Symmetric and Antisymmetric Spin-Orbit Forces in YN Interaction by a Quark Model

Sachiko Takeuchi
Dept of Public Health and Env Sci,
Tokyo Medical and Dental Univ,
Yushima, Bunkyo, Tokyo 113-8519, Japan

The symmetric and antisymmetric spin-orbit forces (SLS and ALS) in the YN interaction are investigated for relative $P$-wave systems by a valence quark model with the instanton-induced interaction (III). The size of the adiabatic potential at the zero range is shown for each of the YN channels. The size of ALS is comparable to SLS. The channel dependence of ALS, which is determined by the flavor SU(3) symmetry when the one-gluon exchange (OGE) and/or the meson exchange interaction are used, deviates after introducing III. In most of the two-baryon channels, including the two-nucleon channel, the spin-orbit force of the YN interaction is strong. A few exceptional channels, however, are found where III and OGE are canceled to each other, and the spin-orbit force becomes small[1].

Recent experiments on the systems with strangeness are making great progress. Especially the gamma spectroscopy has identified several gamma transitions, which give us valuable information on the spin part of the ΛN interaction[2]. From the observed levels of Λ-hypernuclei, it is believed that the spin-orbit force between Λ and nucleon is very small comparing to that between two nucleons. However, it is nontrivial to remove the nuclear effects. Also, only the combined effect of LS and ALS can be measured in the hypernuclei. Information on the noncentral parts of the YN interaction has not given directly from experiments yet. The theoretical investigation of hypernuclei has been performed mainly by using the empirical YN interactions[3]. Here we employ a valence quark model to investigate the properties of the spin-orbit force in the strange systems. The quark model with III is found to have an appropriate size and the channel dependence for the spin-orbit force and therefore will enable us to see the feature from a more fundamental viewpoint.

A valence quark model usually contains three terms in the hamiltonian: the kinetic term, the confinement term, and the OGE term[4,5,6,7]. It is considered that OGE stands for the perturbative gluon effects and that the confinement force represents the long-range nonperturbative gluon effects. We argue that a valence quark model should include III as a short-range nonperturbative gluon effect in addition to the other gluon effects[1,8,9]. The model hamiltonian for quarks can be written as follows:

$$H_{\text{quark}} = K + (1 - p_{\text{III}})V_{\text{OGE}} + p_{\text{III}}V_{\text{III}} + V_{\text{conf}},$$  \hspace{1cm} (1)$$

where $V_{\text{OGE}}$ and $V_{\text{III}}$ are the Galilei invariant terms of the III and OGE potentials. The parameter $p_{\text{III}}$ represents the relative strength of the spin-spin part of III to OGE.

The QCD instantons were originally introduced in relation to the $U_A(1)$ problem. It produces couplings of instantons to the surrounding light-quark zero modes[10]. This leads a flavor-singlet interaction among quarks, which is III in the present model. This interaction is considered to be the origin of the observed large mass difference of $\eta' - \eta$ mesons.

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Talk at the 1st SUT-KEK Seminar on 6 Apr 1998. E-mail: sachiko@thaxp1.tanashi.kek.jp
It is well known that the color magnetic interaction in OGE is responsible to produce many of the hadron properties. By adjusting the strength of OGE, it can reproduce the hyperfine splittings (e.g., ground state N-∆ mass difference) as well as the short-range repulsion of the two-nucleon systems in the relative S-wave. It, however, is also known that the strength of OGE, α_s, determined in this empirical way is much larger than 1, which makes it hard to treat it as the perturbative effect. The spin-spin part of III produces the nucleon-∆ mass difference and the short-range repulsion between the two nucleons as the color magnetic interaction. Thus, one can reduces the empirical strength of OGE, α_s, by introducing III. Moreover, LS of III contributes the spin-orbit force in an interesting way.

The valence quark model including only OGE as an origin of the hyperfine splittings has a spin-orbit problem. The LS part of OGE is strong; it is just strong enough to explain the observed large spin-orbit force between two nucleons. On the other hand, the experimental mass spectrum of the excited baryons indicates that such a strong spin-orbit force should not exist between quarks. A valence quark model in which the spin-orbit parts of the quark interaction are removed by hands can simulate the observed mass spectrum. To explain both of the spin-orbit features at the same time is highly nontrivial.

