Vector meson-baryon octet interaction and resonances generated dynamically

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The interaction potentials between vector mesons and baryon octet are calculated explicitly with a summation of t -, s -, and u - channel diagrams and a contact term originating from the tensor interaction. Altogether, 13 resonances are generated dynamically in different channels of strangeness zero by solving the relativistic Lippman-Schwinger equations in the S-wave approximation, and their masses, decay widths, isospins and spins are determined. Some resonances are well fitted with their counterparts listed in the newest review of Particle Data Group (PDG),¹ while others might stimulate the experimental observation in these energy regions in the future.

Keywords: Hadronic resonances; Hidden gauge symmetry; Coupled-channel unitary approach.

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1. Introduction

The combination of chiral Lagrangian with nonperturbative unitary techniques in coupled channels of mesons and baryons has become a powerful method to study the meson-meson and meson-baryon interactions and new states in the resonance region, which are not easily explained using the conventional constituent quark model. In addition, the theory on the hidden gauge symmetry supplies a mechanism to include the vector meson in the chiral Lagrangian.²⁻⁵ Therefore, the study on the interaction between vector mesons and other hadrons becomes possible. Along this clue, the interactions between the vector meson and the pseudoscalar meson are studied and the radiative decays of some axial-vector mesons generated dynamically are discussed.⁶ Similarly, the scattering amplitudes of two ρ mesons are calculated

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within the framework of coupling-channel approach of the Lippman-Schwinger equation, and two resonances $f_0(1370)$ and $f_2(1270)$ are generated dynamically.⁷ This work has been extended to the $SU(3)$ -space of vector mesons in Ref. 8, where several known resonances are also dynamically generated. In the baryon sector, the interaction of the vector meson and baryon decuplet is addressed in Refs. 9, 10, where only t -channel amplitudes are analyzed in the S-wave approximation. This method is also extended to study the interaction of vector mesons and baryon octet, and several baryon resonances have been found as a result of solving the Lippman-Schwinger equation in the coupled channel formalism.¹¹ However, the resonances generated dynamically are spin degenerate since the amplitude obtained from t -channel interaction is spin independent when the wave function of the initial and final baryons and the polarization vector of the incoming and outgoing mesons are all neglected. Since the masses of vector mesons are comparable to those of baryons, only t -channel diagrams might be incomplete to obtain a reliable interaction of vector mesons and baryons. Thus in Ref. 12, the t -, s -, u -channel diagrams and a contact diagram originating from the tensor term of the vector meson and baryon octet interaction are all taken into account, and four spin-determined resonances are found in a non-relativistic approximation. In the present work, we deduce the interaction kernel of vector mesons and baryon octet including a vector meson exchange in t -channel, octet baryon exchange in s -, u -channels, and a contact diagram related only to the tensor interaction term precisely, and then calculate the scattering amplitudes of vector mesons and baryon octet by solving the Lippman-Schwinger equation in a coupled channel approach. In this article, we only discuss the scattering amplitude in the S-wave approximation, and we shall see that the scattering amplitudes lead to poles in the complex plane which can be associated to some well-known resonances.

In Sect. 2, we will show the basic Lagrangian obtained with the hidden gauge symmetry of $SU(3)$ group, in which a tensor interaction term is included, and then the framework on the Lippman-Schwinger equation of the coupled channel approach will be summarized briefly. The parameters in the Lagrangian are fixed according to the experimental data on coupling constants of baryon octet to vector mesons. In Sect. 3, we will show the resonances found in the complex plane for the vector meson-baryon octet system with total strangeness zero. The masses and decay widths of these resonances and their possible PDG counterparts are also discussed. Finally, we will present a summary of this article.

2. Formalism

We follow the formalism of the vector meson-baryon octet interaction in Ref. 12, and then the Lagrangian for the linearly coupling to vector mesons can be explicitly written as

$$\mathcal{L}_{VBB} = -g \left\{ F_V \langle \bar{B} \gamma_\mu [V_s^\mu, B] \rangle + D_V \langle \bar{B} \gamma_\mu \{V_s^\mu, B\} \rangle \right\}$$

Fig. 1. Feynman Diagrams of the vector meson-baryon interaction. (a) t - channel, (b) u - channel, (c) s - channel, and (d) contact term.

