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Meson-baryon s-wave resonances with strangeness −3

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Abstract. Starting from a consistent $SU(6)$ extension of the Weinberg-Tomozawa (WT) meson-baryon chiral Lagrangian (Phys. Rev. D **74**, 034025 (2006)), we study the s-wave meson-baryon resonances in the strangeness $S = -3$ and negative-parity sectors. Those resonances are generated by solving the Bethe-Salpeter equation with the WT interaction used as kernel. The considered mesons are those of the **35**-$SU(6)$-plet, which includes the pseudoscalar (PS) octet of pions and the vector (V) nonet of the rho-meson. For baryons we consider the **56**-$SU(6)$-plet, made of the $1/2^+$ octet of the nucleon and the $3/2^+$ decuplet of the Delta. Quantum numbers $I(J^P) = 0(3/2^-)$ are suggested for the experimental resonances $\Omega^*(2250)^-$ and $\Omega^*(2380)^-$. Among other, resonances with $I = 1$ are found, which minimal quark content is $sss\bar{l}l'$, being s the *strange* quark and l, l' any of the the light *up* or *down* quarks. A clear signal for such a pentaquark would be a baryonic resonance with strangeness −3 and electric charge −2 or 0, in proton charge units. We suggest looking for $K^-\Xi^-$ resonances with masses around 2100 and 2240 MeV in the sector $1(1/2^-)$, and for $\pi^\pm\Omega^-$ and $K^-\Xi^{*-}$ resonances with masses around 2260 MeV in the sector $1(3/2^-)$.

PACS. 11.30.Hv Flavor symmetries – 11.30.Ly Other internal and higher symmetries – 11.10.St Bound and unstable states; Bethe-Salpeter equations – 11.30.Rd Chiral symmetries

1 Introduction

Using a spin-flavor-$SU(6)$ extended Weinberg-Tomozawa (WT) meson-baryon interaction [1][1], we study the s-wave resonances with strangeness $S = -3$, isospin $I = 0, 1$ and spin-parity $J^P = 1/2^-$, $3/2^-$, $5/2^-$. The resonances are generated by solving the Bethe-Salpeter equation with the extended WT meson-baryon interaction used as a kernel. In this model, the involved mesons are those of the **35**-$SU(6)$-plet $= 8_1 \oplus 8_3 \oplus 1_3$, which includes the PS meson octet of the pions, $(\pi, \eta, K, \bar{K}) \in 8_1$ and the V nonet of the rho-meson, $(\rho, \omega, \phi, K^*, \bar{K}^*) \in 8_3 \oplus 1_3$. We approximate the η-meson as the isospin singlet state of the PS $SU(3)$-octet. For the ω- and ϕ-vector mesons, we assume ideal mixing among the V singlet and octet mesons. The baryons are those of the **56**-$SU(6)$-plet $= 8_2 \oplus 10_4$, which contains the $1/2^+$ octet of the N (N, Λ, Σ, Ξ) and the $3/2^+$ decuplet of the Δ (Δ, Σ^*, Ξ^*, Ω). Masses, widths and couplings of the resonances found are calculated and, when possible, comparison with experimental ones is attempted.

Unitary extensions of chiral perturbation theory to study meson-baryon interactions using a coupled channel scheme were introduced some time ago [3]. They have been successfully applied in the theoretical microscopical description of meson-baryon scattering and of well-known lowest-lying baryon resonances, which were shown to be dynamically generated. Thus different $J^P = 1/2^-$ s-wave resonances ($\subset 8_\pi \times 8_N$, made of PS mesons of the pion octet and of the baryons of the nucleon octet) like $N^*(1535)$, $\Lambda(1405)$, $\Lambda(1670)$, $\Sigma(1620)$ and $\Xi(1620)$ [4] and, more recently, the $J^P = 3/2^-$ d-wave resonances ($\subset 8_\pi \times 10_\Delta$, made of PS mesons of the pion octet and of the baryons of the delta decuplet) like $\Lambda(1520)$, $\Sigma(1670)$ and $\Xi(1820)$ [5] have been found and their properties studied. Those previous chiral Bethe-Salpeter coupled channels unitary approaches using the WT kernel have included hadron multiplets belonging to the flavor $SU(3)$ irreducible representations. In the case of mesons, the only ingredient has been the octet of PS mesons.

