Quark-quark potential from chiral symmetry

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Based on symmetry consideration, more generalized chiral field terms are proposed to restore the chiral $SU(2)_L \times SU(2)_R$ symmetry of strong interaction. As a result, a modified quark-quark interaction is obtained. Applying this interaction to nucleon-nucleon scattering, the agreement between the theoretical phase shifts of partial waves and experimental data is improved.

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I. INTRODUCTION

As is well known, the investigation of nuclear force is a basic problem in nuclear physics. Since the 1960s, meson exchange theories such as the Paris force [1], Bonn force [2], Nijmegen model [3], etc., have been developed, and the *N-N* scattering data can be well explained. However, it is still not satisfied. Because the baryon is composed of quarks and gluons, explaining both baryon structure and baryon-baryon interactions in terms of a basic theory of strong interaction in the unified way is necessary and significant.

Nowadays, more and more evidence indicates that quantum chromodynamics (QCD) is the underlying theory of the strong interaction. However, due to the complexity of the nonperturbative effect of QCD at the lower energy region, the nonperturbative QCD theory has not been completed so far, and QCD-inspired models are still needed.

The constituent quark model (CQM) has intensively been used to study dynamically the *N-N* interaction over the last ten years. The result showed that not only most hadronic properties can successfully be reproduced [4], but also the short range repulsion of the *N-N* interaction can be explained in terms of the one-gluon-exchange (OGE) interaction and the quark exchange effect [5]. Some problems still remain open. For instance, when only OGE and confinement potentials are considered, not enough medium and long range attractions can be provided to describe the baryon-baryon interaction. Usually, the long range part of the interaction can be introduced by direct couplings between quarks and pions, and the medium range part of interaction can be generated by inserting a σ-like exchange potential between two interacting baryons, where the coupling constant $g_\sigma^2/4\pi$ is treated as an adjustable parameter to fit the experimental data [6]. Obviously this hybrid approach is too phenomenological. Moreover, in this model the constituent quark possesses a constituent mass of the order of a few hundred MeV, which is quite different from the current quark mass. This means that the source of the constituent quark mass can be explained in QCD theory. Furthermore, once the quark carries a constituent mass, chiral symmetry breaks down. Since the chiral symmetry is a very important symmetry required in hadron physics, it should be restored to keep the theory chiral symmetric.

In principle, one expects that both the constituent quark mass m_q^{consti} and quark-quark interaction V_{qq} in which an appropriate medium range attraction is included can be derived from the QCD Lagrangian. Recently, a source of the constituent quark mass was discussed. The σ model [7] was commonly adopted. In that model, the interactions between the quark and chiral fields were considered and m_q^{consti} could be generated from spontaneous vacuum breaking. By using the instanton vacuum model, Fernandez *et al.* studied *N-N* scattering [8]. Their result showed that without adjusting the coupling constant of σ, one could obtain a set of reasonable *N-N* scattering phase shifts except in the case of the $^1S_0$ state, where in the lower energy region the theoretical curve of phase shifts was much lower than the measured data. Comparing with the hybrid approach, the model was greatly improved. However, it seems that some isospin-dependent mechanisms was still missing. It should be pointed out that the method of restoring chiral symmetry is not unique. In this investigation, we employ a more generalized chiral symmetry restoration form where four chiral fields are considered. As a consequence, this extension would bring in some new physics on isospin dependence.

II. MODEL

As mentioned above, in the usual σ model, chiral symmetry can be restored by introducing the couplings between the quark and chirals field, i.e.,

$$\mathscr{L}_I = -g_{\text{ch}}\bar{\psi}(\sigma_0 + i\vec{\tau}\cdot\vec{\pi}\gamma_5)\psi \ ; \tag{1}$$

here, ψ is the quark spinor and g_{ch} is the coupling constant of chiral field. When vacuum is spontaneously broken, the mass of the constituent quark can be generated, while the chiral symmetry of the Lagrangian can still be maintained.

