Interactions of η, η'- Mesons with Heavy Quarks

E.Z.Avakyan[*], *S.L.Avakyan*

Gomel State Technical University

Abstract

The η, η', η_c system was investigated in the $q\bar{q} - s\bar{s} - c\bar{c}$ basis. Numerical values for mixing angles φ,θ_c and θ_y were fixed by the experimental data of two photon η-decays. The decay constants of radiative $V \to P\gamma$ and $P \to V\gamma$ ($P \equiv \eta, \eta'$; $V \equiv \rho, \omega, \phi$) decays were calculated and turned out to be in agreement with experimental data.

1 Introduction.

The investigation of simple quark-antiquark systems such as pseudoscalar mesons π^0, η, η'... is of extraordinary interest as a source of information about structure of hadrons. CLEO [1] and L3[2]experiments call the additional interest to this phenomena. It's well known that SU(3)-symmetry predicts the existence of massless pseudoscalar octet $\eta_8 = \frac{1}{\sqrt{6}}(u\bar{u} + d\bar{d} - s\bar{s})$ and massive singlet $\eta_0 = \frac{1}{\sqrt{3}}(u\bar{u} + d\bar{d} + s\bar{s})$.Physical states η, η' are the mixture of η_8 and η_0. The study of $\eta - \eta'$ mixing is very important for understanding of basic properties of quark - hadron matter. This phenomena was considered in different approaches [3]. Also there exists approach connected with quark basis $q\bar{q} = \frac{u\bar{u}+d\bar{d}}{\sqrt{2}}, s\bar{s}$[4].In this case decay constant mixing is considered to be the same as for meson states. There are several ways to define $\eta - \eta'$ mixing parameters:

- The radiative decays of η-mesons [4].
- The radiative J/Ψ - decays [5]

*E-mail:avakyan@tut.by

- Rations of weak decays constants [3].

Very recently Kloe Collaboration has reported new measurement of the ratio $R = Br(\phi \to \eta'\gamma)/Br(\phi \to \eta\gamma)$ [6]. So the subject of admixture of heavy quark or gluonic components in light pseudoscalar mesons has regained interest. Early investigations of this subject already date back to the 70-th,when Kramer [7]and independently Fritzch and Jackson [8]discussed mixing of light and heavy pseudoscalar mesons in the context of radiative J/Ψ - decays.The rather exostive phenomenological analysis of mixing parameters of $\eta - \eta' - \eta_c$ system have been performed by Chao [5]. There is number of approaches where authors trie to explain existing experimental data by admixture of gluonic states (the recent one is [9]).

In this article we study the mixing in the the $\eta - \eta' - \eta_c$ system.The analysis of mixing parameters can be performed by study two-photon decays of η, η' $\eta_c$and mesons.

There is a problem in is the evaluation of the hadronic matrix elements.In our previous work [10] we perform the calculations in the Quark Confinement Model (QCM) [11]. But the heavy quarks interactions cannot be described in the the framework of this model.So in the present work we use Relativistic Constituent Quark Model (RCQM)[12].

2 The description of η mixing

In order to quantify the mixing in the η, η' system, one have to define appropriate mixing parameters, which can be related to physical observables.

The octet-singlet mixing is based on chiral perturbation theory which traditionally leads to description of η, η' mixing in terms of singlet-octet parameters [3]. In this case the physical states η and η' are the mixture of massive singlet $\eta_0 = \frac{1}{\sqrt{3}}(u\bar{u}+d\bar{d}+s\bar{s})$ and massless octet $\eta_8 = \frac{1}{\sqrt{6}}(u\bar{u}+d\bar{d}-s\bar{s})$:

$$\begin{pmatrix} \eta \\ \eta' \end{pmatrix} = \begin{pmatrix} \cos\theta - \sin\theta \\ \sin\theta \cos\theta \end{pmatrix} \begin{pmatrix} \eta_8 \\ \eta_0 \end{pmatrix} \tag{1}$$

Mixing in the quark basis(QBM). The parametrization of the decay constants look simpler in another basis, where the two independent axial-vector currents are taken as [4]

$$J^q_{\mu 5} = \frac{1}{\sqrt{2}}(\bar{u}\gamma_\mu\gamma_5 u + \bar{d}\gamma_\mu\gamma_5 d)$$
$$J^s_{\mu 5} = \bar{s}\gamma_\mu\gamma_5 s \tag{2}$$

