Effects of Instantons on the YN Interaction

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We investigate the symmetric and anti-symmetric spin-orbit forces (SLS and ALS) of the effective ΛN interaction derived from a quark cluster model with the instanton-induced interaction (III), which can reproduce the observed YN cross sections as well as the observed NN scattering data.

It is found that coupling to the ΣN channel enhances ΛN ALS, and therefore that the cancellation between SLS and ALS in the ΛN channel becomes more complete. This may be one of the major reasons why the single-particle spin-orbit force of Λ in nuclei is weak.

1. Introduction

A valence quark model with III contains four terms in the quark hamiltonian: the kinetic term, the confinement term, and the one-gluon exchange (OGE) term, and the III term. It was found that this model can reproduce rough feature of the YN systems as well as the NN scattering data\cite{1}. In ref.\cite{2}, we demonstrated that a valence quark model with III gives the small LS splitting of the excited baryons and the large LS force between two-nucleons, which are difficult to be described simultaneously. Thus, introducing III enables us to see the spin-orbit force from a more fundamental viewpoint. In this work, we discuss the spin-orbit problem in the YN system.

2. Model

Here we employ a valence quark model to investigate the properties of the spin-orbit force in the ΛN systems. The short range feature is supplied by the quark degrees of freedom with the gluonic potentials. The intermediate and long-range interaction is supplied by the meson-exchange: the flavor-singlet and octet scalar mesons, the pseudo-scalar, and the vector mesons. We use some of the coupling constants and masses of the mesons as fitting parameters, which are taken to reproduce the NN phase shifts and the low-energy Λp cross section and the phase shifts. The NN phase shift can be reproduced well: all the partial wave phase shifts at $E_{cm} = 5 \sim 150 \text{ MeV}$ do not deviate more than 4 degrees away from the results of the phase-shift analysis up to the $F$-wave. The Λp $^1S_0$ phase shift is about 10 degrees higher than that of $^3S_1$, which is suggested by the experiments\cite{3}.

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3. ΛN spin-orbit force

In a quark-meson hybrid model, there are two origins of ALS. One comes from the gluonic interaction; the symmetric LS force between quarks produces both of the anti-symmetric and the symmetric LS between baryons. The other is the meson-exchange interaction; the tensor couplings of the vector-meson exchange can produce ALS. Both of them survive at the flavor SU(3) limit and therefore are rather large.

From the observed levels of Λ-hypernuclei, it is believed that the ΛN spin-orbit force is small comparing to that between two nucleons. Since the spin of u- and d-quark in the Λ particle is zero, only the s-quark contributes to the ΛN spin-orbit force. Because of this, the ΛN spin-orbit force (= ΛN SLS + ΛN ALS) is small in a quark model, though each SLS or ALS can be large. As seen in table 1, however, this cancellation seems not enough. Moreover, strong ALS seen in the model can cause a bump in the Λp elastic cross section, which is excluded by the experiments.

4. Coupling to the ΣN channel

The RGM equation of the quark cluster model, $(H - EN)\psi = 0$, can be rewritten as the “Schrödinger” equation, $(\overline{H} - E)\bar{\psi} = 0$, with $\overline{H} = N^{-1/2}HN^{-1/2}$ and $\bar{\psi} = N^{1/2}\psi$. The coupling to the ΣN channel is large in the quark model. To ΛN LS force should be modified as:

$$\tilde{H}_{AN} = \overline{H}_{11} - \overline{H}_{12}(\overline{H}_{22} - E_0)^{-1}\overline{H}_{21}$$

Table 1. LS matrix elements by the quark cluster wave functions with $b_{\text{baryon}}=1.35$ fm.

| Models | $H_{\text{SLS}}$ | $H_{\text{ALS}}$ | $H_{\text{LS}}$ | $\delta\tilde{H}_{\text{SLS}}$ | $\delta\tilde{H}_{\text{ALS}}$ | $\tilde{H}_{\text{LS}}$ |
|--------|-----------------|-----------------|-----------------|----------------|----------------|----------------|
| QCM-B  | −1.03           | 0.31            | −0.72           | 0.58           | 0.67           | 0.53           |
| QCM-C  | −1.22           | 0.26            | −0.95           | 0.56           | 0.50           | 0.10           |
| QCM-D  | −1.20           | 0.22            | −0.98           | 0.54           | 0.45           | 0.01           |

All entries are in MeV.
where the channel 1 [2] denotes the ΛN [ΣN] channel. At $E_0 = E$, eq. (1) is equivalent to the coupled-channel calculation. As $E_0$ deviates from $E$, the result deviates from the exact one, which can be seen, e.g. in the scattering phase shift (Fig. 1).

To see rough size of the effect of the coupling to the ΣN channel, we evaluate the hamiltonian $\tilde{H}_{\Lambda N}$ by the quark-cluster wave functions. Their size corresponds to the ones with $b_{\text{baryon}} = 1.35$ fm, with an extra potential between the baryons. In table 1, we list that of SLS and ALS separately by three parameter sets of QCM [1] (QCM-B has the meson ALS similar to NSC97f, QCM-C [D] without [with] III with no meson ALS). $H_{SLS}$ and $H_{ALS}$ stand for the SLS and ALS terms in the ΛN force, whereas $\delta H_\alpha$ stands for the contribution from the ΣN channel to each LS term. The size of the total LS, which consists of SLS and ALS with the ΣN effect, is listed under the entry $\tilde{H}_\alpha$.

The effect of the ΣN channel is important; it reduces SLS ($\delta \tilde{H}_{SLS}$) and enhances ALS ($\delta \tilde{H}_{ALS}$) largely, so that the size of the whole LS term decreases considerably ($\tilde{H}_{LS}$). The adiabatic LS potentials obtained from the eq. (1) are shown in Fig. 2, which also indicate that the ΣN channel effect is large.

5. Summary

In this work, we investigate the effect of coupling to the ΣN channel on the spin-orbit force in the ΛN interaction. The effect seems important, which reduces the Λ single particle LS force largely.

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