Dynamically Generated $\Xi(1690)$

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We show that the $\Xi(1690)$ resonance can be dynamically generated in the $s$-wave $\bar{K}\Sigma\bar{K}\Lambda-\pi-\eta-\Xi$ coupled-channels chiral unitary approach. In our model, the $\Xi(1690)$ resonance appears near the $\bar{K}\Sigma$ threshold as a $\bar{K}\Sigma$ molecular state and the experimental data are reproduced well. We discuss properties of the dynamically generated $\Xi(1690)$.

KEYWORDS: $\Xi(1690)$, chiral unitary approach, hadronic molecules

1. Introduction

At present, spectroscopy of multi-strangeness baryons is not well understood compared to that with the strangeness $S = 0$ and $-1$ [1]. Nevertheless, we expect that multi-strangeness baryons should contain interesting physics as rich as in the baryons with $S = 0$ and $-1$. For instance, several multi-strangeness baryons would contradict the classification with the $qqq$ configuration by traditional quark models, and hence they would be candidates of the exotic hadrons, like the famous $\Lambda(1405)$ resonance in $S = -1$. Therefore, investigating the baryon spectroscopy in the multi-strangeness sector is important both in the experimental and theoretical sides.

Here we focus on the $\Xi(1690)$ resonance. The $\Xi(1690)$ resonance was experimentally discovered in the $K^{-}p \rightarrow (\bar{K}\Sigma)K\pi$ reaction at 4.2 GeV/$c$ [2], which was followed by experimental studies in, e.g., Refs. [3–9]. The spin/parity of $\Xi(1690)$ has not been fixed yet, but experimental data prefer $J^{P} = 1/2^{−}$ [2, 8]. Then, one of the most interesting properties of $\Xi(1690)$ is its decay pattern. Namely, $\Xi(1690)$ has small decay width $\lesssim 10$ MeV [5] with tiny branching ratio to the $\pi\Xi$ channel, $\Gamma(\pi\Xi)/\Gamma(\bar{K}\Sigma) < 0.09$ [1]. These experimental implications contradict a naive quark model, in which a $qss$ state with $J^{P} = 1/2^{−}$ should inevitably decay to $\pi\Xi$ to some extent. These properties of the decay pattern may imply that $\Xi(1690)$ might be an exotic hadron rather than a usual $qqq$ baryon.

In this Article we show that the $\Xi(1690)$ resonance can be dynamically generated as an $s$-wave $\bar{K}\Sigma$ molecular state in the chiral unitary approach. Furthermore, we solve the difficulty on the decay pattern of $\Xi(1690)$ with $J^{P} = 1/2^{−}$ by using the chiral unitary approach. We note that the multi-strangeness baryons were studied in the chiral unitary approach in Refs. [10–12]. In this study we concentrate on the phenomena around the $\bar{K}\Sigma$ threshold and $\Xi(1690)$ [13].

2. Dynamically generated $\Xi(1690)$

In the chiral unitary approach, we calculate the meson–baryon scattering amplitude $T_{jk}$ with the channel indices $j$ and $k$ by the Lippmann–Schwinger equation in an algebraic form

$$T_{jk}(w) = V_{jk}(w) + \sum_{l} V_{jl}(w)G_{l}(w)T_{lk}(w),$$

(1)

where $w$ is the center-of-mass energy, $V_{jk}$ is the interaction kernel taken from the chiral perturbation theory, and $G_{j}$ is the two-body loop function. In this study, we take the Weinberg–Tomozawa term for
the interaction kernel $V_{jk}$. For the loop function $G_j$, we employ a covariant expression and evaluate it with the dimensional regularization, which brings us a subtraction constant as a model parameter in each channel. We note that only the subtraction constants are model parameters in the present study. The details of the formulation can be found in Ref. [13].

