THE EFFECT OF ISOSPIN VIOLATION ON SCALAR MESON PRODUCTION

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Abstract

We investigate the isospin-violating mixing of the light scalar mesons $a_0(980)$ and $f_0(980)$ within the unitarized chiral approach. Isospin-violating effects are considered to leading order in the quark mass difference and electromagnetism. In this approach both resonances are generated through meson-meson dynamics. Our results provide a description of the mixing phenomenon within a framework consistent with chiral symmetry and unitarity, where these resonances are not predominantly $qar{q}$ states. We discuss in detail the reactions $J/\Psi \to \phi S$, where $S$ denotes a suitable pair of pseudo–scalar mesons in the scalar channel, namely $\pi\eta$, $K^+K^-$, and $K^0\bar{K}^0$. In this work predictions for the cross section in the kaon channels are given for the first time with isospin violating effects included.
1 Introduction

Although the light scalar mesons $a_0(980)$ and $f_0(980)$ have been established as resonances long ago, there is still a heated debate going on in the literature regarding the very nature of these states. Naively one might assign them a conventional $q\bar{q}$ structure, however, at present no quark model is capable of describing both states simultaneously as $q\bar{q}$ states — see, e.g., Ref. 1). On the other hand, as early as 1977 it was stressed that especially in the scalar channel the interaction of four-quark systems (two quarks, two antiquarks) is attractive 2). Some authors have found indications for the existence of compact four-quark states 3−5). However, the same short-ranged interaction can also be the kernel to the scattering of pseudoscalars, giving rise to extended four-quark states that one might call hadronic molecules or extraordinary hadrons 6−9). Independently, a similar conclusion was found in different approaches 10−13).

In Refs. 14, 15) it is stressed that the effective coupling constants of the scalar mesons to the $K\bar{K}$ channel contain the essential structure information. Especially, the larger the molecular component, the larger the residue at the resonance pole, which acquires its maximum value in case of a pure molecule. It should be stressed, however, that this connection can be made rigorous only for stable bound states and if the bound state pole is on the first sheet very close to the elastic threshold 14). However, if the state of interest is narrow and the inelastic threshold is sufficiently far away, the argument should still hold 15). Note that both conditions apply for $a_0(980)$ and $f_0(980)$. Therefore one should aim at observables that are very sensitive to the effective coupling constants. The resonance signal, as seen in production experiments for both states, is not very useful to determine those couplings, for it turned out to be mainly sensitive to ratios of couplings 16). It is therefore important to investigate other observables.

When this formalism was applied to the scalar mesons $a_0(980)$ and $f_0(980)$ it was found from an analysis of a series of reactions 17) that the latter is indeed predominantly a $K\bar{K}$ molecule, in line with the results of Refs. 7, 10, 11, 13), while the results for the former did not lead to an unambiguous interpretation. This might either point at a prominent non–molecular contribution to the $a_0$ structure, or the $a_0$ is not a bound state, but a virtual state. To decide on this issue it is important to collect more information especially on the $a_0$. In Ref. 18) it was stressed that the amplitude for the isospin violating $a_0 − f_0$
transition should be very sensitive to the product of the effective coupling to the two–kaon channels of the $f_0$ and the $a_0$. If we assume that the $f_0$ is a molecule, its coupling to the $K\bar{K}$ channel is fixed, as discussed above. Then the value for the $a_0 - f_0$ mixing amplitude should be very sensitive to the structure of the $a_0$.

The reason why the mixing amplitude of $a_0$ and $f_0$ is sensitive to the effective couplings is that it gets a prominent contribution from the kaon–loops (see Fig. 1). Their isospin violating part is driven by the kaon mass differences giving rise to an effect that can be shown to scale as $\sqrt{(m_d - m_u)/m_s}$. In contrast to this, normal isospin violating effects should be of order $(m_d - m_u)/m_s$ — those could be parameterized, e.g., by isospin–violating coupling constants (see Fig. 2). In Ref. 19) the latter effects were calculated for the first time as well to provide a better quantitative estimate of the mixing amplitude. For this a particular model needs to be used. We chose the chiral unitary approach which is a special unitarization procedure for amplitudes calculated using chiral perturbation theory. The latter provides a systematic inclusion of quark mass effects while the former allows for an extension of the formalism into the resonance region — see Ref. 20) for a recent review. In addition we also include the isospin breaking effect of the soft–photon exchange.

In this work we investigate different final states for the reactions $J/\Psi \rightarrow \phi S$, where $S$ denotes a suitable pair of pseudo–scalar mesons in the scalar channel, namely $\pi^0\eta, K^+K^-$, and $K^0\bar{K}^0$ — predictions for the cross section in the kaon channels are given for the first time with isospin violation included. The latter two channels are expected to constrain the charge dependence of the

\[ \sqrt{(m_d - m_u)/m_s} \]

\[ (m_d - m_u)/m_s \]

\[ \pi^0\eta, K^+K^- \]

\[ K^0\bar{K}^0 \]

\[ J/\Psi \rightarrow \phi S \]

\[ S \]

\[ \pi^0\eta, K^+K^- \]

\[ K^0\bar{K}^0 \]
coupling of the $f_0$ to kaons and should therefore provide an independent cross check for the size of corrections of order $(m_d - m_u)/m_s$. In the next section the formalism is briefly reviewed and the results are given. We close with a short summary.