In this scheme η, η' mixing is defined as

$$\begin{pmatrix} \eta \\ \eta' \end{pmatrix} = \begin{pmatrix} \cos\varphi - \sin\varphi \\ \sin\varphi \cos\varphi \end{pmatrix} \begin{pmatrix} \eta_q \\ \eta_s \end{pmatrix} \quad (3)$$

where $\eta_q = \frac{u\bar{u}+d\bar{d}}{\sqrt{2}}, \eta_s = s\bar{s}$.
The numerical value for mixing angle φ varies as $\varphi = 30^\circ \div 45^\circ$ in different approaches [3].

This scheme can be generalized to the $q\bar{q} - s\bar{s} - c\bar{c}$ basis. One can assume behavior for decay constants of $\eta - \eta' - \eta_c$ to be the similar that one in $q\bar{q} - s\bar{s}$ basis. Then we can write:

$$\begin{pmatrix} f^q_\eta & f^s_\eta & f^c_\eta \\ f^q_{\eta'} & f^s_{\eta'} & f^c_{\eta'} \\ f^q_{\eta_c} & f^s_{\eta_c} & f^c_{\eta_c} \end{pmatrix} = U(\varphi, \theta_y, \theta_c) diag(f_q, f_s, f_c) \quad (4)$$

where $\eta_c = c\bar{c}$. The transformation matrix now involves three angles:

$$U(\varphi, \theta_y, \theta_c) = \begin{pmatrix} \cos\varphi & -\sin\varphi & -\theta_c \sin\theta_y \\ \sin\varphi & \cos\varphi & \theta_c \cos\ \theta_y \\ -\theta_c \sin(\varphi - \theta_y) & -\theta_c \cos(\varphi - \theta_y) & 1 \end{pmatrix} \quad (5)$$

There terms of order θ_c^2 were neglected, since the mixing between $\eta - \eta'$ and η_c is an effect of the order of $\frac{1}{M^2_{\eta c}}$. So we have

$$UU^\dagger = 1 + O(\theta_c^2)$$

The two new mixing angles are related with decay constants of $c\bar{c}$

$$f^c_\eta = -f_{\eta_c}\theta_c \sin\theta_y; \quad f^c_{\eta'} = f_{\eta_c}\theta_c \cos\theta_y$$

3 Two-photon decays and η, η' mixing parameters.

The constant of two-photon decay $P \to \gamma\gamma$ is a very important source of information about η, η' mixing. We can use the experimental data about η, η' decays to fix numerical values of mixing angles φ,θ_c and θ_y.

Analytical expressions for radiative η, η' decay constants in the case of $q\bar{q} - s\bar{s}$ was obtained in QCM [11]both in OSM and QBM in our previous work [10].

In the QBM approach the decay constants were received [10]as

$$g_{\eta\gamma\gamma}(\varphi) = \frac{\sqrt{3h_\eta(\varphi)}}{\pi}(\frac{1}{\sqrt{2}} \cdot \frac{5}{9} \cdot F_{PVV}(m_\eta^2, 0, 0, \Lambda_n) \cdot \cos\varphi - -\frac{1}{9} \cdot F_{PVV}(m_\eta^2, 0, 0, \Lambda_s) \cdot \sin\varphi) \quad (6)$$

$$g_{\eta'\gamma\gamma}(\varphi) = \frac{\sqrt{3h_{\eta'}(\varphi)}}{\pi}(\frac{1}{\sqrt{2}} \cdot \frac{5}{9} \cdot F_{PVV}(m_{\eta'}^2, 0, 0, \Lambda_n) \cdot \sin\varphi + +\frac{1}{9} \cdot F_{PVV}(m_{\eta'}^2, 0, 0, \Lambda_s) \cdot \cos\varphi) \quad (7)$$

The structure integral $F_{PVV}(m^2, 0, 0, \Lambda)$ in (6),(7) arise from triangle diagram with $i\gamma_5$,γ^μ, γ^ν vertexes.

