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MEASUREMENT OF THE PSEUDOSCALAR MIXING ANGLE AND THE η' GLUONIUM CONTENT WITH THE KLOE DETECTOR*

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In this paper the mixing angle and the η' gluonium content extraction from the R_ϕ =Br($\phi(1020) \to \eta'\gamma$)/Br($\phi(1020) \to \eta\gamma$) is updated. The η' gluonium content is estimated by fitting R_ϕ, together with radiative light vector to pseudoscalar gamma and pseudoscalar to vector transitions plus $\eta' \to \gamma\gamma$ and $\pi^0 \to \gamma\gamma$ decays. The extracted parameters are the gluonium fraction $Z_G^2 = 0.11 \pm 0.04$ and the pseudoscalar mixing angle $\varphi_P = (40.7 \pm 0.7)^\circ$.

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1. Introduction

The η' meson, being a pure SU(3) singlet, has been considered for years the meson within which a gluon condensate contribution can show up. The η and η' mixing angle and the presence of a gluonium component in the η' meson has been investigated strongly in the past, but it is still without a definitive conclusion [1].

In this paper we extract the η' gluonium content and the η, η' mixing angle in the constituent quark model according the Rosner [2] approach and using the wave function spatial overlapping parameters introduced by

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Bramon *et al.* [3]. In particular the same method used in Escribano *et al.* [4] is used, but also the $\pi^0 \to \gamma\gamma$ and $\eta' \to \gamma\gamma$ branching fraction are fitted according the prescriptions from Kou [5]. This method is chosen because it relates our measurement of $R_\phi = \mathrm{Br}(\phi \to \eta'\gamma)/\mathrm{Br}(\phi \to \eta\gamma)$ [6] to the η' gluonium content and the η, η' mixing angle.

Following the approach from [2,4] the η and η' wave functions can be decomposed in three terms: the u, d quark wave function $|q\bar{q}\rangle = 1/\sqrt{2}\,(|u\bar{u}\rangle + \left|d\bar{d}\right\rangle)$, the strange component $|s\bar{s}\rangle$ and the gluonium $|\mathrm{glue}\rangle$. The wave functions are written as:

$$\begin{aligned} |\eta'\rangle &= \cos(\varphi_G)\sin(\varphi_P)|q\bar{q}\rangle + \cos(\varphi_G)\cos(\varphi_P)|s\bar{s}\rangle + \sin(\varphi_G)|\mathrm{glue}\rangle\,, \\ |\eta\rangle &= \cos(\varphi_P)|q\bar{q}\rangle - \sin(\varphi_P)|s\bar{s}\rangle\,, \end{aligned}$$

where φ_P is the η, η' mixing angle and $Z_G^2 = \sin^2\varphi_G$ is the gluonium fraction in the η' meson. The ratio of the two branching ratios: $R_{\phi(1020)} = \mathrm{Br}(\phi(1020) \to \eta'\gamma)/\mathrm{Br}(\phi(1020) \to \eta\gamma)$ is related to the φ_P and φ_G parameters by the formula:

$$R_{\phi(1020)} = \cot^2(\varphi_P)\cos^2(\varphi_G)\left(1 - \frac{m_s}{\bar{m}}\frac{Z_{\mathrm{NS}}}{Z_{\mathrm{S}}}\frac{\tan(\varphi_V)}{\sin(2\varphi_P)}\right)^2\left(\frac{p_{\eta'}}{p_\eta}\right)^3 . \tag{1}$$

In this formula $p_{\eta'}$ and p_η are the momenta of the η' and η meson respectively, $m_s/\bar{m} = 2m_s/(m_u + m_d)$ is the constituent quark masses ratio, Z_{NS} describes the spatial wave function overlapping between the $q\bar{q}$ component of the ω meson and η meson, and Z_{S} between the $s\bar{s}$ component of the η and $\phi(1020)$ meson, φ_V is the ω, $\phi(1020)$ mixing angle. In our previous paper [6] the parameters Z_{S}, Z_{NS}, φ_V and $m_s/\bar{m}$ were taken from Bramon *et al.* [7] in which the $\mathrm{Br}\,(\phi(1020) \to \eta'\gamma)$ and $\mathrm{Br}\,(\phi(1020) \to \eta\gamma)$ were fitted together with other light $V \to P\gamma$ decays (V indicates the vector mesons ρ, ω, $\phi(1020)$ and P the pseudoscalars π^0, η, η').

