Search for a Narrow Λ^* Resonance using the $p(K^-, \Lambda)\eta$ Reaction with the hypTPC Detector

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Short summary of the Proposed Experiment

Beamline:	K1.8BR (or K1.1)
Beam:	~735 (±15) MeV/c K^-
Beam intensity:	2×10^4 /spill (4×10^9 in total)
Flat-top:	2 sec (5.52 sec/spill)
Target:	Liquid hydrogen 5 cmϕ
Reaction:	$p(K^-, \Lambda)\eta$
Spectrometer etc.:	hypTPC
Beam time:	14 days + 3 days for beam energy scan +1 day for empty target run + 3 days for setup
Estimated Yield:	3×10^5 events in total

Abstract

Evidence for a narrow Λ^* resonance at a mass of about 1665 MeV (just above the combined mass of the Λ ground state plus the η meson) has been seen in the $M(pK^-)$ mass of the Dalitz plot for $\Lambda_c \to pK^-\pi^+$ decay at the Belle experiment. Additional evidence for this resonance is found in the partial-wave analysis (PWA) of data on K^-p reactions done independently by several groups. The results from the PWA are largely driven by angular distributions of the $K^-p \to \Lambda\eta$ reaction by the Crystal Ball collaboration. If a narrow Λ^* resonance exists at this mass, then the conventional quark model cannot explain it, and a possible explanation is that it is a crypto-exotic baryon with a dominant meson-baryon component to its wave function. Similar conclusions have recently been put forward in the literature for the $\Lambda(1405)$ resonance, which is currently thought to be a mixture of two poles, one $\Sigma\pi$ and one $\bar{K}N$. A definitive experiment for $K^-p \to \Lambda X$, where X is the missing particle (such as the η meson), using the newly built hypTPC detector would establish the existence of the proposed narrow $\Lambda(1665)$ and determine its spin and parity in just two weeks of beamtime at J-PARC.

1 Scientific Justification

This proposal is to measure a possible new Λ^* resonance around $\sim$ 1665 MeV (we tentatively call it $\Lambda(1665)$ in this Proposal) via the $p(K^-, \Lambda)\eta$ reaction on a hydrogen target at the K1.8BR beamline (or possibly the K1.1 beamline). However, before going into the motivation for the new $\Lambda^*(1665)$ resonance, a short review of another related resonance, $\Lambda(1405)$, helps to provide some context for the scientific justification.

It is now a well-known hypothesis that the $\Lambda(1405)$ resonance is a two-pole structure, where one pole is associated with a $\Sigma\pi$ meson-baryon resonance and the other pole is a $\bar{K}N$ resonance. Such a two-pole structure was predicted based on chiral unitary models [1, 2], where interference between the amplitudes of these two poles causes the decays to $\Sigma^+\pi^-$ and $\Sigma^-\pi^+$ to have different invariant mass distributions. This theoretical prediction was clearly shown in photoproduction data from CLAS [3]. Additional theoretical analysis of the residue of the scattering amplitude at the bound state pole [4] also suggests the two-pole nature of the $\Lambda(1405)$, based on fundamental concepts of compositeness in the chiral unitary approach [5]. Further evidence of the meson-baryon structure of the $\Lambda(1405)$ is provided by examining the u and d quark contributions to its magnetic form factors in lattice QCD [6]. In fact, a whole new theoretical understanding of baryon resonances is evolving due to recent data on the $\Lambda(1405)$. This shows the impact that well-planned measurements can have for a single baryon resonance.

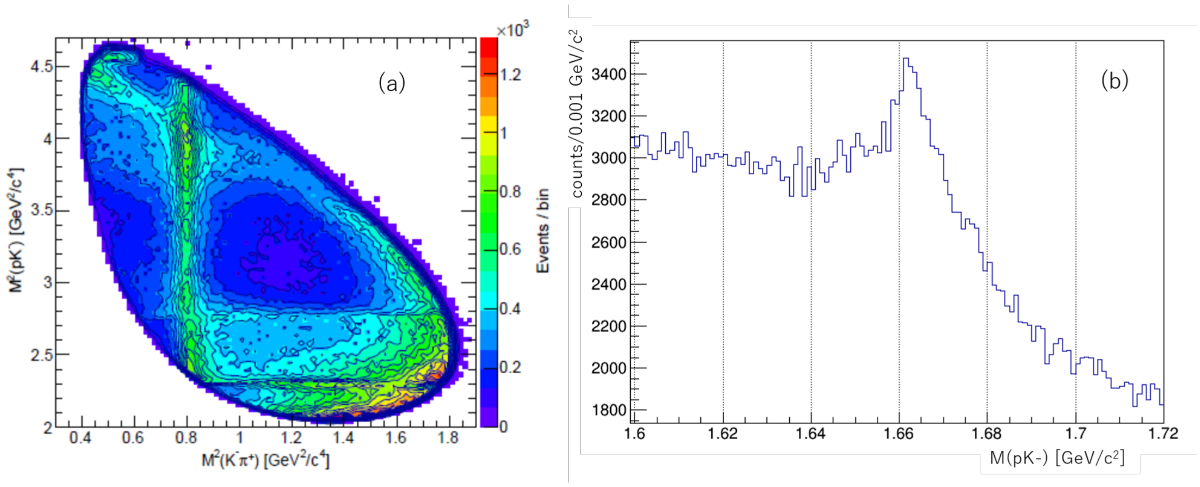

Figure 1: (a) Dalitz plot of $M^2(pK^-)$ vs. $M^2(K^-\pi^+)$ from the decay $\Lambda_c \to pK^-\pi^+$ from Belle [8]. (b) Projection of the square root of the vertical axis ($M(pK^-)$) around 1.66 GeV/c^2.