In Eq. (1) the vertices of the σ_0 field, which is both $\vec{\tau}$ and γ_5 independent, and the π field, which is both $\vec{\tau}$ and γ_5 dependent, are considered. In fact, there are four fields which undergo different combinations together with $\vec{\tau}$ and γ_5 to furnish quark–chiral-field coupling vertices, namely, $\bar{\psi}\sigma_0\psi$, $\bar{\psi}i\vec{\tau}\cdot\vec{\pi}\gamma_5\psi$, $\bar{\psi}\vec{\tau}\cdot\vec{\sigma}_1\psi$, and $\bar{\psi}i\eta\gamma_5\psi$. When the coupling between the quark and chiral field is extended to include all these vertices, the interaction Lagrangian $\mathscr{L}_I$ can be written as

$$\mathscr{L}_I = -g_{\rm ch}\bar{\psi}(\sigma_0 + i\vec{\tau}\cdot\vec{\pi}\gamma_5 + \vec{\sigma}_1\cdot\vec{\tau} + i\eta\gamma_5)\psi. \tag{2}$$

Certainly, one should check that whether the chiral symmetry of Eq. (2) can still be held and whether $m_q^{\rm consti}$ and V_{q-q} can simultaneously be given. It is easy to see that $\mathscr{L}_I$ is invariant under the infinitesimal chiral $SU(2)_L \times SU(2)_R$ transformation, because $\mathscr{L}_I$ is invariant under both axial SU(2) transformations

$$\begin{aligned}
\psi &\to \psi' = \left(1 + \frac{i}{2}\vec{\tau}\cdot\vec{\alpha}\gamma_5\right)\psi, \\
\sigma_0 &\to \sigma' = \sigma_0 + \vec{\alpha}\cdot\vec{\pi}, \\
\vec{\pi} &\to \vec{\pi}' = \vec{\pi} - \sigma_0\vec{\alpha}, \\
\eta &\to \eta' = \eta - \vec{\alpha}\cdot\vec{\sigma}_1, \\
\vec{\sigma}_1 &\to \vec{\sigma'}_1 = \vec{\sigma}_1 + \eta\vec{\alpha}
\end{aligned} \tag{3}$$

and SU(2) transformations

$$\begin{aligned}
\psi &\to \psi' = \left(1 + \frac{i}{2}\vec{\tau}\cdot\vec{\beta}\right)\psi, \\
\sigma_0 &\to \sigma_0' = \sigma_0, \\
\vec{\pi} &\to \vec{\pi'} = \vec{\pi} - \vec{\beta}\times\vec{\pi}, \\
\eta &\to \eta' = \eta, \\
\vec{\sigma}_1 &\to \vec{\sigma'}_1 = \vec{\sigma}_1 - \vec{\beta}\times\vec{\sigma}_1 ,
\end{aligned} \tag{4}$$

where $\{\alpha_i\}$ and $\{\beta_i\}$ are two sets of three-dimensional real infinitesimal parameters. In terms of these transformation matrices, it is also easily shown that the transformations for the $(\sigma_0, \vec{\pi})$ and $(\vec{\sigma}_1, \eta)$ sectors are independent.

Now, consider a theory which includes two isotriplet fields $\vec{\pi}$ and $\vec{\sigma}$, two isoscalar fields σ_0 and η, and isodoubet quarks. The Lagrangian can be written as

$$\mathscr{L}(x) = -\bar{\psi}\gamma_\mu\frac{\partial}{\partial x_\mu}\psi - g_{\rm ch1}\bar{\psi}(\sigma_0 + i\vec{\tau}\cdot\vec{\pi}\gamma_5)\psi - g_{\rm ch2}\bar{\psi}(\vec{\sigma}_1\cdot\vec{\tau} + i\eta\gamma_5)\psi - \frac{1}{2}\left(\frac{\partial}{\partial x_\mu}\sigma_0\right)^2 - \frac{1}{2}\left(\frac{\partial}{\partial x_\mu}\vec{\pi}\right)^2 - \frac{1}{2}\left(\frac{\partial}{\partial x_\mu}\vec{\sigma}_1\right)^2$$
$$-\frac{1}{2}\left(\frac{\partial}{\partial x_\mu}\eta\right)^2 - V_1(\sigma_0^2 + \pi^2) - V_2(\sigma_1^2 + \eta^2), \tag{5a}$$

where no coupling between the $(\sigma_0, \vec{\pi})$ and $(\vec{\sigma}_1, \eta)$ sectors exists, and then

$$V_1(\sigma_0^2 + \pi^2) = \frac{\lambda_1^2}{4}(\sigma_0^2 + \pi^2 - \nu_1^2)^2 \tag{5b}$$

and

$$V_2(\sigma_1^2 + \eta^2) = \frac{\lambda_2^2}{4}(\sigma_1^2 + \eta^2 - \nu_2^2)^2. \tag{5c}$$

