Inclusive spectrum of the $d(\pi^+, K^+)$ reaction at 1.69 GeV/c

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1. Introduction. Studies of hyperon productions off nuclei have provided us useful information on $YN$ interactions. For example, the $(\pi^+, K^+)$ reaction at 1.05 GeV/c has been used to determine the $\Lambda$ potential depth in nuclear matter by observing single-particle energy levels of $\Lambda$ bound states in heavy nuclei [1]. The $\Sigma$-nucleus potential is known to...

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be repulsive in medium-heavy nuclei [2] from the spectrum shape of the $(\pi^-, K^+)$ reaction at 1.2 GeV/c near the binding threshold. Further, importance of $\Sigma N$-$\Lambda N$ coupling was recognized from the observations of a prominent cusp structure at the $\Sigma N$ threshold in $K^- + d \rightarrow \pi^- + \Lambda + p$ reaction [3]. Recently, the $\Sigma N$ cusp has been intensively investigated in the $p + p \rightarrow p + K^+ + \Lambda$ reaction at COSY [4, 5]. These results were listed in Ref. [6].

In the present measurement of the $(\pi^+, K^+)$ reaction at 1.69 GeV/c, the productions of hyperon resonances such as $\Lambda(1405)$ and $\Sigma(1385)$ are possible. Information on the $\Lambda(1405)/\Sigma(1385)$-$N$ interaction would be extracted from the data.

A goal of the present measurement (J-PARC E27 experiment) is to look for a $K^-pp$, a bound state of a $K^-$ with two protons, in the $d(\pi^+, K^+)$ reaction. In this reaction, one possible production mechanism for the $K^-pp$ was discussed in Ref. [7]; a hyperon resonance $\Lambda(1405)$ is produced in the $\pi^+\rightarrow K^+ + \Lambda(1405)$ process as a doorway to the $K^-pp$ formation through $\Lambda(1405)+p\rightarrow K^-pp$. Here, "n" and "p" indicate a neutron and a proton in a deuteron, respectively. In this respect, it should be noted that the $\pi^- + p\rightarrow K^0 + \Lambda(1405)$ reaction at 1.69 GeV/c is one of a few reactions, in which $\Lambda(1405)$ was clearly observed [8]. The incident $\pi^+$ momentum in the E27 was fixed at the same value.

However, a sticking probability of $\Lambda(1405)$ to form the $K^-pp$ would be as low as $\sim 1\%$ [7]. Thus we need coincidence of some decay products of the $K^-pp$ to enhance the signal-to-background ratio. In the E27 experiment, we installed range counter arrays (RCA) surrounding the liquid deuterium target for detection of high-momentum (\geq 250 MeV/c) protons. The detail of the RCAs and their analyses are described elsewhere. In this Letter, we focus on the inclusive missing-mass spectrum in the $d(\pi^+, K^+)$ reaction, and aim to understand the predominant quasi-free processes in this reaction.

At the pion incident momentum of 1.69 GeV/c, a simple quasi-free picture or an impulse approximation is expected to work properly [9]. Here, we considered the following processes.

In the $d(\pi^+, K^+)$ reaction, not only quasi-free hyperon productions of $\Lambda$ and $\Sigma^{+0}$,

$$\pi^+ + "n" \rightarrow K^+ + \Lambda,$$

(1)

$$\pi^+ + "n" \rightarrow K^+ + \Sigma^{+0}; \quad \pi^+ + "p" \rightarrow K^+ + \Sigma^+,$$

(2)

but also hyperon resonance productions of $\Lambda(1405)$ and $\Sigma(1385)^{+0}$,

$$\pi^+ + "n" \rightarrow K^+ + \Lambda(1405),$$

(3)

$$\pi^+ + "n" \rightarrow K^+ + \Sigma(1385)^{0}; \quad \pi^+ + "p" \rightarrow K^+ + \Sigma(1385)^+,$$

(4)

and non-resonant productions of $\Lambda\pi$ and $\Sigma\pi$,

$$\pi^+ + "N" \rightarrow K^+ + \Lambda + \pi; \quad \pi^+ + "N" \rightarrow K^+ + \Sigma + \pi,$$

(5)
take place. The cross sections of elementary processes have been already measured [8, 10].

