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Ground states of all mesons and baryons in a quark model with hidden local symmetry

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Abstract We extend the chiral quark model for u, d, c and b quarks with vector mesons, which we proposed in the previous analysis, to a model with the s quark. We include the nonet pseudo-scalar and vector mesons together with the singlet scalar meson based on the $\mathrm{SU}(3)_L \times \mathrm{SU}(3)_R$ chiral symmetry combined with the hidden local symmetry, which mediate force among u, d and s quarks. We fit the model parameters to the known ground state mesons and baryons. We show that the mass spectra of those hadrons are beautifully reproduced. We predict the masses of missing ground states, 1 meson and 20 baryons, which will be tested in the future experiment.

1 Introduction

The ground states of mesons and baryons are the most compact particles in quantum chromodynamics (QCD), they play a crucial role in enhancing our understanding of the strong interaction among quarks. So far, 21 ground states of mesons and 24 ground states of baryons have been experimentally confirmed. The validity of a model in describing these ground states is a crucial test. There are, however, still 1 meson and 20 baryons that have not been confirmed by experiments. The B_c^* meson is the last missing particle in the ground state of mesons. The missing baryons can be classified into three categories: (1) singly heavy baryons, with only Ω_b^* remaining; (2) doubly heavy baryons, including Ξ_{QQ}, $\Xi_{QQ}^{\prime(*)}$, Ω_{QQ} and $\Omega_{QQ}^{\prime(*)}$; (3) triply heavy baryons, namely Ω_{QQQ} and Ω_{QQQ}^*. Here Q represent c or b quark. Numerous literatures have extensively studied these missing states, as can be found in the review articles of Refs. [1–9] and reference therein.

Recently, Ref. [10] proposed a chiral quark model with inclusion of vector mesons based on the hidden local symmetry (HLS) [11–13], in addition to the scalar and pseudoscalar mesons and color contribution. Several hadrons including ground states constructed from u, d, c, b quarks are studied, and it was shown that, in particular, the spectra of baryons including good diquark are dramatically improved by the inclusion of the vector meson contribution.

In this paper we extend the model to include the strange quark and study the mass spectra of hadrons including the strange quark. In the present chiral quark model phenomenology, various mesons play distinct roles: (1) the exchange of π mesons leads to the $\pi - \rho$ splitting [14]; (2) the exchange of ω meson resolves the "good-diquark" problem that arises when constructing baryons from two light quarks [10]; (3) the exchange of K mesons contributes to the $\eta - \eta'$ [15], $\Lambda - \Sigma$, $\Xi_c - \Xi_c'$ and $\Xi_b - \Xi_b'$ splittings. To ensure a comprehensive framework that incorporates all these meson exchanges consistently, we incorporate the effects of meson exchange using a nonet of pseudo-scalar and vector mesons based on the HLS formalism. We will show that the masses of existing ground states are beautifully reproduced by a suitable choice of the model parameters. Then, we predict mass spectra of missing ground states. We expect that, among the missing ground states, the prediction on the Ω_b^* will be a crucial test

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of the model, since the quark composition of Ω_b^* is ssb, so the force caused by mesonic exchange will affect its mass. On the other hand, the majority of other missing ground states are primarily governed by the color force resulting from one-gluon exchange (OGE) and the confinement potential (CON). However, due to the absence of double beauty and beauty-charm baryons, accurately determining the coupling strengths of b–b and b–c interactions has become a critical challenge. Achieving a systematic description of the missing ground states requires striking a balance between the mesonic and color potentials.