Similar to the treatment used in the usual σ model, the parameters λ_1 and ν_1 in $V_1(\sigma_0^2 + \pi^2)$ should be taken as

$$\lambda_1^2 > 0, \quad \nu_1^2 > 0. \tag{6}$$

Thus, the minimal value of $V_1(\sigma_0^2 + \pi^2)$, the energy of the σ_0 and $\vec{\pi}$ fields, is no longer located at $\sigma_0 = 0$; instead, the minimal values of $V_1(\sigma_0,\ \pi = 0)$ are positioned at $\sigma_0 = \pm\nu_1$ around which the vacuum is spontaneously broken. By shifting σ_0 in the Lagrangian to a distance of ν_1, $\sigma_0 \to \sigma_0 + \nu_1$, $m_q^{\rm consti}$, m_{σ_0}, and a Goldstone boson $\vec{\pi}$ can be obtained in following forms:

$$m_q^{\rm consti} = g_{\rm ch1}\nu_1, \quad m_{\sigma_0}^2 = 2\lambda_1^2\nu_1^2, \quad m_\pi = 0. \tag{7}$$

On the other hand, the normal vacuum is chosen for the $(\vec{\sigma}_1, \eta)$ sector; namely, the values of the parameters λ_2 and ν_2 in $V_2(\sigma_1^2 + \eta^2)$ are taken to be

$$\lambda_2^2 > 0, \quad \nu_2^2 < 0, \tag{8}$$

and consequently

$$m_{\sigma_1} = m_\eta = (-\lambda_2^2\nu_2^2)^{1/2} \tag{9}$$

TABLE I. Model parameters.

Parameter	Model A	Model B I	Model B II
m_q (MeV)	313	313	313
b (fm)	0.5	0.45	0.4
$g_{\rm ch1}$	2.71	2.71	2.71
$g_{\rm ch2}$		2.71	5.42
m_π (MeV)	138	138	138
m_{σ_0} (MeV)	675	625	625
m_η (MeV)		675	958
m_{σ_1} (MeV)		675	958
Λ_1 (MeV)	829	829	829
Λ_2 (MeV)		829	987
α_s	0.40	0.65	0.66
a_c (MeV/fm^2)	57.96	109.8	205.3

is given. It should be emphasized that by introducing $(\vec{\sigma}_1, \eta)$ fields, additional quark-quark interactions $V^{\sigma_1}_{q-q}$ and V^{η}_{q-q} can be produced, but nothing would be contributed to the constituent quark mass.

Based on the instanton fluctuation of QCD vacuum [8,9], the vertices between quarks and chiral fields in Eq. (5) can be extrapolated by introducing an additional form factor $F(q^2)$. Consequently, the constituent quark mass is changed to the dynamic quark mass, $m_q^{\text{consti}} = g_{\text{ch}1} F(q^2) \nu_1$, and the effective interaction Hamiltonian can be expressed as

$$H_{\text{ch}} = g_{\text{ch}1} F_1(q^2) \bar{\psi}(\sigma_0 + i \vec{\tau} \cdot \vec{\pi} \gamma_5) \psi + g_{\text{ch}2} F_2(q^2) \times \bar{\psi}(\vec{\sigma}_1 \cdot \vec{\tau} + i \eta \gamma_5) \psi. \tag{10}$$

As usual, $F_i(q^2)$ is taken as

$$F_i(q^2) = \left(\frac{\Lambda_i^2}{\Lambda_i^2 + q^2} \right)^{1/2} \quad (i = 1,2), \tag{11}$$

where the cutoff mass Λ_i indicates the chiral-symmetry-breaking scale [10]. Considering that the real pion has a mass of 138 MeV, a chiral-symmetry-breaking term $C\sigma_0$ is included in the Lagrangian so that $m_\pi \neq 0$ can be obtained; namely, the pion field is regarded as a massive field.

