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Influence of Spin–Orbit Force on Nucleon–Nucleon Scattering in the Quark Delocalization Colour Screening Model *

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The symmetric spin–orbit interactions of one-gluon-exchange and confinement are included in the nucleon–nucleon phase shift calculation in the framework of quark delocalization colour screening model. The spin–orbit interaction has little influence on D wave phase shift. For the triplet P waves, ^3P_T is in good agreement with the experimental data and $^3P_{\rm LS}$ is attractive but not strong enough, whereas ^3P_C is too strongly repulsive. Our results indicate that the symmetric spin–orbit interaction of one-gluon-exchange and confinement potential cannot give a good description of the triplet P wave phase shifts. More sophisticated considerations, the delocalization depending on the relative orientation between two cluster, might be needed to improve the description of P-wave NN interaction.

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For more than 15 years, the intermediate-range attraction of nucleon–nucleon (NN) interaction has been missing from the quark model calculations. One has had to invoke meson exchange to match data.[1−3]The most common used quark model in the study of NN interaction is the chiral quark model,[4−6] in which the σ meson is introduced to get the intermediate-range nucleon–nucleon attraction. Recently the existence of σ meson is confirmed by experiments.[7] However, the discovered σ-meson, a correlated two pions, cannot give enough intermediate range attraction between two nucleons according to recent calculations.[8] In 1990s, a new version of quark cluster model: quark delocalization colour screening model (QDCSM)[9] is developed. Two ingredients were introduced: quark delocalization (enlarge the model space) and colour screening (account for the dependence of quark–quark interaction on the quark state). The model has been successfully applied to describe NN, hyperon-nucleon scattering. In this model, the quark delocalization which is like the electron percolation in the molecules produces the intermediate-range attraction. The colour screening is needed to make the quark delocalization effective. The model gave a natural explanation of the similarity between molecular force and nuclear force. Since 2000, the model is extended to incorporate the Goldstone-boson-exchange to take into account the long-range tail of the NN interaction.[10] Clearly the difference between the chiral quark model and QDCSM is the intermediate-range attraction mechanism. Recently, we have shown that these two mechanisms could give almost the same result in calculating the deuteron properties and the $^3S_1$, $^3D_1$, $^1S_0$ and $^1D_2$ NN scattering phase shifts.[11] Here we apply the model to odd parity NN channels: $(ST) = (00)$ and (11), with the intention of checking whether QDCSM can describe the spin–orbit force of NN interaction.

A possible source of spin–orbit interaction is the one-gluon exchange (OGE). The nonrelativistic version of OGE between quarks provides two different types of spin–orbit terms, a Galilei-invariant (symmetric) term and a Galilei-noninvariant (antisymmetric) term. The Galilei-invariant spin–orbit term has received considerable attention,[12−16] because it has the same structure as the standard spin–orbit interaction between nucleons. In conventional quark cluster model calculations, the spin–orbit interaction of OGE between quarks yields an NN spin–orbit force which is similar to that of ρ, ω meson exchange, but the strength is too weak if the quark-gluon coupling constant is fixed by the N-Δ mass splitting.[14] Another possible source of the spin–orbit interaction is the confinement. The spin–orbit potential generated by confinement is strongly dependent on the particular confinement model. Although the uncertainties of the confinement mechanism make it difficult to draw definite conclusions at the present stage,[17] it is still interesting to see the effect of the spin–orbit term coming from confinement in QDCSM.

In the chiral quark model, the scalar σ meson exchange between quarks also introduces spin–orbit interaction.[18] In Ref. [11], we have shown the effect of central part of σ meson exchange in the chiral quark

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model can be replaced by quark delocalization with colour screening in QDCSM. Thus, it is also interesting to see whether the effect of the spin–orbit term coming from σ meson exchange on NN phase shift could be reproduced in QDCSM.

