Spin-orbit force in a quark model based nucleon-nucleon potential

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The spin-orbit interaction coming from the scalar meson-exchange potential between quarks is included in a quark cluster model for the nucleon-nucleon interaction. Its influence on the triplet P-wave scattering phase shifts and on the baryon spectrum is analyzed. We require that the deuteron binding energy is simultaneously reproduced. Our results indicate that a considerable part of the nucleon-nucleon spin-orbit force can be explained by gluon and sigma exchange between quarks while improving the description of the excited baryon spectrum.

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I. INTRODUCTION

A challenging problem of intermediate energy physics is to explore the consequences of the quark structure of the nucleon in nuclear phenomena. In particular, the nucleon-nucleon (NN) system has been studied by various groups in the framework of the constituent quark cluster model. Among them, the Tübingen group has developed a realistic model that has been successfully applied to the description of the nucleon-nucleon and hyperon-nucleon interactions and to the electromagnetic properties of light nuclei [1,2]. On the other hand, there are still a number of unsolved problems if the nucleon-nucleon interaction is formulated at the quark level.

A long-standing problem of the constituent quark model description of the nucleon-nucleon interaction and the baryon spectrum is the origin of the spin-orbit force [1–7]. This interaction is known to be of very short range and thus may be explained by the quark model. In meson-exchange models [8], the spin-orbit force is mainly generated by the exchange of the ω meson, which is also responsible for the short-range repulsion. However, in quark-exchange models, the short-range repulsion comes from the exchange of gluons and pions between quarks accompanied by simultaneous quark interchange between the two three-quark clusters [1,9]. Furthermore, Yazaki [10] has shown that pseudoscalar or scalar meson exchange and quark exchange between the clusters can simply be added without risk of double counting. On the other hand, vector meson exchanges between quarks belonging to different clusters provide contributions similar to the quark-exchange mechanism and would lead to double counting [10]. Therefore, vector mesons are not included in quark-exchange models and one has to look for a different source of the spin-orbit force.

A possible source of spin-orbit interaction is the one-gluon exchange (OGE). The nonrelativistic reduction of the OGE diagram 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 in the literature [1–5], because it has the same structure as the standard spin-orbit interaction between nucleons. Using this source of spin-orbit force, Morimatsu, Yazaki, and Oka [4] demonstrated that it is possible to reproduce the observed spin-orbit splitting in the NN interaction using a large quark-gluon coupling constant $\alpha_s \sim 1.6$. However, they used an effective meson-exchange potential between nucleons and not between quarks and therefore they neglected the pion-exchange contribution to the Δ-N mass difference. If this contribution is taken into account, α_s is considerably reduced and the resulting spin-orbit force is not large enough to reproduce the experimental P-wave splitting. In fact, when gluon and pion exchange are consistently treated on the quark level, the OGE spin-orbit force must be multiplied by some numerical factor (usually between 5 and 12 depending on the set of parameters [2,11,12]), in order to reproduce the experimental spin-orbit splitting in the NN phase shifts. Moreover, the OGE Galilei-invariant spin-orbit term severely disturbs the description of the excited P-wave baryon spectrum [4,7].

Other possible sources of the spin-orbit interaction are the confinement and the scalar sigma-meson exchange between quarks. The spin-orbit potential generated by confinement is strongly dependent on the particular confinement model. For example, while the symmetric spin-orbit term associated with a scalar two-body confinement potential cancels the OGE symmetric spin-orbit force in the NN interaction [4], the one coming from a flip-flop confinement interaction interferes constructively with it [5]. In Ref. [6], the uncertainties associated with spin-orbit terms generated by quark confinement have been emphasized by studying an alternative model in which confinement is described through a mass term in the relativistic single-particle equation. The single-particle Thomas term of such a model yields a sign of the NN spin-orbit interaction which is opposite to the one generated by a scalar two-body confining potential. Therefore, since the detailed confinement mechanism is presently not well understood, we leave out for the moment its spin-orbit piece [4,6]. This does not mean that confinement-generated spin-orbit effects do not exist, but the uncertainties surrounding the confinement mechanism make it difficult to draw definite conclusions at the present stage.

