Physics Letters B 742 (2015) 363–369

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

The low lying scalar resonances in the D^0 decays into K_s^0 and $f_0(500)$, $f_0(980)$, $a_0(980)$

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ARTICLE INFO

Article history:
Received 17 October 2014
Received in revised form 27 January 2015
Accepted 2 February 2015
Available online 4 February 2015
Editor: W. Haxton

ABSTRACT

The D^0 decay into K_s^0 and a scalar resonance, $f_0(500)$, $f_0(980)$, $a_0(980)$, are studied obtaining the scalar resonances from final state interaction of a pair of mesons produced in a first step in the D^0 decay into K_s^0 and the pair of pseudoscalar mesons. This weak decay is very appropriate for this kind of study because it allows to produce the three resonances in the same decay in a process that is Cabibbo-allowed, hence the rates obtained are large compared to those of $\bar{B}^0$ decays into J/ψ and a scalar meson that have at least one Cabibbo-suppressed vertex. Concretely the $a_0(980)$ production is Cabibbo-allowed here, while it cannot be seen in the $\bar{B}_s^0$ decay into $J/\psi a_0(980)$ and is doubly Cabibbo-suppressed in the $\bar{B}^0$ decay into $J/\psi a_0(980)$ and has not been identified there. The fact that the three resonances can be seen in the same reaction, because there is no isospin conservation in the weak decays, offers a unique opportunity to test the ideas of the chiral unitary approach where these resonances are produced from the interaction of pairs of pseudoscalar mesons.

1. Introduction

The rates for D^0 decay into K_s^0 and a scalar resonance, $f_0(980)$, $a_0(980)$, are measured by the CLEO Collaboration in Ref. [1] and Ref. [2], respectively, and the rates are relatively large. The $f_0(980)$ is seen through its decay into $\pi^+\pi^-$ and the $a_0(980)$ through the $\pi^0\eta$ channel. Related references on the issue can be seen in the PDG [3]. Theoretical work on these decays is scarce and is mostly devoted to issues related to CP violation or D^0–D^{*0} mixing. In Ref. [4] a thorough study is done of the $D^0 \to K_s^0\pi^+\pi^-$ reaction and the amplitude is parametrized in terms of form factors, resonance parameters and different couplings, amounting to a set of 33 free parameters, which are fitted to the Belle [5] and BaBar [6] data. The purpose is to have a good amplitude that can be used to determine the $D^0 - D^{*0}$ mixing parameters and the Cabibbo–Kobayashi–Maskawa (CKM) angle γ.

The aim of the present work is different: we only evaluate the part of the $D^0 \to K_s^0\pi^+\pi^-$ amplitude corresponding to a K_s^0 and two pions propagating in s-wave, which will show the $f_0(500)$ and $f_0(980)$ resonances. In addition we study the $D^0 \to K_s^0\pi^0\eta$ amplitude, where the $a_0(980)$ resonance shows up, and relate it to the former one. However, we show that, by using basic symmetries and the chiral unitary approach to deal with the meson–meson interaction in coupled channels, one is able to determine the shapes of the different amplitudes and the relative weight to each other with no free parameters. Hence genuine predictions for the shapes of these amplitudes and the relative weights of $f_0(500)$, $f_0(980)$ and $a_0(980)$ can be made and compared with experiment.

The chiral unitary approach for meson–meson interaction makes use of the Bethe Salpeter (BS) equation in coupled channels. One takes all possible meson–meson channels that couple within $SU(3)$ to certain given quantum numbers and the BS equation guaranties exact unitary. The kernel (potential) for the BS equation is taken from the chiral Lagrangians [7,8] and there is freedom for only some regularization scale in the meson–meson loops, which is fitted to the meson–meson scattering data. A good agreement with experimental data is obtained up to 1.2 GeV [9–14]. One of the consequences of this approach is that the resonances $f_0(500)$, $f_0(980)$, $a_0(980)$ and $\kappa(800)$ are automatically generated from these potentials and the use of the BS equations. In this way these

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http://dx.doi.org/10.1016/j.physletb.2015.02.006
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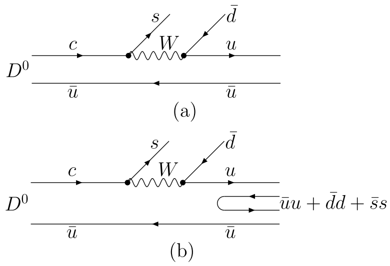

Fig. 1. (a): Dominant diagrams for $D^0 \to \bar{K}^0 u\bar{u})$ and (b): hadronization of the $u\bar{u}$ to give two mesons.

