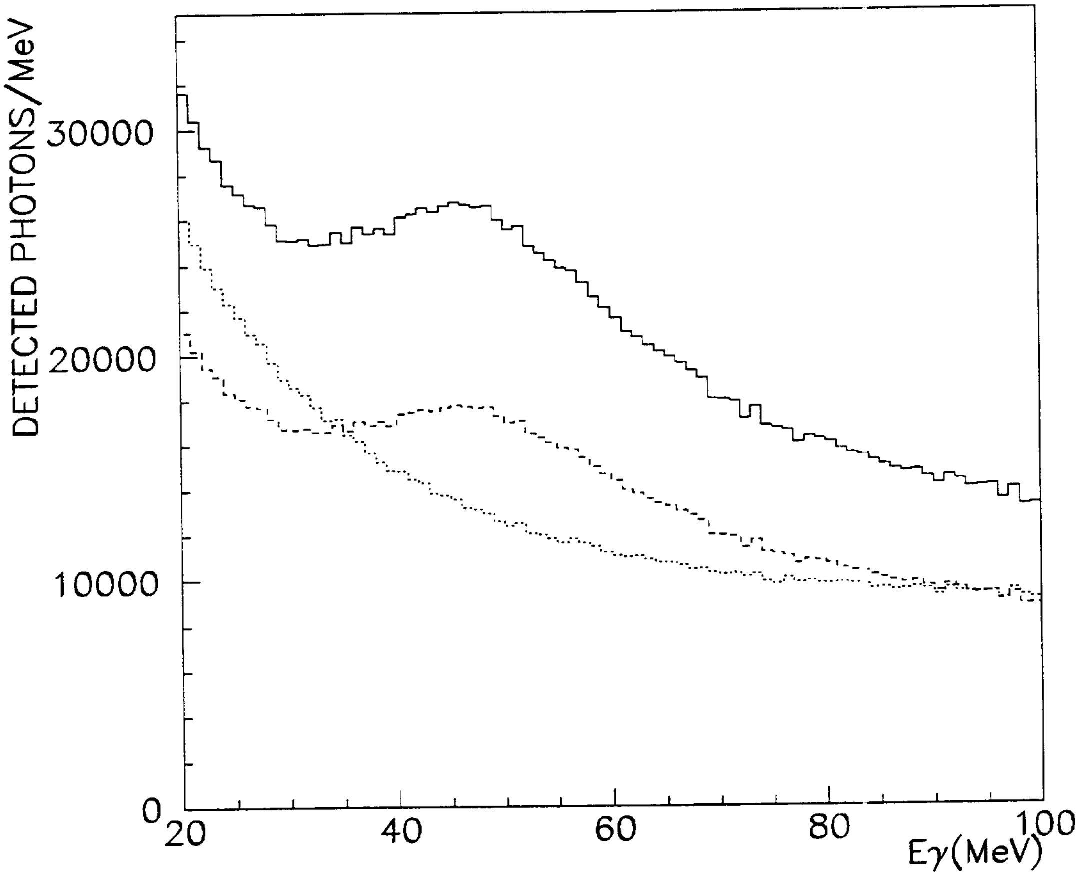

Figure 8. γ spectrum in KLOE from $\phi \to \pi^+\pi^-\gamma$ for BR=2.5×10^{-4} , $5\times10^9\phi$'s (after cuts). Solid and dashed lines are signal + background, constructive and destructive respectively; dotted line is incoherent background alone.