The situation is rather different with respect to the sigma-meson exchange. Recently, the quark cluster model for the nucleon-nucleon interaction of the Tübingen group [1,2] has been extended [11–13] by introducing a scalar meson (σ-meson) exchange between quarks. The σ-meson parameters are related to those of the pion and to the constituent quark mass through chiral symmetry requirements. This scalar quark-quark potential is certainly another source of spin-orbit interaction between baryons and it has been suggested as a possible solution of the spin-orbit problem in the constituent quark model [4,5]. Our aim in this paper is to explore the effect of the spin-orbit term coming from σ-meson exchange on the NN phase shifts, on the deuteron, and on the excited baryon spectrum. In Sec. II we will review the quark cluster model and the different spin-orbit terms considered. In Sec. III we will study the nucleon-nucleon spin-orbit interaction generated by the one-sigma exchange (OSE) and the OGE potentials and show the resulting P-wave phase shifts. Furthermore, we will estimate the effect of the OSE and OGE spin-orbit terms on the description of the excited P-wave baryon spectrum. Finally, in Sec. IV we will discuss and summarize our results.

II. CONSTITUENT QUARK CLUSTER MODEL

Among the different quark models, the constituent quark cluster model is ideally suited to describe the effects of subnucleonic degrees of freedom in few-nucleon systems. This is due to the possibility of performing dynamical calculations [1,2,4,5,9–14]. Other models, like the bag model, have severe problems in describing the two-baryon dynamics mainly due to the center of mass motion problem, the unphysical sharp boundary of the bag, and the question of how and where to join six-quark dynamics with external NN dynamics.

The constituent quark cluster model is mainly based on the concept of constituent quark masses. Nowadays this mass is viewed as a consequence of the spontaneous breakdown of chiral symmetry which goes together with the appearance of Goldstone bosons, the π and σ fields [14]. Based on these assumptions, Fernández *et al.* [11] have proposed a potential model where the primary ingredients of the quark-quark interaction are the confining potential and the one-gluon-exchange term. In the intermediate region, between the scale at which the chiral flavor symmetry is spontaneously broken, $\Lambda_{\rm CSB} \sim 1\,\mathrm{GeV}$, and the confinement scale, $\Lambda_C \sim 200\,\mathrm{MeV}$, QCD is formulated in terms of an effective theory of constituent quarks ($m_q \sim M_N/3$) interacting through the Goldstone modes associated with spontaneous chiral symmetry breaking [15]. The form of this interaction has been derived elsewhere [11]. It contains two pieces corresponding to the exchange of a pseudoscalar [one-pion exchange (OPE)] and a scalar [one-sigma exchange] boson. The specific form of these potentials is

$$V_{\rm OPE}(\vec r_{ij}) = \frac{1}{3}\,\alpha_{\rm ch}\frac{\Lambda^2}{\Lambda^2-m_\pi^2}\,m_\pi\left\{\left[Y(m_\pi\,r_{ij})-\frac{\Lambda^3}{m_\pi^3}\,Y(\Lambda\,r_{ij})\right]\vec\sigma_i\cdot\vec\sigma_j+\left[H(m_\pi\,r_{ij})-\frac{\Lambda^3}{m_\pi^3}\,H(\Lambda\,r_{ij})\right]S_{ij}\right\}\vec\tau_i\cdot\vec\tau_j\,, \quad (1)$$

$$V_{\rm OSE}(\vec r_{ij}) = -\alpha_{ch}\,\frac{4\,m_q^2}{m_\pi^2}\,\frac{\Lambda^2}{\Lambda^2-m_\sigma^2}\,m_\sigma\left[Y(m_\sigma\,r_{ij})-\frac{\Lambda}{m_\sigma}\,Y(\Lambda\,r_{ij})\right]+V_{\rm OSE}^{\rm s.o.,\mathit{S}}(\vec r_{ij})+V_{\rm OSE}^{\rm s.o.,\mathit{A}}(\vec r_{ij})\,, \quad (2)$$

where $\alpha_{\rm ch}$ is the chiral coupling constant and Λ is a cutoff parameter. The i and j indices are associated with the ith and jth quarks, respectively, $\vec r_{ij}$ represents the interquark distance, and the $\vec\sigma_i$'s ($\vec\tau_i$'s) are the spin (isospin) Pauli matrices. $V_{\rm OSE}^{\rm s.o.,\mathit{S}}$ and $V_{\rm OSE}^{\rm s.o.,\mathit{A}}$ are, respectively, the symmetric and antisymmetric spin-orbit terms discussed below. $S_{ij} = 3\,(\vec\sigma_i\cdot\hat r_{ij})(\vec\sigma_j\cdot\hat r_{ij}) - \vec\sigma_i\cdot\vec\sigma_j$ is the quark tensor operator and $Y(x)$ and $H(x)$ are the standard Yukawa functions defined by