2 Quark model with SU(3) hidden local symmetry

In the previous analysis, we have included pions, an iso-singlet scalar meson which expresses the two-pion contribution, iso-singlet ω meson and iso-vector ρ meson, which couple to up and down quarks. In the present analysis, we extend the model to include the strange quark. Associated with this extension, we include the following mesons into the model. (1) Pseudoscalar mesons: we include all the members of nonet pseudoscalar mesons π, K, η and η' as an extension of the previous analysis. We note that the η and η' mesons provide contributions to the up and down quarks which are not included in the previous analysis, so that we will refit hadrons with strange quarks. (2) Vector mesons: we include nonet vector mesons ω, ρ, K^* and ϕ. (3) Scalar mesons: we include a flavor singlet scalar meson as an extension of the iso-singlet scalar meson included in the previous analysis.

Now, the Hamiltonian is written as:

$$H = \sum_{i=1}^{n}\left(m_i + \frac{p_i^2}{2m_i}\right) - T_{CM} + \sum_{j>i=1}^{n}\Big(V_{ij}^{\rm CON} + V_{ij}^{\rm OGE} + V_{ij}^{\bar\sigma} + V_{ij}^{PS} + V_{ij}^{V}\Big), \quad (1)$$

where m_i and p_i are the mass and the momentum of i-th quark, T_{CM} is the kinetic energy of the center of mass of the system. $V_{ij}^{\rm CON}$ and $V_{ij}^{\rm OGE}$ represent the gluonic potential of confinement and one-gluon-exchange. For the purpose of this study, they are expressed as:

$$V^{\rm CON}(\vec r_{ij}) = (\boldsymbol{\lambda}_i^c\cdot\boldsymbol{\lambda}_j^c)\left[-a_c(1-e^{-\mu_c r_{ij}}) + \Delta\right], \quad (2)$$

$$V^{\rm OGE}(\vec r_{ij}) = (\boldsymbol{\lambda}_i^c\cdot\boldsymbol{\lambda}_j^c)\frac{1}{4}\frac{\alpha_0}{\ln\left(\frac{\mu^2+\mu_0^2}{\Lambda_0^2}\right)} \times\left[\frac{1}{r_{ij}} - \frac{\boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j}{6m_i m_j}\frac{e^{-\mu r_{ij}/\hat r_0}}{r_{ij}\hat r_0^2/\mu^2}\right]. \quad (3)$$

Here, $\boldsymbol{\lambda}_i^c$ represents the vector of $SU(3)$ color Gell-Mann matrices, and $\boldsymbol{\sigma}_i$ represents the vector of $SU(2)$ spin Pauli matrices. The reduced mass, denoted as μ, is calculated as $\frac{m_i m_j}{m_i+m_j}$. The model parameters a_c, μ_c, Δ, α_0, μ_0, Λ_0 and $\hat r_0$ are given in Table 1.

$V_{ij}^{\bar\sigma}$, V_{ij}^{PS} and V_{ij}^{V} represent scalar, pseudo-scalar and vector potential, respectively. The pseudo-scalar and vector potentials are decomposed as

$$V_{ij}^{PS} = V_{ij}^{\eta} + V_{ij}^{\eta'} + V_{ij}^{\pi} + V_{ij}^{K},$$
$$V_{ij}^{V} = V_{ij}^{\omega} + V_{ij}^{\phi} + V_{ij}^{\rho} + V_{ij}^{K^*}, \quad (4)$$

where V_{ij}^{η}, $V_{ij}^{\eta'}$, V_{ij}^{π} and V_{ij}^{K} represent the potentials generated by the exchanges of η, η', π and K mesons, respectively, while V_{ij}^{ω}, V_{ij}^{ϕ}, V_{ij}^{ρ} and $V_{ij}^{K^*}$ are by ω, ϕ, ρ and K^* mesons. Their explicit forms are given as