There are two previous measurements on the $d(\pi^+, K^+)$ reaction in this momentum region. One measurement is at a lower incident momentum of 1.4 GeV/c [11], in which the production of hyperon resonances, $\Sigma(1385)$ and $\Lambda(1405)$, is kinematically forbidden. On the other hand, the $\Sigma N$ cusp was observed in the missing-mass spectrum around 2.13 GeV/c\(^2\) in the events with a large multiplicity measured by counters surrounding the target. The other measurement using a deuterium bubble chamber was carried out at incident beam momenta between 1.1 and 2.4 GeV/c [12]. They measured incident energy dependence of
total cross sections for several reactions as well as the $\Lambda$-$\pi$ invariant-mass distributions in the $\pi^+ + d \to K^+ + $ $\Lambda + \pi^+ + (n_s)$ reaction. The present measurement is the first measurement of the inclusive $d(\pi^+, K^+)$ missing-mass spectrum covering a wide missing-mass region from $\Lambda$ and $\Sigma$ to $\Lambda(1405)/\Sigma(1385)$.

2. Experimental Setup. The measurement was carried out at the K1.8 beam line [13] of the J-PARC hadron experimental hall. The detailed information was described in Ref. [13, 14]. A typical beam intensity was $3 \times 10^6$ per 6-second spill cycle with a spill length of about 2 seconds.

The incident pion beams were measured with the K1.8 beam line spectrometer. Their momenta were reconstructed by using a third-order transfer matrix with the estimated momentum resolution of $0.18 \pm 0.01\%$ (FWHM).

A liquid deuterium target of 1.99-g/cm$^2$ thickness was used for the $d(\pi^+, K^+)$ reaction at 1.69 GeV/$c$, and a liquid hydrogen target of 0.85-g/cm$^2$ thickness for the $p(\pi^+, K^+)$ reactions at 1.58 and 1.69 GeV/$c$ for calibrations. The target shape was cylindrical; 67.3 mm in diameter and 120 mm in length. The target fully covered the incident beam with a typical beam size of $\sigma_H = 7.6$ mm (horizontal) and $\sigma_V = 4.2$ mm (vertical).

Scattered kaons were analyzed with the Superconducting Kao n Spectrometer (SKS). The particle momentum was obtained with the Runge-Kutta method by using a calculated field map. The SKS magnetic field was set at 2.36 T. Emitted particles in the momentum range of 0.8–1.3 GeV/$c$ with a scattering angle between 2$^\circ$ and 16$^\circ$ were analyzed. The very forward events (less than 2$^\circ$) were cut out in order to keep good vertex resolution and suppress beam-oriented backgrounds in the $(\pi^+, K^+)$ events, such as $\mu^+$ from $\pi^+$ decay and secondary particles produced from various support structures. By using SKS, the particle momenta were measured with a resolution of about 0.2% (FWHM) in an acceptance range of about 100 msr. Kaons were identified by a time-of-flight in combination with the flight path length obtained for each track.

The acceptance of SKS is shown in Fig. 1 as a function of the particle momentum and scattering angle. It was obtained with a Monte Carlo simulation based on Geant4 [15]. In the figure, three kinematical lines are shown for the $p(\pi^+, K^+)$,$\Sigma^+$ reactions at 1.58 GeV/$c$ (solid line) and 1.69 GeV/$c$ (dashed line) and the $d(\pi^+, K^+)K^-pp$ reaction at 1.69 GeV/$c$ assuming the binding energy of 100 MeV (dotted line).

3. Analysis. After selecting a ($\pi^+, K^+$) event requiring a fiducial volume cut in the target, a missing-mass spectrum is obtained as a double differential cross section of $d^2\bar{\sigma}/d\Omega/dM$ averaged over the scattering angle from 2$^\circ$ to 16$^\circ$. The double differential cross section is calculated as

$$\frac{d^2\bar{\sigma}}{d\Omega dM} = \frac{A}{N_A(\rho x) N_{\text{beam}} \Delta\Omega \Delta M \epsilon},$$

where $A$ is the target mass number, $N_A$ the Avogadro constant, $\rho x$ the target mass thickness, $N_K$ the number of detected kaons in the missing-mass interval $\Delta M$, $N_{\text{beam}}$ the number of beam pions on the target, $\Delta\Omega$ the solid angle of SKS and $\epsilon$ the overall experimental efficiency resulting from DAQ, detectors, and analysis cuts including the $K^+$ decay factor. A typical value of the experimental efficiency is $\epsilon = 17.5 \pm 0.9\%$. 

