Kaon-nucleon interaction in the extended chiral SU(3) quark model

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The chiral SU(3) quark model is extended to include the coupling between the quark and vector chiral fields. The one-gluon exchange (OGE) that dominantly governs the short-range quark–quark interaction in the original chiral SU(3) quark model is now nearly replaced by the vector-meson exchange. By use of this model, the isospin $I = 0$ and $I = 1$ kaon-nucleon S, P, D, F wave phase shifts are dynamically studied by solving the resonating group method (RGM) equation. Similar to those given by the original chiral SU(3) quark model, the calculated results for many partial waves are consistent with the experiment, while there is no improvement in this new approach for the P_{13} and D_{15} channels, of which the theoretical phase shifts are too repulsive and too attractive, respectively, when the laboratory momentum of the kaon meson is greater than 300 MeV.

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I. INTRODUCTION

The kaon-nucleon (KN) scattering process has aroused particular interest in the past, and many works have been devoted to this issue [1–8]. In Ref. [1], the Jülich group presented a meson-exchange model on hadronic degrees of freedom to study the KN phase shifts. Considering single boson exchanges (σ, ρ, and ω) together with contributions from higher-order diagrams involving N, Δ, K, and K^* intermediate states, the authors can give a good description of KN interaction, but the exchange of a short-range ($\sim$0.2 fm) phenomenological repulsive scalar meson $\sigma_{\rm rep}$ had to be added in order to reproduce the S-wave phase shifts in the isospin $I = 0$ channel. The range of this repulsion is much smaller than the nucleon size, which clearly shows that the quark substructure of the kaon and nucleon cannot be neglected. Further, in Ref. [2] the authors refined this model by replacing the phenomenological $\sigma_{\rm rep}$ with one-gluon exchange (OGE), and a satisfactory description of the KN experimental data was gotten. However, in this hybrid model the one-pion exchange is supposed to be absent, which is true on the hadron level but is not the case in a genuine quark model study, because the quark exchange effect in the single boson exchanges has to be considered. In Ref. [3], Barnes and Swanson used the quark-Born-diagram (QBD) method to derive the KN scattering amplitudes and obtained reasonable results for the KN phase shifts, but they are limited to S-wave. Subsequently, the Born approximation was applied to investigate the KN scattering more extensively in Ref. [4]. Nevertheless, the magnitudes of most calculated phase shifts are too small. In Ref. [5], taking the π and σ boson exchanges as well as the OGE and confining potential as the quark–quark interactions, the authors calculated the S-wave KN phase shifts in a constituent quark model by using the resonating group method (RGM). The results are too attractive for the $I = 0$ channel and too repulsive for the $I = 1$ channel, and thus the authors concluded that a consistent description of S-wave KN phase shifts in both isospin $I = 0$ and $I = 1$ channels simultaneously is not possible. In Ref. [6], Lemaire *et al.* studied the KN phase shifts up to the orbit angular momentum $L = 4$ on the quark level by using the RGM. They only considered the OGE and confining potential as the quark–quark interaction, and their results can give a reasonably description of the S-wave phase shifts, but the P and higher partial waves are poorly described. The authors further incorporated π and σ exchanges in addition to OGE and confining potential in the quark–quark interaction in Ref. [7], but the obtained agreement with the experimental data is quite poor, especially in that the signs of the S_{01}, P_{03}, P_{11}, D_{05}, D_{13}, D_{15}, F_{07}, and F_{15} waves are opposite to the experiment values. Recently, Wang *et al.* [8] studied the KN elastic scattering in a quark potential model. Their results are consistent with the experimental data, but in their model the factor of a color-octet component is added arbitrarily, and the size parameter of harmonic oscillator is chosen to be $b_u = 0.255$ fm, which is too small compared with the nucleon radius.

In spite of great successes, the constituent quark model needs to have a logical explanation, from the underlying theory of the strong interaction [i.e., quantum chromodynamics (QCD)], of the source of the constituent quark mass. Thus spontaneous vacuum breaking has to be considered, and as a consequence the coupling between the quark field and the Goldstone boson is introduced to restore the chiral symmetry. In this sense, the chiral quark model can be regarded as a quite reasonable and useful model to describe the medium-range nonperturbative QCD effect. By generalizing the SU(2) linear σ model, a chiral SU(3) quark model is developed to describe the system with strangeness [9]. This model has been quite

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successful in reproducing the energies of the baryon ground states, the binding energy of deuteron, the nucleon–nucleon (*NN*) scattering phase shifts of different partial waves, and the hyperon–nucleon (*YN*) cross sections by performing the RGM calculations [9,10]. Inspired by these achievements, we try to extend this model to study the baryon-meson interactions. In our previous work [11,12], we dynamically studied the *S*-, *P*-, *D*-, and *F*-wave *KN* phase shifts by performing a RGM calculation. Comparing with Ref. [7], we obtained correct signs of the phase shifts of S_{01}, P_{11}, P_{03}, D_{13}, D_{05}, F_{15}, and F_{07} partial waves, and for P_{01}, D_{03}, and D_{15} channels we also got a considerable improvement in the magnitude. At the same time, the satisfactory results also show that the short-range *KN* interaction dominantly originates from the quark and one-gluon exchanges.

It is a consensus that constituent quark is the dominat effective degree of freedom for low-energy hadron physics, but what other proper effective degrees of freedom there may be still is debated [13–18]. Glozman and Riska proposed that the Goldstone boson is the only other proper effective degree of freedom. In Refs. [13,14], they applied the quark–chiral-field coupling model to study the baryon structure and replaced OGE with vector-meson coupling. They pointed out that the spin–flavor interaction is important in explaining the energy of the Roper resonance and got a comparatively good fit to the baryon spectrum. However Isgur gave a critique of the boson exchange model and insisted that OGE governs the baryon structure [15,16]. In Refs. [17,18], Liu *et al.* produced a valence lattice QCD result that supports the Goldstone boson exchange picture, but Isgur pointed out that this is unjustified [15,16]. On the other hand, in the study of *NN* interactions on the quark level, the short-range feature can be explained by OGE interaction and a quark exchange effect, while in the traditional one-boson exchange (OBE) model on the baryon level it comes from vector-meson (ρ, K^*, ω, and ϕ) exchange. Some authors also studied the short-range interaction as stemming from the Goldstone boson exchanges on the quark level [10,19,20], and it has been shown that these interactions can substitute for the traditional OGE mechanism. Anyhow, for low-energy hadron physics, what other proper effective degrees of freedom besides constituent quarks there may be, whether OGE or vector-meson exchange is the right mechanism or both of them are important for describing the short-range quark–quark interaction, is still a controversial and challenging problem.