In ref., we demonstrated that introducing III may solve the above difficulty in the P-wave systems due to the channel-specific cancellation between OGE and III. The mechanism of the cancellation is clearly seen at the flavor SU(3) limit. Since here we consider the spin-orbit force on the P-wave systems, the quark pairs which are orbital-antisymmetric and spin-symmetric, i.e., only the pairs symmetric (or antisymmetric) simultaneously in the flavor and in the color spaces, are relevant. It is found that the contribution from the color-symmetric quark pairs dominates in most of the YN LS interaction, while only color-antisymmetric pairs exist in a baryon. Because III behaves like scalar-particle exchange and OGE is vector-particle exchange, the sign of their spin-orbit parts is opposite to each other. Thus, where both of OGE and III contribute, namely for the color- and flavor-antisymmetric pairs, LS cancellation occurs. Therefore, it was expected that introducing III would explain the strong LS in the two-nucleon systems and weak LS in the excited baryons, which was confirmed numerically.

The negative-parity baryon mass spectrum by the present model shows that there is only weak spin-orbit force between the quarks due to the above cancellation. In the present choice of the parameters, the LS splittings becomes from 0.14 to 0.37 times smaller than that from the model only with OGE (fig. 1).
The LS part of the quark interaction produces both of the LS and ALS terms in the YN interaction. To investigate their feature, we calculate an adiabatic potential for the two baryons at relative distance, \( R = 0 \). It can be obtained by subtracting the single particle value from the matrix element taken by the \((0p)(0s)^5\) harmonic oscillator wave function:

\[
U(R=0) = \langle \Psi |V|\Psi \rangle - \sum_i \langle \phi_i |V|\phi_i \rangle.
\]

This value is considered to express the size of the short-range interaction between the baryons.

The numerical results of \( U_{\text{LS}[\text{ALS}]}(R=0) \) at \( \xi_s = 1 \) and 0.6 with and without III are listed in Table 1. The size of ALS is comparable to SLS in general. Both kinds of the spin-orbit forces depend strongly on the channels.

The symmetric and antisymmetric spin-orbit force between two baryons remains strong in most of the channels after introducing III as was found in the two-nucleon system. There,

![Mass [GeV]](image)

Fig. 1: Negative-parity baryon mass

Table 1: Spin-orbit forces in the two-baryon systems
The values are in MeV with the relative strength to NN SLS.

| \( 2T S S' \) | \( m_u/m_s = 1 \) | \( m_u/m_s = 0.6 \) | \( p_{\text{III}} = 0 \) | \( p_{\text{III}} = 0.4 \) | \( p_{\text{III}} = 0 \) | \( p_{\text{III}} = 0.4 \) |
|---|---|---|---|---|---|---|
| SLS | | | | | | |
| NN-NN | 2 1 1 | -94 | 1.00 | -61 | 1.00 | -94 | 1.00 | -61 | 1.00 |
| NA-NΛ | 1 1 1 | -73 | 0.78 | -51 | 0.83 | -54 | 0.57 | -37 | 0.61 |
| ΣΣ-ΣΣ | 1 1 1 | 22 | -0.24 | -3 | 0.05 | 22 | -0.23 | -4 | 0.06 |
| NA-NΛ | 1 1 1 | -32 | 0.34 | -14 | 0.22 | -28 | 0.30 | -13 | 0.21 |
| ΣΣ-ΣΣ | 3 1 1 | -94 | 1.00 | -61 | 1.00 | -96 | 1.02 | -61 | 0.99 |
| ALS | | | | | | |
| NA-NΛ | 1 1 0 | -37 | 0.39 | -18 | 0.30 | -37 | 0.40 | -23 | 0.38 |
| ΣΣ-ΣΣ | 1 1 0 | 87 | -0.93 | 44 | -0.71 | 79 | -0.85 | 43 | -0.69 |
| NA-NΛ | 1 1 0 | -37 | 0.39 | -18 | 0.30 | -30 | 0.32 | -19 | 0.31 |
| NA-NΛ | 1 0 1 | 87 | -0.93 | 44 | -0.71 | 79 | -0.84 | 42 | -0.69 |
| ΣΣ-ΣΣ | 3 1 0 | 0 | 0.00 | 0 | 0.00 | -1 | 0.01 | 3 | -0.05 |
Fig. 2: LS and ALS parts of the RGM kernel

however, are a few exceptional channels where color-antisymmetric quark pairs play an important role and the OGE-III LS cancellation also gives notable effects: the symmetric spin-orbit force of the \( N\Sigma (I = 1/2) \) and of the \( N\Lambda -N\Sigma \) channels becomes small after introducing III.

