PROCEEDINGS OF SCIENCE

Baryonic resonances dynamically generated from the interaction of vector mesons with stable baryons of the decuplet

E. Oset*
Departamento de Física Teórica and IFIC, Centro Mixto Universidad de Valencia-CSIC, Institutos de Investigación de Paterna, Aptdo. 22085, 46071 Valencia, Spain
E-mail: oset@ific.uv.es

P. Gonzalez, M. J. Vicente Vacas
Departamento de Física Teórica and IFIC, Centro Mixto Universidad de Valencia-CSIC, Institutos de Investigación de Paterna, Aptdo. 22085, 46071 Valencia, Spain

A. Ramos
Departament d'Estructura i Constituents de la Materia, Universitat de Barcelona

J. Vijande
Departamento de Fisica Atomica Molecular y Nuclear, and IFIC, Universidad de Valencia

S. Sarkar
Variable Energy Cyclotron Centre, 1/AF, Bidhannagar, Kolkata 700064, India

Bao Xi Sun
Institute of Theoretical Physics, College of Applied Sciences, Beijing University of Technology, Beijing 100124, China

Using the hidden gauge approach for the interaction of vector mesons we evaluate the interaction of vector mesons of the octet of the ρ with the baryons of the Δ decuplet. Scattering amplitudes are calculated, developing poles for some quantum numbers which we associate to baryonic resonances. Many of these states can be associated to known resonances, while others represent predictions for new states. The method is also applied to the interaction of vectors with the octet of baryons with similar results. In total we obtain about twenty resonances of this type, out of which ten of them can clearly be identified with existing resonances, while the other ones are predictions.

6th International Workshop on Chiral Dynamics, CD09
July 6-10, 2009
Bern, Switzerland

*Speaker.

PoS(CD09)053

1. Introduction

The skilful combination of chiral Lagrangians and unitary techniques in coupled channels of mesons and baryons is an efficient tool to study the interaction of hadrons. Following this approach the interaction of the octet of pseudoscalar mesons with the octet of stable baryons has been studied and leads to $J^P = 1/2^-$ resonances which fit quite well the spectrum of the known low lying resonances with these quantum numbers [1, 2, 3, 4, 5]. Similarly the interaction of the octet of pseudoscalar mesons with the decuplet of baryons also leads to many resonances that can be identified with existing ones of $J^P = 3/2^-$ [6, 7]. Sometimes a new resonance is predicted, as in the case of the $\Lambda(1405)$, where all the chiral approaches find two close poles rather than one, for which experimental support is presented in [8] and [9]. Another step forward in this direction has been the interpretation of low lying $J^P = 1/2^+$ states as molecular systems of two pseudoscalar mesons and one baryon [10, 11, 12, 13, 14].

Much work has been done using pseudoscalar mesons as building blocks, but the consideration of vectors instead of pseudoscalars is also catching up. In the baryon sector the interaction of the $\rho\,\Delta$ has been recently addressed in [15], where three degenerate N^* states and three degenerate Δ states around 1900 MeV, with $J^P = 1/2^-, 3/2^-, 5/2^-$, are found. The underlying theory for this study is the hidden gauge formalism [16, 17, 18], which deals with the interaction of vector mesons and pseudoscalars, respecting chiral dynamics, providing the interaction of pseudoscalars among themselves, with vector mesons, and vector mesons among themselves. It also offers a perspective on the chiral Lagrangians as limiting cases at low energies of vector exchange diagrams occurring in the theory. The extrapolation to SU(3) with the interaction of the vectors of the nonet with the baryons of the decuplet has been done in [19].

In the meson sector, the interaction of $\rho\rho$ within this formalism has been addressed in [20], where it has been shown to lead to the dynamical generation of the $f_2(1270)$ and $f_0(1370)$ meson resonances, with a branching ratio for the sensitive $\gamma\gamma$ decay channel in good agreement with experiment [22]. The extrapolation to SU(3) of the work of [20] has been done in [23], where many resonances are obtained, some of which can be associated to known meson states, while there are predictions for new ones. The resonances found in [20, 23] also pass an important test in the decay of J/ψ into $\phi(\omega)$ plus one of the resonances generated in [20, 23], as shown in [24].

In this talk we present the results of the interaction of the nonet of vector mesons with the decuplet of baryons [19] and with the octet of baryons [25], which have been done using the unitary approach in coupled channels. The scattering amplitudes lead to poles in the complex plane which can be associated to some well known resonances. Under the approximation of neglecting the three momentum of the particles versus their mass, implicit in the chiral Lagrangians, we obtain degenerate states of $J^P = 1/2^-, 3/2^-$ for the case of the interaction with the octet of baryons and $J^P = 1/2^-, 3/2^-, 5/2^-$ for the case of the interaction with the baryons of the decuplet. This degeneracy seems to be followed qualitatively by the experimental spectrum, although in some cases the spin partners have not been identified.