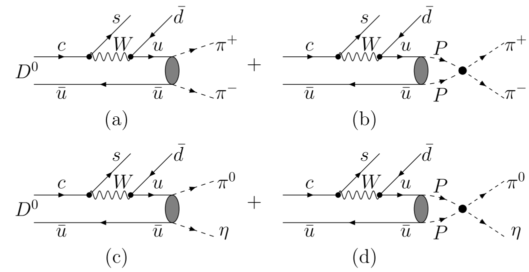

Fig. 2. Diagrammatic representation of $\pi^+\pi^-$ and $\pi^0\eta$ production. (a) direct $\pi^+\pi^-$ production, (b) $\pi^+\pi^-$ production through primary production of a PP pair and rescattering, (c) primary $\pi^0\eta$ production, (d) $\pi^0\eta$ produced through rescattering.

resonances qualify as dynamically generated states, some kind of composite, or molecular, meson–meson states, in the same way as the deuteron qualifies as a bound state of a proton and a neutron and not a more exotic object [15]. The approach not only provides the meson–meson amplitudes but has been tested successfully in virtually any reaction where any of the former resonances is produced. The latest test was the study of the B^0 and B_s^0 decays into $J/\psi f_0(500)$ and $J/\psi f_0(980)$ which was done in Ref. [16] (a list of different reactions where the former resonances are produced can also be found there), where a natural explanation was given of the observed facts that the $\bar{B}_s^0$ decays into $J/\psi f_0(980)$, while no signal is seen for $J/\psi f_0(500)$, and the $\bar{B}^0$ decays into $J/\psi f_0(500)$ and only a small fraction is seen for the $J/\psi f_0(980)$.

The D^0 decay into K_s^0 and a scalar resonance, $f_0(500)$, $f_0(980)$, $a_0(980)$ is a privileged case to test the nature of these resonances. Indeed, as we shall see, the three processes are Cabibbo-allowed and the rates of production are big compared to those of the $\bar{B}^0$ decays into J/ψ and one of these resonances, where necessarily one of the vertices, the V_{cb}, is Cabibbo-suppressed [17–19]. On the other hand, the $a_0(980)$ has not been reported in $\bar{B}^0$, $\bar{B}_s^0$ decays. As one can see in Ref. [16,19], in the decay of $\bar{B}_s^0$ into J/ψ one gets an extra $s\bar{s}$ pair that has $I=0$ and does not allow the $a_0(980)$ production upon hadronization. On the other hand in the B^0 decay into J/ψ one gets an extra $d\bar{d}$ pair that could lead to the $a_0(980)$ upon hadronization, but the process is doubly Cabibbo-suppressed. It is found there that a signal is seen for the $f_0(500)$ production and only a small fraction is reported for $f_0(980)$ production [18]. One should expect also a minor rate for $a_0(980)$ production in this case and, in fact, this mode of decay is not reported. In the present case the $a_0(980)$ production is allowed and the rates are large [2]. The fact that we have now weak interactions that allow for isospin violation permit that both the $f_0(980)$ and $a_0(980)$ resonances are produced in the same reaction. This is a novelty with respect to strong interactions that are isospin conserving. The present weak decay presents then a new challenge since one can determine the relative weight of production of each one of these resonances in the same reaction, a new situation with respect to what one has in strong interaction reactions.

2. Formalism

The process for $D^0 \to K_s^0 R$ of relevance to us proceeds at the elementary quark level as depicted in Fig. 1(a). The process is Cabibbo-allowed, the $s\bar{d}$ pair produces the $\bar{K}^0$, which will convert to the observed K_s^0 through time evolution with the weak interaction. The remaining $u\bar{u}$ pair gets hadronized adding an extra $\bar{q}q$ with the quantum numbers of the vacuum, $\bar{u}u + \bar{d}d + \bar{s}s$. This topology is the same as for the $\bar{B}_s \to J/\psi s\bar{s}$ (substituting the $s\bar{d}$ by $c\bar{c}$) [19], that upon hadronization of the $s\bar{s}$ pair leads to the production of the $f_0(980)$ [16], which couples mostly to the hadronized $K\bar{K}$ components.

The hadronization is implemented in an easy way following the work of Ref. [20]. One starts with the $q\bar{q}$ matrix M

$$M = \begin{pmatrix} u\bar{u} & u\bar{d} & u\bar{s} \\ d\bar{u} & d\bar{d} & d\bar{s} \\ s\bar{u} & s\bar{d} & s\bar{s} \end{pmatrix} \tag{1}$$

which has the property

$$M \cdot M = M \times (\bar{u}u + \bar{d}d + \bar{s}s). \tag{2}$$

Hence the $u\bar{u}$ component of Fig. 1(b) can be written as,

$$u\bar{u}(\bar{u}u + \bar{d}d + \bar{s}s) = (M \cdot M)_{11}. \tag{3}$$

Next, we rewrite the $q\bar{q}$ matrix M in terms of meson components, and we have M corresponding to the matrix ϕ [21–23]

$$\phi = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{3}}\eta + \frac{1}{\sqrt{6}}\eta' & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{3}}\eta + \frac{1}{\sqrt{6}}\eta' & K^0 \\ K^- & \bar{K}^0 & -\frac{1}{\sqrt{3}}\eta + \sqrt{\frac{2}{3}}\eta' \end{pmatrix} \tag{4}$$

This matrix corresponds to the ordinary one used in chiral perturbation theory [7] with the addition of $\frac{1}{\sqrt{3}}\,\mathrm{diag}(\eta_1, \eta_1, \eta_1)$ where η_1 is a singlet of $SU(3)$, taking into account the standard mixing between η and η'. The term $\frac{1}{\sqrt{3}}\,\mathrm{diag}(\eta_1, \eta_1, \eta_1)$ is omitted in the chiral Lagrangians because the $[\phi, \partial_\mu \phi]$ structure of the Lagrangians renders this term inoperative. In Ref. [16] the ordinary ϕ matrix of chiral perturbation theory was also used. Here we consider the full ϕ matrix of Eq. (4) since we are concerned with physical η plus π^0 production.