The model and its extension were discussed in detail in Refs. [9,10]. Here only the Hamiltonian and wavefunction of the extended QDCSM are presented,

$$\begin{aligned}
H_6 &= \sum_{i=1}^{6}\Big(m_i+\frac{p_i^2}{2m_i}\Big)-T_c+\sum_{i<j=1}^{6}V_{ij},\\
V_{ij} &= V_{ij}^{C}+V_{ij}^{G}+V_{ij}^{\pi},\\
V_{ij}^{C} &= \boldsymbol{\lambda}_i\cdot\boldsymbol{\lambda}_j V_{ij}^{c}+V_{ij}^{C,soS}+V_{ij}^{C,soA},\\
V_{ij}^{c} &= -a_c\begin{cases} r_{ij}^2, & \text{if } i,j \text{ occur in the same}\\ & \text{baryon orbit,}\\ (1-e^{-\mu r_{ij}^2})/\mu, & \text{otherwise,}\end{cases}\\
V_{ij}^{G} &= \frac{\alpha_s}{4}\lambda_i\cdot\lambda_j\Big[\frac{1}{r_{ij}}-\frac{\pi}{m_q^2}\Big(1+\frac{2}{3}\sigma_i\cdot\sigma_j\Big)\delta(r_{ij})\\
&\quad -\frac{3}{4m_q^2 r_{ij}^3}S_{ij}\Big]+V_{ij}^{G,soS}+V_{ij}^{G,soA},\\
V_{ij}^{\pi} &= \frac{\alpha_{ch}}{3}\frac{\Lambda^2}{\Lambda^2-m_\pi^2}m_\pi\Big\{\Big[Y(m_\pi r_{ij})-\frac{\Lambda^3}{m_\pi^3}Y(\Lambda r_{ij})\Big]\\
&\quad \sigma_i\cdot\sigma_j+\Big[H(m_\pi r_{ij})-\frac{\Lambda^3}{m_\pi^3}H(\Lambda r_{ij})\Big]S_{ij}\Big\}\tau_i\cdot\tau_j,\\
S_{ij} &= \frac{\boldsymbol{\sigma}_i\cdot\boldsymbol{r}_{ij}\boldsymbol{\sigma}_j\cdot\boldsymbol{r}_{ij}}{r_{ij}^2}-\frac{1}{3}\boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j,
\end{aligned}\tag{1,2}$$

where S_{ij} is the quark tensor operator. $Y(x)$ and $H(x)$ are the standard Yukawa functions, T_c is the kinetic energy of the centre of mass, α_{ch} is the chiral coupling constant, which is determined from π-nucleon coupling constant as usual, $\mu = 1.0$, which is the colour screening constant to be determined by fitting the deuteron mass. All the other symbols have their usual meanings. The parameters of Hamiltonian are given in Table 1, as used before.[11]

In the present calculation, two different sources of spin–orbit interaction are taken into account. The first one is the Galilei-invariant part of OGE potential that can be written as

$$V_{ij}^{G,soS} = -\frac{\alpha_s}{4}\lambda_i\cdot\lambda_j\frac{1}{8m_q^2}\frac{3}{r_{ij}^3}\Big[\boldsymbol{r}_{ij}\times(\boldsymbol{p}_i-\boldsymbol{p}_j)\Big]\cdot(\boldsymbol{\sigma}_i+\boldsymbol{\sigma}_j).\tag{3}$$

There is another term $V_{ij}^{G,soA}$ proportional to $[\boldsymbol{r}_{ij}\times(\boldsymbol{p}_i+\boldsymbol{p}_j)]\cdot(\boldsymbol{\sigma}_i-\boldsymbol{\sigma}_j)$, which is called the frame-dependent antisymmetric term. Both terms have been discussed in detail in Ref. [17], where it has been demonstrated that if only the symmetric spin–orbit term of OGE quark–quark interaction is retained, the spin–orbit interaction from the corresponding resonating group method (RGM) quark-exchange kernels has a sign and magnitude in agreement with the short-range part of phenomenological NN potentials. However, with the inclusion of the antisymmetric spin–orbit OGE terms the strength of the full triplet-odd NN spin–orbit potential is greatly reduced and its sign may even be reversed.[17] Thus, these terms are usually not taken into consideration[15,16,18] and will be left out here, although there is no fundamental reason that would justify this.[19]

