Ξ Baryon Spectroscopy with High-momentum Secondary Beam

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We express our interest in performing the Ξ baryon spectroscopy with high-momentum secondary beams. The experimental information on the excited states of Ξ baryon is largely lacking. The physics cases and possibilities to investigate Ξ^* states using the high-momentum beam line is discussed. The enough sensitivity is expected to determine the excited state up to 2 GeV/c^2 systematically with a reasonable beam time in both kaon and π induced reactions. The high intense secondary beam provide an opportunity to investigate an unknown field of Ξ^* baryons.

CONTENTS

I. INTRODUCTION

A. Introduction

There is hard evidence that Quantum Chromodynamics (QCD) is the basic theory of the strong interactions. However it remains one of the great issue in hadron physics today to understand how QCD works to describe properties of hadrons. The quark model is surprisingly successful in explaining the observed hadron spectrum, especially of ground state hadrons. It seems reasonable to believe that the hadron is a loosely bound system of constituent quarks which have an effective mass of a few hundred MeV. However, the naive quark model seems to be too naive to describe the properties of excited states. It is natural that excited states are not simply explained with spatial excitations of constituent quarks, if it is an effective representation revealing complicated interactions of quarks and gluons inside. Hadron spectroscopy will provide a comprehensive description of hadron structure.

Ξ baryons have strangeness S $= -2$ and baryon number B $=1$ containing two strange quarks and one light quark (ssq). They form isospin doublet (Ξ^-, Ξ^0) as members of SU(3) octet and decuplet. Experimental knowledge about Ξ baryons is still limited, this may be due to lack of intense kaon beams. Only ground states of the octet and decuplet are fully identified and rated with four stars by PDG [1]. Although the excited states are still not established, their width have been known to be narrow; for example, all three-star states have a width less than 30 MeV except for $\Xi(1950)$ whose width was reported to be 60±20 MeV. Therefore, the Ξ baryon spectroscopy can be performed with missing and/or invariant mass technique unlike N^*/Δ^* states which need a partial wave analysis. The high-momentum kaon beam which will be provided at the J-PARC Hadron facility presents important opportunities to explore the undeveloped land of Ξ baryons.

B. Current status of Ξ baryon

There are many predictions of the mass spectrum of Ξ baryons based on quark models, large Nc calculations, QCD Sum Rules *etc.* well summarized in [2]. Figure 1 shows the spectrum of expected Ξ states calculated by Chao, Isgur and Karl [3]. The 12 excited states were predicted up to 2 GeV/c^2, whereas only $\Xi(1820)$ is identified as $J^P = 3/2^-$ state with three stars.

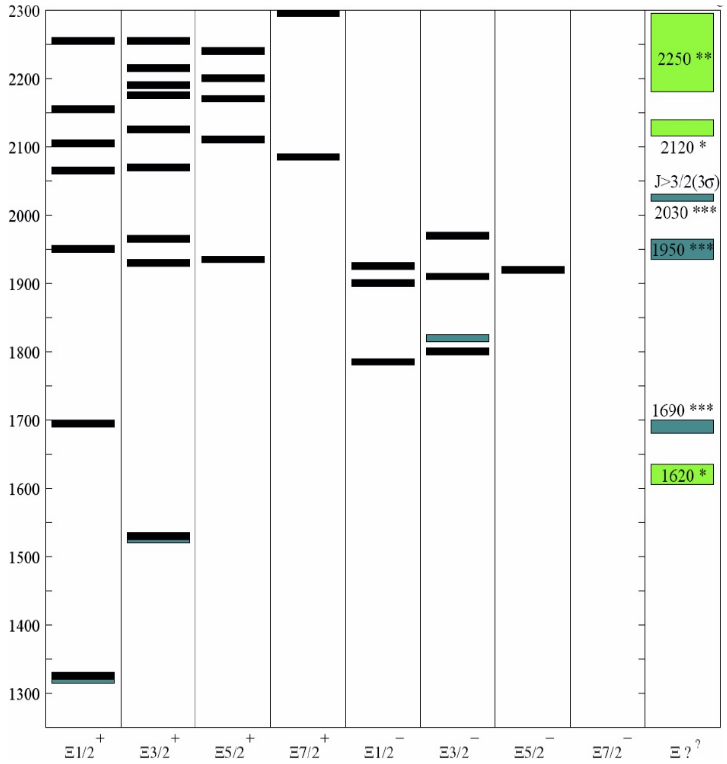

FIG. 1. Black bars: Predicted Ξ spectrum based on the quark model calculation [3]. Colored bars: Observed states. The two ground states and $\Xi(1820)$ are shown in the column of $J^P = 1/2^+, 2/3^-$, respectively. Other unknown J^P states are plotted in the rightest column. The number represents the mass and the size of the box corresponds to the width of each state.