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

The chiral coupling constant $\alpha_{\rm ch}$ is related to the πN coupling constant $g^2_{\pi NN}$ by [11]

$$\alpha_{\rm ch} = \left(\frac{3}{5}\right)^2\frac{g^2_{\pi NN}}{4\pi}\,\frac{m_\pi^2}{4m_N^2}\,. \quad (4)$$

Perturbative effects are included in the model by means of the OGE potential, which is obtained via the nonrelativistic reduction of the one-gluon-exchange diagram in QCD [16]. It takes the form

$$V_{\rm OGE}(\vec r_{ij}) = \frac{1}{4}\,\alpha_s\,\vec\lambda_i\cdot\vec\lambda_j\left\{\frac{1}{r_{ij}}-\frac{\pi}{m_q^2}\left[1+\frac{2}{3}\vec\sigma_i\cdot\vec\sigma_j\right]\delta(\vec r_{ij})-\frac{3}{4m_q^2\,r_{ij}^3}\,S_{ij}\right\}+V_{\rm OGE}^{\rm s.o.,\mathit{S}}(\vec r_{ij})+V_{\rm OGE}^{\rm s.o.,\mathit{A}}(\vec r_{ij})\,, \quad (5)$$

where α_s is an effective QCD coupling constant and the $\vec{\lambda}_i$'s are the SU(3) color matrices.

Finally, the confinement potential that takes into account the multigluon-exchange effects is of the harmonic oscillator form

$$V_{\rm con}(\vec{r}_{ij}) = -a_c\,\vec{\lambda}_i\cdot\vec{\lambda}_j\,r_{ij}^2\,, \tag{6}$$

where a_c is the confinement strength. The presence of the $\vec{\lambda}_i\cdot\vec{\lambda}_j$ term assures that there is no direct confinement contribution to the baryon-baryon interaction (or equivalently the confinement force contributes only to the nucleon mass).

In this framework, we consider two different sources of spin-orbit interaction. The first one is the Galilei-invariant part of the OGE potential that can be written as

$$V_{\rm OGE}^{\rm s.o.,S}(\vec{r}_{ij}) = -\frac{1}{4}\,\alpha_s\,\vec{\lambda}_i\cdot\vec{\lambda}_j\,\frac{1}{8\,m_q^2}\,\frac{3}{r_{ij}^3}\,[\vec{r}_{ij}\times(\vec{p}_i-\vec{p}_j)]\cdot(\vec{\sigma}_i+\vec{\sigma}_j)\,. \tag{7}$$

There is a second term $V_{\rm OGE}^{\rm s.o.,A}$ proportional to $(\vec{\sigma}_i-\vec{\sigma}_j)\cdot[\vec{r}_{ij}\times(\vec{p}_i+\vec{p}_j)]$ called the frame-dependent antisymmetric part. Both terms have been discussed in detail in Ref. [6], where it has been demonstrated that if only the symmetric spin-orbit term of the OGE quark-quark interaction is retained, the spin-orbit interaction derived 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 [6]. This is why these terms have usually not been considered in the literature [4,5] and will not be considered here, although there is no fundamental reason that would justify this.

The second source of spin-orbit interaction is generated by the sigma exchange, with a symmetric term that can be written as

$$V_{\rm OSE}^{\rm s.o.,S}(\vec{r}_{ij}) = -\frac{\alpha_{\rm ch}}{2m_\pi^2}\,\frac{\Lambda^2}{\Lambda^2-m_\sigma^2}\,m_\sigma^3\left[\Gamma(m_\sigma\,r_{ij})-\frac{\Lambda^3}{m_\sigma^3}\,\Gamma(\Lambda\,r_{ij})\right][\vec{r}_{ij}\times(\vec{p}_i-\vec{p}_j)]\cdot(\vec{\sigma}_i+\vec{\sigma}_j)\,, \tag{8}$$

where $\Gamma(x)$ is defined by

$$\Gamma(x) = \frac{e^{-x}}{x^2}\left(1+\frac{1}{x}\right)\,. \tag{9}$$

As in the case of the gluon, the antisymmetric piece $V_{\rm OSE}^{\rm s.o.,A}$ is not included here.

It is important to note that, for reasons given in the Introduction, our model does not contain any massive vector boson-exchange potentials (ρ,ω) and therefore, there are no other sources of spin-orbit interaction.

