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Scalar isoscalar part of the hyperon-nucleon interaction

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Abstract. We study the central part of the ΛN potential by considering the correlated and uncorrelated two-meson exchange besides the ω exchange contribution. The correlated two-meson is evaluated in a chiral unitary approach. We find that a short-range repulsion is generated by the correlated two-meson potential which also produces an attraction in the intermediate distance region. The uncorrelated two-meson exchange produces a sizeable attraction in all cases which is counterbalanced by ω exchange contribution.

PACS. 13.75.Ev Hyperon-nucleon interactions – 12.39.Fe Chiral Lagrangians

1 Introduction

The scalar-isoscalar potential plays an important role in the nucleon-nucleon interaction providing an intermediate-range attraction in all channels which is demanded by the data. In models of the NN interaction using one-boson exchange (OBE) this part of the interaction was traditionally accounted for by allowing the exchange of a "σ" particle whose nature has been a source of controversy.

The picture of the σ as a dynamically generated resonance called for a interpretation of the σ exchange in the NN interaction and this work was performed in [1]. In this work the traditional σ exchange was substituted by the exchange of two interacting mesons within the chiral unitary framework of [2], and an intermediate attraction was found together with a repulsion at short distances, which makes the picture qualitatively different from the ordinary, always attractive, σ exchange.

The work of [1] was complemented in [3], where in addition to the interacting two-pion exchange, the contribution of the uncorrelated two-pion exchange and the repulsive contribution of the ω exchange were considered, leading altogether to a good reproduction of the empirical scalar isoscalar interaction of [4,5].

The purpose of this work is to extend this to the strange sector evaluating the ΛN scalar isoscalar interaction, as shown in fig. 1.

Empirical evaluations of the YN scalar isoscalar interaction are done in several works allowing the exchange of a scalar meson and making fits to data [6–9]. Our approach evaluates directly the correlated two-pion exchange by explicitly using the chiral unitary approach to deal with the pion-pion interaction and using appropriate triangle diagrams to account for the coupling of the two pions to the baryons. The success of this approach providing the scalar isoscalar NN interaction provides solid grounds to extend these ideas to the case of the ΛN interaction, which we present in this work.

2 Formalism

We define the correlated two-meson exchange potential in momentum space as

$$V^{Cor}_{\Lambda N}(q) = \sum_{ij}^{\pi\pi,K\overline{K}} N_{ij}\Delta^i_\Lambda t^{(I=0)}_{i\to j}\Delta^j_N\,, \tag{1}$$

where Δ indicates the triangle scalar loop contribution of two-meson for baryon, which is defined in [1], and N_{ij} is a factor from the isospin summation, concretely $N_{\pi\pi,\pi\pi}=6$, $N_{\pi\pi,K\overline{K}}=N_{K\overline{K},\pi\pi}=2\sqrt{3}$, $N_{K\overline{K},K\overline{K}}=2$. Concretely, the Δ-function for the Λ with the correlated two-pion is given by

$$\Delta^{(\pi\pi)}_\Lambda = \left(\frac{D}{\sqrt{3}f_\pi}\right)^2 V^{(\pi\pi)}_{\Sigma\Lambda} + \frac{2}{3}\left(\frac{f^*_{\pi N\Delta}}{\sqrt{2}m_\pi}\right)^2 V^{(\pi\pi)}_{\Sigma^* N}\,, \tag{2}$$

where $V^{(m_1m_2)}_{B'B}$ is the vertex function which is already evaluated in [1] and given in a generalized form as

$$V^{(m_1m_2)}_{B'B} = \int\frac{\mathrm{d}^3p}{(2\pi)^3}\frac{M_{B'}}{E_{B'}}\frac{(\boldsymbol{p}+\boldsymbol{q})\cdot\boldsymbol{p}}{2\omega_1\omega_2(\omega_1+\omega_2)} \times\frac{\omega_1+\omega_2+E_{B'}-M_B}{(\omega_1+E_{B'}-M_B)(\omega_2+E_{B'}-M_B)} \tag{3}$$

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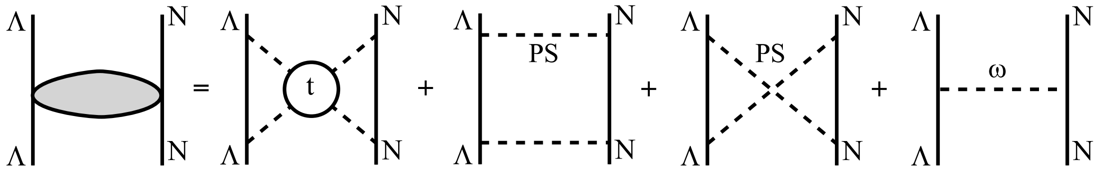

