$P_-$-like pentaquarks in hidden strange sector

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Analogous to the work of hidden charm molecular pentaquarks, we study possible hidden strange molecular pentaquarks composed of $\Sigma$ (or $\Sigma^*$) and $K$ (or $K^*$) in the framework of quark delocalization color screening model. Our results suggest that the $\Sigma K$, $\Sigma K^*$ and $\Sigma^* K^*$ with $IJ^P = \frac{1}{2} \frac{1}{2}^-$ are all resonance states by coupling the open channels. The molecular pentaquark $\Sigma^* K^*$ with quantum numbers $IJ^P = \frac{1}{2} \frac{1}{2}^-$ can be seen as a strange partner of the LHCb $P_c(4380)$ state, and it can be identified as the nucleon resonance $N^*(1875)$ listed in PDG. The $\Sigma K^*$ with quantum numbers $IJ^P = \frac{1}{2} \frac{1}{2}^+$ can be identified as the $N^*(2100)$, which was experimentally observed in the $\phi$ photo-production.

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I. INTRODUCTION

The multi-quark study is essential for understanding the low energy quantum chromodynamics (QCD), because the multi-quark states can provide information unavailable for $q\bar{q}$ meson and $q^3$ baryon, especially the property of hidden color structure. The pentaquark is one of the important topics of the multi-quark study. In 2015, the observations of two hidden-charm pentaquarks $P_c(4380)$ and $P_c(4450)$ at LHCb [1] invoked a renewed interest in the pentaquark states. The JLab also proposed to search for these two $P_c$ states by using photo-production of $J/\psi$ at threshold [2]. Various interpretations of the hidden-charm pentaquarks have been discussed and many other possible pentaquarks were also proposed in the literatures [3–13].

Analogous to the hidden-charm pentaquarks $P_c$ states, one may consider the existence of possible $P_-$-like pentaquarks in hidden strange sector, in which the $cc$ is replaced by the $s\bar{s}$. In fact, as early as 2001, a $\phi - N$ bound state was proposed by Gao et al. [14], which is an analogy to the work of Refs. [15–17], in which they suggested that the QCD van der Waals interaction, mediated by multi-gluon exchanges, will dominate the interaction between two hadrons when they have no common quarks and this supported the prediction of nucleon-charmonium bound state near the charm production threshold. In addition, Liska et al. [17] demonstrated the feasibility to search for the $\phi - N$ bound state from $\phi$ meson subthreshold production; some chiral quark model calculation [18] and lattice QCD calculation [19] also support the existence of such a kind of bound state. Very recently, Xie and Guo studied the possible $\phi$ resonance in the $\Lambda_c^+ \rightarrow \pi^0 \phi p$ decay by considering a triangle singularity mechanism [20]. Our group also investigated the $\phi - N$ bound state in the quark delocalization color screening model (QDCSM) [21], performed a Monte Carlo simulation of the bound state production with an electron beam and a gold target, and found it was feasible to experimentally search for the $\phi - N$ bound state through the near threshold $\phi$ meson production from heavy nuclei. In Ref. [21], we only focus on the $\phi - N$ bound state, however, we also found that the interaction between $\Sigma$ (or $\Sigma^*$) and $K$ (or $K^*$) was strong enough to form bound states, which is similar to that of $\Sigma_c$ (or $\Sigma_c^*$) and $D$ (or $D^*$) [13]. Since the $P_c(4380)$ and $P_c(4450)$ are close to the thresholds of the $\Sigma_c^* D$ and $\Sigma_c D^*$, many work studied two $P_c$ states as the molecular states composed of $\Sigma_c$ (or $\Sigma_c^*$) and $D$ (or $D^*$) [4–5]. Therefore, we expect the existence of some molecular states consisted of $\Sigma$ (or $\Sigma^*$) and $K$ (or $K^*$), which are analogous to the $P_c$ state.