In the quark model, a nucleon is considered to be a cluster made of three quarks,

$$\phi_N(\vec{\rho},\vec{\xi};b) = \mid q^3,\ \ [3]_{ST}\left(S=\frac{1}{2},\,T=\frac{1}{2}\right),\ \ [1^3]_c > \varphi_{\rm int}(\vec{\rho},\vec{\xi};b)\,. \tag{10}$$

The internal radial wave function is defined by

$$\varphi_{\rm int}(\vec{\rho},\vec{\xi};b)\Psi_0\left(\vec{R}_{\rm c.m.},\,\sqrt{\frac{1}{3}}b\right) = \Psi_0(\vec{r}_1,b)\,\Psi_0(\vec{r}_2,b)\,\Psi_0(\vec{r}_3,b)\,, \tag{11}$$

where $\vec{\rho}$ and $\vec{\xi}$ are the Jacobi coordinates, $\vec{r}_i$ is the coordinate of the ith quark, $\vec{R}_{\rm c.m.}$ is the center of mass coordinate of the three-quark system and

$$\Psi_0(\vec{r},b) = \left(\frac{1}{\pi b^2}\right)^{\frac{3}{4}} e^{-\frac{r^2}{2b^2}}\,. \tag{12}$$

The parameters appearing in Eqs. (1), (2), (5)–(8), and (12) are required to reproduce the Δ-N mass difference and the nucleon stability condition $\partial M(b)/\partial b = 0$, where $M(b)$ is the nucleon mass and b is the oscillator parameter of the quark wave function [11]. This determines α_s and a_c as a function of the two remaining parameters b and Λ. Both parameters b and Λ describe the finite hadronic size of the nucleon and can be related to the πN cutoff mass of the phenomenological πN monopole vertex function via [17]

$$\Lambda_{\pi N}^2 = \frac{6}{\langle r_{\pi N}^2\rangle}\,, \tag{13}$$

with

$$\langle r_{\pi N}^2 \rangle = b^2 + \frac{3}{\Lambda^2}\,. \tag{14}$$

Typical values for $\Lambda_{\pi N}$ found in the literature [8,18] lie between 500 and 2000 MeV. The mass of the sigma meson, m_σ, as well as the other parameters b and Λ will be discussed later.

In order to solve the NN scattering problem in the quark model, the six-quark wave function is written in the RGM framework as

$$\Psi_{6q}^{LST;J} = \mathcal{A}(\{[\phi_N(\vec\rho_1,\vec\xi_1;b)\otimes\phi_N(\vec\rho_2,\vec\xi_2;b)]^{ST}\otimes\chi^L(\vec R)\}^J), \tag{15}$$

where $\vec R$ is the relative coordinate between the two three-quark clusters.

The relative wave function $\chi(\vec R)$ is obtained from the variational principle

$$\langle \delta\Psi_{6q} \mid \mathcal{H} - E \mid \Psi_{6q}\rangle = 0\,. \tag{16}$$

III. RESULTS

A. Nucleon-nucleon interaction

As we are interested in studying the effect of the spin-orbit force generated by the one-sigma exchange, the value of m_σ is chosen to provide the best fit to the experimental P-wave phase shifts. However, it also required to reproduce correctly the $^3S_1$ partial wave phase shifts and the deuteron binding energy, which means that the strength of the spin-orbit potential cannot be fitted just by moving m_σ alone. In our model all the parameters are strongly correlated. For example, if we use a smaller value of m_σ, we get more attraction. If we still want to reproduce the $^3S_1$ partial wave and the deuteron binding energy, this must be compensated by increasing the repulsion, which for fixed Λ implies a bigger value of b and therefore a bigger α_s. This in turn reduces the pion contribution because the bigger b, the larger the gluon contribution to the Δ-N mass difference [17].

Let us briefly discuss the determination of the the parameters b and Λ. The parameter Λ [aside from $\alpha_{\rm ch}$, which is fixed by Eq. (4)] governs the strength of the πq interaction which plays a dominant role in determining the deuteron binding energy and D-state probability. This is also evident from Eqs. (13) and (14), which relate both parameters Λ and b to the πN cutoff mass. Increasing Λ increases $\Lambda_{\pi N}$. This will lead to more binding and to a bigger D-state probability, because the larger Λ, the less regularized or more attractive the OPE interaction. On the other hand, the quark core radius b determines the probability for the overlap of the clusters and thus the range of the short-range repulsion. For a larger b, the range of the short-range repulsion is increased, which in turn leads to less binding. We have determined Λ and b such that the NN phase shifts and the deuteron binding energy are reasonably well reproduced and found b=0.53 fm and Λ=3.0 fm^{-1}, as listed in Table I. With these values we obtain for $\Lambda_{\pi N}$=3.12 fm^{-1}, which corresponds to a soft form factor as favored by deep inelastic electron and muon scattering data [19]. Note that in previous works [4,5], where the gluon and meson contributions were not treated consistently, this strong correlation among the parameters did not exist, and the meson-exchange part was fitted independently to the experimental data. The parameters used in the present work are shown in Table I.