The $\Lambda(1405)$ has always been difficult to fit into the mass spectrum predicted by the constituent quark model, and is much better accommodated as a dynamically generated meson-baryon resonance. In the future, lattice QCD calculations will be able to deduce the scattering phase-shifts for meson-baryon systems [7] and show, from first principles, the contributions of each pole to the $\Lambda(1405)$. In the meantime, experiments will continue to provide data on Y^* resonances.

The primary reason for discussion of the $\Lambda(1405)$ is to show that baryons having a significant meson-baryon components in their wave-function can exist, beyond just the 3-quark components predicted by the constituent quark model. It is natural to explore the strange baryon resonances for more examples of non-quark model states.

Recently, another Λ^* (or Σ^*) resonance, at about 1665 MeV, is seen in the pK^- mass spectrum in a Dalitz plot of $\Lambda_c \to pK^-\pi^+$ decay at Belle [8]. The Dalitz plot is shown in Fig. 1(a) and the mass projection, $M(pK^-)$, is shown in Fig. 1(b) (note that the mass projection takes the square root, with M^2 on the Dalitz plot axis). The latter shows a narrow peak, with a Breit-Wigner width of about 10 MeV, at a mass of 1663 MeV. The calibration of the Belle mass spectrum is quite good, being calibrated with the Λ_c mass, and the peak position shown in Fig. 1(b) has an uncertainty of less than 0.4 MeV.

The peak in Fig. 1(b) is very close to the combined mass of the Λ baryon (1115.7 MeV) plus the η meson (547.9 MeV), which suggests that this could be a cusp effect due to opening of the $\Lambda\eta$ decay channel. However, that interpretation can be challenged by doing a PWA of the world data on K^-p scattering. It is important that a coupled channels PWA be done to account for unitarity, and to see whether interference effects between two decay channels (a cusp interpretation) could produce this peak or if a true resonance needs to be invoked in order to explain the data. One such a PWA has been recently published [9] and will be described next.

A dynamical coupled-channels model developed by the ANL-Osaka-KEK group [10] has been applied to a PWA of a comprehensive database that includes most two-body final states from K^-p scattering up to a center-of-mass energy $W = 2.1$ GeV. This PWA confirms the existence of most Y^* resonances rated as 4-star by the Particle Data Group [11] and also finds some new Y^*

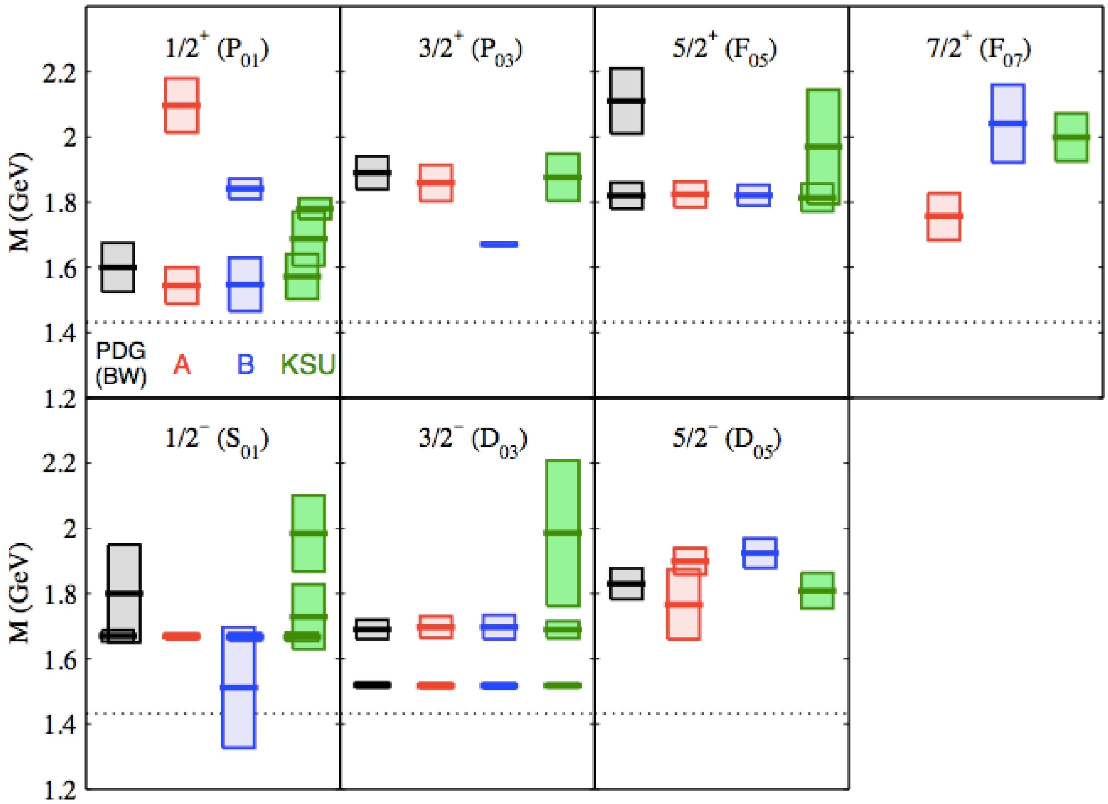

Figure 2: Masses of the Λ^* resonances for the PDG (2012 edition [12]) and the PWA solutions (Kamano-A, Kamano-B [9, 10], KSU [13]) as shown, grouped by spin-parity (J^P).

