PROCEEDINGS OF SCIENCE

Observation of Ξ bound states in the ^{12}C$(\mathbf{K}^-,\mathbf{K}^+)X$ reaction at 1.8 GeV/c in J-PARC

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We have carried out a pilot data taking of the J-PARC E05 experiment to search for the bound state peaks of $^{12}_{\Xi}$Be in the ^{12}C$(K^-,K^+)X$ reaction at 1.8 GeV/c. The measurement was performed at the K1.8 beam line of the J-PARC hadron experimental hall with a typical K^- beam intensity of 6×10^5 every six seconds. So far the best energy resolution of about 6 MeV$_{FWHM}$ was achieved with the existing SKS spectrometer. With a reasonable statistics, we have succeeded to observe peak structures in the bound region, which seems to suggest that the potential depth of Ξ would be deeper than 14 MeV estimated in the previous measurements.

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1. Introduction

By extending the nucleon-nucleon force in flavor $SU(3)$, we would like to establish a modern picture of generalized nuclear force models, in relation to quantum chromo-dynamics (QCD). The forces between two octet baryons, such as N-N, Y-N, Y-Y, are our subjects. Here the Y stands for a baryon with strangeness, that is a hyperon (Λ, Σ, Ξ). Because of the short life time (10^{-10} sec.) of the hyperons, it is difficult to carry out Y-N, Y-Y scattering measurements. Therefore, we have been investigating the spectroscopy of hypernuclei to extract the information on the Y-N and Y-Y interactions. For example, the fine structure of p-shell Λ hypernuclei has revealed spin-dependent interactions of Λ-N force. A precious information on the Λ-Λ force was obtained in the "Nagara" event in emulsion [1, 2]. Knowing that the Σ-N force is repulsive on average, the last key information is the Ξ-N interaction. In a recent study of Lattice QCD calculations [3], the Ξ-N interaction potentials are available for various $S=-2$ channels, although the pion mass is still large compared to its physical mass. Such a comparison between theory and experiment in near future would be very much interesting.

Whether the Ξ hypernuclei exist as bound states or not has been a long-standing issue in strangeness nuclear physics. A recent observation of the "Kiso" event [4] in emulsion strongly suggests that a bound state of ^{14}N-Ξ^- system exists with a binding energy larger than the $3D$ atomic-state binding energy of 0.17 MeV. They observed the process $\Xi^- + ^{14}\mathrm{N} \rightarrow ^{10}_{\Lambda}\mathrm{Be} + ^{5}_{\Lambda}\mathrm{He}$ with the binding energy of Ξ^- to be 4.38 ± 0.25 MeV[1]. If the $^{10}_{\Lambda}$Be is in an excited level, the binding energy is 1.11 ± 0.25 MeV.

There were, so far, two measurements on the $^{12}\mathrm{C}(K^-, K^+)X$ reaction by KEK E224 [5] and BNL E885 [6]. The latter measurement has better statistics. In fact, the BNL E885 claimed evidence for the $^{12}_{\Xi}$Be bound state from a shape analysis near the binding threshold. The potential depth of Ξ was estimated to be about 14 MeV, for which the binding energy was about 4.5 MeV. However, they were not able to observe any bound-state peaks because of their poor energy resolution of 14 MeV_{FWHM}.

The J-PARC E05 experiment is looking for the $^{12}_{\Xi}$Be bound states as clear peaks to determine the binding energies. A new spectrometer called "Strangeness -2 Spectrometer (S-2S)" is now under construction[2] dedicated to the (K^-, K^+) reaction spectroscopy with an energy resolution of $\lesssim 2$ MeV_{FWHM}. The solid angle acceptance is about 55 msr. With this energy resolution, the information on the conversion width of the Ξ bound state would be obtained. If the conversion width through the $\Xi^- p \rightarrow \Lambda\Lambda$ is large, there is a possibility to excite double-Λ hypernuclei, especially their excited levels, directly in the (K^-, K^+) reaction. However, the present K^- beam intensity at J-PARC hadron experimental hall is too low to achieve both good energy resolution and high statistics. Thus, we planned to perform a pilot run having reasonable statistics and moderate energy resolution. With a thick target, we are not able to have a good energy resolution due to energy loss straggling in the target, while we can get more statistics.

[1] Updated values were reported in this conference by K. Nakazawa.

[2] A talk on "S-2S" was presented by S. Kanatsuki in this conference.

