Proposal for 50 GeV Proton Synchrotron

Optimization of Low Momentum K^+ Beam Using a Beam Degrader

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December 9, 2024

Short summary of the Proposed Experiment

Beamline:	K1.8BR
Beam:	0.4–0.6 GeV/c K^+
Beam intensity:	2×10^3 /spill at 0.5 GeV/c
Flat-top:	2 sec (4.24 sec/spill)
Target:	Liquid deuterium ϕ80 mm
Reaction:	$K^+d \to K^0pp$
Spectrometer:	K1.8BR Beamline Spectrometer + Hyperon Spectrometer
Beam time:	2 days
Estimated Yield:	5.0×10^5 events

Abstract

In preparation for the proposal submission following the Letter of Intent (LOI) "Search for the Θ^+ in $K^+d \to K^0pp$ Reaction with Hyperon Spectrometer" submitted to the 38th J-PARC PAC, we request a two-day test beam time to study the K^+ beam at the K1.8BR beamline. Previous tests at the K1.8BR beamline have explored the K^+ beam momentum down to 0.7 GeV/c. However, the Θ^+ experiment requires a lower momentum beam in the 0.4–0.5 GeV/c range. Information on the momentum bite and beam intensity is crucial for determining the appropriate momentum regions and data collection times for the final experiment.

The ultimate goal of this test experiment is to optimize the experimental design by finding low-momentum beam conditions using a beam degrader. This effort will also provide valuable data for future experiments with low-momentum beams at the J-PARC. We propose conducting the test experiment immediately following the scheduled E72 experiment at the K1.8BR beamline, which uses the same detector setup as the Θ^+ experiment.

1 Motivation

We are preparing to propose an experiment using the 0.5 GeV/c K^+ beam at the K1.8BR beamline to search for Θ^+ in the $K^+d \to K^0pp$ reaction. The basic idea has been submitted in the Letter of Intent (LOI) titled "Search for the Θ^+ in $K^+d \to K^0pp$ Reaction with Hyperon Spectrometer"[1]. The decay products of Θ^+ (K^0p, followed by $K^0_S \to \pi^+\pi^-$) will be exclusively measured using the Hyperon Spectrometer, which consists mainly of a time projection chamber (HypTPC)[2] and a 1-T superconducting magnet[3]. This experiment uses one of the simplest direct formations using the K^+ beam with a deuteron target to form the Θ^+ and measures the decay products exclusively, providing an unprecedented opportunity to find an evidence of Θ^+ if it exists.

To design a detailed experimental plan, we conducted Geant4 simulations with the full geometry implemented and incorporated the measured detector resolution. Using the Hyperon Spectrometer analysis software, we obtained the expected experimental results. Events were generated assuming impulse scattering and Θ^+ production as the s-channel added with assumed cross-sections of 5 mb and 500 μb, respectively. The simulations utilized previous measurements of $K^+n \to K^0p$ differential cross-section data[4, 5] and the nucleon momentum distribution in deuterons[6], as described below.

Experimental data for differential cross sections for $K^+n \to K^0p$ reaction near 0.45 GeV/c are available from Refs.[4] and [5], as shown in Fig. 1. In the single-scattering impulse approximation, the differential cross sections were parametrized with spin non-flip and spin-flip nuclear amplitudes for $I = 0$ and $I = 1$ channels in the K^+n c.m. system and so-called inelastic form factors I_0 and J_0 for scattering from a deuteron[5]. In our work, we chose a simpler parametrization. We combined two datasets at 0.434 GeV/c[4] and 0.47 GeV/c[5], and fitted them to a series of Legendre polynomial:

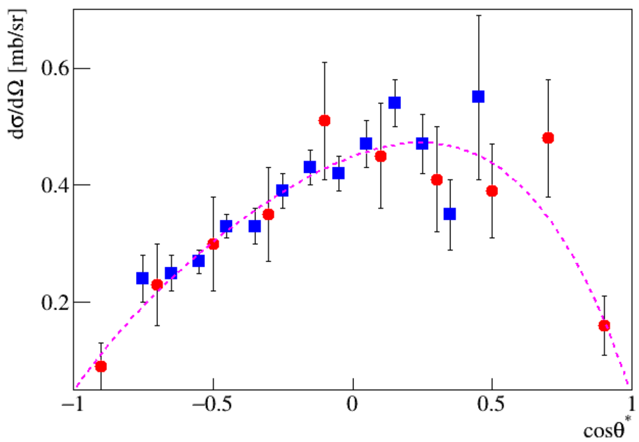


Figure 1: Differential cross sections for $K^+n \to K^0p$ reaction at p_{K^+}=434 MeV/c (circles) and 470 MeV/c (squares). The data were taken from Damerell *et al.*[4] and Glasser *et al.*[5].

$$\frac{d\sigma}{d\Omega} = \sum_{n=0}^{n=4} c_n P_n(\cos\theta^*), \tag{1}$$

where θ^* is defined as the K^0 scattering angle in the K^+n c.m. system assuming a stationary target. The fit results are listed in Table 1.

Table 1: Legendre polynomial coefficients for differential cross section parametrization.

c_0	c_1	c_2	c_3	c_4
0.33025	0.0696241	−0.0257982	−0.0737604	−0.0273651

Nucleons in a deuteron have Fermi motion, and their momenta are generated using the following momentum density function from the fit to (e, e') and $(e, e'p)$ datasets[6];

$$f(k) = ae^{-\alpha k} + be^{-\beta k}, \tag{2}$$

where $a = 13$ [GeV$/c$]$^{-3}$, $\alpha = 8$ [GeV$/c$]$^{-1}$, $b = 3 \times 10^4$ [GeV$/c$]$^{-3}$, and $\beta = 37$ [GeV$/c$]$^{-1}$. Here, k is the nucleon's momentum in GeV$/c$, generated uniformly over three-dimensional space ($\int f(k)k^2 d\Omega = 1$). In the simulation, a K^+ beam interacts with a neutron or a proton in a deuteron. The target nucleon moves initially with a momentum equal to and opposite to the spectator nucleon. For instance, impulse scattering involves the $K^+n \to K^0p$ reaction with a spectator proton carrying the momentum satisfying $\vec{p}_p = -\vec{p}_n$. The K^0 scattering angle in the K^+n c.m. system is determined by Eq. (1).

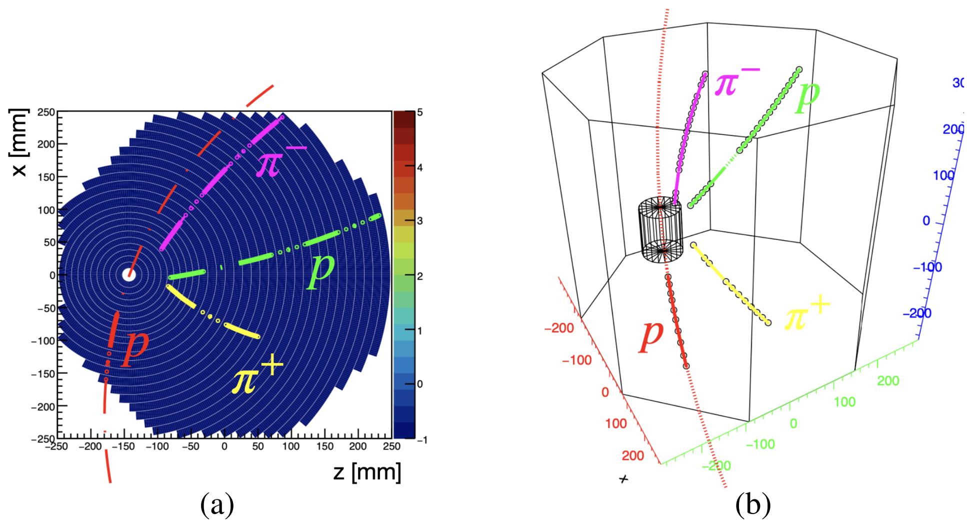


Figure 2: Simulated event displays of the $K^+d \to K^0pp$ reaction in the Hyperon Spectrometer.