In this paper, we extend the chiral SU(3) quark model to include the coupling between the quark and vector chiral fields. The OGE, which dominantly governs the short-range quark–quark interaction in the original chiral SU(3) quark model, is now nearly replaced by the vector-meson exchange. As we did in Refs. [11,12], the mass of the σ meson is taken to be 675 MeV, and the mixing of σ_0 (scalar singlet) and σ_8 (scalar iso-scalar) is considered. The set of parameters that we used can satisfactorily reproduce the energies of the ground states of the octet and decuplet baryons. Using this model, we perform a dynamical calculation of the *S*-, *P*-, *D*-, and *F*- wave *KN* phase shifts in the isospin $I = 0$ and $I = 1$ channels by solving a RGM equation. The calculated phase shifts for different partial waves are similar to those obtained by the original chiral SU(3) quark model. In comparison with a recent RGM study on a quark level [7], our investigation achieves a considerable improvement on the theoretical phase shifts, and for many channels the theoretical results are qualitatively consistent with the experimental data. Nevertheless, there is no improvement in this new approach for the P_{13} and D_{15} partial waves, of which the calculated phase shifts are too repulsive and too attractive, respectively, when the laboratory momentum of the kaon meson is greater than 300 MeV, as it was the case in the past. It would be studied in future work if there are some physical ingredients missing in our quark model investigations.

The paper is organized as follows. In the next section the framework of the extended chiral SU(3) quark model is briefly introduced. The results for the *S*-, *P*-, *D*-, and *F*-wave *KN* phase shifts are shown in Sec. III, where some discussion is presented as well. Finally, the summary is given in Sec. IV.

II. FORMULATION

A. Model

The chiral SU(3) quark model has been widely described in the literature [11,12], and we refer the reader to those works for details. Here we just give the salient features of the extended chiral SU(3) quark model.

In the extended chiral SU(3) quark model, besides the nonet pseudoscalar meson fields and nonet scalar meson fields, the couplings among vector meson fields with quarks are also considered. With this generalization, in the interaction Lagrangian a term of coupling between the quark and the vector meson field is introduced:

$$\mathcal{L}_I^v = -g_{\rm chv}\bar{\psi}\gamma_\mu T^a A_a^\mu \psi - \frac{f_{\rm chv}}{2M_P}\bar{\psi}\sigma_{\mu\nu}T^a\partial^\nu A_a^\mu\psi. \quad (1)$$

Thus the meson fields induced effective quark–quark potentials can be written as

$$V_{ij}^{\rm ch} = \sum_{a=0}^{8} V_{\sigma_a}(\boldsymbol{r}_{ij}) + \sum_{a=0}^{8} V_{\pi_a}(\boldsymbol{r}_{ij}) + \sum_{a=0}^{8} V_{\rho_a}(\boldsymbol{r}_{ij}), \quad (2)$$

where $\sigma_0, \ldots, \sigma_8$ are the scalar nonet fields, $\pi_0, \ldots, \pi_8$ the pseudoscalar nonet fields, and $\rho_0, \ldots, \rho_8$ the vector nonet fields. The expressions of these potentials are

$$V_{\sigma_a}(\boldsymbol{r}_{ij}) = -C\big(g_{\rm ch}, m_{\sigma_a}, \Lambda\big)X_1\big(m_{\sigma_a}, \Lambda, r_{ij}\big) \times [\lambda_a(i)\lambda_a(j)] + V_{\sigma_a}^{\boldsymbol{l}\cdot\boldsymbol{s}}(\boldsymbol{r}_{ij}), \quad (3)$$

$$V_{\pi_a}(\boldsymbol{r}_{ij}) = C\big(g_{\rm ch}, m_{\pi_a}, \Lambda\big)\frac{m_{\pi_a}^2}{12m_{q_i}m_{q_j}}X_2\big(m_{\pi_a}, \Lambda, r_{ij}\big)(\boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j) \times [\lambda_a(i)\lambda_a(j)] + V_{\pi_a}^{\rm ten}(\boldsymbol{r}_{ij}), \quad (4)$$

$$V_{\rho_a}(\boldsymbol{r}_{ij}) = C\big(g_{\rm chv}, m_{\rho_a}, \Lambda\big)\bigg[X_1\big(m_{\rho_a}, \Lambda, r_{ij}\big) + \frac{m_{\rho_a}^2}{6m_{q_i}m_{q_j}} \times \left(1 + \frac{f_{\rm chv}}{g_{\rm chv}}\frac{m_{q_i}+m_{q_j}}{M_P} + \frac{f_{\rm chv}^2}{g_{\rm chv}^2}\frac{m_{q_i}m_{q_j}}{M_P^2}\right) \times X_2\big(m_{\rho_a}, \Lambda, r_{ij}\big)(\boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j)\bigg][\lambda_a(i)\lambda_a(j)] + V_{\rho_a}^{\boldsymbol{l}\cdot\boldsymbol{s}}(\boldsymbol{r}_{ij}) + V_{\rho_a}^{\rm ten}(\boldsymbol{r}_{ij}), \quad (5)$$

with

$$V^{\boldsymbol{l}\cdot\boldsymbol{s}}_{\sigma_a}(\boldsymbol{r}_{ij}) = -C\big(g_{\rm ch}, m_{\sigma_a}, \Lambda\big)\frac{m^2_{\sigma_a}}{4m_{q_i}m_{q_j}}\left[G\big(m_{\sigma_a}r_{ij}\big) - \left(\frac{\Lambda}{m_{\sigma_a}}\right)^3 \times G(\Lambda r_{ij})\right][\boldsymbol{L}\cdot(\boldsymbol{\sigma}_i+\boldsymbol{\sigma}_j)][\lambda_a(i)\lambda_a(j)], \quad (6)$$

