Cascade baryon spectroscopy at J-PARC high-momentum beamline

Megumi Naruki (Spokesperson)*[1], Kotaro Shirotori (co-Spokesperson)[2], Kazuya Aoki[3], Wen-Chen Chang[4], Takatsugu Ishikawa[2], Hiroyuki Noumi[2,3], Hiroaki Ohnishi[5], Kyoichiro Ozawa[3], Fuminori Sakuma[6], Tomonori Takahashi[7], and Natsuki Tomida[1]

[1]Dept. of Physics, Kyoto University, Kitashirakawa Oiwake-cho, Kyoto, 606-8502, Japan
[2]Research Center for Nuclear Physics (RCNP), Osaka University, 10-1 Mihogaoka, Ibaraki, Osaka 567-0047, Japan
[3]Institute of Particle and Nuclear Studies, High Energy Accelerator Research Organization KEK, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan
[4]Institute of Physics, Academia Sinica, Institute of Physics, Academia Sinica, Taipei 11529, Taiwan
[5]1-2-1 Mikamine, Taihaku, Sendai, 982-0826, Miyagi, Japan, Research Center for Electron-Photon Science(ELPH), Tohoku University
[6]2-1 Hirosawa, Wako-shi, Saitama 351-0198, Japan, RIKEN, Advanced Science Institute (ASI)
[7]Wako, Saitama 351-0198, Japan, Nishina Center for Accelerator-Based Science, Institute of Physical and Chemical Research (RIKEN)

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Executive Summary

We propose to perform cascade baryon spectroscopy at the high-momentum secondary beamline of J-PARC. The physics goals is to determine Ξ^{*0} states up to 2.3 GeV/c^2 with 7σ significance for the first time. We will measure the missing-mass spectrum of $\mathrm{K^-p \to K^{*0}\Xi^{*0}}$ reaction and obtain production cross sections of $\mathrm{K^-p \to K^{*0}\Xi^{*0}}$ reactions at the beam momentum of 8 GeV/c. The J-PARC E50 spectrometer is used to measure scattered $\mathrm{K^{*0}}$ together with decay products of Ξ^{*0}. The expected results will shed a light on an effective degree of freedom of baryon, especially the role of (sq) diquarks.

*contact person

Contents

1 Introduction

The first observation of cascade baryon Ξ was announced in 1950's. The charged Ξ was found for the first time in the distinct cascade decay recorded in the cloud chamber, as shown in Fig.1 [1]. Basic information such as mass and decay modes was studied mainly in bubble

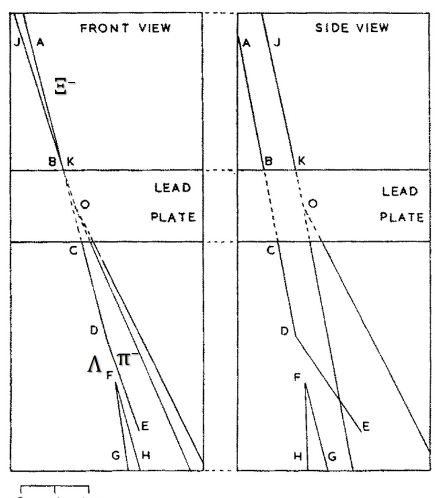

Figure 1: First observation of Ξ^- decayed in the cloud chamber [1]. The names of particle are added by the author.

chamber experiments in the early days. In 1980's, more significant measurements were performed using hyperon beams at FNAL and CERN SPS. They successfully measured a branching ratio of ground state and the production of light excited state $\Xi(1690)$, respectively [2], [3]. Figure 2 shows the invariant mass spectrum of $\Xi^-\pi^+$ measured at the CERN hyperon beam. Above the clear peak of $\Xi(1530)$, $\Xi(1690)$ was observed with 4.7 σ significance [4]. They also reported that the ratio of the product of the production cross section and the branching ratio of Ξ(1690) to Ξ(1530) is 2.2±0.5%. The small decay ratio is indicative of an specific internal structure of Ξ(1690). Besides the hyperon beam experiments, Ξ resonances were also measured in the Kp reaction at the medium energy separated beamline at AGS, and also in the LASS experiment at SLAC. Ξ^* above 2 GeV/c^2 were systematically searched for through the missing mass technique as shown in Fig.3. However, not much information

