Investigation of $qqqs\bar{q}$ pentaquarks in a chiral quark model

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We investigate the pentaquark system $qqqs\bar{q}$ in a framework of chiral quark model. Two structures, $(qqq)(s\bar{q})$ and $(qqs)(q\bar{q})$, with all possible color, spin, flavor configurations are considered. The calculations show that there are several possible resonance states, $\Sigma\pi$ and $N\bar{K}$ state with $IJ^P = 0\frac{1}{2}^-$, $\Sigma^*\pi$ with $IJ^P = 0\frac{3}{2}^-$, $\Sigma^*\rho$ with $IJ^P = 0\frac{5}{2}^-$, $\Delta\bar{K}$ with $IJ^P = 1\frac{3}{2}^-$, and $\Delta\bar{K}^*$ with $IJ^P = 1\frac{5}{2}^-$. Where the $N\bar{K}$ state with $IJ^P = 0\frac{1}{2}^-$ can be used to explain the $\Lambda(1405)$, and together with another state $\Sigma\pi$ is related to the two-pole structure of the scattering amplitude proposed before. The decay properties of $\Lambda(1520)$ prevent the assignment of $\Sigma^*\pi$ with $IJ^P = 0\frac{3}{2}^-$ to $\Lambda(1520)$, although the energy ≈1518 MeV of $\Sigma^*\pi$ is close to experimental value of $\Lambda(1520)$. Other resonance states generally have a large width.

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I. INTRODUCTION

After decades of development, the quark model has been very successful in describing the properties of hadrons. The traditional quark model believes that there are two types of hadrons in nature, baryons (qqq) and mesons ($q\bar{q}$), respectively. But in addition to their existence, quantum chromodynamics (QCD) also allows other forms of hadron states such as glueballs (without quarks and antiquarks), hybrids (gluons mixed with quarks and/or antiquarks), molecular states, and compact multiquark states. At present, the low energy hadron states can be described well by the traditional quark model. But for the excited states, the traditional quark model encountered serious problems. For instance, the first excited state of the nucleon is expected to be N^* with $J^P = \frac{1}{2}^-$, whose energy should be lower than the N^* with the $J^P = \frac{1}{2}^+$ state. Because in the N^* state with $J^P = \frac{1}{2}^+$ one quark is in a radial $n = 1$ excited state. For the N^* state ($J^P = \frac{1}{2}^-$) without s quark, its energy should be significantly lower than that of $\Lambda^*(1405)$ with one s quark in theory. But the experimental results are both opposite.

To solve these problems, pentaquark states are proposed. Zou held that the $N^*(1535)$ might be the lowest $L = 1$ excited $|uud\rangle$ state with a large admixture of $|[ud][us]\bar{s}\rangle$ pentaquark components and the $N^*(1440)$ is probably the lowest radial excited $|uud\rangle$ state with a large component of $|[ud][ud]\bar{d}\rangle$ pentaquarks having two $[ud]$ diquarks in the relative P wave [1]. Similarly, the lighter $\Lambda^*(1405)$ has a dominant pentaquark component $|[ud][us]\bar{u}\rangle$ [1]. In fact, the resonance $\Lambda^*(1405)$ was considered as a quasibound molecule state of the $\bar{K}N$ system before the establishment of quantum chromodynamics [2–4]. In these two decades, there was still a lot of work devoted to the nature of the $\Lambda^*(1405)$ state. In 2001, Oller *et al.* unveiled the two-pole nature of the $\Lambda(1405)$ within a chiral unitary model, and an improved theoretical description for calculating the $\Sigma\pi$ event distribution also introduced in their work [5]. In the framework of the separable potential model the authors confirmed that in the $\pi\Sigma$ mass spectrum the coupled-channels chiral model which employ all possible meson-baryon channels produces two poles which can be related to the $\Lambda^*(1405)$ resonance in the complex energy plane [6]. Based on the the QCD sum rule method, Kisslinger *et al.* claimed that the $\Lambda^*(1405)$ is accordant with a strange hybrid baryon [7]. Using the chiral unitary approach, Sekihara *et al.* have found that the $\Lambda^*(1405)$ resonant state has bigger spatial radii and softer form factors than those of the baryons, more importantly, the structure is dominated by the $\bar{K}N$ component to a large extent [8]. Shevchenko calculated the K^-d scattering length by applying newly obtained coupled-channels $\bar{K}N - \pi\Sigma$ potentials with one- and two-pole versions of the $\Lambda^*(1405)$ resonance, and calculations prove that the two results obtained with it are totally separated from each other, therefore, the authors prefer the $\bar{K}N - \pi\Sigma$ interaction models [9]. Some theorists discussed the spatial structure of the resonance $\Lambda^*(1405)$ state based on the $\bar{K}N$ molecular picture with the chiral $\bar{K}N$ potential [10,11]. However, this resonance state may be obtained not only by two-body channels, but also by multibody channels [12], such as $\bar{K}NN$ [13–18], $\bar{K}KN$ [19–21], $\bar{K}\bar{K}N$ [22].

Except for the $\Lambda^*(1405)$ state, the nature of its excited state $\Lambda^*(1520)$ is also in controversy. In the Review of

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Particle Physics it is a particle marked with four stars [23]. In Ref. [24], the authors calculated the energy of the S- and P-wave Λ family using five sets of parameters in the chiral quark model, two states, $\Lambda^*(1405)$ and $\Lambda^*(1520)$, cannot be described as three-quark baryons. In the chiral unitary approach, a quasibound state of a meson-baryon was taken as $\Lambda^*(1520)$ [25], and the Weinberg compositeness condition showed that the meson-baryon component of $\Lambda^*(1520)$ was as high as 87% [26]. However, the compositeness of $\Lambda^*(1520)$ states was estimated to be ≈23% in Ref. [27].

With the accumulation of the experimental data and the improvement of the quark model, it is expected to do a rigorous calculation of hadron states based on the quark model. In this work, we systematically investigate the energy spectrum of the five-quark state $qqqs\bar{q}$, $q = u, d$ in the framework of the chiral quark model (ChQM), which describes the hadron as well as hadron-hadron interaction successfully [28,29], and a powerful few-body method, the Gaussian expansion method (GEM) [30], which is employed to do the calculation. The GEM has proven its power in the benchmark test calculation on four-nucleon bound state [31]. In the present calculation, two structures, $(qqq)(s\bar{q})$ and $(qqs)(q\bar{q})$, with all possible color, spin, flavor configurations are considered.

The structure of the present paper is organized as follows. In Sec. II the chiral quark model, pentaquark wave functions, and GEM are briefly introduced. The calculated results and a discussion are presented in Sec. III. The summary of our investigation is given in the last section.