Figure 2 shows the simulated event displays. Figure 2(a) depicts the trajectories of charged particles from the K^0pp reaction projected onto the TPC pad plane, while Fig. 2(b) shows the reconstructed tracks in three dimensional space. The LD_2 target, with an 8 cm diameter and 10 cm height, is positioned upstream at z=-143 cm from the center of the TPC. The TPC pad plane has a concentric configuration around the target position with a total of 5,768 pads arranged in 32 layers.

Figure 3 presents the energy loss (dE/dx) versus the magnetic rigidity (p/q) for reconstructed tracks, demonstrating the particle identification performance for π^-, π^+, and protons. Figure 4 shows the invariant mass distribution of K^0p. With 7,000 events, the Hyperon Spectrometer's resolution cannot resolve the Θ^+ signal from the impulse scattering background. However, with approximately 210k events, a distinct Θ^+ peak becomes visible. This indicates that statistics are key for this experiment. Assuming a beam intensity of 2k/spill, these event counts correspond to data collected over one day and 30 days, respectively.

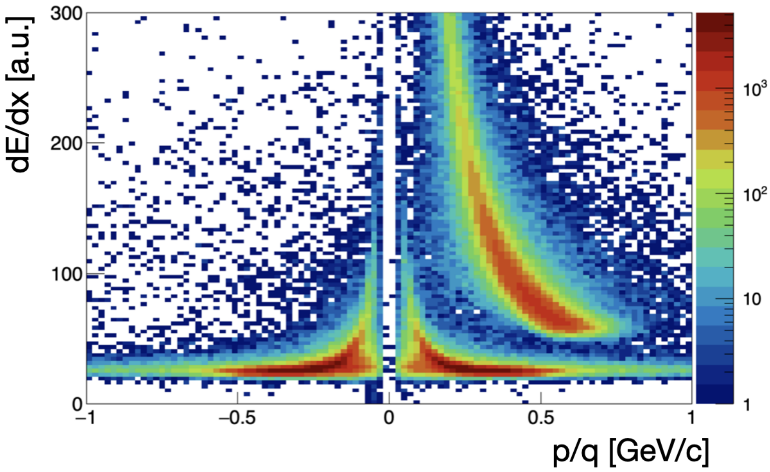
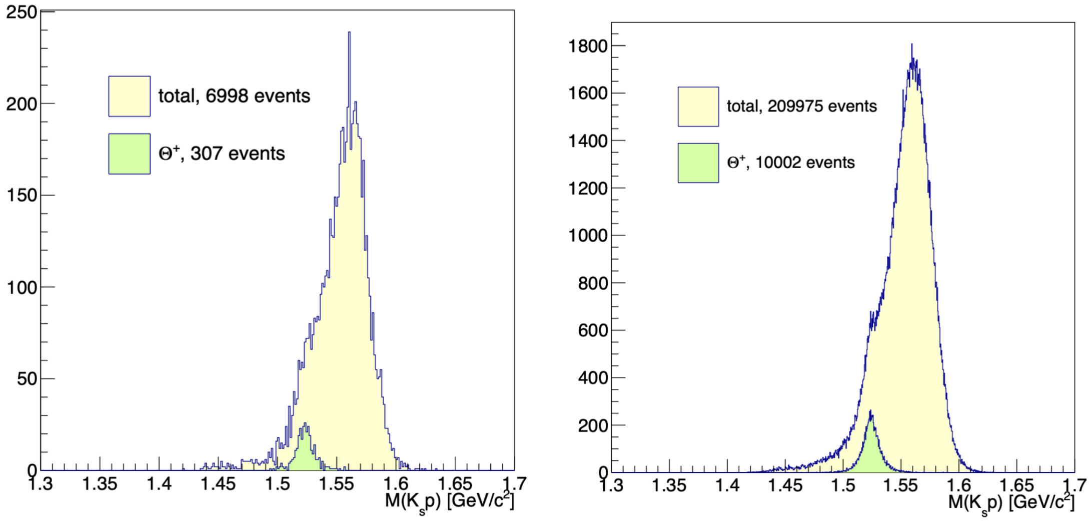


Figure 3: Simulated dE/dx versus momentum/charge spectrum of the $K^+d \to K^0pp$ reaction in the Hyperon Spectrometer. π^-, π^+, and protons are well separated.

