# Hadronic molecular assignment for the newly observed $\Omega^*$ state

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Very recently, a new $\Omega^*$ state was reported by the Belle Collaboration, with its mass of $2012.4 \pm 0.7(\mathrm{stat}) \pm 0.6(\mathrm{syst})$ MeV, which locates just below the $K\Xi^*$ threshold and hence hints to be a possible $K\Xi^*$ hadronic molecule. Using the effective Lagrangian approach as the same as our previous works for other possible hadronic molecular states, we investigate the decay behavior of this new $\Omega^*$ state within the hadronic molecular picture. The results show that the measured decay width can be reproduced well and its dominant decay channel is predicted to be the $K\pi\Xi$ three-body decay. This suggests that the newly observed $\Omega^*$ may be ascribed as the $J^P = 3/2^-$ $K\Xi^*$ hadronic molecular state and can be further checked through its $K\pi\Xi$ decay channel.

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## I. INTRODUCTION

Various models, such as classical quenched quark models with three constituent quarks [1,2], unquenched quark models [3,4], and hadronic dynamical models [5–7], gave very different predictions for the $\Omega^*$ spectrum around 2000 MeV. But experimental knowledge on the $\Omega^*$ spectrum is very poor as listed in the review of the Particle Data Group [8], where the lowest $\Omega^*$ state is $\Omega(2250)$ with its mass about 600 MeV above the $\Omega$ ground state. This is much higher than the predictions of all models for the lowest $\Omega^*$ state.

Very recently, a new $\Omega^*$ state was observed in the $\Xi^0 K^-$ and $\Xi^- \bar{K}^0$ invariant mass distributions in $\Upsilon$ decay, by the Belle Collaboration [9]. Its measured mass and decay width are $2012.4 \pm 0.7(\mathrm{stat}) \pm 0.6(\mathrm{syst})$ MeV and $6.4^{+2.5}_{-2.0}(\mathrm{stat}) \pm 1.6(\mathrm{syst})$ MeV, respectively. The mass is quite close to the previous quark model prediction of 2020 MeV for the P-wave excitation of the $\Omega$ state [1]. After the observation of the new $\Omega(2012)$ state, the $qqq$ picture is further explored and supported by the studies with the chiral quark model [10] and the QCD sum rule method [11], respectively. On the other hand, the mass is just a few MeV below the $\bar{K}\Xi(1520)$ threshold of 2015 MeV, which suggests a possible $\bar{K}\Xi(1520)$ hadron molecule nature for it [12], although various previous hadronic dynamical approaches [5–7] of the $K\Xi(1520)$ interaction gave very different results.

For the hadronic molecular states, there are many theoretical attempts have been done [13,14]. A typical example is the pentaquark-like states $P_c^+(4380)$ and $P_c^+(4450)$ observed by LHCb collaboration [15] in 2015. The reported masses of $P_c^+(4380)$ and $P_c^+(4450)$ locate just below the thresholds of $\bar{D}\Sigma_c^*$ and $\bar{D}^*\Sigma_c$ with around 5 MeV and 10 MeV gap, respectively. Inspired by the property that their masses are close to relevant thresholds, our previous work [16] shows that the observed properties of these two $P_c$ states can be reproduced well with the spin-parity-$3/2^-$ $\bar{D}\Sigma_c^*$ and spin-parity-$5/2^+$ $\bar{D}^*\Sigma_c$ molecular assumption for $P_c^+(4380)$ and $P_c^+(4450)$ respectively. Actually, it is found that the similar molecular states also exist in strange and beauty sectors [17]. If the new $\Omega(2012)$ state is the S-wave $\bar{K}\Xi(1520)$ bound state, its spin-parity should be $3/2^-$, just like $P_c(4380)$ as $\bar{D}\Sigma_c^*$ bound state, $N^*(1875)$ as $K\Sigma^*$ bound state. In the present work, in order to check its hadronic molecular mature, we would like to study the strong decay behaviors of the $\Omega(2012)$ state with the same approach as we did for the $P_c(4380)$ and $N^*(1875)$ states.