II. MODEL AND WAVE FUNCTION

The QCD-inspired quark model is one of the main methods for studying hadron properties, hadron-hadron interactions, and multiquark states [32–34]. Here, we apply ChQM to five-quark systems with one s quark. The broken SU(3) flavor symmetry is used in constructing the Hamiltonian for the u, d, s system. In this model, the interaction between quark and quark (antiquark) is through the color confinement $V^{\rm CON}$, the one-gluon exchange (OGE) $V^{\rm OGE}$, the Goldstone boson exchange V^{χ} ($\chi = \pi, k, \eta$), as well as the scalar nonet (the extension of chiral partner σ meson) exchange V^s ($s = \sigma, a_0, \kappa, f_0$). So the Hamiltonian in the present calculation takes the form [28,29]

$$H = \sum_{i=1}^{5}\left(m_i + \frac{p_i^2}{2m_i}\right) - T_{\rm c.m.} + \sum_{j>i=1}^{5}[V^{\rm CON}(\mathbf{r}_{ij}) + V^{\rm OGE}(\mathbf{r}_{ij}) + V^{\chi}(\mathbf{r}_{ij}) + V^{s}(\mathbf{r}_{ij})], \tag{1}$$

$$V^{\rm CON}(\mathbf{r}_{ij}) = \boldsymbol{\lambda}_i^c \cdot \boldsymbol{\lambda}_j^c[-a_c(1 - e^{-\mu_c r_{ij}}) + \Delta], \tag{2}$$

$$V^{\rm OGE}(\mathbf{r}_{ij}) = \frac{1}{4}\alpha_s \boldsymbol{\lambda}_i^c \cdot \boldsymbol{\lambda}_j^c\left[\frac{1}{r_{ij}} - \frac{1}{6m_im_j}\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j \frac{e^{-r_{ij}/r_0(\mu)}}{r_{ij}r_0^2(\mu)}\right], \quad r_0(\mu) = \hat{r}_0/\mu, \quad \alpha_s = \frac{\alpha_0}{\ln\left(\frac{\mu^2+\mu_0^2}{\Lambda_0^2}\right)}, \tag{3}$$

$$V^{\chi}(\mathbf{r}_{ij}) = v_{\pi}(\mathbf{r}_{ij})\sum_{a=1}^{3}\left(\boldsymbol{\lambda}_i^a \cdot \boldsymbol{\lambda}_j^a\right) + v_K(\mathbf{r}_{ij})\sum_{a=4}^{7}\left(\boldsymbol{\lambda}_i^a \cdot \boldsymbol{\lambda}_j^a\right) + v_{\eta}(\mathbf{r}_{ij})\left[\cos\theta_P\left(\boldsymbol{\lambda}_i^8 \cdot \boldsymbol{\lambda}_j^8\right) - \sin\theta_P\left(\boldsymbol{\lambda}_i^0 \cdot \boldsymbol{\lambda}_j^0\right)\right], \tag{4}$$

$$v_{\chi}(\mathbf{r}_{ij}) = \frac{g_{\rm ch}^2}{4\pi}\frac{m_{\chi}^2}{12m_im_j}\frac{\Lambda_{\chi}^2}{\Lambda_{\chi}^2 - m_{\chi}^2}m_{\chi}\left[Y(m_{\chi}r_{ij}) - \frac{\Lambda_{\chi}^3}{m_{\chi}^3}Y(\Lambda_{\chi}r_{ij})\right](\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j), \quad \chi = \pi, K, \eta, \tag{5}$$

$$V^{s}(\mathbf{r}_{ij}) = v_{\sigma}(\mathbf{r}_{ij})\left(\boldsymbol{\lambda}_i^0 \cdot \boldsymbol{\lambda}_j^0\right) + v_{a_0}(\mathbf{r}_{ij})\sum_{a=1}^{3}\left(\boldsymbol{\lambda}_i^a \cdot \boldsymbol{\lambda}_j^a\right) + v_{\kappa}(\mathbf{r}_{ij})\sum_{a=4}^{7}\left(\boldsymbol{\lambda}_i^a \cdot \boldsymbol{\lambda}_j^a\right) + v_{f_0}(\mathbf{r}_{ij})\left(\boldsymbol{\lambda}_i^8 \cdot \boldsymbol{\lambda}_j^8\right), \tag{6}$$

$$v_s(\mathbf{r}_{ij}) = -\frac{g_{\rm ch}^2}{4\pi}\frac{\Lambda_s^2}{\Lambda_s^2 - m_s^2}m_s\left[Y(m_sr_{ij}) - \frac{\Lambda_s}{m_s}Y(\Lambda_sr_{ij})\right], \quad s = \sigma, a_0, \kappa, f_0, \tag{7}$$

where $T_{\rm c.m.}$ is the kinetic energy of the center-of mass motion; σ represents the SU(2) Pauli matrices; λ^c, λ represent the SU(3) color and flavor Gell-Mann matrices, respectively; μ is the reduced mass between two interacting quarks; α_s denotes the strong coupling constant of one-gluon exchange, and $Y(x)$ is the standard Yukawa functions.

The model parameters fixed by fitting the meson and baryon spectra are listed in Table I. Because in the quark model, we cannot obtain the satisfying outcome of both meson spectra and baryon spectra via the same set of parameters [28,35], two sets of parameters are employed in the present calculation to test the model dependence of the results.

The five-quark states we want to investigate contain one s quark and four light quarks, so only the following states are involved: N, Λ, Σ, Σ^*, Δ, π, $\bar{K}$, ρ, $\bar{K}^*$, ω, η. The calculated masses for these states are listed in Table II.

The wave function of the five-quark system is constructed in the following way. First, the five quarks are separated as two clusters, one is a three-quark cluster, and another is a quark-antiquark cluster. Then, we construct the wave function for each cluster. At last, the wave function of the five-quark system is obtained by coupling the wave functions of two clusters and applying the appropriate antisymmetrization operator to the coupled wave function. The quark has four degrees of freedom: orbital, spin, color, and flavor. The wave functions for each degree of freedom we construct are as follows:

(a) The wave function for the orbital part.

TABLE I. Quark model parameters.

		set I	set II
Quark masses	$m_u = m_d$ (MeV)	378.49	399.05
	m_s (MeV)	504.95	500.90
	Λ_π (fm^{-1})	4.20	4.20
	$\Lambda_\eta = \Lambda_K$ (fm^{-1})	5.20	5.20
	m_π (fm^{-1})	0.70	0.70
Goldstone bosons	m_K (fm^{-1})	2.51	2.51
	m_η (fm^{-1})	2.77	2.77
	$g^2_{ch}/(4\pi)$	0.54	0.54
	$\theta_P(^\circ)$	−15	−15
	a_c (MeV)	198.73	171.85
	μ_c (fm^{-1})	0.50	0.65
Confinement	Δ (MeV)	85.18	62.68
	α_{uu}	0.59	0.85
	α_{us}	0.48	0.60
	m_σ (fm^{-1})	3.42	3.42
	Λ_σ (fm^{-1})	4.20	4.20
scalar nonet	$\Lambda_{a_0} = \Lambda_\kappa = \Lambda_{f_0}$ (fm^{-1})	5.20	5.20
	$m_{a_0} = m_\kappa = m_{f_0}$ (fm^{-1})	4.97	4.97
OGE	$\hat{r}_0$ (MeV fm)	25.32	38.04