$$\begin{aligned}
 & + \frac{1}{4M} \left(F_T \langle \bar{B} \sigma_{\mu\nu} [\partial^\mu V_8^\nu - \partial^\nu V_8^\mu, B] \rangle + D_T \langle \bar{B} \sigma_{\mu\nu} \{ \partial^\mu V_8^\nu - \partial^\nu V_8^\mu, B \} \rangle \right) \\
 & + \frac{C_V}{3} \langle \bar{B} \gamma_\mu B \rangle \langle V_0^\mu \rangle + \frac{C_T}{4M} \langle \bar{B} \sigma_{\mu\nu} V_0^{\mu\nu} B \rangle \Big\}, \quad (1)
 \end{aligned}$$

which will contribute to the vector meson- baryon octet interaction in t -, s - and u - channels . Moreover, the self-coupling terms of vector mesons lead to a contact interaction between the baryon and the vector meson, which is trivially null for singlet meson-baryon interaction, thus

$$\mathcal{L}_{VVBB} = \frac{g}{4M} \left\{ F_T \langle \bar{B} \sigma_{\mu\nu} [ig [V_8^\mu, V_8^\nu], B] \rangle + D_T \langle \bar{B} \sigma_{\mu\nu} \{ ig [V_8^\mu, V_8^\nu], B \} \rangle \right\}. \quad (2)$$

From Eqs. (1) and (2), we can obtain the transition potentials for the t -, s -, u - channels and contact interactions between baryons and vector mesons.

The scattering matrix implies solving the relativistic coupling-channel Lippman-Schwinger equation in the on-shell factorization approach

$$T(\sqrt{s}, \cos \theta) = [1 - V(\sqrt{s}, \cos \theta) G]^{-1} V(\sqrt{s}, \cos \theta), \quad (3)$$

with G being the loop function of a vector meson and a baryon.

Because the amplitude T in Eq. (3) is a function of the scattering angle θ , we can expand the amplitude T in a series of Legendre polynomials, i.e.,

$$T(\sqrt{s}, \cos \theta) = \sum_{l=0}^{\infty} T_l(\sqrt{s}) P_l(\cos \theta), \quad (4)$$

Table 1. The experimental values on the coupling constants of vector mesons to the baryons¹³.

<i>Exp.</i>	ω	ρ	K^*	ϕ
$g^2/4\pi$	2.4	2.4	1.39	12.0

Table 2. The parameters used in the calculation.

F_V	D_V	F_T	D_T	C_V	C_T
1.6405	0.2225	1.6405	0.2225	-5.144	-5.144

with

$$T_l(\sqrt{s}) = \frac{2l+1}{2} \int_0^\pi T(\sqrt{s}, \cos \theta) P_l(\cos \theta) \sin \theta d\theta, \quad (5)$$

where $T_l(\sqrt{s})$ is the amplitude of the l th partial wave. In the S -wave approximation, only the amplitude $T_0(\sqrt{s})$ is calculated for different channels.

The experimental values on coupling constants of vector mesons to baryons are listed in Table 1, which are taken from Ref. 13. Thus we can fit the parameters F_V , D_V and C_V in the Lagrangian with these data. Moreover, we assume the parameters F_T , D_T and C_T take the same values as F_V , D_V and C_V , respectively. The values of these parameters are listed in Table 2.

3. Results and Discussion

We search for poles of the scattering amplitude $|T_0|^2$ at the complex $\sqrt{s}$ plane. If the $Re(\sqrt{s})$ is above the threshold of the channel, the pole might correspond a resonance state of the vector meson and the baryon. Otherwise, if $Re(\sqrt{s})$ of the pole is less than the threshold, it is more possible to be a bound state. We will discuss the cases of isospin $\frac{1}{2}$ and $\frac{3}{2}$ with different spin and strangeness zero, respectively.

3.1. $I = 1/2$, $S = 1/2$

We find 4 poles of $|T_0(\sqrt{s})|^2$ on the complex $\sqrt{s}$ plane, which are summarized in Table 3. The pole at the position of $1620 + i77$ MeV might correspond to the resonance $N(1650)1/2^-$ in the review of the Particle Data Group.¹ The poles at $2071 + i75$ MeV might have the counterpart $N(1895)1/2^-$, which appears in the PDG review as $N^*(2090) S_{11}$ before 2012.¹ Moreover, there are other two poles generated near 1800 MeV, and they are more close to the recent mass value of the resonance $N(1895)1/2^-$,¹⁴ especially, they are almost equivalent to the mass value on this resonance in earlier Refs. 15, 16. It should be pointed out that the resonances at the position of poles $1812 + i42$ MeV and $1825 + i50$ MeV couples strongly to the ϕN and $K^* \Lambda$ channels, respectively, while that at $2071 + i75$ MeV couples to $K^* \Sigma$

Table 3. The properties of the dynamically generated resonances with isospin $I = 1/2$ and spin $S = 1/2$ and their possible PDG counterparts.