Recently it is pointed out that there are two distinct excitation modes when a baryon contains one heavy flavor inside, and the separation of these two modes possibly good enough even at the strange quark mass [4]. Baryons which contain single (Qqq) and double (QQq) strange and/or charm flavors might be understood as a "dual" system based on the spatial parametrization concerning a diquark contribution of (qq) and (QQ). In this sense, it should be noted that cascades and charmed baryons are expected to be closely related.

The Ξ^* states were intensively searched for mainly in bubble chamber experiments using the $K^- p$ reaction in '60s – '70s. The cross section was estimated to be an order of 1 – 10 μb at the beam momentum up to ~10 GeV/c. In '80s – '90s, the mass or width of ground or some excited states were measured with a spectrometer in the CERN hyperon beam experiment. There has been a few experiments to study cascade baryons with the missing mass technique. In 1983, the production of Ξ^* resonances up to 2.5 GeV/c^2 were reported from the missing mass measurement of the $p(K^-, K^+)$ reaction, using multi-particle spectrometer at the Brookhaven National Laboratory [5]. Figure 2 shows squared missing mass spectra of $p(K^-, K^+)$ reaction. With ten times intense kaon beam combined with 5 – 10 times better resolution, each sates is expected to be clearly stated even without tagging any decay particles in the $p(K^-, K^+)$ reaction.

II. THE PHYSICS CASE

The physics case and experimental method are reviewed in the following.

