Baryon Resonances

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Abstract

In this talk I show recent results on how many excited baryon resonances appear as systems of one meson and one baryon, or two mesons and one baryon, with the mesons being either pseudoscalar or vectors. Connection with experiment is made including a discussion on old predictions and recent results for the photoproduction of the $\Lambda(1405)$ resonance, as well as the prediction of one $1/2^+$ baryon state around 1920 MeV which might have been seen in the $\gamma p \to K^+\Lambda$ reaction.

Key words: dynamically generated resonances, chiral dynamics, hidden gauge formalism for vector meson interaction.
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1. Introduction.

The realization that the dynamics of QCD in the hadron world can be addressed at low energies by means of effective theories in which the building blocks are the ground state mesons and baryons [1] has produced tools to address the interaction of mesons or mesons and baryons, mainly through chiral Lagrangians, which have had a tremendous impact in our understanding of the spectrum of mesons and baryon resonances. We all accept that ground states of mesons and baryons are made of $q\bar{q}$ or three q respectively. Yet, the spectrum of excited hadronic states can be much richer as we shall see.

The building blocks in these chiral theories are the low energy hadrons, such as the proton and baryons of its SU(3) octet. To these one adds also the decuplet of the Δ, considered as spin realignments of the three quark ground state. The basic mesons are the pion and mesons of its octet, to which one also adds the nonet of the ρ, which also corresponds to spin realignments of the $q\bar{q}$ ground state .

What about baryon resonances? The logical answer is that they are excitations of the quarks, which is the essence of quark models. This is plausible, but things could be more complicated.

Let us recall basic facts from the baryon spectrum. The first excited N^* states are the $N^*(1440)$ $(1/2^+)$ and the $N^*(1535)$ $(1/2^-)$. In quark models this will require quark excitation of around 500-600 MeV. If this is the case, one may think that it takes less energy to create one pion, or two (140-280 MeV). The question is whether they can be bound or get trapped in a resonant state. How do we know if this can occur? We need dynamics, a potential for the interaction of mesons with ground state baryons and then solve the Schroedinger equation (Bethe Salpeter equation with mesons treated relativistically) in coupled channels. This information can be extracted from chiral Lagrangians: the effective theory of QCD at low energies. This is the philosophy behind the idea of dynamically generated baryons: Many resonances are generated in this way, like the $1/2^-$ states from meson baryon: $N^*(1535)$ [2], two $\Lambda(1405)$ [3] or the $1/2^+$ states from two mesons and a baryon, like the $N^*(1710)$ and others [4, 5].

From the pseudoscalar-baryon octet interaction there are many states generated and one sees them as peaks in the scattering matrices or poles in the complex plane [2, 6, 7, 8, 9, 10, 11, 12]. A feature of the chiral unitary approach is its great predictive power, with the risk that some of the predictions might not be fulfilled in Nature. But, so far, predictions are corroborated in production reactions, partial decay rates, meson baryon scattering amplitudes, helicity amplitudes, transition form factors [13, 14]. As an example we recall in the next section some of the early calculations on photoproduction of the $\Lambda(1405)$, taking advantage that two experiments are now reported in this Conference ten years after the predictions were made.

2. Photoproduction of the $\Lambda(1405)$

Ten years ago, with Spring8/Osaka in its initial stage, an application of the chiral unitary approach was made to predict cross sections for photoproduction of the $\Lambda(1405)$ [15] in the $\gamma p \to K^+\Sigma^+\pi^-$, $\gamma p \to K^+\Sigma^-\pi^+$, $\gamma p \to K^+\Sigma^0\pi^0$ reactions. The cross sections found were within measurable range, the $\Lambda(1405)$ could be clearly seen in the $\pi\Sigma$ mass distribution, as usual, and the signal was much larger than the background. The experiment was early started at Spring8 and preliminary results were shown in 2003 [16]. Five years later final results were published in [17], which have been reported in this Conference [18]. Also Jeff Lab has carried out the experiment with a different set up and the results have also been presented in this Conference [19]. The model used in [15] was a minimal model, in which only the $\gamma p K^+ PB$ vertex coming from minimal coupling, with P and B a pseudoscalar meson from the octet of the π and B a baryon of the octet of the p, was used. Possible effects of baryon resonances in the γp entrance channels were neglected. In spite of this, the agreement of data with the predictions is quite fair. A large signal is seen with small background. The size of the cross section is within 50 % of the predictions. In adidtion, the observed $\Sigma^+\pi^-$, $\Sigma^-\pi^+$ distributions are not equal; they are shifted by a few MeV as predicted. This is a consequence of the effect of an isospin I=1 amplitude, which acts constructively in one case and destructively in the other. The $\gamma p \to K^+\Sigma^0\pi^0$ was predicted to be roughly the average of the other two cross sections. The details of the recent experiments can be seen in the devoted talks [18, 19] and are rather interesting. A remarkable thing is that the peak positions for $\Sigma^+\pi^-$, $\Sigma^-\pi^+$ production seem to be reversed in [19] than predicted, and in [18] they seem to be angle dependent, with opposite trends at forward and backward angles.