However, as the beam momentum decreases, the beam intensity drops significantly due to K^+ decay, decreasing by an order of magnitude for every 0.1 GeV/c reduction. To address this, we propose utilizing a beam degrader to maximize the intensity. In addition, a higher beam momentum shifts the impulse scattering bump to the higher mass region, improving the S/N ratio. Understanding the momentum bite distribution at the K1.8BR beamline, and the momentum spread due to the degrader is also crucial for the experiment. Since the c.m. energy ($\sqrt{s}$) at the reaction inside the LD_2 target must correspond to the expected mass of Θ^+, we will calculate $\sqrt{s}$ using measurements of the final state particles such as K^0pp, and K^+d.



(a) (b)

Figure 4: Simulated invariant mass spectra of K^0p including Θ^+ production and impulse scattering process in $K^+d \to K^0pp$ reaction at 0.5 GeV/c with 7k and 210k events, respectively.

2 Experimental Setup and Run Plan

2.1 Experimental Setup

The experimental setup is entirely consistent with J-PARC E72[7]. As shown in Fig. 5, the Hyperon Spectrometer is integrated with the K1.8BR beamline spectrometer at the K1.8BR beamline. Figure 6 provides a closer view of the setup near the Hyperon Spectrometer. Upstream, the T0 counter provides reference timing, and the Beam Aerogel Cherenkov (BAC) counter distinguishes kaons (K^- in the case of E72) from pions (π^- in E72). As illustrated in Fig. 7, the BAC radiator has a refractive index of 1.115, enabling Cherenkov light radiation for pions above 0.28 GeV/c, while the threshold for kaons is 1.00 GeV/c. This makes the BAC suitable for distinguishing K^+ from π^+ in the 0.4–0.5 GeV/c momentum range as well. The K^+ beam enters the HypTPC in the 1-T superconducting magnet bore and proceeds to the target inside the HypTPC drift volume. While E72 uses an LH_2 target, we will replace it with an LD_2 target. Based on advice from KEK staff, the replacement will take approximately three days and poses no technical challenges.

The trigger logic consists of $T0 \otimes \overline{BAC} \otimes HTOF\text{-}Mpn$, where $HTOF\text{-}Mpn$ is the HTOF multiplicity trigger where we accept the data when the number of the fired segments is greater and equal to n. The HTOF is a scintillator array composed of 34 segments in an octagonal configuration surrounding the TPC vertically. Each side of the octagon has 4 segments, with an additional 2 segments on the side where the beam passes through, as shown in the Fig. 6, for the beam window. Depending on the trigger rate, $HTOF\text{-}Mpn$ may be excluded from the trigger or the smallest possible multiplicity will be chosen to minimize trigger bias.