In fact, the pentaquarks composed of light quarks has a very long history. The $\Lambda(1405)$ resonance was explained as an $NK$ molecular state since the 1960s [22–28]. The quantities of nucleon resonances near 2 GeV were still unclear both in theory and experiment. Some nucleon resonances were investigated by coupling with pentaquark channels. One peculiar state is the $N^*(1535)$ resonance with spin parity $J^P = 1/2^-$, which is found to couple strongly to the pentaquark channels with strangeness [29–34]. Another $J^P = 1/2^-$ nucleon resonance is the $N^*(1895)$, which is a two-star state in the compilation of Particle Data Group (PDG) [35]. However, its existence is supported by the analysis of the new $\eta$ photo production data [36–37], which showed that the $N^*(1895)$ is crucial to describe the cusp observed in the $\eta$ photo production around 1896 MeV. Moreover, Refs. [36–37] suggested that this $N^*(1895)$ had strong coupling to the $N\eta$ and $N\eta'$ channels. In our previous work, we found a $J^P = 1/2^-$ bound state with a mass varying from 1873 to 1881 MeV, and the main component is $N\eta'$ [21], which could correspond to the resonance $N^*(1895)$. Four $J^P = 3/2^-$ nucleon resonances, $N^*(1520)$, $N^*(1700)$, $N^*(1875)$, and $N^*(2120)$ are listed in new versions of the PDG [33], among which a three-star $N^*(1875)$ and a two-star $N^*(2120)$ still have various interpretations about their internal structures [38–40]. J. He investigated both $N^*(1875)$ and $N^*(2120)$.
He interpreted the $N^*(1875)$ as a hadronic molecular state from the $\Sigma^*K$ interaction \cite{40}, and showed that the $N^*(2120)$ in the $K\Lambda(1520)$ photo-production was assigned as a naive three-quark state in the constituent quark model \cite{39,41}. Besides, the structure near 2.1 GeV in the $\phi$ photo-production showed an enhancement in the same energy region as that of $N^*(2120)$ \cite{42,44}. A recent analysis suggested that it has a mass of $2.08 \pm 0.04$ GeV and quantum number of $J^P = 3/2^-$ \cite{45,48}. Ref. \cite{49} denoted this state as $N^*(2100)$, and investigated it from the $\Sigma K^*$ interaction on the hadron level in a quasipotential Bethe-Salpeter equation approach. So it is also interesting to study the $\Sigma^*$ (or $\Sigma^*$) and $K^*$ (or $K^*$) interactions on the quark level to investigate the possibility of interpreting these nucleon resonances as hadronic molecular states.

Generally, one of the important ways to generate and identify multi-quark states is the hadron-hadron scattering process. The multi-quark state will appear as a resonance state in the scattering process. Therefore, to provide the necessary information for experiment to search for the multi-quark states, we should not only calculate the mass spectrum but also study the corresponding scattering process. By using the constituent quark models and the resonating group method (RGM) \cite{50}, we have obtained the $d^*$ resonance in the $NN$ scattering process, and we found that the energy and the partial decay width to the $D$-wave of $NN$ are consistent with the experiment data \cite{51}. Extending to the pentaquark system, we investigated the $N\phi$ state in the different scattering channels: $N\eta^*$, $\Lambda K$, and $\Sigma K$ \cite{14}. Both the resonance mass and decay width were obtained, which provided the necessary information for experimental searching at JLab. Therefore, it is interesting to extend such study to the molecular states composed of $\Sigma$ (or $\Sigma^*$) and $K$ (or $K^*$). In this work, we will investigate the scattering process of the corresponding open channels to search for any possible resonance states composed of $\Sigma$ (or $\Sigma^*$) and $K$ (or $K^*$).

In the next section, the framework of the QDCSM is briefly introduced. Section III devotes to the numerical results and discussions. The summary is shown in the last section.