2 Model

Motivations for extending the previous $SU(3)$-based models to a $SU(6)$ extended model are the following. First, in the large-N_c limit, 8_N and 10_Δ are degenerated and form a 56-multiplet of spin-flavor $SU(6)$. Second, vector mesons do exist, interact and couple to baryons. Third, there are baryonic resonances decaying to a PS meson and a baryon, but also to a V meson and a baryon, for instance, the strangeness −3 resonance $\Omega^*(2380)^-$ decays to $K^-\Xi^{*0}$

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[1] This WT interaction has also been extended to arbitrary number of colors and flavors in ref. [2].

and to $\bar{K}^{*0}\Xi^-$ with similar strengths and of the same order as the other known decay mode ($\bar{K}^-\pi^0\Xi^-$) [6]. All of these call for a "$SU(6)$" model which deals all together with the 56-baryons and 35-mesons like that of ref. [1]. We consider this spin-flavor symmetric scenario as a reasonable first approach. In the "$SU(6)$" approach the interacting kernel V^{IYJ} for a sector with hypercharge Y (strangeness plus one for baryons), isospin I and spin J is given by

$$\langle m_i,\ B_i|V^{IYJ}(s)|m_j,\ B_j\rangle = D^{IYJ}_{ij}\,\frac{2\sqrt{s}-M_{B_i}-M_{B_j}}{4f^2},$$

$$m_i,m_j\in\mathbf{35},B_i,B_j\in\mathbf{56},\qquad D^{IYJ}=\sum_{\nu}\bar{\lambda}_\nu\,\hat{P}^{IYJ}_\nu,$$

$$\bar{\lambda}_{\mathbf{56}}=-12,\ \bar{\lambda}_{\mathbf{70}}=-18,\qquad \bar{\lambda}_{\mathbf{700}}=6,\ \bar{\lambda}_{\mathbf{1134}}=-2,$$

$\hat{P}^{IYJ}_\nu$ is the projector of the meson-baryon into the ν-$SU(6)$-representation, and ν runs over **56**, **70**, **700**, **1134** because $\mathbf{35}\otimes\mathbf{56}=\mathbf{56}\oplus\mathbf{70}\oplus\mathbf{700}\oplus\mathbf{1134}$.

The $\bar{\lambda}_\nu$ positive (negative) means that in channel ν the meson-baryon interaction is repulsive (attractive). When this kernel is restricted to m_i,m_j being only PS mesons, it coincides with the "$SU(3)$" lowest order WT kernels previously used in refs. [4,5].

Note that D is $SU(6)$ invariant, this symmetry being explicitly broken by the different masses of baryons and mesons. In addition we replace the f^2 of the interaction by $f_{m_i}f_{m_j}$ for the ij matrix element. We use $f_\pi=92.4\,\mathrm{MeV}$, $f_K=1.15f_\pi$, $f_\eta=1.2f_\pi$ [7], and $f_{K^*}=f_K$, $f_\rho=f_\pi$, $f_\omega=f_\phi=f_\eta$. This interaction is used to solve the Bethe-Salpeter coupled channel equation for the meson-baryon T-matrix

$$T^{-1}(s)=V^{-1}(s)-J(s),\tag{1}$$

where $J(s)$ is the diagonal matrix of the meson-baryon loop functions [4,5]. For each channel $(m_i,\ B_i)$ it is ultraviolet regularized by subtracting a constant so that $J(s={m_{m_i}}^2+{M_{B_i}}^2)=0$.

We test that the inclusion of the new "$SU(6)$" channels (those involving V mesons not included in the "$SU(3)$" calculations) does not spoil previous results which were successful. See ref. [8] for comparison in the sector ($S=-1,\ I=0,\ J^P=1/2^-$).

Table 1. Masses, widths and absolute values of coupling constants for each channel, in the sector $I=0$, $J^P=1/2^-$ and $S=-3$. The underlining indicates open channels. "$SU(6)$" stands for the full $\mathbf{35}\times\mathbf{56}$ result. "$SU(3)$" for the $\mathbf{8}\times\mathbf{8}$ result.