$$V^{\boldsymbol{l}\cdot\boldsymbol{s}}_{\rho_a}(\boldsymbol{r}_{ij}) = -C\big(g_{\rm chv}, m_{\rho_a}, \Lambda\big)\frac{3m^2_{\rho_a}}{4m_{q_i}m_{q_j}}\left[1+\frac{f_{\rm chv}}{g_{\rm chv}}\frac{2\big(m_{q_i}+m_{q_j}\big)}{3M_P}\right] \times\left[G\big(m_{\rho_a}r_{ij}\big) - \left(\frac{\Lambda}{m_{\rho_a}}\right)^3 G(\Lambda r_{ij})\right] \times[\boldsymbol{L}\cdot(\boldsymbol{\sigma}_i+\boldsymbol{\sigma}_j)][\lambda_a(i)\lambda_a(j)], \quad (7)$$

and

$$V^{\rm ten}_{\pi_a}(\boldsymbol{r}_{ij}) = C\big(g_{\rm ch}, m_{\pi_a}, \Lambda\big)\frac{m^2_{\pi_a}}{12m_{q_i}m_{q_j}}\left[H(m_{\pi_a}r_{ij}) - \left(\frac{\Lambda}{m_{\pi_a}}\right)^3 H(\Lambda r_{ij})\right]\hat{S}_{ij}[\lambda_a(i)\lambda_a(j)], \quad (8)$$

$$V^{\rm ten}_{\rho_a}(\boldsymbol{r}_{ij}) = -C\big(g_{\rm chv}, m_{\rho_a}, \Lambda\big)\frac{m^2_{\rho_a}}{12m_{q_i}m_{q_j}}\left(1+\frac{f_{\rm chv}}{g_{\rm chv}}\frac{m_{q_i}+m_{q_j}}{M_P} + \frac{f^2_{\rm chv}}{g^2_{\rm chv}}\frac{m_{q_i}m_{q_j}}{M_P^2}\right)\left[H\big(m_{\pi_a}r_{ij}\big) - \left(\frac{\Lambda}{m_{\pi_a}}\right)^3 H(\Lambda r_{ij})\right] \times\hat{S}_{ij}[\lambda_a(i)\lambda_a(j)], \quad (9)$$

where

$$C(g_{\rm ch}, m, \Lambda) = \frac{g^2_{\rm ch}}{4\pi}\frac{\Lambda^2}{\Lambda^2-m^2}m, \quad (10)$$

$$X_1(m,\Lambda,r) = Y(mr) - \frac{\Lambda}{m}Y(\Lambda r), \quad (11)$$

$$X_2(m,\Lambda,r) = Y(mr) - \left(\frac{\Lambda}{m}\right)^3 Y(\Lambda r), \quad (12)$$

$$Y(x) = \frac{1}{x}e^{-x}, \quad (13)$$

$$G(x) = \frac{1}{x}\left(1+\frac{1}{x}\right)Y(x), \quad (14)$$

$$H(x) = \left(1+\frac{3}{x}+\frac{3}{x^2}\right)Y(x), \quad (15)$$

$$\hat{S}_{ij} = 3(\boldsymbol{\sigma}_i\cdot\hat{r}_{ij})(\boldsymbol{\sigma}_j\cdot\hat{r}_{ij}) - \boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j, \quad (16)$$

and M_P is a mass scale, taken as proton mass. m_{σ_a} is the mass of the scalar meson, m_{π_a} the mass of the pseudoscalar meson, and m_{ρ_a} the mass of the vector meson.

For the systems with an antiquark $\bar{s}$, the total Hamiltonian can be written as

$$H = \sum_{i=1}^{5} T_i - T_G + \sum_{i<j=1}^{4} V_{ij} + \sum_{i=1}^{4} V_{i\bar{5}}, \quad (17)$$

where T_G is the kinetic energy operator for the center-of-mass motion, and V_{ij} and $V_{i\bar{5}}$ represent the quark–quark (qq) and quark–antiquark ($q\bar{q}$) interactions, respectively,

$$V_{ij} = V^{\rm OGE}_{ij} + V^{\rm conf}_{ij} + V^{\rm ch}_{ij}, \quad (18)$$

where $V^{\rm OGE}_{ij}$ is the one-gluon-exchange interaction,

$$V^{\rm OGE}_{ij} = \frac{1}{4}g_i g_j\big(\lambda^c_i\cdot\lambda^c_j\big)\left\{\frac{1}{r_{ij}} - \frac{\pi}{2}\delta(\boldsymbol{r}_{ij})\left[\frac{1}{m^2_{q_i}}+\frac{1}{m^2_{q_j}} + \frac{4}{3}\frac{1}{m_{q_i}m_{q_j}}(\boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j)\right]\right\} + V^{\boldsymbol{l}\cdot\boldsymbol{s}}_{\rm OGE}, \quad (19)$$

with

$$V^{\boldsymbol{l}\cdot\boldsymbol{s}}_{\rm OGE} = -\frac{1}{16}g_i g_j\big(\lambda^c_i\cdot\lambda^c_j\big)\frac{3}{m_{q_i}m_{q_j}}\frac{1}{r^3_{ij}}\boldsymbol{L}\cdot(\boldsymbol{\sigma}_i+\boldsymbol{\sigma}_j), \quad (20)$$

and $V^{\rm conf}_{ij}$ is the confinement potential, taken as the quadratic form,

$$V^{\rm conf}_{ij} = -a^c_{ij}\big(\lambda^c_i\cdot\lambda^c_j\big)r^2_{ij} - a^{c0}_{ij}\big(\lambda^c_i\cdot\lambda^c_j\big). \quad (21)$$

