I. INTRODUCTION

The recent observation of a near-threshold narrow enhancement in the $pp$ invariant mass spectrum from radiative decay $J/\Psi \rightarrow \gamma pp$ by the BES Collaboration has renewed interest in the $NN$ interaction and its possible baryonium bound states. In fact the enhancement in the $pp$ invariant mass distribution near the threshold has been observed by the Belle Collaboration in the decays $B^+ \rightarrow K^+ pp$ and $B^0 \rightarrow D^0 pp$ [2]. Besides, the Belle Collaboration also observed a near-threshold enhancement in the $p\bar{\Lambda}$ invariant-mass spectrum in $B \rightarrow p\Lambda\bar{\Lambda}$ decays [3]. Then, the same enhancement near the $p\bar{\Lambda}$ mass threshold was observed in the combined $p\Lambda$ and $p\bar{\Lambda}$ invariant-mass spectrum from $J/\Psi \rightarrow pK^-\Lambda + c.e.$ decays by BES Collaboration and it can be fitted with an $s$-wave Breit-Wigner resonance with a mass $m = 2075 \pm 12$ (stat) $\pm 5$ (syst) MeV and a width of $\Gamma = 90 \pm 35$ (stat) $\pm 9$ (syst) MeV or with a $P$-wave Breit-Wigner resonance [4]. However, there is no significant signal in $B^- \rightarrow J/\Psi \Lambda\bar{\Lambda}$ [5]. It is, therefore, of special interest to search for possible resonant structures in other baryon-antibaryon states. In Ref. [6], Fermi-Yang-Sakata-like scheme was used to classify the possible baryon-antibaryon SU(3) nonets. A systematic search of baryon-antibaryon states in color-magnetic interaction model was also performed and several interesting states were proposed [3].

Quantum chromodynamics (QCD) is widely accepted as the fundamental theory of the strong interaction, so it is naturally to expect to understand hadron-hadron interaction from QCD. However, the direct use of QCD on the hadron-hadron interaction is too difficult because of the non-perturbative complications of QCD in the low energy region. Recently, lattice QCD, Dyson-Schwinger approach and other non-perturbative methods have made impressive progresses [8, 9], but it is still far from satisfactory. QCD-inspired quark models are the main tool for detailed studies of the hadron-hadron interaction and multiquark systems at the moment. The commonly used quark model is the constituent quark model, where the complicated interactions between current quarks are approximately transformed into dynamic properties of quasi-particles (constituent quarks) and the residual interactions between these quasi-particles. The multi-gluon effect and other nonperturbative properties of QCD are attributed to the phenomenological confinement potential between constituent quarks. The residue interactions include effective one gluon exchange and one-Goldstone-boson exchange [10]. The constituent quark model gives a good description of properties of hadrons: meson ($qq$) and baryon ($q^3$), because of their unique color structures. Applying to nucleon-nucleon scattering, a reasonable agreement with experimental data is still possible after including the $\sigma$-meson exchange for the chiral quark model (ChQM) [11, 12], although there is a controversy about its effect when taking $\sigma$ meson as a $\pi\pi$ $S$-wave resonance [13]. Another constituent quark model approach is the quark delocalization color screening model (QDCSM) [15], which has been developed with the aim of understanding the well-known similarities between nuclear and molecular forces despite the obvious energy and length scale differences. In this model, two ingredients: quarks delocalization and color screening are introduced to enlarge the Hilbert space and to change the interaction between quarks resident in different baryons and the delocalization parameter that appears is determined by the dynamics of the interacting quark system. Thus the quark system can reach its more favorable configuration through its own dynamics. The main difference between the ChQM and the QDCSM is the mechanism of intermediate-range attraction. The recent calculations showed that both models can give a good description of the low-energy nucleon-nucleon and hyperon-nucleon scattering [16], although they gave a little different dibaryon resonance structures [17, 18]. For $NN$ interaction, almost the same results are also obtained in both models [19, 22], and there is no bound states as indicated by a strong enhancement at threshold of $pp$ in $J/\Psi$ and $B$ radiative decay. Therefore, extending the calculations to $p\bar{\Lambda}$ study is an interesting practice.