resonances, including a possible narrow Λ^* resonance with $J^P = 3/2^+$ that couples strongly to the $\Lambda\eta$ channel. Because of the incompleteness of the data, particularly for polarization observables, there is some ambiguity in the PWA solution. The papers by Kamano *et al.* present two solutions, called models A and B. These solutions are also compared with an independent PWA done by the KSU group [13]. The PWA results for the Λ^* resonances are shown in Fig. 2, where the resonances are grouped by spin-parity (J^P), and compared with the previously known (4-star) resonances of the PDG. (Note that the PDG has since been updated to include several of the Λ^* resonances from these PWAs.) A narrow Λ^* is seen in the solution for model B ($J^P = 3/2^+$) at pole mass 1671^{+2}_{-8} MeV. An updated PWA solution from the IU-KSU group [14] (not shown) also gets a fairly narrow Λ^* $(3/2^+)$ at a higher mass (1690 MeV).

The existing data are not sufficient to clearly support that a narrow Λ^* state is required by the PWA. To better understand the basis in the database for this narrow state, data from the $K^-p \to \Lambda\eta$ final state from the Crystal Ball collaboration [15] are shown in Fig. 3 for models A and B in the PWA solutions by Kamano *et al.*

Clearly, the total cross section data in Fig. 3 can be fit equally well with both models. However, the differential cross section data, shown by the lower panels of Fig. 3, are better fit by Model B, where the difference between the solid and dashed curves is essentially the PWA with and without narrow $\Lambda^*(1665)$ with $J^P = 3/2^+$.

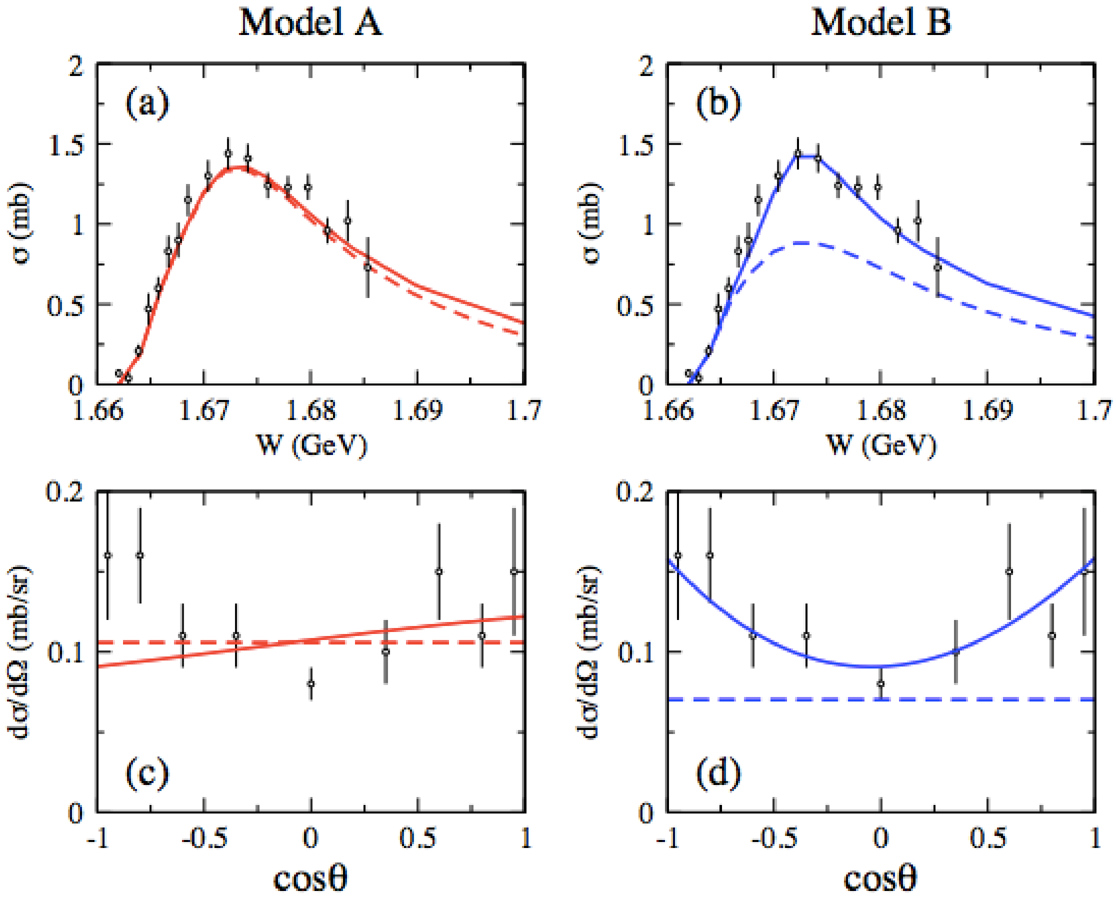

Figure 3: Fits to the cross sections from Crystal Ball data [15] on $K^-p \to \Lambda\eta$ for the full solution (solid) and for the S_{01} partial wave only (dashed).