The new experimental information obtained calls for a theoretical revival of the theory to the light of the findings made in chiral unitary approaches in the last decade. At stake are issues like the nature of the $\Lambda(1405)$ resonance, the existence of the two $\Lambda(1405)$ resonances for which experimental evidence has been claimed [20, 21], and the possibility that the I=1 amplitude, which is clearly visible in the different $\Sigma^+\pi^-$, $\Sigma^-\pi^+$ cross sections, could be of resonant character, evidencing a new Σ resonance around 1400 MeV, for which hints were seen in [3, 22]. Recent claims for this resonance have been made in [23] from the study of the $K^-p \to \Lambda\pi^+\pi^-$ reaction.

3. Resonances from the interaction of vector mesons with baryons

This is a very novel development since, as we shall see, some of the high mass baryon resonances can be represented like bound states of vector mesons and baryons, either from the octet of stable baryons or the decuplet.

3.1. Formalism

We follow the formalism of the hidden gauge interaction for vector mesons of [24, 25, 26] (see also [27] for a practical set of Feynman rules). The Lagrangian involving the interaction of vector mesons amongst themselves is given by

$$\mathcal{L}_{III} = -\frac{1}{4}\langle V_{\mu\nu}V^{\mu\nu}\rangle \;, \tag{1}$$

where the symbol $\langle\rangle$ stands for the trace in the $SU(3)$ space and $V_{\mu\nu}$ is given by

$$V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu - ig[V_\mu, V_\nu] \;, \tag{2}$$

where g is $g = \frac{M_V}{2f}$, with $f = 93$ MeV the pion decay constant. The magnitude V_μ is the ordinary $SU(3)$ matrix of the vectors of the octet of the ρ

The lagrangian $\mathcal{L}_{III}$ gives rise to a contact term coming from $[V_\mu, V_\nu][V_\mu, V_\nu]$, as well as to a three vector vertex

$$\mathcal{L}^{(c)}_{III} = \frac{g^2}{2}\langle V_\mu V_\nu V^\mu V^\nu - V_\nu V_\mu V^\mu V^\nu\rangle \;; \;\; \mathcal{L}^{(3V)}_{III} = ig\langle(V^\mu\partial_\nu V_\mu - \partial_\nu V_\mu V^\mu)V^\nu\rangle, \tag{3}$$

In this case one finds an analogy to the coupling of vectors to pseudoscalars given in the same theory by

$$\mathcal{L}_{VPP} = -ig\langle[P, \partial_\nu P]V^\nu\rangle \;, \tag{4}$$

where P is the SU(3) matrix of the pseudoscalar fields.

In a similar way, one obtains the Lagrangian for the coupling of vector mesons to the baryon octet given by [28, 29] [1]

$$\mathcal{L}_{BBV} = g\left(\langle\bar{B}\gamma_\mu[V^\mu, B]\rangle + \langle\bar{B}\gamma_\mu B\rangle\langle V^\mu\rangle\right) \tag{5}$$

where B is now the ordinary SU(3) matrix of the baryon octet

With these ingredients we can construct the Feynman diagrams that lead to the $PB \to PB$ and $VB \to VB$ interaction, by exchanging a vector meson between the pseudoscalar or the vector meson and the baryon, as depicted in Fig. 1.

From the diagram of Fig. 1(a), and under the low energy approximation of neglecting q^2/M_V^2 in the propagator of the exchanged vector, where q is the momentum transfer, one obtains the same amplitudes as obtained from the ordinary chiral Lagrangian for pseudoscalar-baryon octet interaction, namely the Weinberg-Tomozawa terms. The approximation of neglecting the three momenta of the vectors implies that V^ν in eq. (3) corresponds to the exchanged vector and the analogy with eq. (4) is more apparent. Note that $\epsilon_\mu\epsilon^\mu$ becomes $-\vec{\epsilon}\,\vec{\epsilon}\,'$ and the signs of the Lagrangians also agree.