Introducing III changes the channel dependence of the spin-orbit force. It was reported that if the interaction between baryons holds the flavor SU(3), which corresponds to the \( p_{\Pi I I} = 0 \) and \( \xi_s = 1 \) case here, the channel dependence is determined only by the SU(3) symmetry[12]. The \( U_{\text{SLS}|\text{ALS}}(R) \) from qSLS at \( p_{\Pi I I} = 0 \) were calculated and found to hold the above relation between the channels except for the factor from the norm kernel[12]. Since III affects color- and flavor-antisymmetric quark pairs selectively, this relation deviates when III is switched on. We found that introducing III changes actually the relative strength of the spin-orbit force between the baryons considerably.

The adiabatic potential at \( R > 0 \) looks like a gaussian with the range of about 1 fm[6,12]. Since the potential we are considering here is SLS or ALS between relative \( P \)-wave, the potential at \( R > 0 \) will be more important. Moreover, when we treat the quarks dynamically by, e.g., a quark cluster model, the potential we should consider between baryons is not the adiabatic one but the RGM potential, which is highly nonlocal[5,6,7] (fig. 2). We argue, however, as far as a relative strength of SLS or ALS to the NN SLS is concerned, the conclusion here holds even when one performs more sophisticated calculations.

The ALS term is also in the meson-exchange interaction[12]; it was found that the tensor couplings of the vector-meson exchange can produce ALS at the flavor SU(3) limit. The meson-induced ALS seems much smaller than that of quarks, though the size of the meson coupling is not well known[12].

Experimentally, information on the YN spin-orbit force has been given only through

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The values for ALS in fig. 2 have been revised.
the level splittings in $\Lambda$ hypernuclei. The level splittings, however, gives only the combined strength of SLS and ALS; the strong SLS and ALS originated from the quark interaction may cancels each other. It was reported that the other effect such as the YN tensor interaction may reduce the splitting [3]. More investigations both from the theoretical and experimental sides are necessary to understand the spin properties of the systems with strangeness.

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1 Part of this work is reported in S. Takeuchi, [hep-ph/9807240].
2 S. Ajimura, Proceedings of 1st SUT-KEK seminar (Apr, 1998); K. Tanida, Proceedings of 1st SUT-KEK seminar (Apr, 1998).
3 C. B. Dover and H. Feshbach, Ann. Phys. (N.Y.) 198(1990)321; *ibid.* 217(1992)51; H. Hiyama, *et al.*, Proceedings of 1st SUT-KEK seminar (Apr, 1998).
4 N. Isgur, In. J. of Mod. Phys., 1(1992)465 and references therein; G. Karl, In. J. of Mod. Phys., 1(1992)491.
5 O. Morimatsu, K. Yazaki, and M. Oka, Nucl. Phys. A424(1984)412; S. Takeuchi, K. Shimizu, and K. Yazaki, Nucl. Phys. A504(1989)777; K. Shimizu, Rep. Prog. Phys. 52(1989)1 and references therein.
6 O. Morimatsu, S. Ohta, K. Shimizu, and K. Yazaki, Nucl. Phys. A420(1984)573; Y. Koike, Nucl. Phys. A454(1986)509; M. Oka, Prog. Theor. Phys. Suppl. 120(1995)95.
7 Y. Fujiwara, C. Nakamoto, and Y. Suzuki, Phys. Rev. C54(1996)2180; Phys. Rev. Lett. 76(1996)2242 and references therein.
8 M. Oka and S. Takeuchi, Nucl. Phys. A524(1991)649; Phys. Rev. Lett. 63(1989)1780; S. Takeuchi and M. Oka, Phys. Rev. Lett. 66(1991)1271.
9 S. Takeuchi, Phys. Rev. Lett. 73(1994)2173; S. Takeuchi, Phys. Rev. D53(1996)6619.
10 G. 't Hooft, Phys. Rev. D14(1976)3432; M.A. Shifman, A.I. Vainshtein and V.I. Zakharov, Nucl. Phys. B163(1980)46; E.V. Shuryak, Phys. Rep. C115(1984)151; N.I. Kochelev, Sov. J. Nucl. Phys. 41(1985)291; E.V. Shuryak and J.L. Rosner, Phys. Lett. B218(1989)72.
11 C. Caso, *et al.*, The European Physical Journal C3(1998)1
12 M. Oka, Nucl. Phys. A629(1998)379c; M. Oka and Y. Tani, in preparation.