The parameters are fixed so as to reproduce simultaneously the $\bar{K}^0\Lambda$ and $K^-\Sigma^+$ mass spectra obtained in the decay $\Lambda^+_c \rightarrow \Xi(1690)^0K^- \rightarrow (\bar{K}^0\Lambda)K^+$ and $(K^-\Sigma^+)K^+$ in Ref. [6]. From the best fit, we obtain the mass spectra in Fig. 1. From the figure, we can reproduce the experimental peak structure around the $\bar{K}\Sigma$ threshold ($\approx 1690$ MeV). In addition, the ratio $R \equiv B[\Lambda^+_c \rightarrow \Xi(1690)^0K^- \rightarrow (K^-\Sigma^+)K^+]/B[\Lambda_c \rightarrow \Xi(1690)^0K^- \rightarrow (\bar{K}^0\Lambda)K^+]$ is evaluated as 1.06 in our model, which is within 2$r$ of the experimental value $0.62 \pm 0.33$ [1].

Next, in the scattering amplitude a resonance appears as a pole in the following expression:

$$T_{jk}(w) = \frac{g_j g_k}{w - w_{\text{pole}}} + \text{(regular at } w_{\text{pole}}),$$

where $g_j$ is the coupling constant of the resonance to the scattering state in $j$ channel and $w_{\text{pole}}$ is the resonance pole position. In our model we find the $\Xi(1690)^0$ resonance pole at $w_{\text{pole}} = 1684.3 - 0.5i$ MeV. The structure of the resonance is reflected in $g_j$ and $w_{\text{pole}}$, and recently this is formulated in terms of the so-called compositeness [14–17], which is defined as the norm of the two-body wave function and measures the “amount” of the two-body component inside the resonance. In the present model, the $j$th channel compositeness $X_j$ is expressed as

$$X_j = -g_j^2 \left[ \frac{dG_j}{dw} \right]_{w = w_{\text{pole}}}, \quad Z \equiv 1 - \sum_j X_j = -\sum_{j,k} g_j g_k \left[ G_j \frac{dV_{jk}}{dw} G_k \right]_{w = w_{\text{pole}}},$$

**Table 1.** Properties of $\Xi(1690)^0$ in the present model [13]. The pole position is $w_{\text{pole}} = 1684.3 - 0.5i$ MeV.

| $g_{K^-\Sigma^+}$ | $0.12 \pm 0.60i$ | $X_{K^-\Sigma^+}$ | $0.83 - 0.31i$ |
| $g_{\bar{K}^0\Sigma^0}$ | $-0.76 - 0.41i$ | $X_{\bar{K}^0\Sigma^0}$ | $0.12 + 0.17i$ |
| $g_{K^0\Lambda}$ | $0.38 + 0.20i$ | $X_{K^0\Lambda}$ | $-0.02 + 0.00i$ |
| $g_{\Sigma^-\Sigma^+}$ | $0.06 - 0.05i$ | $X_{\Sigma^-\Sigma^+}$ | $0.00 + 0.00i$ |
| $g_{\Xi^0\Xi^+}$ | $-0.09 + 0.05i$ | $X_{\Xi^0\Xi^+}$ | $0.00 + 0.00i$ |
| $g_{\Xi^0\Xi^+}$ | $-0.66 - 0.48i$ | $X_{\Xi^0\Xi^+}$ | $0.01 + 0.02i$ |
| $Z$ | $0.06 + 0.11i$ |
where we have also introduced the elementariness $Z$, which is given by the rest of the component out of unity and measures contributions from implicit channels that do not appear as explicit degrees of freedom. The last expression of the elementariness in our model is obtained from the generalized Ward identity derived in Ref. [18]. In Table I we show the values of the compositeness and elementariness as well as the coupling constants for the $\Xi(1690)^0$ resonance in our model. Since the sum of the $K^-\Sigma^+$ and $K^0\Sigma^0$ compositeness is almost unity, we can see that $\Xi(1690)^0$ is indeed a $\bar{K}\Sigma$ molecular state. Here we note that $\Xi(1690)^0$ in our model has very small decay width $\sim 1$ MeV with a very small coupling constant to the $\pi\Xi$ channel. This can be understood by the structure of the Weinberg–Tomozawa term for $V_{jk}$. Namely, in the Weinberg–Tomozawa term, the transition between $\bar{K}\Sigma$ and $\eta\Xi$ is strong while the transitions $\bar{K}\Sigma \leftrightarrow \bar{K}\Lambda$ and $\bar{K}\Sigma \leftrightarrow \pi\Xi$ are forbidden and weak, respectively. As a consequence, the dynamically generated $\Xi(1690)$ in our model cannot couple strongly to $\bar{K}\Lambda$ nor $\pi\Xi$. This solves the problem on the decay pattern of $\Xi(1690)$ with $J^P = 1/2^-$. 