Hence upon hadronization of the $u\bar{u}$ component we shall have

$$\begin{aligned} u\bar{u}(\bar{u}u + \bar{d}d + \bar{s}s) &\equiv (\phi \cdot \phi)_{11} \\ &= \frac{1}{2}\pi^0\pi^0 + \frac{1}{3}\eta\eta + \frac{2}{\sqrt{6}}\pi^0\eta \\ &\quad + \pi^+\pi^- + K^+K^-, \end{aligned} \tag{5}$$

where we have omitted the η' term because of its large mass. This means that upon hadronization of the $u\bar{u}$ component we have $D^0 \to \bar{K}^0 PP$, where PP are the different meson–meson components of Eq. (5). This is only the first step, because now these mesons will interact among themselves delivering the desired meson pair component at the end: $\pi^+\pi^-$ for the case of the $f_0(500)$ and $f_0(980)$, and $\pi^0\eta$ for the case of the $a_0(980)$.

The multiple scattering of the mesons is readily taken into account as shown diagrammatically in Fig. 2.

Analytically we shall have

$$t(D^0 \to \bar{K}^0 \pi^+\pi^-)$$
$$= V_P(1 + G_{\pi^+\pi^-} t_{\pi^+\pi^- \to \pi^+\pi^-}$$

$$+\frac{1}{2}\frac{1}{2}G_{\pi^0\pi^0}t_{\pi^0\pi^0\to\pi^+\pi^-}+\frac{1}{3}\frac{1}{2}G_{\eta\eta}t_{\eta\eta\to\pi^+\pi^-}$$
$$+G_{K^+K^-}t_{K^+K^-\to\pi^+\pi^-}), \quad (6)$$

and

$$t(D^0\to\bar{K}^0\pi^0\eta)$$
$$=V_P(\sqrt{\frac{2}{3}}+\sqrt{\frac{2}{3}}G_{\pi^0\eta}t_{\pi^0\eta\to\pi^0\eta}$$
$$+G_{K^+K^-}t_{K^+K^-\to\pi^0\eta}), \quad (7)$$

where V_P is a production vertex, containing the dynamics which is common to all the terms. G is the loop function of two mesons [9] and t_{ij} are the transition scattering matrices between pairs of pseudoscalars [9]. The $f_0(500)$, $f_0(980)$, and $a_0(980)$ are produced in s-wave where $\pi^0\pi^0$, $\pi^+\pi^-$ have isospin $I=0$, hence these terms do not contribute to $\pi^0\eta$ production ($I=1$) in Eq. (7). Note that in Eq. (6) we introduce the factor $\frac{1}{2}$ extra for the identity of the particles for $\pi^0\pi^0$ and $\eta\eta$.

The t matrix is obtained as

$$t=[1-VG]^{-1}V, \quad (8)$$

where V_{ij} are the transition potentials evaluated in Refs. [9,24]. Explicit expressions for $I=0$ are given in Ref. [16]. We have the $I=1$ case new here and we present the matrix elements below

$$V_{K^+K^-\to\pi^0\eta}=\frac{-\sqrt{3}}{12f^2}(3s-\frac{8}{3}m_K^2-\frac{1}{3}m_\pi^2-m_\eta^2), \quad (9)$$

$$V_{K^0\bar{K}^0\to\pi^0\eta}=-V_{K^+K^-\to\pi^0\eta}, \quad (10)$$

$$V_{\pi^0\eta\to\pi^0\eta}=-\frac{1}{3f^2}m_\pi^2, \quad (11)$$

$$V_{K^+K^-\to K^+K^-}=-\frac{1}{2f^2}s, \quad (12)$$

$$V_{K^+K^-\to K^0\bar{K}^0}=-\frac{1}{4f^2}s, \quad (13)$$

$$V_{K^0\bar{K}^0\to K^0\bar{K}^0}=-\frac{1}{2f^2}s, \quad (14)$$

with f the pion decay constant, $f=93$ MeV, and s is invariant mass square of the meson–meson system. It is worth mentioning that we are using only the lowest order chiral tree amplitudes in Eqs. (9)–(14). One can go further and introduce higher order terms from the chiral Lagrangians [7] as done in Ref. [10], but one can see that the approaches lead to remarkable similar results, with good agreement with experimental data, due to the ability of the method to incorporate the effect of higher order terms by a suitable choice of cutoffs. This is also the case when even more sophisticated methods are used implementing crossing through the Roy equations as in Refs. [25–28]. Hence, using the lowest order approach is more than sufficient, given the experimental uncertainties, or the theoretical uncertainties on how to subtract the background, as we shall see below when discussing Eqs. (18) and (21).

