Interference in the reaction $e^+e^- \to \gamma\pi^+\pi^-$ and the final state interaction

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We describe the interference between amplitudes $e^+e^- \to \rho \to \gamma\pi^+\pi^-$ and $e^+e^- \to \phi \to \gamma(f_0+\sigma) \to \gamma\pi^+\pi^-$, with regard to the phase of the elastic $\pi\pi$ scattering background and mixing of the f_0 and σ mesons. It is shown that the Fermi-Watson theorem for the final state interaction in the reaction $e^+e^- \to \rho \to \gamma\pi^+\pi^-$ is not valid in the case of soft photons, $\omega < 100$ MeV, in the region of the ϕ meson. The interference patterns in the spectrum of the photon energy differential cross section and in the full cross section as a function beam energy are obtained. [S0556-2821(97)00823-0]

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As is known, the problem of scalar f_0 and a_0 mesons is the central problem of the spectroscopy of light hadrons. Theoretical investigations have established that the study of the decays $\phi \to \gamma f_0 \to \gamma\pi\pi$ and $\phi \to \gamma a_0 \to \gamma\pi\eta$ can shed light on this problem [1–4]. In this paper we present results on $\phi \to \gamma f_0 \to \gamma\pi^+\pi^-$ decay. Experimentally, the radiative decays $\phi \to \gamma f_0 \to \gamma\pi^+\pi^-$ are studied by observing the interference patterns at the ϕ meson peak in the reaction $e^+e^- \to \gamma\pi^+\pi^-$ which is currently studied in the detector CMD-2 [5] at e^+e^- collider VEPP-2M in Novosibirsk and will be studied at the ϕ factory DAΦNE when it comes into operation.

The analysis of the interference patterns in this reaction, by virtue of a large radiative background, is a rather complex problem which has been actively considered in the current literature; see [6] and references therein.

It is necessary to note that in paper [6] and in all previous papers (see [6]) this problem was actually considered in the approximation of the single f_0 meson production, for example, as with the ρ meson production. However, it is necessary to take into account that the f_0 meson is strongly coupled not only with the $\pi\pi$ and $K\bar{K}$ channels but also with other scalar resonances (such as a σ meson) and also with an elastic background. This fact, as we shall show below, deforms considerably the interference patterns both in the spectrum of photons and in the full cross section of the reaction.

In view of this, we present again the analysis of interference patterns in the reaction $e^+e^- \to \gamma\pi^+\pi^-$ at the ϕ meson peak with regard to the phase of the elastic $\pi\pi$ scattering background and the f_0 and σ meson mixing. As a reference point we consider experiment [5] and preliminary data obtained in this experiment.

Analyzing the phase relations between the amplitudes $\gamma\gamma^*(s) \to \pi\pi$ and $\pi\pi \to \pi\pi$, we show that the Fermi-Watson theorem on the final state interaction in the $e^+e^- \to \gamma^*(s) \to \rho \to \gamma\pi^+\pi^-$ reaction is not valid, i.e., the phase of the amplitude $\gamma^*(s) \to \gamma\pi\pi$ is not determined by the phase of $\pi\pi$ scattering amplitude. For soft photons in the amplitude $\gamma^*(s) \to \rho \to \gamma\pi\pi$ the Born term, i.e., the bremsstrahlung, is dominant, as the Low theorem requires, and the phase of amplitude in the elastic region is determined by the phase of the $\pi\pi$ scattering in the isovector vector channel (by the ρ meson propagator). At $4m_\pi^2/s, 4m_\pi^2/m^2 \ll 1$, where m is the invariant $\pi\pi$ mass, the amplitude is divided into two parts: (i) the bremsstrahlung with the phase of the $\pi\pi$ scattering in isovector vector channel, which dominates in the soft photon region, $s \simeq m^2$, and (ii) the amplitude of structural radiation, the phase of which in the elastic region is determined by a sum of phase of the $\pi\pi$ scattering in the isovector vector channel [$\delta_1^1(E)$] and the phase of the $\pi\pi$ scattering in isoscalar scalar (in our case) channel [$\delta_0^0(m)$], the analogue of the Fermi-Watson theorem [8]. This fact leads to the shift of the interference pattern both in the full and in the differential cross section of the process.

