Mirror matter admixtures in $K_L \to \gamma\gamma$

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Abstract

Based on possible, albeit tiny, admixtures of mirror matter in ordinary mesons we study the $K_L \to \gamma\gamma$ transition. We find that this process can be described with a small $SU(3)$ symmetry breaking of only 3%. We also determine the $\eta-\eta'$ mixing angle and the pseudoscalar decay constants. The results for these parameters are consistent with some obtained in the literature. They favor two recent determinations; one based on two analytical constraints, and another one based on next-to-leading order power corrections.

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The rare decay process $K_L \to \gamma\gamma$ is a flavour-changing radiative transition, which is expected to be of the same order in weak and electromagnetic couplings as $K_L \to \mu^+\mu^-$, yet the branching ratio of the former is $(5.96 \pm 0.15) \times 10^{-4}$, whereas that of the latter is only $(7.25 \pm 0.16) \times 10^{-9}$. The strong suppression of $K_L \to \mu^+\mu^-$ versus $K^+ \to \mu^+\nu$, for example, is understood as being due to the Glashow-Iliopoulos-Maiani mechanism, but $K_L \to \gamma\gamma$ does not appear to be suppressed at all by this mechanism. The process $K_L \to \gamma\gamma$ is likely to be dominated by low-energy contributions [1].

In the present work we use a phenomenological model based on parity and flavour admixtures of mirror matter in ordinary mesons [2], where the $K_L \to \gamma\gamma$ amplitude is assumed to be enhanced by parity and flavour conserving amplitudes, $\pi^0 \to \gamma\gamma$ and $\eta_8 \to \gamma\gamma$, arising with such admixtures via the ordinary electromagnetic interaction Hamiltonian as the transition operator. With experimental inputs and previous results for the mixing angles of the mirror matter admixtures, we determine the $\eta^-\eta'$ mixing angle $\theta$ and the pseudoscalar decay constants ratios $f_{\eta}/f_{\pi}$ and $f_{\eta'}/f_{\pi}$.

In a model with mirror matter mixings, the physical mesons $K_{ph}^0$ and $\bar{K}_{ph}^0$ with parity and $SU(3)$-flavor violating admixtures are given by [3]

$$K_{ph}^0 = K_p^0 - \frac{1}{\sqrt{2}} \sigma_{p}^0 + \sqrt{\frac{3}{2}} \sigma_{s}^0 + \sqrt{\frac{2}{3}} \delta_{s}^0 - \frac{1}{\sqrt{3}} \delta_{1}^0 + \frac{1}{\sqrt{6}} \delta_{s}^0 + \frac{1}{\sqrt{3}} \delta_{1}^0,
$$

$$\bar{K}_{ph}^0 = K_p^0 - \frac{1}{\sqrt{2}} \sigma_{p}^0 - \sqrt{\frac{3}{2}} \sigma_{s}^0 - \sqrt{\frac{2}{3}} \delta_{s}^0 + \frac{1}{\sqrt{3}} \delta_{1}^0 + \frac{1}{\sqrt{6}} \delta_{s}^0 - \frac{1}{\sqrt{3}} \delta_{1}^0. \quad (1)$$

We have used the $SU(3)$-phase conventions of Ref. [4]. The mixing angles $\sigma$, $\delta$, and $\delta'$, are the parameters of the model, which have been fitted previously [5,6]; see later on. The subindices $s$ and $p$ refer to positive and negative parity eigenstates, respectively. Notice that the physical mesons satisfy $CP K_{ph}^0 = -\bar{K}_{ph}^0$ and $CP \bar{K}_{ph}^0 = -K_{ph}^0$.

We can form the $CP$-eigenstates $K_1$ and $K_2$ as

$$K_{1,ph} = \frac{1}{\sqrt{2}}(K_{ph}^0 - \bar{K}_{ph}^0) \quad \text{and} \quad K_{2,ph} = \frac{1}{\sqrt{2}}(K_{ph}^0 + \bar{K}_{ph}^0), \quad (2)$$

the $K_{1,ph}$ ($K_{2,ph}$) is an even (odd) state with respect to $CP$. Here, we shall not consider $CP$-violation and therefore, $|K_{S,L}\rangle = |K_{1,2}\rangle$. 