In the case of $q\bar{q} - s\bar{s} - c\bar{c}$ basis $g_{\eta\gamma\gamma}$,$g_{\eta'\gamma\gamma}$ and $g_{\eta_c\gamma\gamma}$ are written as:

$$g_{\eta\gamma\gamma} = \frac{\sqrt{3h_\eta(\varphi, \theta_c, \theta_y)}}{\pi}(\frac{1}{\sqrt{2}}\frac{5}{9}g_{P_{q\bar{q}}\to\gamma\gamma}(m_\eta^2, \varphi, \theta_c, \theta_y)\cos\varphi - -\frac{1}{9}g_{P_{s\bar{s}}\to\gamma\gamma}(m_\eta^2, \varphi, \theta_c, \theta_y)\sin\varphi - \frac{5}{9}\theta_c \sin\theta_y g_{P_{c\bar{c}}\to\gamma\gamma}(m_\eta^2, \varphi, \theta_c, \theta_y)) \quad (8)$$

$$g_{\eta'\gamma\gamma} = \frac{\sqrt{3h_{\eta'}(\varphi, \theta_c, \theta_y)}}{\pi}(\frac{1}{\sqrt{2}}\frac{5}{9}g_{P_{q\bar{q}}\to\gamma\gamma}(m_{\eta'}^2, \varphi, \theta_c, \theta_y)\sin\varphi + +\frac{1}{9}g_{P_{s\bar{s}}\to\gamma\gamma}(m_{\eta'}^2, \varphi, \theta_c, \theta_y)\cos\varphi + \frac{5}{9}\theta_c \cos\theta_y g_{P_{c\bar{c}}\to\gamma\gamma}(m_{\eta'}^2, \varphi, \theta_c, \theta_y)) \quad (9)$$

$$g_{\eta_c\gamma\gamma} = \frac{\sqrt{3h_{\eta_c}(\varphi, \theta_c, \theta_y)}}{\pi}(-\frac{1}{\sqrt{2}}\frac{5}{9}g_{P_{q\bar{q}}\to\gamma\gamma}(m_\eta^2, \varphi, \theta_c, \theta_y)\theta_c \sin(\varphi - \theta_y) + +\frac{1}{9}g_{P_{s\bar{s}}\to\gamma\gamma}(m_\eta^2, \varphi, \theta_c, \theta_y)\theta_c \cos(\varphi - \theta_y) + \frac{5}{9}g_{P_{c\bar{c}}\to\gamma\gamma}(m_\eta^2, \varphi, \theta_c, \theta_y)) \quad (10)$$

The $g_{P_{q\bar{q}}}, g_{P_{s\bar{s}}}, g_{P_{c\bar{c}}}$ are the constants of two photon decays of P-states with the corresponding quark contents. The QCM failed in description of heavy quarks, so in the present work we use the Relativistic Constituent Quark Model (RCQM)[12] for description of the hadronic interactions of η mesons.

4 Relativistic Constituent Quark Model

The hadronic interactions will be described in the Relativistic Constituent Quark Model (RCQM)[12].This model is based on the effective interaction Lagrangian which describes the coupling of hadrons with their constituent quarks:

$$L_{int}(x) = g_H H(x) \int dx_1 \int dx_2 \Phi_H(x, x_1, x_2) \bar{q}(x_1) \Gamma_H \lambda_H q(x_2). \tag{11}$$

Here λ_H and Γ_H are Gell-Mann and Dirac matrices,respectively, which entail the flavor and spin quantum numbers of the hadron H. The function $\Phi_H$is related to the scalar part of Bete-Salpeter amplitude and characterizes the finite size of hadron.In order to provide Lorence invariance of Lagrangian (11)Φ_H have to be invariant under transition $\Phi_H(x + a, x_1 + a, x_2 + a) = \Phi_H(x, x_1, x_2)$.

In the case of an arbitrary pair of quarks with different masses Φ_H is given by

$$\Phi_H(x, x_1, x_2) = \delta(x - \frac{m_1 x_1 + m_2 x_2}{m_1 + m_2}) f((x_1 - x_2)^2). \tag{12}$$

The choice of vertex function $f((x_1 - x_2)^2)$ will be specified after transition to momentum space.

Let us consider meson mass function, defined by the diagram in Fig.1.