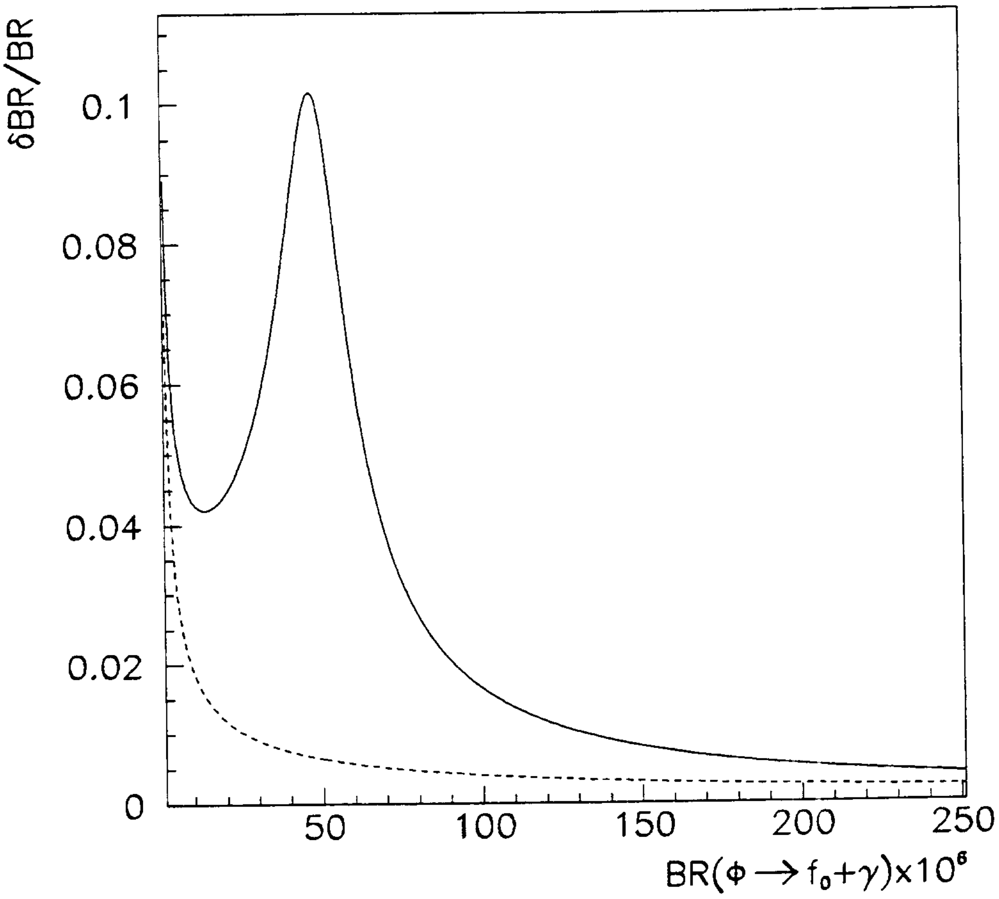

Figure 9. Fractional error on $\mathrm{BR}_{\phi f_0\gamma}$ *vs* $\mathrm{BR}_{\phi f_0\gamma}$. Solid line is for destructive interference, dashed line for constructive interference.

3. $\phi \to \eta'\gamma$

We have also studied the accuracy achievable by KLOE in the measurement of BR($\phi \to \eta'\gamma$), for an equal running period. This ϕ decay mode has never been seen; the experimental upper limit is 4.1×10^{-4}. Measurement of the BR of this mode will shed light on the gluonium content, $Z_{\eta'}$, of the η'.[16] The rate for radiative decays of the ϕ to pseudoscalar mesons containing $\bar{s}s$ pairs is proportional to the amplitude, Y, of the $\bar{s}s$ component of their wave function, giving the scaling law:

$$\frac{\Gamma(\phi \to \eta'\gamma)}{\Gamma(\phi \to \eta\gamma)} = \left(\frac{Y_{\eta'}}{Y_\eta}\right)^2 \left(\frac{k_{\eta'}}{k_\eta}\right)^3 \sim 4.6 \times 10^{-3} \left(\frac{Y_{\eta'}}{Y_\eta}\right)^2 . \tag{3.1}$$

To give an idea of the expected order of magnitude of the branching ratio, for $Z_{\eta'} = 0$ and the $\eta - \eta'$ mixing angle $\theta_p = -20°$;[17] BR($\phi \to \eta'\gamma$) $\sim 1.2\times10^{-4}$.

The signature for $\phi \to \eta'\gamma$, $\eta' \to \eta\pi^+\pi^-$ and $\eta \to \gamma\gamma$ is: a pair of charged pions, two photons whose invariant mass equals that of the η, and one low energy photon. The invariant mass of all particles must equal the ϕ mass. By applying these criteria, the efficiency×acceptance for the signal in KLOE is 74.5%. The possible background events are from:

1. $\phi \to \eta\gamma$, BR=$(1.28 \pm 0.06) \times 10^{-2}$, $\eta \to \pi^+\pi^-\pi^0$, product BR 3.0×10^{-3}. Use of kinematical constraints pushes the background down so that the efficiency×acceptance for this background in KLOE is 2.6×10^{-3}.
2. $\phi \to \omega\gamma$, BR<5%, $\omega \to 3\pi$, product BR=4.4×10^{-2}. After kinematical constraints, one finds an efficiency×acceptance for this background in KLOE of 5.9×10^{-3}.
3. $\phi \to \pi^0\rho^0 \to \pi^0\pi^+\pi^-\gamma$, product BR=$(4.8 \pm 0.6) \times 10^{-3}$. Overall kinematical constraints again result in an efficiency×acceptance for this background in KLOE of 5.6×10^{-3}.

