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Isospin breaking and $f_0(980)$-$a_0(980)$ mixing in the $\eta(1405) \rightarrow \pi^0 f_0(980)$ reaction

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Abstract. We make a theoretical study of the $\eta(1405) \rightarrow \pi^0 f_0(980)$ and $\eta(1405) \rightarrow \pi^0 a_0(980)$ reactions to determine the isospin violation and the mixing of the $f_0(980)$ and $a_0(980)$ resonances. We make use of the chiral unitary approach where these two resonances appear as dynamically generated by the meson-meson interaction provided by chiral Lagrangians. We obtain a very narrow shape for the $f_0(980)$ production in agreement with a BES experiment. As to the amount of isospin violation, assuming constant vertices for the primary $\eta(1405) \rightarrow \pi^0 K\bar{K}$ and $\eta(1405) \rightarrow \pi^0\pi^0\eta$ production, we find results which are much smaller than found in the experimental BES paper. The problem is solved by using the primary production driven by $\eta' \rightarrow K^*\bar{K}$ followed by $K^* \rightarrow K\pi$. Thus, we can predict absolute values for the ratio $\Gamma(\pi^0, \pi^+\pi^-)/\Gamma(\pi^0, \pi^0\eta)$ which are in fair agreement with experiment.

1. Introduction

In a recent paper the BES team has reported an unusually large isospin violation in the decay of the $\eta(1405) \rightarrow \pi^0 f_0(980)$ compared to the $\eta(1405) \rightarrow \pi^0 a_0(980)$ reaction [1]. The signal for the isospin violating channel $\eta(1405) \rightarrow \pi^0 f_0(980)$ is narrow, in agreement with previous findings, but the ratio of the partial decay widths of $\eta(1405) \rightarrow \pi^0\pi^+\pi^-$ to $\eta(1405) \rightarrow \pi^0 a_0(980)$ is abnormally large, 18%. A theoretical description of such a large rate is difficult, unless the same $\eta(1405)$ state already contains a large mixture of $I = 0$ and $I = 1$, in which case the natural width of the $f_0(980)$ of about 50 MeV would be shown instead of the 9 MeV observed in the BES experiment [1].

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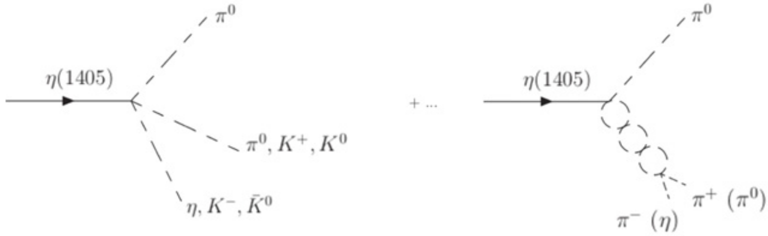

Figure 1. Diagrammatic representation of the $\pi^0\pi^+\pi^-$, $\pi^0\pi^0\eta$ production in the $\eta(1405)$ decay.

In this work we first discussed the problem assuming a contact $\eta' \to \pi^0 K\bar{K}$ vertex, while the second part is devoted to the explicit study of the triangular mechanism of [2] which is quite unique to the present reaction and, together with the use of the chiral unitary approach, enables us to evaluate the ratio for isospin violation rather reliably, obtaining a good agreement with experiment.

2. Formalism

The starting point in the following discussion is to qualify the $f_0(980)$ and $a_0(980)$ as dynamically generated by the meson-meson interaction provided by the chiral Lagrangians. The basic building blocks are $\pi\pi$ and $K\bar{K}$ for the $f_0(980)$ and $\pi\eta$ and $K\bar{K}$ for the $a_0(980)$ [3]. The constituents, pairs of mesons, couple to the external sources and, upon unitarization the resonances are formed.

2.1 Standard formalism assuming local primary $\eta(1405) \to \pi^0 PP$ vertices

We shall assume that the first step consists of $\eta(1405) \to \pi^0 PP$ (P for pseudoscalar) well described by contact vertices. We also accept that the $\eta(1405)$ is an isospin zero state. Then, the mechanism for production of either $\pi^+\pi^-$ or $\pi^0\eta$ in the final state, together with an extra π^0, is given by Fig. 1. The pair of interacting mesons in Fig. 1 will have $I = 1$ if we invoke exact $I = 0$ for the $\eta(1405)$. Then the $K\bar{K}$ pair appears in the $I = 1$ combination $\frac{1}{\sqrt{2}}(K^+K^- - K^0\bar{K}^0)$. Should the kaons have the same mass, the loop functions in the figure would be the same for charged and neutral kaons and the relative minus sign guarantees that $\pi^+\pi^-$ will not be produced, since there is an exact cancellation of the K^+K^- and $K^0\bar{K}^0$ contributions (the $\pi^0\eta \to \pi^+\pi^-$ would also not proceed). However, when the physical masses are considered, there is a partial cancellation, leading to an isospin breaking effect. By analogy to the η and η', we can also assume that in the next pair of η states, the $\eta(1295)$ is largely an octet and the $\eta(1405)$ is mostly a singlet. In this case we have to place the interacting meson pair into an octet to produce a singlet with the octet of the spectator π^0. Then, up to an undetermined reduced matrix element, the weight of K^+K^-, $K^0\bar{K}^0$ and $\pi^0\eta$ is determined by the $SU(3)$ Clebsch-Gordan coefficients of the $8 \otimes 8 \to 1$ decomposition, and we have $M_{K^+K^-} = \sqrt{\frac{3}{5}}$, $M_{K^0\bar{K}^0} = -\sqrt{\frac{3}{5}}$ and $M_{\pi^0\eta} = \sqrt{\frac{4}{5}}$. Then, the scattering matrix for the production of the final state is given by