From Eq. (10), one obtains four chiral-field-induced quark-quark potentials

$$V^{\pi}_{q\text{-}q}(r_{ij}) = \frac{g^2_{\text{ch}1}}{4\pi} \frac{m_\pi^2}{4m_q^2} \frac{\Lambda_1^2}{\Lambda_1^2 - m_\pi^2} \frac{m_\pi}{3} \left\{ \left[Y(m_\pi r_{ij}) - \frac{\Lambda_1^3}{m_\pi^3} Y(\Lambda_1 r_{ij}) \right] (\vec{\sigma}_i \cdot \vec{\sigma}_j) + \left[H(m_\pi r_{ij}) - \frac{\Lambda_1^3}{m_\pi^3} H(\Lambda_1 r_{ij}) \right] S_{ij} \right\} (\vec{\tau}_i \cdot \vec{\tau}_j), \tag{12a}$$

$$V^{\sigma_0}_{q\text{-}q}(r_{ij}) = -\frac{g^2_{\text{ch}1}}{4\pi} \frac{\Lambda_1^2}{\Lambda_1^2 - m_{\sigma_0}^2} m_{\sigma_0} \left\{ \left[Y(m_{\sigma_0} r_{ij}) - \frac{\Lambda_1}{m_{\sigma_0}} Y(\Lambda r_{ij}) \right] + \frac{m_{\sigma_0}^2}{4m_q^2} \left[G(m_{\sigma_0} r_{ij}) - \frac{\Lambda_1^3}{m_{\sigma_0}^3} G(\Lambda_1 r_{ij}) \right] (\vec{\sigma}_i + \vec{\sigma}_j) \cdot \vec{L} \right\}, \tag{12b}$$

$$V^{\eta}_{q\text{-}q}(r_{ij}) = \frac{g^2_{\text{ch}2}}{4\pi} \frac{m_\eta^2}{4m_q^2} \frac{\Lambda_2^2}{\Lambda_2^2 - m_\eta^2} \frac{m_\eta}{3} \left\{ \left[Y(m_\eta r_{ij}) - \frac{\Lambda_2^3}{m_\eta^3} Y(\Lambda_2 r_{ij}) \right] (\vec{\sigma}_i \cdot \vec{\sigma}_j) + \left[H(m_\eta r_{ij}) - \frac{\Lambda_2^3}{m_\eta^3} H(\Lambda_2 r_{ij}) \right] S_{ij} \right\}, \tag{12c}$$

$$V^{\sigma_1}_{q\text{-}q}(r_{ij}) = -\frac{g^2_{\text{ch}2}}{4\pi} \frac{\Lambda_2^2}{\Lambda_2^2 - m_{\sigma_1}^2} m_{\sigma_1} \left\{ \left[Y(m_{\sigma_1} r_{ij}) - \frac{\Lambda_2}{m_{\sigma_1}} Y(\Lambda_2 r_{ij}) \right] + \frac{m_{\sigma_1}^2}{4m_q^2} \left[G(m_{\sigma_1} r_{ij}) - \frac{\Lambda_2^3}{m_{\sigma_1}^3} G(\Lambda_2 r_{ij}) \right] (\vec{\sigma}_i + \vec{\sigma}_j) \cdot \vec{L} \right\} (\vec{\tau}_i \cdot \vec{\tau}_j), \tag{12d}$$

