N-N Interactions in the Extended Chiral SU(3) Quark Model

L. R. Dai
Department of Physics, Liaoning Normal University, 116029, Dalian, P. R. China
Z. Y. Zhang, Y. W. Yu, and P. Wang
Institute of High Energy Physics, 100039, Beijing, P. R. China

Abstract

The chiral SU(3) quark model is extended to include coupling between vector chiral field and quarks. By using this model, the phase shifts of NN scattering for different partial waves are studied. The results are very similar to those of the chiral SU(3) quark model calculation, in which one gluon exchange (OGE) plays dominate role in the short range part of the quark-quark interactions. Only in the $^{1}S_{0}$ case, the one channel phase shifts of the extended chiral SU(3) quark model are obviously improved.

Key words: NN interaction, Quark Model, Chiral Symmetry.

1 Introduction

As is well known, in the light quark system the non-perturbative Quantum Chromodynamics (QCD) effect is important and not negligible. An effective approach to describe such effect can be made by introducing the coupling between the chiral fields and quarks, especially in studying the nucleon-nucleon (N-N) interactions. A chiral SU(3) quark model [1, 2] was proposed by generalizing the idea of the SU(2) $\sigma$ model to the flavor SU(3) case. In the original chiral SU(3) quark model, the nonet pseudo-scalar meson exchanges and the nonet scalar meson exchanges are considered in describing the medium and long range parts of the interactions, and the one gluon exchange (OGE) potential is still retained to contribute the short range repulsion. By using this model, the energies of the baryon ground states, the N-N scattering phase shifts and the hyperon-nucleon (Y-N) cross sections can be reproduced reasonably. It seems that the repulsive core of the N-N interaction can be explained by the OGE and the quark exchange effect.

Since last few years, Shen et al [3], Riska and Glozman [4, 5] applied the quark-chiral field coupling model to study the baryon structure. They found that the chiral field coupling is also important in explaining the structure of baryons. Especially, the $\pi$ field coupling leads to increase the weight of D

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wave components in $N$ and $\Delta$, and improve the mass of the Roper resonance. In the work of Riska et al [4, 5], the vector meson coupling was also included to replace OGE. They pointed out the spin-flavor interaction is important in explaining the energy of the Roper resonance and got a comparatively good fit to the baryon spectra. Despite the fact that this model can not explain the decay properties of the baryon excited states in the framework of three valance quark model space, it is still a big challenge to the Isgur’s model [6], in which the OGE governs the baryon structure.

On the other hand, in the study of baryon-baryon (B-B) interactions on quark level, the short range repulsive feature of N-N interaction can be explained by OGE interaction and quark exchange effect [7, 8], but in the traditional one boson exchange (OBE) model on baryon level [9] the N-N short range repulsion comes from vector meson ($\rho, \omega, K^*$ and $\phi$) exchanges. Some authors [10, 11] also studied short-range NN repulsion as stemming from the Goldstone boson (and rho-like) exchanges on the quark level. It has been shown that these interactions can substitute traditional OGE mechanism. But whether OGE or vector meson exchange is the right mechanism for describing the short range part of the strong interactions, or both of them are important, is still a challenging problem. To study this interesting problem, we extend our chiral $SU(3)$ quark model [2] to involve vector meson exchanges. As we did before in the chiral $SU(3)$ quark model, first we fit the masses of baryon ground states, then the N-N phase shifts are calculated by solving a Resonating Group Method (RGM) equation to see the effect of vector meson exchanges. The results show that the $^1S_0$ phase shifts of one channel calculation are obviously improved in the extended chiral $SU(3)$ quark model.

The paper is arranged as follows. The theoretical framework of the extended chiral $SU(3)$ quark model is introduced in section 2. The N-N phase shifts of $S$, $P$, $D$, and $F$ partial waves are shown and discussed in section 3. Finally a conclusion is made in section 4.