Fig. 1. Diagrammatic representation for the scalar part of ΛN potential. The first diagram stands for the correlated two-meson exchange potential and the last diagram is the contribution of the ω exchange. The others are the ladder and crossed two-meson exchange potentials.

with

$$E_B=\sqrt{\boldsymbol{p}^2+M_B^2};\ \omega_1=\sqrt{\mu_1^2+\boldsymbol{p}^2};\ \omega_2=\sqrt{\mu_2^2+(\boldsymbol{p}+\boldsymbol{q})^2}. \quad (4)$$

As in [1], we have put the initial momentum at rest. We introduce a static form factor in order to regularize the triangle loop function. The form factor employed in this calculation is

$$F(\boldsymbol{p})F(\boldsymbol{p}+\boldsymbol{q})=\frac{\Lambda^2}{\Lambda^2+\boldsymbol{p}^2}\frac{\Lambda^2}{\Lambda^2+(\boldsymbol{p}+\boldsymbol{q})^2}, \quad (5)$$

where the cutoff is chosen as $\Lambda = 1.0\,\mathrm{GeV}$.

The t is the unitarized amplitude of meson-meson scattering which reproduces the π-π phase shift up to 1.2 GeV quite well.

The uncorrelated two-meson potential is given after performing analytically the p^0 integration in terms of the integrals

$$V_{\Lambda N}^{(i,\mu)}(q)=-\int\frac{\mathrm{d}^3p}{(2\pi)^3}\frac{M_\Lambda}{E_\Lambda}\frac{M_N}{E_N}\frac{\left(4p^2-q^2\right)^2}{32\omega_1\omega_2(\omega_1+\omega_2)}R_i(\cdot), \quad (6)$$

where M_Λ and M_N are the Λ and nucleon mass, respectively and i stands for the direct (D) or crossed (C) terms and

$$R_D(\cdot)=\frac{\Omega(\epsilon^2+2\omega_1\omega_2)+(\Omega^2+\omega_1\omega_2+E_1'E_2')\epsilon}{\epsilon(\omega_1+E_1')(\omega_1+E_2')(\omega_2+E_1')(\omega_2+E_2')}, \quad (7)$$

$$R_C(\cdot)=\frac{\Omega\epsilon+\Omega^2-\omega_1\omega_2+E_1'E_2'}{(\omega_1+E_1')(\omega_1+E_2')(\omega_2+E_1')(\omega_2+E_2')}, \quad (8)$$

with $E_i' = E_i - M_i$, $\epsilon = E_1' + E_2'$ and $\Omega = \omega_1 + \omega_2$. It is worth mentioning that, if we compare without coupling constants, the crossed contribution is much smaller than the box-type contribution.

The ω exchange potential for ΛN in momentum space is given by

$$V_{\Lambda N}^{\omega}(q)=\frac{g_{\omega\Lambda\Lambda}g_{\omega NN}}{q^2+m_\omega^2}\left(\frac{\Lambda_\omega^2-m_\omega^2}{\Lambda_\omega^2+q^2}\right)^2, \quad (9)$$

where we choose $g_{\omega NN} = 13$ and $\Lambda_\omega = 1.4\,\mathrm{GeV}$ [3]. The ideal mixing for ω and ϕ leads the relation, $g_{\omega\Lambda\Lambda} = \frac{2}{3}g_{\omega NN}$, which is deduced from the quark contents of the hadrons. For simplicity we assume the same form factor for both the ωNN and $\omega\Lambda\Lambda$ vertices.

The potential in configuration space is given by

$$V(r)=\frac{1}{2\pi^2 r}\int_0^\infty q\sin(qr)V(q)\mathrm{d}q \quad (10)$$

with the relative distance.

3 Results

The left panel of fig. 2 shows the ΛN potential in momentum space. The correlated two-meson contribution has a peak around $q = 400\,\mathrm{MeV}/c$. A similar peak in position and magnitude was found for the NN case in refs. [1,3]. It is worth discussing this shape because it is impossible to parameterize it by a single-meson exchange with usual form factors, like monopole or Gaussian. This contribution could be decomposed in, at least, two parts: a strong repulsive part and a weak attraction. In any case, this contribution is much smaller than the other ones, so that the main contribution comes from the uncorrelated two-meson exchange and from the ω exchange. These two potentials have opposite sign, and the uncorrelated two-meson potential is slightly stronger than the ω exchange potential in the whole range of q. Thus, the sum of these two potentials is always negative.

The total potential has positive strength around $q = 600\,\mathrm{MeV}/c$, which is pushed up by the correlated two-meson potential. The correlated two-meson potential plays a more important role in this region.

We notice the effect of the two-kaon contribution, suppressed due to its heavy mass, is very small and does not change the pionic potential much.