In our case the classical Fermi-Watson theorem is faced with the problem of soft photon radiation. The general theoretical reasons for this case were adduced in [8], where it was noted that the Low theorem on a soft photon is not consistent with the analogue of the Fermi-Watson theorem on the final state interaction. According to the authors of Ref. [8], the way out of this situation lies in the separation of a photon energy spectrum into ''soft'' and ''hard'' parts, in each of which the ''proper'' theorem holds. It is necessary to note that in the formal approach of [8] the separation of a photon spectrum into ''soft'' and ''hard'' parts looks somewhat like a trick that reconciles these two theoretical conclusions. In contrast to [8] we consider a particular representation of the

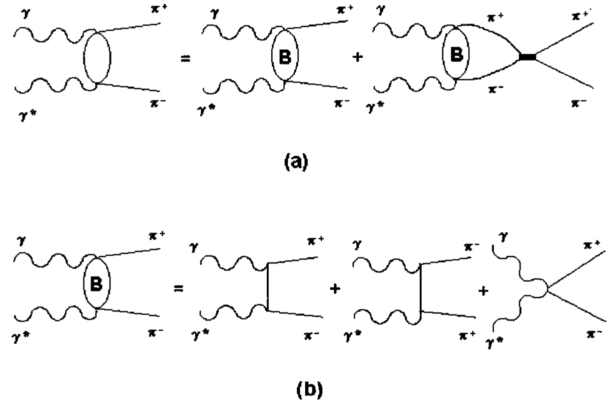

FIG. 1. The diagrams of the model.

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amplitude of the reaction $e^+e^-\to\gamma^*\to\rho\to\gamma\pi^+\pi^-$ (see Fig. 1), and demonstrate when the Fermi-Waston theorem holds, when the amplitude satisfies the Low theorem, and when it is broken up into two contributions: the bremsstrahlung and an amplitude satisfying the analogue of the Fermi-Watson theorem.

Let us consider the two-photon production of pions, $\gamma\gamma^*(s)\to\pi\pi$, below inelastic thresholds of the $\pi\pi$ scattering. In the case when $s<4m_\pi^2$ the pion interaction in the final state results in a common phase of the amplitude which equals the phase of the $\pi\pi$ scattering.

Really, in the approximation, taking into account only two-pion intermediate states, we assume that the amplitude of the $\pi\pi$ scattering [see the last diagram in Fig. 1(a)] lies on the mass shell. Then the full s-wave isoscalar amplitude of the process of interest is determined by the expression (see Fig. 1)

$$T=\frac{2}{3}\frac{e^2g_{\rho\pi\pi}}{8\pi f_\rho}\left[\frac{m^2}{E^2-m^2}\frac{1-\rho_{\pi\pi}(m)^2}{2\rho_{\pi\pi}(m)}\lambda(m)+\frac{E^2}{m^2-E^2}+T_{\pi\pi}^{I=0}(m)g_{\pi\pi}(E,m)\right]\frac{m_\rho^2}{D_\rho(E^2)}, \tag{1}$$

where m is invariant mass of $\pi\pi$ system, $\rho_{\pi\pi}(m)=\sqrt{1-4m_\pi^2/m^2}$, $\lambda(m)=\ln\{[1+\rho_{\pi\pi}(m)]/[1-\rho_{\pi\pi}(m)]\}$ and $1/D_\rho(E^2)$ is the ρ meson propagator presented in [6]. The function $g_{\pi\pi}(E,m)$ is determined by the triangular diagram [1].

When $E<2m_\pi$, $m>2m_\pi$,

$$g_{\pi\pi}(E,m)=\frac{1}{\pi}\left\{1+\frac{1-\rho_{\pi\pi}^2(m)}{\rho_{\pi\pi}(E)^2-\rho_{\pi\pi}(m)^2}\times\left[\rho_{\pi\pi}(m)(\lambda(m)-i\pi)+2|\rho_{\pi\pi}(E)|\times\arctan(|\rho_{\pi\pi}(E)|)-\pi|\rho_{\pi\pi}(E)|-\frac{1}{4}(1-\rho_{\pi\pi}(E)^2)(\pi^2-2\pi\times\arctan(|\rho_{\pi\pi}(E)|)-\lambda(E)^2-(\pi+i\lambda(m))^2)\right]\right\}. \tag{2}$$