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Substituting the expressions given in Eqs. (1), we obtain,

\[ K_{S\text{ph}} = K_S + \frac{1}{\sqrt{3}} (2\delta' + \delta') \eta_{8s} - \delta' \eta_{1s}^0 - \sqrt{\frac{2}{3}} (\delta - \delta') \eta_{1s}, \]

\[ K_{L\text{ph}} = K_L - \sigma \pi^0 + \sqrt{3} \sigma \eta_{8p}, \]

where the usual definitions \( K_{1p} = (K^0_p - K^0_{p'})/\sqrt{2} \) and \( K_{2p} = (K^0_p + K^0_{p'})/\sqrt{2} \) were used.

Mirror matter admixtures in the physical mesons can contribute to the \( K_{S,L} \to \gamma \gamma \) amplitudes via the ordinary parity and flavour-conserving electromagnetic interaction Hamiltonian \( H^{em} \). Using Eqs. (3), a very simple calculation leads to

\[ F_{K_S \gamma \gamma} = \frac{1}{\sqrt{3}} (2\delta + \delta') F_{\eta_{8s} \gamma \gamma} - \delta' F_{\pi^0 \gamma \gamma} - \sqrt{\frac{2}{3}} (\delta - \delta') F_{\eta_{1s} \gamma \gamma}, \]

\[ F_{K_L \gamma \gamma} = -\sigma F_{\pi^0 \gamma \gamma} + \sqrt{3} \sigma F_{\eta_{8p} \gamma \gamma}, \]

where \( F_{K_{S,L} \gamma \gamma} = \langle \gamma \gamma | H^{em} | K_{S,L\text{ph}} \rangle \), \( F_{K_{S,L} \gamma \gamma} = \langle \gamma \gamma | H^{em} | K_{L\text{ph}} \rangle \), and \( F_{\pi^0 \gamma \gamma} = \langle \gamma \gamma | H^{em} | \pi^0 \rangle \), etc.

Given that \( K_S \) and \( K_L \) are \( CP = +1 \) and \( CP = -1 \) pure states respectively, and because the two-photon state is a \( C = +1 \) state, then \( K_S \to \gamma \gamma \) must go through a so-called parity-violating transition while \( K_L \to \gamma \gamma \) goes through a parity-conserving transition. In the first case the two-photon final state is \( P = +1 \) while in the second one, \( P = -1 \). However, as we can see from Eqs. (4) and (5), in the context of mirror matter admixtures all the contributions to both amplitudes are flavour and parity conserving. Notice that the additive terms on the right-hand side of these equations involve only mirror mesons in \( F_{K_S \gamma \gamma} \) and only ordinary mesons in \( F_{K_L \gamma \gamma} \).

We can see from (5) that the parity-conserving amplitude \( F_{K_L \gamma \gamma} \) vanish in the strong-flavour \( SU(3) \)-symmetry limit (\( U \)-spin invariance):

\[ F_{\eta_{8p} \gamma \gamma} = \frac{1}{\sqrt{3}} F_{\pi^0 \gamma \gamma}. \]

The so-called parity-violating amplitude \( F_{K_S \gamma \gamma} \) remains non-zero in this limit. This is the same result obtained as a theorem previously [7].
Let us now concentrate on $K_L \to \gamma\gamma$. As a first approximation, we shall compare Eq. (5) directly with experiment by ignoring any other existent contributions. The two-photon decay widths for $P^0 = K_L, \pi^0, \eta, \eta'$ can be expressed as

\[ \Gamma(P^0 \to \gamma\gamma) = \frac{F_{P^0\gamma\gamma}^2 m_{P^0}^3}{64\pi}, \]

with the decay amplitudes given by the matrix elements $F_{P^0\gamma\gamma} = \langle \gamma\gamma | H | P^0 \rangle$, with $H = H^{\text{em}}$ as the transition operator. From the present experimental values [8] of the decay rates we determine the observed values for the $2\gamma$-amplitudes, they are displayed in Table I. Of the values for the mixing angles of the mirror matter admixtures obtained previously [5,6], we shall only need $\sigma = (4.9 \pm 2.0) \times 10^{-6}$. We do not quote the values of the other two mixing angles because we shall not use them here.