We fitted [6] the ratio $R_{\phi(1020)}$ from our measurement

$$R_{\phi(1020)} = \frac{\mathrm{Br}\,(\phi(1020) \to \eta'\gamma)}{\mathrm{Br}\,(\phi(1020) \to \eta\gamma)} = (4.77 \pm 0.09_{\mathrm{stat}} \pm 0.19_{\mathrm{syst}}) \times 10^{-3}$$

together with the available data [8] on $\Gamma(\eta' \to \gamma\gamma)/\Gamma(\pi^0 \to \gamma\gamma)$, $\Gamma(\eta' \to \rho\gamma)/\Gamma(\omega \to \pi^0\gamma)$ and $\Gamma(\eta' \to \omega\gamma)/\Gamma(\omega \to \pi^0\gamma)$. The dependence of these ratios from the mixing angle φ_P and the gluonium content φ_G is given by the following equations:

$$\frac{\Gamma(\eta' \to \gamma\gamma)}{\Gamma(\pi^0 \to \gamma\gamma)} = \frac{1}{9}\left(\frac{m_{\eta'}}{m_{\pi^0}}\right)^3\left(5\cos\varphi_G\sin\varphi_P + \sqrt{2}\frac{f_q}{f_s}\cos\varphi_G\cos\varphi_P\right)^2 , \tag{2}$$

$$\frac{\Gamma(\eta' \to \rho\gamma)}{\Gamma(\omega \to \pi^0\gamma)} = 3\frac{Z_{\rm NS}^2}{\cos^2(\varphi_V)}\left(\frac{m_{\eta'}^2 - m_\rho^2}{m_\omega^2 - m_\pi^2}\frac{m_\omega}{m_{\eta'}}\right)X_{\eta'}^2\,, \tag{3}$$

$$\frac{\Gamma(\eta' \to \omega\gamma)}{\Gamma(\omega \to \pi^0\gamma)} = \frac{1}{3}\left(\frac{m_{\eta'}^2 - m_\omega^2}{m_\omega^2 - m_\pi^2}\frac{m_\omega}{m_{\eta'}}\right)^3\left[Z_{\rm NS}X_{\eta'} + 2\frac{m_s}{\bar{m}}Z_{\rm S}\,\tan\varphi_V Y_{\eta'}\right]^2. \tag{4}$$

The value of the parameters $Z_{\rm NS}$, $Z_{\rm S}$, φ_V, $m_s/\bar{m}$ were taken from [7] obtaining $\varphi_P = (39.7\pm0.7)^\circ$ and $Z_G^2 = \sin^2\varphi_G = 0.14\pm0.04$, $P(\chi^2) = 49\%$. Imposing $\varphi_G = 0$ the χ^2 probability of the fit decreases to 1 %.

In Escribano *et al.* [4] a similar procedure to the one of [7] was followed taking into account also the possibility of having a gluonium content. They find $Z_G^2 = 0.04 \pm 0.09$ that deviates of 1 σ from our result but with a larger error.

In Escribano *et al.* [4] and Thomas [9] this difference was attributed to the use in our fit of overlapping parameters obtained by a fit which assumes no gluonium content [7]. In order to check this hypothesis we performed [10] several tests on the fit procedure showing good stability of the result respect to the overlapping parameters choice.

In this paper we perform a global fit to the Vector to Pseudoscalar gamma, Pseudoscalar to Vector gamma and $\eta' \to \gamma\gamma$ transition in order to determine the gluonium content, all relevant parameters and to identify the experimental measurement that requires the presence of a gluonium component in the η' meson. To this extent we add to the constraints (2–4) the following further relations that can be derived directly from [4]:

$$\begin{aligned}
\frac{\Gamma(\omega \to \eta\gamma)}{\Gamma(\omega \to \pi^0\gamma)} &= \frac{1}{9}\left[Z_{\rm NS}\,\cos(\varphi_P) - 2\frac{m_s}{\bar{m}}Z_{\rm S}\tan(\varphi_V)\sin(\varphi_P)\right]^2 \\
&\quad\times\cos^2(\varphi_G)\left(\frac{m_\omega^2 - m_\eta^2}{m_\omega^2 - m_{\pi^0}^2}\right)^3, \\
\frac{\Gamma(\rho \to \eta\gamma)}{\Gamma(\omega \to \pi^0\gamma)} &= Z_{\rm NS}^2\,\frac{\cos^2(\varphi_P)}{\cos^2(\varphi_V)}\left(\frac{m_\rho^2 - m_\eta^2}{m_\omega^2 - m_{\pi^0}^2}\frac{m_\omega}{m_\rho}\right)^3, \\
\frac{\Gamma(\phi \to \eta\gamma)}{\Gamma(\omega \to \pi^0\gamma)} &= \frac{1}{9}\left[Z_{\rm NS}\tan(\varphi_V)\cos(\varphi_P) + 2\frac{\bar{m}}{m_s}Z_{\rm S}\sin(\varphi_P)\right]^2 \\
&\quad\times\left(\frac{m_\phi^2 - m_\eta^2}{m_\omega^2 - m_{\pi^0}^2}\frac{m_\omega}{m_\phi}\right)^3, \\
\frac{\Gamma(\phi \to \pi^0\gamma)}{\Gamma(\omega \to \pi^0\gamma)} &= \tan^2\varphi_V\,\left(\frac{m_\phi^2 - m_{\pi^0}^2}{m_\omega^2 - m_{\pi^0}^2}\frac{m_\omega}{m_\phi}\right)^3,
\end{aligned}$$