The full set of the Crystal Ball [15] differential cross sections for $K^-p \to \Lambda\eta$ is shown in Fig. 4. The key point is the differential cross sections at kaon momenta (p_K) of around 734 MeV/c. The concave-up shape of this angular distribution cannot be explained with $J = 1/2$ amplitudes and requires $J = 3/2$ (or higher) partial waves, while it is much more flat, as expected for $J = 1/2$ partial waves, at lower and higher kaon momenta. This behavior is seen only in a narrow region, thus indicating an existence of a narrow resonance. This is a model-independent way to assess the contributions of s-channel resonances in the reaction mechanism. Even if there is some uncertainty to the normalization of these data, the relative shapes of the angular distributions should be robust, since the same detector (and the same facility) is used for all measurements.

An independent analysis using a reaction model (instead of a coupled-channels PWA) has been done for the Crystal Ball data by Liu and Xie [16]. There, they also conclude that a narrow Λ^* resonance at 1668.5 MeV is needed in the D_{03} partial wave to explain the data. The spin-parity of this resonance would be $J^P = 3/2^-$ with the same spin (but opposite parity) as the PWA solution for the narrow $\Lambda^*(1665)$ presented above. The mass is almost the same. As shown by Liu and Xie, the parity of this resonance could be measured via the Λ polarization in the final state, which was not sufficient for the Crystal Ball, but is possible with the proposed experiment at J-PARC.

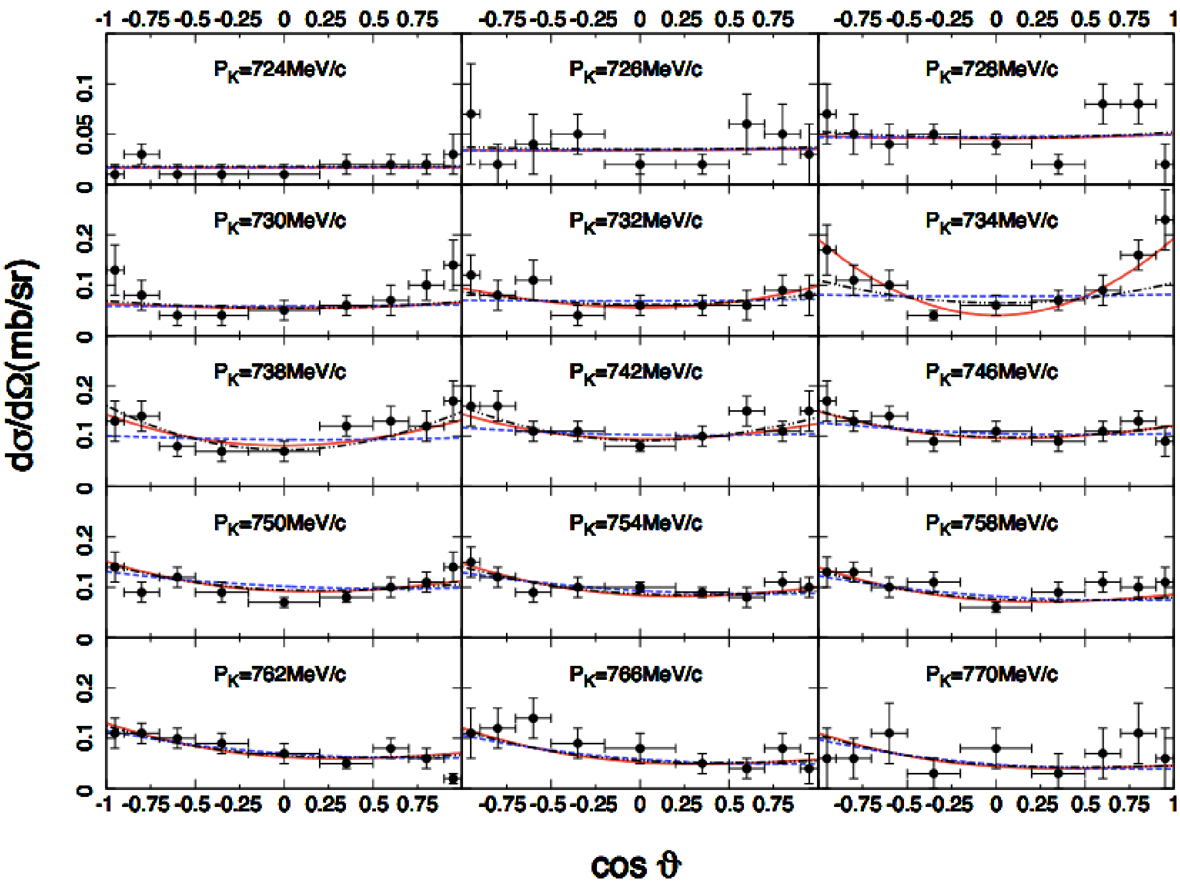

Figure 4: Differential cross sections from Crystal Ball data for $K^-p \to \Lambda\eta$ at the kaon beam momenta shown [15]. The solid red curve includes a narrow $J^P = 3/2^-$ Λ^*.

A similar analysis of these data was done by Shi and Zou [18] with almost the same conclusions.

While these data alone may not be sufficient to conclude that a narrow Λ^* resonance exists at a mass near 1665 MeV, it is only part of a broader picture that includes the Belle data for Λ_c decay. Let us assume, for a moment, that a narrow Λ^* resonance is supported by further measurements. What would be the implications?