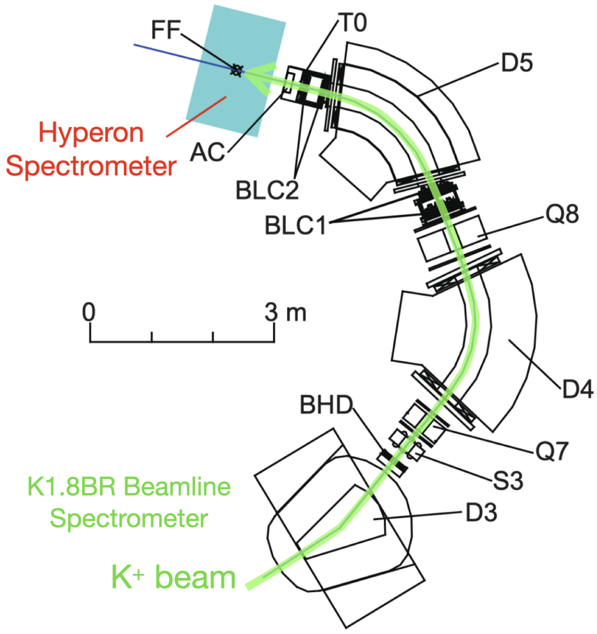


Figure 5: Schematic of the experimental setup at the K1.8BR beamline at J-PARC Hadron Experimental Facility.

The beam degrader, placed immediately upstream of the T0 counter, consists of multiple graphite layers with a maximum total thickness of 15 cm. The thickness is adjusted by varying the number of layers, depending on the desired beam momentum magnitude and intensity setting. The momentum of the beam after passing through the degrader can be measured using the Hyperon Spectrometer. Since the final experiment aims to exclusively measure Θ^+, high precision for the beam momentum resolution is not required.

2.2 Run Plan

We will scan a central beam momentum at four points of 0.41, 0.44, 0.47, and 0.5 GeV/c without using a degrader. We then introduce a degrader and gradually increase the beam momentum to study the effects on beam intensity and the beam momentum/angle spread. These measurements will help optimize the experimental conditions.

Figure 8(a) illustrates the expected beam momentum distributions taken for 1 hour overlaid for central momenta of 0.41, 0.44, 0.47, and 0.5 GeV/c, assuming a momentum bite of $\sigma = 12.7$ MeV/c (FWHM = 30 MeV/c). Here, we also assume a beam intensity of 2k/spill at a central momentum of 0.5 GeV/c and a spill duration is 4.24 seconds. The bin size of the momentum histogram is set to 2.5 MeV/c. Based on the calculation including the Sanford-Wang parameterization for the yield in the pA collisions at the T1 production target and the K^+ decay factor along the 32 m path from the T1 production target to the exit of the K1.8BR beamline, the predicted beam intensity differs by an order of magnitude between 0.4 GeV/c and 0.5 GeV/c. An exponential scaling was assumed to estimate intensity at other momentum

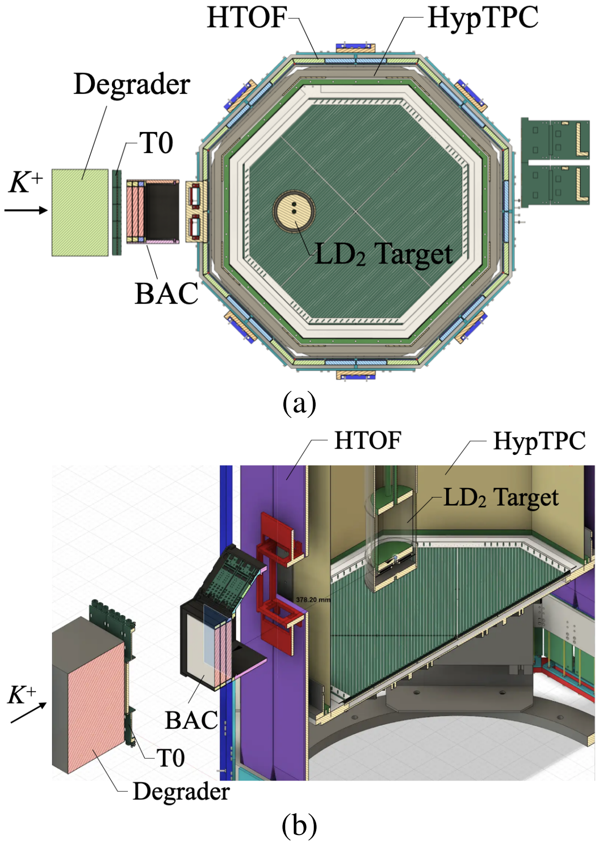


Figure 6: Schematic of the test experiment setup with a beam degrader, placed right upstream of the T0 counter of the E72 setup. (a) Top view and (b) enlarged view of the setup.