This paper is organized as follows: In Sec. II, we introduce formalism and some details about the theoretical tools used to calculate the decay modes of exotic hadronic molecular states. In Sec. III, the numerical results and discussion are presented.

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## II. FORMALISM

With the $\Omega(2012)$ state as the $S$-wave $\Xi(1530)K$ hadronic molecule with spin-parity of $3/2^-$, its decay pattern of this molecular state is calculated by means of the effective Lagrangian approach as the same as in our previous work [16,17]. The important ingredients of the effective Lagrangian approach are briefly summarized as follows.

At first, the $S$-wave coupling of $\Omega(2012)$ to $\Xi(1530)K$ can be estimated model-independently with the Weinberg compositeness criterion. For the pure hadronic molecular case, it gets that [18,19]

$$g^2 = \frac{4\pi}{4Mm_2}\frac{(m_1+m_2)^{5/2}}{(m_1m_2)^{1/2}}\sqrt{32\epsilon}, \tag{1}$$

where $M$, $m_1$, and $m_2$ denote the masses of $\Omega(2012)$, $K$, and $\Xi(1530)$, respectively, and $\epsilon$ is the binding energy which equals $m_1+m_2-M$. Note that while in the case for a bound state of two mesons the coupling constant of the bound state with constituents is convergent in the local case as shown in Ref. [20], in our case for a bound state of a meson and a baryon the local vertices gives the logarithmic divergence. Including a form factor reflecting the size of the hadronic molecule is necessary to derive Eq. (1) and for further calculations. Assuming the physical state in question to be a pure $S$-wave hadronic molecule, the relative uncertainty of the above approximation for the coupling constant is $\sqrt{2\mu\epsilon}r$ where $\mu = m_1m_2/(m_1+m_2)$ is the reduced mass of the bound particles, and $r$ is the range of forces which may be estimated by the inverse of the mass of the particle that can be exchanged. In our case, $r$ may be estimated as $1/m_\rho$.

Note that the decay width of $\Xi(1530)$ listed in PDG is around 9 MeV. Compared with the reported width of $\Omega(2012)$, it is apparent that the three-body decay through the decay of $\Xi(1530)$ must be considered during the calculation. However, the four-body decay through the decays of both two constituents is strongly suppressed by the small width of $K$. The dominant three-body decay is given in Fig. 1, where the interactions between the final states have been neglected. To include the contribution of two-body decays, a meson-exchanged triangle diagram convention is taken as the same as our previous work [16,17]. For the three-strangeness isospin-zero excited $\Omega^*$ molecule, there is only one two-body channel $K\Xi$ need to be considered. The corresponding Feynman diagram is shown in Fig. 2. It should be mentioned that the perturbative formalism is used to provide a rough estimation for the total width of $\Omega(2012)$ as we did before, although the non-perturbative approach may be more elegant to give the total widths for a resonance. The partial width is given by

$$d\Gamma = \frac{F_I}{32\pi^2}\overline{|\mathcal{M}|^2}\frac{|\mathbf{p_1}|}{M^2}d\Omega, \tag{2}$$

where $d\Omega = d\phi_1 d(\cos\theta_1)$ is the solid angle of particle 1, $M$ is the mass of the initial $\Omega(2012)$, the factor $F_I$ is from the isospin symmetry, and the polarization-averaged squared amplitude $\overline{|\mathcal{M}|^2}$ means $\frac{1}{4}\sum_{\rm spin}|\mathcal{M}|^2$. Note that the types of vertices involved in the amplitudes of the diagrams shown in Figs. 1 and 2 are the same as those that appearing in the processes, spin-parity-$3/2^-$ $K\Sigma^*$ molecule decaying into the $K\pi\Lambda$ and $K\Lambda$ channels. The effective Lagrangians which describe these vertices can be found in our previous papers [16,17]. The couplings, $g_{KK\rho}$, $g_{KK\omega}$, $g_{KK\phi}$, $g_{\Xi^*\Xi\rho}$, $g_{\Xi^*\Xi\omega}$, and $g_{\Xi^*\Xi\omega}$ are taken from the $SU(3)$ relations. The exact values of these couplings used in our calculation are summarized in Table I. And $g_{\Xi^*\Xi\pi}$ is deduced from the experimental decay width of $\Xi(1530)$ decaying into $\Xi\pi$.