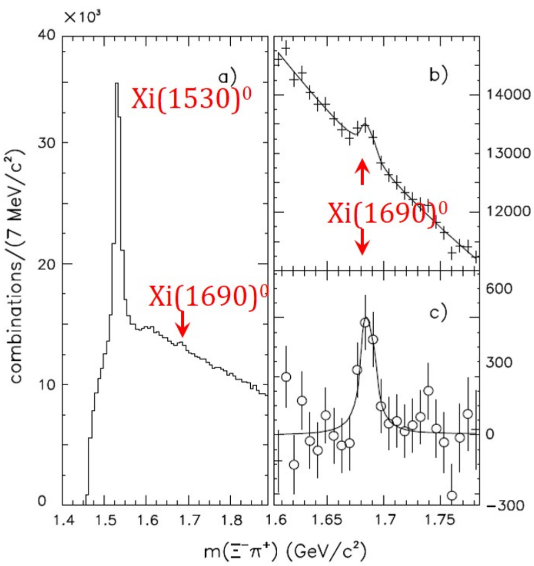

Figure 2: a) Invariant mass spectrum of Ξπ b) its closeup and c) the spectrum after subtracting the background measured in the CERN hyperon beam experiment [4]. Names of state are added by the author.

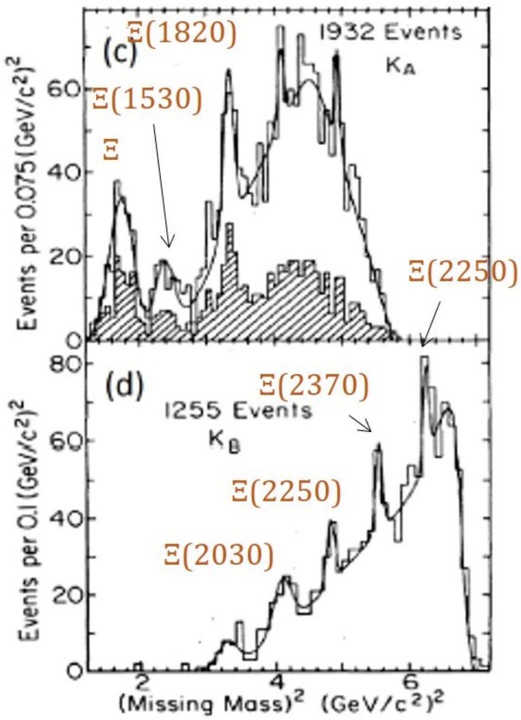

Figure 3: Missing mass squared of 5 GeV/c $K^- p \to$K$^+ X$ reaction, measured at AGS [5]. Names of state are added by the author.

has been added since then. The current status of Ξ resonances is summarized in Fig.4. Only two ground states are listed as a four-star state, whose existence is thought to be certain, as classified by the Particle Data Group (PDG) [6]. This is mainly because the production cross sections are small for Ξ, which has two strange quarks, and there has been a lack of intense kaon beams.

1.1 Theoretical background

One of the main questions in baryon spectroscopy is what are the effective degrees of freedom to describe the spectrum of baryons. Baryon spectroscopy for light baryons has been intensively performed at JLab, well summarized in [7]. They established newly 8 N* states as three- and four-star states in the past 10 years. For a comprehensive review of baryon spectroscopy, see [8]. The quark models are quite successful to describe electromagnetic observable such as magnetic moments and form factors. However, they lead to the problem of *missing resonances*. One of the solution would be given by diquark models, introducing