To answer this question, we turn to another phenomena from the past decade, in the meson sector of hadronic physics. Early on, the hidden charm meson $X(3872)$, first seen in B^+ decays to $K^+\pi^+\pi^-J/\psi$ at Belle [19], was considered an anomaly. It was too narrow to make sense of fitting into the quark model nor was it at the mass predicted by the very-successful heavy-quark chamonium quark models. On the other hand, it was very near to the threshold of the summed masses of the D^0 and the D^{0*} mesons. Could it be a cusp effect? Could it be a meson-meson molecule? Other measurements followed, confirming its existence, and recently its quantum numbers $J^{PC} = 1^{++}$ were measured by LHCb [20], which essentially ruled out a cusp effect. The interpretation of the $X(3872)$ as a meson-meson molecule is still an open question, but almost everyone agrees that it is not a quark-model state.

The reason the $X(3872)$ has elicited so much attention is because it shows that QCD has a richer spectrum of resonances than those predicted by the constituent quark model. Finding out exactly how QCD manifests its equations in terms of resonant states is important if we want to understand the strong force between quarks and gluons. The $X(3872)$ is an indicator of the state of our understanding (or ignorance) of non-perturbative QCD and hence has received much theoretical attention.

If a narrow Λ^* state were clearly identified by measurement, it would have a similar effect on the hadron physics community as the $X(3872)$. If it is found with spin $J = 3/2$, then it could not be a cusp effect (because visible cusps occur only in S-wave). With a proposed width of ~ 10 MeV (in model B of the PWA by Kamano *et al.*), this state does not fit into the quark model. The implication is that it could be a meson-baryon molecule or possibly a state with dominant 5-quark components as suggested by Shi and Zou [18]. The $\Lambda(1405)$ has similarly been found to have a strong component of meson-baryon in its wave function, and finding a narrow Λ^* resonance could have a similar stimulating effect on theoretical models of baryons.

There are three primary reasons why this proposed measurement should be done. First, a narrow Λ^* resonance is newly predicted, based on the recent measurements described above, and hence needs confirmation. Second, a narrow Λ^* resonance is not expected from either the constituent quark model or from systematics of other Λ^* resonances with a mass above 1.55 GeV. If such a narrow Λ^* is confirmed, then it should be of an exotic configuration, such as a meson-baryon molecule, and this would lead to a better understanding of the forces between quarks. Third, the proposed measurement would be a model-independent approach, where measuring the beam energy with a very good resolution (about 1.5 MeV/c) would isolate the effects of a narrow resonance.

The spin of the $\Lambda^*(1665)$ can be deduced from the angular distribution of the final state Λ, and by measuring the Λ polarization (from the Λ weak decay) the parity of the $\Lambda^*(1665)$ can be determined. Calculations of the Λ polarization as a function of the beam momentum are predicted from the theoretical calculation of Liu and Xie [17] as an example, but the Λ polarization itself is sufficient to determine the parity in a model independent way (see Section 3 and Appendix A).

2 Experimental Method

The proposed experiment will be performed at the K1.8BR beamline (or possibly at the K1.1 beamline) together with the hypTPC spectrometer developed for J-PARC E42 experiment. The $\Lambda^*(1665)$ resonance is produced in s-channel pK^- reaction and its decay to $\Lambda\eta$ is to be observed. The Λ is identified by reconstructing invariant mass of its decay daughters, proton and π^-, and the η is identified by the missing mass of $p(K^-, \Lambda)X$ reaction.

2.1 The K1.8BR Beamline and Kaon Beam

A schematic drawing of the K1.8BR beamline is shown in Fig. 5. (The conceptual design does not change for the K1.1 beamline case.) The negative kaon beam is provided by the K1.8BR beamline and is identified by an aerogel Cherenkov counter (AC) and time-of-flight between two trigger counters (BHD and T0) which are 7.7 m apart. The momentum vector of K^- is measured by the drift chambers (BLC1 and BLC2) existing at the beamline, together with information from hypTPC, to a precision of about 0.2%. Based on a measurement done by E62 experiment, the expected intensity of negative kaon beam at 735 MeV/c is about 2×10^4 per 5.52 second spill

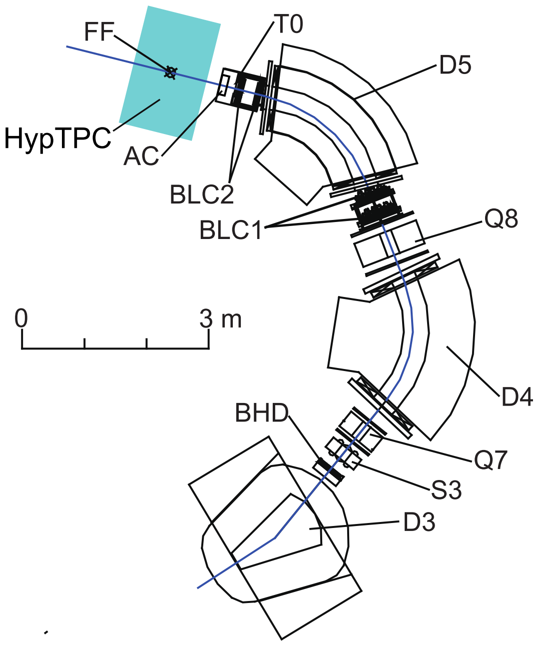

Figure 5: A schematic view of the K1.8BR beamline of the J-PARC Hadron Hall.