$V_{i\bar{5}}$ in Eq. (17) includes two parts: direct interaction and annihilation parts,

$$V_{i\bar{5}} = V^{\rm dir}_{i\bar{5}} + V^{\rm ann}_{i\bar{5}}, \quad (22)$$

with

$$V^{\rm dir}_{i\bar{5}} = V^{\rm conf}_{i\bar{5}} + V^{\rm OGE}_{i\bar{5}} + V^{\rm ch}_{i\bar{5}}, \quad (23)$$

where

$$V^{\rm conf}_{i\bar{5}} = -a^c_{i\bar{5}}\left(-\lambda^c_i\cdot\lambda^{c*}_5\right)r^2_{i\bar{5}} - a^{c0}_{i\bar{5}}\left(-\lambda^c_i\cdot\lambda^{c*}_5\right), \quad (24)$$

$$V^{\rm OGE}_{i\bar{5}} = \frac{1}{4}g_i g_s\big(-\lambda^c_i\cdot\lambda^{c*}_5\big)\left\{\frac{1}{r_{i\bar{5}}} - \frac{\pi}{2}\delta(\boldsymbol{r}_{i\bar{5}})\left[\frac{1}{m^2_{q_i}}+\frac{1}{m^2_s} + \frac{4}{3}\frac{1}{m_{q_i}m_s}(\boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_5)\right]\right\} - \frac{1}{16}g_i g_s\big(-\lambda^c_i\cdot\lambda^{c*}_5\big) \times\frac{3}{m_{q_i}m_{q_5}}\frac{1}{r^3_{i\bar{5}}}\boldsymbol{L}\cdot(\boldsymbol{\sigma}_i+\boldsymbol{\sigma}_5), \quad (25)$$

and

$$V^{\rm ch}_{i\bar{5}} = \sum_j(-1)^{G_j}V^{{\rm ch},j}_{i5}. \quad (26)$$

Here $(-1)^{G_j}$ represents the G parity of the jth meson. For the NK system, $u(d)\bar{s}$ can only annihilate into K and K^* mesons—i.e.,

$$V^{\rm ann}_{i\bar{5}} = V^K_{\rm ann} + V^{K^*}_{\rm ann}, \quad (27)$$

with

$$V^K_{\rm ann} = C^K\left(\frac{1-\boldsymbol{\sigma}_q\cdot\boldsymbol{\sigma}_{\bar{q}}}{2}\right)_s\left(\frac{2+3\lambda_q\cdot\lambda^*_{\bar{q}}}{6}\right)_c \times\left(\frac{38+3\lambda_q\cdot\lambda^*_{\bar{q}}}{18}\right)_f\delta(\boldsymbol{r}), \quad (28)$$

and

$$V^{K^*}_{\rm ann} = C^{K^*}\left(\frac{3+\boldsymbol{\sigma}_q\cdot\boldsymbol{\sigma}_{\bar{q}}}{2}\right)_s\left(\frac{2+3\lambda_q\cdot\lambda^*_{\bar{q}}}{6}\right)_c \times\left(\frac{38+3\lambda_q\cdot\lambda^*_{\bar{q}}}{18}\right)_f\delta(\boldsymbol{r}), \quad (29)$$

where C^K and C^{K^*} are treated as parameters and we adjust them to fit the masses of K and K^* mesons.

TABLE I. Model parameters. Meson masses and the cutoff masses: $m_{a_0} = 980$ MeV, $m_\kappa = 1430$ MeV, $m_{f_0} = 980$ MeV, $m_\pi = 138$ MeV, $m_K = 495$ MeV, $m_\eta = 549$ MeV, $m_{\eta'} = 957$ MeV, $m_\rho = 770$ MeV, $m_{K^*} = 892$ MeV, $m_\omega = 782$ MeV, $m_\phi = 1020$ MeV, $\Lambda = 1500$ MeV for κ and 1100 MeV for other mesons.

	Chiral SU(3) quark model		Extended chiral SU(3) quark model	
	I $\theta^S = 35.264°$	II $\theta^S = -18°$	I $\theta^S = 35.264°$	II $\theta^S = -18°$
b_u (fm)	0.5	0.5	0.45	0.45
m_u (MeV)	313	313	313	313
m_s (MeV)	470	470	470	470
g_u^2	0.7704	0.7704	0.0748	0.0748
g_s^2	0.5525	0.5525	0.0001	0.0001
$g_{\rm ch}$	2.621	2.621	2.621	2.621
$g_{\rm chv}$	0	0	2.351	2.351
m_σ (MeV)	675	675	675	675
a_{uu}^c (MeV/fm^2)	52.9	55.7	56.4	60.3
a_{us}^c (MeV/fm^2)	76.0	72.1	104.1	98.8
a_{uu}^{c0} (MeV)	−51.7	−56.4	−86.4	−91.8
a_{us}^{c0} (MeV)	−68.5	−63.0	−123.1	−116.8

B. Determination of the parameters

The harmonic-oscillator width parameter b_u is taken with different values for the two models: $b_u = 0.50$ fm in the chiral SU(3) quark model and $b_u = 0.45$ fm in the extended chiral SU(3) quark model. This means that the bare radius of baryon becomes smaller when more meson clouds are included in the model, which sounds reasonable in the sense of the physical picture. The up (down) quark mass $m_{u(d)}$ and the strange quark mass m_s are taken to be the usual values: $m_{u(d)} = 313$ MeV and $m_s = 470$ MeV. The coupling constant for scalar and pseudoscalar chiral field coupling, $g_{\rm ch}$, is determined according to the relation

$$\frac{g_{\rm ch}^2}{4\pi} = \left(\frac{3}{5}\right)^2 \frac{g_{NN\pi}^2}{4\pi} \frac{m_u^2}{M_N^2}, \tag{30}$$

with the empirical value $g_{NN\pi}^2/4\pi = 13.67$. Here $g_{\rm chv}$ and $f_{\rm chv}$ are the coupling constants for vector coupling and tensor coupling of the vector meson field, respectively. In the study of nucleon resonance transition coupling to the vector meson, Riska and Brown took $g_{\rm chv} = 3.0$ and neglected the tensor coupling part [21]. From the one-boson exchange theory on the baryon level, we can also obtain these two values according to the SU(3) relation between quark and baryon levels. For example,