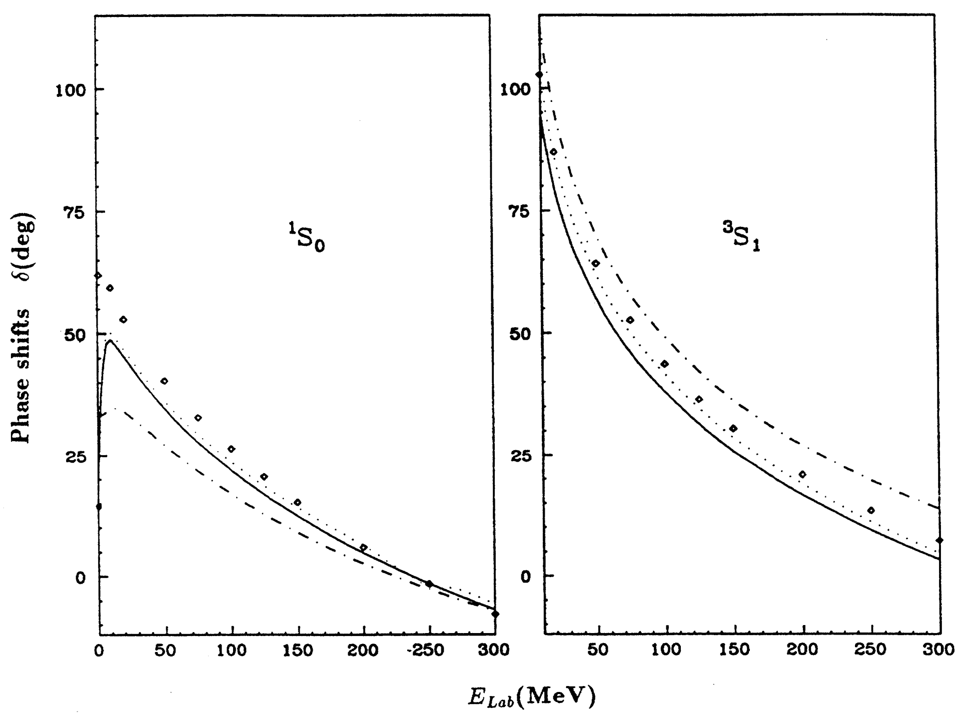

FIG. 1. S-wave phase shifts of N-N scattering. The rhombi represent the experimental data in Ref. [12]. The solid dots denote the experimental data, which are different from the data in Ref. [12] and in Ref. [13]. The dot-dashed, solid, and dotted curves denote the results of model A, model B(I), and model B(II), respectively.

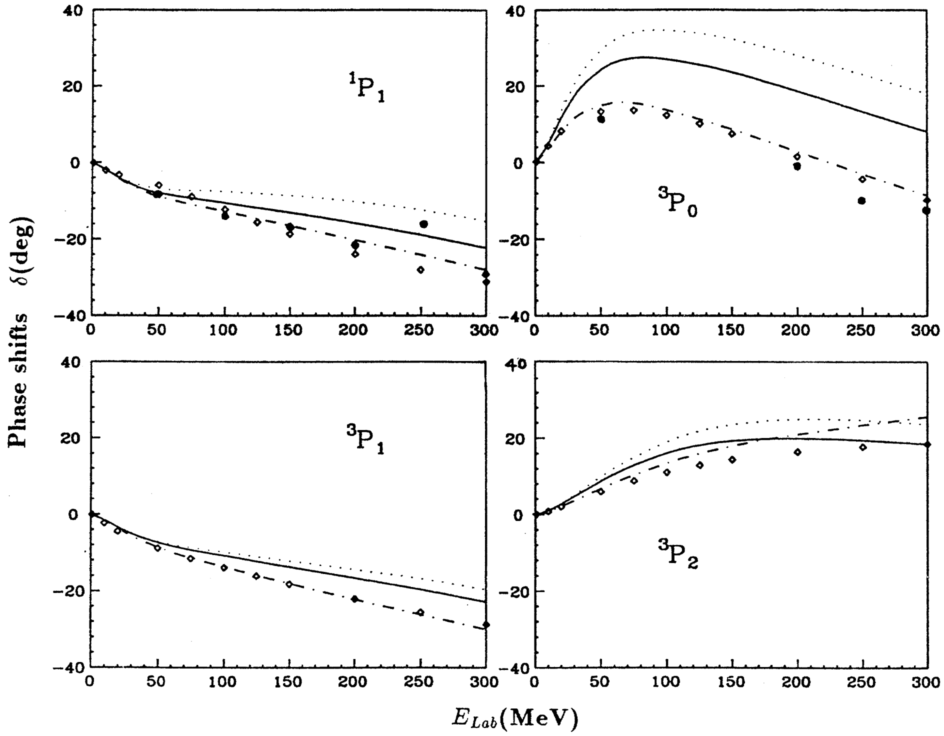

FIG. 2. Same as Fig. 1 for the P wave phase shifts of N-N scattering.

