Dynamically generated resonances from the vector octet-baryon octet interaction

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Received: 11 January 2010 / Revised: 3 March 2010
Published online: 25 April 2010 – © Società Italiana di Fisica / Springer-Verlag 2010
Communicated by Bo-Qiang Ma

Abstract. We study the interaction of vector mesons with the octet of stable baryons in the framework of the local hidden gauge formalism using a coupled-channels unitary approach. We examine the scattering amplitudes and their poles, which can be associated to known $J^P = 1/2^-, 3/2^-$ baryon resonances, in some cases, or give predictions in other ones. The formalism employed produces doublets of degenerate $J^P = 1/2^-, 3/2^-$ states, a pattern which is observed experimentally in several cases. The findings of this work should also be useful to guide present experimental programs searching for new resonances, in particular in the strange sector where the current information is very poor.

1 Introduction

The use of chiral Lagrangians in combination with unitary techniques in coupled channels of mesons and baryons has been a very fruitful scheme to study the nature of many hadron resonances. The analysis of meson baryon scattering amplitudes shows poles in the second Riemann sheet which are identified with existing baryon resonances. In this way the interaction of the octet of pseudoscalar mesons with the octet of stable baryons has lead to $J^P = 1/2^-$ resonances which fit quite well the spectrum of the known low-lying resonances with these quantum numbers [1–9]. 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 $J^P = 3/2^-$ [10,11]. Sometimes a new resonance is predicted, as in the case of the $A(1405)$, where all the chiral approaches find two poles close by, rather than one, a fact that finds experimental support in the analyses of refs. [12,13]. The nature of the resonances is admittedly more complex than just a molecule of pseudoscalar and baryon, but the success of this picture in reproducing many experimental data on decay and production of the resonances provides support to claim very large components of this character for the resonance wave function. In some cases one can even reach the limits of the model and find observables that call for extra components, even if small, but essential to explain some data. This can be seen, for instance, in the radiative decay of the $A(1520)$ [14], or in the helicity form factors of the $N^*(1535)$ [15]. Another promising approach is the one followed in [16], based on the naturalness of the subtraction constants in the dispersion relations that hint in some cases at the existence of non–meson-baryon components, particularly in the case of the $N^*(1535)$. Another step forward in this direction has been the interpretation of low-lying $J^P = 1/2^+$ as molecular states of two pseudoscalar mesons and one baryon [17–21].

Much work has been done using pseudoscalar mesons as building blocks, but the consideration of vectors instead of pseudoscalars is only beginning to be exploited. In the baryon sector the interaction of the $\rho \Delta$ has been recently addressed in [22], where three degenerate $N^*$ states around 1800 MeV and three degenerate $N$ states around 1900 MeV, with $J^P = 1/2^-, 3/2^-, 5/2^-$, are found. This work has been recently extended to the $SU(3)$-space of vectors and baryons of the decuplet in [23]. The underlying theory for this study is the hidden gauge formalism [24–27], which deals with the interaction of vector mesons and pseudoscalars in a way 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. In a more recent work, looking for poles in the $\pi N$ scattering amplitudes, the $pN$ channel is also included [28] and a resonance around 1700 MeV is dynamically generated, having the strongest coupling to this later channel.
In the meson sector, the interaction of $pp$ within this formalism has been addressed in [29], 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 [30]. This work has been extended to the interaction of the $SU(3)$ vector mesons in [31], where several known resonances are also dynamically generated.

In the present work we study the interaction of the octet of vector mesons with the octet of stable baryons, using the unitary approach in coupled channels. We shall see that 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, we obtain degenerate states of $J^P = 1/2^-, 3/2^-$, a pattern which seems to be followed qualitatively by the experimental spectrum, although in some cases the spin partners have not been identified. A different approach to account for the vector-baryon interaction is the one followed in [32] where pseudoscalar mesons, vector mesons and baryons mix, advocating $SU(6)$ symmetry for the interaction. The approach leads to the same pseudoscalar-baryon interaction than the hidden gauge approach, but to different results when it comes to the interaction of the vector mesons with baryons. In particular, the spin degeneracy predicted by the hidden gauge approach does not show up in the matrix elements of the potential in the $SU(6)$ scheme.