## 2 Theoretical framework of the extended chiral $SU(3)$ quark model

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

$$L_i^v = -ig_{chv} \bar{\psi} \gamma_\mu \vec{\varphi}_\mu \cdot \vec{\tau} \psi - \frac{f_{chv}}{2M_p} \bar{\psi} \sigma_{\mu\nu} \partial_\nu \vec{\varphi}_\mu \cdot \vec{\tau} \psi. \tag{1}$$

Thus the Hamiltonian of the system can be written as

$$H = \sum_i T_i - T_G + \sum_{i<j} V_{ij}, \tag{2}$$

and

$$V_{ij} = V_{ij}^{conf} + V_{ij}^{OGE} + V_{ij}^{ch}, \tag{3}$$
where \( \sum T_i - T_G \) is the kinetic energy of the system, and \( V_{ij} \) includes all the interactions between two quarks, \( V_{ij}^{conf} \) is the confinement potential taken as the quadratic form,

\[
V_{ij}^{conf} = -a_{ij}^c(\lambda_i^c \cdot \lambda_j^c) r_{ij}^2 - a_{ij}^s(\lambda_i^c \cdot \lambda_j^s),
\]  

and \( V_{ij}^{OGE} \) is the one gluon exchange (OGE) interaction,

\[
V_{ij}^{OGE} = \frac{1}{4} g_i g_j (\lambda_i^c \cdot \lambda_j^c) \left\{ \frac{1}{r_{ij}} - \frac{\pi}{2} \delta(r_{ij}) \left( \frac{1}{m_{q_i}^2} + \frac{1}{m_{q_j}^2} \right) + \frac{4}{3} \frac{1}{m_{q_i} m_{q_j}} (\vec{\sigma}_i \cdot \vec{\sigma}_j) - \frac{1}{4 m_{q_i} m_{q_j} r_{ij}^2} S_{ij} \right\} + V_{ij}^{\vec{r}_{OE}}
\]

with

\[
V_{ij}^{\vec{r}_{OE}} = -\frac{1}{16} g_i g_j (\lambda_i^c \cdot \lambda_j^c) \frac{3}{m_{q_i} m_{q_j} r_{ij}^3} \vec{L} \cdot (\vec{\sigma}_i + \vec{\sigma}_j).
\]  

\( V_{ij}^{ch} \) represents the interactions from chiral field couplings. In the extended chiral \( SU(3) \) quark model \( V_{ij}^{ch} \) includes scalar meson exchange \( V_{ij}^{s} \), pseudo-scalar meson exchange \( V_{ij}^{ps} \), and vector meson exchange \( V_{ij}^{v} \) potentials,

\[
V_{ij}^{ch} = \sum_{a=0}^{8} V_{sa}(\vec{r}_{ij}) + \sum_{a=0}^{8} V_{psa}(\vec{r}_{ij}) + \sum_{a=0}^{8} V_{va}(\vec{r}_{ij}).
\]  

Their expressions are

\[
V_{sa}(\vec{r}_{ij}) = -C(g_{ch}, m_{sa}, \Lambda_c) X_1(m_{sa}, \Lambda_c, r_{ij})(\lambda_a(i) \lambda_a(j)) + V_{sa}^{\vec{r}_{OE}}(\vec{r}_{ij}),
\]

\[
V_{psa}(\vec{r}_{ij}) = C(g_{ch}, m_{psa}, \Lambda_c) \frac{m_{psa}^2}{12 m_{q_i} m_{q_j}} \left\{ X_2(m_{psa}, \Lambda_c, r_{ij})(\vec{\sigma}_i \cdot \vec{\sigma}_j) + \left( H(m_{psa} r_{ij}) - \left( \frac{\Lambda_c}{m_{psa}} \right)^3 H(\Lambda_c r_{ij}) \right) S_{ij} \right\}(\lambda_a(i) \lambda_a(j)),
\]

\[
V_{va}(\vec{r}_{ij}) = C(g_{chv}, m_{va}, \Lambda_c) X_1(m_{va}, \Lambda_c, r_{ij})(\lambda_a(i) \lambda_a(j)) + C(g_{chv}, m_{va}, \Lambda_c) \frac{m_{va}^2}{6 m_{q_i} m_{q_j}} \left( 1 + \frac{f_{chv} m_{q_i} + m_{q_j}}{g_{chv} M_p} + \frac{f_{chv}^2 m_{q_i} m_{q_j}}{g_{chv}^2 M_p^2} \right) \times \left\{ X_2(m_{va}, \Lambda_c, r_{ij})(\vec{\sigma}_i \cdot \vec{\sigma}_j) - \frac{1}{2} \left( H(m_{va} r_{ij}) - \left( \frac{\Lambda_c}{m_{va}} \right)^3 H(\Lambda_c r_{ij}) \right) S_{ij} \right\}(\lambda_a(i) \lambda_a(j)) + V_{va}^{\vec{r}_{OE}}(\vec{r}_{ij})
\]