In this paper, we study the $p\bar{\Lambda}$ system by using both ChQM and QDCSM. It is quite meaningful to investigate the difference of these two models in baryon-antibaryon
interaction. A brief description of these two quark models of the baryon-antibaryon interaction is given in Section 2. The calculated results and discussions are given in Section 3. Section 4 contains a brief summary.

II. TWO QUARK MODELS

A. Chiral quark model

The Salamanca version of ChQM is used in the present calculation. The model details can be found in Ref.[11, 23, 24]. To extend model from baryon-baryon systems to baryon-antibaryon systems, the annihilation terms (gluon induced and Goldstone boson induced), in addition to scattering terms, have to be taken into account. The detailed description of annihilation interaction has been given in Ref.[20, 25]. The exchange interaction between quark and antiquark can be obtained by the quark-antiquark symmetry. Here we only write down the Hamiltonian for nucleon-antihyperon systems (the annihilation terms take the same form as the ones of Ref.[21] because there is no ss annihilation term in the nucleon-antihyperon system).

\[
H = \sum_{i=1}^{6} \left( m_i + \frac{\lambda_i^2}{2m_i} \right) - T_{CM} + \sum_{i<j=1}^{6} V(r_{ij}) \tag{1}
\]

\[
V(r_{ij}) = V^c(r_{ij}) + V^s(r_{ij}) + V^g_{qq}(r_{ij})
\]

\[
V^s(r_{ij}) = V^c_{qq}(r_{ij}) + V^s_{qq}(r_{ij}) + V^{sc}_{qq}(r_{ij}),
\]

\[
V^c_{qq}(r_{ij}) = \frac{1}{4} \alpha_{c} \lambda_{i} \cdot \lambda_{j} \left( \frac{1}{r_{ij}} - \frac{\pi}{2} \right)
\]

\[
V^{sc}_{qq}(r_{ij}) = \frac{1}{4} \alpha_{c} \lambda_{i} \cdot \lambda_{j} \left( \frac{1}{r_{ij}} - \frac{\pi}{2} \right)
\]

\[
V^{Gc}_{qq}(r_{ij}) = \frac{1}{4} \alpha_{c} \lambda_{i} \cdot \lambda_{j} \left( \frac{1}{r_{ij}} - \frac{\pi}{2} \right)
\]

\[
V^{Gc}_{qq}(r_{ij}) = \frac{1}{4} \alpha_{c} \lambda_{i} \cdot \lambda_{j} \left( \frac{1}{r_{ij}} - \frac{\pi}{2} \right)
\]

Here, all symbols have their usual meanings. \( Y(x) \) is the standard Yukawa function. \( Ge \) and \( Ga \) (\( \chi_e \) and \( \chi_a \)) stand for one-gluon (Goldstone boson) exchange and annihilation interactions, respectively. \( V^{sc} \) is the effective scalar meson exchange potential. When dealing with the strange system, the scalar octet have to be considered. According to Ref.[24], the effect of the scalar octet can be effectively taken into account by a single scalar exchange potential \( V^{sc} \) with different parametrization for spin-singlet and spin-triplet channels (see Table 1 below). According to QCD, the strong coupling constant \( \alpha_s \) should be scale dependent. In the constituent quark model, different strong coupling constants: \( \alpha_{ss}, \alpha_{uu} \) and \( \alpha_{dd} \) (\( u, d \) quarks are taken as the same), are used for different interacting quark pair: \( uu, ss \) and \( ss \).

B. Quark delocalization, color screening model

The model and its extension were discussed in detail in Refs.[15, 26]. Its Hamiltonian has the same form as Eq.(1), but with \( V^{sc} = 0 \) and a different confinement potential is used,

\[
V^c(r_{ij}) = -\alpha_{c} \lambda_{i} \cdot \lambda_{j} [f(r_{ij}) + V_0],
\]

\[
f(r_{ij}) = \begin{cases} \frac{\rho_{ij}^2}{f_{ij}} & \text{if } i, j \text{ occur in the same baryon orbit,} \\ \frac{1-e^{-m_r^2 \rho_{ij}}}{\mu} & \text{if } i, j \text{ occur in different baryon orbits,} \end{cases}
\]

\( \mu \) is the color screening constant which to be determined by fitting the deuteron mass.