The second source of spin–orbit interaction is generated by confinement, with a symmetric term that can be written as

$$V_{ij}^{C,soS} = -\lambda_i\cdot\lambda_j\frac{1}{8m_q^2}\frac{1}{r_{ij}}\frac{dV^c}{dr_{ij}}[\boldsymbol{r}_{ij}\times(\boldsymbol{p}_i-\boldsymbol{p}_j)]\cdot(\boldsymbol{\sigma}_i+\boldsymbol{\sigma}_j).\tag{4}$$

The antisymmetric piece $V_{ij}^{C,soA}$ is not included here with the same reason as in the case of OGE.

The phase shifts are calculated by using the resonating-group method (RGM). The detail of the method can be found in Ref. [20]. For QDCSM, the quark delocalization is realized by writing the single particle orbital wave function as a linear combination of left and right Gaussians, the single particle orbital wave functions in the ordinary quark cluster model.

$$\begin{aligned}
\psi_\alpha(\boldsymbol{S}_i,\epsilon) &= (\phi_\alpha(\boldsymbol{S}_i)+\epsilon\phi_\alpha(-\boldsymbol{S}_i))/N(\epsilon),\\
\psi_\beta(-\boldsymbol{S}_i,\epsilon) &= (\phi_\beta(-\boldsymbol{S}_i)+\epsilon\phi_\beta(\boldsymbol{S}_i))/N(\epsilon),\\
N(\epsilon) &= \sqrt{1+\epsilon^2+2\epsilon e^{-S_i^2/4b^2}}.\\
\phi_\alpha(\boldsymbol{S}_i) &= \Big(\frac{1}{\pi b^2}\Big)^{3/4}e^{-\frac{1}{2b^2}(\boldsymbol{r}_\alpha-\boldsymbol{S}_i/2)^2}\\
\phi_\beta(-\boldsymbol{S}_i) &= \Big(\frac{1}{\pi b^2}\Big)^{3/4}e^{-\frac{1}{2b^2}(\boldsymbol{r}_\beta+\boldsymbol{S}_i/2)^2}.
\end{aligned}\tag{5}$$

Table 1. Parameters of QDCSM.

m_q (MeV)	m_π (MeV)	α_s	a_c (MeV fm^{-2})	b (fm)	α_{ch}	Λ (fm^{-1})
313	138	0.9955	18.55	0.6	0.027	4.2

We have calculated the NN $^3S_1$, $^3D_1$, $^1P_1$ and $^3P_{0,1,2}$ phase shifts with and without the spin–orbit force. All the experimental data are taken from Ref.[21].

For $^3S_1$ and $^3D_1$ (Figs. 1 and 2), the spin–orbit force does not make observable contributions (the two curves coincide with each other in Figs. 1 and 2), which seems to be consistent with the fact that the NN spin–orbit force is known to be very small for even orbital angular momentum states.

For the P wave, the NN $^1P_1$ phase shifts are shown in Fig. 3. Because all the parameters of QDCSM have been fixed and the results here are pure theoretical predictions. The fit shows that the QDCSM predicts a qualitatively correct NN interaction in the $(ST) = (00)$ channel, but a little too strongly repulsive. Because only central part of the interaction plays

the role here, the results show that the P-wave central interaction of QDCSM is a little too repulsive.

