LIGHT PENTAQUARK SEARCHES WITH HADRON BEAMS*

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This review deals with measurements and future experiments of light pentaquark searches using hadron beams.

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1. Introduction

Pentaquarks are predicted to be made of four quarks and one antiquark, forming the simplest multiquark configuration in the baryon sector. In contrast, tetraquark states in the meson sector are firmly established. The discovery of numerous multiquark candidates poses questions about the dripline of multiquark states, such as hexaquark states, in particular, the H-dibaryon. The observation of new multiquark states in different flavor sectors not only tests the flavor-spin symmetry but may also lead to the discovery of new symmetries.

Light pentaquark states in the KN system ($S = +1$) cannot be accommodated in a conventional quark model for baryons ($3q$). In the chiral quark soliton model, the Θ^+ is identified as a member of the $\overline{10}$ multiplet. The mass difference between the members of this multiplet was predicted to be 180 MeV multiplied by their difference in strangeness unit. This prediction from the model highlights the low mass and narrow width of the $\Theta^+(1540)$, as well as its spin-parity of $J^p = 1/2^+$, which is described as a rotating soliton [1].

Early observations of the pentaquark Θ^+ from photoproduction sparked a surge of pentaquark searches in various reactions. Initially, there were nearly equal numbers of positive and negative results from different experiments. However, over time, the weight of evidence began to shift against the existence of the Θ^+ [2–4]. The story of the Θ^+ came to a conclusion

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when the CLAS Collaboration found no evidence for its existence, even after analyzing data with statistics improved by two orders of magnitude. The most stringent limit on the search for Θ^+ is based on the CLAS results, which provides a 95% C.L. upper limit on the cross section 0.7 nb for the $\gamma p \to \bar{K}^0 K^+ n$ and $\gamma p \to \bar{K}^0 K^0 p$ reactions [5].

Despite this limit, there is still ongoing debate about how to conclude the Θ^+ story, as high-statistics data have excluded its existence. The production of the Θ^+ shares the same final state with either the ϕ or the $\Lambda(1520)$ in the γp and γd reactions, as depicted in Fig. 1. Event selection for the KN production at forward angles may enhance the visibility of the Θ^+ signal in the presence of significant background and the interference effects from the overlapping resonance bands [6]. By imposing the condition $|t_\Theta| < 0.45$ GeV^2, the Θ^+ signal becomes distinctly noticeable within the same CLAS dataset [7].

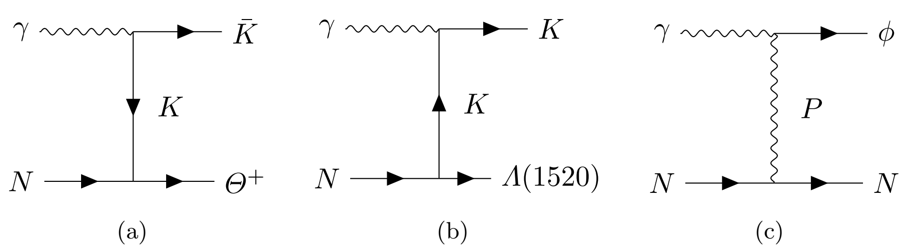


Fig. 1. (a) Feynman diagrams for $\gamma N \to \bar{K} K N$ reactions through the production of either (a) Θ^+, (b) $\Lambda(1520)$, or (c) ϕ.

The Θ^+ therefore remains controversial, prompting us to consider what additional measurements could help clarify the situation. We anticipate large production cross sections from hadron beams compared to those from electromagnetic processes. Pion-induced reactions yield different charge combinations in the final states due to the different charges of the initial states, which complement photoproduction processes. These pion-induced and photoproduction reactions produce associated Θ^+ particles when paired with K^- or $\bar{K}^0$. On the other hand, kaon-induced reactions provide a significant advantage by allowing for defining the strangeness.

Therefore, the new data from KN interactions is expected to considerably impact the question about the existence of the Θ^+. The K^+N reaction involves two isospin states: $I = 0$ and $I = 1$. The isovector ($I = 1$) states have been determined from elastic K^+p reactions. Meanwhile, isoscalar states are determined from the K^+d breakup and elastic reactions, as well as from the $K^0_{\rm L}$ scattering off a proton. The reaction cross section in the $I = 0$ state may provide interesting insight since the dominant Δ production mechanism is forbidden by isospin conservation, leaving other mechanisms more apparent [8]. The potential existence of a narrow Θ^+ state could manifest as a sudden change in the inelastic cross section. This review will focus on the K^+d and K^+p reactions for the Θ^+ study.

