LETTER OF INTENT FOR 50 GEV PROTON SYNCHROTRON

Study of Odd-Parity Σ and Ξ Resonances in K^-p Reactions with the Hyperon Spectrometer

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Abstract

We propose an extensive study of odd-parity Σ and Ξ resonances in K^-p interactions from threshold to 2.0 GeV/c at J-PARC. While partial-wave analyses observe one $J^p = 3/2^-$ $\Sigma(1670)$ resonance, production experiments have found evidence for two Σ resonances in the same mass region, based on a difference in the production angular distributions for $\Sigma\pi$ and $\Sigma\pi\pi$ channels. In a $S = -2$ sector, only the ground octet and decuplet states $\Xi(1320)$ and $\Xi(1530)$ are well-established with four-star ratings. Excited states $\Xi(1620)$ and $\Xi(1690)$ compete for the first orbital excitation of Ξ with $J^p = 1/2^-$. While recent high-energy e^+e^- collision experiments report spin analysis of the $\Xi(1690)$ decays, spin-parity determination and production cross-section measurements are needed. The proposed experiment can be performed using a hydrogen target with the Hyperon Spectrometer at K1.8 beam line, J-PARC Hadron Hall.

1 Physics Motivation

Baryons are strongly interacting particles with baryon number $B = 1$. The ground state of this system has all three quarks in a relative $L = 0$ state and positive parity. Flavor and spin may be combined in an approximate flavor-spin $SU(6)$ ($\mathbf{6} \otimes \mathbf{6} \otimes \mathbf{6}$). The baryons belong to the multiplets on the right side of

$$\mathbf{56}_S \oplus \mathbf{70}_M \oplus \mathbf{70}_M \oplus \mathbf{20}_A,$$

which can be decomposed into flavor $SU(3)$ multiplets as follows:

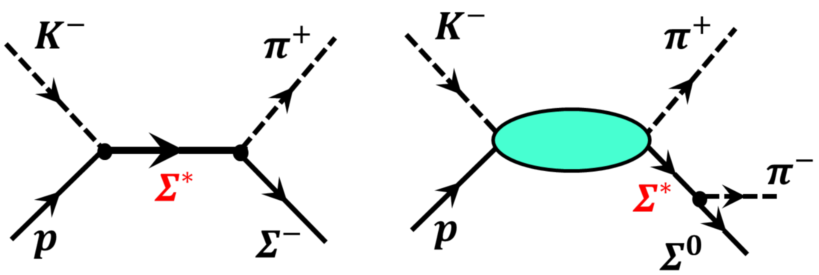
$$\mathbf{56} = {}^{\mathbf{4}}\mathbf{10} \oplus {}^{\mathbf{2}}\mathbf{8}, \quad \mathbf{70} = {}^{\mathbf{2}}\mathbf{10} \oplus {}^{\mathbf{4}}\mathbf{8} \oplus {}^{\mathbf{2}}\mathbf{8} \oplus {}^{\mathbf{2}}\mathbf{1}, \quad \mathbf{20} = {}^{\mathbf{2}}\mathbf{8} \oplus {}^{\mathbf{4}}\mathbf{1},$$

where the superscript $(2S+1)$ gives the net spin S of the quarks for each particle in the $SU(3)$ multiplet [1]. The baryons are also classified into bands with the same quantum number N of excitation. Each band consists of a number of super-multiplets specified by (D, L_N^P), where D is the dimensionality of the $SU(6)$ representation. The $N = 0$ band contains the nucleon and $\Delta(1232)$ of the $(56, 0_0^+)$ super-multiplet. The $N = 1$ band consists only of the $(70, 1_1^-)$ multiplet and contains the negative-parity baryons with masses below about 1.9 GeV. The $\Lambda(1520)$ belongs to the $N = 1$ band.

