Letter of Intent for J-PARC 50 GeV Synchrotron

Study of Σ-N interaction using light Σ-nuclear systems

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abstract

In order to study the Σ-N interaction, we plan to measure the missing mass spectra of ^{2}H(K^{-},π^{+})$\Sigma^{-}n$, ^{2}H(K^{-},π^{-})$^{2}_{\Sigma}$H, and ^{3}He(K^{-},π^{+})$^{3}_{\Sigma}$n reactions using 0.6 and 0.9 GeV/c K^{-} beams at the planned K1.1BR beam line. The purpose of the experiment is to obtain each strength of the four spin-isospin channels ((T, S) = (3/2,1), (3/2,0), (1/2,1) and (1/2,0)) of the Σ-N interaction from spectral shape of these Σ-nuclear systems. In addition, a Σ hypernuclear bound state is expected to be observed in $^{3}_{\Sigma}$n, which would be the lightest Σ-nuclear bound system. We tentatively require a beam time of 900 hours.

Historical Background and Motivation

Although the ΣN interaction at low energies ($<$ 1 GeV/c) has been experimentally studied for a long time via experiments on Σp scattering, Σ atoms, and Σ hypernuclei, we do not know the strength of the interaction well, particularly its spin-isospin dependence.

Several scattering experiments have been carried out at KEK [1, 2] but their data as well as old bubble chamber data suffered from low statistics due to short lifetime of low energy hyperons, being insufficient to extract information even on the strength of the spin-isospin averaged ΣN interaction, though they are used to constrain theoretical models on baryon-baryon interactions.

Through s-shell and p-shell Σ hypernuclear studies in 1980's and 1990's at CERN, BNL and KEK using the $(K^{-}, \pi^{\pm})$ reactions, only the $^{4}_{\Sigma}$He ($T = 1/2, S = 0$) bound state was observed [3], and heavier Σ hypernuclear data exhibited no bound state peaks [4, 5], suggesting a large conversion width and a shallow or repulsive potential for the spin-isospin averaged Σ nuclear potential. According to a theoretical prediction [6], the $^{4}_{\Sigma}$He ($T = 1/2, S = 0$) state is bound due to a particularly large contribution of the attractive ΣN $(T, S) = (3/2, 0)$ and (1/2,1) channels.

It is to be noted that the phenomenological analysis of the Σ-atomic data with a density-dependent potential suggested a Σ-nuclear potential which is attractive at the nuclear surface but strongly repulsive in the inner region [7]. A recent experiment at KEK measured quasi-free Σ production spectra via the (π^{-}, K^{+}) reaction on medium and heavy nuclei [8], which implies that the spin-isospin averaged Σ nuclear potential is strongly (≥ 30 MeV) repulsive [9, 10]. However, it is rather difficult to draw a quantitative conclusion on the interaction strength from the Σ-nuclear continuum spectrum.

The strength of the spin-isospin averaged ΣN interaction is quite sensitive to the hyperon mixing in neutron stars. If the ΣN interaction is attractive or weakly repulsive, Σ^- appears first of all the hyprons when the nuclear matter density increases in the core of neutron stars. If the ΣN interaction is significantly repulsive, Σ^- does not appear.

The $(T, S) = (3/2, 1)$ channel is particularly important from viewpoint of the short range baryon-baryon force. The quark cluster model predicts that this channel has a strong repulsive core due to Pauli effect between quarks. As shown in Table 1, the quark-model-based interaction by Fujiwara et al. predicts a strongly repulsive potential for this channel, while the meson-exchange model by Nijmegen group predicts a weakly repulsive or attractive potential (see Table 1). The strongly repulsive potential suggested by the (π^+,K^+) data and the bound state in ${}^4_\Lambda$He seem to indicate that the (T, S) = (3/2,0) and (1/2,1) channels, of which contribution in ${}^4_\Lambda$He is 94.4%, are significantly attractive, while one or two of the other channels are extremely repulsive. However, we do not have enough data to quantitatively extract the strength of each channel separately.