II. THE QUARK DELocalIZATION COLOR SCREENING MODEL (QDCSM)

The quark delocalization color screening model has been widely described in the literatures \cite{52,53}, and we refer the reader to those works for details. Here, we just present the salient features of the model. The model Hamiltonian is:
\[
H = \sum_{i=1}^{5} \left( m_i + \frac{\mu_i^2}{2m_i} \right) - T_{CM} + \sum_{j>i=1}^{5} \left( V_{ij}^C + V_{ij}^G + V_{ij}^Y \right),
\]
\[
V_{ij}^C = -a_s \lambda_i^c \cdot \Lambda_j \left( r_{ij}^2 + v_0 \right),
\]
\[
V_{ij}^G = \frac{1}{4} a_s g_{s} \alpha_i \cdot \chi_j \left[ \frac{1}{r_{ij}} - \frac{\pi}{2} \delta(r_{ij}) \left( \frac{1}{m_i^2} + \frac{1}{m_j^2} + \frac{4\sigma_i \cdot \sigma_j}{3m_i m_j} \right) - \frac{3}{4m_i m_j r_{ij}} S_{ij} \right],
\]
\[
V_{ij}^Y = V_\pi(r_{ij}) \sum_{a=1}^{3} \lambda_i^a \cdot \lambda_j^a + V_K(r_{ij}) \sum_{a=4}^{7} \lambda_i^a \cdot \lambda_j^a + V_\eta(r_{ij}) \left[ (\lambda_i^8 \cdot \lambda_j^8) \cos \theta_P - (\lambda_i^9 \cdot \lambda_j^9) \sin \theta_P \right],
\]
\[
V_X(r_{ij}) = \frac{g_X}{4\pi} m_X^2 \left( \frac{\Lambda_X^2}{12m_i m_j \Lambda_X^2 - m_X^2} \right) \left( \sigma_i \cdot \sigma_j \right) \left[ Y(m_X r_{ij}) - \frac{\Lambda_X^3}{m_X^3} Y(\Lambda_X r_{ij}) \right] + \left[ \frac{H(m_X r_{ij})}{12m_i m_j} - \frac{\Lambda_X^3}{m_X^3} H(\Lambda_X r_{ij}) \right] S_{ij}, \quad \chi = \pi, K, \eta,
\]
\[
S_{ij} = \left\{ \frac{3(\sigma_i \cdot r_{ij})(\sigma_j \cdot r_{ij}) - \sigma_i \cdot \sigma_j}{r_{ij}} \right\},
\]
\[
H(x) = (1 + 3/x + 3/x^2)Y(x), \quad Y(x) = e^{-x}/x.
\]

Where \( S_{ij} \) is quark tensor operator; \( Y(x) \) and \( H(x) \) are standard Yukawa functions; \( T_c \) is the kinetic energy of the center of mass; \( a_s \) is the quark-gluon coupling constant; \( g_{ch} \) is the coupling constant for chiral field, which is determined from the \( NN \) coupling constant through

\[
g_{ch}^2 = \frac{3}{5} \frac{g_{s}^2}{4\pi} \frac{m_{u,d}^2}{m_N^2}.
\]

The other symbols in the above expressions have their usual meanings. Generally, we use the parameters from our previous work of dibaryons \[14, 53\]. However, the model parameters used in the dibaryon calculation can describe the ground baryons well, but cannot fit the masses of the ground mesons, especially the \( K \) meson, the obtained mass of which is much higher than the experimental value. This situation will lead to a consequence that some bound states cannot decay to the open channels, because of the much larger mass of \( K \). To solve this problem, we adjust the quark-gluon coupling constant \( a_s \) of the \( q\bar{q} \) pair, and keep the other parameters unchanged. By doing this, the parameters can describe the nucleon-nucleon and hyperon-nucleon interaction well, and at the same time, it will lower the mass of \( K \) to the experimental value. The model parameters are fixed by fitting the spectrum of baryons and mesons we used in this work. The parameters of Hamiltonian are given in Table I. Besides, a phenomenological color screening confinement potential is used here, and \( \mu_{ij} \) is the color screening parameter, which is determined by fitting the deuteron properties, \( NN \) scattering phase shifts, \( N\Lambda \) and \( N\Sigma \) scattering phase shifts, respectively, with \( \mu_{uu} = 0.45 \), \( \mu_{us} = 0.19 \) and \( \mu_{ss} = 0.08 \), satisfying the relation, \( \mu_{aa}^2 = \mu_{uu} \mu_{ss} \). The calculated masses of baryons and mesons in comparison with experimental values are shown in Table II.

| \( m_\pi \) (MeV) | \( m_K \) (MeV) | \( m_{\eta} \) (MeV) | \( m_{\eta'} \) (MeV) | \( m_{\eta''} \) (MeV) |
|------------|-------------|-----------------|-----------------|-----------------|
| 0.518      | 313         | 573             | 58.03           | -1.2883         |
| \( \alpha_{ss}^{uu} \) | \( \alpha_{ss}^{uu} \) | \( \alpha_{ss}^{uu} \) | \( \alpha_{ss}^{uu} \) | \( \alpha_{ss}^{uu} \) |
| 0.5652     | 0.5239      | 0.4506          | 1.7930          | 1.7829          |
| \( \alpha_{ss}^{uu} \) | \( \alpha_{ss}^{uu} \) | \( \alpha_{ss}^{uu} \) | \( \alpha_{ss}^{uu} \) | \( \alpha_{ss}^{uu} \) |
| \( \alpha_{ss}^{uu} \) | \( \alpha_{ss}^{uu} \) | \( \alpha_{ss}^{uu} \) | \( \alpha_{ss}^{uu} \) | \( \alpha_{ss}^{uu} \) |