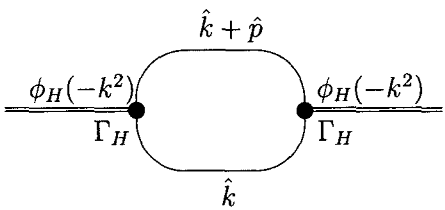

Fig.1

$$\Pi_H(x-y) = \int dx_1 \int dx_2 \Phi_H(x,x_1,x_2) \int dy_1 \int dy_2 \Phi_H(y,y_1,y_2) \cdot \cdot Tr\{S(y_1-x_1)\Gamma_H S(x_2-y_1)\Gamma_H\}. \quad (13)$$

The Fourier-transform of meson mass-function (13) is

$$\tilde{\Pi}_H(p) = \int e^{-ipx}\Pi_H(x)dx = = \int \frac{dq}{(2\pi)^4} \int \frac{dk_1}{(2\pi)^4} \int \frac{dk_2}{(2\pi)^4} \tilde{\Phi}_H(-p,k_1,k_2)\tilde{\Phi}_H(q,-k_1,k_2) Tr\{S(\hat{k}_1)\Gamma_H S(\hat{k}_2)\Gamma_H\}.$$

and finally can be written as

$$\tilde{\Pi}_H(p) = \int \frac{dk}{(2\pi)^4}\phi_H^2(k,p) Tr\{S(\hat{k}+\hat{p})\Gamma_H S(\hat{k})\Gamma_H\} \quad (14)$$

We assume that the vertex function ϕ_H depends only on the loop momentum k. The function ϕ_H is assumed to be the analytical function which decreases sufficiently fast in the Euclidean momentum space. In this work we employ a Gaussian form for the vertex function $\phi_H(k) = \exp(-k^2/\Lambda_H^2)$.The size parameters Λ_H were determined by fit to experimental data or lattice simulations [13]. We use local quark propagators

$$S_i(\hat{k}) = \frac{1}{m_i - \hat{k}} \quad (15)$$

where m_i is the constituent quark mass. As it discussed in [12], we assume that $m_H < m_{q_1} + m_{q_2}$ in order to avoid the appearance the of imaginary parts in the physical amplitudes. The fit values for the constituent quark masses are taken from [13] and are given as

m_u	m_s	m_c
0.235 (GeV)	0.333 (GeV)	1.67 (Gev)

The coupling constants g_H are determined by the co called compositeness condition [14] and had been used in QCM [11]. It means that the renormalization constant of the meson field is equal to zero

$$Z_M = 1 - \frac{3g_H^2}{4\pi^2}\tilde{\Pi}'_H(m_H^2) = 0, \quad (16)$$

where $\tilde{\Pi}'_H(p)$ is the derivative of the mass function (14). It is convenient to use interaction constant in a form:

$$h_H = \frac{3g_H^2}{4\pi^2} = \frac{1}{\tilde{\Pi}'_H(m_H^2)} \quad (17)$$

instead of g_H in the further calculations.

5 Mixing parameters of η, η', η_c - mesons in $q\bar{q} - s\bar{s} - c\bar{c}$ basis.

As it was mentioned above, one has the opportunity to fix the η, η', η_c mixing angles by using the experimental data about the two photon decays of this mesons.

The experimental values of widths of this decays are

$$\begin{aligned} W(\eta \to \gamma\gamma) &= (0.46 \pm 0.04) KeV[15] \\ W(\eta' \to \gamma\gamma) &= (4.27 \pm 0.19) KeV[15] \\ W(\eta_c \to \gamma\gamma) &= (26.97 \pm 2.97) KeV[16] \end{aligned} \quad (18)$$

The matrix element of $\eta, \eta', \eta_c \to \gamma\gamma$ is defined by the diagram in Fig.2 and can be written as

$$A(P \to \gamma\gamma) = e^2 g_{P\gamma\gamma} \varepsilon^{\mu\nu\alpha\beta} \epsilon^\mu(q_1) \epsilon^\nu(q_2). \quad (19)$$

$g_{P\gamma\gamma}$ are just the decay constants from (8)-(10).

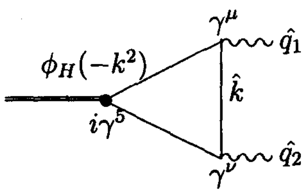

Fig.2

In RCQM $g_{P_{q\bar{q}}}, g_{P_{s\bar{s}}}, g_{P_{c\bar{c}}}$ from (8)-(10) are defined by loop integral

$$g_{P_{q\bar{q}} \to \gamma\gamma} = \int \frac{d^4k}{4\pi^2 i} \phi_P(-\frac{k^2}{\Lambda_P^2}) Tr[\gamma^5 S_q((\hat{k} - \hat{q}_2)\gamma^\mu S_q((\hat{k})\gamma^\nu S_q((\hat{k} + \hat{q}_1)] \quad (20)$$

