Proposal for J-PARC 50 GeV Proton Synchrotron

High-resolution Search for Θ^+ Pentaquark in $\pi^- p \to K^- X$ Reactions

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Abstract

We propose an experimental search for the Θ^+pentaquark resonance by the $p(\pi^-, K^-)$ reaction at the J-PARC K1.8 beamline. This experiment is a natural expansion of KEK-PS E522. Compared to E522, where the same reaction was employed, we will accumulate 100 times more statistics with five times better mass resolution ($\sim$ 2.5 MeV FWHM) and 2-10 times better S/N ratio. With those improvements combined, the expected sensitivity will be 75 nb/sr for a narrow Θ^+ ($\Gamma < 2$ MeV), and 150 nb/sr for $\Gamma = 10$ MeV. Also, if a Θ^+ peak is found, we can determine its width down to 2 MeV.

1 Physics Motivation

The first report on the evidence of the Θ^+ baryon with positive strangeness $S = +1$ [1] has been immediately supported by several collaborations [2, 3, 4, 5, 6, 7, 8, 9, 10]. However the statistics of all experiments were not sufficient to claim a clear observation and better statistics is needed. Recently, null results have been reported from several high energy experiments where they searched for Θ^+ with much higher statistics [11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21], and some of the initial positive evidences were denied by the same collaboration with higher statistics [22, 23]. Thus, the existence of Θ^+ is still controversial [24]. Therefore, the confirmation of the existence (or non-existence) of the Θ^+ is urgent and important. It will open a new vista of multi-quark system which can be used to test the theory of quantum chromodynamics (QCD) in the non-perturbative regime.

It should be noted that there are only few experiments to search Θ^+pentaquarks via hadronic reactions. Especially the meson induced reaction using a proton target is still unique to KEK-PS and J-PARC. The proposed experiment will give a unique contribution to understand the production mechanism of the Θ^+.

In addition, if Θ^+ does exist, the determination of its decay width, as well as its spin and parity, is crucial to understand the nature of Θ^+. Thus, an experiment with high sensitivity and high resolution is of great importance.

1.1 Theoretical Models

To calculate the cross section of the p(π^-,K^-) reaction, several theoretical works using effective Lagrangians have been done by [25, 26].

In 2004, Oh *et al.* estimated the total cross section using hadronic models for the p(π^-,K^-) reaction to be in the range of 2 to 190 μb [25]. They assumed that the the decay width of the $\Theta^+$was 5 MeV in the calculation. They considered two diagrams shown in Figure 1.

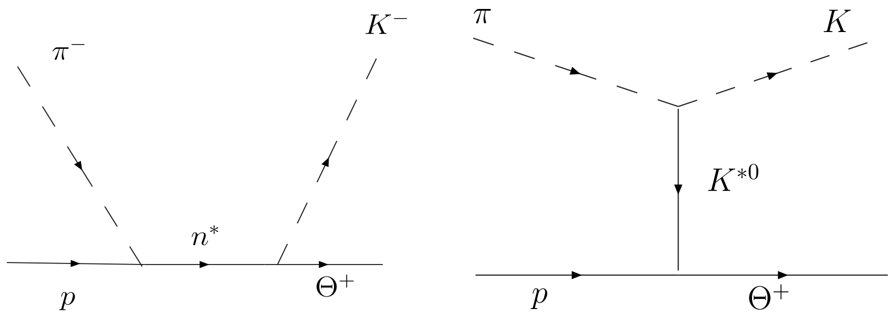

Figure 1: Diagrams for $\pi^- p \to K^-\Theta^+$reaction.

Next year, Hyodo *et al.* [26] evaluated the two-meson couplings of Θ^+, reproducing the known resonances with exotic baryons by an octet-antidecuplet representation mixing scheme. The considered diagrams are shown in Figure 2. They found that the

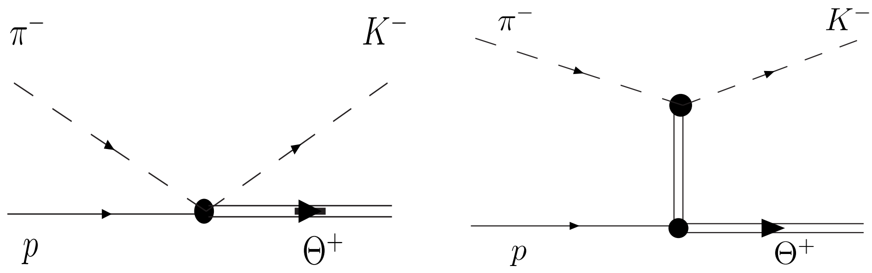

Figure 2: Diagrams for the meson-induced reactions for Θ^+ production.

total cross section could be consistent with zero within the experimental uncertainties for $J^P = 1/2^+$ case, whereas the lower limit would exist for $J^P = 3/2^-$ case. If we obtain a negative result in the proposed experiment, it will indicate that the $\Theta^+$is $J^P = 1/2^+$. They also pointed out that the interference between the two diagrams could help to explain the small cross section, comparing the amount of the cross section between the p(π^-,K^-) and p(K^+,π^+) reactions.