Finally, in order to get rid of the divergence appearing in the loop integration, we take the same convention as our previous work [16,17]. The following Gaussian regulator is adopted to suppress short-distance contributions [13,21–27],

$$f(\boldsymbol{p}^2/\Lambda_0^2) = \exp(-\boldsymbol{p}^2/\Lambda_0^2), \tag{3}$$

where $\boldsymbol{p}$ is the spatial part of the loop momentum and $\Lambda_0$ is an ultraviolet cutoff. During the calculation we vary the $\Lambda_0$ in the range of 0.6–1.4 GeV to estimate the dependence of our results on the cut-off as we did before. In addition, as

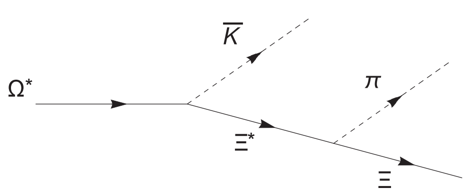


FIG. 1. The three-body decays of $\Omega(2012)$ in the $\Xi(1530)K$ molecular picture.

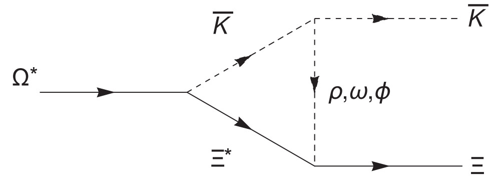


FIG. 2. The triangle diagram for the two-body decay of the $\Omega(2012)$ in the $\Xi(1530)K$ molecular picture.

TABLE I. the coupling constants used in the present work. Note that the parameters used in the SU(3) relations are taken the same values as our previous work. And only absolute values of the couplings are listed with their signs ignored.

| $g_{KK\rho}$ | $g_{KK\omega}$ | $g_{KK\phi}$ | $g_{\Xi^*\Xi\rho}$ (GeV$^{-1}$) | $g_{\Xi^*\Xi\omega}$ (GeV$^{-1}$) | $g_{\Xi^*\Xi\phi}$ (GeV$^{-1}$) |
|---|---|---|---|---|---|
| 3.02 | 3.02 | 4.27 | 8.44 | 8.44 | 11.94 |

TABLE II. Partial decay widths and branch ratios of $\Omega(2012)$ with the $S$-wave $\Xi^* K$ molecular scenario. And the cutoffs are fixed as $\Lambda_0 = 1.0$ GeV, $\Lambda_1 = 1.2$ GeV. All of the decay widths are in the unit of MeV, and the short bars denote that the corresponding channel is closed or its contribution is negligible.

| | $J^P = 3/2^-$ | |
|---|---|---|
| | $\Omega(2012)$ $(\Xi(1530)K)$ | |
| Mode | Widths (MeV) | Branch Ratio(%) |
| $K\Xi$ | 0.4 | 14.3 |
| $K\pi\Xi$ | 2.4 | 85.7 |
| Total | 2.8 | 100.0 |

described in our previous work a usual form factor chosen as Eq. (4) is also introduced to suppress the off-shell contributions for the exchanged particles.

$$f(q^2) = \frac{\Lambda_1^4}{(m^2 - q^2)^2 + \Lambda_1^4}, \tag{4}$$

where $m$ is the mass of the exchanged particle and $q$ is the corresponding momentum. The cut-off $\Lambda_1$ varies from 0.8 GeV to 2.0 GeV.