$I=0, J^P=1/2^-$, "$SU(6)$"						
M_R	Γ_R	$\|g_i\|$				
[MeV]		$\bar{K}\Xi$	$\bar{K}^*\Xi$	$\bar{K}^*\Xi^*$	$\omega\Omega$	$\phi\Omega$
1309	0	1.22	0.61	3.27	0.17	5.78
1871	70	$\underline{1.57}$	3.63	4.17	1.39	3.23
2201	2.8	$\underline{0.22}$	1.63	2.36	0.48	1.38
2334	44	$\underline{0.76}$	$\underline{0.37}$	0.66	3.44	1.08
2454	33	$\underline{0.38}$	$\underline{0.22}$	$\underline{0.97}$	0.18	4.32
–	–	–				"$SU(3)$"

Table 2. Same as table 1 for the sector $I=0$, $J^P=3/2^-$.

$I=0, J^P=3/2^-$, "$SU(6)$"							
M_R	Γ_R	$\|g_i\|$					
[MeV]		$\bar{K}\Xi^*$	$\bar{K}^*\Xi$	$\eta\Omega$	$\bar{K}^*\Xi^*$	$\omega\Omega$	$\phi\Omega$
1969	0	1.78	2.43	2.37	1.44	0.00	2.51
2265	82	$\underline{1.19}$	$\underline{0.34}$	$\underline{0.28}$	3.71	1.21	0.55
2343	36	$\underline{0.42}$	$\underline{0.84}$	$\underline{0.04}$	1.01	3.31	0.16
2437	80	$\underline{0.07}$	$\underline{0.09}$	$\underline{1.19}$	$\underline{0.12}$	0.00	4.38
2051	86	$\underline{1.97}$		3.34			"$SU(3)$"

Table 3. Same as table 1 for the sector $I=0$, $J^P=5/2^-$.

$I=0, J^P=5/2^-$, "$SU(6)$"				
M_R	Γ_R	$\|g_i\|$		
[MeV]		$\bar{K}^*\Xi^*$	$\omega\Omega$	$\phi\Omega$
2376	0	1.41	2.78	0.00

Table 4. Same as table 1 for the sector $I=1$, $J^P=1/2^-$.

$I=1, J^P=1/2^-$, "$SU(6)$"					
M_R	Γ_R	$\|g_i\|$			
[MeV]		$\bar{K}\Xi$	$\bar{K}^*\Xi$	$\bar{K}^*\Xi^*$	$\rho\Omega$
2100	118	$\underline{1.47}$	3.39	1.1	2.1
2241	63	$\underline{0.88}$	$\underline{0.87}$	1.67	3.87
–	–	–			"$SU(3)$"

3 Results

We solve the coupled-channel Bethe-Salpeter equation and look for the T-matrix poles in the second Riemann sheet. Close to a pole the T-matrix behaves as

$$T_{ij}\sim\frac{g_ig_j}{\sqrt{s}-(M_R-i\Gamma_R/2)}\tag{2}$$

and the position of the pole and its residue define the mass M_R, width Γ_R and complex coupling constants g_i to different i channels of the found resonance.

All the calculations are done neglecting the widths of the baryons of the decuplet and of the V mesons. When the orbital angular momentum of the meson-baryon system is zero, the odd-parity $S=-3$ resonances formed by coupling **35**-mesons to **56**-baryons can have the following $I(J^P)$ quantum numbers: $0(1/2^-)$, $0(3/2^-)$, $0(5/2^-)$, $1(1/2^-)$, $1(3/2^-)$ and $1(5/2^-)$. The mass, width and absolute values of the coupling constants of the resonances found for each of those sectors are shown in tables 1, 2, 3, 4, 5 and 6, respectively. Resonances with width below 125 MeV are displayed in fig. 1.

Several ($S=-3$, $I=1$) resonances have been predicted (tables 4, 5 and 6 and full symbols in fig. 1). These resonances have, at least, three s quarks to provide strangeness $S=-3$ and a pair of light (u or d)

Table 5. Same as table 1 for the sector $I = 1,\ J^P = 3/2^-$.

$I = 1, J^P = 3/2^-$, "$SU(6)$"						
M_R [MeV]	Γ_R	$\lvert g_i\rvert$				
		$\pi\Omega$	$\bar K\Xi^*$	$\bar K^*\Xi$	$\bar K^*\Xi^*$	$\rho\Omega$
2018	267	$\underline{2.19}$	1.64	2.14	1.75	0.25
2258	101	$\underline{0.54}$	$\underline{1.23}$	$\underline{0.13}$	3.19	2.33
2288	32	$\underline{0.33}$	$\underline{0.17}$	$\underline{0.93}$	2.29	3.11
2146	359	$\underline{2.30}$	2.47			"$SU(3)$"

Table 6. Same as table 1 for the sector $I = 1,\ J^P = 5/2^-$.