The quark delocalization in QDCSM is realized by writing the simple particle orbital wave function of QDCSM as a linear combination of left and right Gaussians, the single particle orbital wave functions in the ordinary quark cluster models,

\[
\psi_{\alpha}(S_i, \epsilon) = (\phi_{\alpha}(S_i) + e^{\phi_{\alpha}(-S_i)})/N(\epsilon),
\]

\[
\psi_{\beta}(S_i, \epsilon) = (\phi_{\beta}(S_i) + e^{\phi_{\beta}(S_i)})/N(\epsilon),
\]
TABLE I: Parameters of the two quark models used. the masses of $\pi, K, \eta$ take their experimental values, $m_\pi = 0.7$ fm$^{-1}$, $m_K = 2.51$ fm$^{-1}$, $m_\eta = 2.77$ fm$^{-1}$.

| Parameter | ChQM | QDCSM |
|-----------|------|-------|
| $m_u,d$(MeV) | 313 | 313 |
| $m_s$(MeV) | 573 | 573 |
| $b$(fm) | 0.518 | 0.518 |
| $\alpha_s$(MeV fm$^{-2}$) | 48.59 | 58.03 |
| $V_0$(fm$^2$) | -1.2145 | -1.2883 |
| $\mu$(fm$^{-2}$) | – | 0.5 |
| $\alpha_{suu}$ | 0.565 | 0.565 |
| $\alpha_{sus}$ | 0.524 | 0.524 |
| $\alpha_{ss}$ | 0.451 | 0.451 |
| $\rho^2$ | 0.54 | 0.54 |
| $m_{sca}$(fm$^{-1}$) | 3.73 | – |
| $\Lambda_{sca}$(fm$^{-1}$) | 4.2 | – |
| $m_{sca}$(fm$^{-1}$) | 4.12 | – |
| $\Lambda_{sca}$(fm$^{-1}$) | 5.2 | – |
| $\Lambda_s$(fm$^{-1}$) | 4.2 | 4.2 |
| $\Lambda_{K,\eta}$(fm$^{-1}$) | 5.2 | 5.2 |
| $\theta_P$ | $-15^\circ$ | $-15^\circ$ |

III. RESULTS AND DISCUSSIONS

The S-wave $p\bar{\Lambda}$ systems with spin $J = 0$ and $J = 1$ are investigated in both the ChQM and the QDCSM. First the effective potential between $p$ and $\bar{\Lambda}$ is calculated. The attractive potential between two clusters is necessary to form a bound state. The effective potential between two clusters is defined as

$$V_{eff}(s) = E(s) - E(\infty),$$

where $s$ is the separation between the reference centers of two clusters and $E(s)$ is total energy of the system,

$$E(s) = \left\langle \left| \Psi_p \Psi_{\bar{\Lambda}} \right| \right| H \left| \Psi_p \Psi_{\bar{\Lambda}} \right\rangle.$$  

Fig. 1 shows the effective potentials for the $p\bar{\Lambda}$ systems with $J = 0$ and $J = 1$. Clearly from Fig. 1, we can see that for both $J = 0$ and $J = 1$ states, the effective potentials are all attractive in both two models, so it is possible to form a bound state. From Fig. 1, we can also see that the potentials without annihilation interactions are much more attractive than those with the annihilation interactions, so the annihilation interactions provide effective repulsion, which is consistent with the results of Ref. [20, 22].