The quark delocalization in QDCSM is realized by specifying the single particle orbital wave function of QDCSM as a linear combination of left and right Gaussians, the single particle orbital wave functions used in the or-
ordinary quark cluster model,
\[ \psi_\alpha(s_i, \epsilon) = \left( \phi_\alpha(s_i) + \epsilon \phi_\alpha(-s_i) \right) / N(\epsilon), \]
\[ \psi_\beta(-s_i, \epsilon) = \left( \phi_\beta(-s_i) + \epsilon \phi_\beta(s_i) \right) / N(\epsilon), \]
\[ N(\epsilon) = \sqrt{1 + c^2 + 2\epsilon e^{-\alpha^2/4b^2}}. \]  
(9)
\[ \phi_\alpha(s_i) = \left( \frac{1}{\pi b^2} \right)^{3/4} e^{-\frac{1}{2b}(r_n - \frac{1}{2}s_i)^2} \]
\[ \phi_\beta(-s_i) = \left( \frac{1}{\pi b^2} \right)^{3/4} e^{-\frac{1}{2b}(r_\beta + \frac{1}{2}s_i)^2}. \]

Here \( s_i, i = 1, 2, \ldots, n \) are the generating coordinates, which are introduced to expand the relative motion wavefunction \[ \overset{\circ}{\psi}. \] The mixing parameter \( \epsilon(s_i) \) is not an adjusted one but determined variationally by the dynamics of the multi-quark system itself. In this way, the multi-quark system chooses its favorable configuration in the interacting process. This mechanism has been used to explain the cross-over transition between hadron phase and quark-gluon plasma phase \[ \overset{\circ}{\psi}. \]

III. THE RESULTS AND DISCUSSIONS

In this work, we perform a dynamical investigation of the molecular states composed of \( \Sigma \) (or \( \Sigma^* \)) and \( K \) (or \( K^* \)) in the QDCSM. Our purpose is to understand the interaction properties of the \( \Sigma \) (or \( \Sigma^* \)) and \( K \) (or \( K^* \)), and to see whether there exists any \( P_c \)-like pentaquarks in hidden strange sector. Moreover, we also attempt to explore if there is any pentaquark states which can be used to explain some nucleon resonances. For the system with isospin \( I = \frac{1}{2} \) and \( J^P = \frac{1}{2}^- \), we investigate three molecular states \( \Sigma K, \Sigma K^* \) and \( \Sigma^* K^* \); for the system with isospin \( I = \frac{3}{2} \) and \( J^P = \frac{5}{2}^- \), we investigate three molecular states \( \Sigma K, \Sigma^* K \) and \( \Sigma^* K^* \).

Since an attractive potential is necessary for forming bound state or resonance, the effective potentials between \( \Sigma \) (or \( \Sigma^* \)) and \( K \) (or \( K^* \)) are calculated and shown in Figs. 1. The effective potential between two colorless clusters is defined as, \( V(s) = E(s) - E(\infty) \), where \( E(s) \) is the diagonal matrix element of the Hamiltonian of the system in the generating coordinate. For the \( 1J^P = \frac{1}{2}^- \) system (Fig. 1 (a)), one sees that the potentials are all attractive for the channels \( \Sigma K, \Sigma K^* \) and \( \Sigma^* K^* \). The attraction between \( \Sigma^* \) and \( K^* \) is the largest one, followed by that of the \( \Sigma K^* \) channel, then the \( \Sigma K \) channel. This rule is very similar to the interactions between \( \Sigma_L \) (or \( \Sigma_L^* \)) and \( D \) (or \( D^* \)). For the \( 1J^P = \frac{3}{2}^- \) system (Fig. 1 (b)), the potentials are all attractive for channels \( \Sigma K, \Sigma^* K \) and \( \Sigma^* K^* \). The attractions of both \( \Sigma K^* \) and \( \Sigma^* K^* \) channels are larger than that of the \( \Sigma^* K \) channel.