$I = 1,\ J^P = 5/2^-$, "$SU(6)$"			
M_R [MeV]	Γ_R	$\lvert g_i\rvert$	
		$\bar K^*\Xi^*$	$\rho\Omega$
2324	0	1.79	3.09

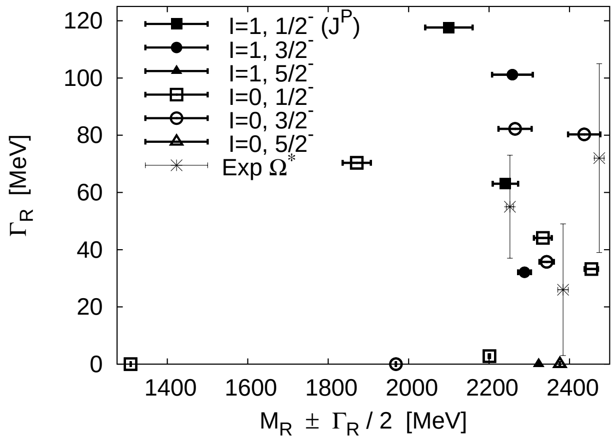

Fig. 1. Spin-parity $J^P = \frac{1}{2}^-, \frac{3}{2}^-$ and $\frac{5}{2}^-$ resonance properties in the $I = 0$ (empty symbols) and $I = 1$ (filled symbols), $S = -3$ ($Y = -2$) sectors. The points with error-bars are defined from the masses (M_R) and widths (Γ_R) of the found resonances as ($M_R \pm \Gamma_R/2, \Gamma_R$). The experimental Ω^* resonance masses and widths with their error bars are from refs. [7,6,9,10].

quark-antiquark to achieve isospin $I = 1$ quantum number. Hence, those dynamically generated ($S = -3$, $I = 1$) resonances are pentaquarks and in principle have a clear experimental signature. A clear signal of them would be a resonance with strangeness $S = -3$ and electric charge $Q = -2$ (this is $I_z = -1$) with minimal quark content $sssd\bar u$. Another clear signature would be a $S = -3$ and $Q = 0$ resonance with a minimal quark content of $sssu\bar d$. From the tables, the best ways for observing pentaquarks would be, in the sector $I(J^P) = 1(1/2^-)$ looking for $K^-\Xi^-$ resonances with masses around 2100 and 2240 MeV, and in the sector $I(J^P) = 1(3/2^-)$ looking for $\pi^\pm\Omega^-$ and $K^-\Xi^{*-}$ resonances with masses around 2260 MeV.

Table 7. Experimentally known Ω^* resonances [7,6,9,10]. The ** and *** refer to the status rating used by the PDG. The branching ratios are relative.

Resonance $I(J)^P$	Mass [MeV]	Width [MeV]	Decay modes	Branching ratios
$\Omega^*(2250)^-$	2252 ± 9	55 ± 18	$\Xi^-\pi^+K^-$	1
$0(?^?)$ ***			$\Xi^{*0}K^-$	0.7 ± 0.2
$\Omega^*(2380)^-$	2384 ± 13	26 ± 23	$\Xi^-\pi^+K^-$	1
$?(?^?)$ **			$\Xi^{*0}K^-$	< 0.4
			$\Xi^-\bar K^{*0}$	0.5 ± 0.3
$\Omega^*(2470)^-$	2474 ± 12	72 ± 33	$\Omega^-\pi^+\pi^-$	
$?(?^?)$ **				

All the experimentally known Ω^* resonances are listed in table 7. Tentatively, we identify the experimental isoscalar $\Omega^*(2250)^-$ to the theoretical $\Omega^*(2265)^-$ of sector $0(3/2^-)$, because of the relative closeness of masses and widths and, also, of observed decay channels. Likewise, the experimental $\Omega^*(2380)^-$ could be assigned to the found $\Omega^*(2343)^-$ of sector $0(3/2^-)$. We do not find a clear assignment for the experimentally observed $\Omega^*(2470)$; the decay to $\Omega^-\pi^+\pi^-$ through $\Omega\rho$ in our model takes place only for smaller resonance masses. Presumably, in this decay other mechanisms, for instance involving p-wave, could be at work.

More details will be given elsewhere.

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