$$t_f = M_f + \sum_{i=1}^{3} M_i G_i T_{if}, \tag{1}$$

where T_{if} is the 5×5 scattering matrix for the channels K^+K^- (1), $K^0\bar{K}^0$ (2), $\pi^0\eta$ (3), $\pi^+\pi^-$ (4), $\pi^0\pi^0$ (5) and M_i in the same basis is given by $M_i = A\left(\sqrt{\frac{3}{5}}, -\sqrt{\frac{3}{5}}, \sqrt{\frac{4}{5}}, 0, 0\right)$, with A a reduced matrix element. The T matrix is obtained using the Bethe-Salpeter equation in the five coupled channels

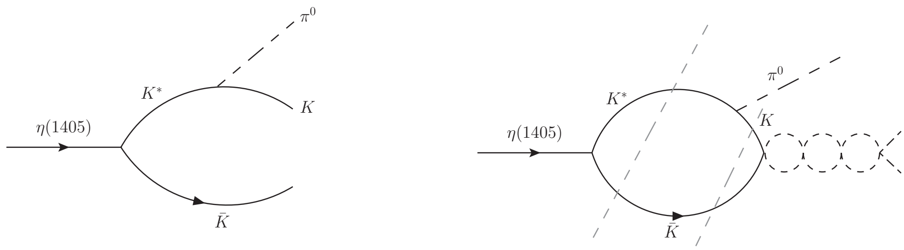

Figure 2. Left: singular mechanism for $\pi^0 K\bar{K}$ production. Right: rescattering mechanism for the production of the f_0 and a_0.

$T = [1 - VG]^{-1}$ V, with V taken from [3]. The G function is the diagonal loop matrix of the propagators of the intermediate particles, regularized by means of a cutoff of $q_{max} = 900$ MeV.

Note that in Eq. (1) we have two sources of isospin violation. The one due to the G_i functions, which now are different for K^+K^- and $K^0\bar{K}^0$, and the T_{if} matrix elements.

2.2 Results with the local vertices

We compare $\frac{d\Gamma}{dm_f} = \beta\ p_1\ \tilde{p}_2\ |t_f|^2$ with experiment, where m_f is the invariant mass of $\pi^+\pi^-$ and $\pi^0\eta$ pairs, β a constant, p_1, $\tilde{p}_2$ the momentum of the spectator π^0 in the $\eta(1405)$ rest frame and the momentum of the interacting pair in the rest frame of the pair, respectively. In the case of the $\pi^+\pi^-$ production we obtain a very narrow peak around 980 MeV like in [1]. Its width is about 10 MeV, in agreement with experimental observations, and appears in the $f_0(980)$ region, in between the thresholds of K^+K^- and $K^0\bar{K}^0$, because now $G_{K^+K^-} - G_{K^0\bar{K}^0}$ is different from zero. However, the difference, due to the different kaon masses, is only significant in a region of energies around the $K\bar{K}$ thresholds, where $\Delta(\sqrt{s})$ is of the order of $m_{K^+} - m_{K^0}$. Away from the thresholds the difference of the two G functions becomes gradually smaller leading to the peculiar narrow shape of the $f_0(980)$ excitation in the $\pi^+\pi^-$ channel. The signal for the $a_0(980)$ excitation, isospin allowed, has a much larger width. if we integrate the strength over m_f in the region of the peaks for the two cases, we find that it is of the order of 1.5%, which is along the lines of the 0.6% observed in the two reactions $J/\psi \to \phi\pi^0\eta(\pi^+\pi^-)$ or $\chi_{c1} \to \pi^0(\pi^+\pi^-)(\pi^0\eta)$ [4], but very far away from the results in [1].

2.3 The primary production vertex with the $K^*\bar{K}$ singularity

In [2] it was shown that using the $\eta(1405)$ decay mode to $K^*\bar{K}$ and the successive decay of K^* into $K\pi$ one obtains a mechanism for $K\bar{K}\pi$ production at tree level by means of which one could obtain good agreement with experimental data on this channel (Fig. 2-left). After rescattering of the $K\bar{K}$ pair (Fig. 2-right), the f_0 and a_0 resonances will be produced. The novelty now is that the first loop is rather different from the one of the ordinary G function for $K\bar{K}$ propagation shown in the second diagram of Fig. 1. The loop in Fig. 2-right has two singularity cuts, one for the $K^*\bar{K}$ on shell and the other one for the $K\bar{K}$ on shell. The kinematics of the two cuts are not too far away, which magnifies the difference in the loop functions in the charged and neutral cases due to the different masses amongst the kaons and the K^*.

