Hidden-Strange $N\phi$ molecular state in a quasipotential Bethe-Salpeter equation approach

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In this work, we study the possibility to produce a hidden-strange molecular state composed of a nucleon and $\phi$ meson from coupled-channel $\Sigma K = N\phi - \Sigma K^*$ interaction. With the help of the effective Lagrangians which couple constants are determined by the SU(3) symmetry, the $\Sigma K = N\phi - \Sigma K^*$ interaction kernel were constructed and inserted into the quasipotential Bethe-Salpeter equation to search for the pole corresponding to the $N\phi$ bound state. No bound state can be found if direct interaction between nucleon and $\phi$ meson is neglected according to the OZI rule. After introduction of a van der Waals force between nucleon and $\phi$ meson, a bound state can be produced from the $N\phi$ interaction with spin parity $3/2^-$, and the coupled-channel effects from the $\Sigma K$ and $\Sigma K^*$ channels are found small in our calculation. Our results also suggest that the structure of $N\phi$ bound state in the invariant mass spectrum may not be a standard resonance, of which the experimentist should be mindful in future possible observation at facilities, such as JLab.

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I. INTRODUCTION

After observation of the $X(3872)$ and claimed $\Theta$ particle, study of the exotic hadron becomes a very hot topic in the hadron physics [1, 2]. With the die-away of the $\Theta$ particle [3], the XYZ particles become the most important candidates of the exotic hadrons and great progresses are made in both experiment and theory. Relatively, the study on the exotic baryon is quiet to some extent until observation of the $P_c(4450)$ and $P_c(3880)$ at LHCb [4]. After the LHCb observation, possible exotic baryons attract more interest from hadron physics community. Even some of the five $\Omega_c$ baryons observed recently at LHCb were interpreted as exotic baryons [5–8].

Now that the candidates of the pentaquark were observed in the charmed sector, the possible candidate of pentaquark in light sector should be reconsidered. In Ref. [11–13], the $P_c(4450)$ and $P_c(3880)$ were interpreted as $\Sigma_c\bar{D}$ and $\Sigma_c\bar{D}$ bound states, respectively. In the light sector, the corresponding hidden-strange pentaquarks counterpart were investigated in a molecular picture [9, 10]. The results suggest that two states with spin-parity $3/2^-$ can be produced from the $\Sigma K$ and $\Sigma K$ interactions, which correspond to the $N(2100)$ observed in the $\phi$ photoproduction and the $N(1875)$, respectively. Such hidden-strange molecular states are also supported by analyses of experimental data of relevant photoproductions as in Refs. [9, 10, 14–16] and a recent calculation in constituent quark model [17].

The $N(2100)$ and LHCb pentaquarks were observed in $N\phi$ and $NJ/\psi$ channels, respectively. In the study about these pentaquarks in the molecular state picture, especially their decays, the $N\phi$ and $NJ/\psi$ interactions should be involved. For example, in Ref. [18] the LHCb pentaquark is assumed to be produced in a $NJ/\psi \rightarrow NJ/\psi$ rescattering process. However, we would like to emphasize that the LHCb pentaquark is not from the direct $NJ/\psi$ interaction, but the interaction of $\Sigma_c^{(*)}$ baryon and $\bar{D}^{(*)}$ meson because the direct $NJ/\psi$ and $N\phi$ interaction should be suppressed according to the well-known OZI rule. In Refs. [19, 20], the $NJ/\psi$ interaction was investigated explicitly, and direct $NJ/\psi$ interaction was neglected also. As $NJ/\psi$ interaction, the quark exchange between nucleon and $\phi$ meson are also forbidden according to the OZI rule, and often neglected [21]. Hence, for studies in the molecular state picture, the interaction between a $s\bar{s}/c\bar{c}$ and a nucleon is often assumed to be very small and such kinds of hidden-strange/hidden-charmed molecular state are not considered.

Since the $\phi$ meson can not interact with the nucleon by the quark exchange, it is a good place to test the effect of the gluon exchange. In Refs. [22, 23], the van der Waals force, which reflects multigluon exchange, has been suggested to be strong enough to produce a bound state. Such proposal is supported by a study in Ref. [24], where it is found that at low velocity the QCD van der Waals interaction is enhanced. A lattice QCD calculation also supports the existence of such kind of bound state [25]. Hence, the $N\phi$ bound state is a good way to study the effect of the gluon exchange, that is, the QCD van der Waals force. Moreover, the the $N\phi$ bound state is also a hidden-strange pentaquark as the interpretations of the $N(2100)$ and $N(1875)$ suggested in Ref. [9, 17]. It is interesting to make a systematic study of bound states from the $N\phi$, $\Sigma K$, and $\Sigma K^*$ interactions in both experiment and theory, which will deep our understanding about the hidden-strange pentaquark.