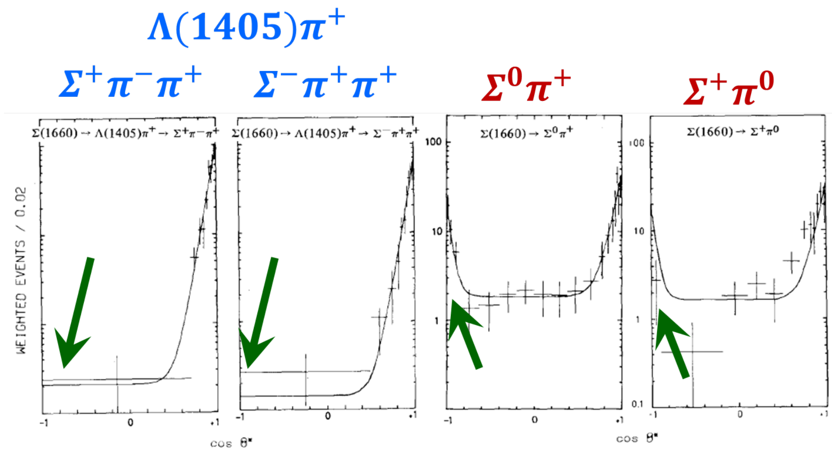
Excited states of hyperons are still much less well known, compared to the nucleon resonances. In the $S = -1$ sector the $\Sigma(1385)$ and $\Lambda(1405)$ lie below the $\bar{K}N$ threshold, and almost all their known properties were from production experiments. The nature of the $\Lambda(1405)$ has been unveiled yet, which may be either of a genuine three-quark state, a meson-baryon molecular state, or even an exotic multiquark state. In the case of $\Lambda(1520)$ above the $\bar{K}N$ threshold production and formation experiments agree quite well. In the 1670 MeV region the existence of three $S = -1$ baryon resonances have been established, $S_{01}\Lambda(1670)$, $D_{03}\Lambda(1690)$, and $D_{13}\Sigma(1670)$. The results of partial-wave analyses agree on the mass, width and branching ratios of these resonances [1, 2, 3].

However, there is some disagreement between production and formation experiments in this mass region. Formation experiments observe one Σ resonance in the 1670 MeV mass region with $J^p = \frac{3}{2}^-$ and decaying primarily to $N\bar{K}$, $\Lambda\pi$, and $\Sigma\pi$. On the other hand, production experiments have found evidence for two Σ resonances in this mass region with comparable values of mass and width. This evidence is based on a difference in the production angular distributions of $\Sigma(1670)$ decaying into $\Sigma\pi$ and into $\Sigma\pi\pi$ [5, 6, 7, 8, 9, 10]. On top of that, a recent report from SPring-8/LEPS on different lineshapes in $\Sigma^+\pi^-$ and $\Sigma^-\pi^+$ channels has attracted much attention in the nature of the resonance(s) in the 1670 MeV mass region, which strongly supports an extensive study of the $\Sigma(1670)$ resonance in other reactions [4].

In the $S = -2$ sector, only the ground octet and decuplet states $\Xi(1320)$ and $\Xi(1530)$ are well-established with four-star ratings. $\Xi(1690)$, $\Xi(1820)$, $\Xi(1950)$ and $\Xi(2030)$ are three-star states. The third state of Ξ has not yet been confirmed between $\Xi(1620)$ and $\Xi(1690)$. In Particle Data Group [1], $\Xi(1620)$ is one-star rating resonance and $\Xi(1690)$ is three-star rating resonance. The $\Xi(1620)$ is near ΛK threshold and the $\Xi(1690)$ is near ΣK threshold. They may be analogues of $\Lambda(1405)$.



