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Studies of NN Scattering Process and Vector Meson Exchange Potential *

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Abstract In this work, the vector meson exchange effect in NN interaction is studied on quark level in the extended chiral $SU(3)$ quark model. The π, ρ and ω-meson exchange GCM potentials of central force and NN scattering phase shifts for all scattering partial waves are given. It shows that the vetor meson exchange potential can substitute one-gluon exchange (OGE) potential to explain repulsive core of the NN interaction.

Key words NN interaction, quark model, chiral symmetry

1 Introduction

In 1997, we proposed a quark-chiral field coupling model which is called the chiral $SU(3)$ quark model[1,2]. 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. 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 important in explaining the structure of baryons. 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 structure of baryon. The quark-chiral field coupling model is a big challenge to the Isgur's model[6], in which the OGE governs the baryon structure. On quark level, the short range repulsive feature of N-N interaction can be explained by OGE interaction and quark exchange effect[7,8]. on baryon level, in the traditional one boson exchange (OBE) model[9] the N-N short range repulsion comes from vector meson (ρ, ω, K^* and ϕ) 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.

2 The extended chiral $SU(3)$ quark model

By generalizing the interaction Lagrangian, a term of coupling between quark and vector meson field is included on the basis of the chiral $SU(3)$ quark model[2].

$$\mathscr{L}_I^v = -\mathrm{i}g_{\mathrm{chv}}\bar{\psi}\gamma_\mu\boldsymbol{\varphi}_\mu\cdot\boldsymbol{\tau}\psi - \mathrm{i}\frac{f_{\mathrm{chv}}}{2M_{\mathrm{p}}}\bar{\psi}\sigma_{\mu\nu}\partial_\nu\boldsymbol{\varphi}_\mu\cdot\boldsymbol{\tau}\psi. \tag{1}$$

Thus the Hamiltonian of the system can be written as

$$\begin{aligned} H &= \sum_i T_i - T_G + \sum_{i<j} V_{ij}, \\ V_{ij} &= V_{ij}^{\mathrm{conf}} + V_{ij}^{\mathrm{OGE}} + V_{ij}^{\mathrm{ch}}, \end{aligned} \tag{2}$$

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where $\sum_i T_i - T_G$ 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}^{ch} represents the interactions from chiral field couplings. In this 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,

$$V_{ij}^{\mathrm{ch}} = \sum_{a=0}^{8} V_{\mathrm{s}_\alpha}(\boldsymbol{r}_{ij}) + \sum_{a=0}^{8} V_{\mathrm{ps}_\alpha}(\boldsymbol{r}_{ij}) + \sum_{a=0}^{8} V_{\mathrm{v}_\alpha}(\boldsymbol{r}_{ij}). \tag{3}$$

The vector meson exchange potential is

$$\begin{aligned} V_{\mathrm{v}_\alpha}(\boldsymbol{r}_{ij}) = {} & C(g_{\mathrm{chv}}, m_{\mathrm{v}_\alpha}, \Lambda_{\mathrm{c}}) X_1(m_{\mathrm{v}_\alpha}, \Lambda_{\mathrm{c}}, r_{ij})(\lambda_a(i)\lambda_a(j)) + \\ & C(g_{\mathrm{chv}}, m_{\mathrm{v}_\alpha}, \Lambda_{\mathrm{c}}) \frac{m_{\mathrm{v}_\alpha}^2}{6 m_{qi} m_{qj}} \left(1 + \frac{f_{\mathrm{chv}}}{g_{\mathrm{chv}}} \frac{m_{qi} + m_{qj}}{M_{\mathrm{p}}} + \right. \\ & \left. \frac{f_{\mathrm{chv}}^2}{g_{\mathrm{chv}}^2} \frac{m_{qi} m_{qj}}{M_{\mathrm{p}}^2}\right) \times \left\{ X_2(m_{\mathrm{v}_\alpha}, \Lambda_{\mathrm{c}}, r_{ij})(\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j) - \right. \\ & \left. \frac{1}{2}\left(H(m_{\mathrm{v}_\alpha} r_{ij}) - \left(\frac{\Lambda_{\mathrm{c}}}{m_{\mathrm{v}_\alpha}}\right)^3 H(\Lambda_{\mathrm{c}} r_{ij}) \right) \hat{S}_{ij} \right\} \times \\ & (\lambda_a(i)\lambda_a(j)) - C(g_{\mathrm{chv}}, m_{\mathrm{v}_\alpha}, \Lambda_{\mathrm{c}}) \times \\ & \frac{3 m_{\mathrm{v}_\alpha}^2}{4 m_{qi} m_{qj}} \left(1 + \frac{f_{\mathrm{chv}}}{g_{\mathrm{chv}}} \frac{2(m_{qi} + m_{qj})}{3 M_p}\right) \times \left\{ G(m_{\mathrm{v}_\alpha} r_{ij}) - \right. \\ & \left. \left(\frac{\Lambda_{\mathrm{c}}}{m_{\mathrm{v}_\alpha}}\right)^3 G(\Lambda_{\mathrm{c}} r_{ij}) \right\} (\boldsymbol{L} \cdot (\boldsymbol{\sigma}_i + \boldsymbol{\sigma}_j)) \times \\ & (\lambda_a(i)\lambda_a(j)), \end{aligned} \tag{4}$$