Calculations in the constituent quark models were also performed to study the possible bound state composed of a nucleon and a $\phi$ meson [26, 27]. In all those calculations, the $N\phi$ bound state can be produced as suggested by Gao et al. [23]. However, in the constituent quark model, only one gluon exchange between two constituent quarks is considered in
the calculation, which contribution vanishes in the $N\phi$ case. The multilgluon exchange between the constituent quarks and the gluon exchange with self interaction are not considered in these models. Hence, the attractiveness between nucleon and $\phi$ meson does not originate from the van der Waals force, which is from multilgluon exchange, but from the delocalization effect in the quark delocalization color screen model (QDCSM) \cite{27} or the $\sigma$ exchange in chiral quark model \cite{26}. In the constituent quark models, the direct $N\phi$ interaction is attractive but not strong enough to produce a bound state and the coupling between this channel and other channels, such as $\Sigma K$ and $\Sigma K^*$ \cite{27} or $\Lambda K^*$ \cite{26}, should be introduced to provide enough attractiveness to produce a $N\phi$ bound state.

In the original proposal by Gao et al. \cite{23}, the QCD van der Waals force from multilgluon exchange is strong enough to produce a bound state while in the constituent quark models the coupled-channel effect becomes more important because the gluon exchange vanishes \cite{26,27}. In our previous work \cite{9}, we studied the $\Sigma^* K - \Sigma K^*$ interaction where the coupled-channel effect is very small and the $\Sigma K$ and $\Sigma K^*$ bound states are almost determined by the corresponding interactions. It is interesting to extend it to include the $N\phi$ case, which will be helpful to understand the interaction of nucleon and a $\phi$ meson and the coupled-channel effect between the $N\phi$ channel and the $\Sigma K - \Sigma K^*$ channel in hadronic level. In this work, we will study the $\Sigma^* K - N\phi - \Sigma K^*$ interaction plus the QCD van der Waals force to study the hidden-strange $N\phi$ molecular state in a quasispontial Bethe-salpeter equation.

This paper is organized as follows. In the section II, we present the effective Lagrangians adopted to describe the $\Sigma K - N\phi - \Sigma K^*$ interaction, and corresponding coupling constants are determined by the SU(3) symmetry. The QCD van der Waals force is also transferred to a form which can be used in our formalism. In Sec. III, the $N\phi$ bound states are searched for and the numerical results are presented. Finally, the paper ends with a brief conclusion.

II. $\Sigma^* K - N\phi - \Sigma K^*$ INTERACTION

In the current work, we will study the coupled $\Sigma^* K - N\phi - \Sigma K^*$ interaction to search for the $N\phi$ bound state. In our previous works \cite{9,10}, the $\Sigma K$ and $\Sigma K^*$ interactions and their couplings were explicitly studied, and the relevant Lagrangians and the coupling constants have been presented explicitly. In this section, we focus on interactions where the $N\phi$ channel involved.

As suggested in Ref. \cite{23}, a $\phi$ meson interacts with nucleon with the van der Waals force, which was adopted as a non-relativistic Yukawa type attractive potential of a form $V_{\phi NN} = -ae^{-\mu r}/r$. The parameters were chosen as $a = 2.55$ and $\mu = 0.6$ GeV, which are consistent with the values adopted for the $c\bar{c}$ charmonium by Brodsky et al. \cite{22}. We would like to remind that as suggested in Ref. \cite{22}, there should be other spin-orbit and spin-spin hyperfine terms because the interaction is vector-like but the parameters are determined with this simple form of the potential. Here we only keep the main part as in Ref. \cite{22,27}, which ensures the discussion about the parameter in the references can be adopted here. In the current work, we work in the momentum space, the van der Waals force above should be transferred to a Yukawa type interaction as,

$$iV_{N\phi} = (4\pi)^2 \frac{\alpha}{q^2 - \mu^2} \bar{N}N \phi \cdot \phi,$$

where $N$ and $\phi$ are the spinor for nucleon and polarized vector for $\phi$ meson, and an additional $4\pi$ is introduced due to the convention adopted in our formalism. The $\mu$ is fixed at the value 0.6 GeV as in Ref. \cite{23}. In this work, we will vary the strength parameter $\alpha$ in a range from 0.85 to 1.65 instead of 1.25 adopted in \cite{23} to test the effect of the strength of the van der Waals force which can not be well determined.