(a)



(b)

Figure 1: (a) Formation and production diagrams for $\Sigma(1670)$ decaying to $\Sigma\pi$, (b) production angular distributions for $\Sigma(1670)$ decaying to $\Sigma\pi\pi$ and $\Sigma\pi$ channels [10].

$$\underbrace{\Xi(1320)}_{J^p=\frac{1}{2}^+} \quad \underbrace{\Xi(1530)}_{J^p=\frac{3}{2}^+} \quad \underbrace{\Xi(1690)}_{J^p=\frac{1}{2}^?} \quad \underbrace{\Xi(1820)}_{J^p=\frac{3}{2}^-}$$

If either Ξ resonance is analogue of $\Lambda(1405)$, it is a general phenomena in hadron physics. About $\Xi(1620)$, there are several negative experiments and its existence is dubious. But it is important to check with higher statistics. The existence of $\Xi(1690)$ is quite probable from several experiments especially with high energy hyperon beams and its width is reported to be 10 MeV. Yet, spin and parity are not determined. The $\Xi(1820)$ is only state of which spin parity is determined ($3/2^-$). The ordinary quark models predict $3/2^-$ and $1/2^-$ should be almost degenerate as in the case of N^*. One of the reason of $\Lambda(1405)$ compositeness comes from the large mass difference ($\approx$ 100 MeV) from the doublet $\Lambda(1520)$. So if $\Xi(1620)$ or $\Xi(1690)$ is $1/2^-$, it is $S = -2$ analogue of $\Lambda(1405)$, namely $\Lambda\overline{K}$ or $\Sigma\overline{K}$ molecular state. It is extremely important to do a high statistics experiment on these Ξ^* production and its decay distribution measurement to determine their spin-parity.

The BaBar collaboration reported $\Xi(1690)$ measurement from $\Lambda_c^+ \to \Lambda K_S^0 K^+$ decays (363 ± 26 events) [11]. $\Xi(1690) \to \Lambda\overline{K}^0$ decay shares $\overline{K}^0$ with $a_0^+(980) \to \overline{K}^0 K^+$ (interference between $\Xi(1690)$ and $a_0(980)$). The angular distribution of the Λ is given by the total intensity:

$$I \propto \sum_{\lambda_i,\lambda_f} \rho_i \left| A^J_{\lambda_f} D^{J*}_{\lambda_i\lambda_f}(\phi,\theta,0)\right|^2,$$

where $\rho_i (i = \pm 1/2)$ are the diagonal density matrix elements. According to different spin hypotheses for the $\Xi(1690)$:

$$\begin{aligned} I &\propto 1 \quad (\text{for } J = 1/2), \\ I &\propto \frac{1}{4}(1 + 3\cos^2\theta_\Lambda) \quad (\text{for } J = 3/2), \\ I &\propto \frac{1}{4}(1 - 2\cos^2\theta_\Lambda + 5\cos^4\theta_\Lambda) \quad (\text{for } J = 5/2) \end{aligned}$$

The BaBar collaboration reported that $J = 1/2$ assignment was favored for $\Xi(1690)$ from its decay angular distribution ($CL = 56\%$).

2 Experiment

We propose extensive measurements of $\Sigma(1670)$ and $\Xi(1690)$ production reactions from threshold to 2 GeV/c at J-PARC. The experiment can be performed with a superconducting Hyperon Spectrometer and a LH_2 target [12, 13]. The central tracking device, time projection chamber (HypTPC), will reconstruct all the decay particles from $\Xi(1690)^- \to \Lambda K^-, \Sigma^- K_S^0$, and $\Xi^-\pi^0$ (or $\Xi^0\pi^-$), and from $\Sigma(1670)^- \to \Sigma^0\pi^-$, $\Sigma^-\pi^-\pi^+$, as shown in Fig. 3.

Experiemental yield for $\Xi(1690)$ is estimated to be 40000 events (assuming $\sigma \approx 3\mu$b), two orders of magnitude higher statistics than 363 events from the BaBar experiment. The