$$V_{ij}^{\bar\sigma} = V_{ij}^{s=\bar\sigma, g_s=g_{\bar\sigma q}}\lambda_i^q\lambda_j^q + V_{ij}^{s=\bar\sigma, g_s=g_{\bar\sigma s}}\lambda_i^s\lambda_j^s,$$
$$V_{ij}^{\eta} = V_{ij}^{p=\eta, g_p=g_{\eta q}}\lambda_i^q\lambda_j^q + V_{ij}^{p=\eta, g_p=g_{\eta s}}\lambda_i^s\lambda_j^s,$$
$$V_{ij}^{\eta'} = V_{ij}^{p=\eta', g_p=g_{\eta' q}}\lambda_i^q\lambda_j^q + V_{ij}^{p=\eta', g_p=g_{\eta' s}}\lambda_i^s\lambda_j^s,$$
$$V_{ij}^{\pi} = V_{ij}^{p=\pi, g_p=g_\pi}\sum_{a=1}^{3}\lambda_i^a\lambda_j^a,$$
$$V_{ij}^{K} = V_{ij}^{p=K, g_p=g_K}\sum_{a=4}^{7}\lambda_i^a\lambda_j^a,$$
$$V_{ij}^{\omega} = V_{ij}^{v=\omega, g_v=g_{\omega q}}\lambda_i^q\lambda_j^q + V_{ij}^{v=\omega, g_v=g_{\omega s}}\lambda_i^s\lambda_j^s,$$
$$V_{ij}^{\phi} = V_{ij}^{v=\phi, g_v=g_{\phi q}}\lambda_i^q\lambda_j^q + V_{ij}^{v=\phi, g_v=g_{\phi s}}\lambda_i^s\lambda_j^s,$$
$$V_{ij}^{\rho} = V_{ij}^{v=\rho, g_v=g_\rho}\sum_{a=1}^{3}\lambda_i^a\lambda_j^a,$$
$$V_{ij}^{K^*} = V_{ij}^{v=K^*, g_v=g_{K^*}}\sum_{a=4}^{7}\lambda_i^a\lambda_j^a. \quad (5)$$

Here λ^a $(a = 1, 2, \ldots, 7)$ are flavor $SU(3)$ Gell-Mann matrices, λ^q and λ^s are expressed as

$$\lambda^q = \begin{pmatrix}1&0&0\\0&1&0\\0&0&0\end{pmatrix},\ \lambda^s = \begin{pmatrix}0&0&0\\0&0&0\\0&0&1\end{pmatrix}. \quad (6)$$

V_{ij}^{s}, V_{ij}^{p} and V_{ij}^{v} are common parts of scalar, pseudo-scalar and vector mesons, respectively. For the current purpose, they are given as:

$$V^s(\vec r_{ij}) = -\frac{g_s^2}{4\pi}\frac{\Lambda_s^2}{\Lambda_s^2 - m_s^2}m_s \times\left[Y(m_s r_{ij}) - \left(\frac{\Lambda_s}{m_s}\right)Y(\Lambda_s r_{ij})\right], \quad (7)$$

$$V^p(\vec r_{ij}) = \frac{g_p^2}{48\pi}\frac{\Lambda_p^2}{\Lambda_p^2 - m_p^2}\frac{m_p^3}{m_i m_j} \times\left[Y(m_p r_{ij}) - \left(\frac{\Lambda_p}{m_p}\right)^3 Y(\Lambda_p r_{ij})\right]\boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j, \quad (8)$$

Table 1 Best fitted values of model parameters, where $\chi^2/\text{dof} = 8.6/23$

