Vector meson-vector meson interaction and dynamically generated resonances

E Oset\(^1\), L S Geng\(^2\) and R Molina\(^1\)

\(^1\)Departamento de Física Teórica and IFIC, Universidad de Valencia-CSIC, E-46071 Valencia, Spain
\(^2\)School of physics and nuclear energy engineering, Beihang University, Beijing 100191, China

E-mail: oset@ific.uv.es

Abstract. We report upon 11 composite meson states, dynamically generated from the vector meson-vector meson interaction using the local hidden gauge formalism within a unitary approach. Six of these states are associated to the \(f_{0}(1370)\), \(f_{0}(1710)\), \(f_{2}(1270)\), \(f_{2}'(1525)\), \(a_{2}(1320)\) and \(K_{2}^{*}(1430)\) resonances. At the same time we predict five other states with the quantum numbers of \(h_{1}\), \(a_{0}\), \(b_{1}\), \(K_{0}^{*}\), and \(K_{1}\) which could be tested by future experiments.

1. Introduction
The chiral unitary approach, combining coupled-channels, unitarity and chiral Lagrangians, has been quite successful to deal with hadron interactions at low energies. The interaction leads to scattering matrices which have poles in the complex plane associated to resonances which are called dynamically generated (see Ref. [1] for an introduction and earlier references). Because these states are dynamically generated from meson-meson or meson-baryon interactions, they are viewed as composite particles or hadronic molecules, instead of genuine \(q\bar{q}\) or \(qqq\) systems. Studies of their behavior in the large \(N_{c}\) limit have confirmed that they are largely meson-meson or meson-baryon composite systems, though some of them may contain a small genuine \(q\bar{q}\) or \(qqq\) component.

The success of the chiral unitary approach has inspired a further extension to study the interaction between two vector mesons and between one vector meson and one baryon [2, 3, 4, 5, 6, 7]. Here, instead of using interaction kernels provided by ChPT, one uses transition amplitudes provided by the hidden-gauge Lagrangians, which lead to a suitable description of the interaction of vector mesons among themselves and of vector mesons with other mesons or baryons. Coupled-channel unitarity works in the same way as in the unitary chiral approach, but now the dynamics is provided by the hidden-gauge Lagrangians [8]. The use of this approach in several recent works [2, 3, 4, 5, 6, 7] has proved rather successful.

In this talk, we report on a recent study of vector meson-vector meson interaction using the unitary approach, briefly discussing the formalism and showing how 11 states are dynamically generated [3].

2. Formalism
We briefly outline the main ingredients of the unitary approach (see Refs. [2, 3] for more details). There are two basic building-blocks in this approach: transition amplitudes provided...
by the hidden-gauge Lagrangians [8] and a unitarization procedure. We adopt the Bethe-
Salpeter equation method $T = (1 - VG)^{-1}V$ to unitarize the transition amplitudes $V$ for $s$-wave
interactions, where $G$ is a diagonal matrix of the vector meson-vector meson one-loop function.

In Refs. [2, 3] three mechanisms, as shown in Fig. 1, have been taken into account for
the calculation of the transition amplitudes $V$: the four-vector-contact term, the $t(u)$-channel
vector-exchange amplitude, and the direct box amplitude with two intermediate pseudoscalar
mesons. Other possible mechanisms, e.g. crossed box amplitudes and box amplitudes involving
anomalous couplings, have been neglected, since their contributions have been shown to be small
in the case of rho-rho scattering in Ref. [2].

Among the three mechanisms considered for $V$, the four-vector-contact term and $t(u)$-channel
vector-exchange are responsible for the formation of resonances or bound states if the interaction
generated by them is strong enough. In this sense, the dynamically generated states can be
thought of as “vector meson-vector meson molecules.” On the other hand, the consideration of
the imaginary part of the direct box amplitude allows the generated states to decay into two
 pseudoscalars. It should be stressed that in the present approach these two mechanisms play
quite different roles: the four-vector-contact term and the $t(u)$-channel vector-exchange one are
responsible for generating the resonances whereas the direct box amplitude mainly contributes
to their decays.

Since the energy regions we are interested in are close to the two vector-meson threshold,
the three-momenta of the external vector mesons are smaller than the corresponding masses,
$|\vec{q}|^2 / M^2 \ll 1$, and therefore can be safely neglected. This considerably simplifies the calculation
of the four-vector-contact term and the $t(u)$-channel vector-exchange amplitude, whose explicit
expressions can be found in Appendix A of Ref. [3]. To regularize the box diagram, one takes
the empirical form factors used in the study of vector-meson decays [9].