In order to gain some qualitative insight prior to the detailed RGM calculation, we estimate the contribution from the one-sigma-exchange spin-orbit force (OSE-LS) to the NN interaction and compare it to the one of the one-gluon-exchange spin-orbit force (OGE-LS) in the adiabatic approximation. Figures 1 and 2 show, respectively, the radial part of the adiabatic spin-orbit potential for P and D waves defined by

$$V_{LS}^{\rm ad}(R)\,\langle (LS)J \mid \vec L\cdot\vec S \mid (LS)J\rangle = \frac{V_{(LS)J}^{\rm RGM}(R,R)}{N_{(LS)J}^{\rm RGM}(R,R)}\,, \tag{17}$$

where L, S, and J are the relative orbital, spin, and total angular momentum of the two-nucleon system, and $V_{(LS)J}^{\rm RGM}(R,R)$ and $N_{(LS)J}^{\rm RGM}(R,R)$ are, respectively, the RGM spin-orbit interaction and normalization kernels projected onto the partial wave $|(LS)J\rangle$. The spin-orbit force coming from OGE is generated only by quark-exchange diagrams, which makes it highly nonlocal, while the one coming from OSE has a non-vanishing direct term. As can be seen in Figs. 1 and 2, this makes the interaction coming from OSE longer ranged. The sign of the adiabatic potential for the OSE-LS force is the same for P and D partial waves, because the direct term dom-

TABLE I. Quark model parameters.

m_q (MeV)	313
b (fm)	0.53
α_s	0.67
a_c (MeV fm^{-2})	48.69
$\alpha_{\rm ch}$	0.026
m_σ (fm^{-1})	2.914
m_π (fm^{-1})	0.70
$\Lambda_{\rm CSB}$ (fm^{-1})	3.0

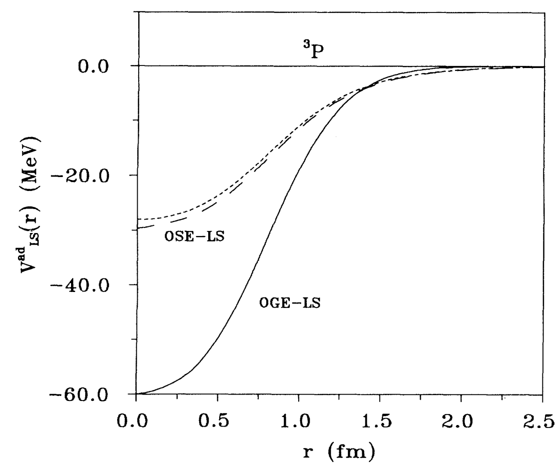

FIG. 1. The adiabatic spin-orbit potential $V_{LS}^{\rm ad}(R)$ defined by Eq. (15) for the ^3P_J partial waves. The solid line corresponds to the contribution of the OGE-*LS* force and the dashed ones represent the contribution of the OSE-*LS* force for two different values of m_σ: short dashed line, m_σ=575 MeV, and long dashed line, m_σ=550 MeV. The OGE-*LS* and the OSE-*LS* terms have the same sign for the triplet *P* waves.

inates the exchange one. However, the OGE-*LS* force has a different sign for the *P* and *D* partial waves since only the exchange terms contribute in this case. Results similar to these were found in Ref. [5] using the spin-orbit force generated by a flip-flop model for confinement, which like the OSE-*LS* interaction studied in this work has a direct term different from zero. For the *P* waves