(flattop: 2 s), with a π/K ratio of about 20, for the primary proton beam power of 50 kW. (Here, the beam intensity is an effective one taking beam profile and our target size into account.)

2.2 Decay Particle Spectrometer, hypTPC

In order to identify Λ, its decay daughters, proton and π^-, are tracked by hypTPC spectrometer, which is a time-projection chamber (TPC) with an embedded target cell (see Fig. 6). Since the target is inside of the TPC, it has a geometrical acceptance of 4π. The TPC is surrounded by a trigger hodoscope (THD) and a Helmholtz magnet. Magnetic field direction is vertical, and its strength will be around 0.6 T[1]. Particle identification for $\pi/K/p$ can be cleanly done using the dE/dx measurement inside hypTPC and time-of-flight using T0 and THD.

The expected performance of hypTPC is described in the Techinical Design Report of E42 experiment [21]. Considering the weaker magnetic field, the expeceted momentum resolution for 0.4 GeV/c proton (0.1 GeV/c pion) is about 15 MeV/c (2.5 MeV/c) in σ. The expected invariant mass resolution for Λ is about 2.5 MeV/c^2, and that for η missing mass is about 1 MeV/c^2 which is mostly determined by the beam momentum resolution.

The acceptance of hypTPC is estimated by simulations. When we conservatively require that both of the decay particles must pass through hypTPC and reach to THD, it is slightly smaller than 60%, as shown in Fig. 7. The figure also shows the reaction angle dependence is modest. When we relax the condition, and only require that both tracks must have hits in at least 8 active pad layers in hypTPC [21], the acceptance is as high as about 85%.

[1] 1.2 T is possible at maximum, but in order to avoid loss of low momentum pions, lower field strength is better.

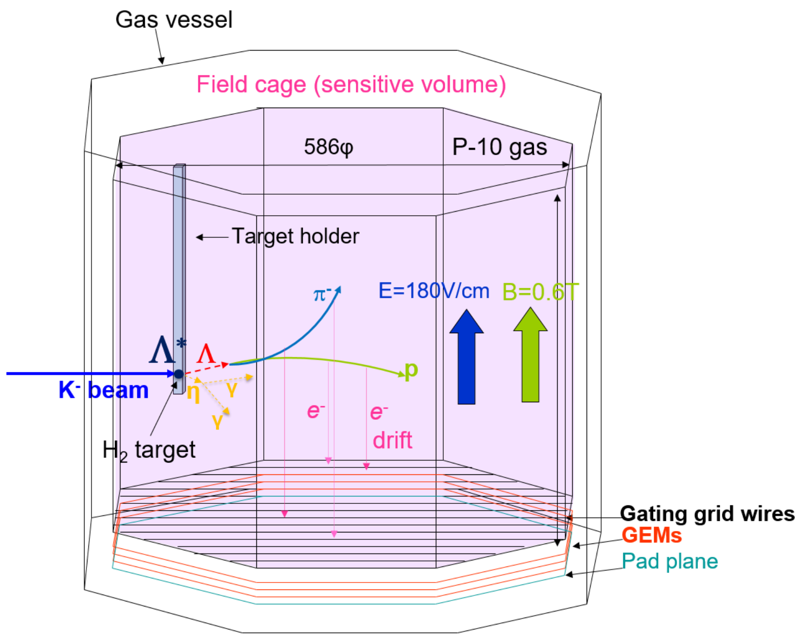

Figure 6: A schematic drawing of hypTPC.

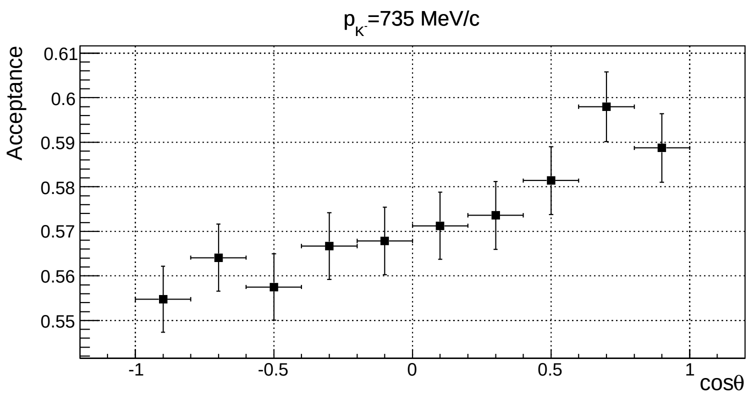

Figure 7: Acceptance of hypTPC as a function of reaction angle (in the CM frame) at $p_K = 735$ MeV/c.

2.3 Trigger

Since the kaon beam intensity of the experiment is as low as 2×10^4 per spill, and the total interaction rate will be 170/spill with a 5 cm liquid hydrogen target, strong trigger is not necessary. Actually, we want to take other channels, such as $\Lambda\pi^0$, $\Lambda\pi\pi$, $\Sigma\pi$, and so on, as much as possible because of the following reasons:

- In order to explain the total cross sections for $K^-p \to \Lambda\eta$, $\Lambda^*(1665)$ must couple to some other channels than K^-p and $\Lambda\eta$ as well. In order to identify the nature of the new resonance, data on other branches are helpful and thus desirable.
- Aside from the importance of $\Lambda^*(1665)$, high quality data in this region are awaited to better understand baryon-meson interactions and properties of hyperon resonances [9, 10].