where $Y(x)$, $H(x)$, and $G(x)$ are standard Yukawa-type functions,

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

$$H(x)=\left(1+\frac{3}{x}+\frac{3}{x^2}\right)Y(x), \tag{13b}$$

$$G(x)=\left(\frac{1}{x}+\frac{1}{x^2}\right)Y(x), \tag{13c}$$

and S_{ij} represents the quark tensor operator,

$$S_{ij}=3(\vec{\sigma}_i\cdot\hat{r}_{ij})(\vec{\sigma}_j\cdot\hat{r}_{ij})-(\vec{\sigma}_i\cdot\vec{\sigma}_j). \tag{14}$$

To study the baryon structure and N-N scattering, along with the interactions from the couplings of chiral fields, one should employ an effective one-gluon-exchange interaction $V_{ij}^{\rm OGE}$ to furnish short distance behavior and a confinement potential $V_{ij}^{\rm conf}$ to confine three quarks in a cluster. Then, the total Hamiltonian of our model can be written as

$$H=\sum_i T_i - T_G + \sum_{i<j} V_{ij}, \tag{15a}$$

with

$$V_{ij}=V_{ij}^{\rm OGE}+V_{ij}^{\rm conf}+V_{ij}^{\rm ch}, \tag{15b}$$

$$V_{ij}^{\rm OGE}=\tfrac{1}{4}\alpha_s(\lambda_i\lambda_j)\left\{\frac{1}{r_{ij}}-\frac{\pi}{m_q^2}\delta(\vec{r}_{ij})[1+\tfrac{2}{3}(\vec{\sigma}_i\cdot\vec{\sigma}_j)] - \frac{1}{4m_q^2r_{ij}^3}S_{ij}-\frac{3}{4m_q^2r_{ij}^3}(\vec{\sigma}_i+\vec{\sigma}_j)\cdot\vec{L}\right\}, \tag{16a}$$

$$V_{ij}^{\rm conf}=-a_c(\lambda_i\lambda_j)r_{ij}^2, \tag{16b}$$

and

$$V_{ij}^{\rm ch}=V_{q\text{-}q}^{\pi}(r_{ij})+V_{q\text{-}q}^{\eta}(r_{ij})+V_{q\text{-}q}^{\sigma_0}(r_{ij})+V_{q\text{-}q}^{\sigma_1}(r_{ij}). \tag{16c}$$

By fitting the mass difference between Δ and N and satisfying the nucleon stability condition, one determines the coupling constant of one gluon exchange, α_s, and the strength of confinement potential, a_c. By further solving the resonating group method (RGM) equation [5], one can study chiral interaction effects on the N-N scattering.

III. RESULTS OF N-N SCATTERING

The model parameters in our calculation are given in Table I. There are three sets of parameters for different cases, respectively. In model A, used by Fernandez *et al.*, [8] only two chiral fields $\vec{\pi}$ and σ_0 were considered. For comparison, the parameters and results of this model are also presented in the relevant places in this paper. In model B, proposed by us, four chiral fields $\vec{\pi}$, σ_0, $\vec{\sigma}_1$, and η are included. In this model, as usual, $g_{\rm ch1}$ is fixed by