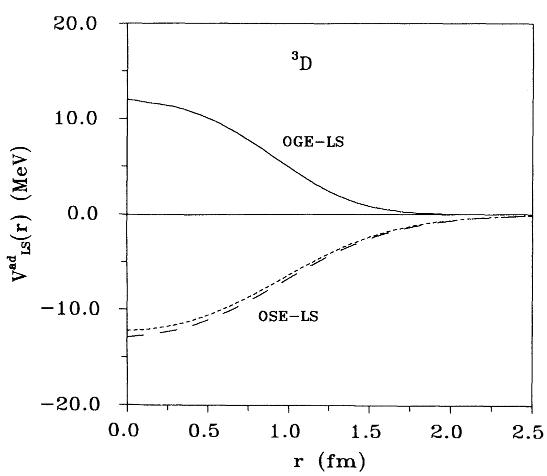

FIG. 2. The adiabatic spin-orbit potential $V_{LS}^{\rm ad}(R)$ defined by Eq. (15) for the ^3D_J partial waves. The solid line corresponds to the contribution of the OGE-*LS* force and the dashed lines represent the contribution of the OSE-*LS* force for two different values of m_σ: short dashed line, m_σ=575 MeV, and long dashed line, m_σ=550 MeV. The OGE-*LS* and the OSE-*LS* terms have the opposite sign for the triplet *D* waves and they almost cancel each other as seems to be suggested by the experimental data.

the strength of the adiabatic potential of the OSE-*LS* force is comparable to that of the OGE-*LS* force and they interfere constructively. For the *D* waves both spin-orbit forces almost cancel each other, 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. This is why one can expect that the spin-orbit interaction coming from OSE can help to solve the problem of the missing spin-orbit *NN* interaction in the nonrelativistic quark model.

Next we carry out the RGM calculation in order to examine the quark contribution to the *NN* spin-orbit more quantitatively. In Fig. 3 we show the result of our model for the $^3S_1$ partial wave in comparison to that obtained in Ref. [11] with a different set of parameters. The agreement is of the same quality. The deuteron binding energy obtained with the present set of parameters is $E_d = -2.2241$ MeV and the *D*-state probability $P_D = 3.76\%$. This guarantees that we are not including an unphysical attraction in our model by using a smaller mass of the scalar meson as compared to Refs. [11,13].

As is well known, states with different angular momenta are coupled due to the tensor term in the nuclear force. For the *P* wave, the $^3P_2$ channel can couple to the $^3F_2$ channel by the tensor force. But the mixing parameter is small in the energy region considered here ($|\epsilon| < 0.05$ for $E_{\rm c.m.} < 200$ MeV). Therefore, we neglect this coupling and perform a single-channel calculation for all the triplet *P* waves. With this hypothesis, the *P* wave phase shifts can be factorized in the following way:

$$^3P_J = {}^3P_C \langle 1 \rangle_J + {}^3P_T \langle S_{12} \rangle_J + {}^3P_{LS} \langle \vec{L} \cdot \vec{S} \rangle_J . \quad (18)$$

Here, $\langle \hat{O} \rangle_J$ is the expectation value of the operator $\hat{O}$ for the quantum numbers of the triplet *P* wave of total angular momentum *J*. ^3P_C, ^3P_T, and $^3P_{LS}$ can be interpreted, in first order, as the contribution of the central, tensor, and spin-orbit part of the nuclear force, and can

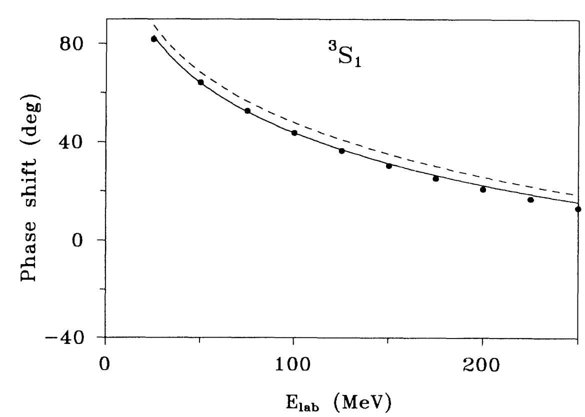

FIG. 3. The *NN* $^3S_1$ phase shifts as a function of the laboratory energy. The solid curve represents the result of the present model. For comparison we show the result of Ref. [11] (dashed line) with a different set of parameters. They are about of the same quality. Experimental data are taken from Ref. [20].

be evaluated as follows:

$$\begin{aligned} {}^3P_C &= \frac{1}{9}\,{}^3P_0 + \frac{1}{3}\,{}^3P_1 + \frac{5}{9}\,{}^3P_2 , \\ {}^3P_T &= -\frac{5}{36}\,{}^3P_0 + \frac{5}{24}\,{}^3P_1 - \frac{5}{72}\,{}^3P_2 , \\ {}^3P_{LS} &= -\frac{1}{6}\,{}^3P_0 - \frac{1}{4}\,{}^3P_1 + \frac{5}{12}\,{}^3P_2 . \end{aligned} \quad (19)$$