Besides the $N\phi$ interaction, the couplings between $N\phi$ channel and the $\Sigma^* K$ and $\Sigma K^*$ channels are also concerned in this work. To describe the couplings, we will consider $N\phi \to \Sigma K$ interaction by $K/K^*$ exchange. The relevant Lagrangians are

$$L_{KK\phi} = -ig_{KK\phi} [K^\mu \phi \partial_\mu K + \partial_\mu K^\mu \phi^\mu] K],$$

$$L_{K^*K\phi} = g_{K^*K\phi} \epsilon^{\mu\nu\sigma\tau} \partial_\mu K^{\nu\sigma} \phi^\tau K, N,$$

$$L_{K^*\Sigma^*N} = \frac{f_{\Sigma^*N}}{m_K} \bar{N} \Sigma^* \phi^\mu K + H.c.,$$

$$L_{K\Sigma^*N} = \frac{f_{\Sigma^*N}}{m_K} N \Sigma^* \phi^\mu K + H.c.,$$

where the $K$, $\phi$, $K^*$, $N$, and $\Sigma^*$ are the fields for $K$ meson, $\phi$ meson, $K^*$ meson, nucleon, and $\Sigma^*$ baryon, and $K^{\mu\nu} = \partial_\mu K^{\nu\sigma} - \partial_\nu K^{\mu\sigma}$. The coupling constants can obtained from the SU(3) symmetry. $f_{KNN}/m_K = -e^{\mu \Sigma} f_{\Sigma\Sigma N}/m_{\Sigma}$ and $f_{KNN}/m_K = -\sqrt{f_{\Sigma NN}/m_{\Sigma}}$ with $f_{\Delta N} = -6.08$ \cite{28} and $f_{\Sigma\Sigma N}/m_{\Sigma} = 1.27$ \cite{29}, $g_{KK\phi} = g_{\pi NN}/\sqrt{2}$, and the value of the $g_{\pi NN}$ is chosen as 6.1 \cite{28,30}, $g_{KK\phi}/(\sqrt{2}(2\alpha - 1)) = g_{\omega NN}/(2\alpha)$ can be obtained with a being 1 \cite{30} and $g_{\omega NN}$ being 11.2 \cite{28}.

With the Lagrangians above, the potentials for the $N\phi \to \Sigma K$ interaction by $K$ and $K^*$ exchanges are written as

$$iV_{K} = \frac{f_{K\Sigma^*N}}{m_K} \epsilon^{\mu\nu\sigma\tau} \phi^\mu K^{\nu\sigma} \phi^\tau K + H.c.,$$

$$iV_{K^*} = \frac{f_{K\Sigma^*N}}{m_K} \epsilon^{\mu\nu\sigma\tau} \phi^\mu K^{\nu\sigma} \phi^\tau K + H.c.,$$

where $q = k_\perp - k_\parallel$, with $k_\perp$ and $k_\parallel$ being the momenta of initial and final mesons, respectively, and $N$ and $\Sigma^*$ are the spinor for nucleon and Rarita-Schwinger spinor for the strange baryon $\Sigma^*$. The potential for $\Sigma^* K \to N\phi$ interaction can be obtained analogously. The flavor factor $f_1 = \sqrt{7}$.

For the coupling to the $\Sigma K^*$ channel by $K$ and $K^*$ exchanges, the Lagrangians required are

$$L_{K^*K\phi} = \frac{g_{K^*K\phi}}{2} (K^{\mu\nu} \phi^\mu K^{\nu\sigma} + K^{\mu\nu} \phi^\nu K^{\mu\sigma} + K^{\mu\sigma} \phi^\nu K^{\nu\sigma}),$$

$$L_{K^*K^*\phi} = \frac{g_{K^*K^*\phi}}{2} \epsilon^{\mu\nu\sigma\tau} \phi^\mu K^{\nu\sigma} \phi^\tau K, N,$$

$$L_{\Sigma K\phi} = \frac{g_{\Sigma K\phi}}{m_{\Sigma} + m_N} \bar{N} \gamma^\nu \Sigma \partial_\nu K + H.c.,$$

$$L_{\Sigma K^*\phi} = -\frac{g_{\Sigma K^*\phi}}{2m_{\Sigma}} \bar{N} \gamma^\nu \Sigma \partial_\nu K^* + H.c.,$$

