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Study of kaonic nuclei by the $d(\pi^+, K^+)$ reaction at J-PARC

Yudai Ichikawa[∗a,b], **H. C. Bhang**[c], **S. Bufalino**[d], **H. Ekawa**[a], **P. Evtoukhovitch**[e], **A. Feliciello**[d], **H. Fujioka**[a], **S. Hasegawa**[b], **S. Hayakawa**[f], **R. Honda**[g], **K. Hosomi**[g], **K. Imai**[b], **S. Ishimoto**[h], **C. W. Joo**[c], **S. Kanatsuki**[a], **R. Kiuchi**[a], **T. Koike**[g], **H. Kumawat**[i], **Y. Matsumoto**[g], **K. Miwa**[g], **M. Moritsu**[j], **T. Nagae**[a], **M. Naruki**[a], **M. Niiyama**[a], **Y. Nozawa**[a], **R. Ota**[f], **A. Sakaguchi**[f], **H. Sako**[b], **V. Samoilov**[e], **S. Sato**[b], **K. Shirotori**[j], **H. Sugimura**[a,b], **S. Suzuki**[h], **T. Takahashi**[h], **T. N. Takahashi**[k], **H. Tamura**[g], **T. Tanaka**[f], **K. Tanida**[c], **A. O. Tokiyasu**[j], **Z. Tsamalaidze**[e], **B. J. Roy**[i], **M. Ukai**[g], **T. O. Yamamoto**[g] **and S. B. Yang**[c]

[a] *Department of Physics, Kyoto University, Kyoto 606-8502, Japan*
[b] *ASRC, Japan Atomic Energy Agency, Ibaraki 319-1195, Japan*
[c] *Department of Physics and Astronomy, Seoul National University, Seoul 151-747, Korea*
[d] *INFN, Istituto Nazionale di Fisica Nucleare, Sez. di Torino, I-10125 Torino, Italy*
[e] *Joint Institute for Nuclear Research, Dubna, Moscow Region 141980, Russia*
[f] *Department of Physics, Osaka University, Toyonaka 560-0043, Japan*
[g] *Department of Physics, Tohoku University, Sendai 980-8578, Japan*
[h] *High Energy Accelerator Research Organization (KEK), Tsukuba, 305-0801, Japan*
[i] *Nuclear Physics Division, Bhabha Atomic Research Centre, Mumbai, India*
[j] *Research Center for Nuclear Physics, Osaka 567-0047, Japan*
[k] *RIKEN, Saitama 351-0198, Japan*
E-mail: yudai@scphys.kyoto-u.ac.jp

An experimental search for the K^-pp bound state, which is considered the simplest kaonic nucleus, is performed by using the $d(\pi^+, K^+)$ reaction at J-PARC K1.8 beam line (J-PARC E27 experiment). The first data taking as a pilot run was carried out in June, 2012. The missing-mass spectrum of this reaction studied at the beam momentum of 1.7 GeV/c, which allows the production of $\Lambda(1405)$, was obtained for the first time and a significant peak shift by $\sim$40 MeV was observed in the Y^* region. In a preliminary proton-coincidence analysis, a sharp spike due to the ΣN-ΛN coupling and a broad enhancement around 2.3 GeV/c^2, which might be attributed to the K^-pp bound state, was clearly observed.

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∗Speaker.

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1. Introduction

An antikaon and a nucleus may form a bound state (a kaonic nucleus), due to the strong attraction of $\bar{K}N$ in I=0 channel. A K^-pp bound state, which is the bound state of an antikaon and two nucleons, with the total charge +1 and the isospin 1/2, is expected to be the simplest kaonic nucleus. Various theoretical calculations for a K^-pp bound state have been carried out and the existence of the bound state is supported in these calculations. However, the binding energy and the decay width depend on the $\bar{K}N$ interactions and the calculation methods. After Akaishi and Yamazaki's theoretically prediction of its existence in 2002 [1], several experiments have been performed to look for a signal of kaonic nuclei.

