P50 status report

the P50 collaboration

7 May, 2014

In this document, we report the studies for the PAC's concerns listed below.
The main concerns of the 17th PAC for P50 are summarized as follows.

i) Analysis of the possible implications of the relative $\sigma(\pi N \to D^* Y_c)$ measurements (for different Y_c states) in comparison with reliable theoretical predictions, in order to further clarify the physics goals of the experiment in the charm-baryon sector beside the spectroscopy study.

ii) enlarge the physics scope of the experiment beyond charm baryons.

I. CROSS SECTION

In the last PAC, we reported estimations of the production cross sections of charmed baryons via the $p(\pi^-, D^{*-})$ reaction. Among the theoretical calculations, the Regge theory gives a plausible estimation that the cross section on the $p(\pi^-, D^{*-})\Lambda_c^+$ is a few nb at an incident pion momentum of 20 GeV/c, which is the 4th orders of magnitude smaller compared with that of the $p(\pi^-, K^{*0})\Lambda$ [1]. We employed a model calculation based on the t-channel D^* exchange scattering at a forward angle to estimate the cross section of excited state relative to the ground state Λ_c^+ [3]. We found the following features.

(1) The cross sections for excited states with larger orbital angular momenta, L, do not go down owing to large momentum transfers $q_{eff}(\sim 1.4$ GeV/$c)$ in the reaction. Here the cross section is proportional to $\sim (q_{eff}/A)^L e^{-(q_{eff}/A)^2}$. The quantity A represents the inverse of the size parameter of relevant baryon's wave functions ($A \sim 0.42$ GeV).

(2) The relative rate depends on the spin/isospin configuration of excited baryons. The Λ_c baryons with the so-called good-diquark configuration of the "ud" pair are relatively well populated compared with the Σ_c baryons.

It is known that a single-meson exchange model does not reproduce s-dependence of the cross section in high energy region properly, while the reggeon exchange model well reproduces the s-dependence in high-energy binary reactions. A. Hosaka and his coworkers refine the model calculation of the binary reactions [2]. They introduces a reggeon instead of an exchange meson in the model calculation, where a propagator $(t - m_M^2)^{-1}$ is replaced by a $(s/s_0)^{\alpha(t)-1}\Gamma(1-\alpha(t))$. Table I (II) shows calculated production rate for charmed baryons (hyperons) relative to the ground state Λ_c^+ (Λ). We find no essential difference from the previous conclusions mentioned above.

TABLE I: Calculated production rate (R) for charmed baryons relative to the ground state Λ_c^+ in the $p(\pi^-, D^{*-})$ reactions at $p_\pi = 20$ GeV/c. The quantities γ and C are the spin and isospin factors [3], respectively.

L=0 (mass)	$\Lambda_c^{1/2+}$ (2286)	$\Sigma_c^{1/2+}$ (2455)	$\Sigma_c^{3/2+}$ (2520)					
γ	1/2	1/6	1/6					
C	1	1/9	8/9					
q_{eff}	1.34	1.44	1.45					
R	1	0.025	0.171					
L=1 (mass)	$\Lambda_c^{1/2-}$ (2595)	$\Lambda_c^{3/2-}$ (2625)	$\Sigma_c^{1/2-}$ (2750)	$\Sigma_c^{3/2-}$ (2800)	$\Sigma_c'^{1/2-}$ (2800)	$\Sigma_c'^{3/2-}$ (2800)	$\Sigma_c'^{5/2-}$ (2800)	
γ	1/2	1/2	1/6	1/6	1/6	1/6	1/6	
C	1/3	2/3	1/27	2/27	2/27	56/135	2/5	
q_{eff}	1.38	1.38	1.49	1.50	1.49	1.51	1.51	
R	0.933	1.751	0.023	0.040	0.046	0.213	0.205	
L=2 (mass)	$\Lambda_c^{3/2+}$ (2940)	$\Lambda_c^{5/2+}$ (2880)	$\Sigma_c^{3/2+}$ (3000)	$\Sigma_c^{5/2+}$ (3000)	$\Sigma_c'^{1/2+}$ (3000)	$\Sigma_c'^{3/2+}$ (3000)	$\Sigma_c'^{5/2+}$ (3000)	$\Sigma_c'^{7/2+}$ (3000)
γ	1/2	1/2	1/6	1/6	1/6	1/6	1/6	1/6
C	2/5	3/5	2/45	3/45	2/45	8/45	38/105	32/105
q_{eff}	1.43	1.42	1.55	1.55	1.55	1.55	1.55	1.55
R	0.49	0.861	0.013	0.020	0.013	0.052	0.106	0.089

II. PHYSICS SCOPE

Baryons with a heavy quark provide a good opportunity to study diquark properties. Thanks to the heavy quark symmetry of QCD, the spin-dependent interactions with a heavy quark become inactive. As a result, in heavy baryons the heavy-quark spin decouples from the others. Although the "others" part may include many states containing light quarks and gluons, such as qqg, $qqq\bar{q}$, and so on, a diquark system is considered to be well singled out. Then, we can learn the quark-quark interaction in a baryon further. In fact, one expects that a collective motion (λ-mode) of the diquark and a relative motion (ρ-mode) in the diquark split in the excited states. The diquark properties appear in the level structure, the production rates, and decay properties in excited heavy baryons.