One technical problem faced in [2] is that when performing the evaluation of the $\eta' \to \pi^0\pi^+\pi^-$ amplitude one has the difference of $\tilde{G}$ for the charged K^-K^+ and the neutral one and the results are convergent, but then the ratio to the $\eta' \to \pi^0\pi^0\eta$ is tied to an unknown form factor. Our approach solves naturally the former problem. The G function is also formally divergent and is regularized by a cutoff which is fitted to the meson-meson scattering data. The natural choice is to use this cutoff in the new loop, but this becomes a necessity when one recalls that the results of the chiral unitary approach with the G function implementing a cutoff $\theta(q_{max} - |\vec{q}|)$ in the integration are obtained formally in a Quantum Mechanical formulation starting with a potential (for s-waves that we study here) $V(\vec{q}, \vec{q}\,') = v\ \theta(q_{max} - |\vec{q}|)\ \theta(q_{max} - |\vec{q}\,'|)$.

2.4 Results with the triangular diagram

The ratio of integrated decay widths is now much bigger, $\frac{\Gamma(\pi^0,\pi^+\pi^-)}{\Gamma(\pi^0,\pi^0\eta)} \simeq 0.13$, which means 13%, much closer to the experimental value of $(17.9 \pm 4.2)\%$, which has a lower limit of 13.7%. This increase by about one order of magnitude with respect to the standard calculation is a consequence of the two neighbouring singularities in the triangle diagram, which is peculiar to the $\eta(1405)$ case.

Now we come back to the BES experiment [1]. In this experiment the $\eta(1405)$ and the $\eta(1475)$ resonance are undistinguishable, so we must assume that they have a mixture of both. In order to account for this possibility, we have evaluated the same ratio of rates as before assuming that we have now the $\eta(1475)$ resonance. We obtain a ratio of 0.16. We discuss here also the case of the $\eta(1295)$. Little is known about the couplings of this resonance to different channels. One might intuitively think that, by complementarity and ortogonality, if the $\eta(1405)$ couples strongly to $K^*\bar{K}$ it indicates that it has a large $s\bar{s}$ component, in which case the $\eta(1295)$ would mostly account for $u\bar{u}$ ($d\bar{d}$). In this case the coupling of the $\eta(1295)$ to $K^*\bar{K}$ would be highly suppressed. We have evaluated the ratio $\Gamma(\pi^0, \pi^+\pi^-)/\Gamma(\pi^0, \pi^0\eta)$ at the peak of the f_0, a_0 for the two situations as before: a) contact primary vertices, b) triangular mechanism via $K^*\bar{K}$ production. In the case a) we find a ratio of 0.017, while in the case b) we find 0.12. Given the argumentation above, where we expect the $\eta(1295)$ to have small $s\bar{s}$ component, and hence small couplings to $K^*\bar{K}$, we would expect rates for $\Gamma(\pi^0, \pi^+\pi^-)/\Gamma(\pi^0, \pi^0\eta)$ of the order of 0.017. Should the experiment find a large value of this ratio, comparable to the one of the $\eta(1405)$, we would face an unexpected situation that could bring new light into the quest for the nature of the $\eta(1295)$ and $\eta(1405)$ resonances.

3. Conclusions

In the first part of the work we assumed the primary production of $\pi^0 PP$ to be given by a contact term and we obtained a rate of $\pi^+\pi^-$ production versus $\pi^0\eta$ of the order of one percent, very small compared with the results claimed by [1].

We tried to understand the situation in the second part, where we followed the approach of [2] using the dominant primary production mechanism given by Fig. 2. The first loop was quite different than for the contact interactions, since the new singularity associated to $\eta' \to K^*\bar{K}$ played a very important role in the reaction. We found that using this new mechanism of production, the ratio of $\Gamma(\pi^0, \pi^+\pi^-)/\Gamma(\pi^0, \pi^0\eta)$ was increased by about one order of magnitude, providing results very close to those in the experiment. These results confirm the claims of [2], where, however, a precise determination of that ratio could not be given since it was tied to unknown form factors needed to regularize the divergent loops. The use of the chiral unitary approach in the present work solved this problem since one could associate the regularizing cutoff in the new loops to the one used in meson-meson scattering to generate the $f_0(980)$ and $a_0(980)$ resonances dynamically. This allowed us to make quantitative predictions for the $\Gamma(\pi^0, \pi^+\pi^-)/\Gamma(\pi^0, \pi^0\eta)$ ratio, with a value (0.16), in basic agreement with experiment, of (0.179 ± 0.04). Then, the chiral unitary approach appears as an appropriate and accurate tool to use in order to analyze these reactions and the present results strengthen the support for the $f_0(980)$ and $a_0(980)$ resonances as dynamically generated from the meson-meson interaction.

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