We can calculate in this way the fractional accuracy achievable in KLOE for the measurement of this BR: 6.3% for a BR of 1.0×10^{-5} and 0.25% for a BR of 4.1×10^{-4}. In Fig. 10 we show the resultant γ spectrum in KLOE. We note that in the first year's run, KLOE can measure BR's of ~1% of the value in eq. 4.1, for zero gluon content.

4. CONCLUSION

We have studied the experimental problems associated with measuring ϕ radiative decays by choosing two typical and interesting ones: $\phi \to f_0\gamma$, where the f_0 decays to two neutral pions or two charged pions, and $\phi \to \eta'\gamma$. We simulated the signal and the expected background, and found that the hermeticity of KLOE makes the measurements for neutral pions almost trivial. However, the charged pion mode is subject to further background that can *only*[18] be controlled in a hermetic detector. We found that despite possible destructive interference between the signal and final state radiation, and a large incoherent background from initial state radiation, by using the charged pions, KLOE will be able to determine the sign of the interference, and the magnitude of $\mathrm{BR}_{\phi f_0 \gamma}$ to accuracies ranging from a fraction of a percent to at most 10 percent in the worst case. The study of $\phi \to f_0\gamma \to \pi^0\pi^0\gamma$ provides an independent measure of the strength of the $\phi f_0 \gamma$ coupling and therefore a check on the determination of its sign in the $\pi^+\pi^-$case, thus completing the picture of the f_0. We found the η' search using KLOE relatively easy.

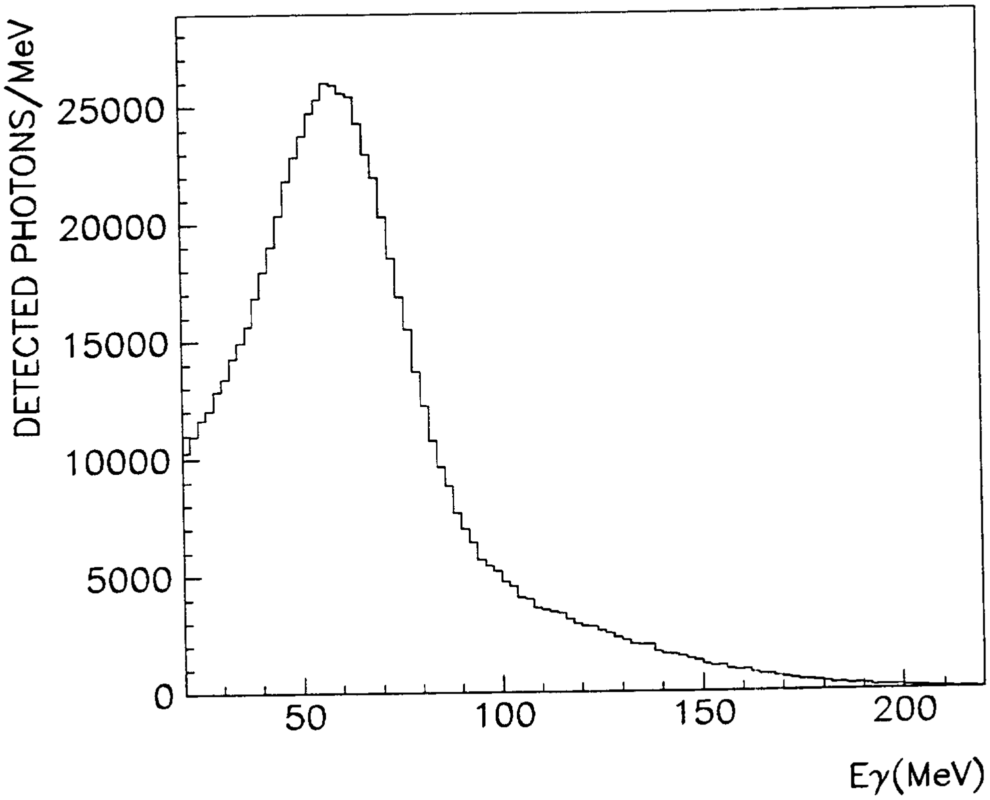

Figure 10. Photon Spectrum in KLOE from $\phi \rightarrow \eta' \gamma$.

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