[1] Correcting a misprint in [28]

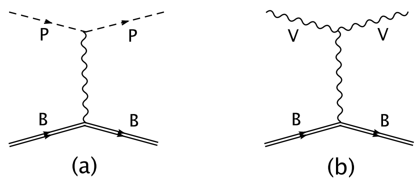

Figure 1: Diagrams contributing to the pseudoscalar-baryon (a) or vector- baryon (b) interaction via the exchange of a vector meson.

A small amendment is in order in the case of vector mesons, which is due to the mixing of ω_8 and the singlet of SU(3), ω_1, to give the physical states of the ω and the ϕ mesons. The practical rule is simple and can be found in [30]. Upon the approximation consistent with neglecting the three momentum versus the mass of the particles (in this case the baryon), we can just take the γ^0 component of Eq. (5) and then the transition potential corresponding to the diagram of 1(b) is given by

$$V_{ij} = -C_{ij}\,\frac{1}{4f^2}\left(k^0 + k'^0\right)\,\vec{\epsilon}\,\vec{\epsilon}\,' \tag{6}$$

where k^0, k'^0 are the energies of the incoming and outgoing vector meson. The C_{ij} coefficients of eq. (6) can also be found in [30], where one can see that the cases with $(I, S) = (3/2, 0)$, $(2, -1)$ and $(3/2, -2)$, the last two corresponding to exotic channels, have a repulsive interaction and do not produce poles in the scattering matrices. However, the sectors $(I, S) = (1/2, 0)$, $(0, -1)$, $(1, -1)$ and $(1/2, -2)$ are attractive and one finds bound states and resonances in these cases.

The scattering matrix is obtained solving the coupled channels Bethe Salpeter equation in the on shell factorization approach of [6, 22]

$$T = [1 - V G]^{-1}\, V \tag{7}$$

with G being the loop function of a vector meson and a baryon. This function is convoluted with the spectral function of the vector mesons to take into account their width as done in [31].

In this case the factor $\vec{\epsilon}\,\vec{\epsilon}\,'$, appearing in the potential V, factorizes also in the T matrix for the external vector mesons. This trivial spin structure is responsible for having degenerate states with spin-parity $1/2^-, 3/2^-$ for the interaction of vectors with the octet of baryons and $1/2^-, 3/2^-, 5/2^-$ for the interaction of vectors with the decuplet of baryons.

What we have done here for the interaction of vectors with the octet of baryons can be done for the interaction of vectors with the decuplet of baryons, and the interaction is obtained directly from that of the pseudoscalar-decuplet of baryons studied in [32, 33]. The study of this interaction in [34, 35] leads also to the generation of many resonances which are described below.

We search for poles in the scattering matrices in the second Riemann sheet, as defined in previous works [36].

3.2. Results

In table 1 we show a summary of the results obtained from the interaction of vectors with the octet of baryons [30] and the tentative association to known states [37].

For the $(I, S) = (1/2, 0)$ N^* states there is the $N^*(1700)$ with $J^P = 3/2^-$, which could correspond to the state we find with the same quantum numbers around the same energy. We also find

I, S	Theory			PDG data				
	pole position	real axis mass	width	name	J^P	status	mass	width
$1/2, 0$	—	1696	92	$N(1650)$	$1/2^-$	★★★★	1645-1670	145-185
				$N(1700)$	$3/2^-$	★★★	1650-1750	50-150
	1977 + i53	1972	64	$N(2080)$	$3/2^-$	★★	$\approx$ 2080	180-450
				$N(2090)$	$1/2^-$	★	$\approx$ 2090	100-400
$0, -1$	1784 + i4	1783	9	$\Lambda(1690)$	$3/2^-$	★★★★	1685-1695	50-70
				$\Lambda(1800)$	$1/2^-$	★★★	1720-1850	200-400
	1907 + i70	1900	54	$\Lambda(2000)$	$?^?$	★	$\approx$ 2000	73-240
	2158 + i13	2158	23					
$1, -1$	—	1830	42	$\Sigma(1750)$	$1/2^-$	★★★	1730-1800	60-160
	—	1987	240	$\Sigma(1940)$	$3/2^-$	★★★	1900-1950	150-300
				$\Sigma(2000)$	$1/2^-$	★	$\approx$ 2000	100-450
$1/2, -2$	2039 + i67	2039	64	$\Xi(1950)$	$?^?$	★★★	1950 $\pm$ 15	60 $\pm$ 20
	2083 + i31	2077	29	$\Xi(2120)$	$?^?$	★	$\approx$ 2120	25

Table 1: The properties of the 9 dynamically generated resonances and their possible PDG counterparts.

in the PDG the $N^*(1650)$, which could be the near degenerate spin parter of the $N^*(1700)$ that we predict in the theory. It is interesting to recall that in the study of Ref. [38] a pole is found around 1700 MeV, with the largest coupling to ρN states. Around 2000 MeV, where we find another N^* resonance, there are the states $N^*(2080)$ and $N^*(2090)$, with $J^P = 3/2^-$ and $J^P = 1/2^-$ respectively, showing a good approximate spin degeneracy.