A quark model provides a good guide line to see how the excited states appear with respect to the diquark motions (λ/ρ modes). Fig. 1 illustrates the level structure of baryons as a function of the heavy quark mass (M_Q), where the Shrödinger equation of a three body system with confinement and spin-dependent interactions is solved [4]. One finds that λ/ρ modes appear separately in excited states, as the excitation energies depend on the heavy

TABLE II: Calculated production rate (R) for hyperons relative to the ground state Λ in the $p(\pi^-, K^{*0})$ reactions at $p_\pi = 5$ GeV/c.

L=0	$\Lambda^{1/2+}$	$\Sigma^{1/2+}$	$\Sigma^{3/2+}$					
(mass)	(1116)	(1192)	(1385)					
γ	1/2	1/6	1/6					
C	1	1/9	8/9					
q_{eff}	0.29	0.32	0.38					
R	1	0.049	0.244					
L=1	$\Lambda^{1/2-}$	$\Lambda^{3/2-}$	$\Sigma^{1/2-}$	$\Sigma^{3/2-}$	$\Sigma'^{1/2-}$	$\Sigma'^{3/2-}$	$\Sigma'^{5/2-}$	
(mass)	(1405)	(1520)	(1670)	(1690)	(1750)	(1750)	(1775)	
γ	1/2	1/2	1/6	1/6	1/6	1/6	1/6	
C	1/3	2/3	1/27	2/27	2/27	56/135	2/5	
q_{eff}	0.36	0.40	0.49	0.50	0.53	0.53	0.55	
R	0.072	0.127	0.002	0.004	0.004	0.020	0.018	
L=2	$\Lambda^{3/2+}$	$\Lambda^{5/2+}$	$\Sigma^{3/2+}$	$\Sigma^{5/2+}$	$\Sigma'^{1/2+}$	$\Sigma'^{3/2+}$	$\Sigma'^{5/2+}$	$\Sigma'^{7/2+}$
(mass)	(1890)	(1820)	(1840)	(1915)	(1880)	(2000)	(2000)	(2000)
γ	1/2	1/2	1/6	1/6	1/6	1/6	1/6	1/6
C	2/5	3/5	2/45	3/45	2/45	8/45	38/105	32/105
q_{eff}	0.56	0.56	0.58	0.63	0.61	0.69	0.69	0.69
R	0.025	0.052	0.001	0.001	0.001	0.002	0.004	0.003

quark mass. Some of the states such as $\Sigma(S, \chi^s)$ and $\Sigma(S, \chi^\lambda)$, and $\Sigma(P_\lambda, \chi^s)$ and $\Sigma(P_\lambda, \chi^\lambda)$ seem to degenerate in the heavy quark limit. We find that λ/ρ modes are mixed each other, as M_Q is close to the light quark mass. This means that the λ/ρ-mode states are degenerated at M_Q equal to the light-quark mass if there is no spin-dependent interaction. Fig. 2 indicates the mixing probability of the λ/ρ-mode states as a function of M_Q. The mode-mixing rapidly decreases as M_Q increases from the light quark mass. It is rather as small as 10 to 20 % already at around the strange quark mass and almost no mixing (well-separated λ/ρ modes) at the charm quark mass. In this sense, charmed baryon spectroscopy is expected to provide us better understanding of diquark properties in well-separated λ/ρ modes.

In this respect, we will study the diquark properties through the hyperon spectroscopy via the (π^-, K^{*0}) and (π^+, K^{*+}) reactions on the hydrogen target. In particular, we will demonstrate the λ/ρ-mode states for known excited states through differences of the production rates and decay branching ratios.

