Λ^* hypernuclei with chiral dynamics

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Abstract. As a strangeness $S = -1$ and baryon number $B = 2$ system, the two-body bound state of $\Lambda^* = \Lambda(1405)$ and a nucleon is studied. To solve the Λ^*N system, we construct the Λ^*N potential by extending the Jülich model with couplings estimated in the chiral unitary approach. We have the Λ^*N quasi-bound state with the mass, $M_{\Lambda^*N} \sim 2366$MeV which is shallowly bound with the binding energy $B \sim 9$MeV in terms of the $\bar{K}NN$ system. Decay width of the fall apart process, where the Λ^*N resonance decays to $\pi\Sigma N$ with a nucleon being as a spectator, is estimated to be $\Gamma_{F.A} \sim 49$MeV.

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One of the most interesting topics of strange nuclear physics is possible existence of the $\bar{K}$ bound state in nuclei. Of them, the $\bar{K}NN$ system, which is the simpelest system of the $\bar{K}$ nuclei, is attractively studied and is believed to make a bound state by the $\bar{K}N$ attraction. Based on several theoretical arguments, we can take the viewpoint that Λ^* is regarded as a fundamental particle in the $\bar{K}NN$ bound system. So we study the Λ^*N two body system by constructing the Λ^*N potential. It is the most fundamental interaction in the "Λ^*-hypernuclei", which we call the nuclei with a Λ^*[1]. The Λ^*N system is labeled by two quantum numbers, the total spin S and the orbital angular momentum L, and we consider $S = 0, 1$ and $L = 0$ cases as a candidate of the ground state.

We construct the Λ^*N potential by extending the Jülich model [2, 3], which is one of the hyperon-nucleon one-boson-exchange potential models. Since the isospin of Λ^* is zero, isoscalar mesons $X(X = \sigma, \omega)$ are exchanged. In addition, considering the $\bar{K}$ exchange which contributes with an interchange of Λ^* and nucleon, the Λ^*N potential can be written by,

$$V = V_\sigma + V_\omega + V_{\bar{K}}, \tag{1}$$

where V_σ, V_ω and $V_{\bar{K}}$ represent σ, ω and $\bar{K}$ meson exchange contributions respectively.

For the lack of the information of Λ^*, vertex properties concerning Λ^* are not clear. To estimate relevant parameters, coupling constants, we adopt the microscopic structure of Λ^* obtained by the chiral unitary approach. In the chiral unitary model, Λ^* is described as a resonance in a coupled-channel meson and baryon($\pi\Sigma, \bar{K}N, \eta\Lambda, K\Xi$) multiple scattering, and we take the Λ^* meson baryon coupling constant from [4, 5]. The $\Lambda^*\bar{K}N$ coupling constant is obtained in the chiral unitary model, while the $\Lambda^*\Lambda^*X(X = \sigma, \omega)$ couplings are to be estimated. Since the exchanged meson couples to the meson and baryon in the multiple scattering, as shown in Fig. 1, the $\Lambda^*\Lambda^*X$ coupling can be estimated by summing up all microscopic contributions. We take only dominant contributions, $\pi\Sigma$ and $\bar{K}N$ for making mechanism more visible. As a necessary parameter for the estimation, meson X and two baryons coupling constant is given by the Jülich model. ω does not couple to two meseons for G-parity conservation, therefore, we have to determine the

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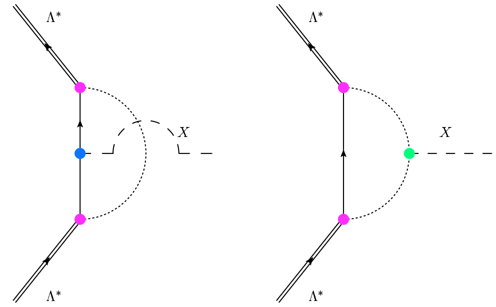

FIGURE 1. Microscopic description of the $\Lambda^*\Lambda^* X(X=\sigma,\omega)$ coupling. Left(Right) panel of the figure represents the meson X coupled diagram to the intermediate baryon(meson) in the Λ^*.

$\sigma\pi\pi$ and $\sigma K\bar{K}$ coupling. The $\sigma\pi\pi$ coupling can be determined by the σ decay and the $\sigma K\bar{K}$ coupling is assumed to be zero, since it is known to be much smaller than the $\sigma\pi\pi$ coupling.