For the case $(I, S) = (0, -1)$ there is in the PDG one state, the $\Lambda(1800)$ with $J^P = 1/2^-$, remarkably close to the energy were we find a Λ state. The state obtained around 1900 MeV could correspond to the $\Lambda(2000)$ cataloged in the PDG with unknown spin and parity.

The case of the Σ states having $(I, S) = (1, -1)$ is rather interesting. The state that we find around 1830 MeV, could be associated to the $\Sigma(1750)$ with $J^P = 1/2^-$. More interesting seems to be the case of the state obtained around 1990 MeV that could be related to two PDG candidates, again nearly degenerate, the $\Sigma(1940)$ and the $\Sigma(2000)$, with spin and parity $J^P = 3/2^-$ and $J^P = 1/2^-$ respectively.

Finally, for the case of the cascade resonances, $(I, S) = (1/2, -2)$, we find two states, one around 2040 MeV and the other one around 2080 MeV. There are two cascade states in the PDG around this energy region with spin parity unknown, the $\Xi(1950)$ and the $\Xi(2120)$. Although the experimental knowledge of this sector is relatively poor, a program is presently running at Jefferson Lab to improve on this situation [39].

The case of the vector interaction with the decuplet is similar [33] and we show the results in

Table 2

S, I	Theory			PDG data				
	pole position	real axis		name	J^P	status	mass	width
		mass	width					
$0, 1/2$	$1850 + i5$	1850	11	$N(2090)$	$1/2^-$	⋆	1880-2180	95-414
				$N(2080)$	$3/2^-$	⋆⋆	1804-2081	180-450
		2270(*bump*)		$N(2200)$	$5/2^-$	⋆⋆	1900-2228	130-400
$0, 3/2$	$1972 + i49$	1971	52	$\Delta(1900)$	$1/2^-$	⋆⋆	1850-1950	140-240
				$\Delta(1940)$	$3/2^-$	⋆	1940-2057	198-460
				$\Delta(1930)$	$5/2^-$	⋆ ⋆ ⋆	1900-2020	220-500
		2200(*bump*)		$\Delta(2150)$	$1/2^-$	⋆	2050-2200	120-200
$-1, 0$	$2052 + i10$	2050	19	$\Lambda(2000)$	$?^?$	⋆	1935-2030	73-180
$-1, 1$	$1987 + i1$	1985	10	$\Sigma(1940)$	$3/2^-$	⋆ ⋆ ⋆	1900-1950	150-300
	$2145 + i58$	2144	57	$\Sigma(2000)$	$1/2^-$	⋆	1944-2004	116-413
	$2383 + i73$	2370	99	$\Sigma(2250)$	$?^?$	⋆ ⋆ ⋆	2210-2280	60-150
				$\Sigma(2455)$	$?^?$	⋆⋆	2455±10	100-140
$-2, 1/2$	$2214 + i4$	2215	9	$\Xi(2250)$	$?^?$	⋆⋆	2189-2295	30-130
	$2305 + i66$	2308	66	$\Xi(2370)$	$?^?$	⋆⋆	2356-2392	75-80
	$2522 + i38$	2512	60	$\Xi(2500)$	$?^?$	⋆	2430-2505	59-150
$-3, 0$	$2449 + i7$	2445	13	$\Omega(2470)$	$?^?$	⋆⋆	2474±12	72±33

Table 2: The properties of the 10 dynamically generated resonances and their possible PDG counterparts. We also include the N^* bump around 2270 MeV and the Δ^* bump around 2200 MeV.

We also can see that in many cases the experiment shows the near degeneracy predicted by the theory. Particularly, the case of the three Δ resonances around 1920 MeV is very interesting. One observes a near degeneracy in the three spins $1/2^-, 3/2^-, 5/2^-$, as the theory predicts. It is also very instructive to recall that the case of the $\Delta(5/2^-)$ is highly problematic in quark models since it has a 3 $\hbar\omega$ excitation and comes out always with a very high mass [34, 40].

The association of states found to some resonances reported in the PDG for the case of Λ, Σ and Ξ states looks also equally appealing as one can see from the table.