with

\[
V_{sa}^{\vec{r}_{OE}}(\vec{r}_{ij}) = -C(g_{ch}, m_{sa}, \Lambda_c) \frac{m_{sa}^2}{4 m_{q_i} m_{q_j}} \left\{ G(m_{sa} r_{ij}) - \left( \frac{\Lambda_c}{m_{sa}} \right)^3 \left( G(\Lambda_c r_{ij}) \right) \right\}(\vec{L} \cdot (\vec{\sigma}_i + \vec{\sigma}_j))(\lambda_a(i) \lambda_a(j)),
\]

\( 3 \)
and

\[
V_{\nu_a}^{\tilde{\sigma} \tilde{\sigma}'}(r_{ij}) = -C(g_{\text{ch}v}, m_{\nu_a}, \Lambda_c) \frac{3m_{\nu_a}^2}{4m_q m_{\nu_j}} (1 + \frac{f_{\text{ch}v} 2(m_q + m_{\nu_j})}{g_{\text{ch}v} 3M_p}) \times \{ G(m_{\nu_a} r_{ij}) - (\frac{\Lambda}{m_{\nu_a}})^3 G(\Lambda_c r_{ij}) \} \hat{L} \cdot (\hat{\sigma}_i + \hat{\sigma}_j)) (\lambda_a(i) \lambda_a(j)),
\]

where

\[
C(g, m, \Lambda) = \frac{g^2 \Lambda^2 m}{4 \pi \Lambda^2 - m^2},
\]
\[
X_1(m, \Lambda, r) = Y(m r) - \frac{\Lambda}{m} Y(\Lambda r),
\]
\[
X_2(m, \Lambda, r) = Y(m r) - (\frac{\Lambda}{m})^3 Y(\Lambda r),
\]
\[
Y(x) = \frac{1}{x} e^{-x},
\]
\[
H(x) = (1 + \frac{3}{x^2} + \frac{3}{x^2}) Y(x),
\]
\[
G(x) = \frac{1}{x} (1 + \frac{1}{x}) Y(x),
\]

\[
\hat{S}_{ij} = 3(\hat{\sigma}_i \cdot \hat{r})(\hat{\sigma}_j \cdot \hat{r}) - (\hat{\sigma}_i \cdot \hat{\sigma}_j),
\]

and \(M_p\) is a mass scale, taken as proton mass.

In the calculation, \(\eta\) and \(\eta'\) mesons are mixed by \(\eta_1\) and \(\eta_8\), the mixing angle \(\theta_\eta\) is taken to be the usual value with \(\theta_\eta = -23^\circ\). \(\omega\) and \(\phi\) mesons consist of \(\sqrt{\frac{1}{2}} (u\bar{u} + d\bar{d})\) and \((s\bar{s})\) respectively, i.e. they are mixed by \(\omega_1\) and \(\omega_8\), with the mixing angle \(\theta_\omega = -54.7^\circ\).

The coupling constant for scalar and pseudo-scalar chiral field coupling, \(g_{\text{ch}v}\), is determined according to the relation

\[
g_{\text{ch}v}^2 = \frac{9}{25} \frac{m^2}{M_N^2} \frac{g_{NN\pi}^2}{4\pi},
\]

where \(g_{NN\pi}^2/4\pi = 13.67\) is taken from the experimental value. \(g_{\text{ch}v}\) and \(f_{\text{ch}v}\) 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 vector meson, Riska et al \[13\] took \(g_{\text{ch}v} = 3.0\) and neglected the tensor coupling part. From the one boson exchange theory on baryon level, we can also obtain these two values according to the \(SU(3)\) relation between quark and baryon levels. For example,

\[
g_{\text{ch}v} = g_{NN\rho},
\]
\[
f_{\text{ch}v} = \frac{3}{5}(f_{NN\rho} - 4g_{NN\rho}).
\]