We made Monte-Carlo simulations of hyperon productions via the (π^-, K^{*0}) reaction at $p_\pi = 5$ GeV/c. The background is evaluated by JAM [5]. The scattered K^{*0}s, as well as K^{*+}s and K_ss, are clearly reconstructed, as shown in Fig. 3. The decay modes

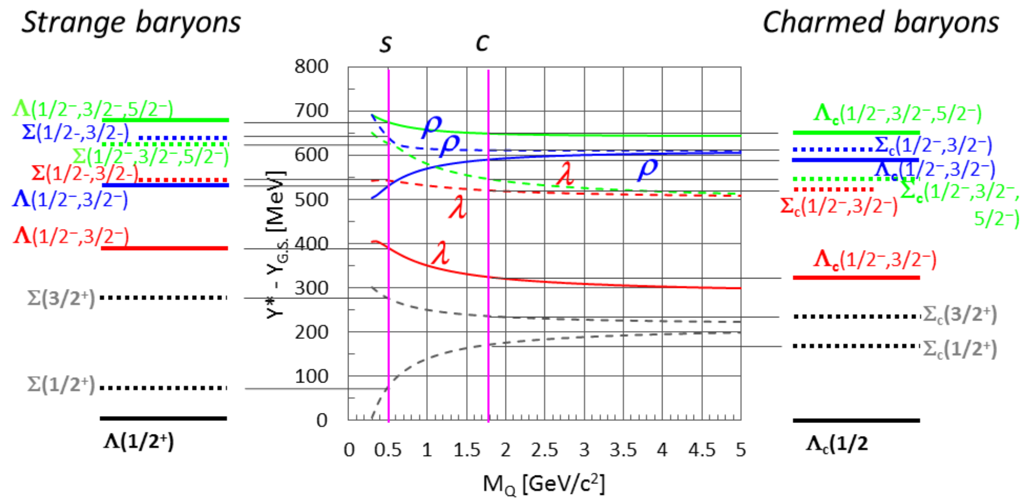

FIG. 1: Level structure of baryons with a heavy quark as a function of the heavy quark mass, expected by the quark model [4].

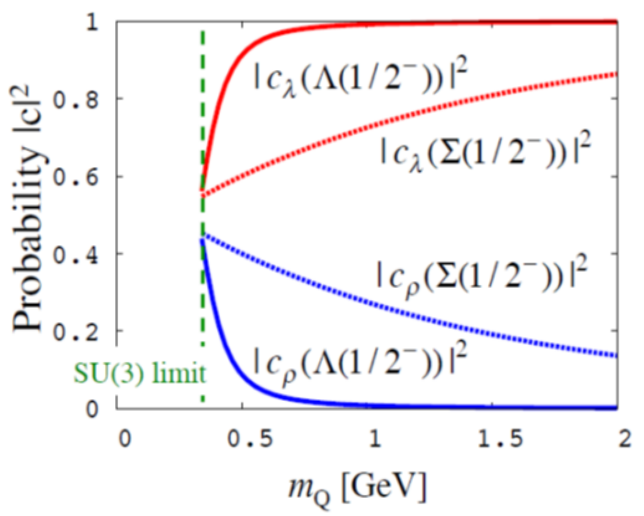

FIG. 2: The mixing probability of λ/ρ modes as a function of the heavy quark mass.

of $Y^* \to K^- p$, $\pi^\pm\Sigma^\mp$, and $\pi^\pm\Lambda$ can be clearly identified, as shown in Fig. 4. Statistics of the simulation at present is based on 4×10^{11} pions irradiated on the hydrogen target of 4 g/cm^2, which corresponds to a beam time for about 3 days. However, it is sufficient to show performances of the spectrometer and feasibility for strange baryon spectroscopy. Fig. 5 shows simulated spectra. The figures in the right hand side are the spectra with the background events subtracted. We identify that a several states are selectively populated. By gating different decay final states of $\bar{K}N$ and πY, observed states are enhanced with respect to corresponding diquark motion modes. From these spectra, we can deduce the branching ratios (partial widths) of the decay modes. In fact, we demonstrates that these

