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## RECENT DEVELOPMENTS IN CHIRAL UNITARY DYNAMICS OF RESONANCES

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In this talk I summarize recent findings made on the description of axial vector mesons as dynamically generated states from the interaction of pseudoscalar mesons and vector mesons, dedicating some attention to the two  $K_1(1270)$  states. Then I review the generation of open and hidden charm scalar and axial states. Finally, I present recent results showing that the low lying  $1/2^+$  baryon resonances for  $S=-1$  can be obtained as bound states or resonances of two mesons and one baryon in coupled channels dynamics.

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### 1. Introduction

The combination of nonperturbative unitary techniques in coupled channels with the QCD information contained in the chiral Lagrangians has allowed one to extend the application domain of traditional Chiral Perturbation theory to a much larger range of energies where many low lying meson and baryon resonances appear. For instance, for the interactions between the members of the lightest octet of pseudoscalars, one starts with the chiral Lagrangian of ref. <sup>1,2</sup> and selects the set of channels that couple to certain quantum numbers. Then, independently of using either the Bethe-Salpeter equation in coupled channels <sup>3</sup>, the N/D method <sup>4</sup> or the Inverse Amplitude one <sup>5</sup>, the well known scalar resonances  $\sigma(600)$ ,  $f_0(980)$ ,  $a_0(980)$  and  $\kappa(800)$  appear as poles in the obtained  $L=0$  meson-meson partial waves. These resonances are not introduced by hand, they appear naturally as a consequence of the meson interaction and they qualify as ordinary bound states or resonances in

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coupled channels. These are states that we call dynamically generated, by contrast to other states which would rather qualify as  $q\bar{q}$  states, such as the  $\rho$ . Similarly, in the baryon sector, the interaction of the pseudoscalar mesons with baryons of the octet of the proton generates dynamically  $1/2^-$  resonances<sup>6,7,8,9,10,11</sup> and the interaction of the pseudoscalar mesons with baryons of the decuplet of the  $\Delta$  generates  $3/2^-$  resonances<sup>12,13</sup>. These last two cases can be unified using SU(6) symmetry as done in<sup>14</sup>. This field has proved quite productive and has been further expanded by combining pseudoscalar mesons with vector mesons, which lead to the dynamical generation of axial vector mesons like the  $a_1(1260)$ ,  $b_1(1235)$ , etc<sup>15,16</sup>. Also in the charm sector one has obtained in this way scalar mesons with charm, like the  $D_{s0}(2317)$ <sup>17,18,19,20</sup>, axial vector mesons with charm like the  $Ds_1(2460)$ <sup>15,21,22</sup>, or hidden charm scalars like a predicted  $X(3700)$  state and two hidden charm axial states, with opposite C-parity, one of which corresponds to the  $X(3872)$  state. In what follows we briefly discuss these latter cases.

## 2. Axial vector mesons dynamically generated

As shown in detail in<sup>15,16</sup>, starting from a standard chiral Lagrangian for the interaction of pseudoscalar mesons of the octet of the  $\pi$  and vector mesons of the octet of the  $\rho$ , and unitarizing in coupled channels solving the coupled Bethe-Salpeter equations, one obtains the scattering matrix for pseudoscalar mesons with vectors for different quantum numbers, which contains poles that can be associated to known resonances like the  $a_1(1260)$ ,  $b_1(1235)$ , etc. The SU(3) decomposition of  $8 \times 8$

$$8 \times 8 = 1 + 8_s + 8_a + 10 + \overline{10} + 27 \quad (1)$$

leads here to two octets, unlike in the case of the interaction of pseudoscalars among themselves where there is only room for the  $8_s$  representation. This is why here one finds different G-parity states like the  $a_1$  and  $b_1$ , the  $f_1(1285)$ ,  $h_1(1380)$ , plus an extra  $h_1(1170)$  that one can identify with the singlet state. One should then find two  $K_1$  states, which do not have defined G-parity. One might think that these states are the  $K_1(1270)$  and the  $K_1(1400)$  states. However the theory fails to predict a state with such a large mass as the  $K_1(1400)$  and with its decay properties. Instead, in<sup>16</sup> two states were found with masses close by, given, after some fine tuning, by 1197 MeV and 1284 MeV, and widths of about 240 MeV and 140 MeV, respectively. The interesting thing about these states is that the first one couples most strongly to  $K^*\pi$ , while the second state couples most strongly to  $K\rho$ . One could hope that these two states could be observed experimentally. Indeed, this is the case as was shown in the recent work<sup>23</sup> by looking at two reactions which have either  $K^*\pi$  or  $K\rho$  in the final state and which clearly show the peak at different positions, as one can observe in fig. 1.