## III. RESULTS AND DISCUSSIONS

With the coupling constants given in Table I, the decay patterns of $\Omega(2012)$ can be calculated numerically. The partial decay widths and the corresponding branch ratios are displayed in Table II with a fixed set of parameters, $\Lambda_0 = 1.0$ GeV, $\Lambda_1 = 1.2$ GeV.

It should be mentioned that a Breit–Wigner distribution function given by Eq. (5) is introduced to include the finite width effect of the intermediate state $\Xi^*$ in the three-body decay.

$$\rho(s) = \frac{N}{|s - m_0^2 + i m_0 \Gamma|^2}, \tag{5}$$

where $m_0$ and $\Gamma$ are the PDG mass and width of $\Xi^*$, respectively. $\sqrt{s}$ is the invariant mass of $\pi\Xi$ final state,

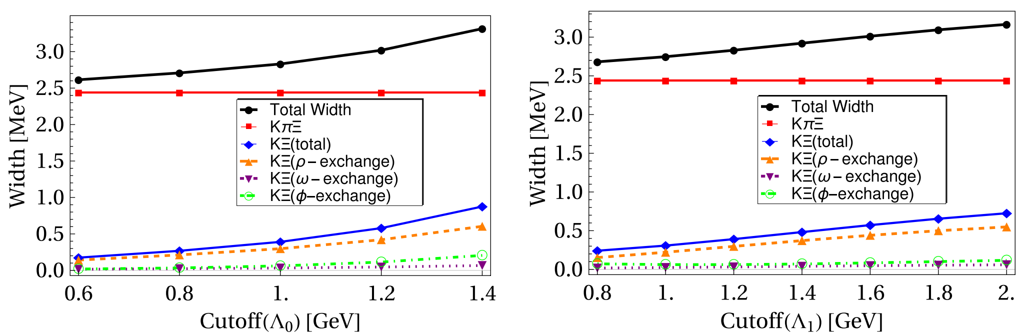


FIG. 3. Dependence of the total decay width and partial decay widths of $K\pi\Xi$, $K\Xi$, as well as the partial widths of $\rho$, $\omega$, $\phi$ exchange in the two-body $K\Xi$ decay channel on the cutoffs in the $S$-wave $K\Xi^*$ molecular scenario for $\Omega(2012)$: (left) $\Lambda_0$ changes with $\Lambda_1$ fixed at 1.2 GeV; (right) $\Lambda_1$ changes with $\Lambda_0$ fixed at 1.0 GeV.

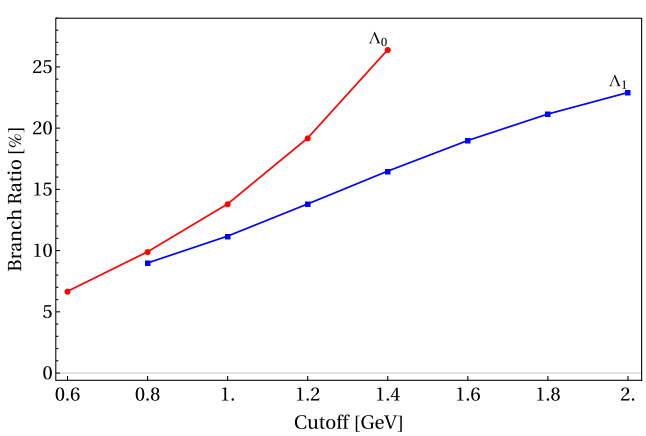


FIG. 4. Dependence of the branch ratio of $K\Xi$ channel on the cutoff $\Lambda_0$ (Red) and $\Lambda_1$ (Blue).