1.2 KEK-PS E522

In this situation, a Θ^+ search was conducted via the $\pi^- p \to K^- X$ reaction with the experimental resolution of 13.4 MeV FWHM using 1.87 and 1.92 GeV/c π^- beam at the K2 beam line of the KEK 12 GeV Proton Synchrotron (KEK-PS) [27]. A polyethylene (CH_2) target was exposed to 3.0×10^9 π^-'s of 1.87 GeV/c and 7.4×10^9 π^-'s of 1.92 GeV/c. Additionally, 2.9×10^9 π^-'s of 1.87 GeV/c were irradiated on a scintillating fiber (mostly CH) target. While no peak corresponding to Θ^+ was observed for 1.87 GeV/c, a hint of peak structure, of which width was consistent with the experimental resolution, was observed at the mass of $1530.6^{+2.2}_{-1.9}$(stat.)$^{+1.9}_{-1.3}$(syst.) MeV with a possible production cross section of about 1.9 μb/sr in the laboratory frame (see Fig. 3) for 1.92 GeV/c.

However the statistical significance of the bump is only 2.5$\sim$2.7σ which is not sufficient to claim the existence of the Θ^+. We have derived the upper limit of the production cross section (averaged over 0° to 20° in the laboratory frame) to be 1.6 μb/sr and 2.9 μb/sr at the 90 % confidence level at the beam momentum of 1.87 and 1.92 GeV/c, respectively.

1.3 Goal of the proposed experiment

The purpose of the proposed experiment is to conclude the existence of the Θ^+produced in the p(π^-,K^-) reactions. This experiment is a natural expansion of E522, which was