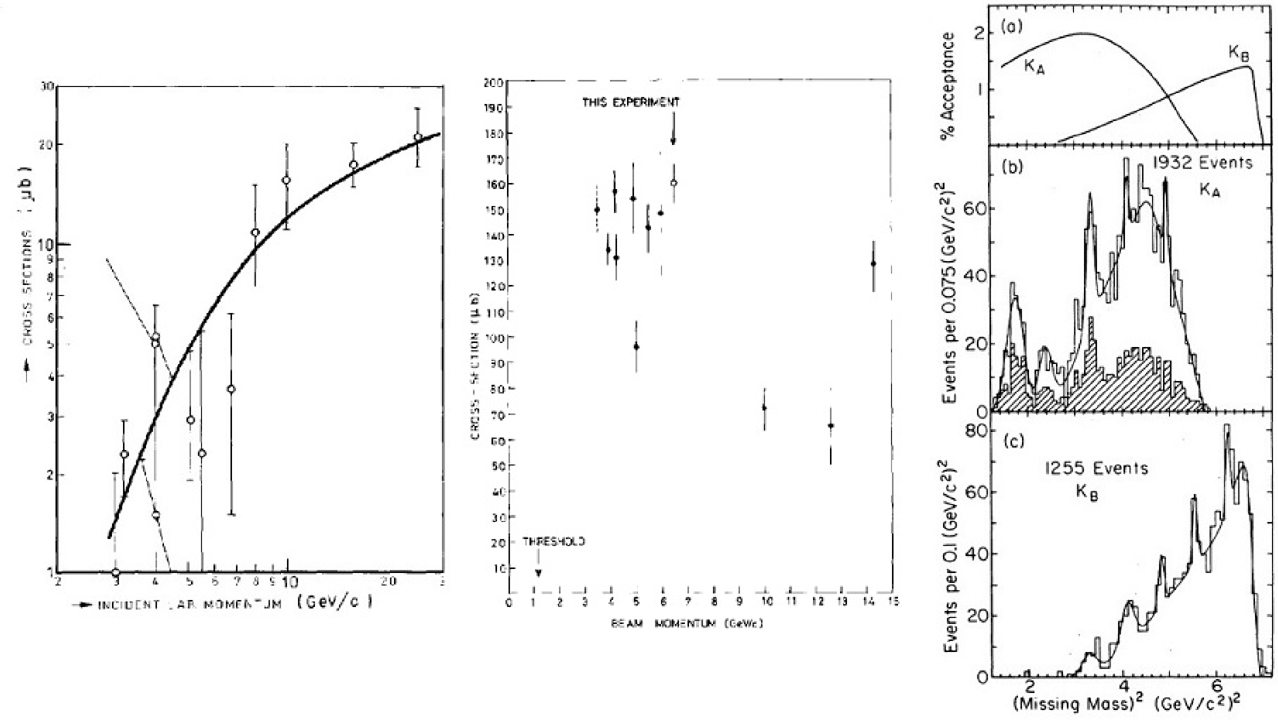

FIG. 2. Left: Inclusive production cross section of Ξ in πp reaction [6]. Middle: Inclusive production cross section of Ξ in Kp reaction [7]. Right: Missing mass squared for $p(K^-, K^+)$ reaction at beam momentum of 5 GeV/c. (b) Spectrum with lower kaon arm. (c) Spectrum with higher kaon arm. Figures are taken from the literature [5].

A. Excited State Spectroscopy

Under the circumstance described in the previous section, the high-momentum secondary beam is expected to provide an opportunity to investigate excited states of Ξ baryon systematically. The current maximum momentum of secondary beam line is 2 GeV/c which is available at the K1.8 beam line. The beam momentum of 2 GeV/c corresponds to $\sqrt{s} = 2.2$ GeV in the $\pi^- p$ and $K^- p$ reactions which is not enough to generate even the first excited state predicted in the quark model. In the momentum range of $5 - 15$ GeV/c, intensities of secondary π and kaon beams reach 10^8 and 10^6 ppp, respectively. In both $K^- p$ and $\pi^- p$ reactions, the Ξ^* production cross sections were measured to be an order of $1 \sim 10$ μb in the corresponding energy region. Enough statistics can be obtained with a reasonable beam time for Ξ^* up to 2.5 GeV/c^2. In addition to the scattered K^+, all or a part of the decay products of Ξ^* are measured simultaneously to determine a spin J of each state. It is possible to reduce background contribution by tagging decay particles and/or the scattered particle having a strangeness. The spectrometer is commonly used with the J-PARC P50 experiment, which aims to perform the charmed baryon spectroscopy with the missing and/or invariant mass spectroscopy. The detail of the yield estimation is discussed in Sec. III.

B. Search for Exotic States

The low-lying negative parity state has not been clearly observed so far. In some theoretical models or lattice QCD calculations, the level crossing is also predicted in cascade sector as in N^* or Λ^* series. For example, $\Lambda(1405)$ has $J^P = 1/2^-$ and the mass lies lower than $1/2^+\Lambda(1600)$, just below the KN threshold. $\Lambda(1405)$ is now thought to be a bound state of $\bar{K}N$, whose properties are intensively studied all over the world. A candidate for such a exotic state is one-star state of $\Xi(1620)$. It is pointed out that it could be a dynamically generated resonance as $\Lambda(1405)$ based on the chiral unitary approach [8]. The experimental evidence of the state is week, however, the production cross section was measured to be a few μb in the K^-p reaction, therefore the existence and spin assignment of the state will be definitely determined in the proposed experimental program, if exists.

III. EXPERIMENTAL APPARATUS

The Ξ spectroscopy experiment will be performed at the J-PARC high-momentum beam line. The beam line can provide a high-momentum secondary beam with a high-intensity of more than 10^6 per spill. The scattered particles from the Ξ production events are measured by the charmed baryon spectrometer which is commonly used for the charmed baryon spectroscopy experiment [9]. The experiment can be performed without any change of the spectrometer setup. In this section, the experimental apparatus will be discussed.

A. High-momentum beam line

The high-momentum beam line is a branch of the primary beam line from the extraction point located at the middle point of the slope in the switch yard as shown in Fig. 3. Since a production target of up to 15-kW beam loss can be installed at the extraction point, an intense secondary beam can be produced for the secondary beam experiments. The high-momentum unseparated secondary beams with a sufficient intensity can be available. The beam momentum up to 20 GeV/c can be provided through the beam line.

The yield of the secondary beam is estimated with the Sanford-Wang formula [10]. We assume a production angle of 0 degree by using a beam swinger mode to irradiate the primary beam, and a 15-kW primary beam lost at the platinum target. In the calculation, in-flight decay through the beam line length of 132 m and the beam line acceptance of $\sim$2 ms are taken into account. Figure 4 shows the estimated yield of the beam intensity as a function of the beam momentum. The beam intensity of more than 10^7 per spill can be used with pion beam experiments, while the beam intensity of $\sim 10^6$ per spill can be provided for the kaon beam experiments. By using those intensive secondary beams, it is possible to obtained a large number of the excited Ξ states.