$$\frac{\Gamma(K^{+*} \to K^+\gamma)}{\Gamma(K^{*0} \to K^0\gamma)} = \left(\frac{2(m_s/\bar{m}) - 1}{1 + (m_s/\bar{m})}\right)^2 \left(\frac{m^2_{K^{*+}} - m^2_{K^+}}{m^2_{K^{*0}} - m^2_{K^0}} \frac{m_{K^{*0}}}{m_{K^{*+}}}\right)^3 .$$

Note that, differently than [4] where the $VP\gamma$ couplings are fitted, we fit directly the partial decay width ratios. This allows on one hand to reduce the parameters involved in the fit (they cancel out in the ratios), and on the other hand to use quantities directly linked to the experimental measurements (branching ratios and decay widths). In fact, in the fit, a ratio of $\Gamma's$ is written as:

$$\frac{\Gamma(\eta' \to \rho\gamma)}{\Gamma(\omega \to \pi^0\gamma)} = \frac{\mathrm{Br}\,(\eta' \to \rho\gamma)}{\mathrm{Br}\,(\omega \to \pi^0\gamma)} \frac{\Gamma_{\eta'}}{\Gamma_\omega} .$$

In this way the correlation matrix among the η' branching ratios (B^{exp}) and the decay widths can be directly used. The fit is performed minimizing a χ^2 function defined as in the following:

$$\chi^2 = \sum_{i,j=1}^{n_{\mathrm{measurements}}} \left(y_i - y_i^{\mathrm{th}}\right) V_{ij}^{-1} \left(y_j - y_j^{\mathrm{th}}\right) ,$$

where V_{ij}^{-1} is the inverse of the covariance matrix obtained summing the contribution from the experimental error on branching ratios, decay widths and their correlations, and the uncertainty coming from theoretical inputs. Differently from the first KLOE fit, where the parameters f_q, f_s, Z_{S}, Z_{NS}, φ_V and $m_s/\bar{m}$ were used in the fit, in this fit procedure only the parameters f_q and f_s are taken as input, they involve only the $\Gamma(\eta' \to \gamma\gamma)/\Gamma(\pi^0 \to \gamma\gamma)$ ratio. The contribution from theoretical error is evaluated by standard error propagation:

$$B^{\mathrm{th}} = A \times C \times A^{\mathrm{T}} ,$$

where C is the covariance matrix of the uncorrelated parameters f_q and f_s and A is the matrix of the derivatives:

$$A_i = \begin{pmatrix} \frac{\partial y_i^{\mathrm{th}}}{\partial f_q} & \frac{\partial y_i^{\mathrm{th}}}{\partial f_s} \end{pmatrix} .$$

The covariance matrix V is indeed:

$$V = B^{\mathrm{exp}} + B^{\mathrm{th}} .$$

The covariance matrix B^{exp} contains the error matrix of the used experimental variable. Particularly interesting is the covariance matrix of the η' branching fractions and the decay width shown in the Table I. From the table large correlations among the measurements are evident. Particularly interesting is the 88% correlation coefficient between the η' width and the

TABLE I

η' branching ratios correlation matrix, from PDG-2006 [8].

