Rare η and η' decays

Rafel Escribano,[1,2,*] Sergi Gonzàlez-Solís,[3,4,†] and Emilio Royo[1,2,‡]

[1] *Grup de Física Teòrica, Departament de Física, Universitat Autònoma de Barcelona, E-08193 Bellaterra (Barcelona), Spain*
[2] *Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Campus UAB, E-08193 Bellaterra (Barcelona), Spain*
[3] *Department of Physics, Indiana University, Bloomington, IN 47405, USA*
[4] *Center for Exploration of Energy and Matter, Indiana University, Bloomington, IN 47403, USA*

This Letter of Interest concentrates on the physics offered by the doubly radiative decays $\eta^{(\prime)} \to \pi^0\gamma\gamma$ and $\eta' \to \eta\gamma\gamma$ and the semileptonic decays $\eta^{(\prime)} \to \pi^0 l^+ l^-$ and $\eta' \to \eta l^+ l^-$ $(l = e, \mu)$.

Rare decays of the neutral η and η' pseudoscalar mesons provide a clean environment to test low-energy QCD while searching for new physics beyond the Standard Model (BSM) [1]. In this letter we focus on two physics channels. On the one hand, we study the doubly radiative decays $\eta^{(\prime)} \to \pi^0\gamma\gamma$ and $\eta' \to \eta\gamma\gamma$, which offer a perfect laboratory for testing Chiral Perturbation Theory, and its natural extensions, and extract relevant information on the properties of the lowest-lying scalar resonances, in particular, the isovector $a_0(980)$ from the two $\eta^{(\prime)} \to \pi^0\gamma\gamma$ processes and the isoscalars $\sigma(500)$ and $f_0(980)$ from the $\eta' \to \eta\gamma\gamma$ decay. On the other hand, we analyze the semileptonic decays $\eta^{(\prime)} \to \pi^0 l^+ l^-$ and $\eta' \to \eta l^+ l^-$, which are specially suited to search for new sources of C, P and CP violation.

$\eta^{(\prime)} \to \pi^0\gamma\gamma$ and $\eta' \to \eta\gamma\gamma$ decays

The $\eta \to \pi^0\gamma\gamma$ decay is one of the very rare meson decays in the Standard Model and has been a stringent test for the predictive power of ChPT. Within this framework, the tree-level contributions at $\mathcal{O}(p^2)$ and $\mathcal{O}(p^4)$ vanish because the pseudoscalar mesons involved are neutral. The first nonvanishing contribution comes at $\mathcal{O}(p^4)$, either from kaon loops, largely suppressed by their mass, or from pion loops, also suppressed since they violate G-parity and, therefore, are proportional to $m_u - m_d$. Quantitatively, Ametller *et al.* found in Ref. [2] that $\Gamma^{(4)}_{\pi} = 0.84 \times 10^{-3}$ eV, $\Gamma^{(4)}_{K} = 2.45 \times 10^{-3}$ eV and $\Gamma^{(4)}_{\pi+K} = 3.89 \times 10^{-3}$ eV for the π, K and π+K loop contributions to the decay width, which turns out to be two orders of magnitude smaller than the PDG value $\Gamma^{\rm exp}_{\eta\to\pi^0\gamma\gamma} = 0.334 \pm 0.028$ eV [3]. The first sizable contribution comes at $\mathcal{O}(p^6)$, but the associated low-energy constants are now well defined and one must resort to phenomenological models to fix them. To this end, for instance, Vector Meson Dominance (VMD) has been used to determine these coefficients by expanding the vector meson propagators and keeping the lowest term. Assuming equal contributions from the ρ and ω mesons, the authors of [2] found that $\Gamma^{(6)}_{\rho+\omega} = 0.18$ eV, which was about 2 times smaller than their "all-order" estimation with the full vector meson propagator, $\Gamma_{\rm VMD} = 0.31$ eV, and in reasonable agreement with older VMD estimates [4–7]. The situation improved after the works by Oset *et al.* [8, 9], which employed a chiral unitary approach for the meson-meson interaction including the contributions of the (dynamically generated) $a_0(980)$ resonance. Using this approach, they found a decay width 0.47 ± 0.10 eV and 0.33 ± 0.08 eV in their 2003 and 2008 works, respectively, and the discrepancy could be down to differences in the radiative decay widths of the vector mesons used as input in their calculations. In any case, both estimations appear to be in good agreement with the empirical value. In more recent analyses of this decay, dispersion-theoretical methods have been employed [10, 11] with fair agreement with data.

Experimental measurement of this decay have a history spanning more than five decades [12] (see [1] for an exhaustive discussion). All existing experimental results [13–17] were limited by large backgrounds from $\eta \to 3\pi^0$ leaking into the 4γ final state data sample and a nonresonant $2\pi^0$ continuum production. A new experiment with a significantly improved reduction in backgrounds would provide greatly reduced statistical and systematic uncertainties leading to a definitive result for the $\eta \to \pi^0\gamma\gamma$ decay width. More importantly, the two-photon invariant mass spectrum, $d\Gamma/dM_{\gamma\gamma}$, will provide key guidance for understanding the underlying dynamics. The approved JEF experiment at Jefferson Lab [18] will measure the branching ratio and the Dalitz distribution with $\sim 5\%$ precision. This would be sufficient to determine the scalar-VMD interference contribution and distinguish it from the VDM mechanism alone for the first time.