The dispersive optics method is used for measuring the beam momentum. The momentum dispersive focal plane is constructed by using the beam line components. The beam momentum is obtained by measuring the beam position at the focal plane. The momentum resolution is estimated through a ray-tracing computer simulation code, TURTLE [11]. When we select a beam position in a 2-mm width bin, it is demonstrated that an r.m.s. width of the momentum distribution in any bin is kept to be a level of 0.1%. The resolution is determined by the 1st order optics. The aberrations of the 2nd order are eliminated by optimizing the beam line optics. The missing mass resolution of less than 10 MeV is estimated from the momentum resolution of 0.1%, when the momentum of the scattered particles are measured with the similar resolution.

Beam particle identification

The high-momentum beam line has no electrostatic separators so that the provided secondary beams are not separated. For experiments use kaon or anti-proton beam, it is necessary to reject the intense pions contaminated in the beam. The beam particle identification is planned to be preformed by using the Ring Image Čerenkov (RICH) counter. Since the secondary particles with the wide momentum range of 2$-$20 GeV/c are needed to be identified, the hybrid-RICH system which is also used for the scattered particle identification in the charmed baryon experiment is designed. The beam RICH counter consists of the Aerogel (n=1.03$-$1.05) and the CO_2 gas (n=1.0005) radiators.

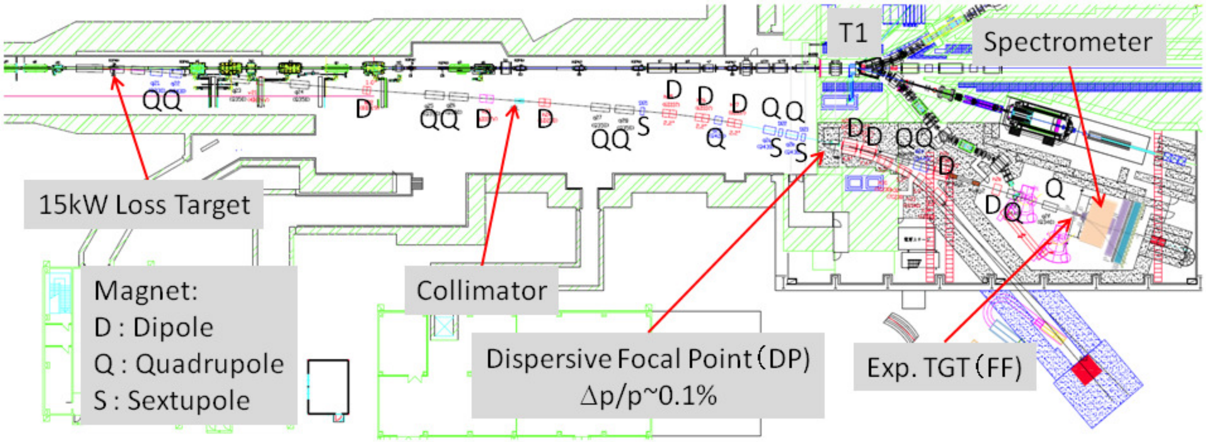

FIG. 3. Layout of the High-momentum beam line.

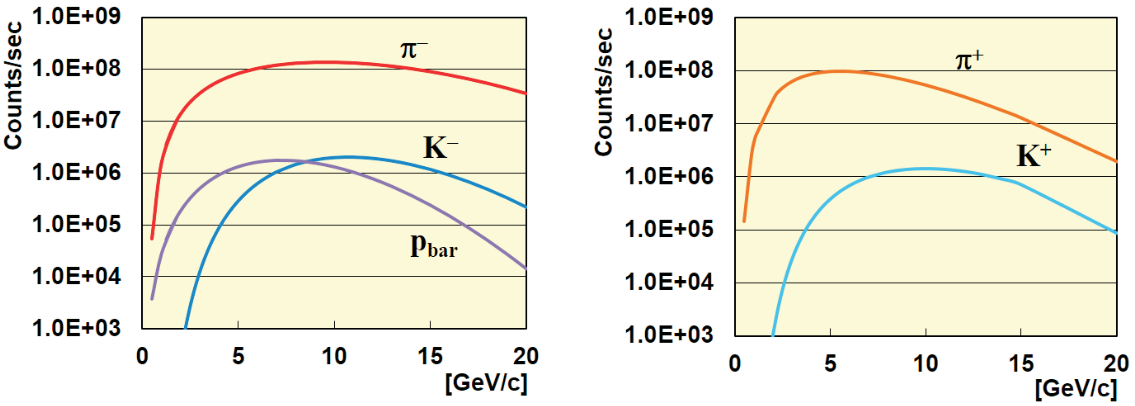

FIG. 4. Yields of secondary particles as a function of the beam momentum at a production angle of 0 degrees for a 15-kW primary beam lost at a platinum target, calculated by the Sanford-Wang formula [10]. The acceptance and the total length of the beam line are 2 msr*% and 132 m, respectively.