Theoretical predictions for interaction

Table 1 shows the contribution (MeV) of the four isospin-spin channels of the ΣN interaction to the Σ nuclear potential U_Σ calculated by G-matrix method. In various meson-exchange models by Nijmegen group (NHC, NHD, NSC89, NSC97f, and ESC04d), (T, S) = (3/2,1) and (1/2,0) channels are weakly repulsive or weakly attractive, and (T, S) = (3/2,0) and (1/2,1) channels are weakly or strongly attractive. This large spin-isospin dependence (namely, a large Lane term) is caused by the π and ρ exchanges. The quark model (fss2), which expresses the short range force using the quark cluster model but the middle and long range forces using the meson-exchange picture, predicts strengths of (T, S) = (3/2,1), (1/2,1), (1/2,0) channels similar to the Nijmegen models, while only the (3/2,1) channel is predicted to be strongly repulsive. This is caused by Pauli blocking between quarks in two different baryons. The purpose of the proposed experiment is to experimentally determine each of these values.

Objectives of the experiment

In the proposed experiment, we measure the missing mass spectrum of the ^{2}H(K^-,π^+)$\Sigma^- n$, ^{2}H(K^-,π^-)${}^2_\Sigma$H, and ^{3}He(K^-,π^+)${}^3_\Sigma$n reactions with and without tagging a Λ to identify $\Sigma N \rightarrow \Lambda N$ conversion. The spectra will be taken for K^- momentum and scattering angle of 0.6 GeV/c; 4^0 and 0.9 GeV/c; 15^0, which correspond to a small momentum transfer (0.10 GeV/c) and a large momentum transfer (0.27 GeV/c).

^{2}H target

Since the ^{2}H(K^-,π^+)$\Sigma^- n$ reaction produces only the $(T, S) = (3/2, 1)$ state, the missing mass spectrum (an unbound continuum spectrum) is expected to be sensitive to the repulsive $(T, S) = (3/2, 1)$ interaction strength. On the other hand, the ^{2}H(K^-,π^-)$\Sigma^+ n$ ($\Sigma^0 p$) reaction produces both the $(T, S) = (3/2, 1)$ and (1/2,1) state. Thus measurement of

Model	(T,S)					
	(3/2,1)	(3/2,0)	(1/2,1)	(1/2,0)	Sum	Ref.
NHC-D	9.4	-5.4	-9.6	2.1	-8.7	[11]
NHC-F	18.6	-5.3	-10.9	4.2	3.5	[11]
NSC89	3.7	-5.8	-4.2	3.0	-3.6	[11]
NSC97f	-2.2	-6.2	-7.6	5.2	-11.6	[11]
ESC04d*	24.0	-20.2	-21.0	6.5	-26.0	[12]
fss2*	41.2	-9.2	-23.9	6.7	7.5	[13]

Fermi momentum is $k_F = 1.0$ fm^{-1} (* $k_F = 1.35$ fm^{-1}).

Table 1: Contribution of the four isospin-spin channels of the ΣN interaction to the Σ nuclear potential U_Σ calculated by G-matrix method. "fss2" is the baryon-baryon interaction model based on the quark cluster model for short range forces, and others are various versions of baryon-baryon interaction models based on meson-exchange picture by the Nijmegen group.

both spectra allows us to extract the strength of the $(T,S) = (1/2,1)$ as well as (3/2,1) channels. In the ^{2}H(K^-,π^-)$^2_\Sigma$H reaction, the spectrum with a Λ in the final state (Λ-tagged spectrum) due to the $\Sigma^0 p$ ($\Sigma^+ n$) $\rightarrow \Lambda p$ conversion provides better information on the interaction.

Since both initial and final states are three body systems in these reactions, the spectrum can be exactly calculated assuming various different strengths of the (T,S) = (3/2,1) and (1/2,1) channel. Therefore, the strengths can be reliably determined from the data. By measuring the spectra at 0.6 GeV/c; 4^0 ($q_\Sigma = 0.10$ GeV/c) and 0.9 GeV/c; 15^0 ($q_\Sigma = 0.27$ GeV/c), we can investigate energy dependence of the ΣN interaction. In addition, the spin-flip amplitude becomes as large as the spin-non-flip one at 0.9 GeV/c for N(K^-,π^-)Σ reaction [15], while the spin-non-flip amplitude dominates at 0.6 GeV/c for both N(K^-,$\pi^\pm$)Σ reactions. Therefore, the $(T,S) = (3/2,0)$ and (1/2,0) channels also contribute to the 0.9 GeV/c ^{2}H(K^-,π^-)$^2_\Sigma$H spectrum.