$m_u = m_d$(MeV)	381.1	$m_{\bar{\sigma}}$(fm^{-1})	2.53
m_s(MeV)	551.6	m_η(fm^{-1})	2.78
m_c(MeV)	1735.0	$m_{\eta'}$(fm^{-1})	4.85
m_b(MeV)	5094.8	m_π(fm^{-1})	0.7
a_c(MeV)	352.7	m_K(fm^{-1})	2.51
μ_c(fm^{-1})	3.3	m_ω(fm^{-1})	3.97
Δ(MeV)	327.6	m_ϕ(fm^{-1})	5.17
α_0	0.703	m_ρ(fm^{-1})	3.93
Λ_0(fm^{-1})	0.835	m_{K^*}(fm^{-1})	4.54
μ_0(MeV)	300.688	θ_p(°)	− 11.3
$\hat{r}_0$(MeV · fm)	23.067	$\Lambda_{\bar{\sigma}} = \Lambda_\pi = \Lambda_\eta = \Lambda_K$(fm^{-1})	4.2
$g_{\bar{\sigma}q}$=$g_{\bar{\sigma}s}$	− 0.003	$\Lambda_\omega = \Lambda_\rho = \Lambda_{K^*}$(fm^{-1})	5.2
$g_\pi = g_K$	2.912	$\Lambda_{\eta'} = \Lambda_\phi$(fm^{-1})	6.2
$g_{\eta q}$	1.177	$f_{\omega q}$	0.42
$g_{\omega q}$	1.118	$f_\rho = f_{K^*}$	− 0.222
$g_\rho = g_{K^*}$	− 0.323		

Table 2 List of operators included in the potentials for $L = 0$ states and the sign of the contributions. The left (right) side of slash represents qq ($q\bar{q}$), respectively

	1	$\lambda_i\lambda_j$	$\sigma_i\sigma_j$	$\sigma_i\sigma_j \cdot \lambda_i\lambda_j$
$\bar{\sigma}$	−/−			
η/η'			+/+	
π/K				+/−
ω/ϕ	+/−		+/−	
ρ/K^*		+/+		+/+
OGE	−/−		+/+	
CON	+/+			

$$V^v(\vec{r}_{ij}) = \frac{\Lambda_v^2}{\Lambda_v^2 - m_v^2}\left\{\frac{g_v^2}{4\pi}m_v\left[Y(m_v r_{ij}) - \left(\frac{\Lambda_v}{m_v}\right)Y(\Lambda_v r_{ij})\right]\right.$$
$$+\frac{m_v^3}{m_i m_j}\left(\frac{g_v(2f_v+g_v)}{16\pi} + \frac{(f_v+g_v)^2}{24\pi}\boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j\right)$$
$$\left.\times\left[Y(m_v r_{ij}) - \left(\frac{\Lambda_v}{m_v}\right)^3 Y(\Lambda_v r_{ij})\right]\right\}. \quad (9)$$

In the above, $m_{s/p/v}$, $\Lambda_{s/p/v}$ and $g_{s/p/v}$ represent the mass, cutoff, electric coupling constants of the relevant scalar/pseudo-scalar/vector meson, respectively. f_v represents the magnetic coupling constants of the relevant vector meson. $Y(x)$ denotes the Yukawa type potential, which is given by e^{-x}/x.

The mesonic potentials for $q\bar{q}$ ($q = u, d$) is obtained by performing a G-parity transformation of that in qq case. In the case that G parity is not well defined, e.g., K and K^*, the transform is given by $\lambda_i^a\lambda_j^a \to \lambda_i^a(\lambda_j^a)^*$ and $\lambda_i^a\lambda_j^a \to -\lambda_i^a(\lambda_j^a)^*$, respectively.

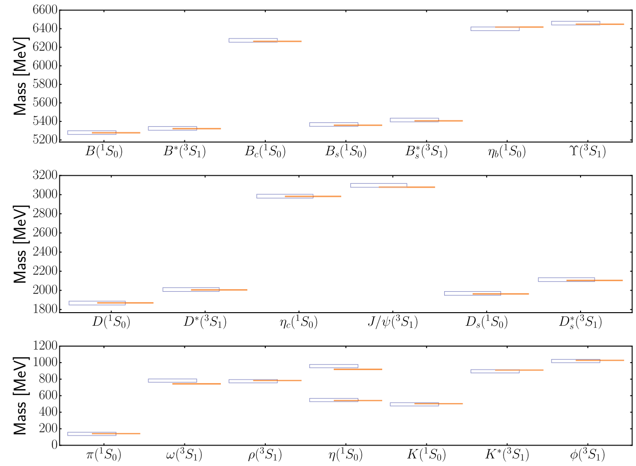

Fig. 1 Mass spectrum of mesons. Blue boxes represent $m(\text{exp}) \pm \text{Err(sys)}$, while the orange lines represent the predicted masses. The values of η_b and Υ shown here are shifted by -3000 MeV