Particle	J^P	Overall status	Status as seen in —				
			$\Xi\pi$	ΛK	ΣK	$\Xi(1530)\pi$	Other channels
$\Xi(1318)$	1/2+	****					Decays weakly
$\Xi(1530)$	3/2+	****	****				
$\Xi(1620)$		*	*				
$\Xi(1690)$		***		***	**		
$\Xi(1820)$	3/2−	***	**	***	**	**	
$\Xi(1950)$		***	**	**		*	
$\Xi(2030)$		***		**	***		
$\Xi(2120)$		*		*			
$\Xi(2250)$		**					3-body decays
$\Xi(2370)$		**					3-body decays
$\Xi(2500)$		*		*	*		3-body decays

Figure 4: Present status of Ξ. Summary table from PDG 2022 [6].

a pair of quark as the effective degree of freedom to describe baryons. All observed baryons seems to be described in terms of a quark-diquark picture, and "missing resonances" are naturally forbidden in diquark models since the colour of diquark is restricted to be $\bar{3}$.

The Ξ is a baryon made of one light quark and two strange quarks, its quark configuration is denoted by qss. They form isospin doublets in the baryon octet and decuplet, as shown in Fig.5. The quark model level diagram predicts 44 states up to 2.3 GeV/c^2 as shown

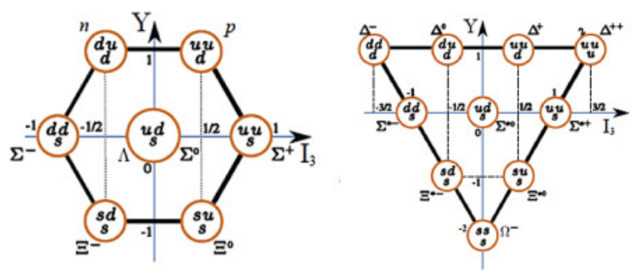

Figure 5: Baryon multiplet [9].

in Fig.6, whereas only 2 four-star states and 4 three-star states were actually measured in experiments. The level structure of Ξ is also calculated base on the quark-diquark model [10]. The spectrum displays a character different from that of three-quark models. As mentioned above, since there is not much information about Ξ, still there are some missing resonances even in the comparison with the quark-diquark model.

1.2 Scientific goal

We aim at measuring the production of Ξ^* up to 2.3 GeV/c^2 in the K^-p reaction systematically through the missing mass technique. We examine the existence of Ξ(1690) and other missing resonances theoretically predicted. It will enable us to obtain the level structure of Ξ for the best quality in the world. For the first time the existence of Ξ^* states are demonstrated with more than 5σ significance for each states. The masses of each state is

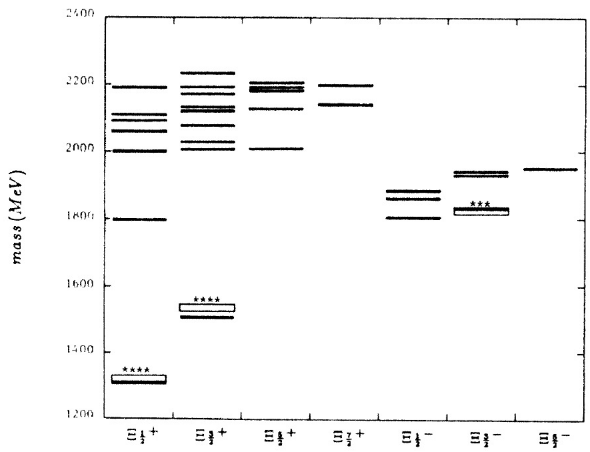

Figure 6: Quark model calculation for Ξ∗ masses [11].

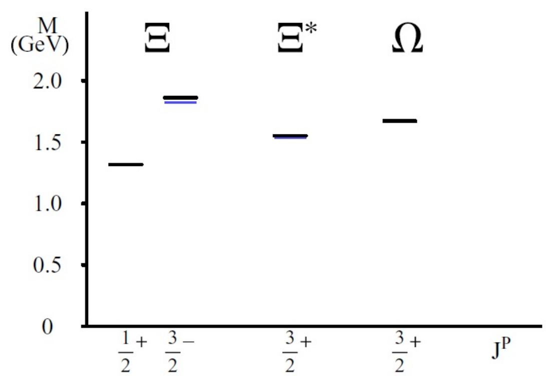

Figure 7: The result of quark-diquark model calculation of Ξ∗ and Ω masses. Bluue boxes are experimental masses from PDG [10].