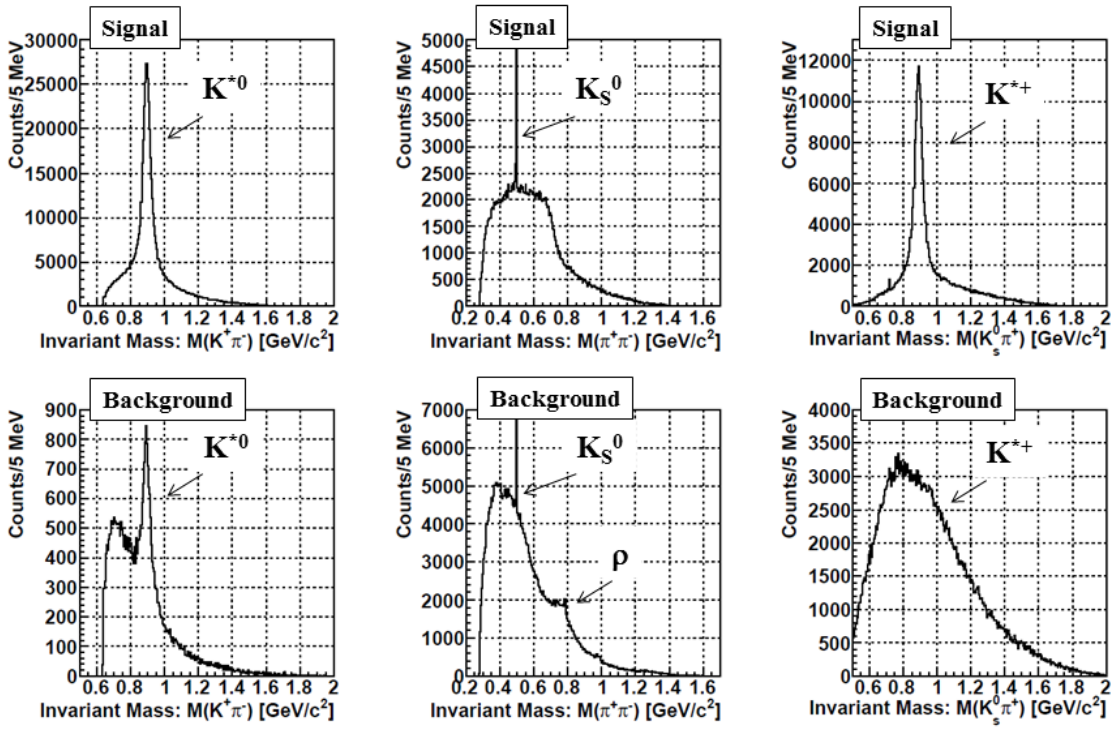

FIG. 3: Reconstructed K^{*0} (left), K_s (middle), and K^{*+}(right). Top figures show only for signals, and bottom ones only for background events generated by JAM.

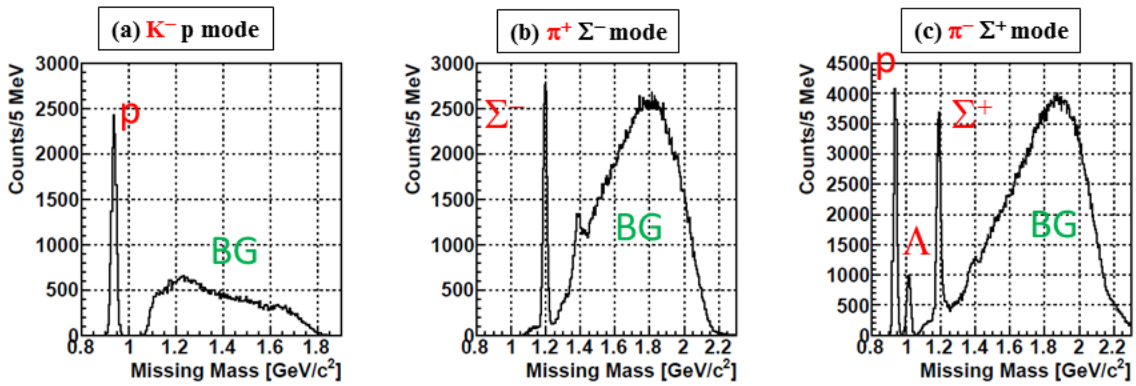

FIG. 4: Missing mass spectra in the $p(\pi^-, K^{*0}x)$ reactions, where $x = K^-$, pi^+, and π^-.

states can be identified from the fitting, as shown in Fig. 6. We could identify the states with better S/N in the spectra gated by the decay modes. Then, we could fit with applying significant constraints on the peak positions and the widths in the inclusive spectra. Further more, we can fix the masses and widths of the Σ states by fitting the (π^+, K^{*+}) spectrum more accurately, as demonstrated in Fig. 7. In fact, the peak fitting of the (π^-, K^{*0}) spectra are done with fixing the masses and widths for the $\Sigma(1670)$ and $\Sigma(1775)$ obtained by fitting