and M_{p} is taken as proton mass. In the calculation, ω and ϕ mesons consist of $\sqrt{\frac{1}{2}}(u\bar{u} + d\bar{d})$ and $(s\bar{s})$ respectively, i.e. they are mixed by ω_1 and ω_8, with the mixing angle $\theta_\omega = -54.7°$. g_{chv} and f_{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 vector meson, Riska et al.[13] took $g_{\mathrm{chv}} = 3.0$ and neglected the tensor coupling part. On baryon level, these two values can be obtained according to the $SU(3)$ relation between quark and baryon levels. For example,

$$g_{\mathrm{chv}} = g_{\mathrm{NN}\rho}, f_{\mathrm{chv}} = \frac{3}{5}(f_{\mathrm{NN}\rho} - 4 g_{\mathrm{NN}\rho}). \tag{5}$$

In the Nijmegen model D, $g_{\mathrm{NN}\rho} = 2.09$ and $f_{\mathrm{NN}\rho} = 17.12$. From Eq. (5), we get $g_{\mathrm{chv}} = 2.09$ and $f_{\mathrm{chv}} = 5.26$. Such information is useful for adjusting the coupling constants of vector meson exchanges on quark level. All the parameters used are listed in Table 1. Here there are only one coupling constant for vector meson of vector coupling 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 ρ, K*, ω, and ϕ exchanges.

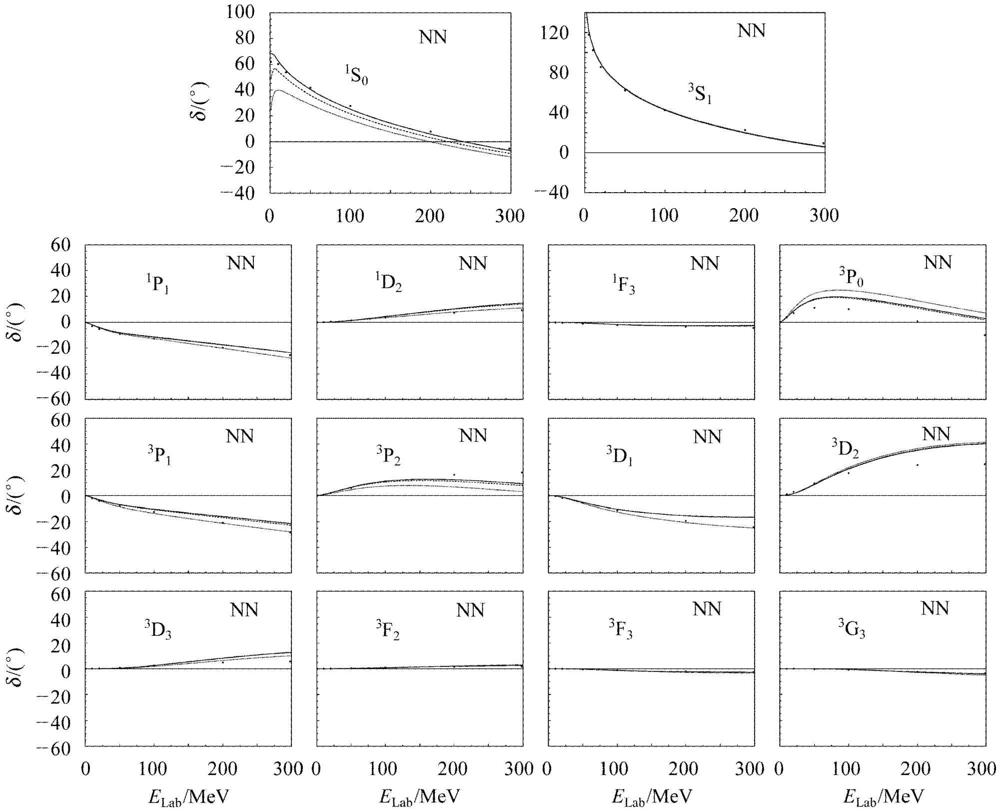

Fig.1. The partial wave phase shifts of N-N scattering.

Table 1. Model parameters and the corresponding binding energies of deuteron.

	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_σ/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}/(MeV/fm^2)	48.1	48.0	42.9
B_{deu}/MeV	2.13	2.19	2.14

The meson masses and the cut-off mass Λ are $m_\pi = 138$MeV, $m_K = 495$MeV, $m_\eta = 548$MeV, $m_{\eta'} = 958$MeV, $m_{\sigma'} = m_\kappa = m_\epsilon = 980$MeV, $m_\rho = 770$MeV, $m_{K^*} = 892$MeV, $m_\omega = 782$MeV, $m_\phi = 1020$MeV and $\Lambda = 1100$MeV.