From information of the Čerenkov emission angles of those radiators, the particles with the momentum of $2-20$ GeV$/c$ can be separated. Both K^- and π^- beams can be measured at the same time.

In the RICH counter, the emitted Čerenkov photons are focused by the spherical mirror. Then, the photons are detected by the photo-sensors at the detection plane. Due to the small beam angle of less than 10 mrad, the ring image is focused to be small region at the detection plane. The counting rate is estimated to be a few MHz/cm^2. The high-rate capability of the photo-detection sensors are necessary to measure the intense pion beams. We plan to use a fine segmented detection plane by using Multi-Pixel Photon Counter (MPPC). By adopting the 1-mm size MPPC to the detection plane, the counting rate per one segment can be suppressed to be lass than 1 MHz. The operation of MPPC in the counting ratio of $\sim$1 MHz has been achieved by the J-PARC K1.8 beam line experiment. To achieve the particle identification in both high-momentum and high-rate beam conditions, the beam RICH counter is a key component for the experiment.

B. Spectrometer system

The scattered particles from the excited Ξ production are detected by the charmed baryon spectrometer system [12]. In the case of the fixed target experiment with the higher momentum beam, all the generated particles, not only the

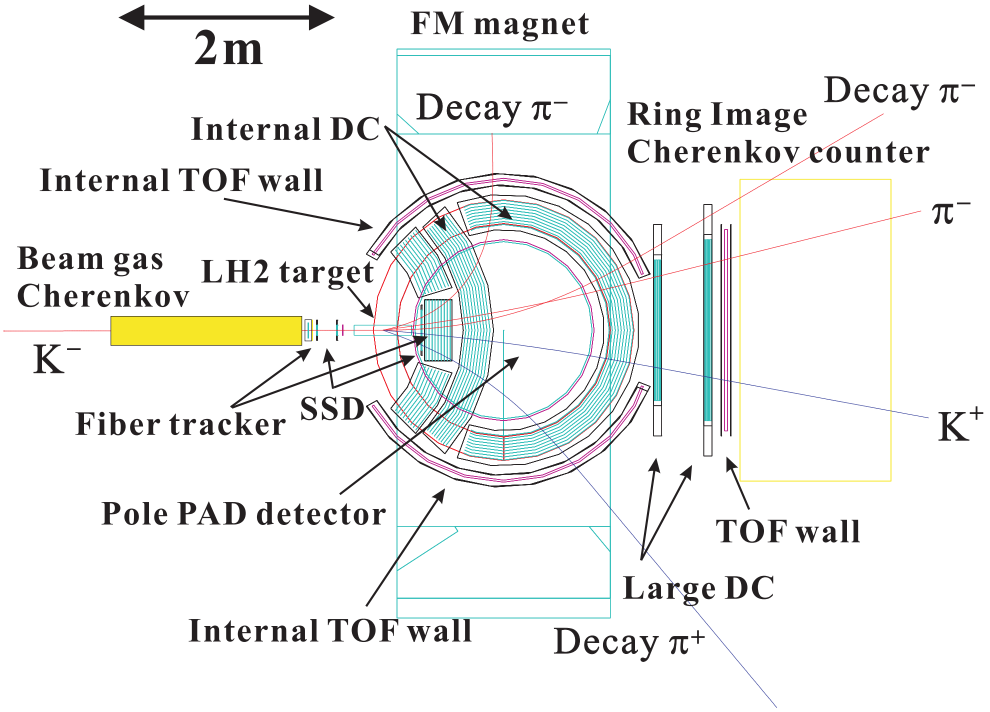

FIG. 5. The schematic view of the charmed baryon spectrometer system.

scattered high-momentum particles from the $K^-p \to \Xi^{*-}K^+$, $K^-p \to \Xi^{*0}K^{*0}$ and $\pi^-p \to \Xi^* KK$ reactions but also the decay products from the $\Xi^* \to \Xi\pi$ and $\Xi^* \to Y\bar{K}$ modes, are scattered to the forward direction. The charmed baryon spectrometer system can commonly measure both particles from the reaction processes for the missing mass method and the decay products from the produced Ξ^* states for the decay measurement. In the experiment, both missing mass and decay property measurement are performed to investigate the excited Ξ states systematically. The properties of excited states, mass, decay width, production cross section and spin/parity, can be obtained by the systematic measurement.