$$g_{\rm chv} = g_{NN\rho}, \tag{31}$$

$$f_{\rm chv} = \tfrac{3}{5}(f_{NN\rho} - 4g_{NN\rho}). \tag{32}$$

In the Nijmegen model D, $g_{NN\rho} = 2.09$ and $f_{NN\rho} = 17.12$ [22]. From the two equations above, we get $g_{\rm chv} = 2.09$ and $f_{\rm chv} = 5.26$. In this work, we neglect the tensor coupling part of the vector-meson field, as did by Riska and Brown [21], and take the coupling constant for vector coupling of the vector-meson field to be $g_{\rm chv} = 2.351$, the same as we used in the NN scattering calculation [10], which is a little bit smaller than the value used in Ref. [21], but slightly larger than the value obtained from the $NN\rho$ coupling constant of Nijmegen model D [22]. The masses of all the mesons are taken to be the experimental values, except for the σ meson, whose mass is treated as an adjustable parameter. We chose $m_\sigma = 675$ MeV, the same as in the original chiral SU(3) quark model [11], where it is fixed by the S-wave KN phase shifts. The cutoff radius Λ^{-1} is taken to be the value close to the chiral symmetry breaking scale [23–26]. After the parameters of chiral fields are fixed, the coupling constants of OGE, g_u and g_s, can be determined by the mass splits between N, Δ and Σ, Λ, respectively. The confinement strengths a_{uu}^c, a_{us}^c, and a_{ss}^c are fixed by the stability conditions of N, Λ, and Ξ and the zero-point energies a_{uu}^{c0}, a_{us}^{c0}, and a_{ss}^{c0} by fitting the masses of N, Σ, and $\overline{\Xi + \Omega}$, respectively.

In the calculation, η and η' mesons are mixed by η_1 and η_8, with the mixing angle $\theta^{\rm PS}$ taken to be the usual value $-23°$. ω and ϕ mesons consist of $\sqrt{1/2}(u\bar{u} + d\bar{d})$ and $(s\bar{s})$, respectively, i.e., they are ideally mixed by ω_1 and ω_8 with the mixing angle $\theta^V = 35.264°$. For the KN case, we also consider the mixing between σ_0 and σ_8. The mixing angle θ^S is an open issue because the structure of the σ meson is still unclear and controversial. We adopt two possible values as in our previous work [11,12], one is 35.264°, which means that σ and f_0 [in our previous work f_0 was named ϵ and a_0 was named σ'] are ideally mixed by σ_0 and σ_8, and the other is $-18°$, which is provided by Dai and Wu based on their recent investigation of a dynamically spontaneous symmetry breaking mechanism [27]. In both of these cases, the attraction of the σ meson can be reduced a lot, and thus we can get reasonable S-wave KN phase shifts.

The model parameters are summarized in Table I. The masses of octet and decuplet baryons obtained from the extended chiral SU(3) quark model are listed in Table II.

TABLE II. Masses of octet and decuplet baryons.

	N	Σ	Ξ	Λ	Δ	Σ^*	Ξ^*	Ω
Theor.	939	1194	1335	1116	1232	1370	1511	1684
Expt.	939	1194	1319	1116	1232	1385	1530	1672

C. Dynamical study of the *KN* phase shifts

With all parameters determined in the extended chiral SU(3) quark model, the *KN* phase shifts can be dynamically studied in the frame work of the RGM. The wave function of the five-quark system is of the following form:

$$\Psi = \mathcal{A}[\hat{\phi}_N(\boldsymbol{\xi}_1, \boldsymbol{\xi}_2)\hat{\phi}_K(\boldsymbol{\xi}_3)\chi(\boldsymbol{R}_{NK})], \tag{33}$$

where $\boldsymbol{\xi}_1$ and $\boldsymbol{\xi}_2$ are the internal coordinates for the cluster N, and $\boldsymbol{\xi}_3$ the internal coordinate for the cluster K. $\boldsymbol{R}_{NK} \equiv \boldsymbol{R}_N - \boldsymbol{R}_K$ is the relative coordinate between the two clusters, N and K. The $\hat{\phi}_N$ is the antisymmetrized internal cluster wave function of N, and $\chi(\boldsymbol{R}_{NK})$ the relative wave function of the two clusters. The symbol $\mathcal{A}$ is the antisymmetrizing operator defined as

$$\mathcal{A} \equiv 1 - \sum_{i\in N} P_{i4} \equiv 1 - 3P_{34}. \tag{34}$$

Substituting Ψ into the projection equation

$$\langle \delta\Psi|(H - E)|\Psi\rangle = 0, \tag{35}$$

we obtain the coupled integro-differential equation for the relative function χ,

$$\int [\mathcal{H}(\boldsymbol{R}, \boldsymbol{R}') - E\mathcal{N}(\boldsymbol{R}, \boldsymbol{R}')]\chi(\boldsymbol{R}')d\boldsymbol{R}' = 0, \tag{36}$$

where the Hamiltonian kernel $\mathcal{H}$ and normalization kernel $\mathcal{N}$ can, respectively, be calculated as

$$\left\{ \begin{array}{c} \mathcal{H}(\boldsymbol{R}, \boldsymbol{R}') \\ \mathcal{N}(\boldsymbol{R}, \boldsymbol{R}') \end{array} \right\} = \left\langle [\hat{\phi}_N(\boldsymbol{\xi}_1, \boldsymbol{\xi}_2)\hat{\phi}_K(\boldsymbol{\xi}_3)]\delta(\boldsymbol{R} - \boldsymbol{R}_{NK}) \left| \left\{ \begin{array}{c} H \\ 1 \end{array} \right\} \right| \mathcal{A}[[\hat{\phi}_N(\boldsymbol{\xi}_1, \boldsymbol{\xi}_2)\hat{\phi}_K(\boldsymbol{\xi}_3)]\delta(\boldsymbol{R}' - \boldsymbol{R}_{NK})] \right\rangle. \tag{37}$$

Equation (36) is the so-called coupled-channel RGM equation. Expanding unknown $\chi(\boldsymbol{R}_{NK})$ by employing well-defined basis wave functions, such as Gaussian functions, one can solve the coupled-channel RGM equation for a bound-state problem or a scattering one to obtain the binding energy or scattering phase shifts for the two-cluster systems. The details of solving the RGM equation can be found in Refs. [11,28–30].