The parametrization of the $\eta$-$\eta'$ mixing has been the subject of many studies for already many years, as can be appreciated in the corresponding reviews in Refs. [8] and [9]. Based on theoretical arguments and on detailed phenomenological analyses, it has been generally accepted that the $\eta$-$\eta'$ mixing cannot be described in a process independent fashion by applying the same rotation (with one angle only) simultaneously to octet-singlet states and to their decay constants. Two separate rotations should be used and two mixing angles are required. In our analysis we shall follow the prescription discussed by Cao and Signal [10], which allows one to still use one-mixing angle at the state level. That is, we shall introduce this angle at the amplitude level only and shall not make the questionable assumption that it also applies to the mixing of the decay constants. Accordingly, we can write at the amplitude level

\[ F_{\eta\gamma\gamma} = F_{\eta'\gamma\gamma} \sin \theta + F_{\eta\gamma\gamma} \cos \theta, \]

\[ F_{\eta'\gamma\gamma} = F_{\eta'\gamma\gamma} \cos \theta - F_{\eta\gamma\gamma} \sin \theta, \]

and the pseudoscalar decay constants ratios are given by

\[ F_{\eta\gamma\gamma} = \frac{\alpha}{\pi} \frac{1}{\sqrt{3} f_\pi} \left( \frac{f_\pi}{f_8} \right) \quad \text{and} \quad F_{\eta\gamma\gamma} = \frac{\alpha}{\pi} \frac{2\sqrt{2}}{\sqrt{3} f_\pi} \left( \frac{f_\pi}{f_1} \right), \]
with $\sqrt{2}f_\pi = (130.7 \pm 0.3)\text{MeV}$ [8].

Before proceeding further, let us make a first estimation. In the previous studies the predictions for $\theta$ vary from $-10^\circ$ [11] to $-23^\circ$ [12,13], the ones for $f_8$ from $(0.94)f_\pi$ [10] to $(1.38)f_\pi$ [14], and the ones for $f_1$ from $(1.04)f_\pi$ [12,13] to $(1.17)f_\pi$ [10]. Within the chiral anomaly sector the most commonly accepted values for the mixing parameters are [14]: $\theta \approx -20^\circ$, $f_8/f_\pi \approx 1.3$, and $f_1/f_\pi \approx 1.0$. Let us use these values in Eq. (8) First, notice that we can not determine the signs of the $2\gamma$-amplitudes from the decays widths so, for definiteness, we will choose $F_{\pi^0\gamma\gamma}$ as positive. In this case, $F_{\eta\gamma\gamma}$ is also positive, as we can see from the $SU(3)$-symmetry limit relation. Besides, for this value of $\theta$ we find from Table I that to get the best agreement with (6), the phases of $F_{\eta\gamma\gamma}$ and $F_{\eta'\gamma\gamma}$ have to be set as positive too. Then, from (8) we obtain $F_{\eta\gamma\gamma} = 1.174 \times 10^{-5} \text{MeV}^{-1}$, with an $SU(3)$-symmetry breaking of 19%. Finally, from expression (5) for $F_{K_L\gamma\gamma}$ in the context of mirror matter admixtures, and the observed values of $F_{\pi^0\gamma\gamma}$ and $\sigma$, we find $F_{K_L\gamma\gamma} = -0.236 \times 10^{-12} \text{MeV}^{-1}$, to be compared with $|F_{K_L\gamma\gamma}| = 3.519 \times 10^{-12} \text{MeV}^{-1}$. So, we are an order of magnitude down from experiment by using the predictions of chiral perturbation theory (ChPT) for the $\eta-\eta'$ parameters. Thus, $K_L \to \gamma\gamma$ is quite sensitive to such mixing.

We can now proceed to determine the value of $\theta$ from the observed values for the $2\gamma$-amplitudes of Table I and $\sigma$. We shall preserve though, the positive phases for the decay amplitudes of $\pi^0, \eta, \eta' \to \gamma\gamma$. The phase of the decay amplitude for the rare transition $K_L \to \gamma\gamma$, to be used in the mirror matter admixtures relation (5), will remain free. From this relation we obtain now, $F_{\eta\gamma\gamma} = (1.494 \pm 0.054) \times 10^{-5} \text{MeV}^{-1}$ if $F_{K_L\gamma\gamma} > 0$ and $F_{\eta\gamma\gamma} = (1.411 \pm 0.054) \times 10^{-5} \text{MeV}^{-1}$ if $F_{K_L\gamma\gamma} < 0$. In this case there is only a $\pm 2.9\%$ $SU(3)$-symmetry breaking, respectively. In other words, the $K_L \to \gamma\gamma$ process is described in the mirror matter admixtures context (relation (5) and the independently determined value of $\sigma$) with just a small $SU(3)$-symmetry flavour breaking of 2.9%. This is made clear if we parametrize the violation of the $SU(3)$-relation (6) as

$$F_{\eta\gamma\gamma} = \frac{1}{\sqrt{3}} F_{\pi^0\gamma\gamma}(1 + b_3),$$  

(11)
so that (5) transforms into

\[ F_{K_L\gamma\gamma} = \sigma F^\mu\pi\gamma\gamma b_3 \]

\[ \approx (4.9 \times 10^{-6})(2.5 \times 10^{-5}\text{MeV}^{-1})(2.9 \times 10^{-2}) \]

\[ \approx 3.5 \times 10^{-12}\text{MeV}^{-1}, \]  

(12)
as experimentally required.

