Coupled $\Lambda N - \Sigma N$ and $\Lambda NN - \Sigma NN$ systems and hyperon-nucleon interactions

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Abstract. This paper summarizes our studies of the hypertriton and describes our findings on the hyperon-nucleon interaction, especially on the role of the $\Lambda N - \Sigma N$ coupling and the strengths of the $S$-wave $YN$ interactions. We briefly comment on our ongoing analyses with electromagnetic probes.

1 Introduction

One of the most prominent features of the $\Lambda N$ interaction is the lack of the one-pion-exchange process$^1$ so that shorter range effects are more important than in the $NN$ interaction. In addition, the presence of the $\Lambda N - \Sigma N$ coupling influences the nature of the interaction. The mass difference between $\Lambda$ and $\Sigma$ is about 80 MeV and this coupling can cause significant effects in hypernuclei. Unfortunately, these features of the $YN$ interaction have not been well examined, mainly because $YN$ scattering data are scarce. Even $S$-wave $\Lambda N$ scattering lengths have yet to be determined.

Since 1993, we have analyzed the hypertriton$^2$, the lowest-mass hypernucleus, using various meson-theoretical $YN$ interactions. These analyses have clarified properties of the $S$-wave $YN$ interactions as well as confirmed the structure of the hypertriton as an extremely loosely bound system. Our findings are twofold: First, the binding energy is sensitive to the strengths of the $^3S_1$ and especially the $^1S_0$ $YN$ forces. The analyses combined with the $\Lambda N$ elastic total cross section data restrict the balance between the two force com-
ponents to a small range. Second, the $\Lambda N - \Sigma N$ coupling plays the decisive role in the binding of the hypertriton. The expectation value of the $\Lambda N - \Sigma N$ coupling potential amounts to about half of the total $YN$ potential.

Our another interest is in the behavior of the $\Lambda N - \Sigma N$ coupling around the $\Sigma N$ threshold. Predictions of the $\Lambda N$ elastic total cross sections based on various $YN$ interaction models show an enhancement just around the $\Sigma N$ threshold. Reference [3] demonstrates that this is not a simple threshold effect but is caused by a $t$-matrix pole around the threshold. This enhancement is being investigated by photo- and electroproduction processes of a $K$ meson and a hyperon on the deuteron and $^3$He targets. We are pursuing such studies [4], and report a part of them in this conference (See H.Yamamura). This paper briefly surveys our recent results.

2 Analyses of the hypertriton

We solve the exact Faddeev equations for the coupled $ANN - \Sigma NN$ system. The formulation has appeared in several articles[2], to which we would like to refer the reader. For the $YN$ system, various modern meson-theoretical interactions are used, the Jülich $A[5]$ model, and the soft core models of the Nijmegen group, NSC89[6] and NSC97[7]. The model NSC97 has six different versions, namely a, b, c, d, e and f, which contain varying relative strengths between the $^1S_0$ and $^3S_1$ force components. Among these models, only NSC89 and NSC97f bind the hypertriton at the correct binding energy. (The experimental $\Lambda$ separation energy is $0.13 \pm 0.05$ MeV.) The Jülich $A$ interaction cannot generate a bound state. This, as shown below, originates from a defect in their $^1S_0$ force.

For the $NN$ sector, we use the Paris, Bonn B and Nijmegen93 interactions, but the results above do not depend on the choice of these potentials. It is the $^1S_0$ and $^3S_1 - ^3D_1$ partial waves in the $NN$ and $YN$ subsystems that dominate the hypertriton binding energy. The convergence with increasing number of partial waves is demonstrated in Ref. [2].

Figure 1(a) illustrates baryon-baryon correlation functions in the hypertriton, the probability to find the two particles at a distance $r$. The $NN$ correlation function is quite similar to the one for the deuteron which demonstrates that the $NN$ state in the hypertriton is close to the deuteron. The correlation functions multiplied by $r^2$ are displayed in Fig. 1(b), showing that the $\Lambda N$ correlation function has a large range. (The functions $\rho$ are normalized as $\int r^2 \rho_{NN} = 1$ and $\int r^2 [\rho_{NA} + \rho_{NN}] = 1$.) Thus, as expected with the small $\Lambda$ separation energy, the hypertriton is a loosely bound system where the $\Lambda$ barely clings to a deuteron.

Table 1 shows expectation values for the kinetic and potential energies in the hypertriton. Using the Nijmegen93 $NN$ and NSC89 $YN$ potentials we see that the $NN$ subsystem is less bound than in the deuteron, and the relative kinetic energy of the $\Lambda$ with respect to the two nucleons $< T_{\Lambda-NN} >$ is larger than its potential energy $< V_{\Lambda\Lambda} >$. It is due to the $\Lambda - \Sigma$ conversion that the hyperon is bound to the two nucleons. The expectation value $< V_{\Lambda N,\Sigma N} >$
Figure 1. (a) Correlation functions for the $NN$, $AN$, and $\Sigma N$ pairs in the hypertriton. The correlation function in the deuteron is also shown for comparison. (b) Correlation functions multiplied by $r^2$.

amounts to more than half of the total $YN$ potential energy. In Table 2, we show the contributions from the $^1S_0$ and $^3S_1 - ^3D_1$ components to various $YN$ potential energies. The $^1S_0$ component dominates the expectation value of the direct potential $<V_{AN,AN}>$, while the $^3S_1 - ^3D_1$ component dominates the coupling potential $<V_{AN,\Sigma N}>$.