The loop function G [9] is regularized by means of a cutoff. When the $\eta\eta$ channel is explicitly taken into account the cutoff needed is smaller than in Ref. [9] and we follow [16] where it was taken equal to $q_{max}=600$ MeV.

Finally, the mass distribution for the decay is given by[1]

$$\frac{d\Gamma}{dM_{inv}}=\frac{1}{(2\pi)^3}\frac{p_{\bar{K}^0}\tilde{p}_\pi}{4M_{D^0}^2}\left|t_{D^0\to\bar{K}^0\pi^+\pi^-}\right|^2, \quad (15)$$

where $p_{\bar{K}^0}$ is the $\bar{K}^0$ momentum in the global CM frame (D^0 at rest) and $\tilde{p}_\pi$ is the pion momentum in the $\pi^+\pi^-$ rest frame,

$$p_{\bar{K}^0}=\frac{\lambda^{1/2}(M_{D^0}^2,M_{\bar{K}^0}^2,M_{inv}^2)}{2M_{D^0}}, \quad (16)$$

$$\tilde{p}_\pi=\frac{\lambda^{1/2}(M_{inv}^2,m_\pi^2,m_\pi^2)}{2M_{inv}}, \quad (17)$$

and similarly for the case of the $\pi^0\eta$ production.

Before closing this section we should mention that in a three hadron final state one must look for the interaction of three particles, for which one must in principle deal with Faddeev equations [29]. Most of the applications of Faddeev equations are done for three baryon systems but calculations for three mesons are becoming available [30]. However, for the purpose of the present work it is instructive to follow the idea in Ref. [31] for the analogous $D^+\to K^-\pi^+\pi^+$ reaction. In this work two body unitarity is imposed on the two body systems and diagrams related to three body unitarity are evaluated perturbatively. They are found relevant close to threshold but fade away rapidly of higher energies. What we have done is in this line and we have unitarized the $\pi^+\pi^-$, $\pi^0\eta$ (and coupled channels pairs) but the $\bar{K}^0$ has been left as a spectator. In principle we should also look at the interaction of $\bar{K}^0\pi^-$ which can lead to the $\kappa(800)$ resonance [10], and higher mass resonances like the $K_0^*(1430)$ in S-wave [4], yet the topology of Fig. 2(a) does not favor S-wave interaction of $\bar{K}^0\pi^-$. And furthermore, the resonances can also come from a different topology of the diagrams than those considered in Fig. 2(a) for instance producing a π^+ meson from the c quark via direct conversions of W into π^+ (see Section 4, Fig. 5(a)). This is why the κ is better seen in the $D^+\to K^-\pi^+\pi^+$ reaction, as discussed in Ref. [31]. We do not consider the πK interaction leading to the κ or other resonances, with the argument that the κ, being a very broad resonance in the πK invariant mass, only contributes a smooth background below the $\pi^+\pi^-$, or $\pi^0\eta$ invariant mass distribution when one looks for the $f_0(980)$ or $a_0(980)$ signals and is taken into account in experimental analysis of these two latter resonances. The same can be said for the other πK resonances since their strength is distributed through the phase space of $\pi^+\pi^-$ or $\pi^0\eta$ in the form of background. In this sense, the diagram of Fig. 1 chosen and the interaction that we have considered is also what corresponds to the $K_s^0[\pi^+\pi^-]_s$, M_2 amplitude of Ref. [4], the one that considers the S-wave interaction of the pions and the $f_0(500)$ and $f_0(980)$ resonances, or the $a_0(980)$ when we consider in addition the $K_s^0[\pi^0\eta]_s$ amplitude, which is not addressed in Ref. [4].

3. Results

In Fig. 3, we show the results of our calculation. We have taken the cutoff $q_{qmax}=600$ MeV as in Ref. [16]. We superpose the two mass distributions $d\Gamma/dM_{inv}$ for $\pi^+\pi^-$ (solid line) and $\pi^0\eta$ (dashed line). The scale is arbitrary, since it corresponds to taking $V_p=1000$ in Eqs. (6) and (7), but it is the same for the two distributions, which allows us to compare $f_0(980)$ with $a_0(980)$ production. As we discussed before, it is a benefit of the weak interactions that we can see simultaneously both the $I=0$ $f_0(980)$ and $I=1$ $a_0(980)$ productions in the same $D^0\to\bar{K}^0R$ decay.

When it comes to compare with the experiment we can see that the $f_0(980)$ signal is quite narrow and it is easy to extract its contribution to the branching ratios by assuming a smooth background (shown in Fig. 3 by the dotted line) below the $f_0(980)$

[1] The decay amplitude $t_{\bar{D}^0\to\bar{K}^0\pi^+\pi^-}$ depends on the invariant mass, $M_{inv}=\sqrt{s}$, of the meson–meson system.