In the Nijmegen model D, \(g_{NN\rho} = 2.09\) and \(f_{NN\rho} = 17.12\). From Eqs. (20) and (21), we get \(g_{\text{ch}v} = 2.09\) and \(f_{\text{ch}v} = 5.26\). Such information is useful for adjusting the coupling constants of vector meson exchanges on quark level. All meson masses, \(m_{ps}, m_s\), and \(m_{\nu}\), are taken to be the experimental values, except the mass of \(\sigma\) meson, \(m_\sigma\). According to the dynamical vacuum spontaneous breaking mechanism, its value should satisfy \[14\]

\[
m^2_\sigma = (2m_u)^2 + m^2_\pi.
\]
This means that it can be regarded as almost reasonable when the value of \( m_\sigma \) is located in the range of around 550 \( \sim \) 650 MeV. In our calculation, we treat it as an adjustable parameter by fitting the binding energy of deuteron and in most other cases within this reasonable range. The cut-off mass, \( \Lambda \), indicating the chiral symmetry breaking scale [15, 16] is taken to be \( \Lambda^{-1} = 0.18 \text{fm} \). Once the parameters of chiral field are fixed, the coupling constant of OGE \( g_u(\alpha_s = g_u^2, g_s) \), and the strength of confinement potential \( a_{uu}, a_{us}, a_{ss} \) can be determined by fitting the baryon masses and by their stability conditions. All the parameters used are listed in Table 1. Here we should mention that there are only one coupling constant for vector coupling of vector meson \( g_{chv} \) and one for tensor coupling \( f_{chv} \) in our model. The number of adjustable parameters are largely reduced in comparison to the one boson exchange theory on baryon level, in which different coupling constants were adopted for \( \rho, K^*, \omega, \) and \( \phi \) exchanges.

Equipped with the extended chiral \( SU(3) \) quark model with all the parameters determined, two baryon systems on dynamical quark level will be studied by solving the RGM equation with the Hamiltonian given by Eqs.(2)-(19).

In the RGM calculation, the trial wave function is taken to be

\[
\Psi_{ST} = \sum_i c_i \Psi_{ST}^{(i)}(s_i) \tag{24}
\]

with

\[
\Psi_{ST}^{(i)}(s_i) = A(\phi_A(\xi_1, \xi_2)S_{iA}T_A\phi_B(\xi_4, \xi_5)S_{iB}T_B\chi(\vec{R}_{AB} - \hat{s}_i)R_{CM}(\vec{R}_{CM}))_{ST}, \tag{25}
\]

where \( A \) and \( B \) describe two clusters, and \( \phi, \chi, \) and \( R \) represent internal, relative, and center of mass motion wave functions, respectively, \( s_i \) is the generator coordinate, and \( A \) is the anti-symmetrization operator

\[
A = 1 - \sum_{i \in A, j \in B} P_{ij}, \tag{26}
\]

where \( P_{ij} \) is the permutation operator of the \( i \)-th and \( j \)-th quarks. The partial wave phase shifts of \( N-N \) scattering are studied, and the results will be shown in the next section.

3 Results of N-N phase shifts and discussions

We calculated the N-N phase shifts of different partial \( S,P,D,F, \) and \( G \) waves using the extended chiral \( SU(3) \) quark model. The results of the phase shifts are shown in Figs.1 - 4. The corresponding deuteron binding energies \( B_{deu} \) are listed in Table 1. For comparison with results from different models, the results of chiral \( SU(3) \) quark model without vector meson exchanges [2] are drawn with short-dashed curves, while long dashed and solid curves are those obtained from the extended chiral \( SU(3) \) quark model with two different sets of parameters. In the case of set I, the tensor coupling of the vector meson exchanges is not considered, namely \( f_{chv} = 0 \), while the tensor coupling of vector meson exchanges is included in the case of set II, where \( f_{chv} = 2/3 \). As mentioned before, we adjust the mass of \( \sigma \) meson \( m_\sigma \) to fit the binding energy of deuteron. From Table 1, one can see
Table 1: Model parameters and the corresponding binding energies of deuteron. The meson masses and the cut-off mass $\Lambda$ are $m_\pi = 138\text{MeV}, m_K = 495\text{MeV}, m_\eta = 548\text{MeV}, m_{\eta'} = 958\text{MeV}, m_\sigma = m_\kappa = m_\epsilon = 980\text{MeV}, m_\rho = 770\text{MeV}, m_{K^*} = 892\text{MeV}, m_\omega = 782\text{MeV}, m_\phi = 1020\text{MeV}$ and $\Lambda = 1100\text{MeV}$.