Pole positions	Name and J^P	Status	Mass	Width
1620 + $i77$ MeV 1812 + $i42$ MeV 1825 + $i50$ MeV 2071 + $i75$ MeV	$N(1650)1/2^-$ $N(1895)1/2^-$	**** **	1645 – 1670 MeV ≈ 2090 MeV	120–180 MeV 100–400 MeV

Table 4. Pole positions and coupling constants to various channels of the resonances found in the $I = 1/2$ and $S = 1/2$ sector.

g_i	1620 + $i77$ MeV	1812 + $i42$ MeV	1825 + $i50$ MeV	2071 + $i75$ MeV
ρN	0.39 – $i0.21$	0.012 + $i0.16$	–0.39 – $i0.26$	–0.027 + $i0.046$
ωN	0.11 + $i0.13$	0.42 + $i0.27$	–0.078 – $i0.17$	–0.02 + $i0.033$
ϕN	1.36 + $i0.17$	1.41 + $i0.18$	–0.0039 – $i0.028$	0.001 + $i0.005$
$K^* \Lambda$	0.73 – $i0.39$	1.07 – $i0.31$	1.30 + $i0.019$	0.0 + $i0.06$
$K^* \Sigma$	–0.10 + $i0.029$	–0.18 – $i0.038$	–0.32 – $i0.0014$	0.52 + $i0.48$

mainly. The coupling constants of these resonances to baryons and vector mesons are listed in Table 4. In a conclusion, there might be more complicated resonance distributions around the thresholds of ϕN , $K^* \Lambda$ and $K^* \Sigma$.

3.2. $I = 1/2$, $S = 3/2$

Altogether, we find five poles on the complex $\sqrt{s}$ plane, which are listed in Table 5. The pole at 1651 + $i9$ MeV might correspond to the resonance $N(1685)?^?$, whose spin and parity are not determined. if so, the spin of these resonance might be $3/2$ and the parity might be negative. It is more interesting to note the poles on 1840 + $i102$ MeV and 2050 + $i14$ MeV, which correspond to the resonances $N(1875)3/2^-$ and $N(2120)3/2^-$, respectively. These two resonances had been labeled as one resonance $N(2080)$ before the 2012 PDG Review. There is new evidence from Ref. 14 for two $3/2^-$ states exist in the region above 1800 MeV. The resonance corresponding to the pole on 1840 + $i102$ MeV couples strongly to ϕN , while the resonance at 2050 + $i14$ MeV has a larger coupling constant to $K^* \Sigma$, as shown in Table 6. Moreover, we find a pole at 1722 + $i5$ MeV, which might correspond to the resonance $N(1700)3/2^-$, and another pole at 1933 + $i16$ MeV, which has no counterpart in the PDG data.¹

3.3. $I = 3/2$, $S = 1/2$

Three poles are found in the complex plane of $\sqrt{s}$, and these poles and their counterparts are listed in Table 7. These three poles couple strongly to $K^* \Sigma$, as summarized in Table 8. It should be iterated that in Ref. 12, the authors also obtained a pole in the 2 GeV region of the channel $I = 3/2$ and $S = 1/2$ using their non-relativistic

Table 5. The properties of the dynamically generated resonances with isospin $I = 1/2$ and spin $S = 3/2$ and their possible PDG counterparts.