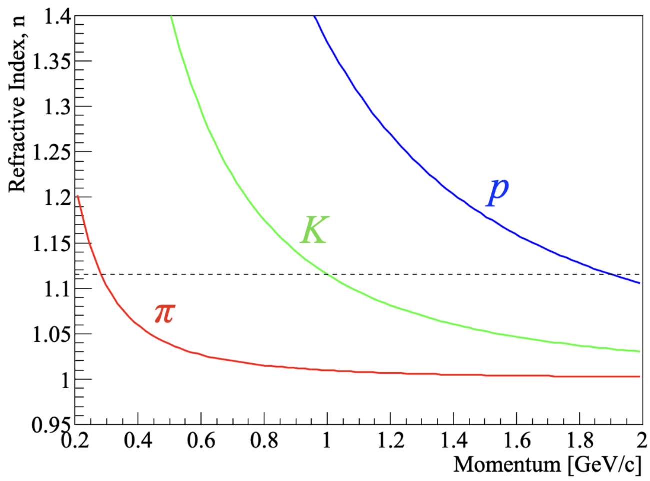
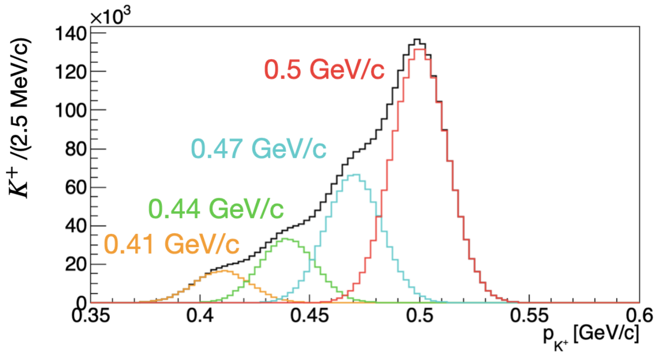
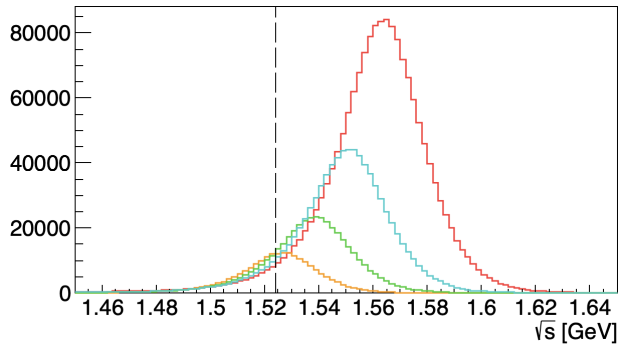


Figure 7: The threshold refractive index for Cherenkov radiation as a function of the momentum of proton, kaon, and pion. The refractive index of the BAC ($n = 1.115$) is indicated as a black dashed line.

settings. Figure 8(b) illustrates the expected c.m. energy distributions for each momentum setting, assuming the nucleon momentum distribution in deuterons, using the method described in the Section 1. The black vertical dashed line indicates the expected Θ^+ mass of 1.524 GeV/c^2.



(a)



(b)

Figure 8: (a) Accumulated K^+ beam momentum spectra over one hour for each central beam momentum setting of 0.41, 0.44, 0.47, and 0.5 GeV/c. (b) The c.m. energy distributions accordingly considering the deuteron nucleon Fermi motion.