The ^{2}H(K^-,$\pi^\pm$)ΣN reactions at 0.76 GeV/c [14], and 0.87 GeV/c [16] were previously studied, where the latter experiment aimed at searching for a strangeness -1 dibaryon state. Those spectra with a poor statistical quality were not analyzed in view of the ΣN interaction. The observed peak at the threshold in the ^{2}H(K^-,π^-)ΣN reaction with a Λ in the final state was simply interpreted as a cusp, although the information on the ΣN interaction is contained in the spectral shape. In the proposed experiment, a precise comparison between calculated spectra and measured ones with much better statistics and for both 0.6 and 0.9 GeV/c beam momenta allows us to extract strengths of the interaction.

^{3}He target

In the $^3_\Sigma$n system, there are four ΣN spin-isospin components with the ratio of 0.004 : 0.496 : 0.496 : 0.004 for (T,S) = (3/2,1), (3/2,0), (1/2,1) and (1/2,0), assuming that the two nucleon (pn) system has both T=1,S=0 and T=0,S=1 components equally. Both of (T,S) = (3/2,0) and (1/2,1) ΣN channels are expected to be attractive due to meson

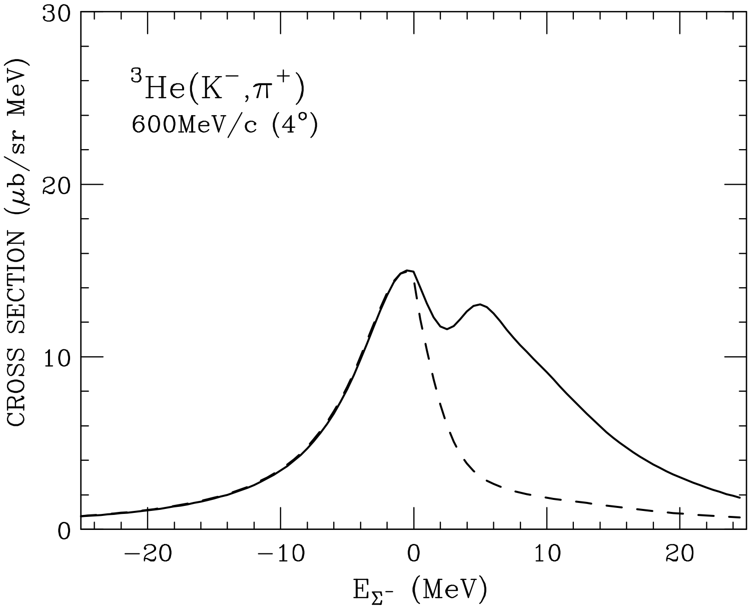

Figure 1: Calculated cross section of $^3\text{He}(K^-,\pi^+)^3_\Sigma\text{n}$ using the ΣN interaction potential called AP-F which is equivalent to Nijmegen model F. Dotted curve shows the spectrum for the final state of Λnn due to the $^3_\Sigma\text{n}\rightarrow \Lambda nn$ conversion.

exchange. Therefore, the $^3_\Sigma$n hypernucleus is predicted to be barely bound [18]. Figure 1 is the missing mass spectrum of the $^3\text{He}(K^-,\pi^+)^3_\Sigma\text{n}$ reaction at 0.6 GeV/c at 4^0 calculated by Harada using the SAP-F interaction equivalent to the Nijmegen F model (NHF in Table 1). The spectrum with a Λ in the final state (Λ-tagged spectrum) due to the $^3_\Sigma\text{n}\rightarrow \Lambda nn$ conversion (as shown in dotted line in Fig. 1) corresponds to a bound state of the hypernucleus, if the peak energy is below the Σ^- production threshold. It would be the second example of the bound Σ hypernucleus, and the lightest Σ-nuclear bound system.