In the right panel of fig. 2, we can see a similar correlated two-meson potential as for the NN case, see fig. 10 in [1]. This should be expected since the definition of the potential is quite similar to the NN case except for the masses of the baryons and coupling constants. In fact both the NN and ΛN potential generated by the correlated two-pion exchange contribution pass through zero at $r \simeq 0.9\,\mathrm{fm}$ and have a minimum at $r \simeq 1.3\,\mathrm{fm}$. This potential is repulsive in the short-range region and, on the other hand, it is attractive beyond 1 fm. The strength of the correlated two-meson potential is much smaller than the other contributions.

The right panel of fig. 2 shows that the uncorrelated two-meson generates a strong attraction and the ω produces a repulsion in the short-range region. The sum of these two potentials produces a relatively strong attraction around 1 fm and leads to large cancellations in the short-range region. We do not give the results below 0.5 fm since there the overlap of the baryons and quark exchange mechanisms can lead the sizeable corrections.

Although the attraction in the total potential is mainly generated by the uncorrelated two-meson potential, part of the repulsion is generated by the correlated two-meson

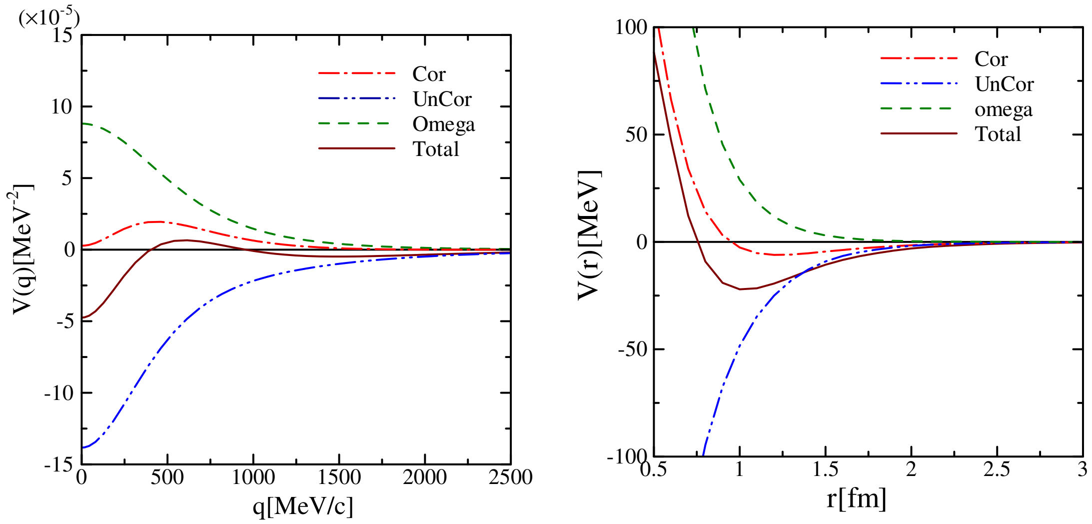

Fig. 2. The left (right) panel shows the ΛN potential in momentum (configuration) space, respectively. In both panels the dot-dashed, double-dot–dashed and dashed lines indicate the correlated two-meson, uncorrelated two-meson and omega exchange potential, respectively. The solid line stands for the total potential of the ΛN interaction in our approach.

potential. This is interesting because the correlated two-meson potential is considered as a σ-meson exchange in other papers and, there, the interaction would be always attractive (see eq. (3.19) of [1]).

The two-kaon contribution slightly enhances the magnitude of both the correlated and uncorrelated two-meson potential, and it makes the total potential a little deeper than the pionic potential.

4 Conclusions

We have evaluated the scalar channel potential between the Λ and nucleon. We have considered the correlated and uncorrelated two-meson exchange contributions in this channel besides ω exchange. The correlated two-meson exchange contribution was calculated by using a chiral unitary approach which reproduces very well the experimental meson-meson phase shift up to 1.2 GeV.

A strong attraction is produced by the uncorrelated two-meson exchange contribution. The ω exchange contribution makes a short-range repulsion, also similar to the NN case, but its strength is two-thirds of the NN case due to the simple counting of non-strange quarks in the baryons. These two contributions drive the attractive potential in the medium-range region and almost cancel each other at shorter distances.

The correlated two-meson exchange contribution is relatively smaller than the other two contributions. This potential produces some attraction at medium range distances and some strong repulsion in the short-range region. This behavior is quite similar to the NN case which is already calculated in [1]. The striking effect is the repulsion in the short-range region where the strong attraction generated by the uncorrelated two-meson potential is cancelled by the repulsion produced by the ω-meson. Thus the correlated two-meson potential plays an important role for both the medium range attraction and the short-range repulsion in the ΛN.

We have also checked the contribution of two-kaon exchange diagrams. We have found that the two-kaon contribution is rather weak and it slightly enhances the magnitude of the potential without changing its main behavior for the ΛN potential. Therefore the two-pion exchange contribution plays a crucial role in the scalar isoscalar ΛN potential as well.

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