LETTER OF INTENT FOR 50 GEV PROTON SYNCHROTRON

Search for the Θ^+ in $K^+d \to K^0pp$ Reaction with Hyperon Spectrometer

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Abstract

The recent LHCb results on the observation of the charm pentaquarks have created a new wave of excitement and raised questions about the existence of the light pentaquarks. Despite the little belief in the existence of Θ^+ today, there are still rooms for more dedicated efforts and scrupulous analyses to answer the question of the existence or nonexistence of light pentaquarks made of u, d, and s quarks. We propose a final attempt to search for Θ^+ in $K^+d \to K^0pp$ reaction at p_{K^+}=0.5 GeV$/c$ at J-PARC. A large acceptance Hyperon Spectrometer, which consists mainly of a time projection chamber and a 1-T superconducting magnet, will exclusively measure the decay products of Θ^+, such that $\Theta^+ \to K^0p$, followed by $K^0 \to \pi^+\pi^-$. Assuming a cross section of 300 μb, we expect to collect approximately three orders of magnitude of Θ^+ events with two days of beam time at J-PARC. We aim to conduct the experiment for three days, including commissioning and physics data taking, immediately after the scheduled E72 experiment at the K1.8BR beam line.

1 Introduction

New forms of the baryonic system beyond the usual qqq configuration have long been searched for many years to understand quantum chromodynamics in low-energy and non-perturbative regimes, such as color confinement and spontaneous breaking of chiral symmetry. The new baryonic forms include pentaquarks, molecular states of a baryon and a meson, hybrid states with gluonic excitation, and glueballs. Among them, the exotic pentaquark states are those where an antiquark has a different flavor than any of its four quarks and its quantum number cannot be defined by three quarks alone.

Such exotic pentaquark states in the KN system ($S = +1$) cannot be accommodated in a conventional quark model for baryons; in particular, an $I = 0$ state would require at least an anti-decuplet ($\overline{10}$) of SU(3)$_f$ symmetry and an $I = 1$ a 27 multiplet. In the chiral soliton model[1], the Θ^+ is a member of the $\overline{10}$ multiplet, as shown in Fig. 1. The mass splitting between the members was predicted to be 180 MeV multiplied by their strangeness unit difference. This model prediction highlighted the low mass and narrow width of the $\Theta^+(1540)$ and its spin-parity of $J^P = 1/2^+$ given as a rotating soliton. The conventional quark model predicts the mass of the $5q$ ground state to be approximately five times the valence quark mass plus an expectation value for the color-magnetic interaction, raising its mass to 1900 MeV in the case of the Θ^+. The $uudd\bar{s}$ configuration requires that the lowest state has either $J^P = 1/2^-$ or $3/2^-$ with no orbital excitation. In this case, the negative-parity state must have a broad width due to the "fall-apart" decay to KN. The orbital excitation can flip the parity sign but raises the mass. Furthermore, many other theoretical approaches predict different spin-parity combinations for the Θ^+ state, which include the QCD sum rule, Lattice QCD, dynamical calculations[2, 3], and quark clustering with colored diquark and triquark clusters[4, 5].

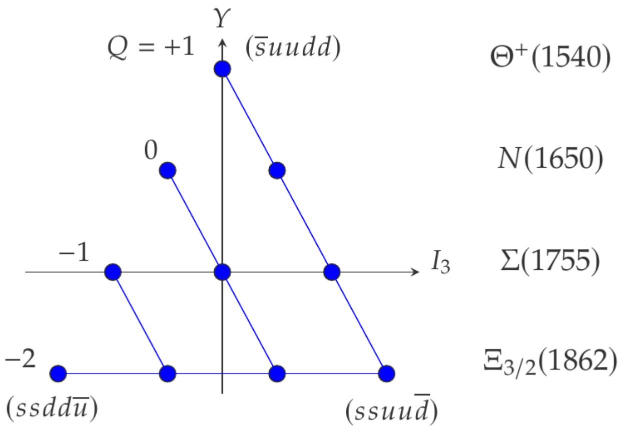

Figure 1: Anti-decuplet of baryons predicted in Ref.[1]. The corners of the diagram are exotic.