As we can see in Fig. 4, the ${}^3P_T$ term is fairly well reproduced, mainly due to the long-range tail of the one-pion-exchange potential. The spin-orbit part of the phase shifts ${}^3P_{LS}$ is now in good agreement with the experimental data. However, in spite of the introduction of the sigma meson, the central part, ${}^3P_C$, seems to be too repulsive. According to Eq. (18), the spin-orbit splitting between the P-wave phase shifts is not only determined by the spin-orbit terms, but it is also very sensitive to the central part of the interaction. We could now modify the sigma mass in order to obtain a good agreement with ${}^3P_C$, but then we would fail to reproduce the ${}^3S_1$ phase shift and the deuteron binding energy. In Fig. 5 we show the calculated phase shifts for the ${}^3P_J$ channel. The agreement with the experimental data is satisfactory. This shows that the quark-quark spin-orbit interaction of our model can contribute to the nucleon-nucleon interaction with a suitable strength.

B. Baryon spectrum

It is well known that the Galilei-invariant term of the OGE-LS interactions, being the best founded for the description of the NN interaction [4,6], severly disturbs the description of the excited negative parity baryon spectrum [7]. Therefore, other sources of spin-orbit interaction which effectively cancel the contribution from the Galilei-invariant spin-orbit interaction of OGE are required in the P-wave baryon spectrum.

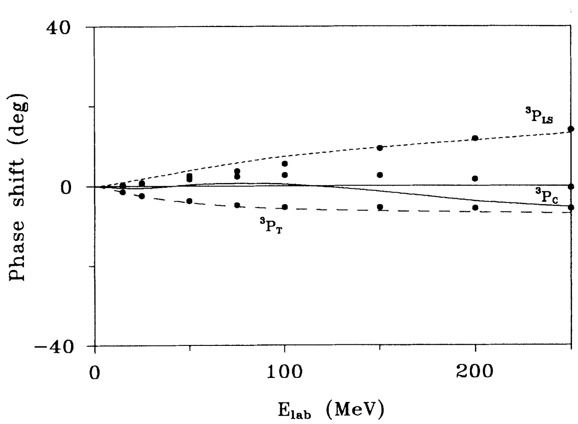

FIG. 4. The decomposed phase shifts for the NN triplet P waves according to Eq. (17) as a function of the laboratory energy. The solid line represents the central ${}^3P_C$, the dashed line the tensor ${}^3P_T$, and the dotted line the spin-orbit ${}^3P_{LS}$ contribution. Experimental data are taken from Ref. [20].

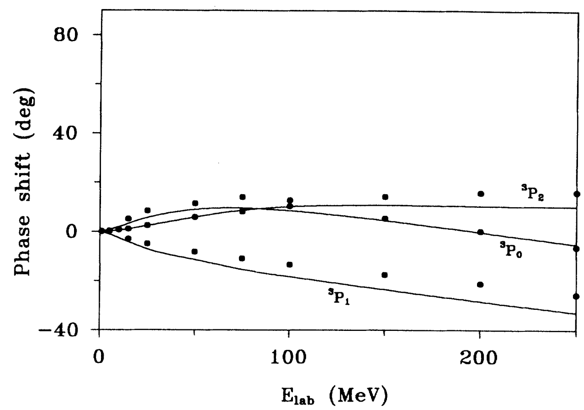

FIG. 5. The NN ${}^3P_{0,1,2}$ phase shifts including the OSE-LS force as a function of the laboratory energy. The solid curves represent the results of the present model. Experimental data are taken from Ref. [20].