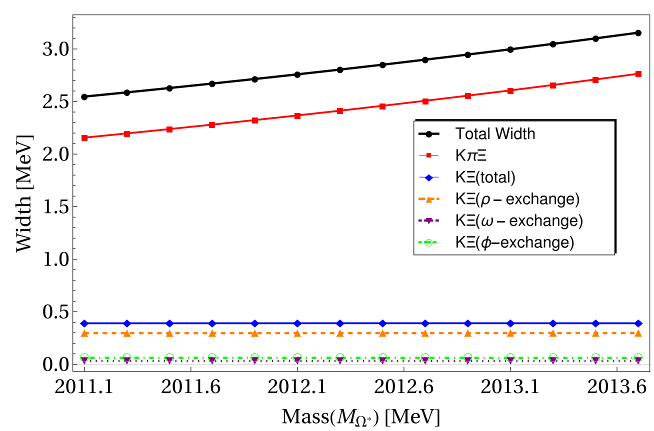


FIG. 5. Dependence of the total decay width and partial decay widths of $K\pi\Xi$, $K\Xi$, as well as the partial widths of $\rho$, $\omega$, $\phi$ exchange in the two-body $K\Xi$ decay channel on the reported mass of $\Omega(2012)$.

varying from $m_0 - \Gamma$ to $m_0 + \Gamma$. And $N$ is the normalization constant defined as

$$\int_{(m_0-\Gamma)^2}^{(m_0+\Gamma)^2} \rho(s)\mathrm{d}s = 1. \tag{6}$$

Note that there is a large and inevitable uncertainty exists in the determination of the coupling constants and the choice of cutoffs $\Lambda_0$ and $\Lambda_1$ in our model. Nevertheless, some qualitative remarks on the decay behaviors of $\Omega(2012)$ can be obtained from our numerical results. First of all, the small total decay width which is compatible with the announced value is obtained with the $S$-wave $\Xi^* K$ molecular assignment for the reported $\Omega(2012)$. And it is found that the three-body $K\pi\Xi$ decay is the dominant decay channel of $\Omega(2012)$, while the two-body $K\Xi$ channel just contributes 14.3 percent of width at $\Lambda_0 = 1.0$ GeV and $\Lambda_1 = 1.2$ GeV. This is rather different from the prediction of chiral quark model claimed in Ref. [10]. Future experimental investigation of the three-body decay needs to be performed for disentangling these different assignments of $\Omega(2012)$. Different from the naive expectation of Ref. [12], the three-body $K\pi\Xi$ decay width is significantly smaller than the decay width of the free $\Xi(1520)$ state. This is due to the binding energy of the molecule as well as the kinetic energy of $\bar{K}$ inside the molecule, which reduce the effective mass of the bound $\Xi(1520)$ significantly. Similar effect was pointed out by Refs. [28,29] in their studies of $d^*(2380)$ as a $\Delta\Delta$ molecule which gets a decay width smaller than the decay width of a single free $\Delta$ state.

The cutoff dependence of decay widths is given in Fig. 3. As we can see from the figure, the $\rho$-exchange is the dominant contribution for the partial width of $K\Xi$ two-body channel. And the partial width of three-body $K\pi\Xi$ channel is larger greatly than that of $K\Xi$ channel in the whole ranges of cutoff $\Lambda_0$ and $\Lambda_1$. A measurement of the three-body $K\pi\Xi$ decay branching of the reported $\Omega^*$ candidate will help to test our model and reveal the nature of this new hyperon. The cut-off dependence of the branch ratio of $K\Xi$ channel is shown in Fig. 4. Finally, we also analyze the sensitivity of our results to the announced mass of $\Omega(2012)$ as shown in Fig. 5. The curvature shows that the partial width of three-body decay changes slightly within the error bar of reported mass, while the result keeps stable for the $K\Xi$ two-body decay.

In summary, our numerical results indicate that the $S$-wave $\Xi^* K$ molecular scenario for the new $\Omega^*$ candidate can provide a reasonable interpretation for its announced width and the three-body $K\pi\Xi$ decay plays a crucial role on the decay behaviors of $\Omega(2012)$. Searching for this three-body decay of $\Omega(2012)$ can help us to understand its nature.

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