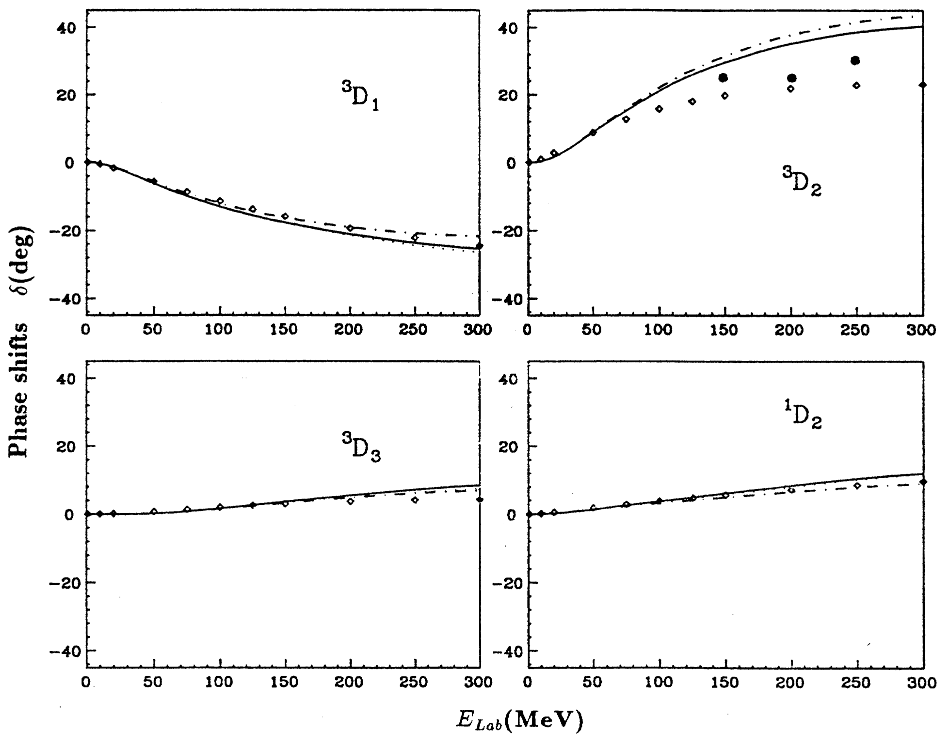

FIG. 3. Same as Fig. 1 for the D wave phase shifts of N-N scattering.

$$\frac{g_{\mathrm{ch1}}^2}{4\pi}=\left(\frac{3}{5}\right)^2\frac{g_{NN\pi}^2}{4\pi}\frac{m_q^2}{M_N^2}, \tag{17}$$

where $g_{NN\pi}^2/4\pi$ is taken to be the experimental value of 14.8. m_π is chosen to be the mass of the real pion; m_σ can be determined according to the following relation [11]:

$$m_{\sigma_0}^2 \simeq (2m_q)^2+m_\pi^2, \tag{18}$$

and $m_{\sigma_1}=m_\eta$ is required by the model. For minimizing the number of parameters, we take

$$g_{\mathrm{ch2}}=g_{\mathrm{ch1}}, \quad \Lambda_2=\Lambda_1. \tag{19}$$

In this case, named model B(I), we find that when $m_{\sigma_1}(=m_\eta)$ is chosen around a value of $2m_q$, the resultant N-N scattering phase shifts can be improved. We also consider another situation, named model B(II). In this case, one takes a value which is close to the mass of the real η' meson for m_η, i.e., $m_{\sigma_1}=m_\eta=958$ MeV, chooses a larger cut mass Λ_2 for the $\vec{\sigma}_1$ and η fields, and readjusts the coupling constant g_{ch2}. Once the values of m_q, b, m_π, m_{σ_0}, m_{σ_1}, $m_\eta(=m_{\sigma_1})$, g_{ch1}, g_{ch2}, and Λ_1,Λ_2 are fixed, the one-gluon-exchange coupling constant α_s and the strength of confinement potential a_c can be determined in the same way mentioned at the end of Sec. II.

The calculated phase shifts for different partial waves are plotted in Figs. 1–4, where small squares represent the experimental data [12,13], and the dot-dashed, solid, and dotted curves denote the calculated results in model A, model B(I), and model B(II), respectively. From these figures, one easily sees that both models B(I) and B(II) can improve theoretical $^1S_0$ phase shifts, and give higher partial wave (P,D,F,G waves) phase shifts in a similar degree as model A's.

Let us discuss the result.