There are four relative motions for a five-quark system, the wave function is constructed as

$$\psi_{\mathrm{LM}_L} = [[[\phi_{n_1l_1}(\boldsymbol{\rho})\phi_{n_2l_2}(\boldsymbol{\lambda})]_l\phi_{n_3l_3}(\boldsymbol{r})]_{l'}\phi_{n_4l_4}(\boldsymbol{R})]_{\mathrm{LM}_L} \quad (8)$$

with Jacobi coordinates

$$\begin{aligned}
\boldsymbol{\rho} &= \boldsymbol{x}_1 - \boldsymbol{x}_2,\\
\boldsymbol{\lambda} &= \left(\frac{m_1\boldsymbol{x}_1 + m_2\boldsymbol{x}_2}{m_1+m_2}\right) - \boldsymbol{x}_3,\\
\boldsymbol{r} &= \boldsymbol{x}_4 - \boldsymbol{x}_5,\\
\boldsymbol{R} &= \left(\frac{m_1\boldsymbol{x}_1 + m_2\boldsymbol{x}_2 + m_3\boldsymbol{x}_3}{m_1+m_2+m_3}\right) - \left(\frac{m_4\boldsymbol{x}_4 + m_5\boldsymbol{x}_5}{m_4+m_5}\right),
\end{aligned} \quad (9)$$

where $\phi_{n_1l_1}(\boldsymbol{\rho})$ represents the relative motion wave function between the first and the second quarks, $\phi_{n_2l_2}(\boldsymbol{\lambda})$ indicates the relative motion between the center of mass of quarks 1 and 2 and the third quarks in the three-quark cluster. Similarly, $\phi_{n_3l_3}(\boldsymbol{r})$ denotes the relative motion between the fourth and fifth quarks in the quark-antiquark cluster, and $\phi_{n_4l_4}(\boldsymbol{R})$ expresses the relative motion between two clusters.

TABLE II. The masses of ground-state baryons and mesons involved in the calculation (unit: Mev).

	N	Λ	Σ	Σ^*	Δ	
ChQM (SET I)	825	1095	1201	1268	1081	
ChQM (SET II)	872	1206	1320	1405	1176	
PDG [23]	939	1116	1193	1385	1232	
	π	$\bar{K}$	ρ	$\bar{K}^*$	η	ω
ChQM (SET I)	123	535	719	844	516	625
ChQM (SET II)	134	663	788	943	484	665
PDG [23]	140	494	775	892	548	783

The orbital wave functions of the system are obtained by solving the Schrödinger equation with the Gaussian expansion method. In this method, the radial part of the orbital wave function is expanded by a set of Gaussians [30],

$$\psi_{\mathrm{lm}}(\mathbf{r}) = \sum_{n=1}^{n_{\max}} c_{\mathrm{nl}}\phi^G_{\mathrm{nlm}}(\mathbf{r}), \quad (10)$$

$$\phi^G_{\mathrm{nlm}}(\mathbf{r}) = N_{\mathrm{nl}} r^l e^{-\nu_n r^2} Y_{\mathrm{lm}}(\hat{\mathbf{r}}), \quad (11)$$

$$N_{\mathrm{nl}} = \left(\frac{2^{l+2}(2\nu_n)^{l+3/2}}{\sqrt{\pi}(2l+1)!!}\right)^{\frac{1}{2}}, \quad (12)$$

where N_{nl} is the normalization constant, and c_{nl} is the variational parameter, which is determined by the dynamics of the system. The Gaussian size parameters are chosen according to the following geometric progression:

$$\nu_n = \frac{1}{r_n^2},\ r_n = r_{\min}a^{n-1},\ a = \left(\frac{r_{\max}}{r_{\min}}\right)^{\frac{1}{n_{\max}-1}}, \quad (13)$$

where the $n_{\max}$ is the number of Gaussian functions. The parameters in GEM are fixed by requiring a stability of the results. In the present work, the stable results of hadron spectra can be obtained with $n_{\max} = 7$, $r_{\min} = 0.1$, $r_{\max} = 2$.

(b) The wave function for the flavor part.

There are two possible separations for a five-quark system containing one s quark, one is $(qqq)(s\bar{q})$ and another is $(qqs)(q\bar{q})$, $q = u, d$. The flavor wave functions for the three-quark and quark-antiquark clusters are

$$\left|B^{f1}_{\frac{1}{2},\frac{1}{2}}\right\rangle = \frac{1}{\sqrt{6}}(2uud - udu - duu),$$

$$\left|B^{f2}_{\frac{1}{2},\frac{1}{2}}\right\rangle = \frac{1}{\sqrt{2}}(udu - duu),$$

$$\left|B^{f1}_{\frac{1}{2},-\frac{1}{2}}\right\rangle = \frac{1}{\sqrt{6}}(udd + dud - 2ddu),$$

$$\left|B^{f2}_{\frac{1}{2},-\frac{1}{2}}\right\rangle = \frac{1}{\sqrt{2}}(udd - dud),$$

$$\left|B^{f}_{\frac{3}{2},\frac{3}{2}}\right\rangle = uuu,$$

$$\left|B^{f}_{\frac{3}{2},\frac{1}{2}}\right\rangle = \frac{1}{\sqrt{3}}(uud + udu + duu),$$

$$\left|B^{f}_{\frac{3}{2},-\frac{1}{2}}\right\rangle = \frac{1}{\sqrt{3}}(udd + dud + ddu),$$

$$\left|B^{f}_{\frac{3}{2},-\frac{3}{2}}\right\rangle = ddd,$$

$$\left|B^{f}_{0,0}\right\rangle = \frac{1}{\sqrt{2}}(uds - dus),$$

$$\left|B^{f}_{1,0}\right\rangle = \frac{1}{\sqrt{2}}(uds + dus),$$

$$\left|B^{f}_{1,1}\right\rangle = uus,$$

$$\left|B^{f}_{1,-1}\right\rangle = dds,$$

$$\left|M^f_{\frac{1}{2},\frac{1}{2}}\right\rangle = s\bar{d},$$
$$\left|M^f_{\frac{1}{2},-\frac{1}{2}}\right\rangle = -s\bar{u},$$
$$\left|M^f_{1,0}\right\rangle = \frac{1}{\sqrt{2}}(-u\bar{u}+d\bar{d}),$$
$$\left|M^f_{1,-1}\right\rangle = -d\bar{u},$$
$$\left|M^f_{1,1}\right\rangle = u\bar{d},$$
$$\left|M^f_{0,0}\right\rangle = \frac{1}{\sqrt{2}}(-u\bar{u}-d\bar{d}). \quad (14)$$