To regularize the two vector-meson one-loop function one has to introduce either cutoffs in
the cutoff method or subtraction constants in the dimensional regularization method. Further
details concerning the values of these parameters can be found in Ref. [3]. The results presented
in this talk are obtained using the dimensional regularization method with the values of the
subtraction constants given in Ref. [3]. In particular, we have fine-tuned the values of three
subtraction constants to reproduce the masses of the three tensor states, i.e., the $f_2(1270)$, the
$f_2'(1525)$, and the $K_2^*(1430)$. The masses of the other eight states are predictions.

3. Results and discussions

By looking at poles of the scattering matrix $T$ on the second Riemann sheet, we find 11 states
in nine strangeness-isospin-spin channels as shown in Table 1. Theoretical masses and widths
are obtained with two different methods: In the “pole position” method, the mass corresponds
to the real part of the pole position on the complex plane and the width corresponds to twice its
imaginary part. In this case, the box diagrams corresponding to decays into two pseudoscalars
Table 1. The properties, (mass, width) [in units of MeV], of the 11 dynamically generated states and, if existing, of those of their PDG counterparts [10]. The association of the dynamically generated states with their experimental counterparts is determined by matching their mass, width, and decay pattern.

| $I^G(J^{PC})$ | Pole position | Real axis | PDG data |
|---------------|---------------|-----------|----------|
|               | $\Lambda_b = 1.4$ GeV $\Lambda_b = 1.5$ GeV |           |          |
| $0^+(0^{++})$ | (1512,51)     | (1523,257) | (1517,396) | $f_0(1370)$ | 1200~1500 | 200~500 |
| $0^+(0^{++})$ | (1726,28)     | (1721,133) | (1717,151) | $f_0(1710)$ | 1724 ± 7 | 137 ± 8 |
| $0^-(1^{--})$ | (1802,78)     | (1802.49)  |           | $h_1$       |           |         |
| $0^+(2^{++})$ | (1275,2)      | (1276,97)  | (1275,111) | $f_2(1270)$ | 1275.1 ± 1.2 | 185.0±2.9 2.4 |
| $0^+(2^{++})$ | (1525.6)      | (1525,45)  | (1525,51)  | $f_2(1525)$ | 1525 ± 5 | 73±6     |
| $1^-(0^{++})$ | (1780,133)    | (1777,148) | (1777,172) | $a_0$       |           |         |
| $1^+(1^{++})$ | (1679,325)    | (1703,188) |           | $b_1$       |           |         |
| $1^-(2^{++})$ | (1569,32)     | (1567,47)  | (1566,51)  | $a_2(1320)$ |           |         |
| $1/2(0^+)$    | (1643,47)     | (1639,139) | (1637,162) | $K_0^*$      |           |         |
| $1/2(1^+)$    | (1737,165)    | (1743,126) |           | $K_1(1650)$ |           |         |
| $1/2(2^+)$    | (1431,1)      | (1431,56)  | (1431,63)  | $K_2^*(1430)$ | 1429 ± 1.4 | 104 ± 4 |

are not included. In the "real axis" method, the resonance parameters are obtained from the modulus squared of the amplitudes of the dominant channel of each state on the real axis (see Tables I, II, and III of Ref. [3]), where the mass corresponds to the energy at which the modulus squared has a maximum and the width corresponds to the difference between the two energies where the modulus squared is half of the maximum value. In this latter case, the box amplitudes are included. The results shown in Table I have been obtained using two different values of the box cut off, which serve to quantify the uncertainties related to this parameter.

Our treatment of the box amplitudes also enables us to obtain the decay branching ratios of the generated states into two pseudoscalar mesons [3]. The branching ratios are given in Tables 2, 3, and 4, in comparison with available data [10].

From Table 2, one can see that our results for the two $f_2$ states agree very well with the data. For the $f_0(1370)$, according to the PDG [10], the $\rho\rho$ mode is dominant. In our approach, however, the $\pi\pi$ mode is dominant, which is consistent with the results of Ref. [11] and the analysis of D. V. Bugg [12]. For the $f_0(1710)$, using the branching ratios given in Table 2, we obtain $\Gamma(\pi\pi)/\Gamma(K\bar{K}) < 1\%$ and $\Gamma(\eta\eta)/\Gamma(K\bar{K}) \sim 49\%$. On the other hand, the PDG gives the following averages: $\Gamma(\pi\pi)/\Gamma(K\bar{K}) = 0.41\pm0.11$, and $\Gamma(\eta\eta)/\Gamma(K\bar{K}) = 0.48 \pm 0.15$ [10]. Our calculated branching ratio for the $\eta\eta$ channel is in agreement with their average, while the ratio for the $\pi\pi$ channel is much smaller. However, we notice that the above PDG $\Gamma(\pi\pi)/\Gamma(K\bar{K})$ ratio is taken from the BES data on $J/\psi \rightarrow \gamma\pi^+\pi^-$ [13], which comes from a partial wave analysis that includes seven resonances. On the other hand, the BES data on $J/\psi \rightarrow \omega K^+K^-$ [14] give an upper limit $\Gamma(\pi\pi)/\Gamma(K\bar{K}) < 11\%$ at the 95% confidence level. Clearly more analysis is advised to settle the issue.