The peak energy directly gives the strengths of the (T,S) = (3/2,0) and (1/2,1) channels. In addition, the peak width gives a strength of the conversion ($\Sigma N \rightarrow \Lambda N$) in these channels. Although similar information has been partly obtained from the $^4_\Lambda$He bound state data [17], the $^3_\Sigma$n bound state provides us with more detailed information on the interaction because the three-body systems can be exactly calculated by Faddeev method and precise comparison between the two-body interaction models and the experimental data is possible.

The $^3\text{He}(K^-,\pi^+)^3_\Sigma\text{n}$ reaction was previously investigated at BNL to search for a dibaryon [19] and for Σ-hypernuclei [20, 21], but the missing mass spectrum of the $^3_\Sigma$n system was not analyzed in the former experiment, and the statistical quality of the missing mass spectrum is quite poor in the latter experiment.

Setup

In the experiment, we use 0.6 GeV/c and 0.9 GeV/c K^- beam from the K1.1BR beam line. The setup is illustrated in Fig. 2. We use the final part of the beam line as a beam

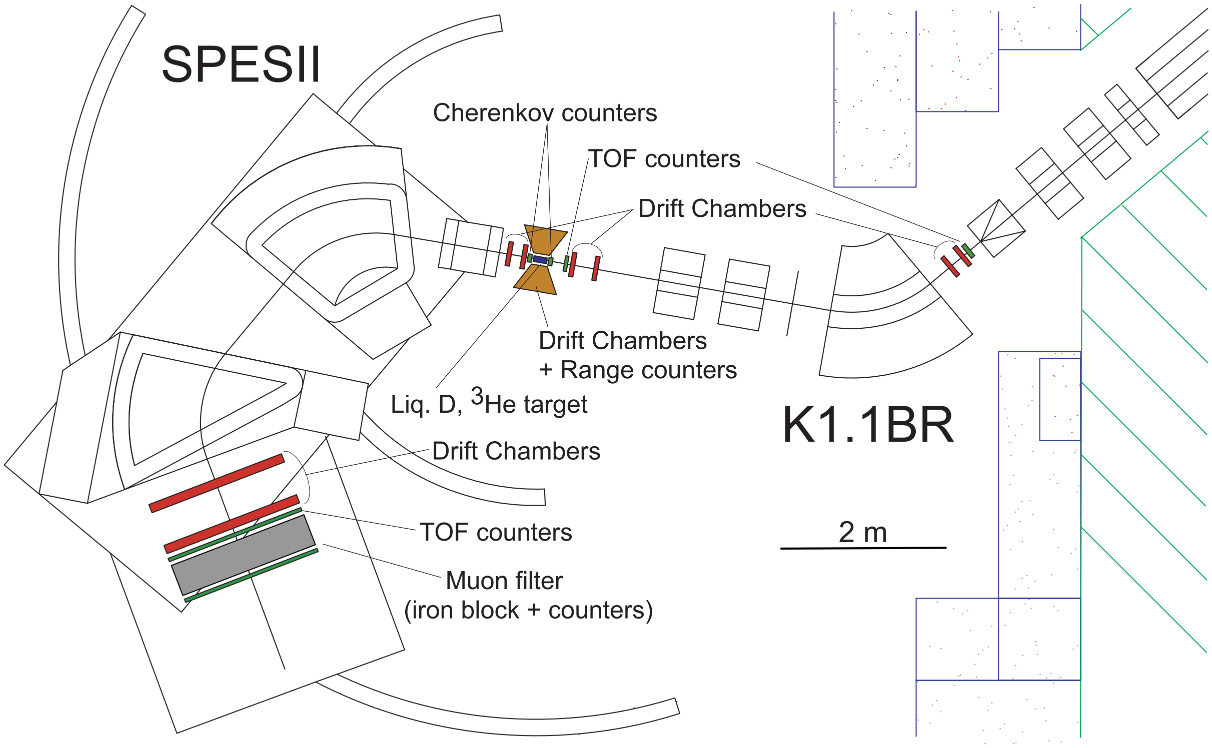

Figure 2: Experimental setup for the proposed experiment at the K11BR beam line.

spectrometer and employ the existing SPESII spectrometer for scattered particles. The beam spectrometer is required to have a momentum resolution better than 1.5 MeV/c (FWHM). We install 1mm-pitch MWPC's at upstream and downstream of the beam spectrometer magnet.