In order to see whether or not there is any bound state, a dynamic calculation is needed. The resonating group method (RGM), a well established method for studying a bound-state problem or a scattering one, is used here. The wave function of the baryon-meson system is of the form
\[ \Psi = \mathcal{A} \left[ \hat{\psi}_A(\xi_1, \xi_2) \hat{\psi}_B(\xi_3) \chi_L(R_{AB}) \right]. \]  
(10)
where \( \xi_1 \) and \( \xi_2 \) are the internal coordinates for the baryon cluster A, and \( \xi_3 \) is the internal coordinate for the meson cluster B. \( R_{AB} = R_A - R_B \) is the relative coordinate between the two clusters A and B. The \( \hat{\psi}_A \) and \( \hat{\psi}_B \) are the antisymmetrized internal cluster wave functions of the baryon A and meson B, and \( \chi_L(R_{AB}) \) is the relative motion wave function between two clusters. The symbol \( \mathcal{A} \) is the anti-symmetrization operator defined as
\[ \mathcal{A} = 1 - P_{14} - P_{24} - P_{34}. \]  
(11)
where 1, 2, and 3 stand for the quarks in the baryon cluster and 4 stands for the quark in the meson cluster. Here, we expand this relative motion wave function by gaussian bases
\[ \chi_L(R_{AB}) = \frac{1}{\sqrt{4\pi}} \left( \frac{6}{5\pi b^2} \right) \sum_{i=1}^{n} C_i \times \int \exp \left[ \frac{-3}{5b^2}(R_{AB} - \vec{S}_i)^2 \right] Y_{LM}(\vec{S}_i) d\vec{S}_i. \]  
(12)
where \( \vec{S}_i \) is the generating coordinate, \( n \) is the number of the gaussian bases, which is determined by the stability of the results. By doing this, the integro-differential equation of RGM can be reduced to algebraic equation, generalized eigen-equation. Then we can obtain the energy of the system by solving this generalized eigen-equation. The details of solving the RGM equation can be found in Ref. \[ \overset{\circ}{\psi}. \] In our calculation, the distribution of gaussians is fixed by the stability of the results. The results
are stable when the largest distance between the baryon-meson clusters is around 6 fm. To keep the dimensions of matrix manageable small, the baryon-meson separation is taken to be less than 6 fm.

For the single channel calculations, the strong attractive interaction between Σ (or Σ∗) and K (or K∗) leads to the total energy below the threshold of the two particles. All the binding energies (labeled as B) and the masses (labeled as M) of molecular pentaquarks are listed in Table III. We need to mention that the mass of the bound state can be generally splitted into three terms: the baryon mass $M_{baryon}$, the meson mass $M_{meson}$, and the binding energy $B$. To minimize the theoretical deviations, the former two terms, $M_{baryon}$ and $M_{meson}$, are shifted to the experimental values.

To confirm whether or not these bound states can survive as resonance states after coupling to the open channels, the study of the scattering process of the open channels is needed. Resonances are unstable particles usually observed as bell-shaped structures in scattering cross sections of their open channels. For a simple narrow resonance, its fundamental properties correspond to the visible cross-section features: mass is the peak position, and decay width is the half-width of the bell shape. To find the resonance mass and decay width of the bound states showed in Table III, we can calculate the cross-section of the corresponding open channels. The cross-section can be obtained from the scattering phase shifts by the formula:

$$\sigma = \frac{4\pi}{k^2} \cdot (2l + 1) \cdot \sin^2 \delta,$$

(13)

where $k = \sqrt{2\mu E_{cm}/h}$; $\mu$ is the reduced mass of two hadrons of the open channel; $E_{cm}$ is the incident energy; $\delta$ is the scattering phase shift of the open channel, which can be obtained by the well-developed RGM [50].