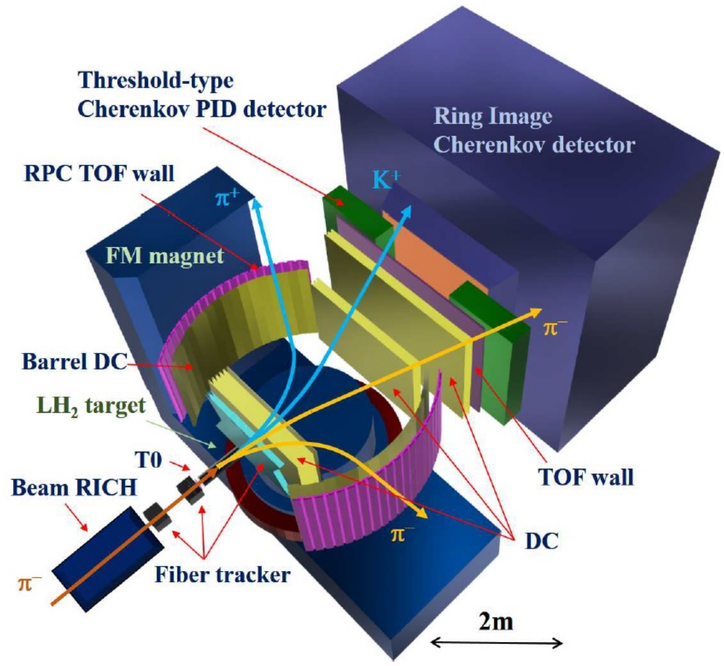

Figure 8: Schematic view of the J-PARC E50 Spectrometer.

determined with the accuracy of 0.1 MeV/c^2. Also the production cross sections in the K^-p reaction are determined. It will contribute to the future expansion of the Ξ^*, Ω spectroscopies which will be performed at K10 beamline in the Extension project of the J-PARC Hadron Experimental Facility [12].

2 Experimental method

Ξ are produced in the K^-p reaction at the high-momentum secondary beamline, which will be utilized in the near future. The 8 GeV/c K$^-$ beam is irradiated into a liquid hydrogen target with the thickness of 4 g/cm^2. The expected beam intensity is 6×10^5 kaons/spill, assuming that the production target of 5kW loss will be installed. The missing mass of the reaction $K^-p \to K^{*0}\Xi^{*0}$ is measured to establish signals of Ξ^* with 7σ. In addition, the missing mass of decays, $\Xi^{*0} \to \Sigma^+K^-/\Xi^-\pi^+$, are measured by detecting K^-/π^+ to suppress the background.

2.1 Spectrometer

The beam, scattered and decay particles are measured with the J-PARC E50 spectrometer. It can be regarded as a multi-purpose spectrometer providing a huge possibility to study all strange baryons such as hyperons, Ξ^*, Ω^* and charm baryons. The schematic view of the spectrometer is shown in Fig.8. The detector R&D have been intensively performed so far. The detail and current status of R&D of the spectrometer is well summarize in [13], [12] and references therein. A brief summary and relevant devices are described here.

The spectrometer dipole magnet for the J-PARC E16 experiment will be reused with a minor change of pole pieces. It enable us to analyze momenta of scattered and decay particles with large geometrical coverage. The experimental target is located just upstream from the spectrometer magnet.

A detection section for beam particles is located upstream the target. A series of scintillating fiber trackers [14] is used for the momentum analysis of beam particles. The time-zero is defined with a fine-segmented acrylic Cherenkov counter placed in front of the target [15]. Since the secondary beam particles are not specially separated, we introduce a RICH-type particle identification detector for beam particles (b-RICH). It is a key device for this measurements to separate beam kaons actively from pions. The detail of the b-RICH is described below.