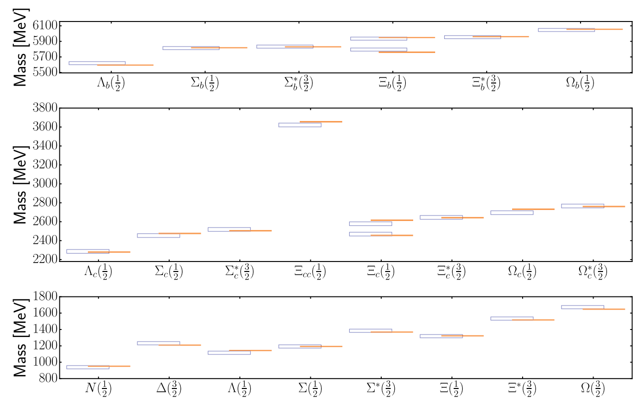

Fig. 2 Mass spectrum of baryons. The colors have the same meaning as shown in Fig. 1

We treat the mass of $\bar{\sigma}$ as a model parameter, while the mass of η, η', π, K, ω, ϕ, ρ and K^* are used as their PDG [16] values. For the coupling constants of those mesons to quarks, we require the following relation based on the SU(3) flavor symmetry.

1. pseudo-scalar mesons: $g_{\eta s} = g_{\eta q} - \sqrt{3}\cos\theta_p g_\pi$, $g_{\eta' q} = -\cot\theta_p g_{\eta q} + \frac{1}{\sqrt{3}\sin\theta_p}g_\pi$, $g_{\eta' s} = -\cot\theta_p g_{\eta q} + \frac{\cos\theta_p\cot\theta_p - 2\sin\theta_p}{\sqrt{3}}g_\pi$ and $g_\pi = g_K$. Here $\theta_p = -11.3°$ is taken from PDG.
2. vector meson: $g_{\omega s} = g_{\omega q} - g_\rho$, $g_{\phi q} = -\sqrt{\frac{1}{2}}(g_{\omega q} - g_\rho)$, $g_{\phi s} = -\sqrt{\frac{1}{2}}(g_{\omega q} + g_\rho)$, $g_\rho = g_{K^*}$ and $f_{\omega s} = f_{\omega q} - f_\rho$, $f_{\phi q} = -\sqrt{\frac{1}{2}}(f_{\omega q} - f_\rho)$, $f_{\phi s} = -\sqrt{\frac{1}{2}}(f_{\omega q} + f_\rho)$, $f_\rho = f_{K^*}$.

Table 3 Predicted mass spectrum (in MeV) of ground states for mesons and baryons

π	ω	ρ	η	η'	K	K^*	ϕ
141.3	745.5	783.4	541.1	918.7	503.3	909.8	1027.6
D	D^*	η_c	J/Ψ	D_s	D_s^*		
1869.4	2005	2981.9	3078	1963	2103.8		
B	B^*	η_b	Υ	B_s	B_s^*	B_c	
5277.6	5321.9	9417.8	9448.2	5358.9	5406.2	6263.5	
N	Δ	Λ	Σ	Σ^*	Ξ	Ξ^*	Ω
951.1	1208.9	1143	1192.5	1368.6	1322.4	1516.5	1647.5
Λ_c	Σ_c	Σ_c^*	Ξ_c	Ξ_c'	Ξ_c^*	Ω_c	Ω_c^*
2279.6	2476	2504.7	2455.2	2614.5	2642.5	2729	2760.4
Λ_b	Σ_b	Σ_b^*	Ξ_b	Ξ_b'	Ξ_b^*	Ω_b	Ξ_{cc}
5594.9	5818	5829.7	5762.3	5949.1	5960.6	6055.1	3653.9
B_c^*	Ξ_{cc}^*	Ξ_{bc}	Ξ_{bc}'	Ξ_{bc}^*	Ξ_{bb}	Ξ_{bb}^*	
6306.9	3698.9	6943.9	6958.4	6976.4	10176	10198.5	
Ω_{cc}	Ω_{cc}^*	Ω_{bc}	Ω_{bc}'	Ω_{bc}^*	Ω_{bb}	Ω_{bb}^*	
3763.9	3806.8	7044.7	7057.7	7076	10266.9	10289	
Ω_b^*	Ω_{ccc}	Ω_{ccb}	Ω_{ccb}^*	Ω_{bbc}	Ω_{bbc}^*	Ω_{bbb}	
6068.1	4795	8014.9	8027.5	11191.9	11207.7	14351.2	