Then, we do a dynamical calculation in both models by solving bound-state RGM equation. We find that for both $J = 0$ and $J = 1$ states, there is no bound state in both two models if the annihilation interaction terms are taken into account. However, the effective potentials without annihilation interactions are deep enough to make bound states for the $p\bar{\Lambda}$ systems. The calculated binding energies are: $B_{p\bar{\Lambda}} = -14.1$ MeV for $J = 0$ and $B_{p\bar{\Lambda}} = -12.5$ MeV for $J = 1$ in QDCSM; $B_{p\bar{\Lambda}} = -14.7$ MeV for $J = 0$ and $B_{p\bar{\Lambda}} = -13.2$ MeV for $J = 1$ in ChQM (Although the effective potentials in ChQM are a little shallow, they have larger width, so almost the same binding energies are obtained in two models). Here, the binding energy $B_{p\bar{\Lambda}}$ is defined as:

$$B_{p\bar{\Lambda}} = E_{p\bar{\Lambda}} - (M_p + M_{\bar{\Lambda}}).$$  

In order to search for $p\bar{\Lambda}$ bound state in a larger space, a channel coupling calculation is performed. Here all the possible color-singlet channels with strangeness 1 and spin 0,1 are taken into consideration. In the calculation, we find the effect of channel-coupling for $p\bar{\Lambda}$ is so small that it can be neglected safely. However, we find there is another interesting state $p\Sigma$, which its energy is smaller than the sum of masses of $p$ and $\Sigma$, but higher than the sum of masses of $p$ and $\bar{\Lambda}$. So it may appears as a resonance state in the $p\bar{\Lambda}$ scattering process. The calculated results are shown in Table II and III, where $ab$ means unbound, set I (II) stands for the calculation without (with) the annihilation interactions.
FIG. 1: The effective potential for an $S$-wave $p\bar{\Lambda}$ system in ChQM and QDCSM.

TABLE II: The masses and widths of the state $p\bar{\Sigma}$ with $J = 0$. The theoretical threshold of $p\Sigma$ is 2176.5 (2191.8) MeV for QDCSM (ChQM). unit: MeV

| Set | $M$ (sc) $M$ (cc) | $\Gamma$ | $M$ (sc) $M$ (cc) | $\Gamma$ |
|-----|------------------|--------|------------------|--------|
| I   | 2131.8 2134.1    | 6.5    | 2164.8 2165.6    | 7.6    |
| II  | 2174.8 2172.9 0.15 | $ub$  | $ub$          | $-\quad$ |

TABLE III: The same as Table II with $J = 1$.

| Set | $M$ (sc) $M$ (cc) | $\Gamma$ | $M$ (sc) $M$ (cc) | $\Gamma$ |
|-----|------------------|--------|------------------|--------|
| I   | 2152.9 2151.9 3.1 | 2191.8 2189.3    | 7.0    |
| II  | $ub$  $ub$  $ub$  $ub$          | $-\quad$ |