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3.1. Calibrations. First we need to adjust the missing-mass scale of the \( d(\pi^+, K^+) \) reaction. The relative momentum scale between the beam line spectrometer and SKS was studied by introducing a beam at 0.9 GeV/c through the two spectrometers without a target. Further, we can study the missing-mass scale in the \( p(\pi^+, K^+) \) reaction at 1.58 and 1.69 GeV/c by looking at the \( \Sigma^+ \) mass. By combining all these information, the incident beam momentum was corrected with a linear function as \( p_{\text{corr}}^{K+} = p_{K+} - 0.0087 \text{ GeV/c} \), where \( p_{\text{corr}}^{K+} \) is the corrected beam momentum and \( p_{K+} \) is the measured beam momentum. The systematic uncertainty of the momentum scale is estimated to be \( \pm 1.1 \text{ MeV/c} \) from these calibrations.

We also optimized the missing-mass resolution of \( p(\pi^+, K^+)\Sigma^+ \) reaction at 1.58 GeV/c by correcting the \( K^+ \) momentum with a fifth order polynomial in the horizontal \( (dx/dz) \) and vertical \( (dy/dz) \) direction cosines of the particle orbit. After this correction, the missing-mass resolution was obtained to be \( 2.8 \pm 0.1 \text{ MeV/c}^2 \) (FWHM), which corresponds to the missing-mass resolution of \( 3.2 \pm 0.2 \text{ MeV/c}^2 \) (FWHM) at the \( \Sigma N \) cusp region in the \( d(\pi^+, K^+) \) reaction. This resolution is at least by a factor of 2 better than the previous measurement with the same reaction (3.2–5.5 MeV/c^2 in \( \sigma \)) [11].

After the missing-mass scale adjustment, the validity of the corrections was tested in the \( \pi^+ + p \to K^+ + \Sigma(1385)^+ \) productions at 1.69 GeV/c. In Fig. 2 (a), we show the missing-mass spectrum in the \( \Sigma(1385)^+ \) region in the \( p(\pi^+, K^+) \) reaction at 1.69 GeV/c. A fitting result with a Lorentzian function for the \( \Sigma(1385)^+ \) (dashed line) and the three-body phase space distributions for the \( \Lambda \pi K^+ \) (dotted line) and the \( \Sigma \pi K^+ \) (dot-dashed line) is also shown. The \( \Sigma(1385)^+ \) mass and width are found to be \( 1381.1 \pm 3.6 \text{ (stat.) MeV/c}^2 \) and \( 42 \pm 13 \text{ (stat.) MeV, respectively, which are consistent with the PDG values [16] within the statistical errors.} \]

Next, we compared the cross section of the \( p(\pi^+, K^+)\Sigma^+ \) reaction between our measurement and an old measurement with the same momenta of 1.58 and 1.69 GeV/c by Candlin et al. [17]. As shown in Fig. 1, the kinematical lines at two different incident momenta run through different acceptance areas. In both cases, we obtained a reasonable agreement.
between our data and the previous ones within the large errors. Here we show the case for 1.69 GeV/c in Fig. 2 (b). The same was true in the cross section of \( \Sigma^+(1385) \) [10].

### 3.2. \( \pi^+ + d \rightarrow K^+ + X \) at 1.69 GeV/c.

Figure 3 (a) shows the obtained missing-mass (denoted as \( MM_d \)) spectrum for the \( d(\pi^+, K^+) \) reaction at 1.69 GeV/c. As we discussed in Sec. 1, we can find three major structures in the spectrum: quasi-free \( \Lambda \) component from the reaction (1), quasi-free \( \Sigma \) component from the reaction (2), and quasi-free \( Y^* \) component from the reactions (3), (4). The non-resonant phase space component from the reaction (5) constitutes a broad structure under the quasi-free \( Y^* \) bump.

We made an attempt to reproduce the double differential cross section \( d^2\sigma/d\Omega/dM \) with a simulation by using the cross sections \( d\sigma/d\Omega \) of each reaction obtained in the past experiments with a smearing by the nucleon Fermi motion in a deuteron. Here, we used a deuteron wave-function derived from the Bonn potential [18]. For the \( \pi^+ + \pi^- + p \) reactions, we used the cross sections and angular distributions of \( \pi^- + p \) reactions in Ref. [8] assuming the isospin symmetry. For the \( \pi^+ + p \) reactions, we used the values in Ref. [10].