The flavor wave functions for the five-quark system with isospin $I = 0$ are obtained by the following couplings:

$$\left|\chi^{f1}_{0,0}\right\rangle = \sqrt{\frac{1}{2}}\left|B^{f1}_{\frac{1}{2},\frac{1}{2}}\right\rangle\left|M^f_{\frac{1}{2},-\frac{1}{2}}\right\rangle - \sqrt{\frac{1}{2}}\left|B^{f1}_{\frac{1}{2},-\frac{1}{2}}\right\rangle\left|M^f_{\frac{1}{2},\frac{1}{2}}\right\rangle,$$
$$\left|\chi^{f2}_{0,0}\right\rangle = \sqrt{\frac{1}{2}}\left|B^{f2}_{\frac{1}{2},\frac{1}{2}}\right\rangle\left|M^f_{\frac{1}{2},-\frac{1}{2}}\right\rangle - \sqrt{\frac{1}{2}}\left|B^{f2}_{\frac{1}{2},-\frac{1}{2}}\right\rangle\left|M^f_{\frac{1}{2},\frac{1}{2}}\right\rangle,$$
$$\left|\chi^{f3}_{0,0}\right\rangle = \sqrt{\frac{1}{3}}\left|B^f_{1,1}\right\rangle\left|M^f_{1,-1}\right\rangle - \sqrt{\frac{1}{3}}\left|B^f_{1,0}\right\rangle\left|M^f_{1,0}\right\rangle + \sqrt{\frac{1}{3}}\left|B^f_{1,-1}\right\rangle\left|M^f_{1,1}\right\rangle,$$
$$\left|\chi^{f4}_{0,0}\right\rangle = \left|B^f_{0,0}\right\rangle\left|M^f_{0,0}\right\rangle. \quad (15)$$

Similarly, the flavor wave functions with isospin $I = 1$ are

$$\left|\chi^{f4}_{1,1}\right\rangle = \left|B^{f1}_{\frac{1}{2},\frac{1}{2}}\right\rangle\left|M^f_{\frac{1}{2},\frac{1}{2}}\right\rangle,$$
$$\left|\chi^{f5}_{1,1}\right\rangle = \left|B^{f2}_{\frac{1}{2},\frac{1}{2}}\right\rangle\left|M^f_{\frac{1}{2},\frac{1}{2}}\right\rangle,$$
$$\left|\chi^{f6}_{1,1}\right\rangle = \sqrt{\frac{3}{4}}\left|B^f_{\frac{3}{2},\frac{3}{2}}\right\rangle\left|M^f_{\frac{1}{2},-\frac{1}{2}}\right\rangle - \sqrt{\frac{1}{4}}\left|B^f_{\frac{3}{2},\frac{1}{2}}\right\rangle\left|M^f_{\frac{1}{2},\frac{1}{2}}\right\rangle,$$
$$\left|\chi^{f7}_{1,1}\right\rangle = \left|B^f_{0,0}\right\rangle\left|M^f_{1,1}\right\rangle,$$
$$\left|\chi^{f8}_{1,1}\right\rangle = \sqrt{\frac{1}{2}}\left|B^f_{1,1}\right\rangle\left|M^f_{1,0}\right\rangle - \sqrt{\frac{1}{2}}\left|B^f_{1,0}\right\rangle\left|M^f_{1,1}\right\rangle,$$
$$\left|\chi^{f9}_{1,1}\right\rangle = \left|B^f_{1,1}\right\rangle\left|M^f_{0,0}\right\rangle, \quad (16)$$

and the flavor wave functions with isospin $I = 2$ are

$$\left|\chi^{f9}_{2,2}\right\rangle = \left|B^f_{\frac{3}{2},\frac{3}{2}}\right\rangle\left|M^f_{\frac{1}{2},\frac{1}{2}}\right\rangle,$$
$$\left|\chi^{f10}_{2,2}\right\rangle = \left|B^f_{1,1}\right\rangle\left|M^f_{1,1}\right\rangle. \quad (17)$$

(c) The wave function for the spin part.

In a similar way as the flavor part, the spin wave functions of the three-quark and quark-antiquark clusters are written as

$$\left|B^{\sigma1}_{\frac{1}{2},\frac{1}{2}}\right\rangle = \frac{1}{\sqrt{6}}(2\alpha\alpha\beta-\alpha\beta\alpha-\beta\alpha\alpha),$$
$$\left|B^{\sigma2}_{\frac{1}{2},\frac{1}{2}}\right\rangle = \frac{1}{\sqrt{2}}(\alpha\beta\alpha-\beta\alpha\alpha),$$
$$\left|B^{\sigma1}_{\frac{1}{2},-\frac{1}{2}}\right\rangle = \frac{1}{\sqrt{6}}(\alpha\beta\beta+\beta\alpha\beta-2\beta\alpha\alpha),$$
$$\left|B^{\sigma2}_{\frac{1}{2},-\frac{1}{2}}\right\rangle = \frac{1}{\sqrt{2}}(\alpha\beta\beta-\beta\alpha\beta),$$
$$\left|B^{\sigma}_{\frac{3}{2},\frac{3}{2}}\right\rangle = \alpha\alpha\alpha,$$
$$\left|B^{\sigma}_{\frac{3}{2},\frac{1}{2}}\right\rangle = \frac{1}{\sqrt{3}}(\alpha\alpha\beta+\alpha\beta\alpha+\beta\alpha\alpha),$$
$$\left|B^{\sigma}_{\frac{3}{2},-\frac{3}{2}}\right\rangle = \beta\beta\beta,$$
$$\left|B^{\sigma}_{\frac{3}{2},-\frac{1}{2}}\right\rangle = \frac{1}{\sqrt{3}}(\alpha\beta\beta+\beta\alpha\beta+\beta\beta\alpha),$$
$$\left|M^{\sigma}_{1,0}\right\rangle = \frac{1}{\sqrt{2}}(\alpha\beta+\beta\alpha),$$
$$\left|M^{\sigma}_{1,1}\right\rangle = \alpha\alpha,$$
$$\left|M^{\sigma}_{1,-1}\right\rangle = \beta\beta,$$
$$\left|M^{\sigma}_{0,0}\right\rangle = \frac{1}{\sqrt{2}}(\alpha\beta-\beta\alpha). \quad (18)$$

The spin wave functions for the five-quark system with spin $S = \frac{1}{2}$ are obtained by the following couplings:

$$\left|\chi^{\sigma1}_{\frac{1}{2},\frac{1}{2}}\right\rangle = \left|B^{\sigma1}_{\frac{1}{2},\frac{1}{2}}\right\rangle\left|M^{\sigma}_{0,0}\right\rangle,$$
$$\left|\chi^{\sigma2}_{\frac{1}{2},\frac{1}{2}}\right\rangle = \left|B^{\sigma2}_{\frac{1}{2},\frac{1}{2}}\right\rangle\left|M^{\sigma}_{0,0}\right\rangle,$$
$$\left|\chi^{\sigma3}_{\frac{1}{2},\frac{1}{2}}\right\rangle = -\sqrt{\frac{2}{3}}\left|B^{\sigma1}_{\frac{1}{2},-\frac{1}{2}}\right\rangle\left|M^{\sigma}_{1,1}\right\rangle + \sqrt{\frac{1}{3}}\left|B^{\sigma1}_{\frac{1}{2},\frac{1}{2}}\right\rangle\left|M^{\sigma}_{1,0}\right\rangle,$$
$$\left|\chi^{\sigma4}_{\frac{1}{2},\frac{1}{2}}\right\rangle = -\sqrt{\frac{2}{3}}\left|B^{\sigma2}_{\frac{1}{2},-\frac{1}{2}}\right\rangle\left|M^{\sigma}_{1,1}\right\rangle + \sqrt{\frac{1}{3}}\left|B^{\sigma2}_{\frac{1}{2},\frac{1}{2}}\right\rangle\left|M^{\sigma}_{1,0}\right\rangle,$$
$$\left|\chi^{\sigma5}_{\frac{1}{2},\frac{1}{2}}\right\rangle = \sqrt{\frac{1}{2}}\left|B^{\sigma}_{\frac{3}{2},\frac{3}{2}}\right\rangle\left|M^{\sigma}_{1,-1}\right\rangle - \sqrt{\frac{1}{3}}\left|B^{\sigma}_{\frac{3}{2},\frac{1}{2}}\right\rangle\left|M^{\sigma}_{1,0}\right\rangle + \sqrt{\frac{1}{6}}\left|B^{\sigma}_{\frac{3}{2},-\frac{1}{2}}\right\rangle\left|M^{\sigma}_{1,1}\right\rangle. \quad (19)$$

Similarly, the spin wave functions with spin $S = \frac{3}{2}$ are

$$\left|\chi^{\sigma6}_{\frac{3}{2},\frac{3}{2}}\right\rangle = -\left|B^{\sigma1}_{\frac{1}{2},\frac{1}{2}}\right\rangle\left|M^{\sigma}_{1,1}\right\rangle,$$
$$\left|\chi^{\sigma7}_{\frac{3}{2},\frac{3}{2}}\right\rangle = -\left|B^{\sigma2}_{\frac{1}{2},\frac{1}{2}}\right\rangle\left|M^{\sigma}_{1,1}\right\rangle,$$
$$\left|\chi^{\sigma8}_{\frac{3}{2},\frac{3}{2}}\right\rangle = \left|B^{\sigma}_{\frac{3}{2},\frac{3}{2}}\right\rangle\left|M^{\sigma}_{0,0}\right\rangle,$$
$$\left|\chi^{\sigma9}_{\frac{3}{2},\frac{3}{2}}\right\rangle = \sqrt{\frac{3}{5}}\left|B^{\sigma}_{\frac{3}{2},\frac{3}{2}}\right\rangle\left|M^{\sigma}_{1,0}\right\rangle - \sqrt{\frac{2}{5}}\left|B^{\sigma}_{\frac{3}{2},\frac{1}{2}}\right\rangle\left|M^{\sigma}_{1,1}\right\rangle, \quad (20)$$

and the spin wave functions with spin $S = \frac{5}{2}$ are

$$\left|\chi^{\sigma10}_{\frac{5}{2},\frac{5}{2}}\right\rangle = \left|B^{\sigma}_{\frac{3}{2},\frac{3}{2}}\right\rangle\left|M^{\sigma}_{1,1}\right\rangle. \quad (21)$$

(d) The wave function for the color part.

For the color wave function, two configurations, color singlet and hidden color, are considered. The color wave functions for two subclusters are

$$|B^{c_1}\rangle = \frac{1}{\sqrt{6}}(rgb - rbg + gbr - grb + brg - bgr),$$
$$|B^{c_{2,1}}\rangle = \frac{1}{\sqrt{6}}(2rrg - rgr - grr), \quad |B^{c_{2,2}}\rangle = \frac{1}{\sqrt{2}}(rgr - grr),$$
$$|B^{c_{3,1}}\rangle = \frac{1}{\sqrt{6}}(rgg + grg - 2ggr), \quad |B^{c_{3,2}}\rangle = \frac{1}{\sqrt{2}}(rgg - grg),$$
$$|B^{c_{4,1}}\rangle = \frac{1}{\sqrt{6}}(2rrb - rbr - brr),$$
$$|B^{c_{4,2}}\rangle = \frac{1}{\sqrt{2}}(rbr - brr),$$
$$|B^{c_{5,1}}\rangle = \frac{1}{\sqrt{12}}(2rgb - rbg + 2grb - gbr - brg - bgr),$$
$$|B^{c_{5,2}}\rangle = \frac{1}{\sqrt{4}}(rbg + gbr - brg - bgr),$$
$$|B^{c_{6,1}}\rangle = \frac{1}{\sqrt{12}}(2rgb + rbg - 2grb - gbr - brg + bgr),$$
$$|B^{c_{6,2}}\rangle = \frac{1}{\sqrt{4}}(rbg - gbr + brg - bgr),$$
$$|B^{c_{7,1}}\rangle = \frac{1}{\sqrt{6}}(2ggb - gbg - bgg),$$
$$|B^{c_{7,2}}\rangle = \frac{1}{\sqrt{2}}(gbg - bgg),$$
$$|B^{c_{8,1}}\rangle = \frac{1}{\sqrt{6}}(rbb + brb - 2bbr),$$
$$|B^{c_{8,2}}\rangle = \frac{1}{\sqrt{2}}(rbb - brb),$$
$$|B^{c_{9,1}}\rangle = \frac{1}{\sqrt{6}}(gbb + bgb - 2bbg),$$
$$|B^{c_{9,2}}\rangle = \frac{1}{\sqrt{2}}(gbb - bgb),$$
$$|M^{c_1}\rangle = \frac{1}{\sqrt{3}}(\bar{r}r + \bar{g}g + \bar{b}b),$$
$$|M^{c_2}\rangle = \bar{r}b, \quad |M^{c_3}\rangle = -\bar{g}b, \quad |M^{c_4}\rangle = -\bar{r}g,$$
$$|M^{c_5}\rangle = \frac{1}{\sqrt{2}}(\bar{r}r - \bar{g}g), \quad |M^{c_6}\rangle = \frac{1}{\sqrt{6}}(2\bar{b}b - \bar{r}r - \bar{g}g),$$
$$|M^{c_7}\rangle = -\bar{g}r, \quad |M^{c_8}\rangle = -\bar{b}g, \quad |M^{c_9}\rangle = -\bar{b}r,$$
$$|\chi^{c1}\rangle = |B^{c_1}\rangle|M^{c_1}\rangle = \frac{1}{\sqrt{6}}(rgb - rbg + gbr - grb + brg - bgr) \times \frac{1}{\sqrt{3}}(\bar{r}r + \bar{g}g + \bar{b}b),$$
$$|\chi^{c2}\rangle = \frac{1}{\sqrt{8}}(|B^{c_{2,1}}\rangle|M^{c_2}\rangle - |B^{c_{3,1}}\rangle|M^{c_3}\rangle - |B^{c_{4,1}}\rangle|M^{c_4}\rangle - |B^{c_{7,1}}\rangle|M^{c_7}\rangle - |B^{c_{8,1}}\rangle|M^{c_8}\rangle + |B^{c_{9,1}}\rangle|M^{c_9}\rangle),$$
$$|\chi^{c3}\rangle = \frac{1}{\sqrt{8}}(|B^{c_{2,2}}\rangle|M^{c_2}\rangle - |B^{c_{3,2}}\rangle|M^{c_3}\rangle - |B^{c_{4,2}}\rangle|M^{c_4}\rangle - |B^{c_{7,2}}\rangle|M^{c_7}\rangle - |B^{c_{8,2}}\rangle|M^{c_8}\rangle + |B^{c_{9,2}}\rangle|M^{c_9}\rangle), \tag{22}$$

where $|\chi^{c1}\rangle$ denotes the color singlet configuration, $|\chi^{c2}\rangle$ and $|\chi^{c3}\rangle$ represent the hidden color configuration.