$\rho\gamma$	0.34					
$\pi^0\pi^0\eta$	−0.78	−0.29				
$\omega\gamma$	−0.35	−0.24	0.32			
$\gamma\gamma$	−0.26	−0.12	0.26	0.08		
$3\pi^0$	−0.28	−0.11	0.35	0.11	0.09	
$\Gamma_{\eta'}$	0.32	−0.02	−0.24	−0.05	−0.88	−0.08
	$\pi^+\pi^-\eta$	$\rho\gamma$	$\pi^0\pi^0\eta$	$\omega\gamma$	$\gamma\gamma$	$3\pi^0$

$\eta' \to \gamma\gamma$ branching ratio. This is because the η' width is obtained using the cross-section $\sigma(e^+e^- \to \eta' e^+e^-)$ that measures directly the partial width $\Gamma(\eta' \to \gamma\gamma)$ and the η' width is extracted using the $\eta' \to \gamma\gamma$ branching ratio. The matrices C, A and $B^{\rm th}$ depend on the parameters of the fit. They are, therefore, re-computed at each minimization step. The fit results are shown in the Table II, left column. The gluonium component is at $2.8\,\sigma$ from zero. In order to understand what measurement requires the presence of the gluonium in the η' we have repeated the fit fixing the gluonium fraction (Z_G^2) at zero. The results of the fit are shown in the Table II, right column. The χ^2 probability is now quite low, reflecting the 2.8 σ effect of the previous fit, while the pseudoscalar mixing angle is quite stable. In Fig. 1 we show the pulls of the two fits. The pull for each ratio i (pl_i) is defined as $pl_i = (y_{i\rm measure} - y_{i\rm fit}^{\rm th})/\sigma_{y_{i\rm measure}}$. The pulls study shows that the measurement which does not fit in the *no-gluonium* picture is the ratio $\Gamma(\eta' \to \gamma\gamma)/\Gamma(\pi^0 \to \gamma\gamma)$. The pull of this quantity is greater than 3, bringing the χ^2 probability to 1.1 % in the *no-gluonium* hypothesis, and is ~ 1 in the *gluonium* hypothesis. Therefore, the origin of the discrepancy with the

TABLE II

Fit results.

	Gluonium allowed	Gluonium at zero
$\chi^2/n.d.f$(Prob)	5/3 (17.5 %)	13/4 (1.1 %)
Z_G^2	0.105 ± 0.037	0 fixed
φ_P	$(40.7 \pm 0.7)^\circ$	$(41.6 \pm 0.5)^\circ$
$Z_{\rm NS}$	0.866 ± 0.025	0.863 ± 0.024
$Z_{\rm S}$	0.79 ± 0.05	0.78 ± 0.05
φ_V	$(3.15 \pm 0.10)^\circ$	$(3.17 \pm 0.10)^\circ$
$m_s/\bar{m}$	1.24 ± 0.07	1.24 ± 0.07

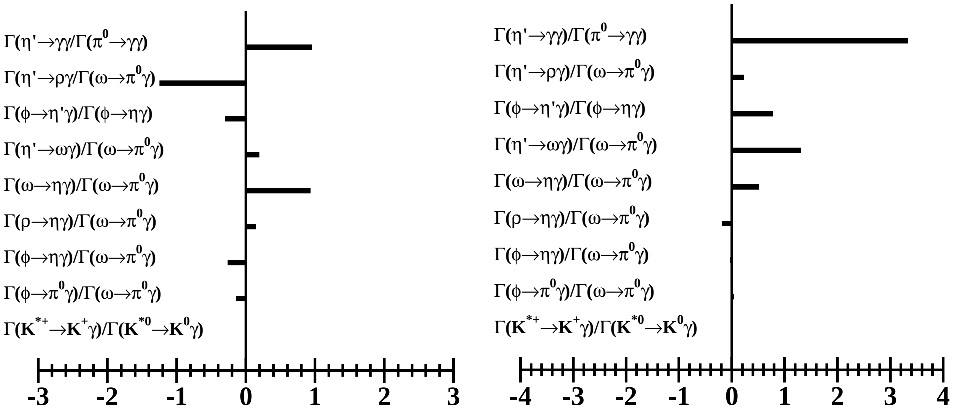

Fig. 1. Pulls of the fit to the ratio of Γ's, left-hand side gluonium fitted, right-hand side gluonium fixed at zero.

Escribano *et al.* paper [4] is the presence of the $\Gamma(\eta' \to \gamma\gamma)/\Gamma(\pi^0 \to \gamma\gamma)$ constraint in our fit. Leaving free the Z_{S} and Z_{NS} parameters does not change substantially the result. We have also repeated the fit without using the $\eta' \to \gamma\gamma/\pi^0\gamma\gamma$ constraint. The result is shown in the Table III, first column compared with Ref. [4] results (second column).

The result of the fit are in agreement making evident that the origin of the difference is due to the $\eta' \to \gamma\gamma/\pi^0 \to \gamma\gamma$ measurement.

TABLE III

Comparison among the fit results without the $\eta' \to \gamma\gamma/\pi^0 \to \gamma\gamma$ measurement and the Escribano *et al.* results.