The first observation of the K^-pp bound state was reported by the FINUDA Collaboration at DAΦNE [2]. They investigated the stopped K^- reaction on several kinds of targets and observed a number of Λp pairs emitted in back to back. They observed a bump structure in the invariant mass spectrum of these Λp pairs from the ^{6}Li, ^{7}Li and ^{12}C targets. By assuming that this structure is due to the K^-pp bound state, the binding energy and the decay width were evaluated to be $115^{+6}_{-5}(stat)^{+3}_{-4}(syst)$MeV and $67^{+14}_{-11}(stat)^{+2}_{-3}(syst)$ MeV, respectively. Another positive result of the K^-pp bound state was also reported by the DISTO Collaborations at SATURNE [3]. They reanalyzed the data-set of the $p + p \rightarrow \Lambda + p + K^+$ reaction at $\mathrm{T_p} = 2.85$ GeV and observed a bump structure in ΔM_{K^+} missing-mass and $M_{p\Lambda}$ invariant-mass spectra in large transverse momentum of protons and kaons. The binding energy and decay width were determined as $103 \pm 3(stat) \pm 5(syst)$ MeV and $118 \pm 8(stat) \pm 10(syst)$MeV, respectively.

However, these results are not sufficient to draw firm conclusion about the existence of the K^-pp bound state. There is a theoretical interpretation that the observed bump structure of the FINUDA experiment could be explained by the final state interaction [4]. Furthermore, the binding energy and the decay width are not consistent with each other. Therefore it is important to further investigate the bound state experimentally in different reactions.

2. J-PARC E27 experiment

The J-PARC E27 experiment was proposed to search for the K^-pp bound state by using the (π^+, K^+) reaction on a liquid deuterium target at 1.7 GeV/c. This experiment is performed at the K1.8 beam line of J-PARC hadron experimental facility [5].

Incident pions were momentum-analyzed with the K1.8 beam line spectrometer. Their momentum was reconstructed by using the third-order transport matrix method. The momentum resolution was expected to be less than 0.1% (FWHM). The beam pion was selected by the time-of-flight(TOF) between two sets of plastic scintillation hodoscopes.

Emitted kaons ware measured with the Superconducting Kaon Spectrometer (SKS). Their momentum was calculated by using the Runge-Kutta method. The SKS magnetic field was set at 2.36 T. Emitted particles in the momentum range of 0.8-1.1 GeV/c and with a production angle between 2° and 16° were detected. The spectrometer has a solid-angle acceptance of 100 msr and a momentum resolution of ∼0.2% (FWHM). The kaon was identified by TOF in combination with the flight path length.

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The formation process of the K^-pp bound state in this reaction was theoretically discussed by Yamazaki and Akaishi [6]. They treated the formation of the K^-pp bound state with a Λ(1405) production as a doorway. In this model, the $\Lambda(1405)$ is first produced of a neutron in a deuteron, $\pi^+ + n \to \Lambda(1405) + K^+$, and the $\Lambda(1405)$ merges with a proton in the deuteron to produce the K^-pp bound state. The sticking probability of the $\Lambda(1405)$ is estimated to be on the order of 1%. There are many background processes of quasi-free hyperon production such as Λ, Σ, Λ(1405), Σ(1385), $\Lambda\pi$ and $\Sigma\pi$. Therefore, the signal of K^-pp is estimated to be very small compared with the background and it would be difficult to be observed in the inclusive measurement.

In this experiment, a coincidence of a proton from the decay of K^-pp was requied in order to suppress these quasi-free background contributions. In the quasi-free hyperon productions, a proton in high momentum (>250 MeV/c) can be emitted from the decay of the hyperon in the forward direction within 60° in the laboratory frame kinematically, while a spectator proton in a deuteron has low momentum below the energy threshold for a proton to escape from the liquid target and is not detected. Therfore, if we detect one proton at >60°, the quasi-free backgrounds are eliminated and the signal for the decay of K^-pp bound state such as $K^-pp \to \Lambda p$, $\Lambda \to p\pi^-$ is enhanced. If we further require two protons, we can reject the quasi-free background completely, because two detectable protons cannot be emitted from the quasi-free process.

Such a proton was detected with a range counter array (RCA) which comprises of six units surrounding the deuterium target from 39° to 122° and its geometrical coverage is ∼26%. Each unit consists of five layers of plastic scintillators with the thickness of 1 cm, 2 cm, 2 cm, 5 cm and 2 cm. The particle velocity was measured as the TOF between the target center and the first layer with a 50-cm distance. Particles (π/p) were identified by using the TOF and range information.