Finally, the total wave function of the five-quark system is written as

$$\Psi^{i,j,k}_{JM_J} = \mathcal{A}\left[\left[\psi_L \chi_S^{\sigma_i}\right]_{JM_J} \chi_j^f \chi_k^c\right], \times (i = 1, \dots, 10,\ j = 1, \dots, 10,\ k = 1, \dots, 3), \tag{23}$$

where J is the total angular momentum and M_J is the third component of the total angular momentum, and the $\mathcal{A}$ is the antisymmetry operator of the system,

$$\mathcal{A} = (1 - (13) - (23))(1 - (12)) \tag{24}$$

in the $(qqq)(s\bar{q})$ case. Because the symmetry between 1 and 2 particles has been taken into account when the wave function is constructed, so the antisymmetrization operator can be simplified to

$$\mathcal{A} = 1 - (13) - (23). \tag{25}$$

Similarly the simplified antisymmetrization operator is

$$\mathcal{A} = 1 - (14) - (24) \tag{26}$$

in the $(qqs)(q\bar{q})$ case. The eigenenergy of system is obtained by solving the following eigenequation:

$$H\Psi_{\mathrm{JM}_J} = E\Psi_{\mathrm{JM}_J}, \tag{27}$$

by using the variational principle. The eigenfunctions Ψ_{JM_J} are the linear combination of the above channel wave functions.

III. RESULTS AND DISCUSSIONS

In the present work, we investigate the five-quark systems with quantum numbers $IJ^P(I = 0, 1, 2; J = \frac{1}{2}, \frac{3}{2}, \frac{5}{2}; P = -)$ in the chiral quark model. Two structures, $(qqq)(s\bar{q})$ and $(qqs)(q\bar{q})$ with color singlet and hidden-color configurations are considered. We are interested in the low energy states of the pentaquark systems, so here we set all the orbital angular

TABLE III. The possible channels of $(qqq)(s\bar{q})$ and $(qqs)(q\bar{q})$ systems.

IJ^P	Channel
$0\frac{1}{2}^-$	$N\bar{K}, N\bar{K}^*, \Sigma\pi, \Sigma\rho, \Sigma^*\rho, \Lambda\eta, \Lambda\omega$
$0\frac{3}{2}^-$	$N\bar{K}^*, \Sigma\rho, \Sigma^*\pi, \Sigma^*\rho, \Lambda\omega$
$0\frac{5}{2}^-$	$\Sigma^*\rho$
$1\frac{1}{2}^-$	$N\bar{K}, N\bar{K}^*, \Delta\bar{K}^*, \Lambda\pi, \Lambda\rho, \Sigma\pi, \Sigma\rho, \Sigma^*\rho, \Sigma\eta, \Sigma\omega, \Sigma^*\omega$
$1\frac{3}{2}^-$	$N\bar{K}^*, \Delta\bar{K}, \Delta\bar{K}^*, \Lambda\rho, \Sigma\rho, \Sigma^*\pi, \Sigma^*\rho, \Sigma\omega, \Sigma^*\eta, \Sigma^*\omega$
$1\frac{5}{2}^-$	$\Delta\bar{K}^*, \Sigma^*\rho, \Sigma^*\omega$
$2\frac{1}{2}^-$	$\Delta\bar{K}^*, \Sigma\pi, \Sigma\rho, \Sigma^*\rho$
$2\frac{3}{2}^-$	$\Delta\bar{K}, \Delta\bar{K}^*, \Sigma\rho, \Sigma^*\pi, \Sigma^*\rho$
$2\frac{5}{2}^-$	$\Delta\bar{K}^*, \Sigma^*\rho$

TABLE IV. The energy of the pentaquark system with $IJ^P = 0\frac{1}{2}^-$. c.c. denotes all color singlet channels coupling.

Index	$c_i\sigma_j f_k$	Physical content	E (MeV)	$E_{\text{th}}^{\text{Theo}}$ (MeV)	$E_{\text{th}}^{\text{Exp}}$ (MeV)	E' (MeV)
1	$i=1; j=1,2; k=1,2$	$N\bar{K}$	1358	1362	1434	1430
2	$i=2,3; j=1,2; k=1,2$		1933			
3	$i=1,2,3; j=1,2; k=1,2$		1358			
4	$i=1; j=3,4; k=1,2$	$N\bar{K}^*$	1671	1670	1831	1831
5	$i=2,3; j=3,4; k=1,2$		1913			
6	$i=1,2,3; j=3,4; k=1,2$		1671			
7	$i=1; j=1; k=3$	$\Sigma\pi$	1320	1324	1329	1325
8	$i=2,3; j=1,2; k=3$		1949			
9	$i=1,2,3; j=1,2; k=3$		1320			
10	$i=1; j=3; k=3$	$\Sigma\rho$	1923	1920	1964	1964
11	$i=2,3; j=3,4; k=3$		2405			
12	$i=1,2,3; j=3,4; k=3$		1923			
13	$i=1; j=5; k=3$	$\Sigma^*\rho$	1990	1987	2158	2158
14	$i=3; j=5; k=3$		2223			
15	$i=1,3; j=5; k=3$		1990			
16	$i=1; j=2; k=4$	$\Lambda\eta$	1614	1611	1664	1664
18	$i=2,3; j=1,2; k=4$		1873			
17	$i=1,2,3; j=1,2; k=4$		1614			
19	$i=1; j=4; k=4$	$\Lambda\omega$	1724	1720	1898	1898
20	$i=2,3; j=3,4; k=4$		1978			
21	$i=1,2,3; j=3,4; k=4$		1724			
c.c.(SET I)			1267	1324	1329	1292
			1359	1362	1434	1404
c.c.(SET II)			1396	1535	1434	1282
			1505	1454	1329	1389

momenta to zero. Then the parity of the five-quark system is negative. The possible channels of the two structures are listed in Table III.