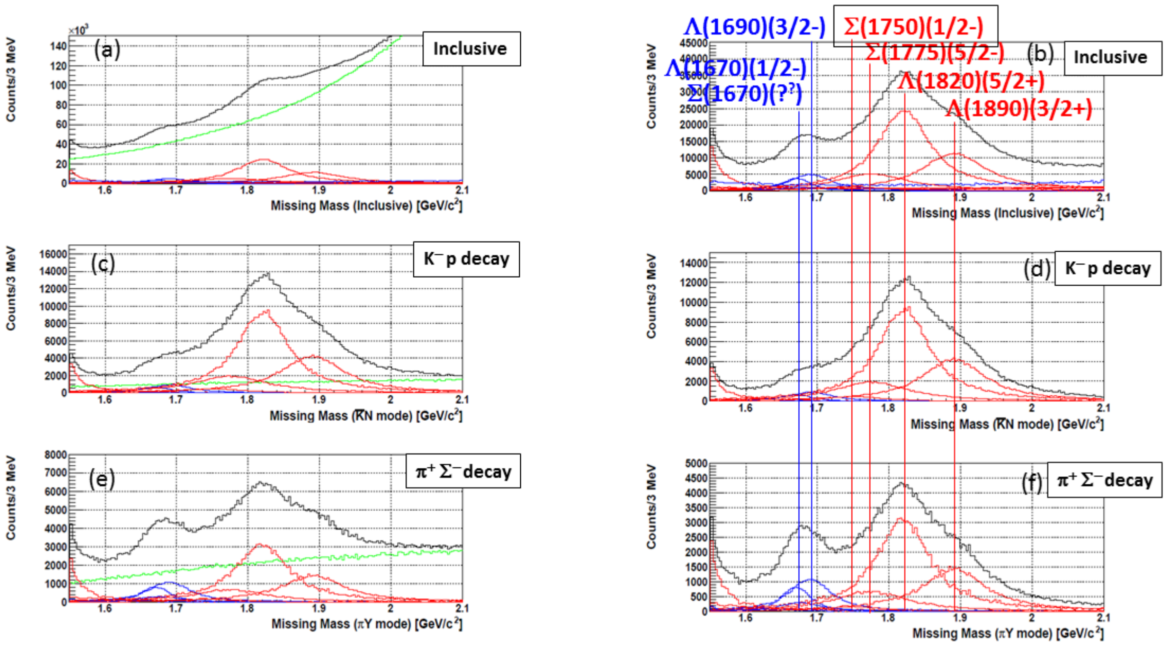

FIG. 5: Simulated hyperon spectra via the (π^-, K^{*0}) reaction. Background subtracted spectra are shown in the right-hand side.

TABLE III: Results of the peak fit for the inclusive (π^-, K^{*0}) spectrum. Initial parameters for the states are also listed for comparison. Γ, M, and R are the decay width, mass, and production rate, respectively. Those with a subscript "input" are input values in the simulation. Here, the masses and widths for the $\Sigma(1670)$ and $\Sigma(1775)$ are fixed at the values obtained by fitting the (π^+, K^{*+}) spectrum gated with the $\bar{K}N$ mode.

State	J^P	Mode	Γ_{input} [MeV]	Γ [MeV]	M_{input} [GeV/c^2]	M [GeV/c^2]	R_{input}	R
$\Lambda(1670)$	$1/2^-$	ρ	35	35±3	1.670	1.668(3)	0.0088	0.0098(12)
$\Sigma(1670)$	$3/2^-$	ρ	60	61±2	1.670	1.674(2)	0.0032	0.0029(5)
$\Lambda(1690)$	$3/2^-$	ρ	60	57±5	1.690	1.687(3)	0.0173	0.0173(3)
$\Sigma(1750)$	$1/2^-$	λ	90	92±1	1.750	1.754(2)	0.0060	0.0067(2)
$\Sigma(1775)$	$5/2^-$	λ	120	121±1	1.775	1.777(1)	0.0320	0.0355(3)
$\Lambda(1820)$	$5/2^+$	λ	80	82±1	1.820	1.822(1)	0.0108	0.0100(10)
$\Lambda(1890)$	$3/2^+$	λ	100	98±2	1.890	1.892(1)	0.0600	0.0500(60)

the (π^+, K^{*+}) spectrum gated with the $\bar{K}N$ mode. We could extract the states the masss, widths, and production rates for the identified states at error levels of 3 MeV, 5 MeV, and 10 %, as listed in Table III. We will be able to de-convolute the states from measurements of decay angular distribution. From the angular distribution, we could decompose overlapped states with different spins further more.