	Fit with width ratios	Escribano *et al.*, *JHEP* **05**, 6 (2007)	Fit with couplings
$\chi^2/n.d.f$(Prob)	1.8/2 (41 %)	4.2/4 (38 %)	4.7/4 (32 %)
Z_G^2	0.03 ± 0.06	0.04 ± 0.09	0.04 ± 0.07
φ_G	$(10 \pm 10)^\circ$	$(12 \pm 13)^\circ$	$(11 \pm 11)^\circ$
φ_P	$(41.6 \pm 0.8)^\circ$	$(41.4 \pm 1.3)^\circ$	$(41.5 \pm 1.1)^\circ$
Z_{NS}	0.85 ± 0.03	0.86 ± 0.03	0.86 ± 0.03
Z_{S}	0.78 ± 0.05	0.79 ± 0.05	0.78 ± 0.05
φ_V	$(3.16 \pm 0.10)^\circ$	$(3.2 \pm 0.1)^\circ$	$(3.18 \pm 0.10)^\circ$
$m_s/\bar{m}$	1.24 ± 0.07	1.24 ± 0.07	1.24 ± 0.07
Z_K		0.89 ± 0.03	0.89 ± 0.03
g		0.72 ± 0.01	0.72 ± 0.01

2. Fit to the couplings

In the Escribano *et al.* paper [4] the couplings among the vectors and the pseudoscalars are used instead of the width ratio. In order to make a full comparison between the two methods we have performed the fit again using the couplings. The couplings are related to the partial decay widths of the Vector to Pseudoscalar gamma and Pseudoscalar to Vector gamma transitions by the formula [4]:

$$\Gamma(V \to P\gamma) = \frac{1}{3}\frac{g_{VP\gamma}^2}{4\pi}\,|\vec{p}_\gamma|^3\,, \qquad \Gamma(P \to V\gamma) = \frac{g_{VP\gamma}^2}{4\pi}\,|\vec{p}_\gamma|^3\,.$$

In this case no correlation among the measurements is taken into account and all measurements are taken form [8]. The results of the fit are shown in the Table III last column. The results are well compatible both with Escribano *et al.* and the fit to the width ratio showing that changing the formal approach does not change the result (as expected). If we add to all measurements the ratio $\Gamma(\eta' \to \gamma\gamma)/\Gamma(\pi^0 \to \gamma\gamma)$ we obtain the results showed in the Table IV. Comparing Table IV and Table II is possible to see that the fit results are almost unchanged. The significance of the fit is different. In particular the fit using the width ratios has a lower χ^2 probability in the hypothesis of null gluonium and an higher χ^2 probability in the gluonium hypothesis, indicating the higher sensitivity of the width ratio fit respect to the coupling fit. This is the outcome of the correct utilization of the full correlation matrix of the measured branching ratio and decay width in the first case respect to the second.

TABLE IV

Results of the fit with couplings adding the $\eta' \to \gamma\gamma/\pi^0 \to \gamma\gamma$ measurement.

	Without gluonium	With gluonium
$\chi^2/n.d.f$(Prob)	13/5 (2.3 %)	7.2/4 (13 %)
Z_G^2	fixed at 0	0.11 ± 0.05
φ_G	fixed at 0	$(20 \pm 4)^\circ$
φ_P	$(40.1 \pm 0.9)^\circ$	$(41.2 \pm 1.1)^\circ$
$Z_{\rm NS}$	0.85 ± 0.02	0.88 ± 0.03
$Z_{\rm S}$	0.80 ± 0.05	0.79 ± 0.05
φ_V	$(3.2 \pm 0.1)^\circ$	$(3.2 \pm 0.1)^\circ$
$m_s/\bar{m}$	1.24 ± 0.07	1.24 ± 0.07
Z_K	0.89 ± 0.03	0.89 ± 0.03
g	0.72 ± 0.01	0.72 ± 0.01

3. Conclusions

The origin of the discrepancy between the KLOE result and Escribano *et al.* [4] result is in the use of the $\eta' \to \gamma\gamma/\pi^0 \to \gamma\gamma$ measurement in the former approach. A global fit to all measured $V \to P\gamma$ and $P \to V\gamma$ transitions of light mesons has been performed extracting all the relevant parameters. The result of the fit is slightly different than the original KLOE result but it does not affect the statement of the presence of a significant gluonium contribution in the η' meson. The origin of this contribution has been also exploited showing that the $\eta' \to \gamma\gamma/\pi^0\gamma\gamma$ measurement is the only measurement that points for such a contribution. An updated fit with all recent measurements from PDG-2008 [11] and the recent KLOE measurement of the $\omega \to \pi^0\gamma$ branching ratio [12] is in progress.

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