|                          | chiral SU(3) quark model | extended chiral SU(3) quark model |
|--------------------------|--------------------------|----------------------------------|
|                          | set I                    | set II                           |
| $b_u (fm)$               | 0.5                      | 0.45                             | 0.45                             |
| $g_{nn\pi}$              | 13.67                    | 13.67                            | 13.67                            |
| $g_{ch}$                 | 2.621                    | 2.621                            | 2.621                            |
| $g_{chv}$                | 0                        | 2.351                            | 1.972                            |
| $f_{chv}/g_{chv}$        | 0                        | 0                                | 2/3                              |
| $m_\sigma (\text{MeV})$  | 595                      | 535                              | 547                              |
| $g_u$                    | 0.886                    | 0.293                            | 0.399                            |
| $\alpha_s (g_u^2)$       | 0.785                    | 0.086                            | 0.159                            |
| $a_{uu}(\text{MeV}/fm^2)$| 48.1                     | 48.0                             | 42.9                             |
| $B_{\text{deu}} (\text{MeV})$ | 2.13                     | 2.19                             | 2.14                             |

that $m_\sigma$ is almost located in the reasonable range $550 \sim 650 \text{ MeV}$ for all these three cases when the binding energy of deuteron $B_{\text{deu}}$ is fitted.

From Table 1 and Figs.1-4, some interesting results are shown: (1) The one channel calculation of $^1S_0$ phase shifts is improved in the extended chiral SU(3) quark model in comparison to that obtained from chiral SU(3) quark model, especially in the case of set II, in which the tensor coupling of the vector meson exchange is considered though $f_{chv}/g_{chv} = 2/3$ is not so large as that in the Nijmegen model D. Originally in the chiral SU(3) quark model, we need to consider $(NN)_{LSJ=000}$ and $(N\Delta)_{LSJ=220}$ channel coupling to get reasonable $^1S_0$ phase shifts [2]. In that case, since the non-diagonal matrix elements between these two channels offered by pion tensor interactions are quite large, the coupling effect becomes very important. In this work, we also performed coupled channel calculation for $^1S_0$ state. The results are shown in Figs. 5a-5c, in which dashed curve represents the one channel calculation results, and solid curves are those with $(NN)_{LSJ=000}$ and $(N\Delta)_{LSJ=220}$ channel coupling. Fig.5a is the result of the chiral SU(3) quark model. It shows that the coupled channel effect is quite important in the chiral SU(3) quark model[2]. Figs. 5b and 5c are results of the extended chiral SU(3) quark model with parameters of set I and set II. In the extended chiral SU(3) quark model, since the tensor parts of vector mesons ($\rho$ and $\omega$) have opposite sign to that of pion in the $T = 1$ case, the non-diagonal matrix elements between $(NN)_{LSJ=000}$ and $(N\Delta)_{LSJ=220}$ channels can be reduced due to the vector meson contribution, so that the coupled channel effect becomes smaller. But for all these three cases, the $^1S_0$ phase shifts of the coupled channel calculation are a little bit higher than the corresponding experimental values. (2) The $^3S_1$ phase shifts of different models are almost the same, and all of them are in good agreement with experimental data. To get
the right trend of the phase shift versus scattering energy, the size parameter $b_u$ is taken with different values for these 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. This physical picture looks reasonable. (3) When the vector meson field coupling is considered, the coupling constant of OGE is greatly reduced by fitting the mass difference between $\Delta$ and $N$. For both set I and II, $g_{\alpha}^2(\alpha_s) < 0.2$, which is much smaller than the value (0.785) of chiral $SU(3)$ quark model (see Table 1). It means that the OGE interaction is rather weak in the extended chiral $SU(3)$ quark model. Instead, the vector meson exchanges play an important role for the short range interaction between two quarks. Hence, mechanisms of the quark-quark short range interactions of these two models are totally different. In the chiral $SU(3)$ quark model, the short range interaction