2. E05 pilot run

We have carried out a pilot run of the J-PARC E05 experiment at the K1.8 beam line of J-PARC hadron experimental hall, from October 26 to November 19 in 2015. The typical K^- beam intensity at 1.8 GeV/c was $6 \times 10^5 K^-$ per spill (2.4-sec. beam duration every 6 seconds) with a primary proton beam power of 39 kW. The K^-/π^- ratio was about 0.8. We took data using a 9.36-g/cm^2 ^{12}C target for about 10 days and a 9.54-g/cm^2 CH_2 target for about 2 days. The CH_2 target was used for the $p(K^-,K^+)\Xi^-$ reactions at five different incident momenta between 1.5 and 1.9 GeV/c. The total number of K^-'s irradiated on targets amounted to 100 G.

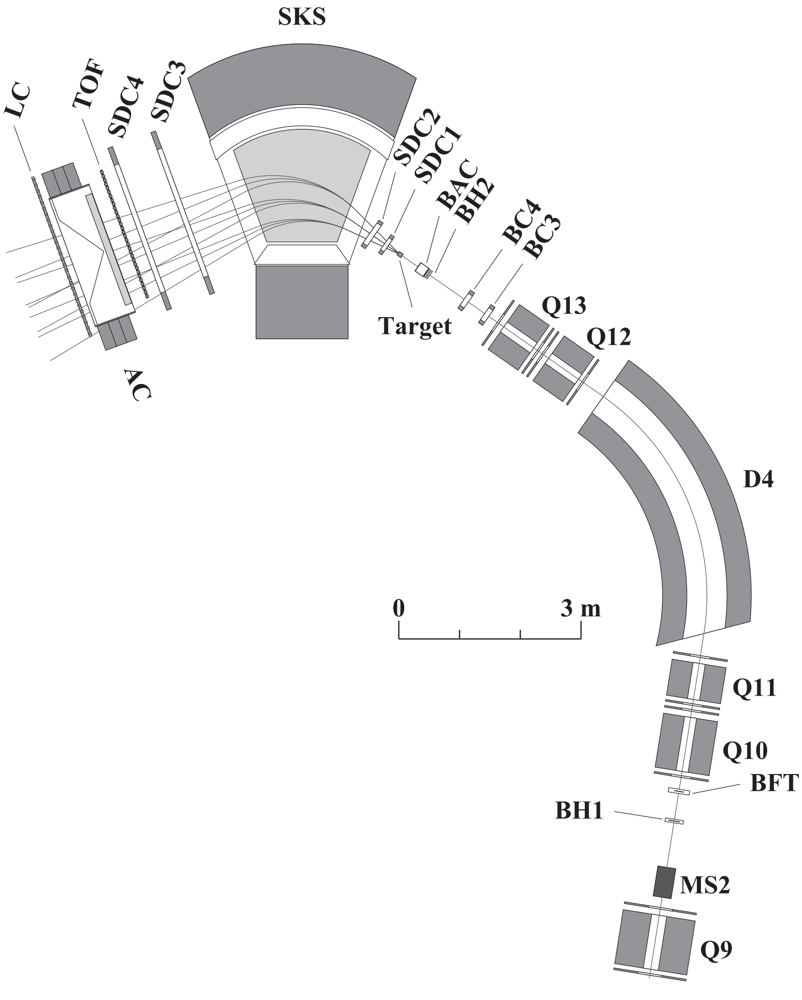

Figure 1: A schematic view of the experimental setup during the E05 pilot run.

The experimental setup of the E05 pilot run is shown in Fig. 1. In the upstream part of the K1.8 beam line, we have a double-stage electrostatic separator system, and the K^- beam was finally selected through a mass slit (MS2). The incident K^- beam was defined with two sets of plastic scintillation counters (BH1 and BH2) and an aerogel Čerenkov counter (BAC) to suppress π^-'s at the on-line trigger level. The beam momentum was analyzed track by track with the tracking detectors (BFT, BC3 and BC4). The beam line spectrometer was composed of 4 quadrupole magnets

(Q10-Q13) and one dipole magnet (D4). The design momentum resolution of the spectrometer was $\Delta p/p \sim 5 \times 10^{-4}_{FWHM}$.

The outgoing K^+ was momentum analyzed with the SKS spectrometer with four sets of drift chambers (SDC1-4). In the pilot run, the SKS central momentum was set at about 1.3 GeV/c covering about 110 msr. The momentum resolution of the SKS was $\Delta p/p \sim 3 \times 10^{-3}$. These are great advantages of the SKS compared with the spectrometers used for the (K^-, K^+) reaction in the past.