It is interesting to recall that in the experimental analysis done in<sup>24</sup> only one  $K_1(1270)$  resonance was included (together with the  $K_1(1400)$  which shows up at higher energies), but the background was very large and the peaks appeared from

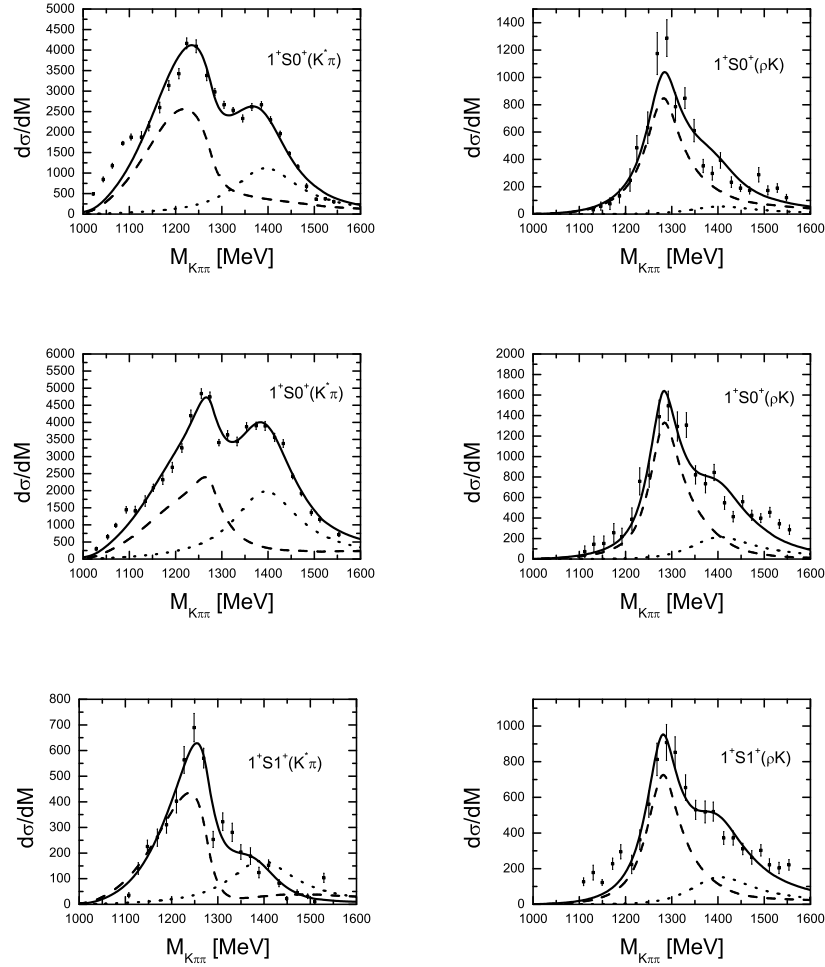


Fig. 1. Results for the  $\pi\pi K$  invariant mass distribution in the  $K^-p \rightarrow K^-\pi^+\pi^-p$  reaction.

interference of large background terms rather than from the effect of the resonance. Instead in <sup>23</sup>, with the introduction of the two resonances obtained in our approach and the background generated by the same chiral unitary approach, together with a contribution from the  $K_1(1400)$  considered phenomenologically, the description of all data in fig 1 follows in a natural way.

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 Table 1: Pole positions for the model. The column Irrep shows the results in the  $SU(3)$  limit.

C	Irrep Mass (MeV)	S	$I(J^P)$	$\text{RE}(\sqrt{s})$ (MeV)	$\text{IM}(\sqrt{s})$ (MeV)	Resonance ID
1	$\bar{3}$ 2327.96	1	$0(0^+)$	2317.25	0	$D_{s0}^*(2317)$
		0	$\frac{1}{2}(0^+)$	2129.26	-157.00	$D_0^*(2400)$
	6 2394.87 -i219.33	1	$1(0^+)$	2704.31	-459.50	(?)
		0	$\frac{1}{2}(0^+)$	2694.69	-441.89	(?)
		-1	$0(0^+)$	2709.39	-445.73	(?)
0	1	0	$0(0^+)$	3718.93	-0.06	(?)

### 3. Dynamically generated scalar mesons with open and hidden charm

A generalization to  $SU(4)$  of the  $SU(3)$  chiral Lagrangian for meson-meson interaction is done in <sup>20</sup> to study meson-meson interaction including charm. The breaking of  $SU(4)$  is done as in <sup>25,26</sup>, where the crossed exchange of vector mesons is employed as it accounts phenomenologically for the Weinberg-Tomozawa term in the chiral Lagrangians. With this in mind, when the exchange is due to a heavy vector meson the corresponding term is corrected by the ratio of square masses of the light vector meson to the heavy one (vectors with a charmed quark). We also use a different pattern of  $SU(4)$  symmetry breaking by following the lines of a chiral motivated model with general  $SU(N)$  breaking <sup>27</sup>. The picture generalizes the model used in <sup>17,18,19</sup>, where only the light vector mesons are exchanged. The same states generated in <sup>12,19</sup> are also generated in <sup>20</sup> with some changes, but in addition one obtains states with hidden charm. The changes refer to the states of the sextet, which in <sup>20</sup> appear rather broad, while in the other works are narrow states. In table 1 we show the states with charm or hidden charm obtained in the approach.