2. Formalism for VV interaction

We follow the formalism of the hidden gauge interaction for vector mesons of [16, 17] (see also [26] for a practical set of Feynman rules). The Lagrangian involving the interaction of vector mesons amongst themselves is given by

$$\mathcal{L}_{III} = -\frac{1}{4}\langle V_{\mu\nu} V^{\mu\nu}\rangle \ , \tag{2.1}$$

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

$$V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu - ig[V_\mu, V_\nu] \ , \tag{2.2}$$

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

$$V_\mu = \begin{pmatrix} \frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & \rho^+ & K^{*+} \\ \rho^- & -\frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & K^{*0} \\ K^{*-} & \bar{K}^{*0} & \phi \end{pmatrix}_\mu \ . \tag{2.3}$$

The interaction of $\mathcal{L}_{III}$ gives rise to a contact term coming from $[V_\mu, V_\nu][V_\mu, V_\nu]$

$$\mathcal{L}^{(c)}_{III} = \frac{g^2}{2}\langle V_\mu V_\nu V^\mu V^\nu - V_\nu V_\mu V^\mu V^\nu\rangle \ , \tag{2.4}$$

and on the other hand it gives rise to a three vector vertex from

$$\mathcal{L}^{(3V)}_{III} = ig\langle(\partial_\mu V_\nu - \partial_\nu V_\mu)V^\mu V^\nu\rangle = ig\langle(V^\mu \partial_\nu V_\mu - \partial_\nu V_\mu V^\mu)V^\nu\rangle \ , \tag{2.5}$$

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

$$\mathcal{L}_{VPP} = -ig\ tr\left([P, \partial_\mu P]V^\mu\right), \tag{2.6}$$

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

In a similar way, we have the Lagrangian for the coupling of vector mesons to the baryon octet given by [32, 33] [1]

$$\mathcal{L}_{BBV} = \frac{g}{2}\left(tr(\bar{B}\gamma_\mu[V^\mu, B] + tr(\bar{B}\gamma_\mu B)tr(V^\mu)\right), \tag{2.7}$$

where B is now the SU(3) matrix of the baryon octet [27]. Similarly, one has also a lagrangian for the coupling of the vector mesons to the baryons of the decuplet, which can be found in [29].

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 .

In the approach we make an approximation, implicit in the chiral Lagrangians used for the interaction of pseudoscalar mesons with baryons, which is the neglect of three momenta of the external vectors with respect to their mass. It is not obvious that this approximation remains good for the more massive vector mesons and that the singularities associated to the exchange of vector

[1] Correcting a misprint in [32]

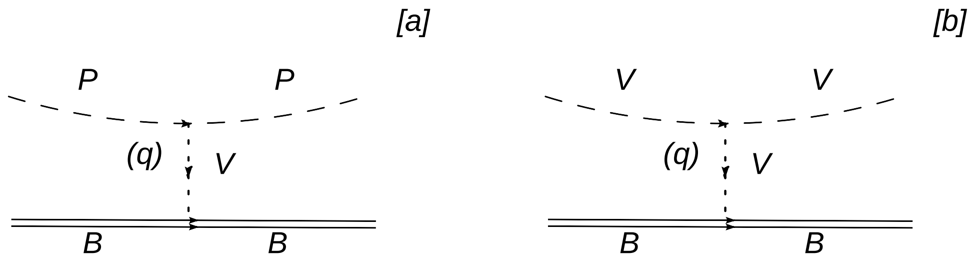

Figure 1: Diagrams obtained in the effective chiral Lagrangians for interaction of pseudoscalar [a] or vector [b] mesons with the octet or decuplet of baryons.

mesons (analytical left hand cut) can be neglected, but a thorough discussion is made in [19] concluding that the same approximations implicit in the chiral Lagrangians for pseudoscalar-baryon interaction can be equally done here.

By looking at the Lagrangian of eq. (2.5) we see that the field V^ν cannot correspond to an external vector meson. Indeed, if this were the case, the ν index must be spatial, because ε^0 is zero in the limit of zero three momentum, and then the partial derivative ∂_ν leads to a three momentum of the vector mesons which are neglected in the approach. Then V^ν corresponds to the exchanged vector and the analogy with the pseudoscalar and vector interaction is much closer (see Eq. (2.6)). Actually, they are formally identical substituting the octet of pseudoscalar fields by the octet of the vector fields, with the additional factor $\vec{\varepsilon}\vec{\varepsilon}\,'$ in the case of the interaction of the vector mesons. Note that $\varepsilon_\mu \varepsilon^\mu$ in Eq. (2.5) becomes $-\vec{\varepsilon}\vec{\varepsilon}\,'$ and the signs of the Lagrangians also agree.