In this work, we study the pentaquarks composed of $uudds\bar{s}$, so the open channels composed of $uudd$ are not considered at the present stage. For the $IJ^P = \frac{1}{2}^-$ system, the bound state $\Sigma K$ can be coupled to one open channel: the $S$-wave $\Lambda K$; the bound state $\Sigma K^*$ can be coupled to eight open channels: the $S$-wave $N\eta'$, $N\phi$, $\Lambda K$, $\Lambda K^*$, $\Sigma K$ and the $D$-wave $N\phi$, $\Lambda K^*$, $\Sigma K^*$; the bound state $\Sigma^* K^*$ can be coupled to ten open channels: the $S$-wave $N\eta'$, $N\phi$, $\Lambda K$, $\Lambda K^*$, $\Sigma K^*$, $\Sigma K$ and the $D$-wave $N\phi$, $\Lambda K^*$, $\Sigma K^*$, $\Sigma K$. All these open channels are listed in the first column of Table IV, and the resonance states are listed in the first row of Table IV.

We calculate the scattering phase shifts of all these open channels, and then the cross-section by using the Eq. (13), finally we can obtain the resonance mass and decay width of the resonance states, which are show in Table IV. For the $IJ^P = \frac{1}{2}^-$ system, we do the same calculation as that of the $IJ^P = \frac{3}{2}^-$ system, and all resonance states and the corresponding open channels, as well as the resonance mass and decay width are shown in Table IV.

To save space, here we only show the cross-section of all open channels for the state $\Sigma K^*$ with $IJ^P = \frac{3}{2}^-$. (see Fig. 2). The resonance mass and decay width of this state are obtained from the cross-section of those related open channels. There are several features which are discussed below.

First, the bound states showed in Table III are all resonance states by coupling the corresponding open channels. Because only the hidden strange channels are considered here, the total decay width of the states given below is the lower limits. For the $IJ^P = \frac{1}{2}^-$ system, the resonance mass of $\Sigma K$ is 1668.0 MeV, and the decay width is very small which is only 1.3 MeV; the $\Sigma K^*$ is also possible a narrow resonance state with the mass range of 2056.6 $\sim$ 2083.4 MeV and the decay...
width is ~ 10 MeV; the mass of the resonance $\Sigma^*K^*$ is between 2219.0 ~ 2261.5 MeV, while the decay width is much larger, which is about 150 MeV at least. For the $IJ^P = \frac{1}{2}^-$ system, both the $\Sigma^*K$ and $\Sigma^*K^*$ are very narrow resonance states with the mass range of 1871.6 ~ 1875.7 MeV and 2265.5 ~ 2270.5 MeV respectively. Besides, the resonance mass range of $\Sigma^*K$ state is 2046.1 ~ 2061.4 MeV and the decay width is about 30 MeV.

Secondly, it is obvious that the decay width of decaying to $D$–wave channels is much smaller than that of decaying to the $S$–wave channels. This is reasonable. In our quark model calculation, the coupling between $S$–wave channels is through the central force, while the coupling between $S$– and $D$–wave channels is dominated by the tensor force, and the effect of the tensor force is much smaller than that of the central force. This conclusion is consistent with our previous calculation of the dibaryon systems [57, 58]. Besides, we only consider the two-body decay channels in this work. The calculation of more decay channels will change the total decay width of the resonance states.

Thirdly, our results in the hidden strange sector is similar to our previous study of the hidden charm molecular pentaquarks [13]. In Ref. [13], we found that three states with $IJ^P = \frac{1}{2}^-$: $\Sigma D$, $\Sigma^* D^*$, and $\Sigma^* D^*$, and the other three states with $IJ^P = \frac{3}{2}^-$: $\Sigma^* D$, $\Sigma^* D$, and $\Sigma^* D^*$ were all quasi-stable states. Analogously, in this work, we find that three states with $IJ^P = \frac{1}{2}^-$: $\Sigma K$, $\Sigma K^*$, and $\Sigma^* K^*$, and the other three states with $IJ^P = \frac{3}{2}^-$: $\Sigma^* K$, $\Sigma^* K$, and $\Sigma^* K^*$ are all resonance states. Besides, in Ref. [13], the molecular pentaquark $\Sigma^* D$ with quantum numbers $IJ^P = \frac{1}{2}^-$ can be used to explain the LHCb $P_c(4380)$ state. So here, the molecular pentaquark $\Sigma^* K$ with quantum numbers $IJ^P = \frac{1}{2}^-$ can be seen as a strange partner of the LHCb $P_c(4380)$ state. This conclusion is consistent with the work on the hadron level [49].