On the experimental side, after the first claim of the discovery by LEPS Collaboration[6], there have been considerable efforts to reconfirm the Θ^+ in various reactions. Early attempts reported controversial results with similar statistical significance. Some experiments supported[7, 8, 9, 10, 11, 12, 13, 14] and others ruled out the Θ^+ existence in the K^0p and K^+n mass spectra[15, 16, 17, 18, 19, 20, 21]. However, the experiments repeated in same reactions with much higher statistics refuted previous positive results[22, 23, 24] except for LEPS[25], which still showed positive sign. No positive signal was observed in the high statistics experiment with hadron beams[26, 27]. Subsequent unsuccessful searches for the Θ^+ led to the end of enthusiasm in the Θ^+ search[28]. The Particle Data Group put a final remark on the pentaquarks that the conclusion that pentaquarks in general, and the Θ^+, in particular, do not exist, appears compelling[29, 30]. Later, the Θ^+ was removed from the PDG list, supporting the null results from high-statistics photoproduction experiments as irrefutable evidence.

Nevertheless, there is still a glimmer of hope that has not yet been extinguished. The cross section upper limits are in some reactions a level of nanobarn, based on the assumptions about the narrow width of the pentaquark and its production angular distribution. A new Θ^+ search is now ongoing at SPring-8 from photoproduction[31]. A large-acceptance LEPS2 solenoid detector is placed in the high-intensity polarized photon beam line[32]. The LEPS2 detector can see the Θ^+ with even broader angular coverage than CLAS and LEPS detectors. The following two processes are unique to leave all charged particles in the final state associated with the Θ^+ production: (1) $\gamma n \to K^-\Theta^+$ and (2) $\gamma p \to \overline{K}^{*0}\Theta^+$, where the Θ^+ can be reconstructed from the sequential decays of $\Theta^+ \to K^0_S p,\ K^0_S \to \pi^+\pi^-$, and $\overline{K}^{*0} \to K^-\pi^+$. Because of its complete kinematics with detection of all final-state particles, no Fermi-motion correction is necessary unlike previous measurements. Moreover, detection of K^- ensures production of $S = +1$ baryon, and $\Lambda(1520)$ in K^-p can be kinematically separated from the Θ^+ band in K^0p above $E_\gamma = 2.2$ GeV. The expected K^0p mass resolution near the mass of Θ^+ is approximately 6 MeV.

Using hadron beams, high-statistics Θ^+ search experiments can also be considered. The reaction $K^+p \to \Theta^+\pi^+$ is available above the threshold K^+ momentum of 735 MeV$/c$. However, the final state involves $K^+n\pi^+$ or $K^0p\pi^+$ systems in which Δ^+ or Δ^{++} background is overwhelmingly produced. For the $\pi^-p \to \Theta^+K^-$ reaction, threshold π^- momentum is 1.72 GeV$/c$. This reaction shares the final state K^0pK^- or K^+nK^- with the Θ^+ channel, which could involve background contribution associated with $a_0(980)$ or ϕ resonance. Such a huge background from resonances hinders the Θ^+ search. In this regard, a direct formation reaction $KN \to \Theta^+$ deserves a final attempt to decide the Θ^+'s destiny in the hadronic sector, which will be discussed in the next Section.

2 A Formation of Θ^+ in KN Interaction

A direct formation of the Θ^+ is available via either K^0p or K^+n reaction. The K^0p reaction is free from the Fermi motion effect and accessible to the low-$|t|$ or small scattering angle range where low-momentum proton measurement is most significant. However, a K_L beam comprises K^0 and $\overline{K}^0$ with almost equal fractions, so only $K_Lp \to K^+n$ reaction can be viable. The significant drawback with the K_L beam is that one can hardly determine the neutral beam momentum. There is a way to achieve the definite determination of K_L beam momentum by tagging primary production reactions, such as $\pi^- p \to \Lambda K^0$ reaction. However, neutron detection cannot provide sufficient precision for K^+n mass measurement for the Θ^+ search.

On the other hand, the K^+n reaction is ideal for the Θ^+ search. A liquid deuterium target can provide target neutrons. The Θ^+ lies 110 MeV above the KN threshold and 25 MeV below the $KN\pi$ threshold. A pion can barely be produced near the Θ^+ production threshold. Therefore, near the threshold, only the following three processes are available: (1) coherent elastic scattering $K^+d \to K^+d$, (2) incoherent breakup reaction $K^+d \to K^+np$, and (3) incoherent charge-exchange breakup reaction $K^+d \to K^0pp$.

Because of this nuclear target, an assumption must be made about the influence of the spectator proton. There is no unique way to correct the bound neutron in deuteron. In addition, one must cope with energy smearing due to the Fermi motion of the neutron. Nevertheless, the Θ^+ search must rely on the $K^+d \to K^0pp$ reaction. As the final state contains two identical protons, we need to identify which proton is associated with the Θ^+ formation.