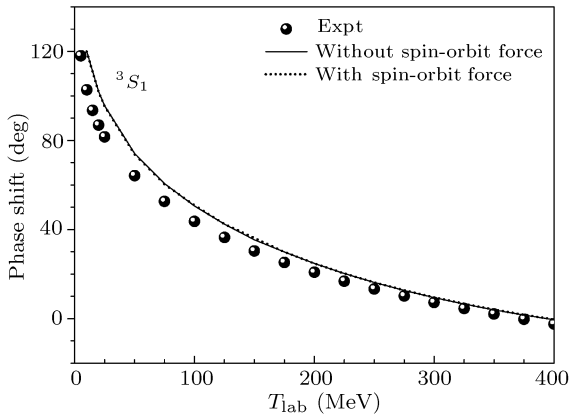


Fig. 1. NN $^3S_1$ phase shifts.

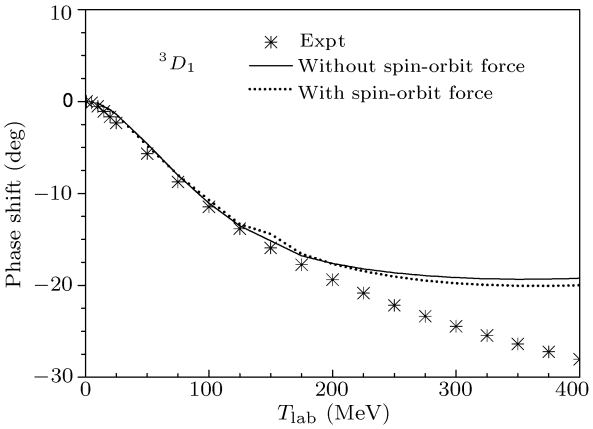


Fig. 2. The NN $^3D_1$ phase shifts.

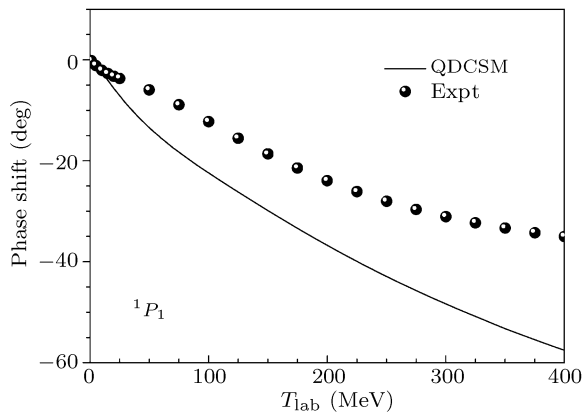


Fig. 3. NN $^1P_1$ phase shifts.

For the triplet P wave, the phase shifts can be factorized in the following way:

$$
\begin{aligned}
{}^3P_C &= \frac{1}{9}{}^3P_0 + \frac{1}{3}{}^3P_1 + \frac{5}{9}{}^3P_2,\\
{}^3P_T &= -\frac{5}{36}{}^3P_0 + \frac{5}{24}{}^3P_1 - \frac{5}{72}{}^3P_2,\\
{}^3P_{\rm LS} &= -\frac{1}{6}{}^3P_0 - \frac{1}{4}{}^3P_1 + \frac{5}{12}{}^3P_2. \qquad (6)
\end{aligned}
$$

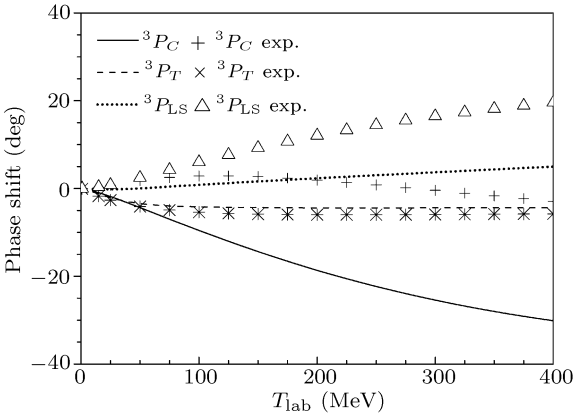


Fig. 4. Decomposed P waves phase shifts for the NN.