is dominantly from OGE, and in the extended chiral $SU(3)$ quark model, it is from combined effect of ps- and vector meson exchanges. (4) To see the contributions from different meson exchanges in the N-N interactions in our extended chiral $SU(3)$ quark model, we print out the diagonal generator coordinating method (GCM) matrix elements for $\pi$, $\rho$ and $\omega$ mesons respectively. As an example, Fig. 6 gives the potentials of $\pi$, $\rho$ and $\omega$ mesons for the $^1S_0$ state (for set I). The $\pi$, $\rho$ and $\omega$ meson exchange potentials are drawn with solid, long-dashed and short-dashed curves, respectively. One can see that the $\omega$ meson exchange offers repulsion not only in the short range region, but also in medium range part. This property is different from that of $\pi$ meson, which only contributes repulsive core. (5) As for the coupling constants of the vector meson exchange $g_{\text{chv}}$ and $f_{\text{chv}}$, when we take $f_{\text{chv}}/g_{\text{chv}} = 0$, we get $g_{\text{chv}} = 2.35$, which is a little bit smaller than the value used by Riska et al [13], but slightly larger than the value obtained from the $NN\rho$ coupling constant of Nijmegen model D [9]. When $f_{\text{chv}}/g_{\text{chv}} = 2/3$, we get $g_{\text{chv}} = 1.97$ (see Table 1), which is very closed to the value obtained from the Nijmegen model D, but $f_{\text{chv}}/g_{\text{chv}}$ are much smaller than that from Nijmegen model D. The results indicate that the coupling constant of vector meson exchange on quark level is much weaker than the corresponding coupling constant on baryon level. Since on the quark level the size effect and the quark exchanges between two nucleon clusters also contribute short range repulsion, the smaller coupling constant of vector meson exchange on quark level can easily be understood. From the phase shift calculations, one can also see that the results are not very sensitive to $f_{\text{chv}}/g_{\text{chv}}$. For both case I and II, the calculated phase shifts are almost consistent with the experimental data. When $f_{\text{chv}}/g_{\text{chv}} = 2/3$, it is slightly helpful to increase the one channel $^1S_0$ phase shifts. It seems that on quark level the tensor coupling part of the vector meson exchanges is not very important in explaining the $S$ wave phase shifts. But for the $^3P_0$, $^3P_2$, $^3D_2$, and $^3D_3$ partial waves, the calculated results are still not good enough, because in the extended chiral $SU(3)$ quark model, there is only one coupling constant $g_{\text{chv}}$ for the vector coupling of the vector meson exchanges, and one coupling constant $f_{\text{chv}}$ for the tensor coupling part. In the one boson exchange model on baryon level, such as Nijmegen model, and the work on quark level [12], however, the coupling constants of $\rho$ and $\omega$ mesons are taken to be quite different. Especially, the tensor coupling constant $\omega$, $f_{NN\omega}$ are quite large [9]. If we take different $g_{\text{chv}}$ and $f_{\text{chv}}$ for $\rho$ and $\omega$ exchanges, possibly the results of $^3P_0$, $^3P_2$, $^3D_2$, and $^3D_3$ partial waves can be improved.
4 Conclusions

The vector meson exchange effect in N-N scattering processes on quark level is studied in the extended chiral SU(3) quark model. The differences between the chiral SU(3) quark model and the extended chiral SU(3) quark model are discussed in detail. It is found that in the extended chiral SU(3) quark model, the phase shifts of $^1S_0$ and $^3S_1$ waves can be fitted rather well. All other partial waves calculated are also consistent with the experimental results. In the extended chiral SU(3) quark model, the strength of OGE interaction is greatly reduced and the short range NN repulsion is due to combined effect of ps- and vector meson exchanges, which also results in smaller size parameter $b_u$. The tensor coupling constant of the vector meson exchange $f_{\text{chev}}$ also becomes smaller than that on baryon level. All of these features shown above are reasonable and helpful in better understanding the short range mechanism of the quark-quark interactions.

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Fig. 1 The S-wave phase shifts of the N–N scattering
Fig. 2 The P-wave phase shifts of the N–N scattering
Fig. 3. The D-wave phase shifts of the N–N scattering.
Fig. 4. The $F$- and $G$-wave phase shifts of the $N-N$ scattering.
Fig. 5: The $^1S_0$ phase shifts of coupled channel calculation.
Fig. 6 The GCM potentials of π, ρ and ω mesons exchange