Here, since the cross section for the quasi-free \( \Sigma^0 \) process [8, 19, 20] features rather large errors in the forward angles, an adjustment for the normalization of the cross section was applied within the measurement errors for the quasi-free \( \Sigma \) component. By taking into account the Fermi motion \( p_F \), the participant nucleon is assumed to be in the off-mass shell as \( M_p^{*2} = \left( M_d - \sqrt{M_d^2 + p_F^2} \right)^2 - p_F^2 \), where \( M_d \) and \( M_s \) are deuteron and the spectator on-shell nucleon mass (spectator model [21]). The outgoing \( K^+ \) momentum, \( p_K \), was distributed according to the reaction kinematics with the mass of the participant nucleon \( M_p^* \) and its momentum \( p_F^* \). Then, the missing-mass \( MM_d \) was calculated as \( MM_d^2 = (E_{\pi} + M_d - E_K)^2 - |p_{\pi} - p_K|^2 \). Thus, we obtained the simulation result as shown in Fig. 3 (a) indicated by a solid line.

We find an overall structure of the spectrum is well reproduced except for two distinct differences. One difference is a cusp structure observed at around 2.13 GeV/c; a magnified view is shown in Fig. 3 (b) for the forward scattering angles from 2° to 8° in the laboratory.
Fig. 3  (a) The missing-mass spectrum (\(MM_d\)) of the \(d(\pi^+, K^+)\) reaction for the scattering angle from \(2^\circ\) to \(16^\circ\) (Lab) per 2 MeV/c\(^2\). The crosses and solid line show the experimental data and the simulated spectrum, respectively. The result of the \(Y^*\) peak fitting is also shown with a dashed red line for the experimental data. (b) The missing-mass spectrum (\(MM_d\)) in 2.09 to 2.17 GeV/c\(^2\) region for the forward scattering angle from \(2^\circ\) to \(8^\circ\) (Lab) per 0.5 MeV/c\(^2\), which is shown by crosses. The fitting results are shown by solid and dashed lines (\(\chi^2/ndf = 1.11\)). See details in the text.

frame. A peak at \(\Sigma N\) thresholds (2.1289 GeV/c\(^2\) for \(\Sigma^+ n\) and 2.1309 GeV/c\(^2\) for \(\Sigma^0 p\)) is prominent in the figure. When we chose the scattering angle larger than \(8^\circ\), the cusp is less prominent due to the large quasi-free backgrounds. Although this \(\Sigma N\) cusp may not necessarily distribute according to a Lorentzian function, here we fit the cusp structure with this function in order to compare with the previous results summarized in Ref. [6]. Through a fit of the Lorentzian function folded with the resolution of 1.4 MeV/c\(^2\) in \(\sigma\) for the cusp (solid line) and a third-order polynomial function for a continuum background (dashed line), we obtained the peak position at 2130.5 \(\pm\) 0.4 (stat.) \(\pm\) 0.9 (syst.) MeV/c\(^2\), the width of \(\Gamma = 5.3^{+1.4}_{-1.2}\) (stat.) \(^{+0.6}_{-0.3}\) (syst.) MeV and the differential cross section of \(d\sigma/d\Omega = 10.7 \pm 1.7 \mu b/sr\). The \(\chi^2/ndf\) of this fitting was 1.11. The systematic errors of these values were estimated in \(\sigma\) taking into account uncertainties in the missing-mass scale, fitting ranges, the missing-mass resolution (\(\pm\) 0.08 MeV/c\(^2\)), the binning of the missing-mass spectrum and background functional shapes by changing the third to fifth order polynomials. This result is the first observation of the \(\Sigma N\) cusp structure in the inclusive spectrum of the \(d(\pi^+, K^+)\) reaction.

Such a cusp can appear at the opening of a new threshold in order to conserve the flux and the associated unitarity of the \(S\)-matrix. However, the cusps are not always seen in experimental cross sections. On the other hand, a cusp structure can be pronounced when a pole exists near the threshold [22]. Miyagawa and Yamamura [23] suggested that the poles exist near the \(\Sigma N\) threshold in a second or third quadrant of the complex plane of the \(\Sigma N\) relative momentum by using several \(YN\) potential models. Therefore, the cusp structure at the \(\Sigma N\) threshold would not be a simple threshold effect but could be caused by a nearby pole.

The obtained peak position is consistent with the previous measurements in Ref. [6]. In several reactions existence of a shoulder at about 10 MeV higher mass was reported [6]. We can conclude nothing on the existence of the shoulder structure because of the large quasi-free \(\Sigma\) backgrounds. In addition, the width seems to be smaller than the averaged value of

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12.2 ± 1.3 MeV in other reactions [6]. In order to discuss the possible pole position, we need realistic theoretical calculations taking into account the $(\pi^+, K^+)$ reaction mechanism. It will be very interesting to further compare our results including angular distributions and coincidence data with high momentum protons in the RCA. Note that we can suppress the quasi-free Λ/Σ productions in the coincidence data because the decay particles of such hyperons are out of the RCA acceptance.