Pole positions	Name and J^P	Status	Mass	Width
1651 + $i9$ MeV	$N(1685)?^?$	*	1670 – 1685 MeV	≈ 25 MeV
1722 + $i5$ MeV	$N(1700)3/2^-$	***	1650 – 1750 MeV	100 – 250 MeV
1840 + $i102$ MeV	$N(1875)3/2^-$	***	1820 – 1920 MeV	160 – 320 MeV
1933 + $i16$ MeV				
2050 + $i14$ MeV	$N(2120)3/2^-$	**	≈ 2120 MeV	≈ 300 MeV

Table 6. Pole positions and coupling constants to various channels of the resonances found in the $I = 1/2$ and $S = 3/2$ sector.

g_i	1651 + $i9$ MeV	1722 + $i5$ MeV	1840 + $i102$ MeV	1933 + $i16$ MeV	2050 + $i14$ MeV
ρN	0.36 + $i0.63$	-0.022 - $i0.050$	-0.46 + $i0.48$	0.051 + $i0.12$	0.013 + $i0.073$
ωN	-0.14 + $i0.061$	0.10 + $i0.15$	0.74 + $i0.023$	0.14 - $i0.33$	0.019 + $i0.049$
ϕN	1.69 - $i0.15$	0.67 + $i0.20$	1.66 - $i0.28$	1.14 - $i0.38$	0.0048 - $i0.023$
$K^* \Lambda$	1.18 - $i0.10$	-0.029 + $i0.048$	1.12 - $i0.43$	-0.54 - $i0.48$	0.070 + $i0.058$
$K^* \Sigma$	-0.24 - $i0.095$	-0.018 - $i0.045$	-0.17 - $i0.099$	0.075 + $i0.12$	0.89 + $i0.003$

Table 7. The properties of the dynamically generated resonances with isospin $I = 3/2$ and spin $S = 1/2$ and their possible PDG counterparts.

Pole positions	Name and J^P	Status	Mass	Width
1588 + $i27$ MeV	$\Delta(1620)1/2^-$	****	1600–1660 MeV	130–150 MeV
2002 + $i28$ MeV	$\Delta(1900)1/2^-$	**	1840–1920 MeV	140–300 MeV
2056 + $i37$ MeV	$\Delta(2150)1/2^-$	*	≈ 2150 MeV	120–200 MeV

potential between vector mesons and baryon octet, which is related to the resonance $\Delta(1900)1/2^-$, just as we have done.

3.4. $I = 3/2$, $S = 3/2$

In the case of isospin $I = 3/2$ and spin $S = 3/2$, only one pole is found in the complex plane of $\sqrt{s}$, which might correspond to the resonance $\Delta(1700)3/2^-$ in the PDG data. Contrary to the case of spin $S = 1/2$, this resonance couples strongly to the channel ρN , as depicted in Tables 9 and 10.

Table 8. Pole positions and coupling constants to various channels of the resonances found in the $I = 3/2$ and $S = 1/2$ sector.

g_i	1588 + $i27$ MeV	2002 + $i28$ MeV	2056 + $i37$ MeV
ρN	0.43 - $i0.20$	0.16 + $i0.15$ MeV	0.27 + $i0.25$ MeV
$K^* \Sigma$	1.70 - $i0.53$	0.71 - $i0.084$ MeV	1.22 - $i0.29$ MeV

Table 9. The properties of the dynamically generated resonance with isospin $I = 3/2$ and spin $S = 3/2$ and its possible PDG counterpart.

Pole positions	Name and J^P	Status	Mass	Width
$1603 + i72$ MeV	$\Delta(1700)3/2^-$	****	1670–1750 MeV	200–400 MeV

Table 10. Pole position and coupling constants to various channels of the resonance found in the $I = 3/2$ and $S = 3/2$ sector.

g_i	$1603 + i72$ MeV
ρN	$0.81 - i0.29$
$K^*\Sigma$	$0.30 + i0.11$

4. Summary

We have studied the the vector meson- baryon octet interaction in a coupled channel unitary approach, and obtained the kernels between vector mesons and baryon octet from a summation of diagrams corresponding a vector meson exchange in the t -channel, octet baryon exchange in s -, u - channels, and a contact interaction. In the S -wave approximation, the scattering amplitudes are calculated by solving the relativistic Lippman-Schwinger equations of coupling channels.

Altogether 13 poles are observed in the complex plane of the total energy in the center of mass system in channels with different isospins and spins. Many of these poles are associated to known states in PDG, In the channel of isospin $I = 1/2$ and spin $S = 3/2$, the resonances $N(1875)3/2^-$ and $N(2120)3/2^-$, which are split with the older data in the newest PDG review,¹ are generated dynamically. Moreover, for some resonances in our prediction, there are not PDG counterparts for them, and this might give a stimulus to search experimentally for these resonance states.

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