A spectator p_s is slowly knocked out, and the recoil p_t comes faster with higher momentum. If the K^0p pair is produced purely from the $K^+n \to K^0p$ reaction process, a remaining proton in a deuteron is little involved in the reaction. While two protons carry a considerable relative momentum, a combination of K^0p can take relative momentum over a wide range. In this case, we should consider the interference effect among all three possible combinations with K^0pp. Furthermore, there is no unique way of defining the KN c.m. system in a K^+d interaction, so the K^0p_t system determines the c.m. frame of reference.

The $K^+n \to K^0p$ reaction has considerably been studied since the bubble-chamber era. The charge exchange reactions $K^+n \to K^0p$ and $K^-p \to \overline{K}^0 n$ are related by a transformation from the s-channel to the u-channel. The reactions $K^+p \to K^0\Delta^{++}$ and $K^-n \to \overline{K}^0\Delta^-$ are also similar. Many experimental approaches focused on the formation of baryons with $S = +1$ and $S = -1$ in s- and u-channels and a t-channel contribution with exchange mesons. The question is then raised as to why this particle was missed in the early searches decades ago. The answers from a series of theoretical studies with old data lie in the narrow width of the Θ^+.

Sibirtsev *et al.*[33] investigated the impact of the $\Theta^+(1540)$ on differential and integrated cross sections for the reaction $K^+d \to K^0pp$. Using the Jülich KN model[34], they considered effects due to the Fermi motion of the nucleons within the deuteron and the final three-body kinematics. The old data available were found to constrain the width of the Θ^+ to be less than 1 MeV.

Quite recently, Sekihara *et al.*[35] studied the feasibility of the $K^+d \to K^0pp$ reaction for the Θ^+ search. The theoretical results show that the impulse scattering process (in Fig. 2(a)) is dominant over the two-step scattering processes (in Fig. 2(b) and (c)) near $p = 0.40$ GeV/c, whereas the two-step processes exceed the impulse scattering in higher-momentum regions. Their model predicts that the $\Theta^+(1524)(\Gamma = 0.5\ \mathrm{MeV})$ production cross section is of the order of a few hundred μb to 1 mb at $p_{K^+} \approx 0.40$ GeV/c, and drops to ≤ 1 μb at $p_{K^+} \approx 0.85$ GeV/c. Moreover, the $\Theta^+(1524)$ production is peaked when a spectator proton (p_s) goes backward at $p_{K^+} \approx 0.40$ GeV/c.

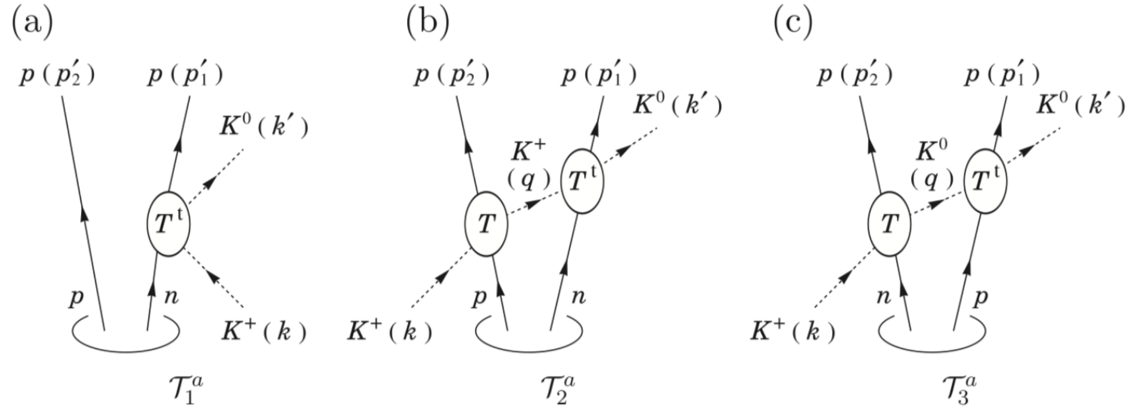

Figure 2: Diagrams for the $K^+d \rightarrow K^0pp$ reaction[35]. (a) Impulse scattering and (b),(c) two-step scattering processes.