3. Analysis and preliminary result

A pilot run of the J-PARC E27 experiment was carried out in June, 2012. The overall performance of the spectrometer system was checked in the $p(\pi^+,K^+)\Sigma^+$ reaction at 1.58 GeV/c. The mass resolution of the Σ^+ hyperon was found to be 2.4 MeV/c^2 (FWHM), and the obtained cross section of the Σ^+ production was consistent with an old measurement [7].

In order to check the contribution of proton in deuterium, we took the $p(\pi^+,K^+)X$ data at the same beam momentum for the deuterium target of 1.7 GeV/c. In this reaction, hyperons such as Σ^+, $\Sigma^+(1385)$, $\Sigma\pi$ and $\Lambda\pi$ are expected to be produced. The Σ^+ peak was clearly separated from other processes in the missing-mass spectrum and the obtained cross section was consistent with an old measurement [7]. Figure 1 shows a missing-mass spectrum in the $\Sigma^+(1385)$ and $Y\pi$ production region fitted with these two components. The obtained cross section and the spectrum shape for the $\Sigma^+(1385)$ production were also consistent with old data [8].

3.1 Inclusive analysis

The measurement of $d(\pi^+,K^+)X$ reaction at the beam momentum of 1.7 GeV/c was performed for the first time. The beam intensity was typically 3.0×10^6 pion/spill and the total number of beam pions were 3.3×10^{11}.

Figure 2 shows a comparison of an obtained (π^+,K^+) missing-mass spectrum (filled circles) with a simulation (histogram) for the quasi-free processes. The simulation takes account of the

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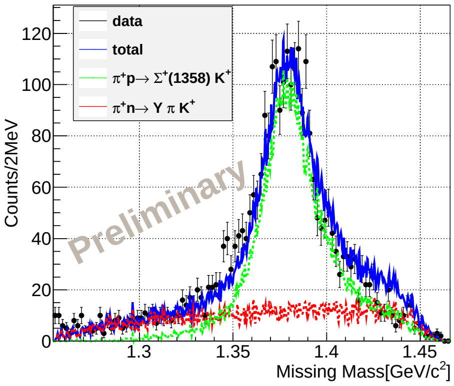

Figure 1: A preliminary missing-mass spectrum of the $p(\pi^+,K^+)$ reaction at 1.7 GeV/c. The experimental data are shown by black circles with statistical errors. The spectrum was fit with the $\Sigma(1385)^+$ and $Y\pi$ productions.

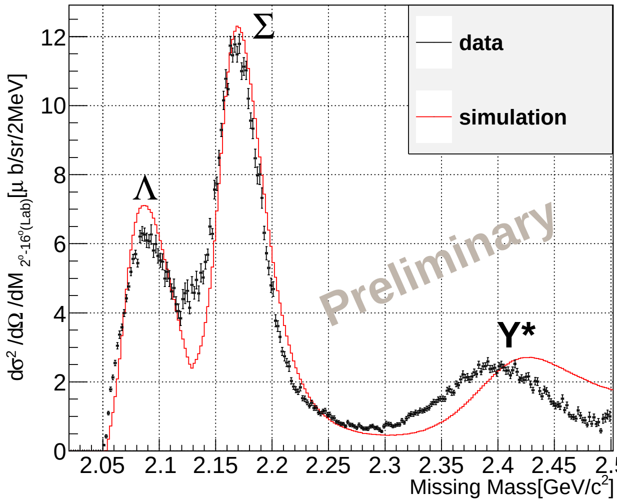

Figure 2: A preliminary missing-mass spectrum of the $d(\pi^+,K^+)$ reaction at 1.7 GeV/c. The experimental data are shown by black circles with statistical errors. A simulated spectrum is shown by a red histogram.

known elementary cross sections of these hyperon productions [8, 9] folded with the momentum distribution of a nucleon inside deuteron according to the Bonn potential [10]. In the quasi-free Λ / $\Sigma^{0/+}$ region, the simulation almost reproduces the experimental spectrum, except for an enhancement around 2.13 GeV/c^2, which can be attributed to a cusp structure due to the strong ΣN-$\Lambda N(I=1/2)$ coupling.