Moreover, from the analysis of Λ^* with the chiral unitary approach, Λ^* is a superposition of two states. Therefore, $\Lambda^* N$ system consists of two states, $\Lambda^*_1 N$ and $\Lambda^*_2 N$. Here, we call higher(lower) energy state $\Lambda^*_1(\Lambda^*_2)$. Then, we solve the two-channel coupled Schrödinger equation given by,

$$H\psi = E\psi,\ H = T + V, \tag{2}$$

with

$$T = \begin{pmatrix} T_1 & 0 \\ 0 & T_2 \end{pmatrix},\ V = \begin{pmatrix} V_{11} & V_{12} \\ V_{21} & V_{22} \end{pmatrix},\ \psi = \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix}, \tag{3}$$

where T_a, V_{aa} and ψ_a stand for the kinetic energy term, potential term and wave function of Λ^*_a, while, off-diagonal components of V contribute to the transition of the $\Lambda^*_1 N$ system and the $\Lambda^*_2 N$ system.

In order to convert the $\bar{K}$ exchange amplitude into the potential, an exchange factor should be applied, which introduces the spin dependence. Since the $\Lambda^*\bar{K}N$ vertex is a scalar type and the scalar exchange in the NN potential is an attractive force, $\bar{K}$ exchange contribution is attractive(repulsive) for total spin $S=0(S=1)$. Nonzero energy transfer, due to the difference of the mass between Λ^* and nucleon, is included by the use of an effective $\bar{K}$ mass given by,

$$\tilde{m}_{\bar{K}} = \sqrt{m_{\bar{K}}^2 - (M_{\Lambda^*} - M_N)^2}, \tag{4}$$

where $m_{\bar{K}}$, M_{Λ^*} and M_N stand for $\bar{K}$, Λ^* and nucleon masses respectively. Since the effective $\bar{K}$ mass become lighter as a mass of Λ^* get closer to the $\bar{K}N$ threshold, the $\bar{K}$ exchange is stronger in the $\Lambda^*_1 N$ system than in the $\Lambda^*_2 N$ system.

In Fig. 2, we show the $\Lambda^* N$ potential in $S=0$. The $\Lambda^* N$ potential has an attractive pocket due to the attraction in the $\bar{K}$ exchange, which is not the case in $S=1$. It can be seen that the $\Lambda^*_1 N$ potential is more attractive because of the lighter effective

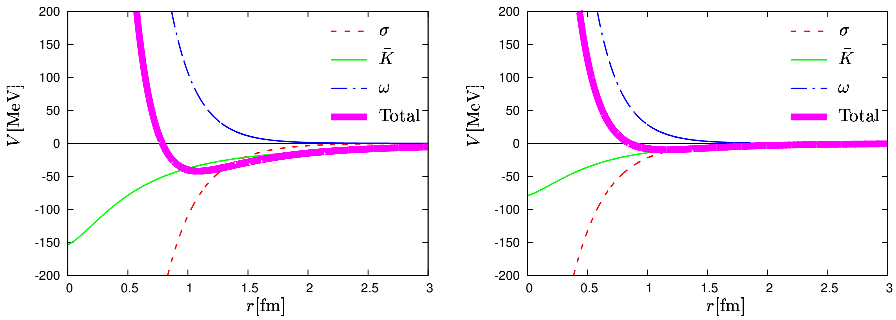

FIGURE 2. $\Lambda^* N$ potential for $S = 0$. Left(Right) panel of the figure corresponds to $V_{11}(V_{22})$.

$\bar{K}$ mass. Before solving the full coupled channel Schrödinger equation, we study the property of each $\Lambda^*_a N$ system. Then, we search for the possible bound state of each $\Lambda^*_a N$ channel separately by switching off the off-diagonal components of the $\Lambda^* N$ potential, $V_{12} = V_{21} = 0$ We find the bound state of the $\Lambda^*_1 N$ system_for total spin $S = 0$ only, with the binding energy $B = 9.5$ MeV measured from the $\bar{K}NN$ threshold. In the next place, performing the full coupled channel calculation, the $\Lambda^*_1 N$ bound state aquire a finite width through the coupling to the $\Lambda^*_2 N$ channel. We find the resonance state of the $\Lambda^* N$ system by using the real scaling method, with the two body mass in the resonance,

$$M_{\Lambda^* N} \sim 2366 \text{ MeV}. \tag{5}$$

Since it seems that the $\Lambda^*_1 N$ bound state is dominant in the $\Lambda^* N$ resonance, the resonance can be regarded as the $\Lambda^*_1 N$ quasi-bound state. Using the wave function of the $\Lambda^*_1 N$ bound state, we estimate the decay width $\Gamma_{F.A}$. In the fall apart process where the $\Lambda^* N$ resonance decay to $\pi\Sigma N$ with a nucleon being as a spectator, we obtain $\Gamma_{F.A} \sim 49$ MeV.

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