Figure 9 presents the past K^0pp cross-section data, where, for the yield calculation, the K^0pp reaction cross-section is assumed to vary simply linearly within the 0.35 to 0.6 GeV/c momentum range, and the yield for each momentum bin in the Fig. 8(a) is calculated using the following formula:

$$N = N_{beam} \times \frac{\rho \times L \times N_A}{A} \times \sigma \times \epsilon_{det} \times \epsilon_{decay} \times \sigma_{target}, \tag{3}$$

where N_{beam} is the number of kaon beams, ρ and L are the density and effective length of the target, respectively, N_A is Avogadro's number, and A is the atomic mass of the target. The σ represents the production cross section, and ϵ_{det} and ϵ_{decay} are the overall detection efficiency and the decay branching ratios, respectively. The σ_{target} refers to the LD_2 target coverage with respect to the beam profile. Table 2 summarizes the constants used in the calculations.

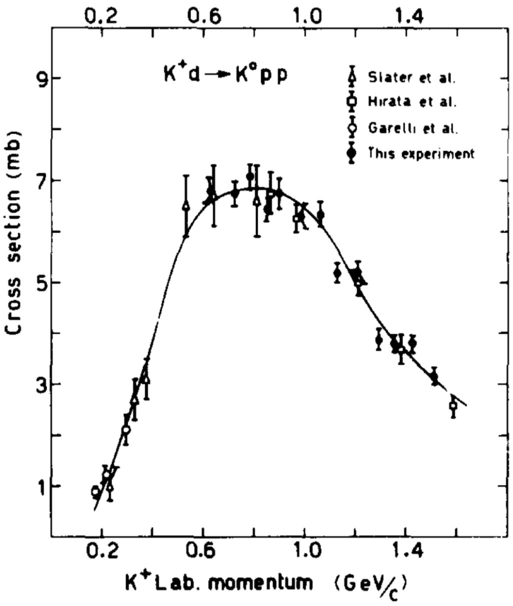


Figure 9: Cross section data as a function of K^+ lab momentum of $K^+d \rightarrow K^0pp$ reaction[8].

Table 2: Constants used in the yield calculation.

ρL	1.03 g/cm^2 (ϕ8 cm)
N_A	6.022×10^{23}
A	2
ϵ_{det}	0.3
ϵ_{decay}	0.5(K^0-K_S conversion)$\times 0.692$($K_S \rightarrow \pi^+\pi^-$)
σ_{target}	0.35

The resulting $K^+d \rightarrow K^0pp$ yield distribution is shown in Fig. 10. To balance the total yield across the four momentum settings, the beam times are allocated as follows: 11.2 hours for 0.41 GeV/c, 5.0 hours for 0.44 GeV/c, 2.2 hours for 0.47 GeV/c, and 1.0 hour for 0.5 GeV/c. With this setup, it is expected that over 7k $K^+d \rightarrow K^0pp$ events will be collected for each 2.5 MeV/c momentum bin within the 0.41 GeV/c to 0.5 GeV/c momentum range. This strategy ensures uniform statistics for analysis across the different beam momentum. Including the time required for beamline magnet tuning, data collection for all four momentum settings without a beam degrader is planned to be completed within 24 hours.

Figure 11 shows the simulated beam momentum distribution and the xy spatial distribution at the LD_2 target, located 50 cm downstream of the upstream side of a 13-cm graphite degrader, assuming a K^+ beam with a momentum of 0.6 GeV/c emitted along the z-axis from the origin ($x = 0$, $y = 0$). After passing through the degrader, the beam momentum spreads to $\sigma_p = 2.9$ MeV/c, while the spatial spread at the target is measured as $\sigma_x = 9.9$ mm and $\sigma_y = 9.6$ mm. Compared to the case without a degrader, the number of events reaching the