(1) As mentioned above, when only the $\vec{\pi}$ and σ_0 chiral fields are considered (model A), the curve of $^1S_0$ phase shifts is too low in comparison with the experimental data. However, this curve can be moved upward by including two more chiral fields $\vec{\sigma}_1$ and η. Although in our model (model B) m_{σ_1} is still a parameter, due to the inclusion of $V_{q-q}^{\sigma_1}$ and V_{q-q}^{η}, the isospin dependence is improved. It should bementioned that very small underestimations of our $^3S_1$ and $^1S_0$ phase shift curves can be compensated by further considering the contribution from the $\Delta\Delta$ channel. Of course, the coupling of $(N\Delta)^5D_0$ channel also has an influence on $^1S_0$ phase shifts. The coupled channels effect in the framework of this model will be studied in the next step. (2) From the chiral symmetry requirement, both fields $\vec{\pi}$ and σ_0 and fields $\vec{\sigma}_1$ and η are related, respectively. The coupling constant of the σ_0 field is no longer an adjustable parameter. In this sense, this model is more QCD inspired, and can reduce the number of parameters. (3) The spin-orbit force is still an open problem. To fit $^3P_2$ phase shifts, the strength of the spin-orbit interaction of V^{OGE} was multiplied by a factor of 8 in the calculation of Fernandez *et al.* (model A) [8]. In our case, the additional spin-orbit coupling terms from $V_{q-q}^{\sigma_0}$ and $V_{q-q}^{\sigma_1}$ [see Eqs. (12b) and (12d)] are introduced. As a result, the factor of 8 can be reduced to 3.5. This means that the spin-orbit interactions of the σ_0 and $\vec{\sigma}_1$ chiral fields can partly improve the results, but it is still not strong enough to solve the whole problem. There must be some other mechanisms in explaining the spin-orbit coupling. (4) Because of

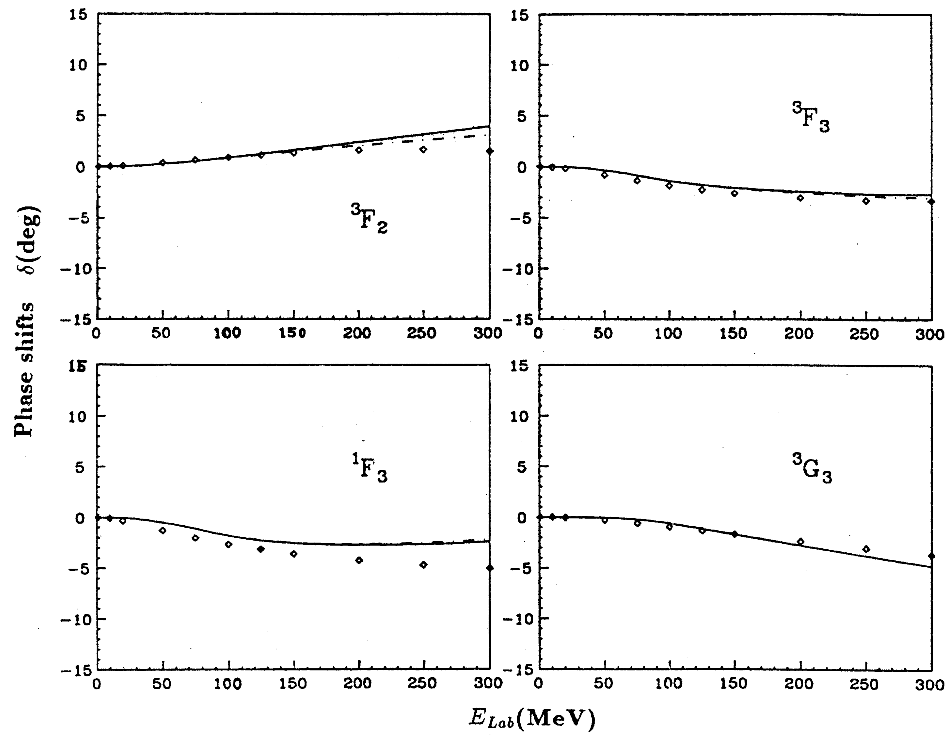

FIG. 4. Same as Fig. 1 for the F and G wave phase shifts of N-N scattering.

the complexity of nonperturbative QCD, one still cannot theoretically derive the parameters involved in chiral fields. Thus, one takes m_π as the mass of the real pion and g_{ch1} related to $g_{NN\pi}$. In this paper, we also use these values, which are not from the basic theory. Moreover, we treat m_{σ_1} and g_{ch2} as adjustable parameters, and choose two sets of m_{σ_1} and g_{ch2} to study the influence of the chiral fields $\vec{\sigma}_1$ and η. The resultant phase shifts indicate that although this treatment is still a phenomenological approach, modifying the model to include the σ_1 and η chiral fields, which can offer the correct isospin dependence in the study of the N-N interaction, is significant.

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