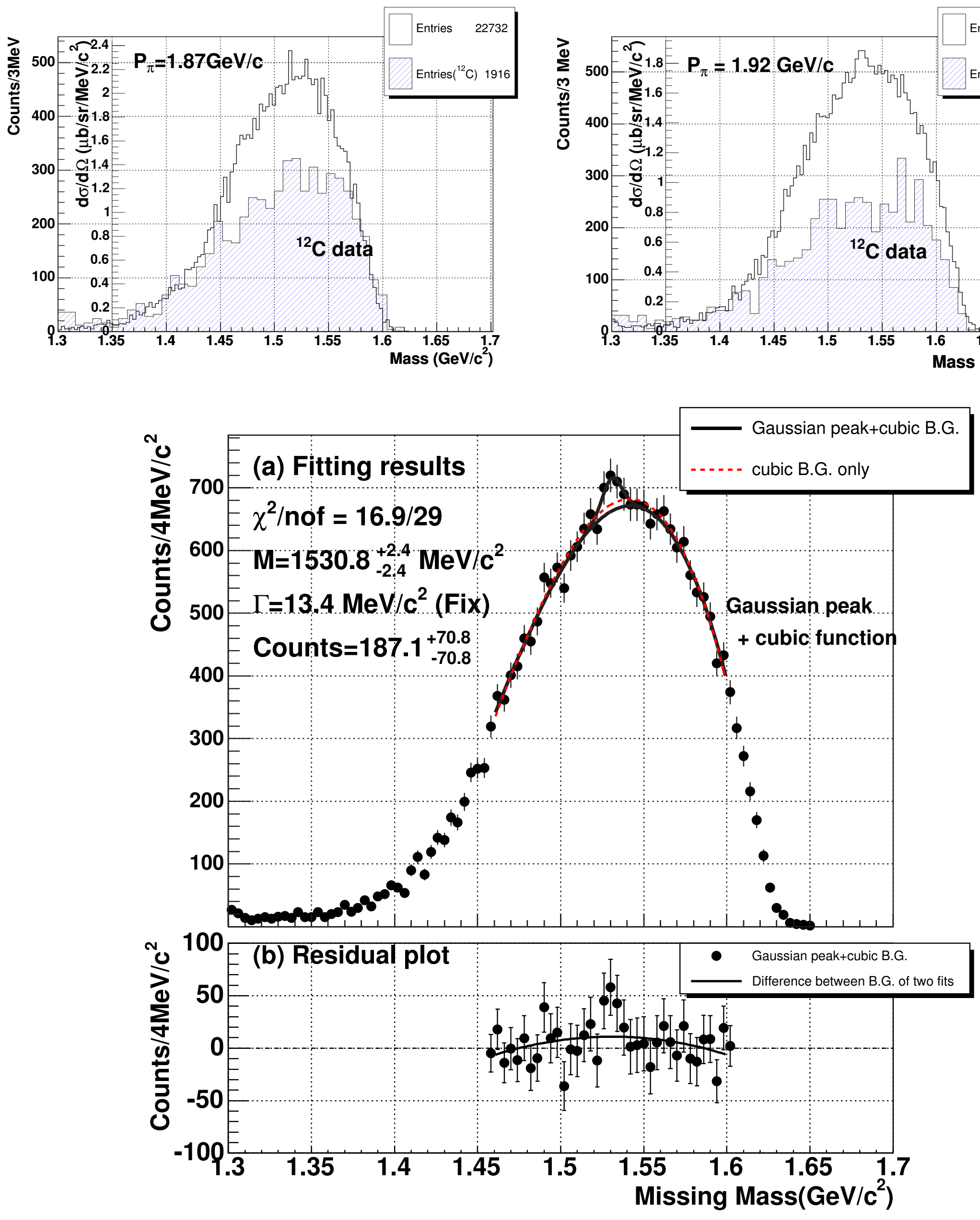

Figure 3: Missing mass spectrum obtained in E522. Top: $p_{\pi^-} = 1.87$ GeV/c. Bottom: $p_{\pi^-} = 1.92$ GeV/c. A bump structure is seen at 1.53 GeV for p_{π^-} =1.92 GeV/c.

performed at KEK-PS K2 beam line. Compared to E522, where the same reaction was employed, we will accumulate 100 times more statistics with five times better mass resolution ($\sim$ 2.5 MeV FWHM) and 2-10 times better S/N ratio. With those improvements combined, the expected sensitivity in the laboratory frame will be 75 nb/sr for a narrow Θ^+ ($\Gamma < 2$ MeV), and 150 nb/sr for $\Gamma = 10$ MeV.

The threshold momentum of the reaction is 1.71 GeV/c. Since the peak structure was found only at the beam momentum of 1.92 GeV/c in E522 experiment, the beam momentum of 1.97 GeV/c is also used in the proposed experiment. The use of three kind of beam-momentum settings enables us to study the momentum dependence of the production cross section.

If the bump observed in E522 is not statistical fluctuation but a real peak, we can detect the Θ^+ with the yield of 1.2×10^4 within 20 shifts beam time with an excellent missing mass resolution as mentioned later. This experiment will become the starting point to measure the spin or parity to understand the nature of the Θ^+. If the Θ^+ is not identified in the proposed experiment, a quite severe upper limit of 75 nb/sr will be obtained. The differential cross section of 75 nb/sr at laboratory frame corresponds to the total cross section of about 100 nb. It is quite unusual that production cross section via hadronic reaction is less than 100 nb.

Here we can compare the value with theoretical calculations done by some authors. In their calculations, it is sure that there are unknown parameters such as the coupling constants $g_{KN\Theta}$ and $g_{K^*N\Theta}$, but the framework is adjusted to reproduce the known hyperon productions such as $\pi p \to K\Lambda$. Y. Oh *et al.* predicted 2 μb for the width of 5 MeV/c^2 and $J^P = 1/2^+$ assignment at beam momentum of 1.92 GeV/c, which is the smallest value in their calculation. If the cross section is linear to the width, their lower limit of the cross section for $\Gamma = 1$ MeV/c^2 can be estimated to be 0.4 μb. Our sensitivity is four times better than this calculation. Therefore, if the Θ^+ is not detected, our upper limit would be quite severe for the production of Θ^+ in this reaction.

As for the decay width, if a Θ^+ peak is found, we can determine its width down to 2 MeV with the expected missing mass resolution. If it is less than 2 MeV, this experiment will give a world record of the upper limit of the decay width.

2 Experimental Methods

Here we are intending to repeat the same experiment with much higher statistics and much better mass resolution. We will obtain 100 times higher statistics with 5 times better mass resolution and 2-10 times better S/N ratio as explained below.