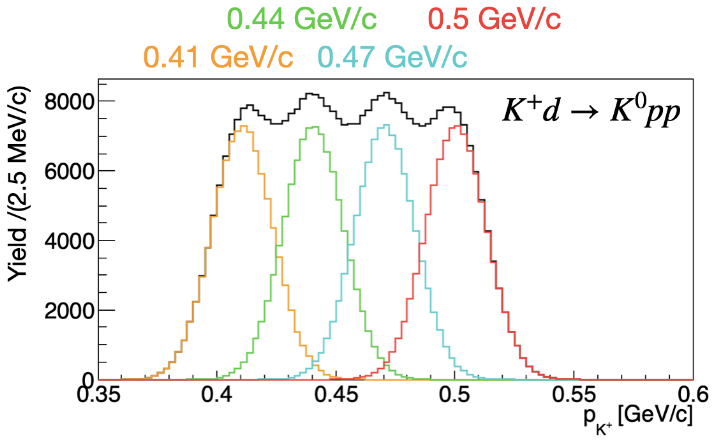
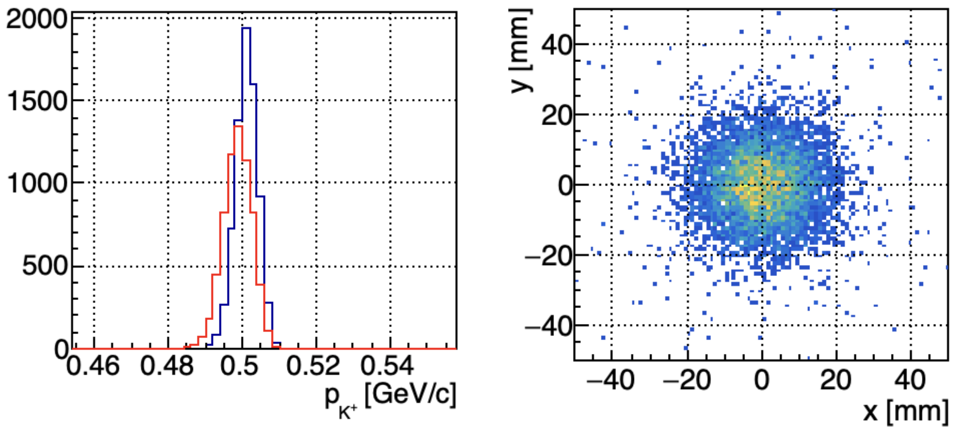


Figure 10: Calculated $K^+d \to K^0pp$ yield distribution for momentum settings of 0.41, 0.44, 0.47, and 0.5 GeV/c, with data collection times of 11.2 hours, 5.0 hours, 2.2 hours, and 1.0 hour, respectively.

target decreases to 81.4% as the beam profile spreads spatially due to multiple scattering. The actual beam profile's x, y, dx/dz, and dy/dz distributions will be obtained during the test experiment to evaluate the beam intensity and the resulting $\sqrt{s}$ distribution at the target. This information is crucial for understanding the experimental conditions and optimizing the beam setup for the Θ^+ experiment. The beam momentum scan with a beam degrader will take another 24 hours.



(a) (b)

Figure 11: (a) The momentum distribution of the 0.6 GeV/c K^+ beam after passing through a 13-cm graphite degrader. The red line represents the subset of the beam that falls within the target after losing energy inside the target. (b) The xy beam profile distribution at the target position, approximately 50 cm downstream from the degrader, assuming the beam was emitted along the z-axis from $x = y = 0$. This profile illustrates the spatial spread of the beam after multiple scattering in the degrader.

3 Final Remark

The proposed test beam experiment aims to serve as a foundation for the detailed design of the Θ^+ experiment. This work is not only a step forward in experimental preparation but also holds intrinsic physics significance, as it provides an opportunity to significantly improve upon the K^+d data collected over four decades ago, with modern, high-resolution measurements. The findings, including information on low-momentum beam intensity, beamline magnet settings, and the effects of the degrader, will also greatly benefit future experiments at J-PARC utilizing low momentum beams.

Recently, a proposal from Jefferson Lab was published under the KLF project to search for Θ^+ using K_L beams in the direct formation reaction $K^0p \to K^+n$[9]. To complement this effort, J-PARC, as the world's only facility capable of producing high-intensity K^+ beams, should conduct a corresponding experiment using another direct formation reaction, $K^+d \to K^0pp$. To achieve this, the only two-day test beam request proposed here will be of great significance.

References

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