3 Experimental Consideration

We propose a dedicated experiment to measure $K^+d \rightarrow K^0pp$ charge exchange reactions at the K^+ beam momentum from 0.45 to 0.55 GeV$/c$. This experiment is viable at the current K1.8BR beam line at J-PARC Hadron Experimental Facility[37], as shown in Fig. 3. The K^- beam intensity at the K1.8BR beam line was measured to be 38 k/spill at 0.735 GeV/c at the main ring power of 82 kW with a cycle of 4.24 s in May 2024. Considering the beam line length of approximately 32 m and kaon beam decay, the K^- beam intensity is estimated to decrease to about 2 k/spill at 0.5 GeV/c. Typically, the K^+ beam intensity is approximately three times higher than that of the K^- beam.

The charge exchange reaction $K^+d \rightarrow K^0pp$ involves three particles in the final state, and the K^0 decays shortly via $K_S \rightarrow \pi^+\pi^-$. Therefore, four charged particles (two pions and two protons) are detected by the Hyperon Spectrometer. The spectrometer comprises a liquid target system and a GEM-based time projection chamber (HypTPC)[38] surrounded by time-of-flight scintillator array (HTOF) in the 1-T superconducting Helmholtz-type dipole magnet[39], as shown in Fig. 4. This spectrometer facilitates a large acceptance and precise measurement of the $K^+d \rightarrow K^0pp$ reaction. A simulated event for $K^+d \rightarrow K^0pp$ reaction is displayed in Fig. 5. The tracks can be recorded in the HypTPC volume of $50(\phi)$ cm$\times 55$ cm. The HypTPC measures charged particles produced from a liquid deuterium target over nearly 4π solid angle. The π/p separation can readily be achieved using the energy-loss (dE/dx) and time-of-flight information.

Among them, the spectator proton carries low momentum and mostly cannot reach the HTOF which is placed at a 25–50 cm distance from the target. Therefore, the online trigger should be imposed such that the number of charged particle hits on the HTOF is at least three. This condition suppresses the detection of elastic scattering processes, $K^+d \rightarrow K^+d$ (or $K^+p(n) \rightarrow K^+p(n)$ or vice versa) and $\pi^+d \rightarrow \pi^+d$.

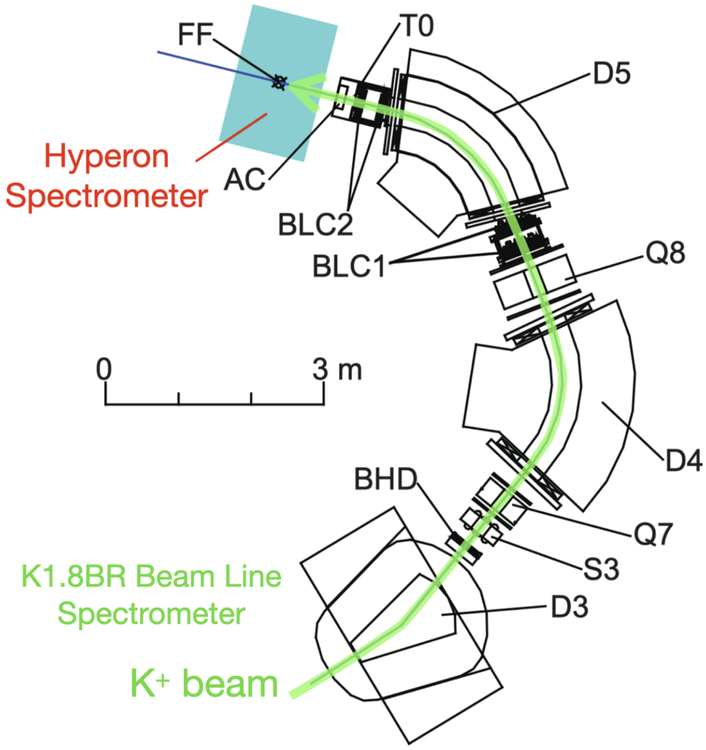

Figure 3: Schematic of the experimental setup at the K1.8BR beam line at J-PARC Hadron Experimental Facility.