The particles detected in the SKS were identified with a time of flight measured with a plastics scintillation counter wall of "TOF" correcting with the flight path and momentum obtained from the tracking chambers. The aerogel Čerenkov counter wall "AC" was installed to suppress pions in the trigger level, and the "Lucite Counter (LC)" for suppression of protons.

3. Analysis for the $p(K^-, K^+)\Xi^-$ reaction

The overall energy resolution was evaluated with the peak for the $p(K^-, K^+)\Xi^-$ reaction at 1.8 GeV/c as shown in Fig. 2, and was confirmed to be 5.4 MeV_{FWHM}. It is a factor of two better with respect to the 10 MeV of the BNL E885 for proton target. In the Carbon kinematics, the BNL E885 resolution was estimated to be 14 MeV, while our estimate is about 6 MeV which was dominated by the target energy loss straggling. Absolute energy scale of the (K^-, K^+) missing mass was adjusted with this peak position. About 6,000 Ξ^-'s were identified per day.

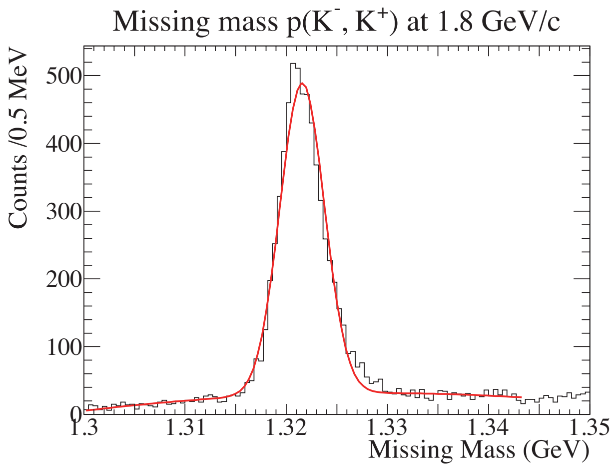

Figure 2: Missing-mass spectrum for the $p(K^-, K^+)X$ reaction at 1.8 GeV/c obtained with a CH_2 target. The peak corresponds to the reaction on proton and the continuous background below the peak is the contribution of quasi-free Ξ production from ^{12}C.

The incident momentum dependence of the forward cross sections of the $K^- + p \to K^+ + \Xi^-$ reaction was obtained at 1.5, 1.6, 1.7, 1.8 and 1.9 GeV/c. The statistics at each momentum was more than about 20 times of the statistics of the old bubble chamber data. At 1.8 GeV/c, the statistics was about 100 times to obtain the angular distribution in detail. In a preliminary analysis, we have confirmed with improved statistics that the relative strengths of the cross sections peaks at about 1.8 GeV/c as suggested by Dover and Gal [7].

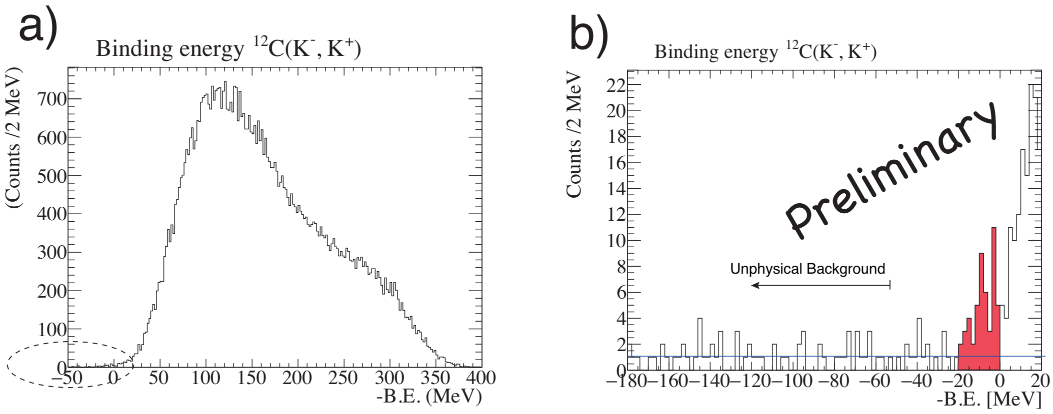

Figure 3: Missing-mass spectra for the ^{12}C$(K^-,K^+)X$ reaction at 1.8 GeV/c. a) in a wide energy range, and b) a close-up view near the binding energy threshold indicated with a dashed oval in a).