In order to estimate the behavior of the OSE-LS force in the baryon spectrum, we have calculated the contribution of the OGE-LS term and the OSE-LS term to the mass of P-wave baryons. It can be easily checked that due to the different structure of both interactions in color space, their contributions have opposite sign and tend to cancel each other. To be more precise we have calculated the contribution of both spin-orbit terms to the $N^*(1/2^-)(1520)$ mass. The contribution of the symmetric OGE-LS term is given by

$$m_{N^*}^{L\cdot S}(\mathrm{OGE}) = -\sqrt{\frac{2}{\pi}}\,\frac{\alpha_s}{3\,b^3\,m_q^2} , \quad (20)$$

while the contribution of the symmetric OSE-LS term is given by

$$m_{N^*}^{L\cdot S}(\mathrm{OSE}) = \frac{4\sqrt{2}}{3}\,\frac{\Lambda^2}{\Lambda^2 - m_\sigma^2}\,\frac{\alpha_{\mathrm{ch}}}{m_\pi^2\,b^3}\,\{I(m_\sigma\,b) - I(\Lambda\,b)\} , \quad (21)$$

where $I(x)$ is defined by

$$I(x) = \frac{x^3}{2}\exp\left(\frac{x^2}{4}\right)\mathrm{erfc}\left(\frac{x}{2}\right) - \frac{x^2}{\sqrt{\pi}} + \frac{2}{\sqrt{\pi}} . \quad (22)$$

The contribution of the symmetric OGE-LS term alone would severely disturb the description of the baryon spectrum. Using the parameters of Ref. [7] the contribution of this term is -125 MeV, and using the parameters of Ref. [5] one obtains a contribution of -146 MeV. However, in the present work the contribution of the OGE-LS term is -93.87 MeV and the corresponding one of the OSE-LS is 30.48 MeV, which translates into a smaller overall contribution of the two spin-orbit forces. This cancellation could be made more complete by using a different parameter set, however at the expense of simultaneously describing the deuteron binding energy and phase shifts. There are alternative explanations of the spin-orbit problem in the baryon spectrum. For example, Blask, Huber and Metsch [21], who took both spin-orbit terms (Galilei invariant and noninvariant) of the OGE and confining potentials into account, suggested that the spin-orbit force is suppressed due to the coupling of the N^* resonances to the meson-baryon decay channels. However, they did not study the effect of this mechanism on the NN interaction.

IV. SUMMARY AND DISCUSSION

In this paper we have calculated the spin-orbit force generated by the exchange of a scalar particle (the sigma meson) between quarks and studied its effect on the nucleon-nucleon interaction and on the excited baryon spectrum. The Hamiltonian used contains only interactions between quarks.

As possible sources of the NN spin-orbit interaction we have considered the Galilei-invariant spin-orbit terms generated by one-gluon and one-sigma exchange. The results we obtained are qualitatively similar to those reported by Koike [5] using the spin-orbit force generated by one-gluon exchange and by a flip-flop model for confinement, and can be summarized as follows.

(a) For the triplet P waves, the OSE-LS and the OGE-LS forces interfere constructively. They are of the same order of magnitude and their sum gives roughly the strength required by the empirical NN spin-orbit force.

(b) For the triplet D waves the above mentioned sources of spin-orbit interaction have opposite sign and almost cancel each other, which is consistent with the experimental fact that the spin-orbit interaction is weak in the triplet even states.

(c) As in our previous work [13], the deuteron binding energy and the NN phase shifts are simultaneously described.

(d) For the excited negative parity baryon spectrum, the two spin-orbit forces are of the same order of magnitude but of opposite sign, the total contribution being reduced as required by the experimental data.

The essential feature leading to the above results is that the direct term in the OSE-LS forces dominates the exchange one, while a direct term does not exist for the OGE-LS force.

When this work was finished, we learned that in Ref. [22] very similar conclusions with respect to the baryon spectrum have been reached. Takeuchi has studied the spin-orbit interaction using an instanton model interaction ($V_{\rm III}$) and the usual one-gluon-exchange potential ($V_{\rm OGE}$). As in our work, all Galilei-noninvariant terms as well as all spin-orbit terms related to confinement were neglected. Here, we have shown that the π and σ exchange interactions between quarks provide the same qualitative effect in the baryon spectrum and in the NN interaction as the instanton-induced interaction suggested in Ref. [22]. While in Ref. [22] there is only a qualitative discussion of the instanton-induced interaction in the two-nucleon system, we have demostrated in this work that the scalar-meson-exchange interaction between quarks leads to a satisfactory description of the P-wave NN phase shifts and the deuteron binding energy.

As we have discussed in this paper the situation of the spin-orbit force in quark potential models is still quite controversial [6,7]. To remove some of the aforementioned problems a better understanding of the quark confinement is clearly needed. In spite of the remaining uncertainties, one can still conclude that the symmetric spin-orbit force generated by the scalar meson and one-gluon exchange between quarks provides a very important part of the spin-orbit force between nucleons while it improves the description of the excited baryon spectrum.

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