As we can see, the  $D_{s0}(2317)$  and  $D_0(2400)$  appear in the approach, the last one at lower energies than experiment, but consistent with the data considering the large width of the state and the theoretical and experimental uncertainties on the mass. The other three charm states in the table come from a sextet and they are very broad in our approach ( $\Gamma \sim \text{IM}(\sqrt{s})$ ).

The very interesting and novel thing with respect to other theoretical works is the heavy state with zero charm. It is a hidden charm state mostly built from  $D\bar{D}$  and  $D_s\bar{D}_s$ . The fact that this state has such a narrow width in spite of having all the meson-meson states of the light sector open for decay, is an interesting consequence of the work, which largely decouples the light sector from the heavy one respecting basic OZI rules. There is no experimental information on this state now, but an enhancement of the cross section of the  $e^+e^- \rightarrow J/\psi D\bar{D}$  close to threshold seen in

Table 2: Pole positions for the model. The column Irrep shows the results in the  $SU(3)$  limit. The results in brackets for the  $Im\sqrt{s}$  are obtained taking into account the finite width of the  $\rho$  and  $K^*$  mesons.

C	Irrep Mass (MeV)	S	$I^G(J^{PC})$	RE( $\sqrt{s}$ ) (MeV)	IM( $\sqrt{s}$ ) (MeV)	Resonance ID
1	3 2432.63	1	$0(1^+)$	2455.91	0	$D_{s1}(2460)$
		0	$\frac{1}{2}(1^+)$	2311.24	-115.68	$D_1(2430)$
	6 2532.57 -i199.36	1	$1(1^+)$	2529.30	-238.56	(?)
		0	$\frac{1}{2}(1^+)$	Cusp (2607)	Broad	(?)
		-1	$0(1^+)$	Cusp (2503)	Broad	(?)
	3 2535.07 -i0.08	1	$0(1^+)$	2573.62	-0.07 [-0.07]	$D_{s1}(2536)$
		0	$\frac{1}{2}(1^+)$	2526.47	-0.08 [-13]	$D_1(2420)$
	6 Cusp (2700) Narrow	1	$1(1^+)$	2756.52	-32.95 [cusp]	(?)
		0	$\frac{1}{2}(1^+)$	2750.22	-99.91 [-101]	(?)
		-1	$0(1^+)$	2756.08	-2.15 [-92]	(?)
0	1 3867.59	0	$0^+(1^{++})$	3837.57	-0.00	$X(3872)$
	1 3864.62	0	$0^-(1^{+-})$	3840.69	-1.60	(?)

<sup>28</sup> could be interpreted in <sup>29</sup> as a consequence of the effect close to  $D\bar{D}$  threshold of the  $X(3700)$ , a bound state below threshold.

#### 4. Dynamically generated axial vector mesons with open and hidden charm

With the interaction of pseudoscalar mesons with vector mesons in <sup>22</sup> one obtains the results shown in Table 2. In addition to the well known  $D_{s1}(2460)$ ,  $D_1(2430)$ ,  $D_{s1}(2536)$  and  $D_1(2420)$  (and all those in the light sector already found in <sup>15,16</sup>) one obtains new states, which could be observed, although some of them are either too broad or correspond to cusps.

Very interesting and novel of the present approach is the generation of the  $X(3872)$  with positive C-parity and another state nearly degenerate with negative C-parity. It would be interesting to see if a state with negative C-parity is observed, but the large branching fraction

$$\frac{B(X \rightarrow \pi^+\pi^-\pi^0 J/\psi)}{B(X \rightarrow \pi^+\pi^- J/\psi)} = 1.0 \pm 0.4 \pm 0.3 \quad (2)$$

indicates either a very large G-parity (isospin) violation (quite unlikely), or the existence of another state with different C-parity (G-parity also in this case).

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### 5. Dynamically generated $1/2^+$ baryon states from the interaction of two mesons and one baryon

We discussed before how the low lying  $1/2^-$  baryon resonances appear dynamically generated in the chiral unitary approach. The low lying  $1/2^+$  resonances are not less problematic and quark models have difficulties in reproducing them<sup>30</sup>. Experimentally some of them are poorly understood, few of them possess four-star status and three possess three-star status. Among the rest some resonances are listed with unknown spin parity and two are controversial in nature. The situation is slightly better with the  $\Lambda$  resonances in the same energy region, except for the  $\Lambda(1600)$  and  $\Lambda(1810)$ , where the peak positions and widths, obtained by different partial wave analysis groups, vary a lot. Many of these  $S=-1$  states seem to have significant branching ratios for three-body, i.e., two meson-one baryon, decay channels. However, no theoretical attempt has been made to study the three body structure of these resonances, until recently when a coupled channel calculation for two meson one baryon system was carried out using chiral dynamics<sup>32</sup>.