Using integration technique in detailed described in [16],one then arrives at the following analytical representation of $g_{P_{q_i\bar{q}_i}}$ $(q_i = q, s, c)$

$$g_{P_{q_i\bar{q}_i}\to\gamma\gamma} = m_{q_i}\int_0^\infty dt(\frac{t}{t+1})^2\int_0^1 d^3\alpha\delta(1-\sum_{i=1}^{3}\alpha_i)(-\phi'_P(z_0)), \qquad (21)$$

where

$$z_0 = t(m_{q_i}^2 - \alpha_1\alpha_2 p^2) - \frac{t}{1+t}\alpha_1\alpha_2 p^2$$

The coupling constants $h_\eta, h_{\eta'}, h_{\eta_c}$ are defined by (17), with $\Pi_{\eta,\eta'}$

$$\Pi_\eta(m_\eta^2) = \Pi(m_\eta^2, m_q)\cos^2\varphi + \Pi(m_\eta^2, m_s)\sin^2\varphi + \Pi(m_\eta^2, m_c)\theta_c^2\sin^2\theta_y, \quad (22)$$

$$\Pi_{\eta'}(m_{\eta'}^2) = \Pi(m_{\eta'}^2, m_q)\sin^2\varphi + \Pi(m_{\eta'}^2, m_s)\cos^2\varphi + \Pi(m_{\eta'}^2, m_c)\theta_c^2\cos^2\theta_y \quad (23)$$

$$\Pi_{\eta_c}(m_{\eta_c}^2) = \Pi(m_{\eta_c}^2, m_q)(\theta_c\sin(\varphi-\theta_y))^2 + \Pi(m_{\eta_c}^2, m_s)(\theta_c\cos(\varphi-\theta_y))^2 + \Pi(m_\eta^2, m_c), \quad (24)$$

Mass functions $\Pi(p^2, m_q)$ in the case of pseudoscalars can be written according to (14)

$$\Pi(p^2, m_q) = \int\frac{dk}{(2\pi)^4}\phi_P^2(-\frac{k^2}{\Lambda_P^2})Tr\{S_q(\hat{k}+\hat{p})i\gamma^5 S_q(\hat{k})i\gamma^5\} \qquad (25)$$

The derivative of mass function $\Pi(p^2, m_q)$ can be received as

$$\frac{d}{dp^2}\Pi(p^2, m_q)|_{p^2=m_H^2} = \frac{1}{2}\int_0^\infty dt(\frac{t}{t+1})^2\int_0^1 d\alpha F(\alpha, t) \qquad (26)$$

where

$$F(\alpha,t) = \phi_H^2(z)\tfrac{1}{1+t}(4 - 3\tfrac{\alpha t}{1+t}) - -(\phi_H^2(z))'\{2m_q^2 + \tfrac{\alpha t}{1+t}[m_H^2 - m_q^2] - m_H^2(\tfrac{\alpha t}{1+t})^2(2 - \tfrac{\alpha t}{1+t})\}$$

with

$$z = t(m_q^2 - \alpha(1-\alpha)m_H^2) - \frac{\alpha^2 t}{1+t}m_H^2 \qquad (27)$$

The decay width of two photon decay of pseudoscalar meson is written in standard form

$$W(P\to\gamma\gamma) = \frac{\pi}{4}m_P^3\alpha^2 g_{P\gamma\gamma}^2 \qquad (28)$$

To define mixing angles we have calculated $g_{P\to\gamma\gamma}$ for η, η', η_c as described above and have used the experimental values for $g^{exp}_{\eta,\eta',\eta_c\to\gamma\gamma}$ extracted from (18) by (28). So, the following numerical values were received

$$\varphi = 33.1°; \theta_c = -1.1°; \theta_y = 51.3° \tag{29}$$

Now using the above values for the mixing angles φ, θ_y and θ_c we can find for quark content of the physical mesons

$$\begin{aligned} \eta\rangle &= 0.72\eta_q\rangle - 0.65\eta_s\rangle - 0.005\eta_c\rangle \\ \eta'\rangle &= 0.65\eta_q\rangle + 0.72\eta_s\rangle - 0.016\eta_c\rangle \\ \eta_c\rangle &= 0.012\eta_q\rangle + 0.009\eta_s\rangle + 0.005\eta_c\rangle \end{aligned} \tag{30}$$

6 Radiative decays of η, η' mesons.

Let us calculate the constants of $V \to P\gamma$ and $P \to V\gamma$ ($P \equiv \eta, \eta'$; $V \equiv \rho, \omega, \phi$)decays using the mixing parameters received in previous section.