3 Numerical results

We solve two and three body problems for mesons and baryons by using Gaussian expansion method (GEM) [17]. We determine the model parameters by minimizing the χ^2 of the system defined by

$$\chi^2 = \sum_i \left(\frac{m_i(\text{the}) - m_i(\text{exp})}{\text{Err}_\text{i}(\text{sys})} \right)^2, \tag{10}$$

where $m_i(\text{the})$ and $m_i(\text{exp})$ are theoretical and experimental mass of each particle, respectively. The system error is determined as

$$\text{Err}(\text{sys}) = \sqrt{\text{Err}(\text{exp})^2 + \text{Err}(\text{the})^2}, \tag{11}$$

where Err(exp) is the experimental error taken from PDG, while Err(the) represents the model limitation error. In this study, we assume that all the ground states of mesons and baryons are pure 2 and 3 quark states, respectively, and we check the validity of this assumption within the current framework. We take Err(the) as 40 MeV for ground-state of mesons and baryons. In the present study we use 21 meson ground states, together with 24 baryon ground states, totally 45 hadron states as inputs. We take η–η' mixing parameter θ_p and 8 masses of pseudoscalar and vector mesons which contribute to the potential from PDG so the number of free parameter (including cutoffs) is $22 = 31 - 9$. As a result, the degree of freedom (dof) is $23 = 45 - 22$.

In Table 1, we list the values of model parameters for best fitted case, where $\chi^2/\text{dof} = 8.6/23$. Here, to understand Table 1 we clarify the operators included in the potentials with the sign of each contribution, which are summarized in Table 2. Combining Tables 1 and 2, we observe that the most significant meson exchanges are π/K and ω/ϕ. This observation is understandable since these mesons play opposite roles in the qq and $q\bar{q}$ sectors. ρ/K^* mesons make minor modifications to the π/K mesons in the $\sigma_i\sigma_j \cdot \lambda_i\lambda_j$ sector, and they have little impact on the $\lambda_i\lambda_j$ sector. Forces mediated by $\bar{\sigma}$ and η/η' mesons exhibit similar characteristics to the V^{OGE} and V^{CON}, albeit with modified strength or effective range.

In Figs. 1 and 2, we show mass spectrum of mesons and baryons, respectively, obtained by using best fitted model