III. RESULTS AND DISCUSSION

In the extended chiral SU(3) quark model, the coupling of quarks and vector-meson field is considered, and thus the coupling constants of OGE are greatly reduced by fitting the mass difference between N, Δ and Λ, Σ. From Table I, one can see that for both set I and set II, $g_u^2 = 0.0748$ and $g_s^2 = 0.0001$, which are much smaller than the values of the original chiral SU(3) quark model ($g_u^2 = 0.7704$ and $g_s^2 = 0.5525$). This means that the OGE, which plays an important role of the *KN* short-range interaction in the original chiral SU(3) quark model, is now nearly replaced by the vector-meson exchanges. In other words, in the *KN* system the mechanisms of the quark–quark short-range interactions of these two models are totally different.

A RGM dynamical calculation of the *S*-, *P*-, *D*-, and *F*-wave *KN* phase shifts with isospin $I = 0$ and $I = 1$ is performed, and the numerical results are shown in Figs. 1–4. Here we use the conventional partial-wave notation: the first subscript denotes the isospin quantum number, and the second one twice the total angular momentum of the *KN* system. For comparison, the phase shifts calculated in the original chiral SU(3) quark model are also shown in these figures.

Let us first concentrate on the *S*-wave results (Fig. 1). In a previous quark model study [5] where the π and σ boson exchanges as well as the OGE and confining potential are taken as the quark–quark interaction, the authors concluded that a consistent description of the *S*-wave *KN* phase shifts simultaneously in both isospin $I = 0$ and $I = 1$ channels is not possible. Another recent work in a constituent quark model based on the RGM calculation gave an opposite sign for the S_{01} channel phase shifts [7]. From Fig. 1 one can see that we obtain a successful description of the S_{01} channel phase shifts,

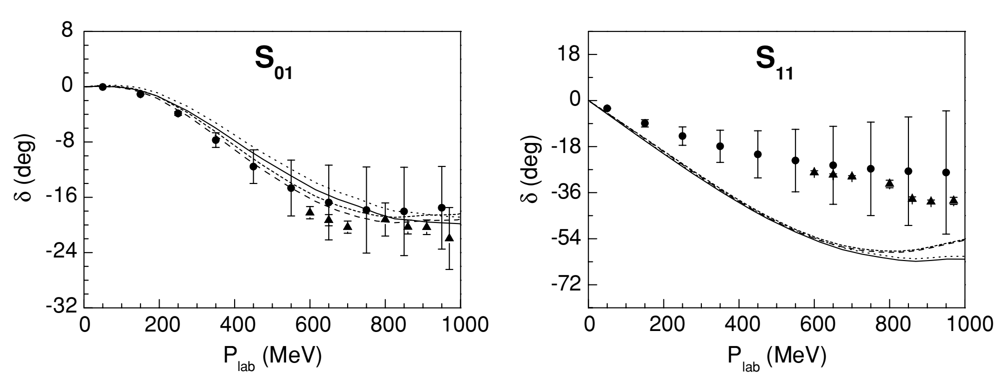

FIG. 1. KN *S*-wave phase shifts as a function of the laboratory momentum of kaon meson. The solid and dotted curves represent the results obtained in the extended chiral SU(3) quark model by considering $\theta^S = 35.264^\circ$ and -18°, respectively. The dashed and short-dashed curves show the phase shifts of the original chiral SU(3) quark model by taking θ^S as 35.264° and -18°, respectively. Experimental phase shifts are taken from Refs. [31] (circles) and [32] (triangles).

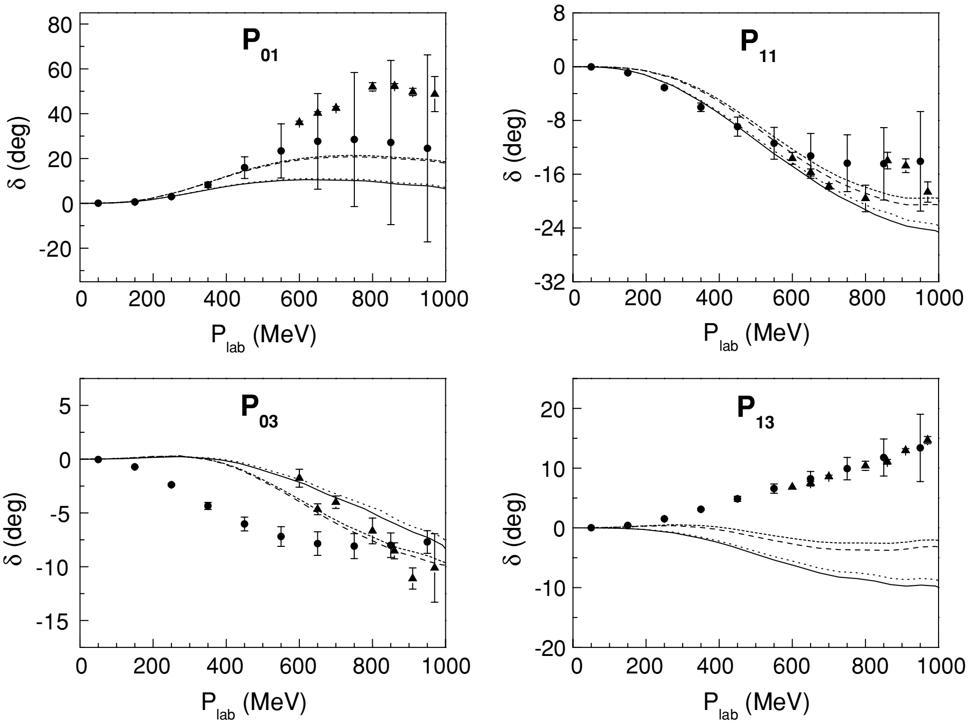

FIG. 2. KN P-wave phase shifts. Same notation as in Fig. 1.

and for the S_{11} partial wave, similar to that obtained in the original chiral SU(3) model, the trend of the theoretical phase shifts is also in agreement with the experiment. Since there is no contribution coming from the spin–orbit coupling in the S-wave, only the central force of the quark–quark interaction can enter the scattering process and thus it plays a dominantly important role. To understand the contributions of various chiral fields to the KN interaction, in Fig. 5 we show the central force diagonal matrix elements of the generator coordinate method (GCM) calculation [28] of the σ, a_0, π, ρ, and ω boson exchanges in the extended chiral SU(3) quark model, which can describe the interaction between two clusters N and K qualitatively. In Fig. 5, s denotes the generator coordinate and $V(s)$ is the effective boson-exchange potential between the two clusters. Form this figure we can see that the σ exchange always offers attraction and ω exchange offers repulsion in