The decay amplitudes are defined as

$$A(V \to P\gamma) = eg_{VP\gamma}\varepsilon^{\mu\nu\alpha\beta}\epsilon^{\mu}(p_V)\epsilon^{\nu}(q_\gamma)q^{\alpha}_{\gamma}p^{\beta}_{V} \tag{31}$$

$$A(P \to V\gamma) = eg_{PV\gamma}\varepsilon^{\mu\nu\alpha\beta}\epsilon^{\mu}(q_\gamma)\epsilon^{\nu}(p_V)q^{\alpha}_{\gamma}p^{\beta}_{V} \tag{32}$$

and the corresponding decay widths are

$$W(P \to V\gamma) = m_V^3 \alpha g^2_{PV\gamma} \tag{33}$$

$$W(V \to P\gamma) = \frac{1}{3} m_p^3 \alpha g^2_{VP\gamma} \tag{34}$$

The following expressions for decay constants were received :

$$g_{\eta\rho\gamma} = \sqrt{h_\rho h_\eta(\varphi, \theta_c, \theta_y)} \cos\varphi g_{PV\gamma}(m^2_\eta, m^2_\rho, 0, mq) \tag{35}$$

$$g_{\eta'\rho\gamma} = \sqrt{h_\rho h_{\eta'}(\varphi, \theta_c, \theta_y)} \sin\varphi g_{PV\gamma}(m^2_{\eta'}, m^2_\rho, 0, mq) \tag{36}$$

$$g_{\eta\omega\gamma} = \sqrt{h_\omega h_\eta(\varphi, \theta_c, \theta_y)} \cos\varphi \frac{1}{3} g_{PV\gamma}(m^2_\eta, m^2_\omega, 0, mq) \tag{37}$$

$$g_{\eta'\omega\gamma} = \sqrt{h_\omega h_{\eta'}(\varphi, \theta_c, \theta_y)} \sin\varphi \frac{1}{3} g_{PV\gamma}(m^2_{\eta'}, m^2_\omega, 0, m_q) \tag{38}$$

$$g_{\eta\phi\gamma} = \sqrt{h_\phi h_\eta(\varphi,\theta_c,\theta_y)}\sin\varphi\frac{2}{3}g_{PV\gamma}(m_\eta^2,m_\phi^2,0,m_s) \quad (39)$$

$$g_{\eta'\phi\gamma} = \sqrt{h_\phi h_{\eta'}(\varphi,\theta_c,\theta_y)}\cos\varphi\frac{2}{3}g_{PV\gamma}(m_{\eta'}^2,m_\phi^2,0,m_s) \quad (40)$$

The analytical expression for function $g_{PV\gamma}(m_P^2,m_V^2,0,m_q)$ in (35)- (40) can be received by evacuation of one loop integral as described in previous section. The numerical values for $V \to P\gamma$ and $P \to V\gamma$ decays are given in tables 1 and 2.

Table 1

$g_{V\eta\gamma}(GeV^{-1})$	Experiment [15]	$q\bar{q}-s\bar{s}-c\bar{c}$basis with $\varphi=33.1°;\theta_c=-1.1°;\theta_y=51.3°$
$g_{\rho\eta\gamma}$	$1.47+0.25-0.28$	1.51
$g_{\omega\eta\gamma}$	0.5 ± 0.04	0.51
$g_{\phi\eta\gamma}$	0.69 ± 0.02	0.72

Table 2

$g_{V\eta'\gamma}(GeV^{-1})$	Experiment [15]	$q\bar{q}-s\bar{s}-c\bar{c}$ basis with $\varphi=33.1°;\theta_c=-1.1°;\theta_y=51.3°$
$g_{\rho\eta'\gamma}$	1.31 ± 0.06	1.24
$g_{\omega\eta'\gamma}$	0.45 ± 0.03	0.37
$g_{\phi\eta'\gamma}$	1.00 ± 0.28	0.79

One can see that numerical results are in agreement with experimental data.

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