When $E>2m_\pi$, $m>2m_\pi$,

$$g_{\pi\pi}(E,m)=\frac{1}{\pi}\left\{1+\frac{1-\rho_{\pi\pi}^2(m)}{\rho_{\pi\pi}(E)^2-\rho_{\pi\pi}(m)^2}\times\left[\rho_{\pi\pi}(m)(\lambda(m)-i\pi)-\rho_{\pi\pi}(E)(\lambda(E)-i\pi)-\frac{1}{4}(1-\rho_{\pi\pi}(E)^2)((\pi+i\lambda(E))^2-(\pi+i\lambda(m))^2)\right]\right\}. \tag{3}$$

We consider the parametrization of the s-wave amplitude of the $\pi\pi$ scattering below the inelastic thresholds in the following manner:

$$T_{\pi\pi}^{I=0}(m)=\frac{e^{2i\delta_0^0(m)}-1}{2i\rho_{\pi\pi}(m)}. \tag{4}$$

Substituting the amplitude (4) in Eq. (1) one easily gets, in the case $E<2m_\pi$,

$$T=\frac{2}{3}\frac{e^2g_{\rho\pi\pi}}{8\pi f_\rho}e^{i\delta_0^0(m)}\left[\left(\frac{m^2}{E^2-m^2}\frac{1-\rho_{\pi\pi}(m)^2}{2\rho_{\pi\pi}(m)}\lambda(m)-\frac{E^2}{E^2-m^2}\right)\cos[\delta_0^0(m)]+\sin[\delta_0^0(m)]\times\frac{\mathrm{Re}[g_{\pi\pi}(E,m)]}{\rho_{\pi\pi}(m)}\right]\frac{m_\rho^2}{D_\rho(E^2)} \tag{5}$$

and the Fermi-Watson theorem is valid; i.e., the phase of the $\gamma\gamma^*(E)\to\pi\pi$ process is determined by the phase of the $\pi\pi$ scattering. However, it is easily seen from Eqs. (1) and (3) that the $\rho_{\pi\pi}(E)$ and $\lambda(E)$ terms in the imaginary part of the triangular diagram destroy the Fermi-Watson theorem in the case $E>2m_\pi$.

For soft photons ($E\simeq m$) the triangular diagram is proportional to the factor (E^2-m^2), see Eq. (3), and in Eq. (1) the Born term, i.e., the bremsstrahlung, is dominant in full agreement with the Low theorem[1] and the amplitude phase is determined by the phase of the ρ meson propagator.

In the case when $E^2\sim m^2\gg 4m_\pi^2$ the imaginary part of the triangular diagram

$$\mathrm{Im}[g_{\pi\pi}(E,m)]\simeq\frac{2m_\pi^2}{m^2}\left(1+\frac{m^2}{E^2-m^2}\ln\frac{m^2}{E^2}\right) \tag{6}$$

is small since the imaginary parts from the E and m channels compensate each other. The amplitude of the process in this region is broken up into two contributions: the bremsstrahlung which dominates in the soft photon region and the amplitude satisfying the analogue of the Fermi-Watson theorem [8]:

$$T=\frac{2}{3}\frac{e^2g_{\rho\pi\pi}}{8\pi f_\rho}\left[\frac{E^2}{m^2-E^2}+e^{i\delta_0^0(m)}\sin[\delta_0^0(m)]\mathrm{Re}[g_{\pi\pi}(E,m)]\right]\frac{m_\rho^2}{D_\rho(E^2)}. \tag{7}$$

At $E>m>2m_\pi$ our amplitude describes the process $e^+e^-\to\gamma^*\to\rho\to\gamma\pi^+\pi^-$. In the soft photon region (energy of a photon $\omega<100$ MeV) which we consider below, since $m_{f_0}\simeq m_\phi$, the second term in Eq. (7) is negligible in comparison to the first one and it is negligible also in comparison to the contribution of the ϕ meson, $e^+e^-\to\phi\to\gamma(f_0+\sigma)$

[1]Actually, this conclusion does not depend on our assumption that the amplitude of the $\pi\pi$ scattering in the last diagram in Fig. 1(a) lies on a mass shell since this diagram vanishes in the soft photon region due to the gauge invariance.