Therefore, we only want (and have) to reject pion induced events and kaon decays at the trigger level. Pions in the beam are rejected by the kaon beam trigger (KB) in the same way as E15, E31 and E62 experiments. Namely, KB is generated by a coincidence signal of the beam hodoscope detector (BHD), the time zero counter (T0), and the beam definition counter (DEF), with a veto of AC. Inefficiency of AC for pion is about 1%, and thus pion contamination in the KB trigger is expected to be about 20%.

We are thinking two kinds of triggers for decay particles in addition to the KB trigger:

1. Hits in two (or more) segments in THD.
2. One high ΔE hit in the forward segments of THD.

The first trigger is simple and has advantage for detecting reaction channels other than $\Lambda\eta$. It is also good for rejecting kaon decays, more than 90% of which emit only one charged particle. However, its acceptance is limited to about 60% for the pions of interest due to the limited size. (About 25% of the pions pass through the TPC, but escape the THD acceptance. The remaining 15% are lost due to stoping in the target cell (10%) and decay in the TPC volume (5%).) The second trigger aims to detect proton from Λ decay which goes to the forward direction and hits a limited number of THD segments. Furthermore, the energy deposit from the proton is about 4 MIP, so we can set a higher threshold for THD to reject minimum-ionizing particles from kaon decays. However, this trigger has limited acceptance for other channels.

Considering these pros and cons, we will add these two triggers. An estimation for trigger rate is 200/spill from reactions in the target, with a similar number from the other materials such as target support, and 500/spill from kaon decay. These add up to 900/spill (450 Hz), which can be rather easily handled by our electronics with a DAQ efficiency of better than 90%.

3 Expected Result

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

$$N = N_{K^-} \times t \times \sigma_{\Lambda\eta} \times \epsilon_\Lambda \times \epsilon_0$$

where N_{K^-} is the number of beam kaons (effectively 2×10^4/spill taking the target size into account), t is the target thickness in (number of protons)/cm^2 (2.1×10^{23} protons/cm^2), $\sigma_{\Lambda\eta}$ is the cross section (1 mb in average) deduced from the measurement of Crystal Ball [15], $\epsilon_\Lambda = 0.64 \times 0.6$ is the detection efficiency for Λ (including the decay branching ratio), and $\epsilon_0 = 0.8$ is the overall efficiency (DAQ, analysis, etc.).

In total, the expected event rate is 900/hour. We can reach to the level of Crystall Ball data (2700 events in total) in a few hours. In order to just confirm the angular distribution of the Crystal Ball data, a beam time of only 1 day is necessary, and still we can acquire an order of magnitude

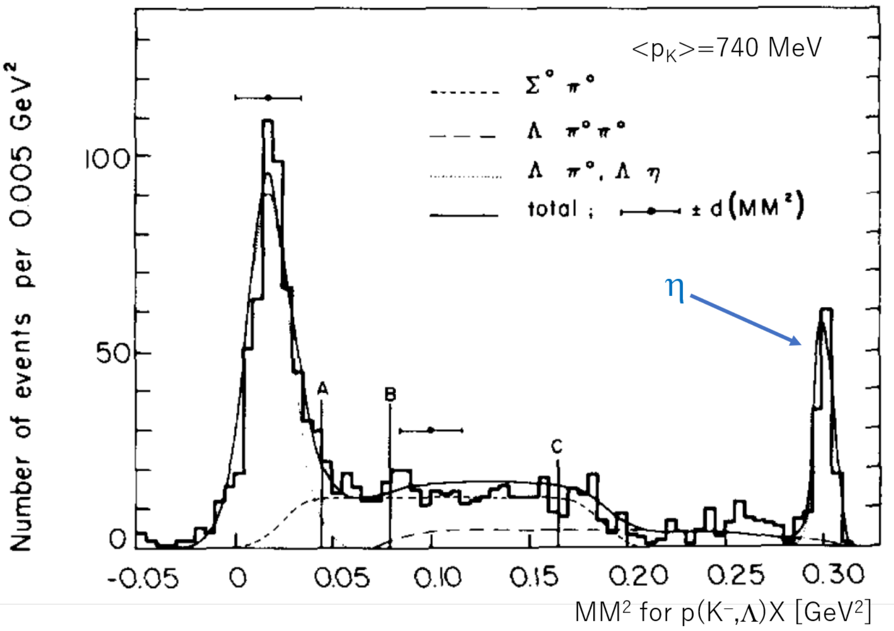

Figure 8: Spectrum of squared-missing-mass for the $p(K^-, \Lambda)X$ reaction at average $p_K = 740$ MeV/c from an old bubble chamber experiment at CERN [22]. The peak for η is clearly seen with a good signal-to-noise ratio.

higher statistics. However, in order to accumulate enough statistics to determine parity, we need about 2 weeks. The reason is the following: In general, baryon parity can not be determined from decay angular distribution to the spin 1/2 ground state (e.g., Λ) and a spin 0 meson (e.g., π or η), because the distribution is (accidentally) the same for $L = J + 1/2$ and $L = J - 1/2$ cases. Here, in order to determine the parity in a model independent way, one have to measure polarization of final Λ, requiring much higher statistics. If the parity is negative (D-wave decay), the polarization curve has a node at $\cos\theta = 0$, while there would be no such node if the parity is positive (P-wave decay) (see Appendix A). We can determine the parity in this way, without complicated partial wave analysis.