4. Analysis for the ^{12}C(K^-,K^+) reaction

The missing mass spectrum of the ^{12}C(K^-,K^+) reaction is shown in Fig. 3-a) as a function of negative values of binding energy (B.E.) of Ξ^- in ^{11}B. Owing to the large momentum acceptance of the SKS, we were able to obtain the spectrum in a wide energy range. The largest part of the spectrum comes from the quasi-free production of Ξ's peaking at about 110 MeV, and the contribution of Ξ^* can be seen in the higher energy region. Due to the large momentum transferred to Ξ (∼550 MeV/c) in this reaction, the sticking probability is small, so that there are very few events in the bound region ($-$B.E. < 0) in this vertical scale. A large shift of the quasi-free peak is also due to the large momentum transfer.

Next we magnify the view in the bound region as indicated in Fig. 3-a) as a dashed oval, and plot it in Fig. 3-b). Here, there should be no physical processes with a binding energy value larger than about 40 MeV ($-$B.E.≤ -40 MeV), where the ground state of $^{12}_{\Lambda\Lambda}$Be exists. Therefore, we think these events in this region should be the background, mostly coming from Kaon decay-in-flight and having almost flat distribution (1.08 counts/ 2 MeV). Then, we observed a significant event excess of about 55 events in the binding energy region between 0 and 20 MeV (-20 MeV$\geq$ $-$B.E.$\geq$0 MeV) shown in red in Fig. 3-b). This is the same level of statistics obtained by the BNL E885 (42-67 events). Above the binding threshold ($-$B.E.$\geq$ 0 MeV), we clearly see a rise for the quasi-free production.

The momentum acceptance of the SKS corresponding to this energy region is almost flat. We, therefore, tried a fit to the spectrum assuming there exist two gaussian peaks in the bound region and a quasi-free component as a straight line convoluted with the detector energy resolution of 5.4 MeV. We also assumed a flat background component as suggested from the Fig. 3-b). The fitting result is shown in Fig. 4. The red solid line is the fit where the dotted lines show each component. The peak positions were obtained to be about 9 MeV and 2 MeV. If this is the case, the potential depth of the Ξ in $A = 12$ must be deeper than 14 MeV. Alternative idea could be that there exists one broad structure in the bound region; assuming such a fit model the width was about 16 MeV and the peak position was still deep at around 7 MeV. Such a large width is not expected in Ξ

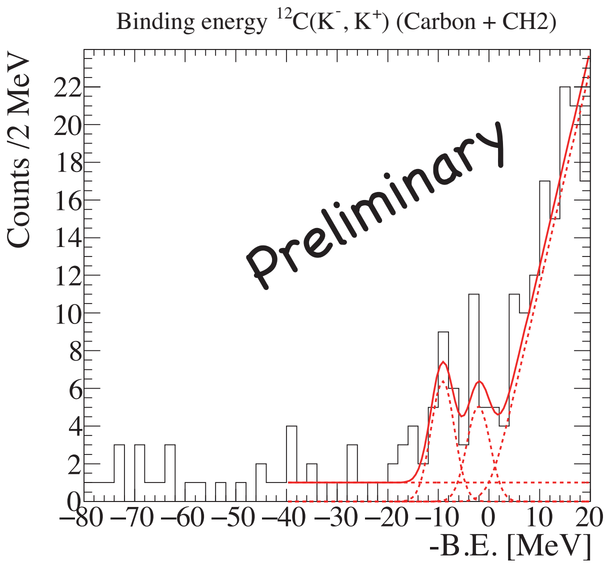

Figure 4: Missing-mass spectrum for the $^{12}\mathrm{C}(K^-,K^+)X$ reaction at 1.8 GeV/c near the binding energy threshold fitted with two gaussian peaks. The width was fixed at 6 MeV$_{FWHM}$.

hypernuclei, and it is statistically significant of the two peak structure.

5. Summary

In the pilot run of the J-PARC E05 experiment, we were able to observe peak structures in the bound region of the $^{12}\mathrm{C}(K^-,K^+)X$ reaction. The energy resolution was estimated to be about 6 MeV$_{FWHM}$ which was a great improvement from the previous resolution of 14 MeV. With this improvement of the energy resolution, we were able to observe the peaks in the bound region; at least, two peaks. The analysis is still preliminary, but a fit to the spectrum with two gaussians suggest the binding energy would be about 9 MeV. It implies that the potential depth of the Ξ in $A = 12$ would be deeper than 14 MeV.

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