Finally, we find the mass of the $\Sigma^* K$ with quantum numbers $IJ^P = \frac{1}{2}^-$ is close to the nucleon resonance $N^*(1875)$ listed in PDG [52]. Obviously, both the mass and the quantum numbers of this molecular pentaquark $\Sigma^* K$ correspond to the $N^*(1875)$. This conclusion is also consistent with the work on the hadron level [49], in which the molecular state $\Sigma^* K$ was investigated in a quasipotential Bethe-Salpeter equation approach and it was identified as the $N^*(1875)$ listed in PDG. Moreover, Ref. [49] also found that the $\Sigma K$ interaction produced a bound state with quantum numbers $IJ^P = \frac{1}{2}^-$, which was related to the experimentally observed $N^*(2100)$ in the $\phi$ photo-production. Our results of the $\Sigma^* K$ state in the quark level is also consistent with that of Ref. [49], so we also support that the molecular pentaquark $\Sigma^* K$ can be identified as the $N^*(2100)$.

### IV. SUMMARY

In summary, we perform a dynamical investigation of the molecular states composed of $\Sigma$ (or $\Sigma^*$) and $K$ (or $K^*$) within the QDCSM. We calculate the effective potential, the mass and decay widths of these molecular states. Our results show: (1) The interactions between $\Sigma$ (or $\Sigma^*$) and $K$ (or $K^*$) are strong enough to form the bound states, which are $\Sigma K$, $\Sigma^* K$, and $\Sigma^* K^*$ with $IJ^P = \frac{1}{2}^-$ and $\Sigma K^*$, $\Sigma^* K$ and $\Sigma^* K^*$ with $IJ^P = \frac{1}{2}^-$.

And all these states are transferred to the resonance states by coupling the open channels. (2) Our results in the hidden strange sector is similar to our previous study of the hidden charm molecular pentaquarks [13], and the molecular pentaquark $\Sigma^* K$ with quantum numbers $IJ^P = \frac{1}{2}^-$ can be seen as a strange partner of the LHCb $P_c(4380)$ state. (3) This $\Sigma^* K$ state can also

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**TABLE IV**: The resonance mass and decay width (in MeV) of the molecular pentaquarks with $IJ^P = \frac{1}{2}^-$.  

| $S$–wave | $\Sigma K$ | $\Sigma K^*$ | $\Sigma^* K^*$ |
|----------|------------|-------------|---------------|
| $\eta'$  | $M_\eta$  | $\Gamma_\eta$ | $M_\eta$  | $\Gamma_\eta$ |
| $\phi$   | $M_\phi$  | $\Gamma_\phi$ | $M_\phi$  | $\Gamma_\phi$ |
| $\Lambda K$ | $1668.0$  | $1.3$       | $2261.5$  | $20.0$ |
| $\Lambda K^*$ | $2056.6$  | $0.2$       | $2219.0$  | $58.0$ |
| $\Sigma K$ | $2071.6$  | $4.6$       | $2253.2$  | $6.0$ |
| $\Sigma K^*$ | $2253.9$  | $16.0$      | $- -$     | $- -$ |

**TABLE V**: The resonance mass and decay width (in MeV) of the molecular pentaquarks with $IJ^P = \frac{3}{2}^-$.  

| $S$–wave | $\Sigma K$ | $\Sigma K^*$ | $\Sigma^* K^*$ |
|----------|------------|-------------|---------------|
| $\eta'$  | $M_\eta$  | $\Gamma_\eta$ | $M_\eta$  | $\Gamma_\eta$ |
| $\phi$   | $M_\phi$  | $\Gamma_\phi$ | $M_\phi$  | $\Gamma_\phi$ |
| $\Lambda K$ | $2046.1$  | $15.0$      | $2256.5$  | $2.0$ |
| $\Sigma K$ | $2054.1$  | $2.3$       | $2263.6$  | $3.7$ |
| $\Sigma K^*$ | $- -$     | $- -$       | $- -$     | $- -$ |

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be identified as the nucleon resonance $N^*(1875)$ listed in PDG. The $\Sigma K^*$ with quantum numbers $I\!J^P = \frac{3}{2}^{-}$ can be identified as the $N^*(2100)$, which was experimentally observed in the $\phi$ photo-production.

In this work, we only study the pentaquarks composed of $uudd\bar{s}$, so the open channels composed of $uudd\bar{u}$ are not considered at the present stage. Besides, we only consider the two-body decay channels. The calculation of more decay channels will change the total decay width of the resonance states. We will do this work in future.

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