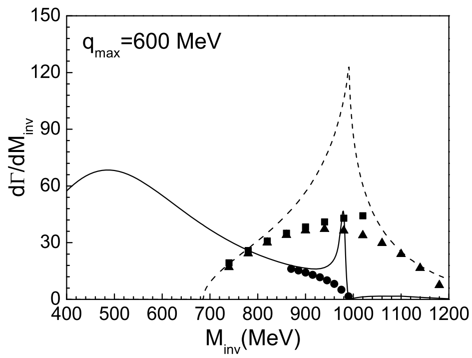

Fig. 3. The $\pi^+\pi^-$ (solid line) and $\pi^0\eta$ (dashed line) invariant mass distributions for the $D^0 \to \bar{K}^0\pi^+\pi^-$ decay and $D^0 \to \bar{K}^0\pi^0\eta$ decay, respectively. A smooth background is plotted below the $a_0(980)$ (Triangle: phase space distribution method; Square: quadratic function method. More details can be found in the text.) and $f_0(980)$ peaks.

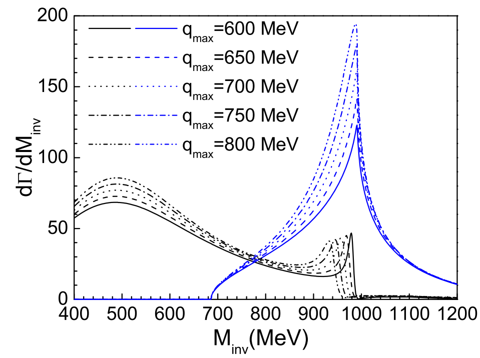

Fig. 4. (Color online.) The $\pi^+\pi^-$ (black curves) and $\pi^0\eta$ (blue curves) invariant mass distributions with different cutoff q_{max} for the $D^0 \to \bar{K}^0\pi^+\pi^-$ decay and $D^0 \to \bar{K}^0\pi^0\eta$ decay, respectively.

peak as a continuation of the $f_0(500)$ broad structure at lower energies. For the case of the $\pi^0\eta$ distribution we get a clear peak that we associate to the $a_0(980)$ resonance, remarkably similar in shape to the one found in the experiment [2]. Yet it is obvious that not all the strength seen in Fig. 3 can be attributed to the $a_0(980)$ resonance. One should recall that the chiral unitary approach provides amplitudes, in this case the $\pi^0\eta$ amplitude, but the amplitudes provide poles that one associates to resonances but also background contributions, and this is the case of the $\pi^0\eta$ distribution. In order to get a "$a_0(980)$" contribution we subtract a smooth background. By doing that we have a remaining "resonant" shape with an apparent width of 80 MeV, which is in the middle of the 50–100 MeV of the PDG [3].

We use two methods to estimate the background in the case of the $a_0(980)$. One of them is to take a phase space distribution that fits the lower part of the $M_{\rm inv}$ spectrum and stop where it cuts the calculated distribution at higher $M_{\rm inv}$. The other one is to take a quadratic function in $M_{\rm inv}$ that reproduces the distribution in three points where the $a_0(980)$ should have negligible strength (we have chosen 740 MeV, 820 MeV and 1100 MeV). The two backgrounds are shown in Fig. 3. For the case of the $f_0(980)$ resonance, since it is narrower, we assume a Breit–Wigner distribution only for the lower $M_{\rm inv}$ half of the resonance peak (the Flatte effect from the $K\bar{K}$ channel at higher $M_{\rm inv}$ does not allow one to do the same in the higher $M_{\rm inv}$ half), and extrapolate that smoothly in the higher mass part till it vanishes at the point where the calculated distribution vanishes around 1000 MeV. Integrating the area below these structures we obtain

$$R = \frac{\Gamma(D^0 \to \bar{K}^0 a_0(980), a_0(980) \to \pi^0\eta)}{\Gamma(D^0 \to \bar{K}^0 f_0(980), f_0(980) \to \pi^+\pi^-)} = 6.7 \pm 1.3, \quad (18)$$

where we have added a 20% theoretical error due to uncertainties in the extraction of the background. In the real experiment the background can be different due to the contribution of other channels neglected here, but the extraction of the "signal" for the resonance is done in a similar way as we have done here. The uncertainty assumed is in line with the experimental uncertainties [2].

Experimentally we find from the PDG and Refs. [1,2],

$$Br(D^0 \to \bar{K}^0 a_0(980), a_0(980) \to \pi^0\eta) = (6.5 \pm 2.0) \times 10^{-3}, \quad (19)$$

$$Br(D^0 \to \bar{K}^0 f_0(980), f_0(980) \to \pi^+\pi^-) = (1.22^{+0.40}_{-0.24}) \times 10^{-3}. \quad (20)$$

The ratio that one obtains from there is

$$R = 5.33^{+2.4}_{-1.9}. \quad (21)$$

The agreement found between Eq. (18) and Eq. (21) is good, within errors. This is, hence, a prediction that we can do parameter free.