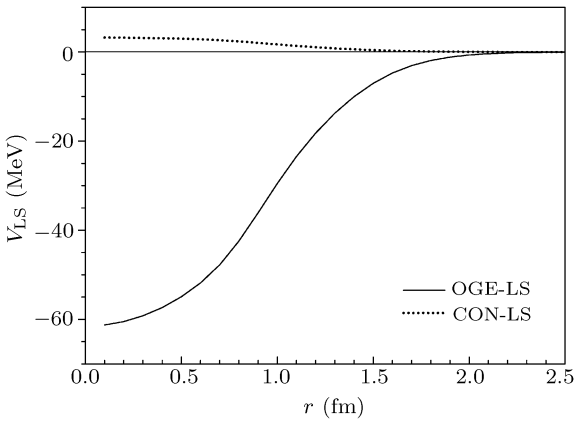


Fig. 5. Spin-orbit potential $V_{\rm LS}$ of OGE and confinement (CON) for the ^3P_J partial waves.

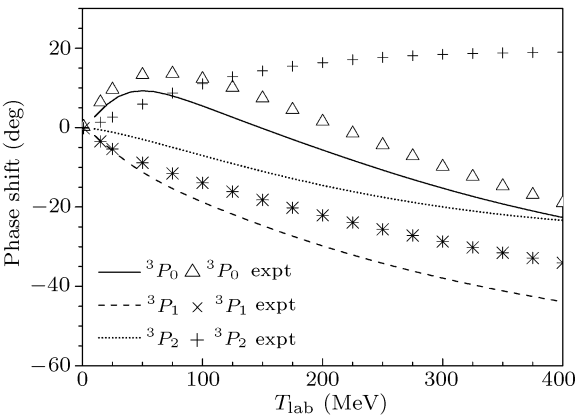


Fig. 6. NN $^3P_{0,1,2}$ phase shifts.

From Fig. 4, we can see that the ^3P_T term, mainly coming from the long-range tail of the one-pion-exchange potential, is fairly well reproduced, whereas

the central part of the phase shifts ^3P_C are too repulsive compared with the experimental data and the spin–orbit part $^3P_{\rm LS}$, the QDCSM cannot yield strong enough attraction as the chiral quark model did[18] (although different set of parameters from Ref. [22], where almost a perfect S, D-wave phase shifts fitting to experimental data are obtained, was used). The reason is that the different sources of spin–orbit interactions are used in the two models. Although the symmetric spin–orbit OGE term (OGE-LS) was used in both models, the symmetric spin–orbit interaction generated by σ meson exchange (OSE-LS), which is missing in QDCSM, is used in the chiral quark model. It is just the OSE giving the enough attraction for central and spin–orbit force. The including of symmetric spin–orbit confinement term (CON-LS) does not help us, the phase shifts with and without CON-LS are almost the same. Figure 5 shows the contribution of CON-LS to effective potential between two nucleons, it is negligible compared to OGE-LS. Figure 6 shows the phase shifts for $^3P_J, J = 0, 1, 2$. Due to the strong repulsive central force and too weak attractive spin–orbit force, all phase shifts are lower than experimental data, especially for $^3P_2$. To try to improve the agreement with experimental data, the more realistic delocalization may be invoked. The delocalization parameter ϵ, which is assumed to be a function of the separation of two nucleon, may not only depend on the separation, but also depends on the relative orientation of two nucleons for non-S wave. It is quite complicated and we leave it for the future.

In summary, we have calculated the spin–orbit force generated by one-gluon-exchange and confinement potentials in QDCSM. The effect of the CON-LS on phase shifts is very small, it can be neglected safely. For D waves, the spin–orbit interaction affects the phase shifts only a little bit, which is consistent with the fact that the NN spin–orbit force is weak in the even orbital angular momentum states. For the singlet P waves, QDCSM gives a qualitatively correct but too strong repulsive results and for triplet P waves, the OGE-LS yields attraction, but it is not strong enough. More work, especially on the orientation dependent delocalization, might be needed to describe the P-wave phase shifts of NN scattering in QDCSM.

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