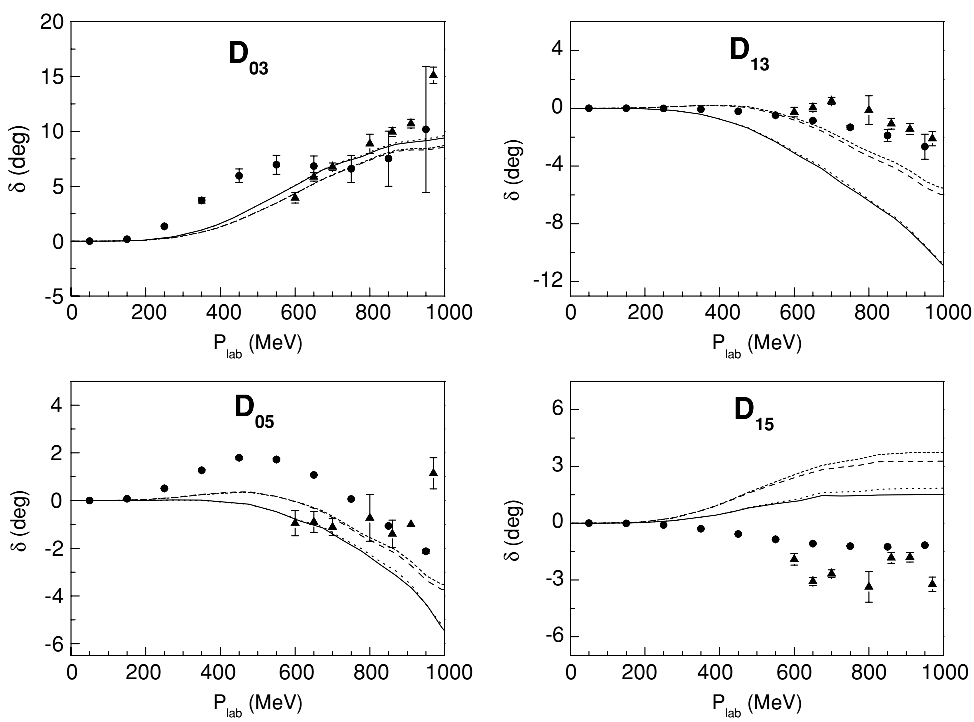

FIG. 3. KN D-wave phase shifts. Same notation as in Fig. 1.

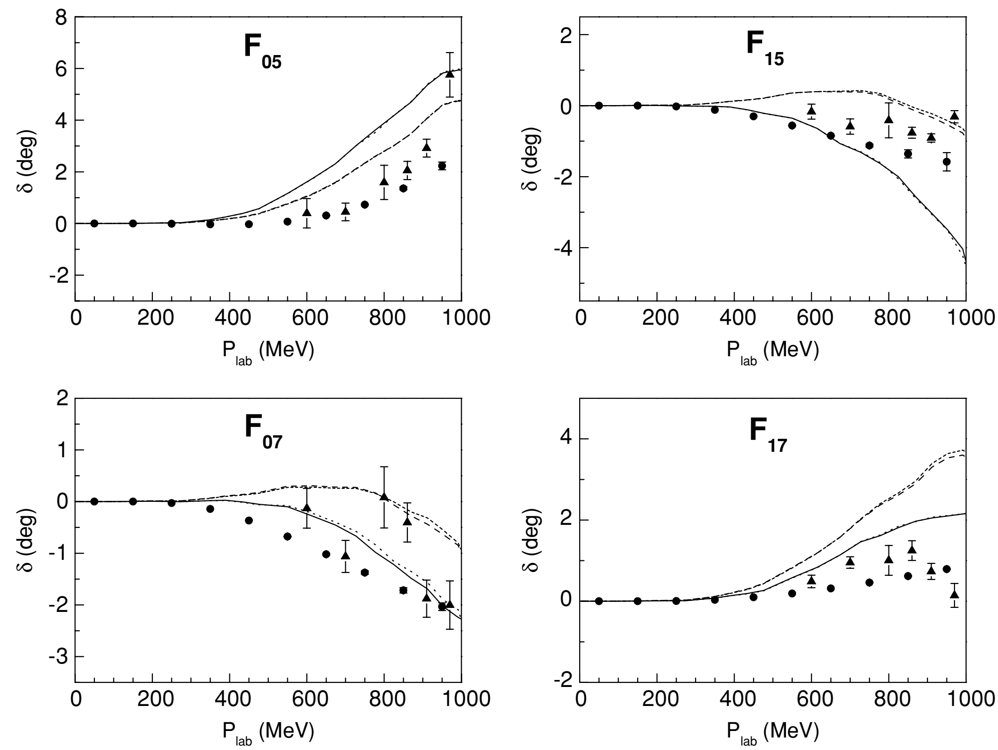

FIG. 4. KN F-wave phase shifts. Same notation as in Fig. 1.

both isospin $I = 0$ and $I = 1$ channels. This is reasonable, since the σ and ω exchanges are isospin independent. In contrast, the a_0, π, and ρ exchanges are isospin dependent. In the S_{01} partial wave the a_0 exchange offers repulsion and the ρ exchange offers a little attraction, while in the S_{11} partial wave the a_0 exchange offers a little attraction and the ρ exchange offers repulsion. In both of these channels the π exchange, existing owing to the quark exchange required by the Pauli principle, always offers much strong repulsion, though the repulsion strength is different. This means that the one-pion exchange is important and cannot be neglected on the quark level, which is quite different from the work on the hadron level, where the one-pion exchange is absent in the KN interaction.