As we mentioned, the explicit consideration of the $\eta\eta$ channel in the meson–meson interaction, required to use a cutoff $q_{max} =$ 600 MeV [16] to agree with experimental amplitudes, smaller than in Ref. [9] where this channel was omitted. We use the same cutoff here. Yet, we want to show explicitly that the ratio obtained does not get spoiled even if a wide range of cutoffs are used. In Fig. 4, we show the results for five different, higher values of q_{max}. The magnitude of the $a_0(980)$ production grows a bit with q_{max}, with the prescription taken above, but the strength of the $f_0(980)$ production also grows as a consequence of an increase in the width. One can also see that the peak of the $f_0(980)$ moves to lower energies, what puts constraints on q_{max}, but by performing a similar estimate of the background as done in Fig. 3, we find that, even within this broad range of values of q_{max}, the ratio of Eq. (18) remains within the errors of this equation and is a solid prediction.

It should not go unnoticed that we also predict a sizeable fraction of the decay width into $D^0 \to \bar{K}^0 f_0(500)$, with a strength several times bigger than for the $f_0(980)$. The $\pi^+\pi^-$ distributions is qualitatively similar to that obtained in Ref. [16] for the $\bar{B}^0 \to J/\psi\pi^+\pi^-$ decay, although the strength of the $f_0(500)$ with respect to the $f_0(980)$ is relatively bigger in this latter decay than in the present case (almost 50% bigger). The $\bar{B}^0 \to J/\psi f_0(500)$, $f_0(500) \to \pi^+\pi^-$ decay mode, together with the $f_0(980)$ one have been identified in Ref. [32] through a partial wave analysis, and the rates obtained are comparable with the findings of Ref. [16]. Such a partial wave analysis is not available from the work of Ref. [1], where the analysis was done assuming a resonant state and a stable meson, including many contributions, but not the $K^0_s f_0(500)$. Yet, a discussion is done at the end of the paper [1] in which the background seen is attributed to the $f_0(500)$. With this assumption they get a mass and width of the $f_0(500)$ compatible with other experiments. Further analyses in the line of [32] would be most welcome to separate this important contributions to the $D^0 \to K^0_s\pi^+\pi^-$ decay.

4. Further considerations

Our results are based on the dominance of the quark diagrams of Fig. 1. In the weak decay of mesons the diagrams are classified in six different topologies [33,34]: external emission, internal emission, W-exchange, W-annihilation, horizontal W-loop and

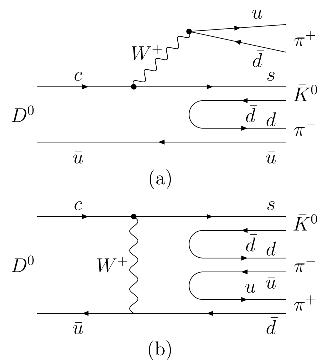

Fig. 5. External emission diagram (a) and the W-exchange diagram (b) for $D^0 \to \bar{K}^0\pi^+\pi^-$.

vertical W-loop. As shown in Ref. [35], only the internal emission graph (Fig. 1 of the present work) and W-exchange[2] contribute to the $D^0 \to \bar{K}^0 f_0(980)$ and $D^0 \to \bar{K}^0 a_0(980)$ decays. In Ref. [4] the $D^0 \to \bar{K}^0\pi^+\pi^-$ decay is studied. Hence, only the $D^0 \to K^0_s f_0(980)$ decay can be addressed, which is accounted for by proper form factors and taken into account by means of the M_2 $(K^0_s[\pi^+\pi^-]_s)$ amplitude, which contains the tree level internal emission, and W-exchange (also called annihilation mechanism). In order to establish connection with the work of Ref. [4], let us draw the external emission and W-exchange diagrams pertinent to the $D^0 \to \bar{K}^0\pi^+\pi^-$ decay, as shown in Fig. 5.

It is also instructive to recall the basic non-leptonic Hamiltonian at the quark level responsible for this transition [36–38]

$$H_{\rm W} = \frac{G_F}{\sqrt{2}} V_{cs}V_{ud}\bar{c}\gamma_\mu(1-\gamma_5)s\bar{d}\gamma^\mu(1-\gamma_5)u + {\rm h.c.} \tag{22}$$

This Hamiltonian transforms as an isospin $I = 1$ operator. Consequently the decay amplitude of $D^0 \to K\pi\pi$ is

$$T(D^0 \to K\pi\pi) = \langle K^0_s M_1 M_2 | H_{\rm W} | D^0\rangle, \tag{23}$$

where the two meson system M_1M_2 ($\pi^+\pi^-$ here) can have $I = 0,\ 1,\ 2$. This is the case in the diagram of Fig. 5(a) where the $c\bar{u}$, π^+ intermediate state can have $I = 1/2,\ 3/2$, which allows the $\pi^+\pi^-$ system to have $I = 0,\ 1,\ 2$ in the final $\bar{K}^0\pi^+\pi^-$ state. However, the diagram of Fig. 5(a) will not contribute to our resonance production which requires the $\pi^+\pi^-$ S-wave loop, as seen in Fig. 2, due to the vector structure of Eq. (22) in the csW^+ vertex of Fig. 5(a). This is also the case in the phenomenological analysis of Ref. [35]. Then, in the remaining mechanisms of Fig. 2 and Fig. 5(b) the $\pi^+\pi^-$ can only be in $I = 0$ or 1.