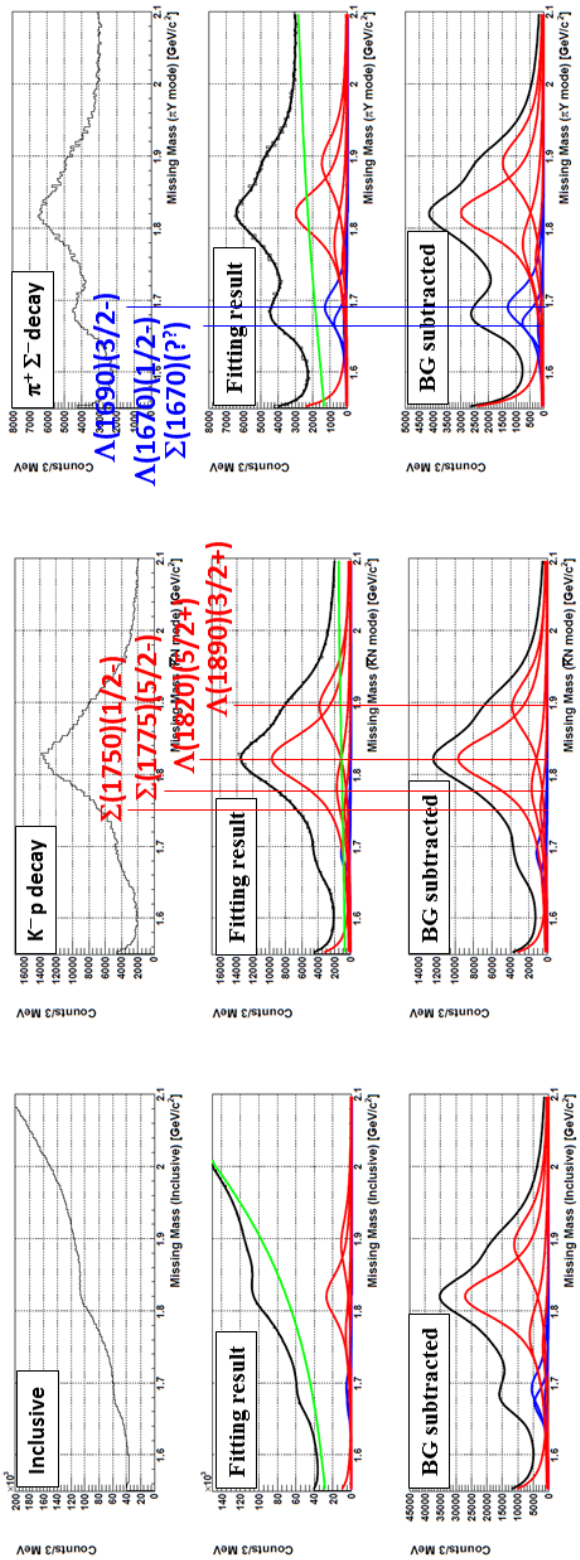

FIG. 6: Identified states with fitting the simulated hyperon spectra via the (π^-, K^{*0}) reaction.

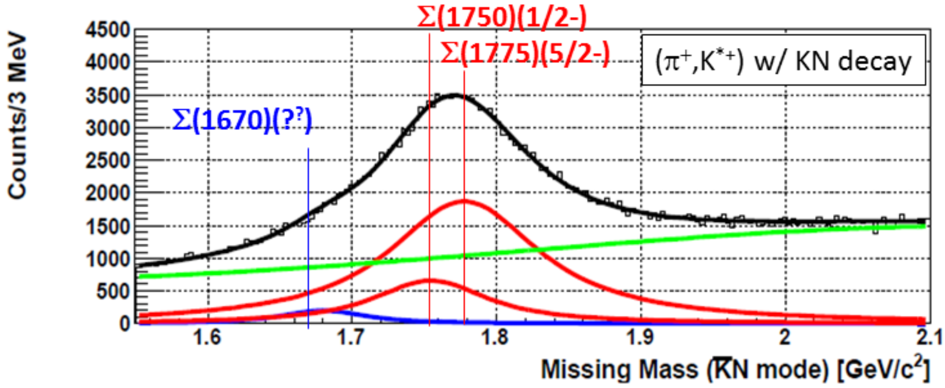

FIG. 7: Identified states with fitting the simulated hyperon spectra via the (π^+, K^{*+}) reaction.