In the Y^* region around 2.4 GeV/c^2, a significant peak shift by $\sim$40 MeV/c^2 to lower mass side is observed. Both $\Sigma(1385)$ and $\Lambda(1405)$ productions have the same order of production cross sections in the elementary processes in this region. Here, it is worthwhile to mention that the LEPS collaboration has reported a missing-mass spectrum of the $d(\gamma,K^+\pi^-)X$ reaction and they did not find such a peak shift [11]. In the case of their reaction, the $\Sigma(1385)$ production is dominant in the Y^* region. Therefore, if the spectrum shape of the $\Sigma(1385)$ would not change in deuteron as in the case for the LEPS data, the $\Lambda(1405)$ spectrum shape might be a cause of the present mass shift.

3.2 Exclusive analysis

We can define a proton/pion coincidence probability as a function of the (π^+,K^+) missing-mass by taking a ratio of two missing-mass histograms; one with the coincidence of one proton/pion and the other for the inclusive (π^+,K^+) spectrum. The obtained pion coincidence probability is almost consistent with a simulation for the quasi-free processes considering the angular distributions and decay branches for pion emissions.

As mentioned in the previous subsection, protons from hyperon decays in the quasi-free processes cannot be emitted in the side-ward angles (>60°). Thus, by requiring the proton hit in the middle segment of RCA, which covers from 69° to 92°, the contribution of the quasi-free background should be negligible. Figure 3 shows a preliminary missing-mass spectrum with one proton coincidence in the middle segment of RCA. Figure 4 shows a preliminary proton coincidence probability spactrum for the middle segment. It should be noted that a sharp excess for the ΣN-ΛN cusp is clearly observed at around 2.13 GeV/c^2. In addition, a broad enhancement is observed

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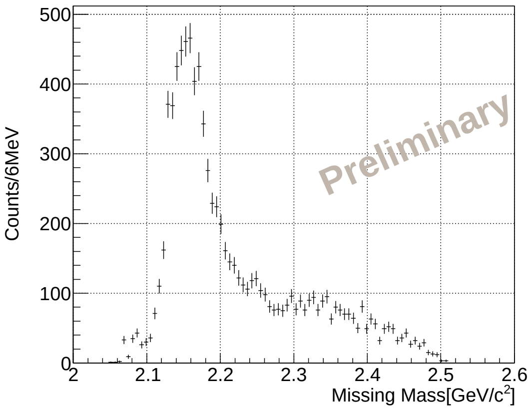

Figure 3: A preliminary missing-mass spectrum of $d(\pi^+,K^+)$ reaction at 1.7 GeV/c with one-proton coincidence in the middle segment of RCA (see text).

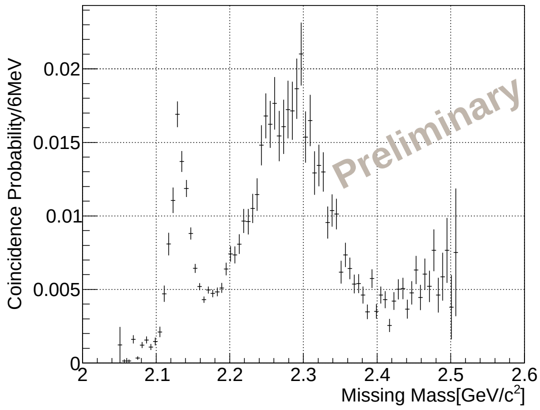

Figure 4: A preliminary proton coincidence probability spectrum as a function of the missing-mass in the $d(\pi^+,K^+)$ reaction at 1.7 GeV/c for the middle segment of RCA.

around 2.3 GeV/c^2 with high statistical significance. It indicates that there is a sizable source of proton emission in this mass region (hardly from a quasi-free process). A possible origin of this broad enhancement is the production of K^-pp bound state.

4. Summary and future work

We measured the missing-mass spectrum of the $d(\pi^+,K^+)X$ reaction at 1.7 GeV/c for the first time in the pilot data taking of the J-PARC E27. Together with the $p(\pi^+,K^+)X$ data, the overall shape of the inclusive missing-mass spectrum was well reproduced based on a quasi-free picture except for a significant peak shift in the Y* region. In the proton coincidence analysis, a ΣN-ΛN cusp structure at 2.13 GeV/c^2 and a broad enhancement around 2.3 GeV/c^2 were clearly observed. The enhancement may originate from the K^-pp bound state. A detailed analysis on the acceptance and detection efficiencies of the RCA is in progress as well.

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