The other difference is a "shift" of the broad bump position for the $Y^*$ productions. In this region the contributions of $\Sigma(1385)^{+0}$ and $\Lambda(1405)$ overlap each other, and it is not possible to disentangle them in an inclusive measurement. When we fit the bump with a Gaussian function, we obtained the peak position at 2400.6 ± 0.5 (stat.) ± 0.6 (syst.) MeV/$c^2$ for the present data and at 2433.0 $^{+2.8}_{-1.6}$ (syst.) MeV/$c^2$ for the simulation. The systematic error for the simulation was estimated taking into account uncertainties of the differential cross sections of $Y^*$, the $Y^*$ mass and fitting ranges. The same fitting procedure was applied for a $MM_p' (=\sqrt{(E_\pi + M_p - E_K)^2 - |\vec{p}_\pi - \vec{p}_K|^2})$ spectrum, which is the missing-mass spectrum calculated assuming a proton at rest as the target. We obtained the peak position at 1376.1 ± 0.4 (stat.) ± 0.5 (syst.) MeV/$c^2$ and 1398.5 $^{+2.6}_{-1.6}$ (syst.) MeV/$c^2$, respectively. The amount of the peak shift is 32.4 ± 0.5 (stat.) $^{+2.9}_{-1.7}$ (syst.) (22.4 ± 0.4 (stat.) $^{+2.7}_{-1.7}$ (syst.) MeV/$c^2$ for the $MM_\Lambda$ ($MM_p$) spectra to the low mass side. Even if the peak position of the simulated spectrum was adopted instead of the fitted one, the difference is reduced by just 4 MeV/$c^2$. There could be an uncertainty of several MeV to the low-mass side arising from our simple spectator model in the simulation, which was estimated from the difference of the peak positions when the balance of the off-shellness between the participant and spectator nucleons was changed. The small difference of about 3 MeV/$c^2$ for the quasi-free $\Sigma$ productions is within this uncertainty.

More sophisticated theoretical analyses taking into account $Y^*N$ interactions in the final state might explain the observed puzzling "shift".

It should be noted that the LEPS group recently reported a similar inclusive spectrum for the $d(\gamma, K^+\pi^-)$ reaction at a 1.5–2.4 GeV photon energy region and found no significant shift in the $Y^*$ region [24]. As we mentioned in Sec. 1, the old deuterium bubble chamber experiment measured the invariant mass distribution of $\Lambda + \pi^+$ in the $\pi^+ + d \to K^+ + \Lambda + \pi^+(n_s)$ reaction. The $\Sigma(1385)^+$ mass and width in deuterium turned out to be 1386.6 ± 4.4 MeV/$c^2$ and 49 ± 11 MeV when it decays into $\Lambda + \pi^+$.

4. Summary. The inclusive missing-mass spectrum of the $d(\pi^+, K^+)$ reaction at the beam momentum of 1.69 GeV/c was obtained in high statistics and high energy resolution for the first time. The present data cover a wide missing-mass range from the $\Lambda$ production threshold to the $\Lambda(1405)/\Sigma(1385)$ region. The overall structure of the spectrum was understood with a simple quasi-free picture based on the known elementary processes.

However, there were two peculiar deviations from this picture. One observation is the $\Sigma N$ cusp, of which position was found to be 2130.5 ± 0.4 (stat.) ± 0.9 (syst.) MeV/$c^2$ with the width of $\Gamma = 5.3^{+1.4}_{-1.2}$ (stat.) $^{+0.6}_{-0.3}$ (syst.) MeV. The peak position is consistent with previous measurements. Further detailed studies including the present data would reveal the information on the $\Sigma N$-$\Lambda N$ coupling strength and the pole position. Moreover, the centroid of the broad bump structure in the $Y^*$ production region was significantly shifted to low mass.
side as compared with a simple quasi-free simulation, by about 32.4 ± 0.5 (stat.) +2.9 −1.7 (syst.) (22.4 ± 0.4 (stat.) +2.7 −1.7 (syst.)) MeV/c² for MM_p (MM_d) spectra. In order to clarify the origin of the peak shift, further experimental and theoretical studies are necessary.

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