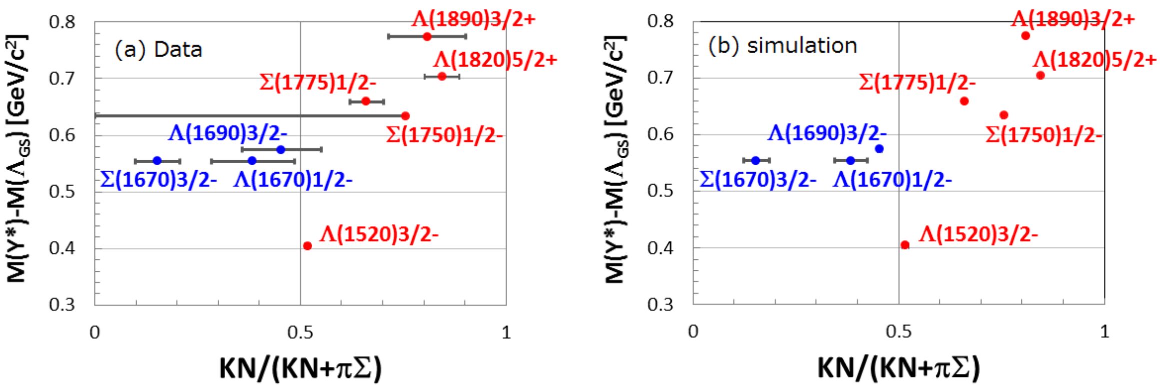

FIG. 8: The ratios of the hyperon decay rate to $\bar{K}N$ with the sum of the decay rates to $\bar{K}N$ and πY. Phase space corrections are made with assuming an allowed lowest wave in a decay. (left) The ratios are plotted based on the PDG data [7]. (right) Expected improvement of the ratios estimated by simulations. The errors are expected at a level of a few %.

As already pointed out, the diquark motions affect the decay rates to $\bar{K}N$ (a heavy meson and a nucleon) and πY (a light meson and a hyperon). This feature is suggested by some of experimental data, as illustrated in Fig. 8-left. However, the experimental data have still large errors. As we can identify the states with much better S/N in the spectra gated in the decay modes, we can improve precision of the ratios at a level of a few % (Fig. 8-right).

III. ANOTHER POSSIBLE PHYSICS CASES

We briefly comment on (A) the $\Lambda(1405)$ state and (B) the spectroscopic studies of the Ξ hyperons. As for the latter, a Letter of Intent has been submitted by M. Naruki and K. Shirotori [6].

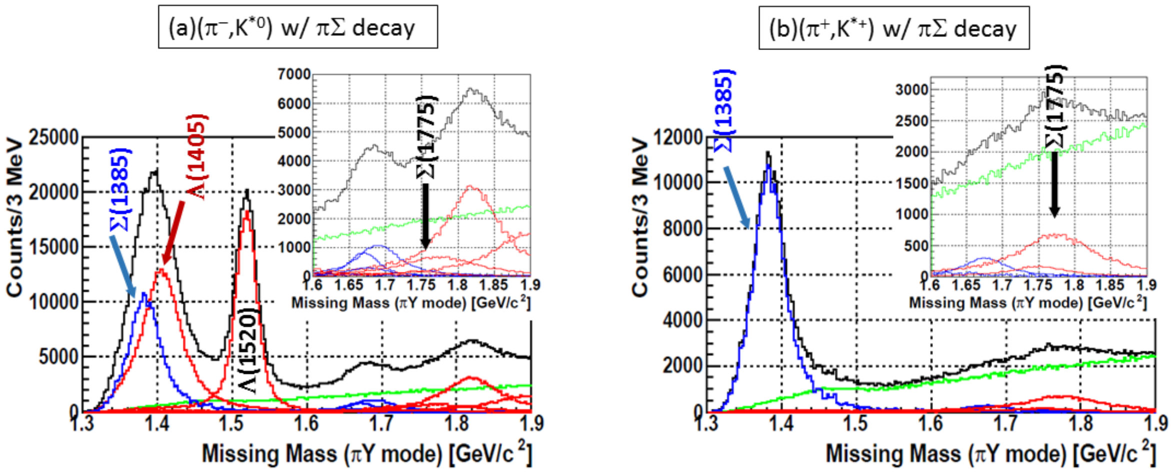

FIG. 9: Simulated missing mass spectra of the $p(\pi^-, K^{*0})$ (left) and $p(\pi^+, K^{*+})$ (right) reactions with gating the $\pi^+\Sigma^-$-decay mode are shown including the $\Lambda(1405)$ resonance region.

A. $\Lambda(1405)$ state

As suggested by the PAC committee, the $\Lambda(1405)$ is an interesting resonance if it is a $\bar{K}N$ molecular state. The (π^-, K^{*0}) reaction is one of the most promising reactions to form the $\Lambda(1405)$ state through a kaon exchange in the t-channel reaction at a K^{*0} forward scattering angle. As already mentioned above, the production cross section is as large as a few μb so that we can collect a large number of event samples. Significant yields of $\Lambda(1405)$ can be expected as shown in the spectrum with tagging the $\pi^+\Sigma^-$ decay mode (Fig. 9). A similar spectrum with tagging the different charge mode of $\pi^-\Sigma^+$ decay can also be obtained. We can deduce contributions of the isospin $I = 0$ and $I = 1$ amplitudes from differences of the two decay modes. It is important to remove contributions from $\Sigma(1385)$ productions. Typical analysis are to fit the simultaneously with taking a Breit-Wigner shape $\Sigma(1385)$, non-resonant $\pi\Sigma$ production, and a contribution from the $\Lambda(1405)$ resonance. This can be done with taking advantage of high statistics. In addition, we also obtain a spectral shape of pure I=1 channel from the (π^+, K^{*+}) reaction, which provides important information to estimate the contributions of the $\Sigma(1385)$ and non-resonant productions. Relative strengths of $\Sigma(1385)$ to higher excited Σ resonance, such as $\Sigma(1775)$, in both the (π^-, K^{*0}) and (π^+, K^{*+}) spectra can be monitored, as already demonstrated in Fig 7. This should be noted as an another advantage of the present experiment, thanks to the spectrometer performance to measure a wide mass range of hyperons simultaneously.