Decay products of scattered K^{*0} are detected with the forward detectors located downstream the target. Scintillating fiber hodoscopes and three planer drift chambers are combined for momentum analysis of K^+ and π^- to cope with the high interaction rate. The momentum of these particles ranges from 0.8 to 2.3 GeV/c. For particle identification, the Time-Of-Flight and Ring Imaging Cherenkov measurements are combined. The TOF detector is composed of plastic scintillators. In the higher momentum region, K/π identification is accomplished with a RICH together with a threshold-type Cherenkov detector. There has been a substantial progress in the R&D of the Cherenkov detector [16]. Performances of photo sensors, mirrors and light-collecting cones have been minutely inspected and the study led to the development of a transparent radiator of aerogel applicable to the momentum region of 2 to 4 GeV/c. It is concluded that the required efficiency of 95% will be accomplished with the agerogel radiator.

For the decay measurement, barrel-shaped drift chambers together with resistive-plate chambers (RPCs), originally developed for the LEPS/LEPS2 experiments [17], will be installed into the sideway of a pole gap of the spectrometer magnet. The tracking devices of the fiber hodoscopes and the inner drift chambers placed just after the target are commonly used with the forward measurement.

In the E50 experiment, a trigger-less DAQ will be implemented. This is called as a streaming DAQ which enable us to realize the DAQ efficiency of 100%. The performance of the DAQ system is evaluated with a prototype recently and it demonstrated the feasibility successfully [18].

2.2 RICH detector for beam particle

Since the intensity of beam pions is larger by two orders of magnitude compared with that of kaon's, it is crucial to develop a detector which actively identifies kaons. We have developed the RICH type detector named as b-RICH, which is able to identify kaons up to 10 GeV/c [19]. The conceptual design is shown in Fig.9. We use aerogels with index of 1.02 as radiator which are suitable to separate kaons from pions for momenta greater than 5 GeV/c. The ring image is once reflected at a concave mirror with radius of curvature of 1.0 m and focused onto MPPC arrays. The performance of the prototype detector was evaluated using electrons at the SPring-8 LEPS beamline, as summarized in [20]. The measured resolution of the Cherenkov angle is shown in Fig.10. With the depth of 10 cm agerogels in total, the enough Cherenkov angle resolution of 2.1 mrad has been achieved. Since the number of

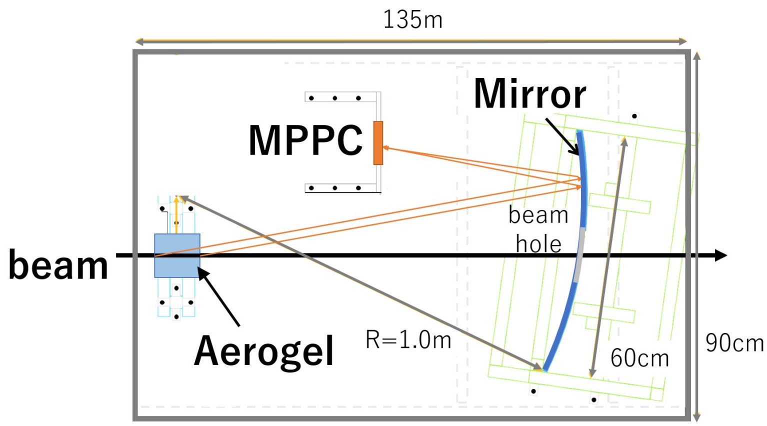

Figure 9: conceptual design of RICH detector for beam particles.

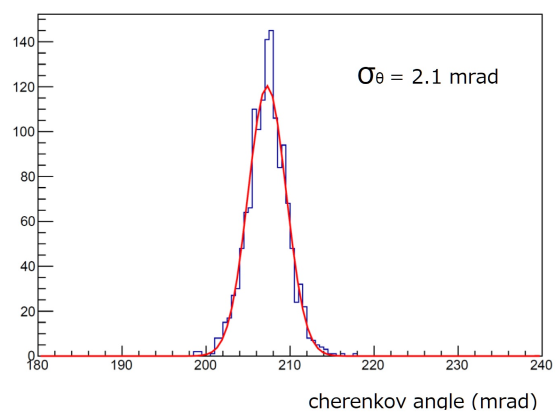

Figure 10: Measured Cherenkov angle for the prototype b-RICH.

photo sensor will be doubled, the angle resolution is expected to be improved to 1.5 mrad in the case of the real device. Keeping the rejection of pions to 3%, the efficiency for kaon is expected to be 95%.