The calculated results of $IJ^P = 0\frac{1}{2}^-$ are given in Table IV, where the first column is the index of the channels involved in the calculation, and the second column lists the indices of color, spin, and flavor wave functions for every channel, the physical contents of channels are shown in the third column. The fourth column shows the calculation results, while the fifth and the sixth columns give the theoretical and experimental thresholds (the sum of the masses of the corresponding baryon and meson), respectively. The last column shows the corrected energies of the states, which are obtained by

$$E' = E + E_{\text{th}}^{\text{exp}} - E_{\text{th}}^{\text{Theo}} \tag{28}$$

for the single channel calculation. However for the results of channel coupling calculation, the corrected energy is defined as

$$E' = E + \sum_i p_i\left(E_{\text{th},i}^{\text{exp}} - E_{\text{th},i}^{\text{Theo}}\right), \tag{29}$$

where p_i is the percentage of the color singlet channel i in the eigenstate. Because the chiral quark model cannot give the satisfying outcome of both meson spectra and baryon spectra via the same set of parameters, we can minimize the systematic error in calculating the energy of the pentaquark state by using the corrected energy. The last four rows show the lowest and the first excited state energies of all the coupled color-singlet channels with two sets of parameters. The hidden-color channels do not affect the low-lying energies because of their high energies compared to the color singlet channel. The percentages of each color singlet channel in the lowest eigenstate are listed in Table V. All the results shown in Tables IV (except the last two rows) and V are obtained with the first set of parameters.

In the following part we analyze the results in detail.

(a) $IJ^P = 0\frac{1}{2}^-$ (Tables IV and V): For the color-singlet states, $N\bar{K}^*$, $\Sigma\rho$, $\Sigma^*\rho$, $\Lambda\eta$, $\Lambda\omega$, no bound states are found in the single-channel calculation, and coupling the color-singlet state to the corresponding hidden-color channel does not change the lowest energy of the state. However, we find two bound states in the single-channel calculation, $N\bar{K}$ and $\Sigma\pi$, with binding energies -4 MeV both. The coupling of the corresponding hidden-color channel has no effect on the energy of the state. So the influence of the hidden color channels on the low-lying energy states of the system can be neglected. This result is different from that of Ref. [36] where the NK state is unbound in the single channel calculation. The reason is that the value of color factor $\boldsymbol{\lambda}_i^c\boldsymbol{\lambda}_j^c$ for qq is half of that for $q\bar{q}$, and π meson exchange potential is attractive for the $u\bar{u}$

TABLE V. The percentages of color-singlet channels in the lowest and next to lowest eigenstates with $IJ^P = 0\frac{1}{2}^-$.

E' (MeV)	$N\bar{K}$	$N\bar{K}^*$	$\Sigma\pi$	$\Sigma\rho$	$\Sigma^*\rho$	$\Lambda\eta$	$\Lambda\omega$
1292	29.8%	1.8%	66.4%	0.6%	0.1%	0.2%	1.1%
1404	59.1%	0.1%	40.3%	0.1%	0.0%	0.1%	0.3%

TABLE VI. The energy of the pentaquark system with $IJ^P = 0\frac{3}{2}^-$. c.c. denotes all color singlet channels coupling.

Index	$c_i\sigma_j f_k$	Physical content	E (MeV)	$E_{\rm th}^{\rm Theo}$ (MeV)	$E_{\rm th}^{\rm Exp}$ (MeV)	E' (MeV)
1	$i=1; j=6,7; k=1,2$	NK^*	1664	1669	1831	1826
2	$i=2,3; j=6,7; k=1,2$		1913			
3	$i=1,2,3; j=6,7; k=1,2$		1664			
4	$i=1; j=6; k=3$	$\Sigma\rho$	1919	1920	1964	1963
5	$i=2,3; j=6,7; k=1,2$		2398			
6	$i=1,2,3; j=6,7; k=1,2$		1919			
7	$i=1; j=8; k=3$	$\Sigma^*\pi$	1390	1391	1523	1522
8	$i=3; j=8; k=3$		1987			
9	$i=1,3; j=8; k=3$		1390			
10	$i=1; j=9; k=3$	$\Sigma^*\rho$	1989	1987	2158	2158
11	$i=3; j=9; k=3$		2123			
12	$i=1,3; j=9; k=3$		1989			
13	$i=1; j=7; k=4$	$\Lambda\omega$	1723	1720	1898	1898
14	$i=2,3; j=6,7; k=4$		2297			
15	$i=1,2,3; j=6,7; k=4$		1723			
c.c.(SET I)			1380	1391	1523	1512
c.c.(SET II)			1534	1539	1523	1518

pair and is repulsive for the uu pair. The results of coupling all color singlet channels are given in the last four rows of Table IV. The results show that there is a strong coupling between $N\bar{K}$ and $\Sigma\pi$, the main component of the lowest state is $\Sigma\pi$, 66.4%, while the $N\bar{K}$ state takes the percentage 29.8%. For the next to the lowest state, the percentages for $\Sigma\pi$ and $N\bar{K}$ are 40.3% and 59.1%, respectively. The corrected energies of two states are 1292 MeV and 1404 MeV. The state with mass 1404 MeV is naturally taken as a candidate of $\Lambda^*(1405)$. Our results can be compared with that of Ref. [5], in which the author put forward two poles of the scattering amplitude between the $N\bar{K}$ and $\Sigma\pi$ thresholds in the complex energy plane to explain the $\Lambda^*(1405)$ resonance state. Two-pole structure of $\Lambda^*(1405)$ was also claimed in Refs. [37–40]. To check parameter-sensitivity of the results, the second set of parameters is employed to do the calculation. The similar results are obtained, besides the lowest state dominated by $\Sigma\pi$ has mass 1282 MeV and the second lowest state dominated by $N\bar{K}$ has the mass 1389 MeV, 10 MeV and 15 MeV away from the value of first set of parameters, respectively.

(b) $IJ^P = 0\frac{3}{2}^-$ (Tables VI and VII): There are three states, $N\bar{K}^*$, $\Sigma\rho$, and $\Sigma^*\pi$ having energy below the corresponding thresholds in the single-channel calculation. The binding energies are -5 MeV, -1 MeV, and -1 MeV, respectively. Similar to the case of $IJ^P = 0\frac{1}{2}^-$, coupling to the hidden-color channel does not change the energies of the states. It is interesting to find herein that after coupling all the color-singlet channels in the $IJ^P = 0\frac{3}{2}^-$ system, we can get the corrected energy of the lowest state 1512 MeV, which is very close to the experimental mass of $\Lambda^*(1520)$. As above, we checked the dependence of the results on the parameters. The corrected energy of the lowest state is 1518 MeV under the second set of parameters, 6 MeV away from the value of the first set of parameters. However, there is a problem to assign the $\Lambda^*(1520)$ state as the pentaquark state $\Sigma^*\pi$. From Table VII, we can see that the dominant component of the lowest state is $\Sigma^*\pi$, and the partial decay width of $\Sigma^*\pi \to \Sigma\pi\pi$ is about 3 MeV, which is obtained from the decay width of $\Sigma^* \to \Sigma\pi$, ≈ 4 MeV with phase space correction. But the experimental value of partial decay width of $\Lambda^*(1520) \to \Sigma\pi\pi$ is $0.009 \times 15.6 = 0.14$ MeV, which is far smaller than 3 MeV. The fact that the main decay modes of $\Lambda^*(1520)$ are $N\bar{K}$ and $\Sigma\pi$ also supports the $3q$ structure of the state $\Lambda^*(1520)$. Garcia-Recio *et al.* studied the compositeness of $\Lambda^*(1520)$, $1 - Z = 0.227$ also disfavors the baryon-meson explanation of the state [27]. Nevertheless, the $\Sigma^*\pi$ as a sizable component of $\Lambda^*(1520)$ is possible when we go beyond the quenched picture of baryon.