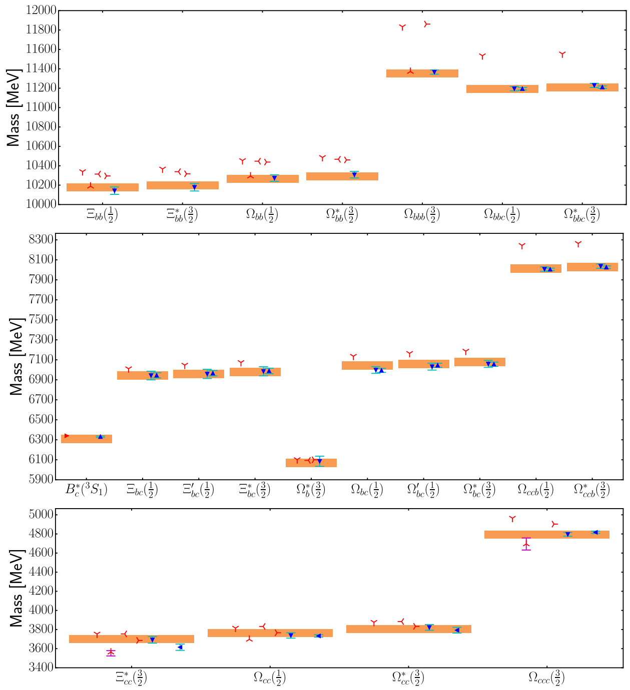

Fig. 3 Predicted mass spectrum of missing meson and baryons which have not been experimentally confirmed shown by orange line with 40 MeV error. Predictions of some other quark models (▶ [18], ⋎ [19], ⅄ [20–22], ≺ [23], ≻ [24]) and lattice QCD calculations (▼ [25], ▲ [26], ◀ [27]) are shown for comparison. The values of Ω_{bbb} shown here are shifted by −3000 MeV

parameters. These figures show that all the existing ground states of mesons and baryons are beautifully reproduced.

We present the predicted mass spectra of mesons and baryons, including missing ground states that have not been observed experimentally, in Table 3. In Fig. 3, we compare our results (orange line with 40 MeV error) with those obtained from other quark models (▶ [18], ⋎ [19], ⅄ [20–22], ≺ [23], ≻ [24]) and lattice QCD calculations (▼ [25], ▲ [26], ◀ [27]). It is evident that our mass spectra are consistent with lattice calculations in Refs. [25–27]. In the limited comparison shown in Fig. 3, the state Ω_b^* is the most accurately predicted among all the models. This can be understood as Ω_b^* being an extension of Ω_b, similar to the relation between Ω_c^* and Ω_c. When dealing with double beauty and beauty-charm quarks, many quark models encounter challenges in predicting their properties. This difficulty arises from the limited availability of experimental data on double beauty and beauty-charm baryons, which hampers the determination of the coupling strengths between b–b and b–c quarks. However, we can still gather some insights into the b–b and b–c systems by assuming that meson exchange exclusively occurs among the light u, d and s quarks. In this regard, we can draw knowledge from the b–$\bar{b}$ and b–$\bar{c}$ systems, such as the Υ, η_b and B_c families. In the present analysis, by utilizing the chiral quark model with the HLS, we can achieve a better understanding of the ground states in both experimental and lattice QCD studies.

4 Summary

We constructed a chiral quark model, in which the nonet pseudo-scalar and vector mesons together with the singlet scalar meson are included based on the $SU(3)_L \times SU(3)_R$ chiral symmetry to mediate force among u, d and s quarks. We performed a fitting of the model parameters to the known masses of 45 hadron states, yielding a χ^2/dof value of 0.37. The obtained results demonstrate a remarkable agreement, with the masses of all 45 experimentally confirmed hadrons being accurately reproduced. Furthermore, the predictions for 21 ground states align well with the results obtained from lattice QCD analyses. Based on our current understanding, this paper represents a pioneering achievement in describing all 45+21 ground states of mesons and baryons using a single parameter set. Notably, we have accomplished this feat with an overall error of approximately 40 MeV, marking a significant milestone as it is the first instance where such comprehensive results have been successfully attained. In order to reduce the overall error, it may be necessary to consider the following aspects: (1) isospin breaking effects, (2) mixing effects such as S-D and P-F mixings, (3) the mixing between 2-quark and 4-quark states for mesons, as well as the mixing between 3-quark and 5-quark states for baryons. These aspects are worth exploring in future research. The predictions concerning the masses of missing ground states, will be tested in future experiments.

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Data Availability Statement This manuscript has no associated data or the data will not be deposited. [Authors' comment: This is a theoretical study and no experimental data.]

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