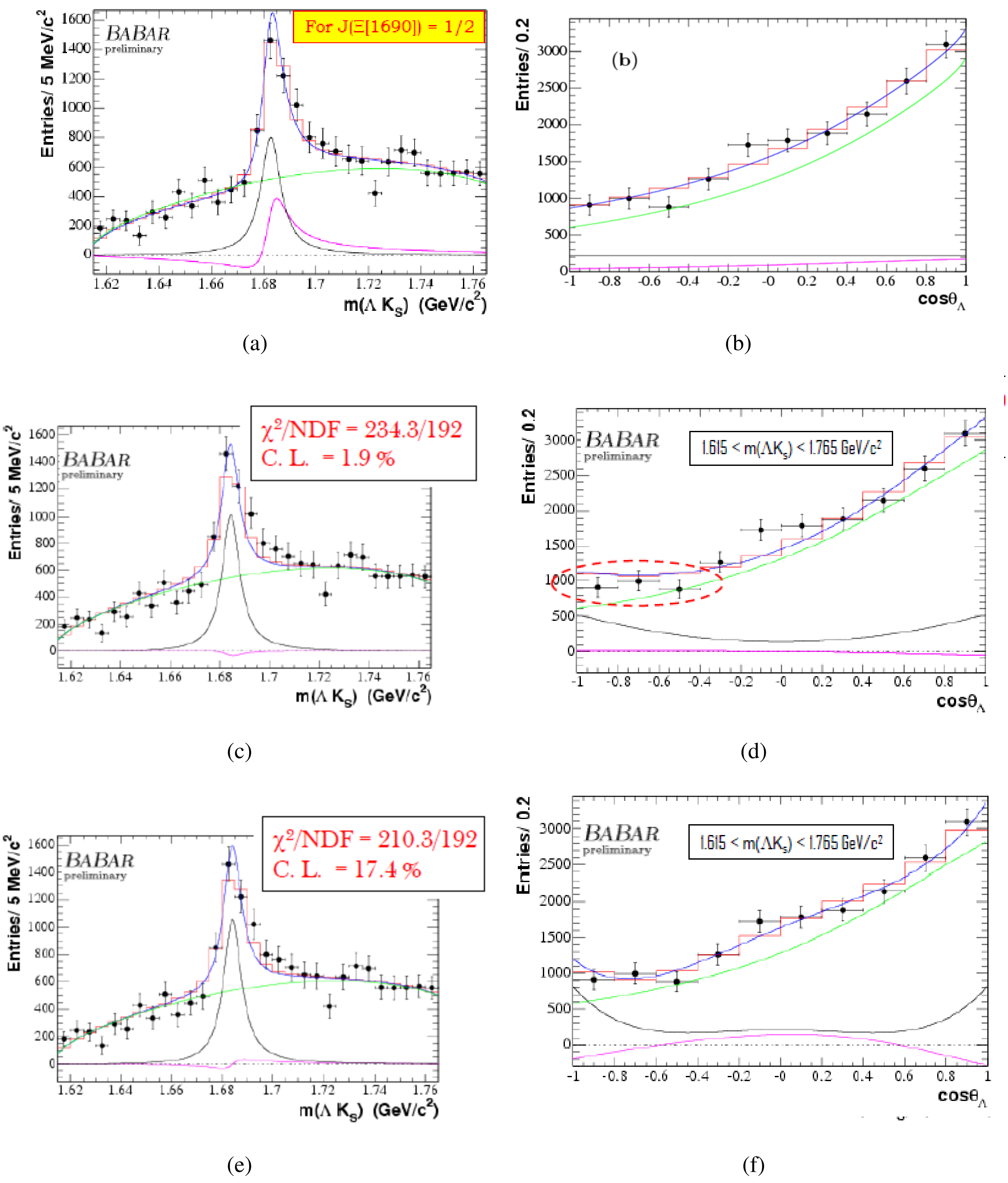


Figure 2: (a) ΛK_S invariant mass spectrum for $J = 1/2$ $\Xi(1690)$, (b) decay angular distribution with a fit for $J = 1/2$ hypothesis (CL$=$ 56%), (c) ΛK_S invariant mass spectrum for $J = 3/2$ $\Xi(1690)$, (d) decay angular distribution with a fit for $J = 3/2$ hypothesis (CL$=$ 1.9%), (e) ΛK_S invariant mass spectrum for $J = 5/2$ $\Xi(1690)$, (f) decay angular distribution with a fit for $J = 1/2$ hypothesis (CL$=$ 17.4%)