2 Formalism and Results

Details on the formalism are given in Ref. 19). Thus, here we will only repeat the essential physics that went into the calculations. In the Standard Model there are two sources of isospin violation present, namely the up-down quark mass difference as well as electromagnetism. Both appear in a well defined form in the corresponding Lagrangian density formulated in terms of the fundamental degrees of freedom, here photons, gluons, and quarks. Chiral perturbation theory 23, 24) allows for a consistent representation of those terms for a theory describing the interaction of the (pseudo) Goldstone bosons with each other. At leading order in the chiral Lagrangian the only parameter that appears, in addition to the various particle masses, is the pion decay constant. Thus, also the leading effect of isospin violation is predicted. It should be stressed that already at leading order both isospin violating mass differences as well as isospin violating interactions are present.

Already in isospin symmetric calculations of meson–meson scattering amplitudes, when unitarizing the leading chiral Lagrangian, an a priori unknown constant needs to be adjusted to the data. In addition, a few more parameters need to be fitted to the production data — in our case they were fixed from a fit to the data on $J/\Psi \rightarrow \phi\pi^+\pi^-$, $K^+K^-$ as well as $J/\Psi \rightarrow \omega\pi^+\pi^-$ 25). Once this is done, the isospin violating signals emerge as predictions. Our results
Figure 3: Left: predicted signal for \(J/\Psi \rightarrow \phi \pi^0 \eta\). The solid line shows the result without isospin violation in the production operator (IVPO), while the band shows the effect of its inclusion. Right: predicted signal for \(J/\Psi \rightarrow \phi K\bar{K}\). For both kaon channels the solid band, which includes the uncertainties, is the full result, while for the dashed line the same decay amplitude was used in both channels (see text).

for the various channels are shown in Fig. 3. The predicted signal in the \(\pi^0 \eta\) channel was already published in Ref. 19). Note that in an isospin symmetric world this reaction would not be allowed, thus any signal is directly proportional to the square of an isospin violating amplitude. Based on very general scale arguments one can show that in addition this amplitude is dominated by the isospin violation that emerges from \(a_0 - f_0\) mixing \(26)\). This was confirmed on the grounds of the current model: the filled band in the left panel of Fig. 3 shows the effect of possible isospin violation in the production operator. The right panel of the same figure shows the \(J/\Psi\) decay with a pair of kaons in the final state. Please note that for these two channels there would be a decay rate also in an isospin symmetric world, however, then both signals would agree. The solid lines show our results for the two channels including the effects of isospin violation as described in Ref. 19). In addition, the presence of charged particles in the final state called for an additional treatment of soft photons. Here we followed Ref. \(27)\). The decay spectrum for \(J/\Psi \rightarrow \phi K^+ K^-\), based on an isospin symmetric calculation, is shown in Ref. \(25)\).

To see how much of the difference in the two kaon channels originates from the different phase space thresholds alone \(2m_{K^+} - 2m_{K^0} = 8\) MeV), in the
figure we also show the signals that emerge when the same decay amplitude is used for both channels (dashed lines). For this calculation we took the average of the charged and the neutral kaon amplitudes, corresponding to a formal isospin 0 combination. Obviously the by far most important difference between the channels is driven by the displacement of the thresholds, the effect of which is further enhanced by the strongly varying amplitudes precisely in this threshold region. The original idea was to extract information on the charge dependence of the couplings of the \( f_0 \) to kaons from a comparison of \( J/\Psi \to \phi K^+K^- \) and \( J/\Psi \to \phi K^0\bar{K}^0 \). However, as can be seen from the figure, the differences between the solid and the dashed lines are too small to be accessible experimentally. Therefore we do not expect data for the kaon channels to be sufficiently sensitive to extract isospin violating effects in the decay amplitudes.

### 3 Summary

In this work we calculated the reactions \( J/\Psi \to \phi S \), where \( S \) denotes a suitable pair of pseudo–scalar mesons in the scalar channel, namely \( \pi^0\eta \), \( K^+K^- \), and \( K^0\bar{K}^0 \). The goal of this study was to gain a better quantitative understanding of the phenomenon of \( a_0-f_0 \) mixing, which should eventually reveal important information on the structure of the \( a_0(980) \). In addition to the \( \pi^0\eta \) channel, the kaon channels including isospin violation were discussed here for the first time. We found that, at least within the current model, the impact of the charge dependence of the coupling of the \( f_0 \) to kaons is too small to be deduced from a comparison of the rates for \( K^+K^- \), and \( K^0\bar{K}^0 \). On the other hand the \( \pi^0\eta \) decay channel appears to be not only very sensitive to the effective coupling constants that encode the structure information but also theoretically under control \(^{19}\). For a discussion of additional background effects see Ref. \(^{22}\). The corresponding measurements can be performed, once BES III is in operation.

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