The SPESII spectrometer has an acceptance of 20 msr and a momentum resolution of ∼1 MeV (FWHM). Since we need a resolution of ∼3 MeV, we can use a target with ∼3 g/cm^2 thickness (18cm for liquid D_2 and 28 cm for liquid ^{3}He). We employ a set of drift chambers at upstream and downstream of the SPESII magnet. Aerogel Čerenkov counters around the target and muon filter counters at the end of the spectrometer are necessary to identify the reaction, as used in our E13 experiment at the K1.8 beam line.

In order to identify $\Sigma N \rightarrow \Lambda N$ conversion events, we install two sets of drift chambers and a set of plastic counters (range counters) around the target to identify a Λ particle by tracking protons and pions from a Λ decay.

Beam time estimate

With the full proton beam (9 μA) at 30 GeV/c, we expect 2.7×10^5 K^-/spill at 0.6 GeV/c and 2.3×10^6 K^-/spill at 0.9 GeV/c. We choose the scattering angle around 4^0 at 0.6 GeV/c (momentum transfer ∼0.1 GeV/c) and 15^0 at 0.9 GeV/c (momentum transfer ∼0.27 GeV/c)

At $p_K = 0.6$ GeV/c, the cross section of the $K^-p \rightarrow \Sigma^-\pi^+$ reaction at $\sim 0^0$ is 1.2 mb/sr, and those of $K^-p \rightarrow \Sigma^+\pi^-$ and $K^-n \rightarrow \Sigma^0\pi^-$ reactions at $\sim 0^0$ are 0.1 and 1.0

mb/sr, respectively. Here we roughly assume that the cross section on deuteron target is the same by neglecting distortion.

The analysis efficiency of the spectrometers is assumed to be 0.4. The efficiency to detect Λ's from $\Sigma N \to \Lambda N$ conversion is assumed to be 0.05, and the probability of Σ conversion to Λ is roughly assumed to be 0.3 for 0.6 GeV/c beam.

Then the yield of the Σ^0 plus Σ^+ production events is 2100/hour, and that of the Λ-tagged events is 32/hour. To collect 5×10^3 tagged events in ^{2}H(K^-,π^-) spectrum, we need about 160 hours for ^{2}H(K^-,π^-) at 0.6 GeV/c. At 0.9 GeV/c; 15^0, the beam intensity is 8.5 times higher but the Σ^0 production cross sections is about 1/3 and the probability of conversion should be much smaller. Therefore, we require the same beam time of 160 hours. On the other hand, for the ^{2}H(K^-,π^+) spectrum, the $\Sigma^- n$ system does not undergo Σ conversion and we do not have to measure the tagged spectrum. So, much less beam time, say, 30 hours, is necessary for each of the beam momenta.

In the case of ^{3}He target run, the expected cross section at 0.6 GeV/c; 4^0 for Λ-tagged events shown in Fig. 1 ($\sim$ 140 μb/sr) gives 9 events/hour. To collect 2×10^3 tagged events, we require 200 hours. At 0.9 GeV/c GeV/c; 15^0, we also require 200 hours for the same reason as the deuteron target case.

By adding 120 hours for detector tuning, we tentatively require 900 hours of beam time, although the present estimate may be largely changed depending on the results of theoretical calculations.

Future possibilities

In the future, we also measure a ^{3}He(K^-,π^0)$^3_\Sigma$H spectrum using 0.6 GeV/c K^-, employing a π^0 spectrometer. This hypernuclear system has a different contributions of the four spin-isospin components in the ΣN interaction. Here, a high-resolution π^0 spectrometer will be also planned to be constructed for the purpose of γ-ray spectroscopy of mirror and neutron-rich Λ hypernuclei via the (K^-,π^0) reaction.

Another possible experiment is to observe Coulomb-assisted Σ hypernuclear bound states in medium heavy nuclei. Even if the Σ-nuclear potential is repulsive, several Σ bound states are predicted to be observed on Ni target by the (K^-,π^+) reaction. Such experiments will also provide information on the Σ nuclear potential and the spin-isospin averaged ΣN interaction [15]. If a spin-orbit splitting of a Σ single-particle orbit is observed, we can obtain valuable information on the strength of the ΣN spin-orbit interaction.

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