The single channel (sc) calculations of $p\Sigma$ states show that $p\Sigma$ states are bound states if the annihilation interactions are not included in both models. The state with spin 0 is more bound than the one with spin 1, even it is still bound with the inclusion of the annihilation interactions in QDCSM. After including the annihilation interactions, the state with spin 1 becomes unbound in both models, the state with spin 0 is also unbound in ChQM, while it is still bound state in QDCSM. When the state $p\Sigma$ couples to the open channel $p\Lambda$, the bound state will change into an elastic resonance in the $p - \Lambda$ scattering. The $S$-wave phase shifts of $p\Lambda$ ($J = 0, 1$) are calculated, and the effect of channel-coupling with $p\Sigma$ are taken into account. The $s$-wave phase shifts of $p\Lambda$ ($J = 0, 1$) are illustrated in Fig. 2. From the Fig. 2, we can see that the phase shifts of $p\Lambda$ rise though $\pi/2$ at resonance masses, which listed in Tables II and III, for $J = 0$ (set I and II) and $J = 1$ (set I) in QDCSM. The resonance masses are a little larger or smaller than the energies obtained from single-channel calculations. Generally, if there is a bound state of $p\Lambda$, then the resonance mass of $p\Sigma$ will be pushed up comparing with its stand alone mass, otherwise the resonance mass will be pulled down. From the Table II, the resonance mass for set I is pushed up, so it may infer that there is a bound state of $p\Lambda$. However, from the single-channel and channel coupling calculations, we do not find a bound state for $p\Lambda$. Maybe there is a zero-energy resonance of $p\Lambda$. Further study is needed. Comparing the results with set I and II, it is clear that the annihilation interactions play an non-negligible role in the baryon-antibaryon systems. The inclusion of annihilation interactions pushes the state $p\Sigma$ with spin 0 up about 40 MeV and pushes the state $p\Sigma$ state with spin 1 above the threshold. So from our calculation, there is a $(p\Sigma)_{J=0}$ resonance state with resonance mass 2172.9 MeV and decay width 0.15 MeV in QDCSM in the $(p\Lambda)_{J=0}$ scattering phase shifts. The small width comes from the fact that only $\pi$-exchange contributes and the effect of $\pi$-exchange is greatly reduced due to no exchange term between particle and antiparticle. For example, for nucleon-hyperon system, the $p\Lambda - p\Sigma$ transition potential at separation 0.5 fm is about 1800 MeV, the direct term contributes 90 MeV only. Fig. 3 shows the
transition potential for $p\bar{\Lambda} - p\bar{\Sigma}$. Clearly, the coupling between $p\Lambda$ and $p\Sigma$ is larger if the annihilation interactions are not taken into account. Including the annihilation interactions, the transition potential will be reduced. So the decay width in the case I is larger. However the repulsive nature of the annihilation interaction will push the energies of $p\Sigma$ high in the case II, so the energy of $p\Sigma$ is higher in the case of II than that in case I. Therefore we have a paradox: the state with larger binding energy has a larger decay width. In fact, these are two different calculations, where different interactions are used. No $p\Sigma$ resonance will appear in $(p\bar{\Lambda})_{J=1}$ scattering phase shifts. However, in the ChQM, no resonance can be found if the annihilation interactions are included.

IV. SUMMARY

In summary, we perform a dynamical study of $p\bar{\Lambda}$ systems with $J = 0$ and $J = 1$ in the framework of the ChQM and the QDCSM by solving the RGM equation. All the model parameters are taken from our previous work, which gave a good description of the proton-antiproton $S$-wave elastic scattering cross section data. The numerical results show that the $p\bar{\Lambda}$ systems with both $J = 0$ and $J = 1$ are bound states in these two quark models if the annihilation interaction is neglected. When the annihilation interaction is considered, the $p\bar{\Lambda}$ systems become unbound. At the same time, the $p\bar{\Lambda}$ elastic scattering processes with coupling to $p\Sigma$ state are also investigated. The calculated phase shifts are qualitatively similar in these two quark models. The results show that, there is no $S$-wave bound state of $p\bar{\Lambda}$ as indicated by an enhancement near the threshold of $p\bar{\Lambda}$ in $J/\psi$. However, it is worthy of notice that QDCSM gives a $IJ = \frac{1}{2} 0 p\Sigma$ resonance state, and the state become unbound in ChQM if a single effective scalar exchange is used in the strange system to replace the $\sigma$ meson used in the study of $pp$.

It is generally believed that to describe the nucleon-nucleon interaction, the effect of one-gluon-exchange in quark model can be mimicked by the vector-meson exchanges in one-boson exchange model [27]. However, for nucleon-antihyperon conversion process, $N\bar{\Lambda} - N\bar{\Sigma}$, one-gluon-exchange gives null contribution, while $\rho$-meson has nonzero contribution. So this conversion process is a good place to test the two mechanisms of baryon-antibaryon interaction in the short-range part.

Obviously our conclusion is based on the assumption that both ChQM and QDCSM, which gave a good description of the proton-antiproton $S$-wave elastic scattering cross section experimental data, are suitable for $p\bar{\Lambda}$ system. In addition we assume that the $p\bar{\Lambda}$ system is in a $(q^3) - (\bar{q}^3)$ configuration. More elaborating study of $p\bar{\Lambda}$ system is worth doing in the future.

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FIG. 3: The transition potential for $p\Lambda - p\Sigma$ in QDCSM.

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