The experiment will be performed at the K1.8 beamline. We will use 1.87, 1.92 and 1.97 GeV/c π^- beams which are delivered to a liquid hydrogen target of 12.5 cm thick (re-use of the one constructed for the KEK-PS E559). The momentum of scattered K^- is measured in the range of 0.7 to 0.95 GeV/c with the SKS spectrometer [28]. A correlation between the scattered angle and the momentum is shown in Figure 4.

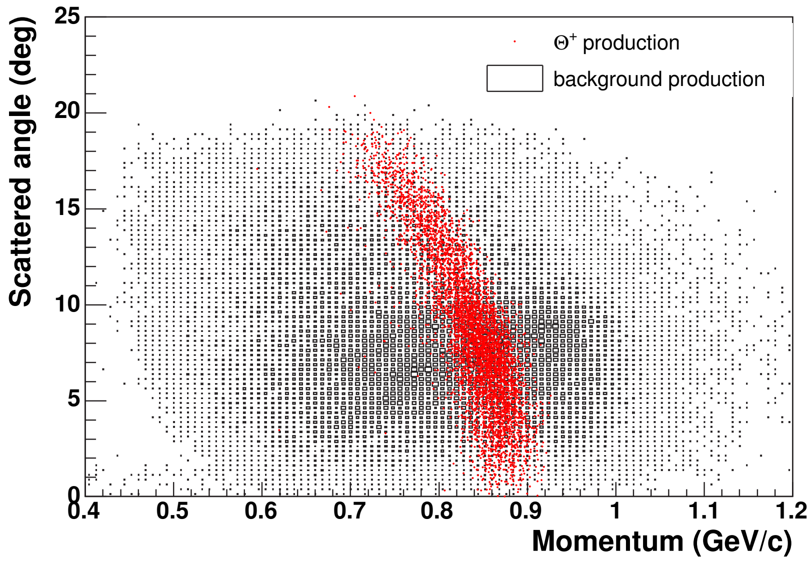

Figure 4: Correlation between scattered angle and the momentum of K^-.

The intensity of the π^- beam is determined by the rate capability of the detector system and is assumed to be 1×10^7 per 4 second cycle. Required intensity of primary proton beam to achieve this is less than 10% of the designed intensity of J-PARC, and so the experiment is feasible at the very early stage. The requested beam time is 20 shifts (160 hours) with additional time for setting up detector systems.

The SKS spectrometer, together with the beamline spectrometer of K1.8, gives us an excellent mass resolution. We expect about 2.5 MeV FWHM for the mass resolution, which is 5 times better than E522, from our experience on the SKS spectrometer and the design performance of the beamline spectrometer. It is also noted that SKS was long used for hypernuclear experiments using the (π^+, K^+) reactions, and has enough capability to distinguish kaons from pions (and protons). The use of the liquid hydrogen target gives us twice better S/N ratio compared to the polyethylene target.

2.1 K1.8 Beamline and Beam Analyzer

Figure 5 shows a beamline layout together with a K^- spectrometer in the K1.8 experimental area. In Table.1, design parameters are listed [29].

The π^- beam is analyzed with the K1.8 beam line spectrometer which is located after MS2. The beam analyzer is consist of $QQDQQ$ magnets, tracking detectors and timing counters. The expected momentum resolution $\Delta p/p$ is 1.4×10^{-4} in rms when a position resolution of 200 μm is realized in the tracking detectors placed before and after the $QQDQQ$ system.