where $N$ and $\phi$ are the spinor for nucleon and polarized vector for $\phi$ meson, and an additional $4\pi$ is introduced due to the convention adopted in our formalism. The $\mu$ is fixed at the value 0.6 GeV as in Ref. \cite{23}. In this work, we will vary the strength parameter $\alpha$ in a range from 0.85 to 1.65 instead of 1.25 adopted in \cite{23} to test the effect of the strength of the van der Waals force which can not be well determined.
The coupling constants can be predicted from SU(3) flavor symmetry as \( g_{KKN} = [(m_K + m_N) - 2\alpha_{
NPN}] = g_{CN} = m_N \) with \( \alpha_{
NPN} = 0.4 \) and \( J_{\nNPN} = 1 \) [30], \( g_{KKN} = g_{NNPN} - [(m_N - 2\alpha_{
NPN})] \) and \( J_{\nNPN} = g_{NNPN}/2 \) with \( g_{NNPN} \) chosen as \( g_{NNPN}/2, \kappa_\rho = 6.1, \) and \( \alpha_{
NPN} = 1.15 \) as in Refs. [28, 30].

The obtained potential is

\[
\begin{align*}
\bar{r}V_K &= \frac{\bar{f}_1g_{KKN}g_{K*K}}{(m_N + m_K)(q^2 - m_K^2)} \\
&\quad \cdot \left[ -(k'_1 + k_1)\phi \cdot K^* + (k'_1 + q) \cdot K^* \phi \right] \\
&\quad + (k_1 - q) \cdot \phi K^* - g^{\mu\nu} q^\nu / m_N \tilde{N} [\phi^{\mu} / 2m_N \alpha_{
NPN} q^\nu \phi] \Sigma. \\
\bar{r}V_K &= \frac{\bar{f}_1g_{KKN}g_{K*K}}{(m_N + m_K)(q^2 - m_K^2)} \tilde{d}^{\mu\nu\tau} q^\nu \phi^{\tau} k'_1 K^* \tilde{N} \gamma_\tau \Sigma. \quad (5)
\end{align*}
\]

With the potentials presented above and those in Refs. [9, 10], the \( \Sigma K - N \phi - \Sigma K^* \) interaction can be inserted into the Bethe-Salpeter equation to find the rescattering amplitude. Due to the difficulty in solving the Bethe-Salpeter equation in Minkovskis space, as in previous work [31–34], a spectator quasipotential approximation will be introduced by putting one of the two particles on shell [35, 36]. In Ref. [37], author suggested that the heavier particle should be put on shell when one-boson exchange is adopted while in Ref [9], a test of different choices of the on-shell particle was made and the effect on numerical results were found small. In this work, we will put all baryons on-shell. The method was explained explicitly in the appendixes of Ref. [38].

The possible bound state produced from the \( \Sigma K - N \phi - \Sigma K^* \) interaction is reflected by a pole of the scattering amplitude \( \bar{M} \). The quasipotential Bethe-Salpeter equation for partial-wave amplitude with fixed spin parity \( J_p \) reads [12, 38]

\[
iM_{J_p,1}^{\rho}(p', p) = \bar{r}V_{J_p,1}^{\rho}(p', p) + \sum_{J_p} \int \frac{p''^2 dp''}{(2\pi)^3} \\
&\quad \cdot \bar{r}V_{J_p,1}^{\rho''}(p'', p'') G_0(p'') iM_{J_p,1}^{\rho''}(p'', p'). \quad (6)
\]

The potential kernel \( V_{J_p,1} \) obtained in previous section can be transferred to partial wave potential with fixed spin parity \( J_p \) as

\[
\bar{r}V_{J_p,1}(p', p) = 2\pi \int d \cos \theta \left[ d_{J_p,1}^{\phi}(\theta) \bar{r}V_{J_p,1}(p', p) \right. \\
&\left. + g_{d} d_{J_p,1}^{\tau}(\theta) \bar{r}V_{J_p,1}(p', p) \right], \quad (7)
\]

where initial and final relative momenta are chosen as \( \rho = (0, 0, p) \) and \( p' = (p' \sin \theta, 0, p' \cos \theta) \) with a definition \( \rho^I = [\rho] \), and \( d_{J_p,1}^{\phi}(\theta) \) is the Wigner d-matrix. This equation can be extended to coupled-channel case as in Ref. [39]. An exponential regularization is introduced as a form factor in the propagator of a from

\[
G_0(p) \rightarrow G_0(p) \left[ e^{-(k_1^2 - m_1^2)p^I / M^2} \right]^2, \quad (8)
\]

where \( k_1 \) and \( m_1 \) are the momentum and mass of the off-shell meson, respectively. The interested reader is referred to Ref. [38] for further information about the regularization.