3 Expected Results

We demonstrate the sensitivity of Ξ^* measurement in Fig.11. The expected missing-mass resolution is 6.6 MeV/c^2, enough good to separate each states. The signal yields is estimated to be 1.3×10^4 for $\Xi(1530)$ to $\Xi(1950)$ states, 8.4×10^3 for $\Xi(2030)$ and 4.5×10^3 for higher excited states, respectively, with 30-day beamtime. The achievable sensitivity is discussed in Sec.3.2. It should be noted that the S/N is improved by 30 times applying the decay event measurement especially for higher resonances. Here we assume the following conditions:

- The beam intensity of 8 GeV/c kaon is estimated to be 6×10^5/spill based to the Sanford-Wang parameterization assuming that;
  - the primary beam power of 30 kW
  - A 5kW-loss production target for the high-momentum secondary beamline
  - The intensity of pion is less than 6×10^7, which is acceptable with the E50 spectrometer
  - repetition : 5.2 sec
  - spill length : 2.0 sec
- The thickness of the liquid hydrogen target is 4.0 g/cm^2
- the geometrical acceptance of the spectrometer is estimated using Geant4 simulation.
- The background estimation is performed based on the event generator of nuclear cascade code JAM [21] that reproduces well non-strange and strange baryon productions at the corresponding energy region. The detector effects are taken into account through Geant4 simulation.
- The resolution of the missing mass is estimated with Geant4 using the measured position resolution of fiber trackers, 150μm and 250 μm for drift chambers which is reasonably achievable on the basis of past experiences. The effect of energy loss caused by detector materials, especially of the experimental target is taken into account in the simulation.
- Efficiencies of detectors and analysis are evaluated through the detector R&D and past experience, as summarized in Tab.1.
- Production cross sections for each Ξ^*, $\sigma_{\Xi*}$, are summarized in Tab.2. Since the cross section with K* scattering is one third of that with K in hyperon productions, we expect that $\sigma_{\Xi*}$ are scaled by 1/3 compared with the measured values [5].