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. In this case, all one must do is to take the matrix elements known for the PB interaction and wherever P is the η_8 multiply the amplitude by the factor $1/\sqrt{3}$ to get the corresponding ω contribution and by $-\sqrt{2/3}$ to get the corresponding ϕ contribution. Upon the approximation consistent with the neglect of the three momentum versus the mass of the particles (in this case the baryon), we can just take the γ^0 component of eq. (2.7) and then the transition potential corresponding to the diagram of fig 1(b) is given by

$$V_{ij} = -C_{ij}\,\frac{1}{4f^2}\,(k^0 + k'^0)\;\vec{\varepsilon}\vec{\varepsilon}\,', \tag{2.8}$$

where k^0, k'^0 are the energies of the incoming and outgoing vector mesons. The same occurs in the case of the decuplet.

The $C_{i,j}$ coefficients of eq. (2.8) can be obtained directly from [2, 30, 31] with the simple rules given above for the ω and the ϕ, and substituting π by ρ and K by K^* in the matrix elements. The coefficients are obtained both in the physical basis of states or in the isospin basis. Here we will show results in isospin basis. The coefficients for the case of the decuplet can be found in [7].

The next step to construct the scattering matrix is done by solving the coupled channels Bethe Salpeter equation in the on shell factorization approach of [2, 3], which is revisited and justified for the present case in [19]

$$T = [1 - V\,G]^{-1}V, \tag{2.9}$$

with G the loop function of a vector meson and a baryon which we calculate in dimensional regularization using the formula of [3] and similar values for the subtraction constants. The G function is convoluted with the spectral function for the vector mesons to take into account their width.

The iteration of diagrams implicit in the Bethe Salpeter equation in the case of the vector mesons propagates the $\vec{\varepsilon}\vec{\varepsilon}'$ term of the interaction, thus, the factor $\vec{\varepsilon}\vec{\varepsilon}'$ appearing in the potential V, factorizes also in the T matrix for the external vector mesons.

3. Results

In this section we show results for the amplitudes obtained in the attractive channels mentioned above. Since the spin dependence only comes from the $\vec{\varepsilon}\vec{\varepsilon}'$ factor and there is no dependence on the spin of the baryons, the interaction for vector-baryon states with $1/2^-$ and $3/2^-$ is the same and then we get two degenerate states each time with the two spins. In the case of the decuplet we get degeneracy for $1/2^-, 3/2^-, 5/2^-$.

We summarize the results in the two Tables below

As one can see in Table 1 there are states which one can easily associate to known resonances. There are ambiguities in other cases. One can also see that in several cases the degeneracy in spin that the theory predicts is clearly visible in the experimental data, meaning that there are several states with about 50 MeV or less mass difference between them. In some cases, the theory predicts quantum numbers for resonances which have no spin and parity associated. It would be interesting to pursue the experimental research to test the theoretical predictions.

The results for the decuplet, summarized in Table 2, are equally interesting. We observe here that one gets Δ states as well as N^*, some of which can be clearly identified with known resonances. It is also nice to see the spin degeneracy present in N^*, Δ and Σ experimental data. The predictions made here for resonances not observed should be a stimulus for further search of such states. In this sense it is worth noting the experimental program at Jefferson Lab [34] to investigate the Ξ resonances. We are confident that the predictions shown here stand on solid grounds and anticipate much progress in the area of baryon spectroscopy and on the understanding of the nature of the baryonic resonances.

Further tests and improvements should be done. One of the test is the radiative decay of these resonances, which is generally accepted as a good test for the nature of the baryons. In this sense some work is already done in [35] about the radiative decay of the baryons made from the decuplet. An extension of this to the resonances stemming from the octet of baryons is already done [36], where the helicity amplitudes of the predicted N^* states are also evaluated and compared with experiment. In those cases where a clear association to known states can be done, the agreement with experiment is good.

As to the improvements, a first step to be done is to include the intermediate pseudoscalar baryon states, which are the main source of decay width of the states. This can be done following the steps of [20, 23] where intermediate two pseudoscalar states were introduced in the study of the vector vector interaction. There it was found that they contributed little to the mass of the

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

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

resonances, implying they are not important building blocks of these states, but because of the large phase space for decay, they contributed to the resonance decay width. Given the analogy of the two cases, we expect something similar to occur here.

Acknowledgments

This work is partly supported by DGICYT contract number FIS2006-03438. This research is part of the EU Integrated Infrastructure Initiative Hadron Physics Project under contract number RII3-CT-2004-506078.

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

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