Now look at the P-wave KN phase shifts (Fig. 2). The results for the P_{13} channel, which are too repulsive in the original chiral SU(3) quark model when the laboratory momentum of the kaon meson is greater than 300 MeV, the same as in

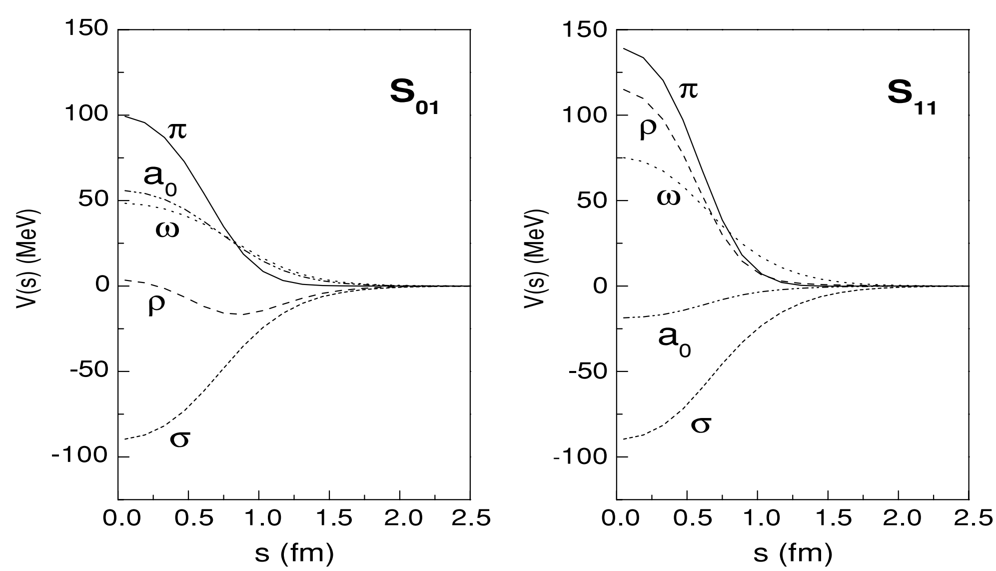

FIG. 5. GCM matrix elements of σ, a_0, π, ρ, and ω exchanges in the extended chiral SU(3) quark model.

Black's previous work [4], are now much more repulsive in the extended chiral SU(3) quark model. For the other channels the results in both of these models are similar. Comparing with Ref. [7], we get correct signs and proper magnitudes of P_{11} and P_{03} waves in both the extended chiral SU(3) quark model and the original chiral SU(3) quark model.

For higher-angular-momentum partial waves (Figs. 3 and 4), the theoretical phase shifts of D_{15} and F_{17} in the extended chiral SU(3) quark model are improved in comparison with those obtained from the original chiral SU(3) quark model, while in the case of the D_{13} the situation is somewhat less satisfying. For the other channels, the trends of the calculated phase shifts in both of these models are all in qualitative agreement with the experiment. Comparing with Ref. [7], in both of these models we can get correct signs of D_{13}, D_{05}, F_{15}, and F_{07} waves, and for D_{03} and D_{15} channels we also obtain a considerable improvement on the theoretical phase shifts in the magnitude.

As discussed in Refs. [11,12], the annihilation interaction is not clear, and its influence on the phase shifts should be examined. We omit the annihilation part entirely to see its effect and find that the numerical phase shifts have only very small changes. This is because in the *KN* system the annihilations to gluons and vacuum are forbidden, and $u(d)\bar{s}$ can only annihilate into a K or K^* meson. This annihilation part originating from the *S*-channel acts in the very short range, so that it plays a negligible role in the *KN* scattering process.

The other thing that we would like to mention is that our results for *KN* phase shifts are independent of the confinement potential in the present one-channel two-color-singlet-cluster calculation. Thus the numerical results will remain almost unchanged even though the color quadratic confinement is replaced by the color linear one.

From the above discussion, one sees that though the mechanisms of the quark–quark short-range interactions are totally different in the original chiral SU(3) quark model and the extended chiral SU(3) quark model, the theoretical *KN* phase shifts of S, P, D, and F waves in these two models are very similar. Comparing with others' previous quark model studies, we can obtain a considerable improvement for many channels. However, in the present work the P_{13} and D_{15} partial waves have not yet been satisfactorily described. In this sense, one can say that the present quark model still has some difficulties in describing the *KN* scattering well enough for all of the partial waves. Future work should explore the possibility of whether there are some physical ingredients missing in our quark model investigations, as well as the relativistic effects and the nonelastic channel effects on the *KN* phase shifts.

By the way, to study the short-range quark–quark interaction more extensively, or in other words, to examine whether the OGE or the vector-meson exchange governs the short-range interaction between quarks, besides the *KN* systems, the $\overline{K}N$ is also an interesting case, since there is a close connection of the vector-meson exchanges between the *KN* and $\overline{K}N$ interactions due to *G*-parity transition. Specially, the repulsive ω exchange changes sign for $\overline{K}N$, because of the negative G parity of the ω meson, and becomes attractive. However, one should note that the treatment of the $\overline{K}N$ channel is more complicated than the *KN* system, since it involves *s*-channel gluon and vacuum contributions. Still, the extension of our chiral quark model to incorporate the gluon and vacuum annihilations in the $\overline{K}N$ system would be a very interesting new development. Investigations along this line are planned for the future.

IV. SUMMARY

In this paper, we extend the chiral SU(3) quark model to include the coupling between quarks and the vector chiral field. The OGE, which dominantly governs the short-range quark–quark interactions in the original chiral SU(3) quark model, is now nearly replaced by the vector-meson exchange. Using this model, a dynamical calculation of the *S*-, *P*-, *D*-, and *F*-wave *KN* phase shifts is performed in the isospin $I = 0$ and $I = 1$ channels by solving a RGM equation. The calculated phase shifts of different partial waves are similar to those given by the original chiral SU(3) quark model. Comparing with Ref. [7], a recent RGM calculation in a constituent quark model, we can obtain correct signs for several partial waves and a considerable improvement in the magnitude for many channels. Nevertheless, in the present work we do not obtain a satisfactory improvement for the P_{13} and D_{15} partial waves, of which the theoretical phase shifts are too repulsive and too attractive, respectively, when the laboratory momentum of the kaon meson is greater than 300 MeV. The effects of the coupling to the inelastic channels and hidden color channels will be considered and the interesting and more complicated $\overline{K}N$ system will be investigated in future work.

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