2 Formalism for the VV interaction

We follow the formalism of the hidden gauge interaction for vector mesons of [24–27] (see also [33] for a practical set of Feynman rules). The Lagrangian involving the interaction of vector mesons amongst themselves is given by

$$\mathcal{L}_{III} = -\frac{1}{4} (V_{\mu\nu} V^{\mu\nu}),$$  \hspace{1cm} (1)

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

$$V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu - ig[V_\mu, V_\nu],$$  \hspace{1cm} (2)

where $g$ is

$$g = \frac{M_V}{2f},$$  \hspace{1cm} (3)

with $f = 93$ MeV the pion decay constant. With the value of $g$ of eq. (3) one fulfills the KSF rule [34] which is tied to vector meson dominance [35]. The magnitude $V_\mu$ is the $SU(3)$-matrix of the vectors of the octet of the $\rho$

$$V_\mu = \begin{pmatrix} \frac{\rho^0}{\sqrt{2}} + \frac{\rho^-}{\sqrt{2}} & \rho^+ & K^{*+} \\ \rho^- & \frac{\rho^0}{\sqrt{2}} - \frac{\rho^-}{\sqrt{2}} & K^{*0} \\ K^{*-} & K^{*0} & \phi \end{pmatrix}. $$  \hspace{1cm} (4)

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

$$\mathcal{L}_{III}^{(c)} = \frac{g^2}{2} (V_\mu V_\nu V^\mu V^\nu - V_\nu V_\mu V^\mu V^\nu),$$  \hspace{1cm} (5)

as well as to a three-vector vertex from

$$\mathcal{L}_{III}^{(3V)} = ig (\partial_\mu V_\nu - \partial_\nu V_\mu)V^\mu V^\nu. $$  \hspace{1cm} (6)

It is convenient to re-write the Lagrangian of eq. (6) as

$$\mathcal{L}_{III}^{(3V)} = ig[V^\mu \partial_\mu V_\nu - \partial_\nu V_\mu V^\mu V^\nu] = ig[[V^\mu \partial_\mu V_\nu - \partial_\nu V_\mu V^\mu V^\nu].$$  \hspace{1cm} (7)

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

$$\mathcal{L}_{VPP} = -ig[[P_\mu \partial_\mu P_\nu],$$  \hspace{1cm} (8)

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 [36,37]

$$\mathcal{L}_{BBV} = g \left( \langle \bar{B} \gamma_\mu [V^\mu, B] \rangle + \langle \bar{B} \gamma_\mu B \rangle [V^\mu] \right),$$  \hspace{1cm} (9)

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

$$B = \begin{pmatrix} \frac{1}{\sqrt{2}} \Sigma^0 + \frac{1}{\sqrt{6}} \Lambda & \frac{\Sigma^+}{\sqrt{2}} & p \\ \frac{1}{\sqrt{2}} \Sigma^- - \frac{1}{\sqrt{6}} \Lambda & \frac{1}{\sqrt{6}} \Lambda & n \\ \Xi^0 & \Xi^- & \frac{1}{\sqrt{6}} \Lambda \end{pmatrix}. $$  \hspace{1cm} (10)

With these ingredients we can construct the Feynman diagrams that lead to the $PB \rightarrow PB$ and $VB \rightarrow VB$ 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 the pseudoscalar-baryon octet interaction [38,39], namely the Weinberg-Tomozawa terms. One could anticipate some analogies between the vector-baryon amplitudes with the pseudoscalar-baryon ones, given the similarity of the Lagrangians in the way we have written them in eqs. (7) and (8). However, one also anticipates differences. Indeed, in the case of the pseudoscalar, fig. 1(a), there is only one