The reasonable results reported here produced by the hidden gauge approach should give a stimulus to search experimentally for the missing spin partners of the already observed states, as well as possible new ones.

4. States of two mesons and a baryon

There are two specific talks on this issue in the Workshop [41, 42]. I will summarize a bit the important findings in this area by different groups. In [4, 5] a formalism was developed to study Faddeev equations of systems of two mesons and a stable baryon. The interaction of the pairs was obtained from the chiral unitary approach, which proves quite successful to give the scattering amplitudes of meson-meson and meson-baryon systems in the region of energies of interest to us. The spectacular finding is that, leaving apart the Roper resonance, whose structure is far more elaborate than originally thought [43, 44], all the low lying $J^P = 1/2^+$ excited states are obtained as bound states or resonances of two mesons and one baryon in coupled channels.

Particularly relevant to this Conference is the issue of a possible bound state of $K\bar{K}N$. In [45], using variational methods, the authors found a bound state of $K\bar{K}N$, with the $K\bar{K}$ being in the $a_0(980)$ state [45]. The system was studied a posteriori in [46] and it was found to appear at the same energy and the same configuration, although with a mixture of $f_0(980)N$, see fig. 2. This state appears around 1920 MeV with $J^P = 1/2^+$. In a recent paper [47] some arguments were given to associate this state with the bump that one sees in the $\gamma p \to K^+\Lambda$ reaction around this energy, which is clearly visible in recent accurate experiments [48, 49]. If this association was correct there would be other experimental consequences, as an enhanced strength of the $\gamma p \to K^+K^-p$ cross section close to threshold, as well as a shift of strength close to the $K\bar{K}$ threshold in the invariant mass distribution of the kaon pair. This experiment is right now under study [50]. Another suggestion of [47] is to measure the total γp spin $S_z = 1/2$ and $S_z = 3/2$ amplitudes, the z-direction along the photon momentum, since this would discriminate the cases where the peak around 1920 MeV is due to a $1/2^+$ or a $3/2^+$ resonance.

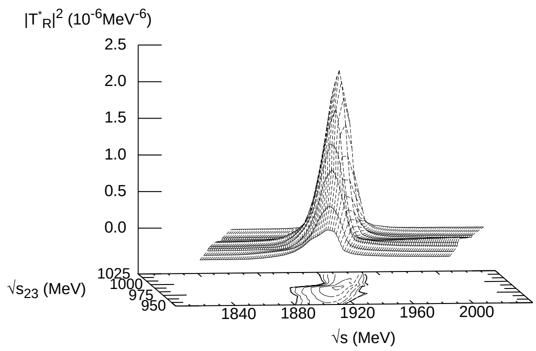

Figure 2: A possible $N^*(1910)$ in the $NK\bar{K}$ channels.

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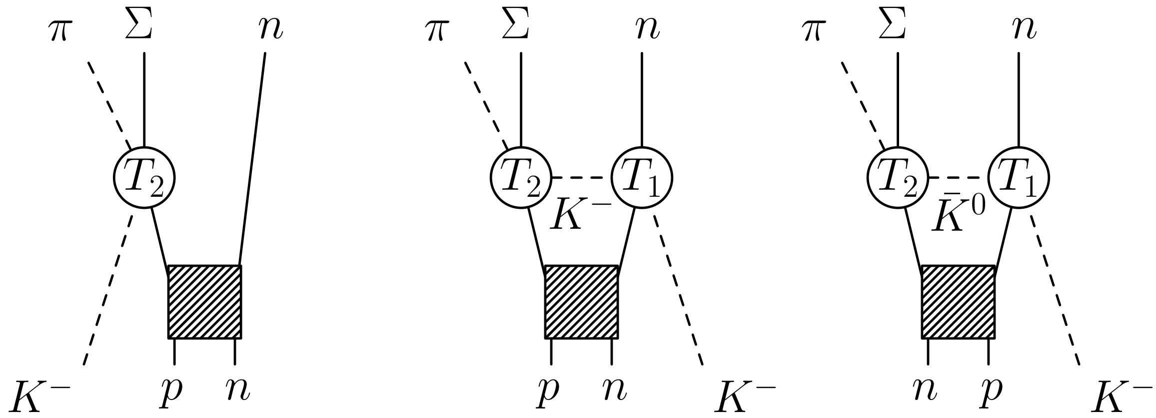
Calc.
Data
dσ/dM$_{\pi\Sigma}$ [arbitrary unit]
1360
1380
1400
1420
1440
M$_{\pi\Sigma}$ [MeV]



Dia. 1 Dia. 2 Dia. 3