The corresponding value for the \( \eta-\eta' \) mixing angle is now determined from Eq. (8) and the pseudoscalar decay constants ratios \( f_1/f_\pi \) and \( f_8/f_\pi \) are obtained using Eqs. (9) and (10). The results of this approach are shown in row I of Table II, where for the sake of comparison we have included the results of previous determinations of the \( \eta-\eta' \) mixing parameters.

A different possibility in our analysis is revealed by noticing that in the context of mirror matter admixtures for physical hadrons, all the amplitudes on the right hand side of Eqs. (4) and (5) may be affected by the mass of the physical \( K^0_{ph} \) involved in the decaying \( K_{S_{ph}} \) and \( K_{L_{ph}}, \) respectively. At this point, we have ignored such dependence. We will take this into account by changing the normalization of \( F^\pi\pi\gamma\gamma, F^\eta\pi\gamma\gamma, \) and \( F^\eta\pi\gamma\gamma \) in Eqs. (4) and (5), from \( f_\pi \) to \( f_K, \) with \( \sqrt{2}f_K = (159.8 \pm 1.6)\text{MeV} \) [8]. This means,

\[ F^\pi\pi\gamma\gamma = \frac{\alpha}{\pi} \frac{1}{f_\pi} \rightarrow \frac{\alpha}{\pi} \frac{1}{f_K} \equiv F^{(K)}_{\pi\pi\gamma\gamma}, \]  

(13)

\[ F^\eta\pi\gamma\gamma = \frac{\alpha}{\pi} \frac{1}{\sqrt{3}f_\pi} \left( \frac{f_\pi}{f_8} \right) \rightarrow \frac{\alpha}{\pi} \frac{1}{\sqrt{3}f_K} \left( \frac{f_\pi}{f_8} \right) \equiv F^{(K)}_{\eta\pi\gamma\gamma}, \]  

(14)

\[ F^\eta\pi\gamma\gamma = \frac{\alpha}{\pi} \frac{\sqrt{2}}{\sqrt{3}f_\pi} \left( \frac{f_\pi}{f_1} \right) \rightarrow \frac{\alpha}{\pi} \frac{\sqrt{2}}{\sqrt{3}f_K} \left( \frac{f_\pi}{f_1} \right) \equiv F^{(K)}_{\eta\pi\gamma\gamma}. \]  

(15)

From (13) we find the value for the intermediate transition \( \pi \rightarrow \gamma\gamma \) normalized to \( f_K: \)

\[ F^{(K)}_{\pi\pi\gamma\gamma} = (2.056 \pm 0.020) \times 10^{-5}\text{MeV}^{-1}. \]  

With this value and repeating the steps of the previous analysis we obtain, from the mirror matter admixtures relation (5), \( F^{(K)}_{\eta\pi\gamma\gamma} = (1.229 \pm 0.021) \times 10^{-5}\text{MeV}^{-1} \) if \( F_{K_L\gamma\gamma} > 0 \) and \( F^{(K)}_{\eta\pi\gamma\gamma} = (1.145 \pm 0.021) \times 10^{-5}\text{MeV}^{-1} \) if \( F_{K_L\gamma\gamma} < 0, \) with a \( \pm 3.5\% \) \( SU(3)\)-symmetry breaking, respectively. As above, from Table I and Eq. (8) we
determine $\theta$, while $f_8/f_\pi$ is evaluated using now (14) and $f_1/f_\pi$ is determined from (9) and (15). The results of this approach are displayed in row II of Table II.

As we can see from Table II, our predictions for the $\eta$-$\eta'$ mixing angle are consistent with those reported in the literature. The results of row I agree with those given in Refs. [10,15,16,19–22], which were obtained by considering various decay processes. The $\theta$-values of row II are consistent with the predictions based on the chiral Lagrangian and phenomenological mass formulas [12–14,17,18]. Also, our results for $f_8/f_\pi$ are smaller than the most accepted prediction of ChPT, $f_8/f_\pi = 1.3$, and most phenomenological analyses, but they are in agreement with the values obtained in Refs. [10,20]. Our predictions for the ratio $f_1/f_\pi$ of row I are consistent with all the previous determinations reported, but those of row II are smaller than them.