Figure 5 shows the schematic view of the charmed baryon spectrometer system. The spectrometer consists of the forward detection sector (Scintillating Fiber Trackers, Drift chambers, TOF wall and RICH) for measuring the high momentum particles of more than 2.0 GeV/c and the decay detection sector (Internal drift chambers, Internal TOF walls and pole PAD detector) for the slow momentum particles from the decay processes of 0.2$-$2.0 GeV/c. The higher and lower momentum particles are identified by the RICH counter from the ring image analysis and the internal TOF counter by the Time-Of-Flight analysis, respectively. All the produced particles from the excited Ξ states are measured by using both forward and decay detection sectors.

C. Production measurement

1. *Kaon beam reactions*

The excited Ξ states can be produced from the 2-body reactions induced by the kaon beam. For understating the reaction processes and determining the spin/parity, the binary reactions are essential part to produce the excited Ξ states. The production cross section is expected to be 1$-$10 μb so that the large number of events can be obtained from the intense beam of 10^6 per spill.

In the kaon beam experiment, the $K^-p \to \Xi^{*-}K^+$ or K^{*+} and $K^-p \to \Xi^{*0}K^{*0}$ reactions are measured. Both isospin states can be produced and studied from those reaction channels. Although the detection of K^0_S can also be performed by the spectrometer system, the detection with the strangeness tagging are necessary to suppress the background from the "K^0" detection, such as just charge exchanging process ($K^-p \to K^0n$) and $K\bar{K}$ production events. By only detecting K^0_S, those reactions which have a large cross section cannot be identified. Therefore, to produce the excited Ξ states, we will detect K^+ or $K^{*+}(K^{*+} \to K^0_S\pi^+ \to \pi^+\pi^-\pi^+)$ and $K^{*0}(K^{*0} \to K^+\pi^-)$ for the

Ξ^{*-} and Ξ^{*0} production, respectively.

In the case of using the beam momentum of 5 GeV/c, the momentum range of kaons and pions from the Ξ^* production is 0.5–3.5 GeV/c. The acceptances of the K^+ and K^{*0} from the $K^+\pi^-$ mode are estimated to be 50% and 50% by assuming the isotropic angular distribution in the center-of-mass system, respectively. The missing mass resolution are estimated to be less than 10 MeV. It is enough good to study the excited states by taken into account the Ξ^* decay width of ∼20 MeV.

2. Pion beam reactions

The π^- beam can also be available at the same time, when the K^- beam is used for the production of the excited Ξ states. The excited Ξ states can also be produced from the pion beam reaction, such as $\pi^- p \to \Xi^{*-} K^{*0} K^+$ reaction. The reaction cross section by the pion beam reaction is expected to be one order smaller than that of kaon beam at the high momentum region. We expect the cross section of 0.1–1 μb for the $\pi^- p \to \Xi^{*-} K^{*0} K^+$ reaction. Owing to the 100 times higher beam intensity of the pion beam, the comparable number of the excited Ξ states can be produced. In addition, the background events including the double strange production by the pion beam is estimated to be 30 times smaller than that by the kaon beam using the cascade-code JAM [13]. The signal to noise ratio is expected to be better by using the pion beam. Although we loose the information from the 2-body reaction processes, it is necessary to search for the known excited states by using the pion beam reaction. The other channels such as $\pi^- p \to \Xi^{*-} K_S^0 K^+$ and $\pi^- p \to \Xi^{*0} K^{*0} K_S^0$ reactions can also be able to generate the excited states. It is expected for those reactions which include the K_S^0 production to have worse signal to noise ratio due to the wrong strangeness tagging from the "K^0" detection. To keep the quality to search for the excited states, the $\pi^- p \to \Xi^{*-} K^{*0} K^+$ reaction will be used for the pion beam reaction.