Due to the small statistics, Crystal Ball divided the whole data into only 2 beam momentum bins (and 10 decay angle bins). Their statistical uncertainty for each bin was $\delta P_\Lambda \sim 0.2$. On the other hand, in order to unambiguously determine the parity, we need a level of $\delta P_\Lambda \sim 0.05$ in finer bins (2 MeV/c size), considering theorists predict $|P_\Lambda| = 0.2 \sim 0.8$ at maximum [16, 17]. Then we need 100 times higher statistics than Crystal Ball, corresponding to the beam time of 2 weeks.

The background level is demonstrated to be small by the old bubble chamber data at CERN [22]. In the experiment, statistics is not enough (only ~ 100 counts in total) to discuss the angular distribution, but is enough to show the signal-to-noise ratio, which is already good (see Fig. 8). In the proposed experiment, the missing mass resolution for η is expected to be improved (to about ~ 1 MeV/c^2) thanks to the good beam momentum resolution, and hence an even better S/N ratio is expected.

4 Run Plan and Beam Time Request

We request 14 days for the main beam time, based on yield estimation described in the previous section. In addition, we need following beam times.

- 3 days for detector and target commissioning.
- 3 days for beam energy calibration by beam energy scanning.
- 1 day for empty target run.

While our beam spectrometer has a good resolution of $\delta p/p \sim 10^{-3}$, absolute momentum scale is not well calibrated. In Crystal Ball [15], the beam momentum scale was calibrated by using the $K^-p \to \Lambda\eta$ data themselves, assuming the total cross section is proportional to the eta momentum in the CM system. We will use the same technique.

Assuming the nominal beam momentum setting could be wrong by 5% at maximum, we will take data at 5 settings, 685, 705, 725, 745, and 765 MeV/c, for a half day each (plus another half day for beam tuning). Taking the dispersion of $\pm 2\%$ (FWHM) into account, a region from 670 to 780 MeV/c is covered. Then we will make a quick analysis for the yield of $p(K^-, \Lambda)\eta$ events (without corrections for efficiency etc.), and roughly determine the absolute momentum scale. (It is noted that the data for this scan is also an important input for coupled-channel analyses by theorists [9, 10, 13, 14].) The main physics run will be performed at a setting that is found to be optimum from the above beam scan.

We will be able to start the proposed experiment by the end of FY2018, when the commissioning of hypTPC is finished. However, the proposed experiment shares hypTPC spectrometer with E42 and E45 experiments, and we cannot start within one month of beamtimes of these experiments.

5 Summary

We propose to search for a new exotic spin 3/2 Λ^* resonance [$\Lambda^*(1665)$] near the $\Lambda\eta$ threshold by the $p(K^-, \Lambda)\eta$ reaction. A quadratic shape of differential cross section in the narrow region is the signal for a spin 3/2 resonance, as hinted in the Crystall Ball data. We will confirm the Crystal Ball data with much higher statistics. Furthermore, we will also measure polarization of Λ in the final state and determine its parity in a model independent way. If the $\Lambda^*(1665)$ is confirmed, conventional quark model cannot explain it at all, so it has a huge impact in the field of hadron physics.

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Appendix

A Simple calculation on Λ polarization

The Λ polarization P_Λ is given by

$$P_\Lambda = \frac{2\mathrm{Im}(fg^*)}{|f|^2 + |g|^2}$$

where $f(W,\theta)$ and $g(W,\theta)$ are usual spin-nonflip and spin-flip amplitudes, respectively. These amplitudes can be further expanded as

$$f(W,\theta) = \sum_{L=0}^{\infty} \left[(L+1)T_{L+}(W) + LT_{L-}(W)\right] P_L(\cos\theta)$$

$$g(W,\theta) = \sum_{L=0}^{\infty} \left[T_{L+}(W) - T_{L-}(W)\right] P_L^1(\cos\theta)$$

in terms of partial waves, with L being the initial orbital angular momentum, $P_L(\cos\theta)$ being a Legendre polynomial, $P_L^1(\cos\theta) = \sin\theta \times dP_L(\cos\theta)/d(\cos\theta)$ being an associated Legendre function, and $T_{L+}(W)$ ($T_{L-}(W)$) being partial-wave amplitudes for $J = L + 1/2$ ($J = L - 1/2$).

In the present case, we assume the amplitudes are dominated by two partial waves, namely, S-wave (T_{0+}) which is for $\Lambda(1670)$ (and for background near the threshold), and P (T_{1+}) or D (T_{2-}) wave for $\Lambda(1665)$. Then, since S-wave gives only spin-nonflip amplitude and one single partial wave can not contribute to polarization (because there is no phase difference between spin-flip and spin-nonflip partial amplitudes), the polarization is given by interference of spin-nonflip amplitude from S-wave and spin-flip amplitude from P or D-wave. In the former case,

$$P_\Lambda \propto P_0(\cos\theta) P_1^1(\cos\theta) \propto \sin\theta$$

has no node, while in the latter case

$$P_\Lambda \propto P_0(\cos\theta) P_2^1(\cos\theta) \propto \sin\theta\cos\theta$$

has a node at $\theta = 90°$.