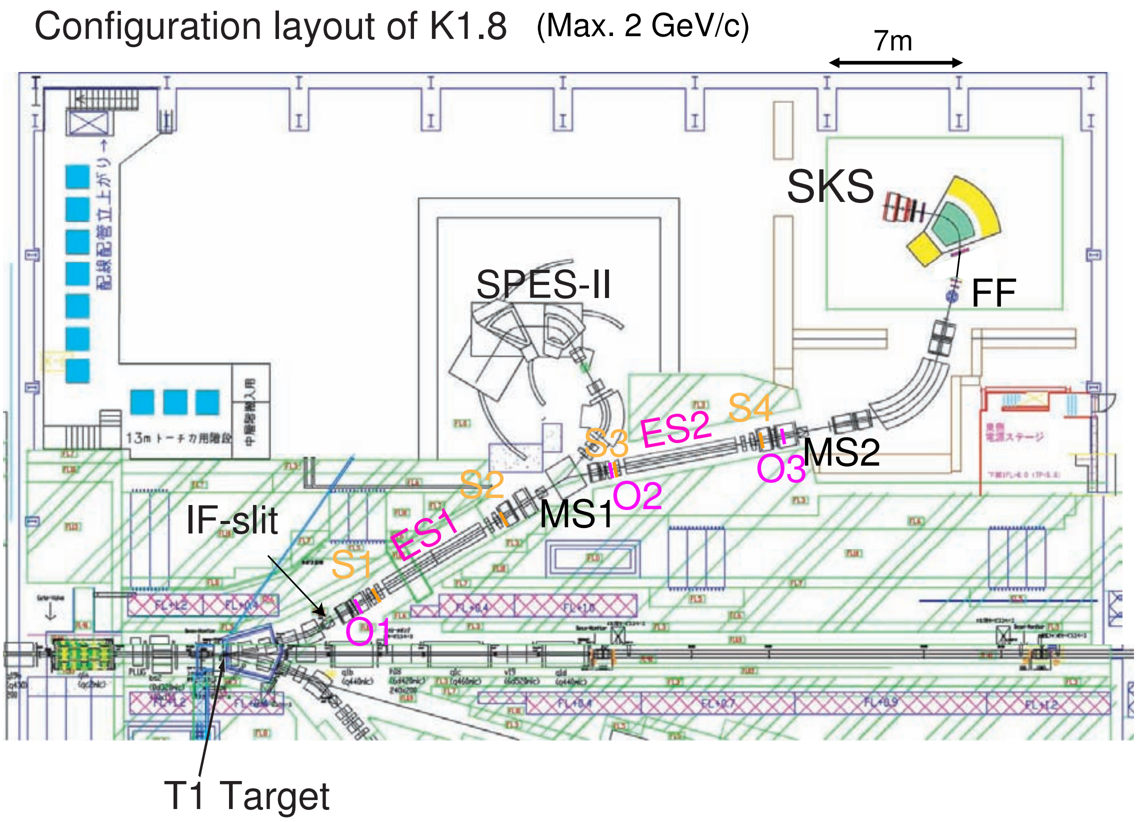

Figure 5: The layout of K1.8 beamline.

Table 1: Design parameters of K1.8 beamline. The paramteres are tuned for K$^-$ beam.

	Phase-II (50GeV-15μA)	Phase-I (30GeV-9μA)
Max. Mom. [GeV/c]	2.0	
Length [m]	45.853	
Acceptance [msr·%]	1.4	
Electro-static Separator	750 kV/10 cm, 6 m $\times$ 2	
K^- Intensity [/spill]		
1.8 GeV/c	6.6×10^6	1.4×10^6
1.1 GeV/c	3.8×10^5	8.0×10^4
K^-/π^- @ FF @ 1.8 GeV/c	8	6.9
X / Y(rms) size @ FF [mm]	19.8 / 3.2	
Singles-rate @ MS2 @ 1.8 GeV/c	$>3.3 \times 10^7$	$>8 \times 10^6$

The rate at tracking chambers is most severe that it determines the acceptable beam intensity at K1.8. They should be as thin as possible to keep good energy or momentum resolution of the beam analyzer. They should also work with good enough resolutions and good efficiencies under high rate environment. At KEK-PS K6 beamline, we operated drift chambers with the anode-spacing of 5 mm under $3 - 4 \times 10^6$ π^+/spill after the target with the flat-top length of 1.8 seconds. Compared with plus charged mesons, the π^- beam has no proton contamination which raises the particle rate 10%, thus the acceptable rate becomes 4.4×10^6 π^-/spill. Since the particle rate at the upstream of the beam spectrometer was estimated to be twice as high as that at the downstream, these chambers should be able to be operated under the rates of $2 \times 4.4 \times 10^6$ / 1.8 sec = 5×10^6 /sec. As the tracking chambers, 1mm pitch MWPC's will be newly constructed in the middle of 2006, whose maximum acceptable rate can be estimated to be 5×10^6 /sec $\times$ 5 mm/1 mm = 2.5×10^7 /sec. Therefore, the rate capability of the detector system after the $QQDQQ$ system is expected to be 1.3×10^7 /sec. The rate per spill is 1×10^7 /spill with the flat top of 0.7 sec. If the flat top could be extend to 1.4 seconds, the acceptable rate of the tracking chambers will be 1.5×10^7 /spill.

Segmented plastic scintillator hodoscopes will be located at the upstream and downstream of the beam analyzer for a trigger and an offline particle identification with TOF technique.