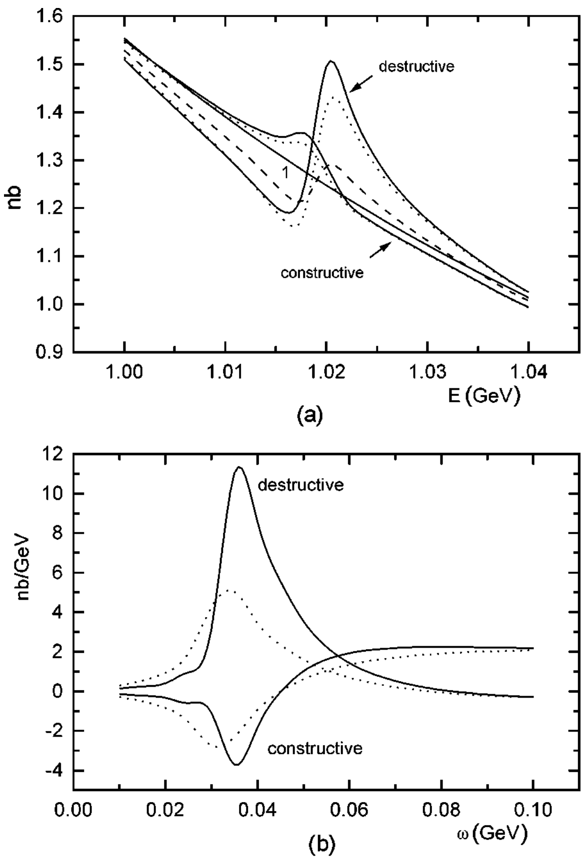

FIG. 2. (a) The interference pattern in the total cross section. The solid line 1 corresponds to the pure background and the dashed line is the background with the $\phi-\rho$ transition, see [6]. The solid lines for destructive and constructive interferences correspond to $\Gamma_{\rm eff}=0.025$ GeV. The dotted lines for destructive and constructive interferences correspond to $\Gamma_{\rm eff}=0.085$ GeV, see the text. (b) The interference pattern in the spectrum of photons. The solid lines correspond to the narrow f_0 resonance $\Gamma_{\rm eff}=0.025$ GeV, and the dotted lines correspond to the relatively wide resonance $\Gamma_{\rm eff}=0.085$ GeV.

$\to\gamma\pi^+\pi^-$, because of the narrow width of the ϕ meson (smallness is proportional to $\Gamma_\phi m_\phi/(m_\phi^2-m_\rho^2)\simeq 1/100$).

The whole formalism for the description of the reaction under study $e^+e^-\to\phi\to\gamma f_0\to\gamma\pi^+\pi^-$ was stated in [6]; here we write out only the basic formulas modified by the mixing of the f_0 and σ mesons and by an elastic background of the $\pi\pi$ scattering [7].

The amplitude of the $e^-(p_1)e^+(p_2)\to\phi\to\gamma(f_0+\sigma)\to\gamma(q)\pi^+(k_+)\pi^-(k_-)$ reaction is written down in the following way [9,7]:

$$M=e\overline{u(p_1)}\gamma^\mu u(p_2)\,\frac{em_\phi^2}{f_\phi}\,\frac{e^{i\delta_B(m)}g(m^2)}{sD_\phi(s)}\times\left(q^\mu\frac{e(\gamma)p}{pq}-e(\gamma)^\mu\right)\times\sum_{RR'}[g_{RK^+K^-}G^{-1}_{RR'}(m)g_{R'\pi^+\pi^-}], \tag{8}$$

where $s=E^2=p^2=(p_1+p_2)^2$, $t=m^2=(k_-+k_+)^2$, and the summation is over the two resonances $R=f_0,\sigma$. The definition of the function $g(m^2)$ and the ϕ meson propagator $1/D_\phi(s)$ are given in [7]. The data on the $\pi\pi$ scattering in the isoscalar channel are parametrized as follows [9,7]:

$$T(\pi\pi\to\pi\pi)=\frac{\eta_0^0e^{2i\delta_0^0(m)}-1}{2i\rho_{\pi\pi}(m)}=\frac{e^{2i\delta_B(m)}-1}{2i\rho_{\pi\pi}(m)}+e^{2i\delta_B(m)}T^{\rm res}_{\pi\pi}(m), \tag{9}$$

where $\delta_0^0(m)=\delta_B(m)+\delta_{\rm res}(m)$ and

$$T^{\rm res}_{\pi\pi}(m)=\sum_{RR'}\frac{g_{R\pi\pi}g_{R'\pi\pi}}{16\pi}G^{-1}_{RR'}(m). \tag{10}$$