TABLE VII. The percentages of color-singlet channels in the lowest and next to lowest eigenstates with $IJ^P = 0\frac{1}{2}^-$.

E' (MeV)	$N\bar{K}^*$	$\Sigma\rho$	$\Sigma^*\pi$	$\Sigma^*\rho$	$\Lambda\omega$
1512	2.3%	0.1%	96.5%	0.1%	1.0%

(c) $IJ^P = 0\frac{5}{2}^-$ (Table VIII): In this case there is only one channel $\Sigma^*\rho$. The energy of the $\Sigma^*\rho$ state obtained is just 2 MeV lower than its threshold, and 4 MeV below the threshold in the calculation with the second set of parameters. The hidden-color channel does not change the energy of the system as before. As a result, we can predict it as the pentaquark configuration of the Λ^* with $IJ^P = 0\frac{5}{2}^-$. Because of the weak bind, the decay width of the state can be estimated as the sum of Σ^* decay width and ρ decay width, the state will decay to the $\Lambda\pi\pi\pi$ with the width $\Gamma \approx 185$ MeV. In the Particle Data Group (PDG) [23], there are two states with masses in the range 2.1–2.2 GeV, $\Lambda(2100)\frac{7}{2}^-$, $\Lambda(2110)\frac{5}{2}^+$, but the quantum number is a mismatch.

For both systems with $I = 1$ and $I = 2$, the channel coupling calculation shows that there exists no bound state, so we omit the numerical results here and just give a brief discussion in the following.

TABLE VIII. The energy of the pentaquark system with $IJ^P = 0\frac{5}{2}^-$.

Index	$c_i\sigma_j f_k$	Physical content	E (MeV)	$E_{\rm th}^{\rm Theo}$ (MeV)	$E_{\rm th}^{\rm Exp}$ (MeV)	E' (MeV)
1 (SET I)	$i = 1; j = 10; k = 3$	$\Sigma^*\rho$	1985	1987	2160	2158
2 (SET I)	$i = 3; j = 10; k = 3$		2128			
3 (SET I)	$i = 1, 3; j = 10; k = 3$		1985			
1 (SET II)	$i = 1; j = 10; k = 3$	$\Sigma^*\rho$	2189	2193	2160	2156

(d) $IJ^P = 1\frac{1}{2}^-$: The possible channels are shown in Table III. The single channel calculation cannot find any bound state, and the channel coupling does not push down any state below the threshold. Two sets of parameters obtain the similar results. So in this system, no bound states or resonant states may be found.

(e) $IJ^P = 1\frac{3}{2}^-$: The single channel calculation reveals that all the states are unbound except the $\Delta\bar{K}$ state which has binding energy 4 MeV, and the corrected energy is 1723 MeV. The lowest energy of the system is 1523 MeV, which is the sum of the masses of Σ^* and π. So $\Delta\bar{K}$ may turn out to be a resonance state after coupling to the $\Sigma^*\pi$ channel, and the dominant decay mode is $N\bar{K}\pi$ with decay width $\approx$120 MeV, which mainly comes from the decay width of Δ. Because there exist a lot of Σ states around 1700 MeV, the $\Delta\bar{K}$ state is difficult to be observed experimentally due to its large width.

(f) $IJ^P = 1\frac{5}{2}^-$: There are three channels, $\Delta\bar{K}^*$, $\Sigma^*\rho$, and $\Sigma^*\omega$. The $\Delta\bar{K}^*$ state is proved to be a bound state which has the binding energy of 8 MeV in our single channel calculation, however, the other two channels are unbound. The corrected energy of the $\Delta\bar{K}^*$ state is 2116 MeV, and its decay width is estimated to be $\approx$200 MeV. So far there is no appropriate candidate in the PDG [23].

(g) $IJ^P = 2\frac{1}{2}^-$ channel, $IJ^P = 2\frac{3}{2}^-$ channel, and $IJ^P = 2\frac{5}{2}^-$ channel: The results are similar to case (d), there is no bound state showing up in the single channel calculation and the channel coupling does not help to push down the energy below the threshold. So there exist no bound state or resonance states with high isospin.

IV. SUMMARY

In the present work, we investigated the pentaquark state $qqqs\bar{q}$ in two structures, $(qqq)(s\bar{q})$ and $(qqs)(q\bar{q})$ based on the chiral quark model and the Gaussian expansion method. The interesting results are demonstrated in the following: (1) For the $IJ^P = 0\frac{1}{2}^-$ system, two states are found, one of which is the $\Sigma\pi$ state with the energy of 1282–1292 MeV and another is the $N\bar{K}$ state with its energy of 1389–1401 MeV. The results echo the two-pole structure of the scattering amplitude between the $N\bar{K}$ and $\Sigma\pi$ thresholds proposed in explaining the $\Lambda^*(1405)$ resonance state.Particularly, because the energy of the $N\bar{K}$ state is much closer to the $\Lambda(1405)$ state, so we are more inclined to interpret the $\Lambda(1405)$ state as the $N\bar{K}$ state. (2) For the $IJ^P = 0\frac{3}{2}^-$ system, a resonance state with energy 1512–1518 MeV is obtained, the main component of which is $\Sigma^*\pi$. Although the energy of the state is close to the experimental value of $\Lambda^*(1520)$, the assignment is prevented by the decay properties of $\Lambda^*(1520)$. However, the $\Sigma^*\pi$ as a high Fock component of $\Lambda^*(1520)$ is possible. (3) Although in the $IJ^P = 0\frac{5}{2}^-$ system, there exists only one channel, $\Sigma^*\rho$. It can be a good wide pentaquark resonance with the energy $\approx$2156 MeV and width $\approx$185 MeV. (4) For $I = 1$ states, $\Delta\bar{K}$ with $J^P = \frac{3}{2}$ and $\Delta\bar{K}^*$ with $J^P = \frac{5}{2}$ are possibly two wide resonance states. Besides, to check the sensitivity of the results to the model parameters, two sets of parameters are employed to perform the calculation and similar results are obtained. In addition, the AL1 model [41] is also employed in the calculation, the results show that there is no bound state in the AL1 model, which is different from the results of the chiral quark model. The reason we think is that the AL1 model has only potential terms from gluon exchange, which can describe the q^3 baryon and $q\bar{q}$ meson spectra well, but it cannot describe the hadron-hadron interactions. Just as the Isgur-Karl model describes hadron spectra well, but it cannot describe nucleon-nucleon interaction, no intermediate range attraction is obtained. While the chiral quark model incorporates the Goldstone boson exchange and it can give a good description of hadron-hadron interactions. So we believe that the Goldstone boson exchange term in our model contributes a lot to the result.

All calculations in the present work are carried out for the baryon and meson in the ground state. The calculation involved P-wave and D-wave hadrons, and the pentaquark states in other structures will be pursued in a future work.

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