Compared to the decay branching ratios into two pseudoscalar mesons of the isospin 0 states, those of the isospin 1 states with spin either 0 or 2 are relatively small, as shown in Table 3.
Table 2. Branching ratios of the \( f_0(1710) \), \( f_0(1370) \), \( f_2(1270) \), and \( f_2'(1525) \) in comparison with data [10].

|          | \( \Gamma(\pi\pi)/\Gamma(\text{total}) \) | \( \Gamma(\eta\eta)/\Gamma(\text{total}) \) | \( \Gamma(K\bar{K})/\Gamma(\text{total}) \) | \( \Gamma(VV)/\Gamma(\text{total}) \) |
|----------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
|          | Our model | Data | Our model | Data | Our model | Data | Our model | Data |
| \( f_0(1370) \) | \sim 72\% | &lt; 1\% | &lt; 1\% | &sim 10\% | \sim 18\% |
| \( f_0(1710) \) | &lt; 1\% | \sim 27\% | \sim 55\% | &lt; 1\% | &lt; 1\% | &sim 10\% | 4.6\% | &lt; 1\% |
| \( f_2(1270) \) | \sim 88\% | 84.8\% | &lt; 1\% | &lt; 1\% | \sim 10\% | \sim 18\% |
| \( f_2'(1525) \) | &lt; 1\% | 0.8\% | \sim 21\% | 10.4\% | \sim 66\% | 88.7\% | \sim 13\% |

Table 3. Branching ratios of the \( a_0 \) and \( a_2 \) states.

|          | \( \Gamma(K\bar{K})/\Gamma(\text{total}) \) | \( \Gamma(\pi\eta)/\Gamma(\text{total}) \) | \( \Gamma(VV)/\Gamma(\text{total}) \) |
|----------|---------------------------------|---------------------------------|---------------------------------|
|          | Our model | Data | Our model | Data | Our model | Data |
| \( a_0 \) | \sim 27\% | &lt; 23\% | \sim 50\% |
| \( a_2 \) | \sim 21\% | \sim 17\% | \sim 62\% |

Table 4. Branching ratios of the \( K_0^* \) and \( K_2^*(1430) \) states in comparison with data [10].

|          | \( \Gamma(K\pi)/\Gamma(\text{total}) \) | \( \Gamma(K\eta)/\Gamma(\text{total}) \) | \( \Gamma(VV)/\Gamma(\text{total}) \) |
|----------|---------------------------------|---------------------------------|---------------------------------|
|          | Our model | Data | Our model | Data | Our model | Data |
| \( K_0^* \) | \sim 65\% | &lt; 9\% | \sim 26\% |
| \( K_2^*(1430) \) | \sim 93\% | 49.9\% | \sim 5\% | &lt; 1\% | \sim 2\% |

In Table 4, one can see that the dominant decay mode of the \( K_2^*(1430) \) is \( K\pi \) both theoretically and experimentally. However, other modes, such as \( \rho K \), \( K^*\pi \), and \( K^*\pi\pi \), account for half of its decay width according to the PDG [10]. This is consistent with the fact that our \( K_2^*(1430) \) is narrower than its experimental counterpart, as can be seen from Table 1.

The three spin 1 states with the quantum numbers of \( h_1 \), \( b_1 \) and \( K_1 \), do not decay into two pseudoscalars in our approach since the box diagrams do not contribute as explained in Ref. [3].

It is interesting to note that out of the 21 combinations of strangeness, isospin and spin, we have found resonances only in nine of them. In all the “exotic” channels, from the point of view that they cannot be formed from \( q\bar{q} \) combinations, we do not find dynamically generated resonances, including the three (strangeness=0, isospin=2) channels, the three (strangeness=1, isospin=3/2) channels, the six strangeness=2 channels (with either isospin=0 or isospin=1).

On the other hand, there do exist some structures on the real axis. For instance, in the (strangeness=0, isospin=2) channel, one finds a dip around \( \sqrt{s} = 1300 \) MeV in the spin=0 channel, and a broad bump in the spin=2 channel around \( \sqrt{s} = 1400 \) MeV, as can be clearly seen from Fig. 7 of Ref. [3]. In the (strangeness=1, isospin=3/2) and (strangeness=2, isospin=1) channels, one observes similar structures occurring at shifted energies due to the different masses of the \( \rho \) and the \( K^* \), as can be seen from Figs. 8 and 9 of Ref. [3]. However, these states do not correspond to poles on the complex plane, and hence, according to the common criteria, they do not qualify as resonances.
4. Further applications