The phase of the elastic background $\delta_B(m)$ is taken in the form $\delta_B=\theta\rho_{\pi\pi}(m)$, where $\theta\simeq 60°$. The matrix of the inverse propagator $G_{\underline{RR'}}(m)$ is presented in [9,7]. The amplitude of the $\pi\pi\to KK$ process is

$$T_{K\overline{K}}=e^{i\delta_B(m)}\sum_{RR'}\frac{g_{R\pi\pi}g_{R'K\overline{K}}}{16\pi}G^{-1}_{RR'}(m). \tag{11}$$

Thus, for the differential cross section of the signal we obtain the expression

$$\frac{d\sigma_\phi}{d\omega}=\frac{\alpha^2\omega}{8\pi s^2}\left(\frac{m_\phi^2}{f_\phi}\right)^2\frac{|g(m^2)|^2}{|D_\phi(s)|^2}\sqrt{1-\frac{4m_\pi^2}{m^2}}\left(a+\frac{a^3}{3}\right)b\times\left|\sum_{RR'}[g_{RK^+K^-}G^{-1}_{RR'}(m)g_{R'\pi^+\pi^-}]\right|^2H_{\rm rad}(s,\omega_{\rm min}), \tag{12}$$

where $\omega=|\vec{q}|$ is energy of the photon, a is the cut on θ_γ, the angle between the photon momentum and the electron beam in the center-of-mass frame of the reaction, $-a\leqslant\cos\theta_\gamma\leqslant a$, and b is the cut on $\theta_{\pi\gamma}$, the angle between the photon and pion momenta in the dipion rest frame, $-b\leqslant\cos\theta_{\pi\gamma}\leqslant b$.

The function $H_{\rm rad}(s,\omega_{\rm min})$ takes into account the radiative corrections, the contribution of which reduces the cross section by 20%, see [6,7].

As was shown in the previous papers, see [6], the main background to process under study has come from the initial electron radiation and the radiation from the final pions. The background from nonresonant invariant mass of the $\pi^+\pi^-$ system processes was estimated in [6,7] and in our region of the spectrum, $20<\omega<100$ MeV, was found to be negligible.

The differential cross sections for the background processes connected with the final state radiation and the initial one have the following expressions:

$$\frac{d\sigma_f}{d\omega}=2\sigma_0(s)\frac{1}{\sqrt{s}}F(x,a,b)\left|1-\frac{3\Gamma(\phi\to e^+e^-)\sqrt{s}}{\alpha D_\phi(s)}\right|^2\times H_{\rm rad}(s,\omega_{\rm min}), \tag{13}$$

$$\frac{d\sigma_i}{d\omega}=2\sigma_0(m^2)\frac{1}{\sqrt{s}}H(x,a,b)\left|1-\frac{3\Gamma(\phi\to e^+e^-)m}{\alpha D_\phi(m^2)}\right|^2\times H_{\rm rad}(m,\omega_{\rm min}),$$

where $x=2\omega/\sqrt{s}$. The functions $F(x,a,b)$, $H(x,a,b)$ and the cross section $\sigma_0(s)$ of the $e^+e^-\rightarrow\pi^+\pi^-$ process are presented in [6].

The interference of the amplitude (8) with the amplitude of the final pions radiation is

$$\frac{d\sigma_{\rm int}}{d\omega}=\sqrt{\frac{3}{2}}\frac{\alpha^3}{s\sqrt{s}}\left(\frac{g_{\rho\pi\pi}}{f_\rho f_\phi}\right)\mathrm{Re}\left[\frac{m_\phi^2 m_\rho^2 g(m^2)e^{i\delta_B(m)}}{\sqrt{4\pi\alpha}D_\phi D_\rho^*}\right.$$
$$\times\left(1-\frac{3\Gamma(\phi\rightarrow e^+e^-)\sqrt{s}}{\alpha D_\phi^*(s)}\right)$$
$$\left.\times\left(\sum_{RR'}g_{RK^+K^-}G_{RR'}^{-1}g_{R'\pi^+\pi^-}\right)\right]$$
$$\times\left\{f(x)+\frac{\xi}{2}\ln\frac{1-f(x)}{1+f(x)}\right\}\left(a+\frac{a^3}{3}\right)H_{\rm rad}(s,\omega_{\rm min}),\tag{14}$$

where $f(x)=b\sqrt{1-(\xi/1-x)}$ and $\xi=4m_\pi^2/s$.

The total differential cross section is $d\sigma/d\omega=d\sigma_\phi/d\omega+d\sigma_i/d\omega+d\sigma_f/d\omega\pm d\sigma_{\rm int}/d\omega$.