In the case of using the beam momentum of 5 GeV/c, the momentum range of kaons and pions from the Ξ^* production is 0.3–2.0 GeV/c. The acceptance of the $\pi^- p \to \Xi^{*-} K^{*0} K^+$ reaction is estimated to be 50% by assuming the isotropic angular distribution in the center-of-mass system. The missing mass resolution are estimated to be 5 MeV. It is enough value to study the excited states.

At the high-momentum beam line, both K^- and π^- beams are available at the same time. It is a great advantage to use both kaon and pion beam productions for investigating the excited Ξ states.

D. Decay measurement

The recoil momentum of the excited Ξ states is measured by the missing mass method so that the mass of the decay products from $\Xi^* \to \Xi\pi$ and $\Xi^* \to Y\bar{K}$ can be obtained by only detecting the emitted pions and kaons. The mass of the decay daughters can be measured without the full reconstruction of the Ξ^* decay chain.

The decay properties are measured from the $\Xi\pi$ and $Y\bar{K}$ modes. For the $\Xi\pi$ mode, the $\Xi^{*-} \to \Xi^0\pi^-$ and the $\Xi^{*0} \to \Xi^-\pi^+$ channels are measured. The $\Xi^{*-} \to \Xi^-\pi^+\pi^-$ and $\Xi^{*0} \to \Xi^0\pi^+\pi^-$ channels can also be measured. For the $Y\bar{K}$ modes, we can measure the $\Xi^{*-} \to \Lambda K^-, \Sigma^0 K^-$ and $\Xi^{*0} \to \Sigma^+ K^-$ modes. Although the detection of the decay mode with K_S^0 ($\Xi^{*-} \to \Sigma^- K_S^0$, $\Xi^{*0} \to \Lambda K_S^0$) can also be performed by the spectrometer system, the detection with the strangeness tagging decay modes are much clear to suppress the background from K^0 detection, such as $K\bar{K}$ production events.

For the decay measurement with the wider angular coverage, the decay products are detected by the internal detector system of the charmed baryon spectrometer. The horizontal direction can be covered by using the detectors installed around the magnet pole. The coverage for the polar angle is $\cos\theta_{CM} > -0.9$ for the 2-body $\Xi\pi$ and $Y\bar{K}$ decay angle in the center-of-mass frame. In addition, for covering the vertical direction, the detector which has at least the function to measure the timing information has to be installed on the magnet pole face. The vertical direction can be covered from $\cos\theta_{CM} > -0.5$. The coverage of the decay products are estimated to be ∼80% with both the polar and azimuthal angle completely covered more than $\cos\theta_{CM} = -0.5$ for the 2-body decay mode. The mass resolution for the decay products was estimated to be ∼10 MeV. The main contribution to the decay mass resolution is from the missing mass resolution. The contribution from the momentum resolution by measuring the emitted pions and kaons does not affect to the resolution.

E. Yield estimation

We estimate an yield of the excited Ξ states. The cross sections of the excited states by the kaon and pion reactions are assumed to be 1 μb and 0.1 μb, respectively. The beam intensity of the kaon and pion beams are assumed to

TABLE I. The estimated yield per month of each reaction, $K^-p \to \Xi^{*-}K^+$, $K^-p \to \Xi^{*-}K^{*+}$, $K^-p \to \Xi^{*0}K^{*0}$ and $\pi^-p \to \Xi^{*-}K^{*0}K^+$. Y_{Total} and $\mathrm{Y}_{Decay/bin}$ are yields per month for the total number of the produced Ξ^* states and the average counts per bin of the decay angles in the center-of-mass system divided into 10 bins.

Reaction	σ [μb]	Beam [/spill]	B.R.	Acceptance [%]	Y_{Total}	$\mathrm{Y}_{Decay/bin}$
$K^-p \to \Xi^{*-}K^+$	1.0	10^6	1.0	50	3.1×10^5	2500
$K^-p \to \Xi^{*-}K^{*+}$	1.0	10^6	0.23	50	0.7×10^5	580
$K^-p \to \Xi^{*0}K^{*0}$	1.0	10^6	0.67	50	2.1×10^5	1700
$\pi^-p \to \Xi^{*-}K^{*0}K^+$	0.1	10^7	0.67	50	3.1×10^5	2500

be 10^6 and 10^7 per spill, respectively. The target thickness of the liquid hydrogen are assumed to be 4 g/cm^2. The decay branching ratios of the K^{*+} and K^{*0} decay chain, 0.23 and 0.67, are taken into account, respectively. The live time of the data acquisition is assumed to be 0.9. We estimate the tracking efficiency of the tracking devices to be 0.7. The efficiencies of pion and kaon identifications are obtained as 95% for the RICH counter.