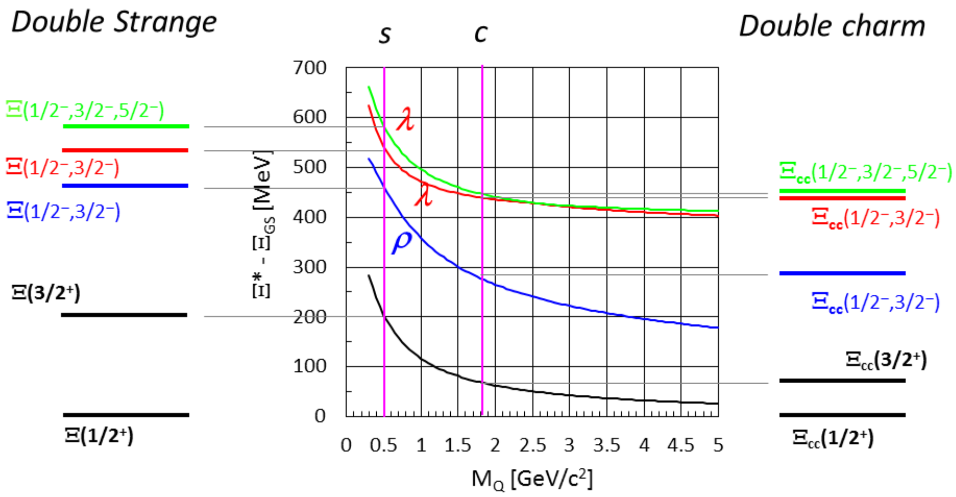

FIG. 10: Level structure of baryons with two heavy quarks as a function of the heavy quark mass, expected by the quark model [4].

B. Ξ hyperons

As illustrated in Figure 10, a unique feature of level structure appears in baryons with two heavy quarks. Once again, one can see that a collective motion (λ-mode) of the two heavy quarks and a relative motion (ρ-mode) in the two heavy quarks split in the excited states. In the qQQ system, however, the ordering of the ρ mode and the λ mode interchange in comparison with the case of the qqQ system. It is expected that the nature of these quark motions is reflected in production rates and decay properties, as already discussed in the qqQ system. However, little is known about the Ξ hyperons although existence of several states have been reported. Spin/parity and/or decay branching ratios for many of states have yet to be measured. As mentioned in the Letter of Intent, several states up to $\sim$2.5 GeV/c^2 have been observed rather clearly in the missing mass spectra of the (K^-, K^+) reaction [8], although the statistics are limited. We expect to measure the Ξ resonances in the missing mass spectra of the (K^-, K^+), $(K^-, K^{*+,0})$, or $(\pi^-, K^{*0}K^+)$ reactions at a level of 10^5 in statistics in a month if the cross sections for the kaon and pion induced reactions are 1 μb and 0.1 μb, respectively. A few ten thousand of events can be collected for Ξ decays, which are quite enough to measure angular distribution and determine the spins. It is also a theoretical challenge to understand the production mechanism of Ξ baryons, because the process requires at least two steps to generate two strangenesses. High statistics data are vital to reveal the reaction mechanism, which must be related to the quark dynamics in baryons.

TABLE IV: Properties of Ξ hyperons reproted in PDG [7]

	J^P	Rating	Width [MeV]	branch [%] $\to \Xi\pi$	$\to \Lambda K$	$\to \Sigma K$
$\Xi(2500)$	??	1^*	150?			
$\Xi(2370)$	??	2^*	80?			
$\Xi(2250)$	??	2^*	47±27?			
$\Xi(2120)$	??	1^*	25?			
$\Xi(2030)$	≥5/2?	3^*	20^{+15}_{-5}	small	~ 20	~ 80
$\Xi(1950)$	??	3^*	60±20	seen	seen	
$\Xi(1820)$	3/2-	3^*	24^{+15}_{-10}	small	Large	Small
$\Xi(1690)$	??	3^*	<30	seen	seen	seen
$\Xi(1620)$	??	1^*	20∼40?			
$\Xi(1530)$	3/2+	4^*	19	100		

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