### 6. Formalism for the three body systems

We take advantage of the fact that there are strong correlations in the meson baryon sector in  $L=0$ , and with  $S=-1$  one obtains many  $1/2^-$  resonances. The  $\Lambda(1405) S_{01}$  ( $J^P = 1/2^-$ ) couples strongly to the  $\pi - \Sigma$  and its coupled channels. Considering this we build the three body coupled channels by adding a pion to combinations of a pseudoscalar meson of the  $0^-$  SU(3) octet and a baryon of the  $1/2^+$  octet which couple to  $S = -1$ . For the total charge zero of the three body system we get twenty-two coupled channels.

To solve the Faddeev equations we write the two body  $t$ -matrices using unitary chiral dynamics. These  $t$ -matrices can be split into an on-shell part, depending only on the respective center of mass energy, and an off-shell part, which is inversely proportional to the propagator of the off-shell particle. This off-shell part cancels a propagator in the three body scattering diagrams, leading to a diagram with a topological structure equivalent to that of a three body force<sup>32</sup>. To this, one must add the three body forces originating directly from the chiral Lagrangians. Interestingly, in our case, we find the three forces from the two sources to get canceled in the SU(3) limit and in case of low momentum transfer to the baryon. In a realistic case, we find them to sum-up to merely 5 % of the total on-shell contribution of the  $t$ -matrices to the Faddeev equations. The formalism is thus developed further in terms of the on-shell parts of the two body  $t$ -matrices.

We begin with Faddeev equations

$$T^i = t^i \delta^3(\vec{k}'_i - \vec{k}_i) + t^i g [T^j + T^k], \quad (3)$$

which if iterated while neglecting the terms with  $\delta^3(\vec{k}'_i - \vec{k}_i)$ , which correspond to the disconnected diagrams, will give

$$T^i = t^i g^{ij} t^j + t^i g^{ik} t^k + t^i g^{ij} t^j g^{jk} t^k + t^i g^{ij} t^j g^{ji} t^i + t^i g^{ik} t^k g^{kj} t^j + t^i g^{ik} t^k g^{ki} t^i + \dots$$

In order to factorize the Faddeev equations one writes the terms with three successive interactions explicitly, which already involve a loop evaluation. One finds technically how to go from the diagrams with two interactions to those with three interactions and the algorithm found is then used for the next iterations, leading thus to a set of algebraic equations, which are solved within twenty two coupled channels.

The resulting equations have been solved with the input two body  $t$ -matrices obtained by solving the Bethe-Salpeter equation as in <sup>3,7,34</sup>. We find four  $\Sigma$  and two  $\Lambda$  states <sup>31</sup> as dynamically generated resonances in the two meson-one baryon systems, implying a strong coupling of the  $S=-1$  resonances, in this region, to the three body decay channels. In Fig. 2, we show one of the resonances, corresponding to the  $\Sigma(1660)$  <sup>31</sup> found in our study in the squared amplitude for the  $\pi^0\pi^0\Sigma^0$  channel. In addition to this, we find evidence for (1) another  $1/2^+$  resonance, i.e., the  $\Sigma(1770)$ , (2) for the controversial  $\Sigma(1620)$  and (3) for the  $\Sigma(1560)$ , which is listed with unknown spin-parity <sup>31</sup>. In the isospin 0 sector we find evidence for the  $\Lambda(1600)$  and  $\Lambda(1810)$ . To conclude, we are finding a new picture for the low lying  $1/2^+$  baryon states which largely correspond to bound states or resonances of two mesons and a baryon.

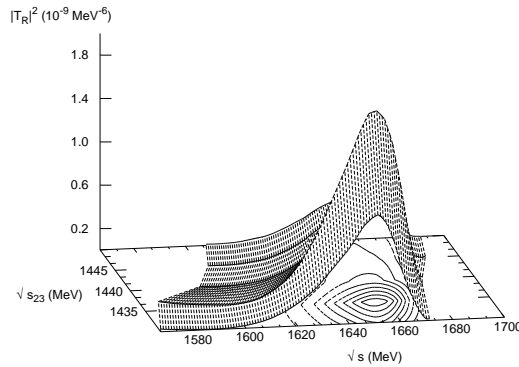


Fig. 2. The  $\Sigma(1660)$  resonance in the  $\pi^0\pi^0\Sigma^0$  channel.

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