### III. NUMERICAL RESULTS

With above preparation, the bound states from the \( \Sigma K - N \phi - \Sigma K^* \) interaction can be searched for after analytic continuation of total energy \( W \) into complex plan as \( \z \). In this work, we focus on the cases of spin parities 1/2 and 3/2, which are in S-wave and were studied in constituent quark model [27]. First, we present the results with single channel with the variation of the cutoff in a range from 0.5 to 2 GeV. The bound states from the \( \Sigma K \) and \( \Sigma K^* \) interactions were explicitly discussed in Ref. [9]. For the \( N \phi \) interaction where we fix the strength parameter \( \alpha \) at 1.25, only one state with spin parity 3/2 is produced with a cutoff about 1 GeV. No pole is found in the case of spin parity 1/2. The 3/2 case, two relatively stable bound states are produced from the \( \Sigma K \) and \( \Sigma K^* \) interactions, respectively [9]. These two states can be related to the experimentally observed \( N(1875) \) and \( N(2100) \), and listed with the \( N \phi \) bound state in Table I.

| \( N \phi \) | \( \Sigma K \) | \( \Sigma K^* \) |
|---|---|---|
| \( \Lambda \) | \( W \) | \( \Lambda \) | \( W \) | \( \Lambda \) | \( W \) |
| 0.8 | 1955 | 1.5 | 1880 | 0.8 | 2086 |
| 0.9 | 1952 | 1.6 | 1879 | 0.9 | 2085 |
| 1.0 | 1948 | 1.7 | 1874 | 1.0 | 2081 |
| 1.1 | 1944 | 1.8 | 1862 | 1.1 | 2076 |
| 1.2 | 1939 | 1.9 | 1832 | 1.2 | 2068 |

From the results in above table, one can find that if an appropriate cutoff is adopted, the bound states can be produced from all three considered channels. Particularly, the \( N \phi \) bound state can be produced from the \( N \phi \) interaction directly at \( \alpha = 1.25 \). Considering that the strength of van der Waals force between \( s \bar{s} \) and nucleon can not be well determined, here we will vary both cutoff \( \Lambda_{N \phi} \) and the strength parameter \( \alpha \) to discuss effect of the \( \alpha \) on the results. The results with binding energy smaller than 50 MeV are listed in Table II. With the increase of the \( \alpha \), the \( N \phi \) system with 3/2 becomes deeper binding. At strength parameter \( \alpha = 0.85 \), the bound state appears at cutoff \( \Lambda_{N \phi} \) of 1 GeV while at \( \alpha = 1.65 \), the binding energy is about 30 MeV at cutoff of 1 GeV. From the results, the \( \alpha \) and \( \Lambda_{N \phi} \) play similar role in the strength of the \( N \phi \) interaction.

Generally speaking, the \( N \phi \) bound state can be produced from the single \( N \phi \) interaction, which is consistent with the original proposal by Gao et al. [23], but seems to be different from the results in the constituent quark model where the interaction is attractive but not strong enough to bind nucleon and \( \phi \) meson [26, 27]. However, in our approach, the cutoff is a free parameter which cannot be predetermined. It is still
possible to give a similar results as in QDCSM at a small cutoff $\Lambda_{\phi}$ in the case where only $N\phi$ interaction is considered [27]. Hence, in the following, we will present the bound state with couplings between $N\phi$ and $\Sigma K - \Sigma K^*$ channels to find their roles in binding nucleon and $\phi$ meson, which is important in QDCSM [27]. If the binding of the $N\phi$ bound state became deeper after the couplings included, the results in our approach might be still consistent with these in QDCSM. In Table III, we list the positions of the poles for the $N\phi$ bound states with coupled-channel effect at different strength parameter $\alpha$ and different cutoff $\Lambda_{N\phi}$. Here the cutoffs for the $\Sigma K$ and $\Sigma K^*$ channels are chosen as 1.7 GeV and 1.3 GeV which were chosen to be consistent with those in Ref. [9].