The fitting of the $\pi\pi$ scattering data shows that a number of parameters describe well the $\pi\pi$ data in the region of interest $0.7<m<1.8$ GeV, see [7].

By way of an illustration we present the interference patterns for two sets of parameters, see Fig. 2, for the narrow and relatively wide f_0 resonance.

(i) $m_{f_0}=980$ MeV, $m_\sigma=1.47$, $R=8$, $g_{f_0K^+K^-}^2/4\pi=2.25$ GeV^2, $g_{\sigma\pi\pi}^2/4\pi=1.76$ GeV^2, $g_{\sigma K\bar{K}}=0$, $\theta=60°$, the subtraction constant for nondiagonal elements of the matrix of the inverse propagator $C_{f_0\sigma}=-0.31$ GeV [7], the effective width of the f_0 meson $\Gamma_{\rm eff}$=0.025 GeV. The branching ratios of the decay for this set of parameters are $B(\phi\rightarrow\gamma f_0\rightarrow\gamma\pi\pi,\omega<250$ MeV$)=3.36\times10^{-4}$, $B(\phi\rightarrow\gamma(f_0+\sigma)\rightarrow\gamma\pi\pi,\omega<250$ MeV$)=2.74\times10^{-4}$ and $B(\phi\rightarrow\gamma f_0\rightarrow\gamma\pi\pi,\omega<100$ MeV$)=0.79\times10^{-4}$, $B(\phi\rightarrow\gamma(f_0+\sigma)\rightarrow\gamma\pi\pi,\omega<100$ MeV$)=1.0\times10^{-4}$.

(ii) $m_{f_0}=985$ MeV, $m_\sigma=1.38$, $R=2$, $g_{f_0K^+K^-}^2/4\pi=1.47$ GeV^2, $g_{\sigma\pi\pi}^2/4\pi=1.76$ GeV^2, $g_{\sigma K\bar{K}}=0$, $\theta=45°$, the subtraction constant for nondiagonal elements of the matrix of the inverse propagator $C_{f_0\sigma}=-0.31$ GeV [7], the effective width of the f_0 meson $\Gamma_{\rm eff}$=0.085 GeV. The branching ratios of the decay for this set of parameters are $B(\phi\rightarrow\gamma f_0\rightarrow\gamma\pi\pi,\omega<250$ MeV$)=2.32\times10^{-4}$, $B(\phi\rightarrow\gamma(f_0+\sigma)\rightarrow\gamma\pi\pi,\omega<250$ MeV$)=1.67\times10^{-4}$, and $B(\phi\rightarrow\gamma f_0\rightarrow\gamma\pi\pi,\omega<100$ MeV$)=0.68\times10^{-4}$, $B(\phi\rightarrow\gamma(f_0+\sigma)\rightarrow\gamma\pi\pi,\omega<100$ MeV$)=0.59\times10^{-4}$.

The interference patterns in the full cross section of the reaction $e^+e^-\rightarrow\gamma\pi^+\pi^-$, $\sigma_\phi\pm\sigma_{\rm int}+\sigma_f+\sigma_i$, by energy of beams at the ϕ meson region for both sets of parameters are shown in Fig. 2(a). Being guided by [5], we have chosen the angular cuts $a=0,66$ and $b=0.955$ which suppress the contribution of the initial state radiation by a factor of 9. However, despite the strong suppression, the initial state radiation remains dominant and is about $\frac{2}{3}$ of the total background. The photon energy is in the interval $20<\omega<100$ MeV.

The interference pattern in the photon spectrum $d\sigma_\phi/d\omega\pm\sigma_{\rm int}/d\omega$ at the ϕ meson peak is shown in Fig. 2(b).

This analysis of the interference patterns in reaction $e^+e^-\rightarrow\gamma\pi^+\pi^-$ shows that the study of this reaction is an interesting and rather complex problem. In this contribution we have shown that the analysis of the interference patterns in the $e^+e^-\rightarrow\gamma\pi^+\pi^-$ reaction needs to be performed along with the analysis of reactions $\pi\pi\rightarrow\pi\pi$ and $\pi\pi\rightarrow K\bar{K}$. The experimental study of the $e^+e^-\rightarrow\gamma\pi^+\pi^-$ reaction can obviously enrich our knowledge about nontrivial manifestations of the strong interactions and the features of the f_0 meson.

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