Then, the estimated yields of the excited Ξ states per day are 1.0×10^4, 0.7×10^4 and 1.0×10^4 events for the $K^-p \to \Xi^{*-}K^+$, $K^-p \to \Xi^{*0}K^{*0}$ and $\pi^-p \to \Xi^{*-}K^{*0}K^+$ reactions, respectively. The large number of the excited Ξ states can be obtained by the data taking with one week. For the decay angular measurements, the decay angles in the center-of-mass system are divided into 10 bins. When the branching ratio of each decay mode are assumed to be 0.1, the yields of each bin for analyzing the angular distribution are estimated to be 70−100 counts/day/bin. The 30 days beam time gives a few 1000 counts/bin for analyzing the angular distribution by the decay measurement. The enough sensitivity to determine the angular distribution can be obtained by the data taking with one month. Table I shows the estimated yield per month of each reaction.

IV. REQUEST TO FACILITY

A. beam time

We consider a staged approach for determining the spin state of Ξ^* as follows. The goal of each stage is to;

1. confirm the existence of one- to three-star states with plenty statistics of an order of $\sim 10^4$ counts, determine the mass and width of each state with a spectral analysis.

2. determine the spin with the yield of $\sim 10^5$ for each state.

With the approach, requested beam time is one week for stage-1 and one month for stage-2.

B. cost estimation

Since the spectrometer is commonly used with the J-PARC P50 experiment, we require only running cost to perform the experiment. Main contribution comes from the purchase cost for liquid helium-4 used to cool down and preserve the target system. It costs 2 million yen at the stage-1, and 6.5 million yen at the stage-2.

V. EXTENSION

The idea to measure the parity of Ξ baryon was discussed in [14]. In replacement of the liquid hydrogen target to a polarized one, the parity can be determined in the $\bar{K}N \to K\Xi$ reaction due to the self-analyzing property of the Ξ.

We also discussing a possibility to reduce backgrounds by installing an additional vertex tracker around the target region to the current spectrometer design of J-PARC P50 experiment. Since the Ξ^* is expected to decay into $\Xi\pi \to \Lambda\pi \to p\pi$, the event can be cleanly selected with a multi-vertex cut. The almost background free spectrum will be obtained as in counter experiments reporting the ground state Ξ with the multi-vertex cut [15].

VI. SUMMARY

We express our interest to perform the Ξ baryon spectroscopy with the high-momentum secondary beams. The possibility to determine the mass, width and spin of the Ξ^* states up to 2 GeV/c^2 is discussed. With the spectrometer commonly used with the J-PARC P50 experiment, the expected yield of the excited states is $3{-}4\ \times 10^5$ per month in both K^-p and π^-p reactions. The future prospect is refereed to measure the parity of Ξ^* states. The excellent signal to noise ratio will be expected by installing an additional vertex tracker to identify double decay vertices which is distinctive in the Ξ^* decay.

[1] J. Beringer *et al.*, Phys. Rev. D **86**, 010001 (2012).
[2] Y. Oh, Phys. Rev. D **75**, 074002 (2007).
[3] K. T. Chao, N. Isgur, and G. Karl, Phys. Rev. D **23**, 155 (1980).
[4] M. Oka, PoS **(Hadron 2013)**, 001 (2014).
[5] C. M. Jenkins *et al.*, Phys. Rev. Lett. **51**, 951 (1983).
[6] E. Balea *et al.*, Nucl. Phys. B **150**, 345 (1979).
[7] J. K. Hassall *et al.*, Nucl. Phys. B **189**, 397 (1981).
[8] A. Ramos, E. Oset, and C. Bennhold, Phys. Rev. Lett. **89**, 252001 (2002).
[9] H. Noumi *et al.*, J-PARC Proposal P50 (2013).
[10] J. R. Sanford and C. L. Wang, BNL 11279 and BNL 11479 (1967).
[11] K. L. Brown, C. Iselin, and D. C. Carey, CERN **74-2** (1974).
[12] K. Shirotori *et al.*, PoS **(Hadron 2013)**, 130 (2013).
[13] Y. Nara *et al.*, Phys. Rev. C **61**, 024901 (2000).
[14] K. Nakayama, Y. Oh, and H. Haberzettl, Phys. Rev. C **85**, 042201 (2012).
[15] M. Sumihama, PoS **(Hadron 2013)**, 024 (2013).