After inclusion of the coupled-channel effect from $\Sigma K$ and $\Sigma K^*$ channels, the $N\phi$ bound state becomes a resonance with a small width, which is due to the openness of lower channel $\Sigma K$. However, it is surprise to find that the mass of the $N\phi$ bound state is almost unchanged compared with the results only with $N\phi$ interaction as shown in Table II. Such results suggest that the coupled-channel effect is small compared with van der Waals force. Based on the results, it is difficult to find a cutoff at which the $N\phi$ can not be produced with direct interaction but can be produced after the coupled-channel effect included as in the QDCSM. Instead, our conclusion is consistent with the original proposal by Gao et al. [23], that is, the $N\phi$ bound state are totally from a van der Waals force.

In Fig. 1, the explicit about the poles from the $\Sigma K - N\phi - \Sigma K^*$ interaction are illustrated at chosen cutoffs $\Lambda_{\Sigma K}=1.7$ GeV, $\Lambda_{N\phi}=0.9$ GeV, $\Lambda_{\Sigma K^*}=1.3$ GeV, and strength parameter $\alpha=1.25$. From the figure, the bound states are produced under the thresholds for all three channels. The two higher bound states have small widths due to the openness of the threshold lower than the production channel. The $N\phi$ bound state is very narrow with the channels considered in thee current work, which is consistent with the small coupled-channel effect in our approach.
Im(ζ)=0 with the variation of Re(ζ) in middle panel of Fig. 1. Three dips can be obviously observed in the curve. The square of the amplitude, $\sum_{i,j} |M_{i,j}|^2$ for the lowest channel $\Sigma K$, is presented in the lower panel of Fig. 1 (see thick blue line). Though only the $\Sigma K - N\phi - \Sigma K^*$ interaction is considered here, it is surprise to find that the pole does not exhibit itself as a standard resonance which can be described in Breit-Wigner form. The square of amplitude decreases rapidly first with the increase of Re(ζ), then increases sharply, following with a rapid drop around the position of two poles for $N\phi$ and $\Sigma K^*$ bound states. Such situation corresponds to a Breit-Wigner form resonance plus a background. We also find that the poles can manifest themselves as standard peak after a proper background including (see thin brown curve).

IV. SUMMARY

In this work, we study the $N\phi$ bound state from coupled $\Sigma^* K - N\bar{\phi} - \Sigma K^*$ interaction. The interaction are described with the help of the effective Lagrangians and the coupling constants are determined with the SU(3) symmetry. The potentials are inserted into the quasipotential Bethe-salpeter equation to find the pole corresponding the $N\phi$ bound state. It is found that no bound state can be produced from the coupled $\Sigma^* K - N\bar{\phi} - \Sigma K^*$ interaction if the $N\phi$ direct interaction is assumed to be neglected according to the OZI rule. If the van der Waals force between the nucleon and $\phi$ meson is included, a stable bound state can be produced from the direct $N\phi$ interaction. Our results suggest that the coupled-channel effect from the $\Sigma^* K$ and $\Sigma K^*$ channels is very small on binding the nucleon and $\phi$ meson. Besides, the square of the amplitude for the lowest channel $\Sigma^* K$ is also presented to give a picture of the contribution of the poles in physics. Our results suggest that the $N\bar{\phi}$ bound state may not exhibit itself as a standard resonance. Though the current results can not be compared with future real observation directly, experimentist should be mindful of it when searching for $N\phi$ molecular state in invariant mass spectrum.

In all model calculations including the original proposal by Gao et al., two constituent quark models, lattice QCD [25], and the current work, the direct interaction between nucleon and $\phi$ meson is attractive, and bound state can be produced from the $N\phi$ interaction. However, difference can be found in the explicit formation of the $N\phi$ bound state in these models. In Ref. [23] and current work, the multigluon effect as QCD van der Waals force is considered, and it plays an dominant role in binding nucleon and $\phi$ meson even after the coupled-channel effect included. In the constituent quark models [26, 27], the one-gluon exchange is considered, however, its contribution vanishes in the $N\phi$ case. The $N\phi$ interaction is still attractive but relatively weak, and coupled-channel effect becomes important.

The $N\phi$ molecular state is a hidden-strange pentaquark state along with $\Sigma^* K$ and $\Sigma K^*$ bound states which were suggested in both QDCSM [17] and our approach. And it is also important to understand the gluon exchange, especially the multigluon exchange, between two hadrons. Now that all model calculations favor the existence of the hidden-strange molecular $N\phi$ bound state, the search of such state in experiment at the facility, such as JLab, is strongly suggested. The experimental research and further theoretical study will be helpful to clarify this interesting issue.

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