2.2 Spectrometer for Scattered Particles

For the K^- spectrometer, we will use the existing SKS spectrometer. The scattered K^-s are identified with the counters located at a downstream of the magnet. The momentum of K^- is analyzed by use of the SKS magnet and the tracking chambers. The solid angle of $\sim$0.1 sr with the wide angular coverage up to 20° is achieved. The measured momentum resolution is represented in a following equation [30];

$$\frac{dp}{p} = 0.096 \times p[GeV/c]\% + 0.092\% \tag{1}$$

We will use 4 sets of drift chambers (SDC1–4) as tracking detectors of the SKS spectrometer. The SDC1 and SDC2 located after the target should be high-rate chambers, since the beam particles will pass through. These chambers are similar to the beamline chambers except for the size. Other chambers are not required high-rate tolerance, since the beam does not pass through these detectors thanks to the double charge exchange reaction.

At the exit of the superconducting magnet, we also have SDC3 and SDC4. For trigger and particle identification, following detectors will be used; TOF wall, aerogel Cerenkov counters, Lucite Cerenkov counter. These detectors as well as SDC1–4 are reused ones of the existing SKS detectors.

2.3 Missing Mass Resolution

The SKS spectrometer enable us to measure the width of Θ^+ with a highest resolution in the world. The missing mass resolution is estimated as follows.

The missing mass, M, is expressed as,

$$\begin{aligned} M^2 &= (E_{\pi^-} + m_p - E_{K^-})^2 - (\vec{p}_{\pi^-} - \vec{p}_{K^-})^2 \\ &= m^2_{\pi^-} + m^2_{K^-} + m^2_p + 2\left(m_p E_{\pi^-} - m_p E_{K^-} - E_{\pi^-} E_{K^-} + p_{\pi^-} p_{K^-} \cos\theta\right), \quad (2) \end{aligned}$$

where θ is a scattering angle, m, E, $\vec{p}$ and p are mass, energy, momentum and magnitude of the momentum, respectively. Suffixes π^-, K^- and p mean the beam, , scattered K^- and the target, respectively. Therefore the missing mass resolution, ΔM is expressed as follows;

$$\Delta M^2 = \left(\frac{\partial M}{\partial p_{\pi^-}}\right)^2 \Delta p^2_{\pi^-} + \left(\frac{\partial M}{\partial p_{K^-}}\right)^2 \Delta p^2_{K^-} + \left(\frac{\partial M}{\partial \theta}\right)^2 \Delta\theta^2, \quad (3)$$

$$\frac{\partial M}{\partial p_{\pi^-}} = \frac{1}{M}[\beta_{\pi^-}(m_p - E_{K^-}) + p_{K^-} \cos\theta], \quad (4)$$

$$\frac{\partial M}{\partial p_{K^-}} = -\frac{1}{M}[\beta_{K^-}(m_p + E_{\pi^-}) - p_{\pi^-} \cos\theta], \quad (5)$$

$$\frac{\partial M}{\partial \theta} = -\frac{1}{M} p_{\pi^-} p_{K^-} \sin\theta, \quad (6)$$

where β_{π^-} and β_{K^-} are velocities of the beam and scattered particles, respectively. Δp_{π^-}, Δp_{K^-} and $\Delta\theta$ are resolutions of the measurement for momenta of the beam, scattered particles and the scattering angle, respectively.

The momentum resolution of the beam analyzer at 1.97 GeV/c is estimated to be 0.6 MeV/c(FWHM) using the beam momentum resolution of 1.4×10^{-4} at 1 GeV/c [29]. The momentum resolution of the scattered K^- is estimated from the measured momentum resolution of the SKS spectrometer described in the previous Section. The resolution of the scattered angle is estimated to be 0.26 degree through a Monte Carlo simulation using Geant4 [31]. Using these values, the missing mass resolution can be estimated to be 2.5 MeV. With this expected missing mass resolution, we can determine the width of the Θ^+. If it is less than 2 MeV, this experiment can give us a world record of the upper limit of the width.

3 Expected Sensitivity

In 160 hours of beam time, the target will be irradiated with 1.44×10^{12} pions in total (4.8×10^{11} for each π^- momentum), which is 100 times more than E522. The detector acceptance is 0.1 sr and the expected analysis efficiency is 0.5. In addition, about 50% of K^- is lost in the SKS due to its decay. Then, assuming 1.9 μb/sr for the production cross section of Θ^+, based on the E522 result, we will obtain

$$4.8 \times 10^{11} \times 5.3 \times 10^{23} \times 1.9 \times 10^{-30} \times 0.1 \times 0.5 \times 0.5 = 1.2 \times 10^4$$

events for each momentum setting.