Likewise, the study of the $\eta' \to \pi^0\gamma\gamma$ and $\eta' \to \eta\gamma\gamma$ decays are of interest for several reasons. First, they complete existing calculations of the sister process $\eta \to \pi^0\gamma\gamma$. Second, the BESIII collaboration has recently reported the first

* rescriba@ifae.es
† sgonzal@iu.edu
‡ eroyo@ifae.es

measurements for these decays [19, 20], thus making them of timely interest. Third, the analysis of these processes could help extract relevant information on the properties of the lowest-lying scalar resonances, in particular the $a_0(980)$ from the $\eta' \to \pi^0\gamma\gamma$, and the isoscalar $\sigma(500)$ and $f_0(980)$ from the $\eta' \to \eta\gamma\gamma$. In Ref. [21], we have presented a thorough theoretical analysis of these two decays and provided, to the best of our knowledge, the first published calculations for their associated decay widths and diphoton energy spectra in terms of intermediate scalar and vector meson exchange contributions using the Linear Sigma Model and VMD frameworks, respectively. Our predictions, $\mathrm{BR}(\eta' \to \pi^0\gamma\gamma) = [2.91(21), 3.57(25)] \times 10^{-3}$ and $\mathrm{BR}(\eta' \to \eta\gamma\gamma) = [1.07(7), 1.17(8)] \times 10^{-4}$ (see [21] for details), are found to be in good agreement with recent measurements performed by BESIII, $\mathrm{BR}(\eta' \to \pi^0\gamma\gamma) = 3.20(7)(23) \times 10^{-3}$ and $\mathrm{BR}(\eta' \to \eta\gamma\gamma) = 8.25(3.41)(0.72) \times 10^{-5}$. It is worth highlighting that, while vector meson exchanges vastly dominate over the scalar contributions in $\eta' \to \pi^0\gamma\gamma$, for the $\eta' \to \eta\gamma\gamma$, the scalar meson effects turn out to be substantial, specially that of the σ meson, and this represents an opportunity for learning details about this (still poorly understood) scalar state. In particular, we thus look forward to the release of the energy spectrum data for the $\eta' \to \eta\gamma\gamma$ process by BESIII to asses the robustness of our theoretical approach.

$\eta^{(\prime)} \to \pi^0 l^+ l^-$ and $\eta' \to \eta l^+ l^-$ decays

The semileptonic $\eta^{(\prime)} \to \pi^0 l^+ l^-$ and $\eta' \to \eta l^+ l^-$ decays (with $l = e, \mu$) are of special interest given that they can be used as fine probes to asses if new physics BSM is at play. This is because any contribution from BSM physics ought to be relatively small and these decay processes only get a contribution from the SM through C-conserving exchange of two photons that is highly suppressed, as there is no contribution at tree-level but only corrections at one-loop and higher order. This small SM contribution would presumably be of the same order of magnitude as that of physics BSM, which, in turn, means that the η-η' phenomenology might play an interesting role and be an excellent arena for stress testing SM predictions [1, 22]. As a example, the $\eta^{(\prime)} \to \pi^0 l^+ l^-$ and $\eta' \to \eta l^+ l^-$ decays could be mediated by a single intermediate virtual photon, but this would entail that the electromagnetic interactions violate C-invariance and, therefore, would represent a departure from the SM.

On the experimental front, new upper limits have recently been established by the WASA-at-COSY collaboration for the $\eta \to \pi^0 e^+ e^-$ decay width [23], $\mathrm{BR}(\eta \to \pi^0 \mathrm{e}^+\mathrm{e}^-) < 7.5 \times 10^{-6}$ (CL=90%), while measurements for the other five processes date from decades back in time [3]. The experimental state of play is expected to be further improved in the near future with the advent of new experiments such as the REDTOP collaboration [24], which will focus on rare decays of the η and η' mesons, providing increased sensitivity in the search for violations of SM symmetries by several orders of magnitude beyond the current experimental state of the art.

On the theoretical side, a complete theoretical analysis of the SM C-conserving contribution to the six decay processes has recently been carried out within the framework of the Vector Meson Dominance model in [25]. The results presented in this paper supersede previous theoretical calculations for the decay modes $\eta \to \pi^0 l^+ l^-$ [7, 26, 27], which contained several approximations, and represent, to the best of our knowledge, the first theoretical predictions for the four $\eta' \to \pi^0 l^+ l^-$ and $\eta' \to \eta l^+ l^-$ decay widths and dilepton energy spectra. Nevertheless, the associated results are still many orders of magnitude smaller than the current experimental upper limits [3, 23]. For this reason, we would like to encourage experimental groups, such as the WASA-at-COSY and REDTOP [24] collaborations, to study these semileptonic decay processes, as we believe that they can represent a fruitful arena in the search for new physics beyond the Standard Model.

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