One of the appealing features of the coupled channel unitary approach is that one can make many predictions concerning properties of the dynamically generated resonances, as well as rates of production in different reactions. This is so because these states are molecular states of ground state meson or baryon components, with well known couplings to external sources which allow one to obtain the coupling of the resonances to these sources. As examples there has been work on the radiative decay of the resonances reported here to two photons, or one vector and one photon in [15, 16], with good agreement with experiment whenever comparison is possible. Similarly, in [17] there has been work on the decay modes of the $J/\psi$ into a vector meson ($\phi$, $\omega$ or $K^{*0}$) and a tensor meson, taking into account the nature of the $f_2(1270)$, $f_2^*(1525)$, $K_2^*(1430)$ as dynamically generated states as has been discussed here. The agreement of the predictions, free of any parameter, with the data is fair. Also, the radiative decay modes of the $J/\psi$ into a photon and one of the tensor mesons $f_2(1270)$, $f_2^*(1525)$, as well as the scalar ones $f_0(1370)$ and $f_0(1710)$ has been investigated in [18] and the agreement with data is also acceptable. Similarly, good agreement with the scarce data is found in [19] for the decay of these resonances into a photon and a pseudoscalar meson. In this work it is also found that the association of the $a_2$ state found to the $a_2(1320)$ is a fair assumption.

5. Summary and conclusions

We have presented the results of a study of vector meson-vector meson interaction using a unitary approach. Employing the coupled-channel Bethe-Salpeter equation to unitarize the transition amplitudes provided by the hidden-gauge Lagrangians, we find that 11 states get dynamically generated in nine strangeness-isospin-spin channels. Among them, five states are associated to those reported in the PDG, i.e., the $f_0(1370)$, the $f_0(1710)$, the $f_2(1270)$, the $f_2^*(1525)$, the $K_2^*(1430)$. The association of two other states, the $a_2(1320)$ and the $K_1(1650)$, are likely, but less certain. Four of the 11 dynamically generated states can not be associated with any known states in the PDG. Finally, we also reported on very recent developments, where application of the results to different decays processes has been made. The consistent agreement with data of the results obtained gives progressively strong support for the nature of these resonances as being dynamically generated from the vector-vector interaction.

6. References

[1] J. A. Oller, E. Oset and A. Ramos, Prog. Part. Nucl. Phys. 45, 157 (2000).
[2] R. Molina, D. Nicmorus and E. Oset, Phys. Rev. D 78, 114018 (2008).
[3] L. S. Geng and E. Oset, Phys. Rev. D 79, 074009 (2009).
[4] R. Molina, H. Nagahiro, A. Hosaka, E. Oset, Phys. Rev. D80, 014025 (2009).
[5] P. Gonzalez, E. Oset and J. Vijande, Phys. Rev. C 79, 025209 (2009).
[6] S. Sarkar, B. -X. Sun, E. Oset, M. J. Vicente Vacas, Eur. Phys. J. A44, 431-443 (2010).
[7] E. Oset, A. Ramos, Eur. Phys. J. A44, 445-454 (2010).
[8] M. Bando, T. Kugo, S. Uehara, K. Yamawaki and T. Yanagida, Phys. Rev. Lett. 54, 1215 (1985); M. Bando, T. Kugo and K. Yamawaki, Phys. Rept. 164, 217 (1988); U. G. Meissner, Phys. Rept. 161, 213 (1988).
[9] A. I. Titov, B. Kampfer and B. L. Reznik, Eur. Phys. J. A 7, 543 (2000); A. I. Titov, B. Kampfer and B. L. Reznik, Phys. Rev. C 65, 065202 (2002).
[10] C. Amsler et al. [Particle Data Group], Phys. Lett. B 667, 1 (2008).
[11] M. Albajardejo and J. A. Oller, Phys. Rev. Lett. 101, 252002 (2008).
[12] D. V. Bugg, Eur. Phys. J. C 52, 55 (2007).
[13] M. Ablikim et al., Phys. Lett. B 642, 441 (2006).
[14] M. Ablikim et al. [BES Collaboration], Phys. Lett. B 603 (2004) 138.
[15] H. Nagahiro, J. Yamagata-Sekihara, E. Oset, S. Hirenzaki and R. Molina, Phys. Rev. D 79, 114023 (2009)
[16] T. Branz, L. S. Geng, E. Oset, Phys. Rev. D81, 054037 (2010).
[17] A. Martinez Torres, L. S. Geng, L. R. Dai, B. X. Sun, E. Oset and B. S. Zou, Phys. Lett. B 680, 310 (2009)
[18] L. S. Geng, F. K. Guo, C. Hanhart, R. Molina, E. Oset, B. S. Zou, Eur. Phys. J. A44, 305-311 (2010).
[19] R. Molina, H. Nagahiro, A. Hosaka, E. Oset, Phys. Rev. D83, 094030 (2011).