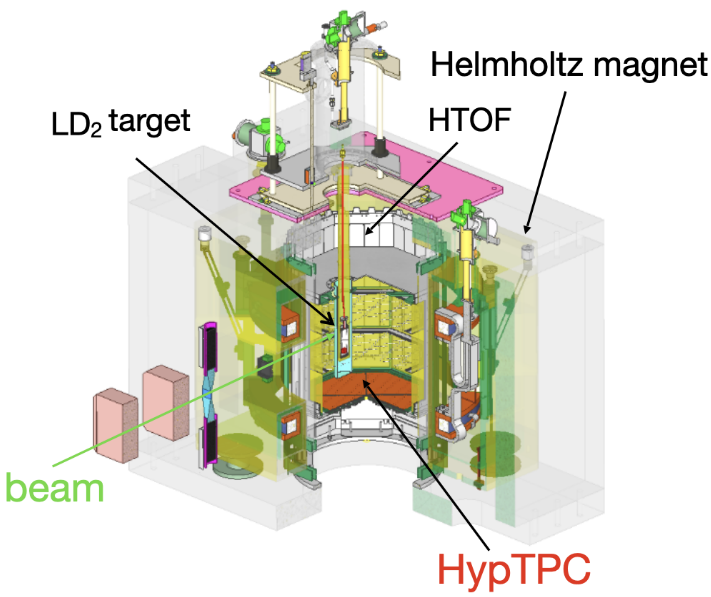

Figure 4: Schematic view of Hyperon Spectrometer.

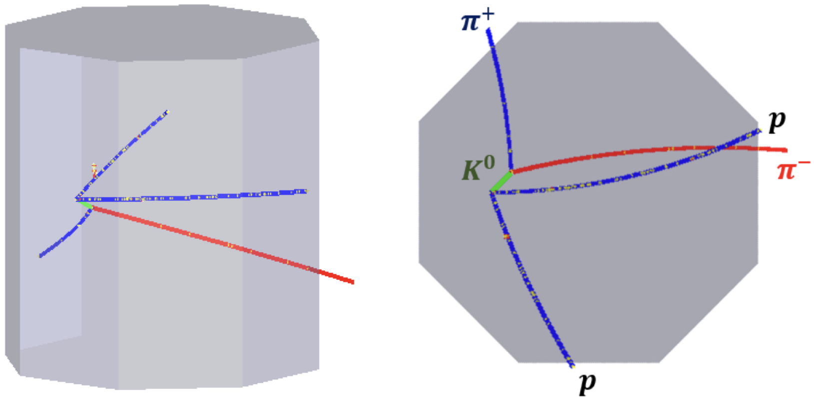

Figure 5: Simulated event displays of $K^+d \to K^0pp$ reaction in HypTPC.

4 Yield Estimation and Run Plan

The yield N (per spill) is estimated in the following way:

$$N = N_{beam} \times \frac{\rho \times L \times N_A}{A} \times \sigma \times \epsilon_{det} \times \epsilon_{decay}, \quad (1)$$

where N_{beam} is the number of beam kaons per spill, 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.

For yield estimation, we conservatively assume that 2k K^+ beam particles come every 4.24 s and interact with an 8-cm diameter liquid deuterium (LD_2) target inside the HypTPC. The detection efficiency is also conservatively assumed to be 50%. We also account for the branching ratios for K^0-K_S conversion (50%) and $K_S \to \pi^+\pi^-$ decay (69.2%).

For two days of beam time, the total number of observed $K^+d \to K^0pp$ events is estimated to be 2.6×10^4, which includes approximately 1.3×10^3 Θ^+ events, assuming Θ^+ production cross section of 300 μb. The cross section is taken similar to the predicted value of few hundreds μb at 0.40 GeV$/c$[35].

Table 1: Estimated yield for the $K^+d \to K^0pp$ reaction and Θ^+ production.

	σ	N [/spill]	N [/hr]	N [/day]
$K^+d \to K^0pp$	6 mb	0.64	547	13k
Θ^+	300 μb	0.03	27	656

We aim to conduct the experiment immediately after the J-PARC E72 experiment[36] at the K1.8BR beam line, using the same experimental setup but switching the target from LH_2 to LD_2. The run plan includes 1 day for commissioning and 2 days for the physics run. With just 3 additional days following the E72, we expect to confirm the existence of Θ^+.

5 Summary

We suggest a final attempt to search for Θ^+ using direct formation in K^+d reactions near 0.5 GeV$/c$ at J-PARC. Recently, the KLF project in the Jefferson Lab also proposed an experiment to search for Θ^+ using direct formation in K^0p reactions with a K_L beam [40]. Additionally, regardless of the existence of Θ^+, the low-energy KN scattering data will provide a good playground to test the non-perturbative QCD due to the advantage of being free from hyperon background. Lastly, we emphasize that J-PARC is currently the only facility in the world capable of utilizing a K^+ beam.

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