Table 1. Expectation values for the various kinetic and potential energies in the hypertriton using the NSC89 $YN$ and Nijmegen93 $NN$ interactions.

|            | $<T_{NN}>$ | $<T_{AN,NN}>$ | $<T_{\Sigma NN}>$ |
|------------|------------|---------------|-------------------|
| $<V_{NN}>$ | -22.32     | -1.65         | -2.05             |
| $<V_{AN,AN}>$ | -2         | -0.40         | 0.03              |
| $<V_{AN,\Sigma N}>$ | 0.02       | -1.61         | -0.06             |

Table 2. Contributions from the $^1S_0$ and $^3S_1 - ^3D_1$ force components to the expectation values of the $YN$ potential energies.

|           | $<V_{AN,AN}>$ | $<V_{AN,\Sigma N}>$ | $<V_{\Sigma N,\Sigma N}>$ |
|-----------|---------------|---------------------|-----------------------------|
| $^1S_0$   | -1.67         | -0.40               | 0.03                        |
| $^3S_1 - ^3D_1$ | 0.02       | -1.61         | -0.06                      |

Let us discuss the strengths of the $^1S_0$ and $^3S_1$ force components in relation to the restriction imposed by the binding of the hypertriton. In Fig. 2, the $AN$ elastic total cross sections are shown for the various force models. All of the curves are adjusted to the sparse experimental data which have large error bars.
Figure 2. The $\Lambda N$ elastic total cross sections $\sigma$ predicted by the various $YN$ interactions as a function of the $\Lambda$ lab momentum.

![Graph showing the elastic total cross sections as a function of the lab momentum for different potentials.](image)

Figure 3. Partial $\Lambda N$ elastic total cross sections (a) for $^1S_0$, and (b) for $^3S_1$, which are defined as $\sigma = \frac{1}{4}\sigma_s + \frac{3}{4}\sigma_t$.

![Graph showing the partial elastic total cross sections for different potentials.](image)

Among these potentials, NSC89 and NSC97f bind the hypertriton. The NSC97 potential, as mentioned, has six versions with different magnitudes between the $^1S_0$ and $^3S_1$ force components. Here, we take NSC97d as an example which does not bind the hypertriton. In Figs. 3(a) and 3(b), the separate contributions from the $^1S_0$ and $^3S_1$ states to the $\Lambda N$ elastic total cross sections are shown. They are defined as $\sigma = \frac{1}{4}\sigma_s + \frac{3}{4}\sigma_t$. As is seen in Figs. 3(a) and 3(b), the two potentials with the largest $^1S_0$ and small $^3S_1$ cross sections at low energies.
reproduce the hypertriton. From that we deduce that the scattering lengths are restricted to within $-2.7 \sim -2.4$ fm for $^1S_0$ and $-1.6 \sim -1.3$ fm for $^3S_1$.

3 Electromagnetic probes for the $YN$ and $YN N$ systems

$YN$ scattering experiments would be the best way to clarify the properties of the $YN$ interaction, but it is difficult to carry them out experimentally under present circumstances. Alternative and hopefully equally promising ways are experiments with electromagnetic probes such as $\gamma + d \rightarrow K^+ + Y + N$ and $e + d \rightarrow e' + K^+ + Y + N$, and similar experiments on $^3$He. One can obtain the information on the $YN$ interaction by analyzing the final state interactions among $YN$ or $YN N$. An inclusive $d(e, e'K^+)YN$ experiment has already been performed at TJNAF at Hall C, while the data for $d(\gamma, K^+YN)$ are being analyzed in Hall B.

What dominates the $\Lambda N$ elastic total cross section curve is an enhancement around the $\Sigma N$ threshold which is predicted by all force models. We have investigated the amplitude for the $\Lambda N - \Sigma N$ system and found that it has a pole close to that threshold in the complex momentum plane. This pole will have a significant influence on various observables in the reactions mentioned above.

Beginning with photoproduction, we recently studied the inclusive $d(\gamma, K^+)YN$ and exclusive $d(\gamma, K^+YN)$ processes for $\theta_K = 0^\circ$ and found sizeable effects of the $YN$ final state interaction. This is reported by H. Yamamura in this conference. Even more pronounced are the final $YN$ interaction effects on double polarization observables involving the recoil hyperon polarization along with a circularly polarized incoming photon. We plan to study the $e + d \rightarrow e' + K^+ + Y + N$ and $\gamma + ^3$He $\rightarrow K^+ + Y + N + N$ processes next. In the latter case, the $^3$H bound state just below the $\Lambda d$ threshold ($0.13$ MeV) is expected to yield significant effects on observables near threshold.

4 Summary

We have analyzed the hypertriton using various meson-theoretical $YN$ interactions. Among them, only NSC89 and NSC97I give the correct binding energy. The hypertriton is dominated by the $^1S_0$ and $^3S_1 - ^3D_1$ partial waves in the $NN$ and $YN$ subsystems, and has a structure such that a $\Lambda$ clings to a deuteron as expected from the small $\Lambda$ separation energy. The $\Lambda N - \Sigma N$ coupling plays the decisive role in this binding. The expectation value $<V_{\Lambda N, \Sigma N}>$ amounts to about half of the total potential energy $<V_{YN}>$. The strengths of the $^1S_0$ and $^3S_1$ $YN$ forces can be restricted by the combined analyses of the hypertriton and the $\Lambda N$ elastic cross section data. The scattering lengths have to lie within the intervals $-2.7 \sim -2.4$ fm for $^1S_0$ and $-1.6 \sim -1.3$ fm for $^3S_1$.

For further study of the $YN$ interaction, we believe experiments with electromagnetic probes are promising. We have studied the $\gamma + d \rightarrow K^+ + Y + N$ processes and found sizeable effects of the $YN$ final state interaction. The anal-
yses of $e + d \rightarrow e^\prime + K^+ + Y + N$ and $\gamma^{2}\text{He} \rightarrow K^+ + Y + N + N$ processes are underway.

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