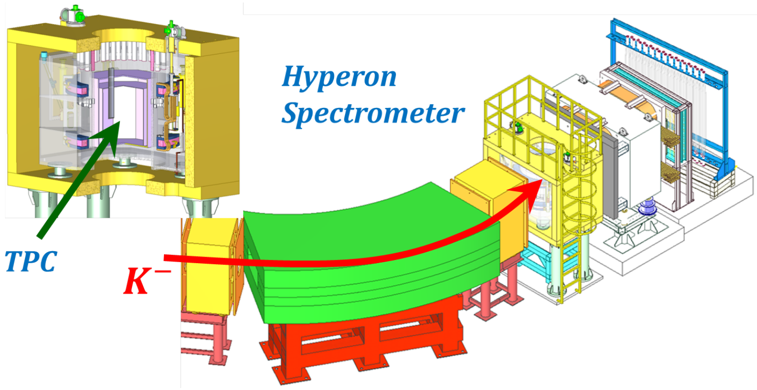
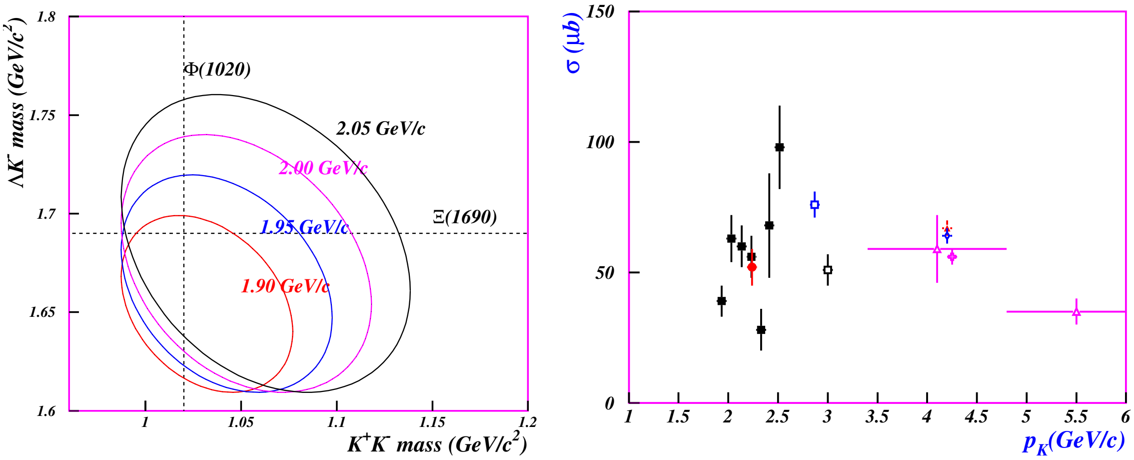


Figure 3: The proposed experimental setup for odd-parity hyperon measurements.

estimated cross section of 3 μb is based on the world-data compilation for $K^-p \to \Lambda K^+K^-$ reactions, as shown in Fig. 4b. Some fraction of the cross sections should be due to $K^-p \to \phi\Lambda$ reaction, and some others are from non-resonant reactions.



(a) (b)

Figure 4: (a) Phase-space contours for ΛK^+K^- final states from the K^-p reaction in terms of the K^- beam momentum. (b) the world-data compilation of cross sections for the $K^-p \to \Lambda K^+K^-$ reaction.