Now let us compare the pole position of $\Xi(1690)$ in our model with that obtained by the previous studies in the chiral unitary approach. Namely, the $\Xi(1690)$ pole position was found at $1663 - 2i$ MeV [11] and at $1651 - 2i$ MeV [12], both of which give binding energy of several ten MeV from the $\bar{K}\Sigma$ threshold. The difference between our result and their ones can be understood by the $\bar{K}\Sigma$ interaction strength. First, while we use $f_K = 1.2 f_{\pi}$ with $f_{\pi}$ = 92.2 MeV, to which we refer as the physical kaon decay constant, the authors in Ref. [11] used $f_K = 90$ MeV, which makes the $\bar{K}\Sigma$ interaction about 1.5 times stronger than ours. Actually, from Fig. 2, in which we show the shift of the pole position by changing the value of $f_K$, we can see that the case of $f_K = 90$ MeV gives the binding energy $\approx 20$ MeV due to a stronger $\bar{K}\Sigma$ interaction. We note that the physical $\Xi(1690)^0$ pole (filled box) exists above the $K^-\Sigma^+$ threshold but in the first Riemann sheet. In this sense, strictly speaking, the peak seen in Fig. 1 is a cusp at the $K^-\Sigma^+$ threshold rather than a usual Breit–Wigner resonance peak. Second, in Ref. [12] they introduced channels with vector mesons, which would assist more the $\bar{K}\Sigma$ interaction, and hence the mass of $\Xi(1690)$ could shift to lower energies.

Finally, we discuss the spatial size of the $\Xi(1690)$ resonance, which could be an important piece of the structure for hadrons [18, 19]. Here we evaluate the $\bar{K}\Sigma$ scattering length $a$, which is related to the mean squared distance between two constituents ($r^2$). Actually, in quantum mechanics we have $a^2 = 2(r^2)$ if the state is weak binding and is dominated by the two-body component, i.e., $X \approx 1$ [20]. The scattering length in channel $j$, $a(j)$, is calculated as $a(j) = M_j T_{jj}(M_j^{th})/(4\pi M_j^{th})$ with $M_j$ and $M_j^{th}$ being the baryon mass and threshold in channel $j$, respectively. In Fig. 3 we show the scattering length $a(K\Sigma(I = 1/2))$, which is obtained as $2a(K^-\Sigma^+) - a(K^0\Sigma^0)$, by changing the value of the kaon decay constant $f_K$. From the figure, we can see that the real part of the scattering length $a(\bar{K}\Sigma(I = 1/2))$ becomes large as $f_K$ increases and the pole approaches the $K^-\Sigma^+$ threshold (see also Fig. 2). In particular, around $f_K = 105$ MeV the scattering length becomes $\approx 4$ fm, which indicates that $\Xi(1690)$ would be a diffuse system composed of $\bar{K}$ and $\Sigma$. At the physical value of the kaon decay
constant, however, $\Xi(1690)$ exists above the $K^-\Sigma^+$ threshold, and the real part of the scattering length becomes much small while its imaginary part is negatively large.

3. Conclusion

We have shown that the $\Xi(1690)$ resonance can be dynamically generated in the $s$-wave $\bar{K}\Sigma$-$\bar{K}A$-$\pi\Xi-\eta\Xi$ coupled-channels chiral unitary approach. The $\Xi(1690)$ resonance appears near the $\bar{K}\Sigma$ threshold. In our model, we can describe the $\Xi(1690)$ resonance as a $\bar{K}\Sigma$ molecular state and reproduce well the experimental data, including the decay pattern of the $\Xi(1690)$.

We think that, in addition to the attractive interaction between kaon and hadrons in chiral dynamics, the relatively heavy kaon mass compared to the pion mass would be essential to the appearance of hadronic molecules in the spectrum of multi-strangeness baryons such as $\Xi(1690)$ in the present study, $\bar{K}KN$ predicted in Refs. [21, 22], and so on.

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