In our study we have isolated the S-wave of the pions in order to get the $f_0(500)$, $f_0(980)$ resonances, and the $a_0(980)$ in the case of $\pi^0\eta$. Certainly, the operator of Eq. (22) allows other angular momenta, and indeed experimentally ρ meson and other mesons can be obtained, but the experimental analysis of Refs. [1,2] with partial wave analysis separate the contributions of $f_0(980)$ and $a_0(980)$ production, which allows us to compare directly with these data without the need to look into other channels. Also, although in principle the amplitudes depend on two independent Mandelstam variables as seen in Ref. [4], the fact that we do not consider the $\bar{K}^0\pi^-$ interaction (leading to the $\kappa(800)$ and other resonances), which would just provide a background in the $\pi^+\pi^-$ mass distribution for the reasons discussed at the end of Section 2, makes our amplitude dependent upon the invariant mass of $\pi^+\pi^-$ or $\pi^0\eta$.

Concerning the W-exchange diagrams, which we have ignored in our approach, we would like to argue in favor of its relative smallness with two arguments: firstly, in Fig. 1(a) we can see that the $\bar{u}$ quark of the D^0 is a spectator. We thus have a one body operator at the D^0 quark level. However, in the W-exchange one involves the two quarks of D^0 and the amplitude squared involves the probability to find two quarks, smaller than that of finding one quark. This situation is typical in nuclear reactions, where the W-exchange would have its equivalent in the exchange currents [39]. The second argument is that in the W-exchange diagram of Fig. 5(b) there is a double hadronization compared to the single hadronization of Fig. 1(b). The hadronization reverts into a decreased rate for two meson production compared to the single meson of the original $q\bar{q}$, which we can estimate in about one order of magnitude from the experimental rate [3,40] (see Ref. [16] for details),

$$\frac{\Gamma(\bar{B}^0_s \to J/\psi f_0(980);\ f_0(980) \to \pi^+\pi^-)}{\Gamma(\bar{B}^0_s \to J/\psi\phi)} = 0.14. \tag{24}$$

In the literature there is much discussions about the relevance of the W-exchange mechanism. In Ref. [35] an empirical analysis is done based on giving a weight to the different topological mechanisms, and the W-exchange mechanism (evaluated under the assumption that the f_0 and a_0 resonances are $q\bar{q}$ or tetraquark states) appears of the same order of the internal conversion, with opposite sign, that makes the $C - E$ combination in a_0 production bigger than the $C + E$ combination in f_0 production.[3] However, in the same paper, a factorization approach is followed (see Section V of Ref. [35]) in which the W-exchange contribution is claimed to be suppressed and is neglected in that approach. The present work neglects the W-exchange mechanism and produces a large $a_0(980)$ production relative to $f_0(980)$ due to the mechanism of final state interaction.

The dominance of the internal emissions in this kind of processes is also supported in other works [19,32,41–43]. In Ref. [4] a detailed discussion is made of results in different works. The W-exchange mechanism in Ref. [4] depends on two unknown form factors which are fitted to the data and a phase which is unknown. From a fit to the data, a minimal strength of about 20% is obtained for the W-exchange mechanism, suggesting that the contribution could be bigger. It is clear that this issue is still open but the relative smallness of the W-exchange mechanism has many arguments in favor, and our study, producing a big ratio of $a_0(980)$ versus $f_0(980)$ production due to final state interaction in coupled channels, neglecting the W-exchange mechanism, provides extra support for its smallness. Note that this a_0/f_0 large ratio was the main reason of the relatively large weight of the W-exchange mechanism in the fit of Ref. [35]. Studies along the lines of Ref. [4] for $D^0 \to \bar{K}^0\pi^0\eta$ would help bring extra light into this issue.

We come now to a different sort of discussion. In Ref. [4] a thorough and useful work is done with the aim to reproduce the full experimental information on the $D^0 \to K^0_s\pi^+\pi^-$ reaction. This information is quite rich and contains the strength of the reaction in a Dalitz plot. There is more information there than in the single $d\Gamma/dM_{\rm inv}$ distribution. The authors of Ref. [4] have introduced explicitly the $\kappa(800)$, $K^*_0(1430)$ in S-wave, $K^*(892)$ in P-wave, and $K^*_2(1430)$ in D-wave for the πK channel. Similarly, the $f_0(500)$,

[2] The W-exchange and W-annihilation are often referred together as weak annihilation diagrams.

[3] The C and E are the contributions of the internal conversion and W-exchange, and $C - E$ and $C + E$ the combinations found in Ref. [35] for a_0 and f_0 production, respectively.