We can determine the parity of $\Xi(1690)$ from the Λ polarizaiton measurement. For $1/2^p \to 1/2^+ + 0^-$ decay, the polarization of Λ is directly transfered from that of $\Xi(1690)$ with $L = 0$, while it varies with the Λ decay angles for $L = 1$:

$$\vec{P}_{\Xi^*} = \vec{P}_\Lambda \quad (L=0), \qquad \vec{P}_{\Xi^*} = -\vec{P}_\Lambda + 2(\vec{P}_{\Xi^*}\cdot\hat{e}_3)\hat{e}_3 \quad (L=1).$$

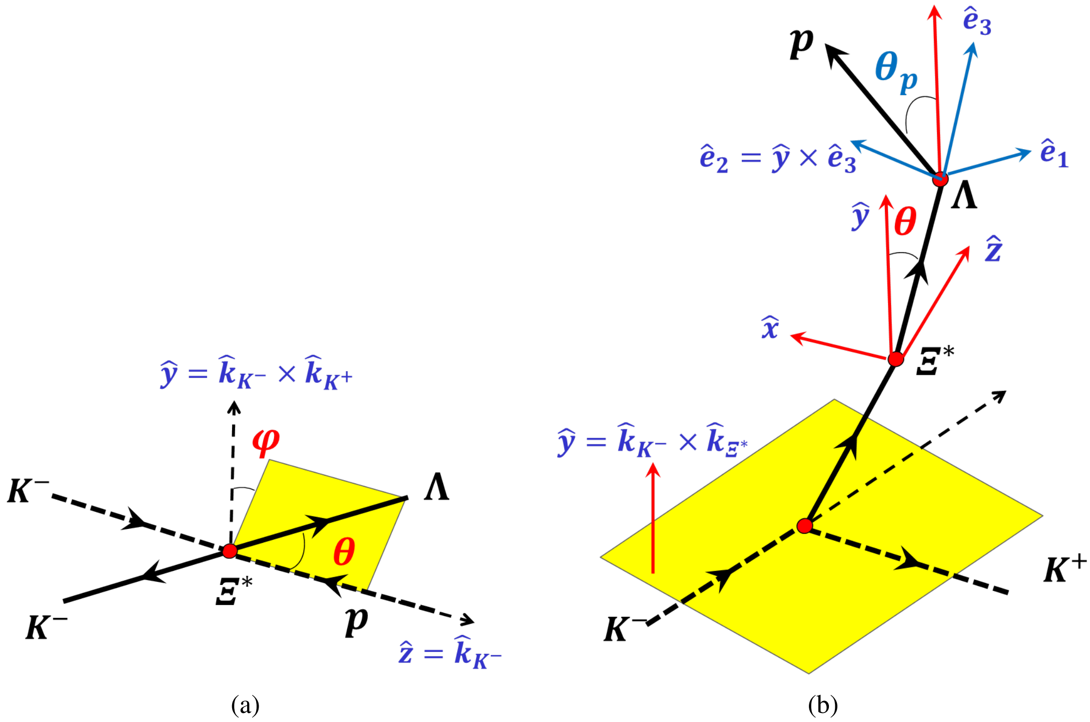


Figure 5: (a) Reaction plane for $K^-p \to \Xi(1690)^-K^+$ reaction, (b) decay angles from $\Xi(1690)$.

The Ξ^- polarization is defined as the direction normal to the production plane:

$$I(\theta) = 1 + \alpha_{\Xi^*} P_{\Xi^*} \cos\theta,$$

as shown in Fig. 5. The Λ polarization is given at a fixed angle θ:

$$I(\theta_p) = 1 + \alpha_\Lambda P_\Lambda \cos\theta_p$$

In the $K^- p \rightarrow \Lambda K^+ K^-$ reaction, there could be a quantum interference between production amplitudes for $\Xi(1690)$ and ϕ, and/or with nucleon resonances decaying to ΛK^+. We could investigate such possible interference among the production amplitudes which contribute to $\Lambda K^+ K^-$ final state. The interference effect between $\Xi(1690)$ and ϕ production amplitudes is described as

$$Y(m, m') = \left| \underbrace{\frac{a}{m^2 - m_\phi^2 + i m_\phi \Gamma_\phi}}_{\mathcal{M}_\phi} + e^{i\psi} \underbrace{\frac{b}{m'^2 - m'^2_{\Xi^*} + i m'_{\Xi^*} \Gamma_{\Xi^*}}}_{\mathcal{M}_{\Xi^*}} \right|^2$$