The background can also be estimated from the E522 result. In E522, background cross section was 0.8 μb/sr/MeV for a proton target[1] at 1530 MeV. The beam momentum dependence of the background cross section was found to be reasonably small. In this experiment, this corresponds to 5.0×10^3 counts/MeV for each momentum setting.

With these estimations combined, we expect an unambiguous observation of a 62σ peak if Θ^+ is a narrow resonance ($\Gamma < 2$ MeV). If it is as wide as $\Gamma = 10$ MeV, still the significance of the peak is high enough (48σ). These high statistics enable us to determine angular distribution of the production cross section.

In case the production cross section is much smaller than what E522 suggests, or Θ^+ does not exist, sensitivity of the experiment will be 75 nb/sr and 150 nb/sr for $\Gamma < 2$ MeV and $\Gamma = 10$ MeV, respectively. As for the width, we are sensitive down to $\Gamma = 2$ MeV or even better thanks to the excellent resolution of the spectrometer system.

4 Time Schedule

Figure 6 shows the time schedule of the proposed experiment.

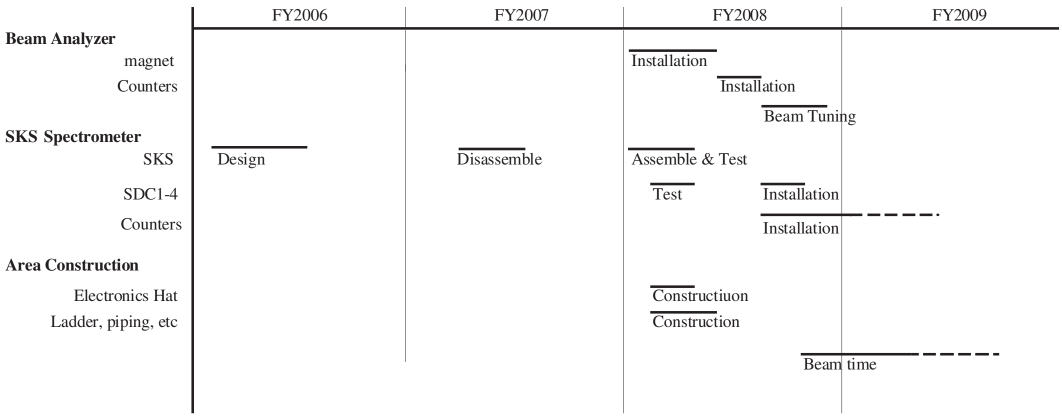

Figure 6: Time Schedule of the preparation for the proposed experiment. The Blue parts are optional.

[1]This is obtained by a subtraction method using CH_2 and C targets.

5 Cost Estimate

Most of the detector systems including the readout and front-end electronics will be recycled or reused ones. Beam line detectors including their readout and some of detectors will be constructed with the budget of the Grant-In-Aid for Priority Areas, "Quark many-body systems with strangeness" (2005 – 2009). Items and their costs are listed bellow.

Item		Cost [kJY]	
Beam Analyzer			
1mm MWPC ×2	New	4,000	Grand-In-Aid
3mm DC ×2	New	3,000	Grand-In-Aid
Readout Amp.& Discri.	New	9,000	Grand-In-Aid
MWPC Encoder	New	20,000	Grand-In-Aid
DC MultiHit TDC	Existing	0	
Beam Hodoscope	New	3,000	Grand-In-Aid
Support Frame etc.	New	2,000	
SKS Spectrometer			
DC (SDC1–4)	Existing		
TOF	Existing	1,000	Grand-In-Aid
AC ×2	Existing	2,000	Grand-In-Aid
LC	Existing	1,000	Grand-In-Aid
DC M.H.Tdc and DrT-II	Existing	0	
Support Frame etc.	New	5,000	
Area Construction etc.			
Electronics Hat	Reuse	5,000	
SKS Ref. Control Hat		8,000	
AVR etc.	Recycle	4,000	
Cable Ladder	New	5,000	
Gas piping, alarm system	New	7,000	
Gas mixer system	Existing		
Cables	N/R	10,000	
Electronics etc.			
PMT P.S.	Existing		Electronics Pool
Racks, Bin, Crates etc	Existing		
NIM,CAMAC, TKO modules	Existing		Electronics Pool
Discriminators	New		
Trigger Logic (FPGA)	New		
DAQ System	New		
Analysis Computer System	New	6,000	
Data Storage	New	6,000	

6 Additional Note

6.1 Future Plan

If the existence of Θ^+ is confirmed in this experiment, we are planning to determine its spin by measuring angular distributions of the decay particles.