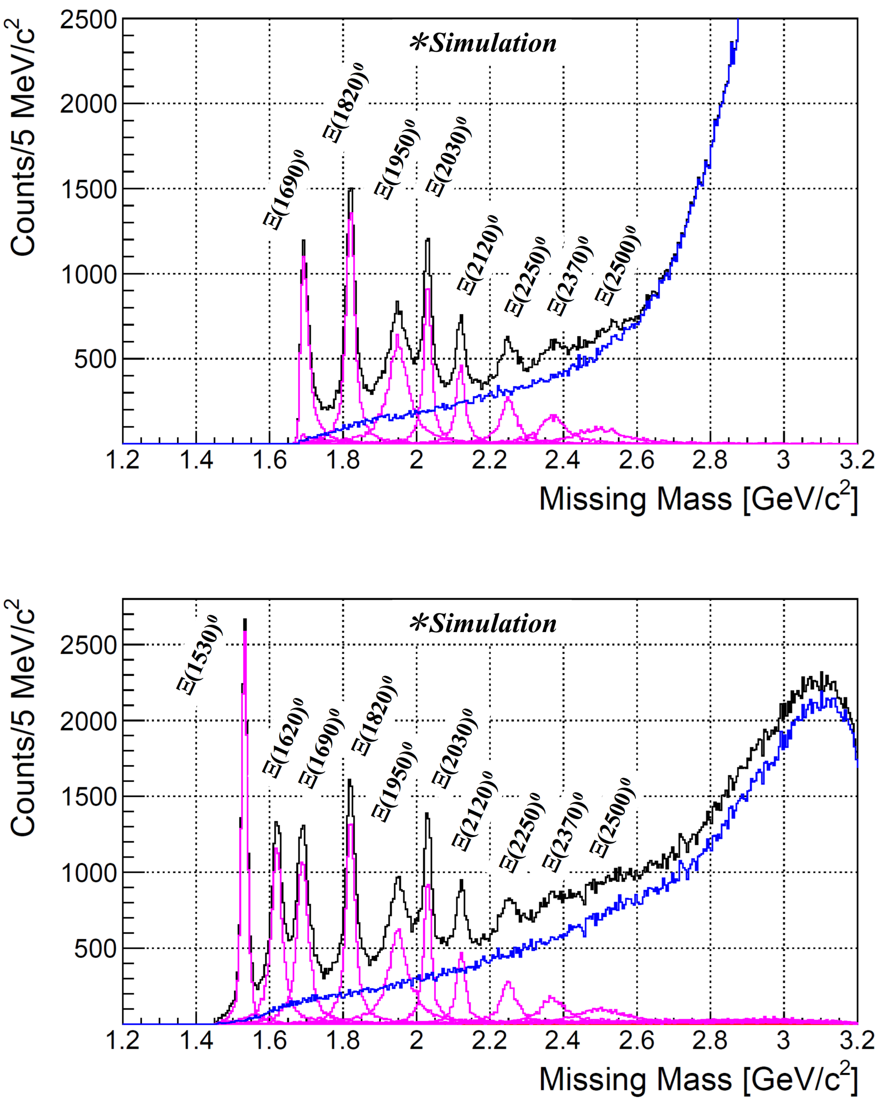

Figure 11: Expected missing mass spectra with event tagging for (top) $\Xi^{*0} \to \Sigma^+ K^-$ and (bottom) $\Xi^{*0} \to \Xi^- \pi^+$ decays.

- Widths of Ξ^* are not well determined. Data are spread in a wide range with large errors, as summarized in Tab.3. The most large value is adopted for each resonances.
- Branching ratios of $\Xi^{*0} \to \Sigma^+ K^-$ and $\Xi^{*0} \to \Xi^- \pi^+$ are assumed to be 0.1.
- The beamtime is assumed to be 30 days.

Table 1: Expected efficiencies considered in estimation of yields.

item	efficiency
fiber tracker	98% [14]
drift chamber	98%
PID detector	95% [16]
DAQ	99% [18]
b-RICH	95% [19]
analysis	70%

Table 2: Assumed cross sections of all appeared Ξ^* states in PDG. The measured cross section in the 5 GeV/c Kp $\to$ K$^+$X reaction [5] is also listed for reference.

	cross section (μb)	
state	measured	assumed
$\Xi(1320)$	7.2±0.6	2.0
$\Xi(1530)$	2.8±0.6	0.80
$\Xi(1620)$	< 1	0.80
$\Xi(1690)$	< 1	0.80
$\Xi(1820)$	3.1±0.5	0.80
$\Xi(1950)$	< 0.8	0.80
$\Xi(2030)$	1.7±0.4	0.48
$\Xi(2120)$	< 1.1	0.28
$\Xi(2250)$	1.0±0.3	0.28
$\Xi(2370)$	0.9±0.3	0.28
$\Xi(2500)$	1.0±0.5	0.28

Figure 12 shows the missing mass spectrum of the K$^-$p$\to$K$^{*0}\Xi^{*0}$ reaction, without decay tagging. States below 1.9 GeV/c^2 are well reconstructed with good S/N of 2 without the decay measurement. The signal yield in this case is enlarged to be 1.7×10^5.

3.1 Schedule and Cost

The proposed experiment will be performed at the high-momentum secondary beamline which provides 5 GeV/c or more higher momentum kaons. The schedule depends on the construction schedule of the beamline. The construction of the E50 spectrometer is at almost

Table 3: Width of Ξ^*. Data are taken from PDG [6].

state	width (MeV/c^2) measured	assumed
$\Xi(1530)$	9.1 ± 0.5	9.1
$\Xi(1620)$	21 ± 7	30
	40 ± 15	
$\Xi(1690)$	20 ± 15	30
$\Xi(1820)$	24 ± 5	24
$\Xi(1950)$	$25 \sim 140$	60
$\Xi(2030)$		20
$\Xi(2120)$	25 ± 12	25
$\Xi(2250)$	46 ± 27	47
	130 ± 80	
$\Xi(2370)$	80	80
	80 ± 25	
	75 ± 69	
$\Xi(2500)$	150^{+60}_{-40}	150
	59 ± 27	

the final stage. The construction budget for main components of spectrometer together with b-RICH has been secured. The b-RICH will be completed till the end of FY2023. The last big element of RICH detector for scattered particles is now being developed and will be completed by FY2026 at the latest.