$$I(m, m') = \frac{2|ab|(c\cos\psi + d\sin\psi)}{c^2 + d^2}$$

where c and d are given as:

$$\begin{aligned} c &= (m^2 - m_\phi^2)(m'^2 - m'^2_{\Lambda^*}) + m_\phi \Gamma_\phi m'_{\Lambda^*} \Gamma_{\Lambda^*} \\ d &= m'_{\Lambda^*} \Gamma_{\Lambda^*} (m^2 - m_\phi^2) - m_\phi \Gamma_\phi (m'^2 - m'^2_{\Lambda^*}) \end{aligned}$$

The maximum constructive and destructive interference effects are plotted in Fig. 6.

3 Summary

We propose an extensive study of odd-parity $\Sigma(1670)$ and $\Xi(1690)$ resonances in $K^- p$ interactions from threshold to 2.0 GeV/c at J-PARC. While partial-wave analyses observe one $J^p = 3/2^-$ $\Sigma(1670)$ resonance, production experiments have found evidence for two Σ resonances in the same mass region, based on a difference in the production angular distributions for $\Sigma\pi$ and $\Sigma\pi\pi$ channels. In a $S = -2$ sector, only the ground octet and decuplet states $\Xi(1320)$ and $\Xi(1530)$ are well-established with four-star ratings. The proposed experiment will be performed using a hydrogen target with the Hyperon Spectrometer at K1.8 beam line, J-PARC Hadron Hall. The parity of $\Xi(1690)$ can be determined and also possible interference effects among the production amplitudes for $\Xi(1690)$, ϕ and N^*(decaying to ΛK^+).

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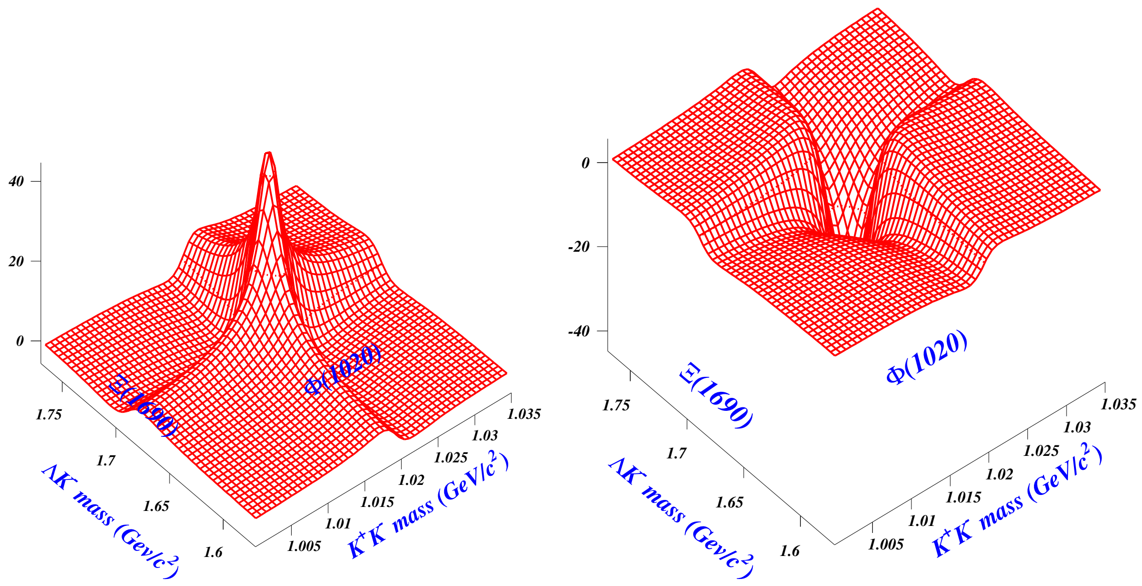

(a) (b)

Figure 6: (a) Mass distributions for the maximum constructive interference between $\Xi(1690)$ and ϕ, (b) for the maximum destructive interference between them.

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