6.2 Compatibility between other proposed experiments

The experiment is proposed to investigate a spectroscopic information of Ξ-hypernuclei via the (K^-,K^+) reaction at the K1.8 beam line by T.Takahashi [32]. They intend to modify the SKS spectrometer, which is able to measure the higher momentum of 1.3 GeV/c for scattered K^+'s corresponding to the production of Ξ-hypernuclei, installing a new dipole magnet, tracking chambers and Čerenkov counters. If we use this modified SKS, the acceptance for the Θ^+will be reduced to roughly 1/4 compared to the current SKS setting. Therefore, the same sensitivity will be achieved if the four times longer beam time will be approved.

Also the experiment for gamma-ray spectroscopy of hypernuclei will be proposed [33]. They intend to modify the bending angle of the scattered particles to be able to detect 1.4 GeV/c π^-'s, by changing the magnetic field strength and the geometrical alignment of downstream detectors. The acceptance for the K^- corresponding the Θ^+production could be reduced after this modification, but it will take only few days for the rearrangement of the downstream detectors and the proposed experiment could be compatible with this experiment.

References

[1] T. Nakano et al. *Phys. Rev. Lett.*, 91:012002, 2003.

[2] V. V. Barmin *et al.* *Phys. Atom. Nucl.*, 66:1715, 2003.

[3] S. Stepanyan *et al.* *Phys. Rev. Lett.*, 91:252001, 2003.

[4] V. Kubarovsky *et al.* *Phys. Rev. Lett.*, 92:032001, 2004.

[5] J. Barth *et al.* *Phys. Lett. B*, 572:127, 2003.

[6] A. G. Dolgolenko A. E. Asratayn and M. A. Kubantsev. *Phys. Atom. Nucl.*, 67:682, 2004.

[7] A. Airapetian *et al.* *Phys. Lett. B*, 585:213, 2004.

[8] S. Chekanov *et al.* *Phys. Lett. B*, 591:7, 2004.

[9] M. Abdel-Bary *et al.* *Phys. Lett. B*, 595:127, 2004.

[10] A. Aleev *et al.* hep-ex/0401024.

[11] J. Z. Bai *et al.* *Phys. Rev. D*, 70:012004, 2004.

[12] B. Aubert *et al.* hep-ex/0502004.

[13] K. Abe *et al.* hep-ex/0409010.

[14] S. Schael *et al.* *Phys. Lett. B*, B599:1, 2004.

[15] I. Abt *et al.* *Phys. Rev. Lett.*, 92:212003.

[16] Yu. M. Antipov *et al.* *Eur. Phys. J.*, A21:455, 2004.

[17] M. J. Longo *et al.* *Phys. Rev. D*, 70:111101(R), 2004.

[18] D. O. Litvintsev *et al.* *Nucl. Phys. B, (Proc. Suppl.)*, 142:374, 2005.

[19] K. Stenson *et al.* *Int. J. Mod. Phys.*, A20:3745, 2005.

[20] *Phys. Lett. B*, 632:173, 2006.

[21] C. Pinkerton *et al.* *J. Phys.*, G30:S1201, 2004.

[22] M. Battaglieri *et al.* *Phys. Rev. Lett.*, 96:042001, 2006.

[23] B. McKinnon *et al.* hep-ex/0603028.

[24] K. H. Hicks. *Prog. Part. Nucl. Phys.*, 55:647, 2005.

[25] Y. Oh et al. *Phys. Rev. D*, 69:014009, 2004.

[26] T. Hyodo and A. Hosaka. *Phys. Rev. C*, 72:055202, 2005.

[27] K. Miwa *et al.* *Phys. Lett. B*, 635:72, 2006.

[28] T. Fukuda et al. *Nucl. Inst. Meth.*, A361:485–496, 1995.

[29] H. Noumi. Status of the secondary beam lines in the hadron hall at j-parc. 2005.

[30] H. Hotchi. PhD thesis, 2000.

[31] S. Agostinelli et al. *Nucl. Inst. Meth.*, A 506:250–303, 2003.

[32] T. Takahashi et al. Spectroscopic study of ξ-hypernucleus, $^{1}2_{\Xi}$be, via the ^{1}2c(k^{-},k^{+}) reaction. Proposal for J-PARC 50 GeV Proton Synchrotron.

[33] H. Tamura et al. Gamma-ray spectroscopy of light hypernuclei. Proposal for J-PARC 50 GeV Proton Synchrotron.