$f_0(980)$ in S-wave, the ρ in P-wave and the $f_2(1270)$ in D-wave are also considered in the $\pi\pi$ channel. The amplitudes obtained are converted into a double differential cross section to fit the information in the Dalitz plot from experiment. Although the authors of Ref. [4] need to fit 33 free parameters, this is still an improvement over other approaches, like Belle in Ref. [44] which has used 40 parameters and BaBar [6] where 43 parameters are used, since it also implements unitarity, analyticity and chiral symmetry constraints. It might look that in Ref. [4] they neglect the $K\bar{K}$ component, explicitly considered in the preset work, but this is not the case. Indeed they have form factors for the resonance production which are properly unitarized. This means that the $(1-VG)^{-1}$ factor in Eq. (8) is properly considered and the fit to the data provides the strength needed in the numerator. The novelty of our approach is that we explicitly use the $K\bar{K}$ and other channels assuming that the D^0 decay process via $D^0 \to K^0 PP$. This can be done for the resonances which are dynamically generated by the PP interaction, like the $f_0(500)$, $f_0(980)$ and $a_0(980)$, but cannot be used to account for other resonances which have a dominant character of $q\bar{q}$, or non-meson–meson component [45]. This is why a study like the one of Ref. [4] is unavoidable if one wishes to address the full experimental information. Our aim here has been different. We have concentrated on a particular amplitude of Ref. [4], which can also be disentangled using other analyses, but we could make predictions for the relative weight of $f_0(500)$, $f_0(980)$ and $a_0(980)$ production based on the assumption that these resonances are dynamically generated from the PP interaction. The agreement of the predictions with experiment gives support to that assumption. Note that in Ref. [4] the $D^0 \to K^0\pi^0\eta$ is not addressed. The approach of Ref. [4] could be generalized to this decay mode making again fits to the data. The real value of our approach is that it makes a prediction for the $a_0(980)$ production once the $f_0(500)$ strength is known.

5. Summary and conclusions

We have studied the decay of the D^0 decay into K_s^0 and a scalar resonance, $f_0(500)$, $f_0(980)$, $a_0(980)$. For this purpose we have identified the weak mechanism that allows the formation of a $\bar{K}^0$, that will act as a spectator, and a pair of mesons, $K\bar{K}$, $\pi\pi$, $\pi^0\eta$, $\eta\eta$, etc., that upon interaction will give rise to the $f_0(500)$, $f_0(980)$, $a_0(980)$ resonances. The first step is the production of a $\bar{K}_s^0$ and a pair of $q\bar{q}$, which upon hadronization leads to these pairs of mesons. The hadronization is done in an easy way, by looking at the flavor content in meson–meson of the hadronized $q\bar{q}$ pair. This is sufficient in the present case where we only aim at determining the shape of the invariant mass distributions and the relative weight of the different production modes, but not absolute rates. Once the weight of the different $\bar{K}^0$-meson–meson components has been determined we then allow these meson–meson components to interact, using for it the chiral unitary approach, and they give rise to the $f_0(500)$, $f_0(980)$, $a_0(980)$ resonances. They are seen in the $\pi^+\pi^-$ invariant mass distributions [$f_0(500)$, $f_0(980)$] and the $\pi^0\eta$ distribution [$a_0(980)$], and we not only get the poles of these resonances but also realistic mass distributions that can be compared with experiment. We found the shape of the $\pi^0\eta$ distribution rather similar to the one found in the experiment, and we obtained a ratio of the branching ratios for $a_0(980)$ and $f_0(980)$ production in good agreement with experiment, all of it accomplished without any free parameter, meaning that the parameters of the theory have been determined before hand in the study of the meson–meson interaction. To reach this level of prediction some assumptions were made, which were justified in the discussions. But there is a main assumption, the fact that $f_0(500)$, $f_0(980)$ and $a_0(980)$ resonances are dynamically generated from the meson–meson interaction. Although the idea has been tested in many previous reactions, we present the agreement with the experiment found in this paper as a further and novel test of this idea.

We emphasized the fact that it is the nature of the weak interactions, that allows for isospin violations, what made possible the production of the $a_0(980)$ and $f_0(980)$ resonances in the same decay. This is a most welcome feature that has allowed to test simultaneously the production of the two resonances in the same reaction offering new test for the chiral unitary approach than allowed in strong interaction reactions, providing yet one more example of support for the dynamically generated nature of the low lying scalar mesons.

Acknowledgements

One of us, E.O., wishes to acknowledge support from the Chinese Academy of Sciences (CAS) in the Program of Visiting Professorship for Senior International Scientists. This work is partly supported by the Spanish Ministerio de Economía y Competitividad and European FEDER funds under the contract numbers FIS2011-28853-C02-01 and FIS2011-28853-C02-02, and the Generalitat Valenciana in the program Prometeo, 2009/090. We acknowledge the support of the European Community – Research Infrastructure Integrating Activity Study of Strongly Interacting Matter (acronym HadronPhysics3, Grant Agreement No. 283286) under the Seventh Framework Programme of EU. This work is also partly supported by the National Natural Science Foundation of China under Grant Nos. 11105126, 11475227, 11375080, and 10975068, and the Natural Science Foundation of Liaoning Scientific Committee under Grant No. 2013020091. The Project is Sponsored by the Scientific Research Foundation for the Returned Overseas Chinese Scholars, Ministry of Education of the People's Republic of China.

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