In summary, in the framework of mirror matter admixtures, the description of the $K_L \rightarrow \gamma\gamma$ process is possible and only requires an $SU(3)$-symmetry breaking of just a 3%. Also, the results for the $\eta$-$\eta'$ mixing parameters in this approach are consistent with the values obtained in the literature. Two important remarks are in order here. First, the approach and the data used here and in references [10] and [20] are very different. Ref. [10] obtains two analytical constraints on the parameters by considering the two-photon decays of $\eta$ and $\eta'$, and the production of these states in $e^+e^-$ scattering at large momentum transfer, the parameters are determined from the data on the decay processes and CLEO measurements on the meson-photon transition form factors. Ref [20] evaluates the next to leading order power corrections to the $\eta\gamma$ and $\eta'\gamma$ form factors and employs them to evaluate the $\eta$-$\eta'$ mixing parameters. Second, the agreement of our results in row I and those of these two references lends support to the expectation that the parametrization of this mixing phenomenon is both process and energy independent, an expectation that has been clearly emphasized by Feldmann [9]. It is in this spirit that the results of row I are more attractive than those of row II. Finally, let us stress once more that our one-angle mixing scheme does not use the questionable assumption of applying the same rotation to the decay constants and, as emphasized in Ref. [10], our favored values must be taken as suggestive, too. A
connection with other parametrizations deserves further study and we hope to address it in the near future.

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TABLES

| TABLE I. Observed values for the $2\gamma$ decay amplitudes of $K_L$, $\pi^0$, $\eta$, and $\eta'$ in MeV$^{-1}$. |
|---|
| $|F_{K_L\gamma\gamma}|$ | $(3.519 \pm 0.046) \times 10^{-12}$ |
| $|F_{\pi^0\gamma\gamma}|$ | $(2.516 \pm 0.089) \times 10^{-5}$ |
| $|F_{\eta\gamma\gamma}|$ | $(2.39 \pm 0.11) \times 10^{-5}$ |
| $|F_{\eta'\gamma\gamma}|$ | $(3.13 \pm 0.16) \times 10^{-5}$ |
TABLE II. Comparison of different determinations of the mixing parameters $\theta$, $f_8/f_\pi$, and $f_1/f_\pi$. The values of rows I and II were determined in the present work. Row I by direct comparison with experiment and row II by normalizing the decay amplitudes to the $f_K$ decay constant. Upper and lower values in these rows correspond to the choices $F_{K_{L\gamma\gamma}} > 0$ and $F_{K_{L\gamma\gamma}} < 0$, respectively.

| Ref. | $\theta^o$ | $f_8/f_\pi$ | $f_1/f_\pi$ |
|------|------------|-------------|-------------|
| I    | $-15.1 \pm 1.6$ | $0.971 \pm 0.035$ | $1.128 \pm 0.056$ |
|      | $-16.4 \pm 1.6$ | $1.028 \pm 0.039$ | $1.115 \pm 0.055$ |
| II   | $-19.2 \pm 1.4$ | $0.966 \pm 0.019$ | $0.895 \pm 0.039$ |
|      | $-20.5 \pm 1.4$ | $1.036 \pm 0.022$ | $0.890 \pm 0.039$ |
| [12,13] | $-23 \pm 3$ | 1.25 | 1.04 $\pm 0.04$ |
| [10]  | $-14.5 \pm 2.0$ | $0.94 \pm 0.07$ | 1.17 $\pm 0.08$ |
| [14]  | $-22.0 \pm 3.3$ | $1.38 \pm 0.22$ | 1.06 $\pm 0.03$ |
| [15]  | $-16.4 \pm 1.2$ | $1.11 \pm 0.06$ | 1.10 $\pm 0.02$ |
| [16]  | $-15.4$ | 1.26 | 1.17 |
| [17]  | $-21.4 \pm 1.0$ | $1.185 \pm 0.040$ | $1.095 \pm 0.020$ |
| [18]  | $-19.3$ | 1.254 | 1.127 |
| [19]  | $-18.1 \pm 1.2$ | $1.28 \pm 0.04$ | 1.13 $\pm 0.03$ |
| [20]  | $-16.4$ | 0.99 | 1.08 |
| [21]  | $-17.3 \pm 1.8$ | — | — |
| [22]  | $-16.9 \pm 1.7$ | — | — |