3 Result and discussion

The N-N phase shifts are calculated and shown in Fig.1 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 $f_{chv}/g_{chv} = 0$, while the tensor coupling of vector meson exchanges is included in the case of set Ⅱ, where $f_{chv}/g_{chv} = 2/3$. we adjust the mass of σ meson m_σ to fit the binding energy of deuteron. From Table 1, one can see that m_σ is almost located in the reasonable range 550—650MeV for all these three cases when

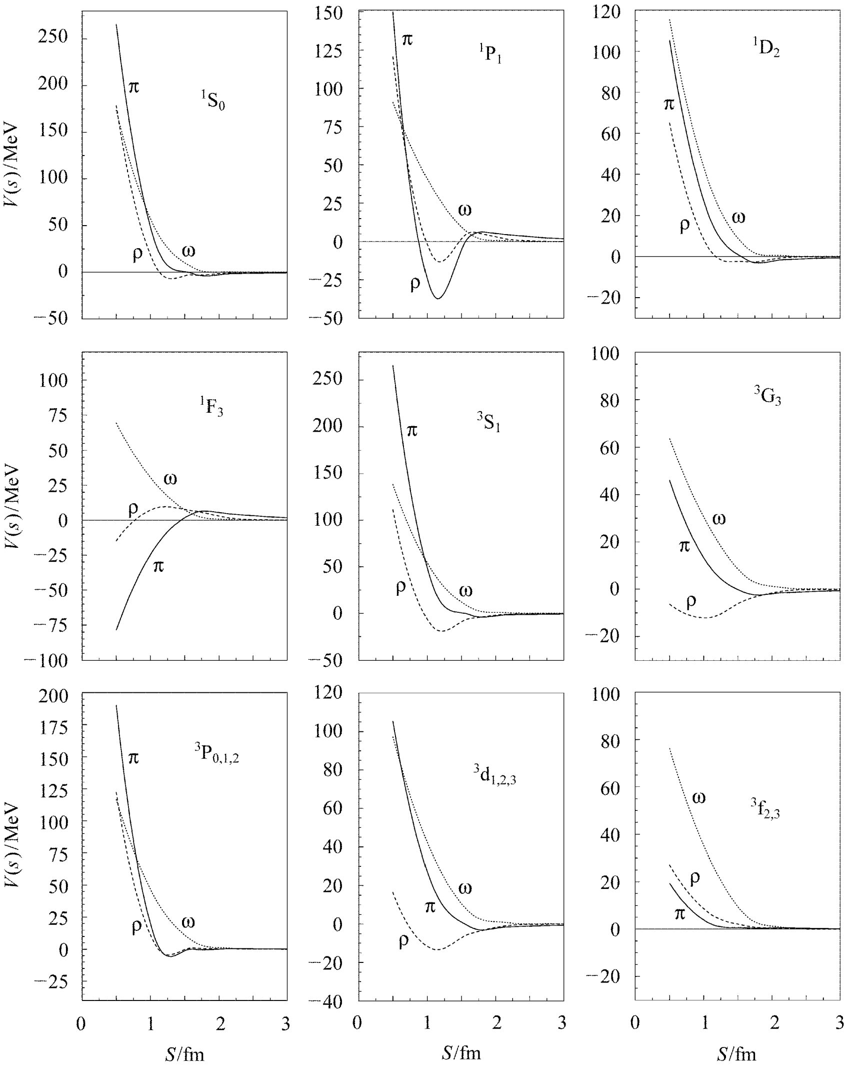

Fig.2. The GCM central potentials of π, ρ and ω mesons exchange.

the binding energy of deuteron $B_{\rm deu}$ is fitted.

From Table 1 and Fig.1, (1) we can see 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 ($\alpha_s < 0.2$) interaction is greatly reduced and the short range NN repulsion is dominantly due to vector meson exchanges, which also results in smaller size parameter b_u. Hence, mechanisms of the quark-quark short range interactions of these two models are totally different. Coupling constant of vector meson exchange ($g_{\rm chv}$ and $f_{\rm chv}$) on quark level is much weaker than the corresponding coupling constant on baryon level (2) Fig.2 gives the central generator coordinating method (GCM) matrix elements of π, ρ and ω mesons for the all states (for set Ⅰ). Here we can see the contributions from different meson exchanges for different partial waves in the N-N interactions in our extended chiral $SU(3)$ quark model. One can see that the ω meson exchange offers repulsion not only in the short range region, but also in medium range part. This property is different from that of π meson, which only contributes repulsive core. All above results are reasonable and helpful in better understanding the short range mechanism of the quark-quark interactions.

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核子－核子散射过程的研究和矢量介子交换势*

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摘要　在推广的手征 $SU(3)$ 夸克模型下讨论了核子－核子散射过程和矢量介子交换势. 给出了赝标 π 介子和矢量 ρ 和 ω 介子的 GCM 中心力的交换势和 NN 散射 14 个分波的相移. 研究表明, 矢量介子交换势可以替代单胶子交换势以解释核力的短程排斥.

关键词　核子与核子相互作用　夸克模型　手征对称性

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