3.2 Beam Time Request

We request the beamtime of 30 days. We aim at observing the Ξ^* up to 2.3 GeV/c^2 with more than 7σ significance. With 30-day beamtime, the yields of $\Xi(1530)$ to $\Xi(1950)$ is estimated to be 1.3×10^4. The background level is equal or less than the signal yield, therefore we are able to realize the significance of 10σ for these resonances. For $\Xi(2030)$ to $\Xi(2250)$, the yield is decreased to 4.5×10^3 mainly because of the small cross section. However the S/N is kept to be greater than 0.8, therefore the significance for these resonances is estimated to be 7σ.

Depend upon schedule, we kindly request additional beamtime for beamline and detector commissioning. Since the production cross section of Ξ^* is expected to be larger by an order of magnitude than that of charmed baryons, the proposed experiment is naturally expected to be performed before the E50. Moreover the outputs will give a good input for the E50, as described in the next section. Therefore it will take a significant time for commissioning including beam momentum optimization, targeting to optimize b-RICH operation, detector timing and threshold optimization and obtaining control data samples. We expect that it will take 4 days to start up completely new beamline and spectrometer.

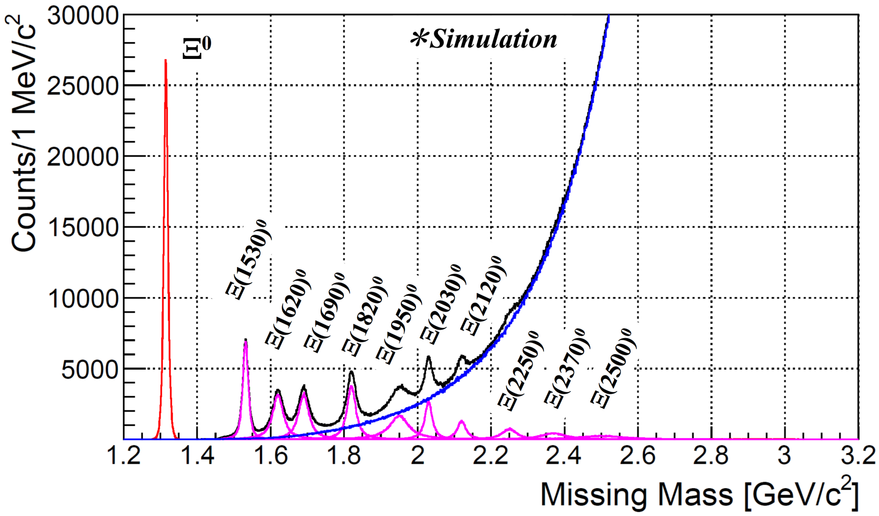

Figure 12: Expected missing mass spectrum of $K^-p \to K^{*0}\Xi^{*0}$ reaction.

4 Impact for other baryon spectroscopic studies at J-PARC

In this program, the production cross section of Ξ^* up to 2.3 GeV/c^2 will be measured. Also the strange production, especially K^+ production can be studied from the background analysis. Since the strangeness production in hadronic reactions at this energy region is not well established, it would be useful for estimating the background in the production of charmed baryon before the J-PARC E50 based on real measurements. Also the knowledge obtained from this experiment will provide basic information for decays of Ω baryons, which will be mainly studied at the K10 beamline in the future extension project of the J-PARC Hadron Experimental Facility. The kaon intensity at the K10 will be increased by an order of magnitude compered with that of the high-momentum secondary beamline, therefore spin-parity determination for Ξ^* will be possible. It will give us the comprehensive understanding of key role of (sq) diquark possibly realized in Ξ baryons.

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