2. K^+p reactions

The $K^+p \to \Theta^+\pi^+$ two-body reaction is one of the most promising candidates for the search for the Θ^+. In the K^+p interaction, the elastic channel is dominant up to 0.8 GeV/c, and its cross section decreases gradually when the $KN\pi$ channels become accessible, as shown in Fig. 2 (a). The cross sections for the $K^+p \to KN\pi$ reactions increase rapidly near the threshold and reach the maximum at 1.5 GeV/c. In contrast, the cross sections for the $KN2\pi$ channels increase slowly and remain quite small until 1.5 GeV/c. At around 1.5 GeV, the cross sections for the K^+p elastic and $K^+p \to KN\pi$ channels are nearly equal.

Old bubble chamber experiments provide cross-section data for the $K^+p \to K^0p\pi^+$, $K^+p \to K^+p\pi^0$, and $K^+p \to K^+n\pi^+$ reactions between 1.2 and 1.7 GeV/c. There appears to be little nonresonant background, and the Dalitz plots indicate constructive interference at the crossing of the Δ and K^* bands. The production and decay of the Δ and K^* resonances dominate the $K^0p\pi^+$ final state. Most features of the KN spectra typically reflect these resonances [9]. There is no clear indication of the Θ^+ band. The $K^+p \to K^+n\pi^+$ reaction demonstrates a weak Δ resonance, although only 359 events have been recorded for this channel [10].

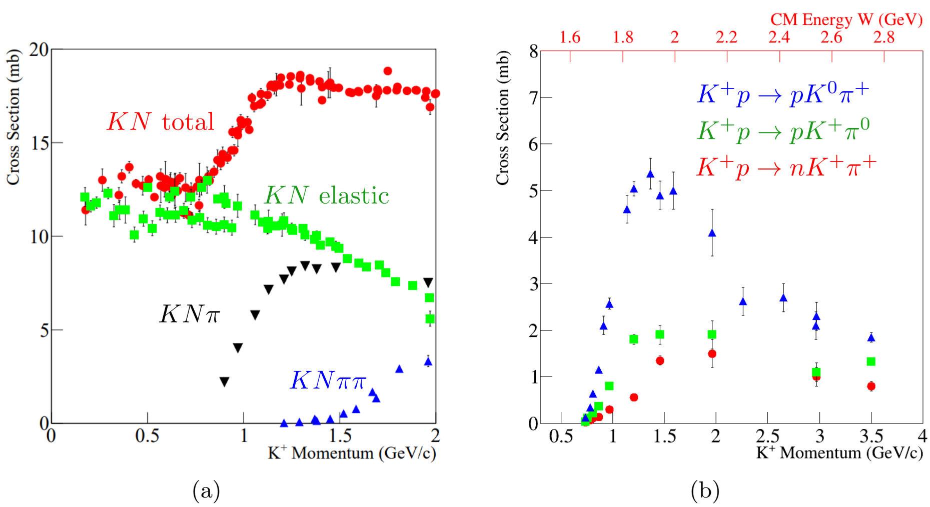


Fig. 2. (a) K^+p cross sections in the momentum range up to 2 GeV/c and (b) $K^+p \to KN\pi$ cross sections in the momentum range up to 4 GeV/c [11].

At approximately 1.5 GeV/c, two earlier bubble chamber experiments reported the cross sections for the $K^+p \to K^0p\pi^+$ reaction at momenta of 1.52 GeV/c [12] and 1.585 GeV/c [10], where only the K^* band intersects the phase space. The cross sections for the $KN\pi$ reactions are displayed for three different isospin channels in Fig. 2 (b). The Θ^+ was also searched for in the K_Sp mass spectrum for the $K^+p \to K_Sp\pi^+$ reaction at 11 GeV/c [13], but no evidence of the Θ^+ signal was found.

KEK-PS E559 searched for Θ^+ via (K^+, π^+) at a momentum of 1.2 GeV/c using a beam of 5×10^9 K^+ [14]. The analysis of the missing-mass spectrum for the $p(K^+, \pi^+)X$ reaction revealed no evidence of the Θ^+ signal within the forward lab angles ranging from $\theta_\pi^L = 2°$ to $22°$. An upper limit of 3.5 μb/sr was established at a 90% C.L. These findings suggest either a suppression of the K^* exchange contribution in the t channel in Fig. 3 (a) or points to a very small value of the coupling constant $g_{K^*N\Theta}$. If the u-channel processes Fig. 3 (b) can only contribute to the Θ^+ production, then the π^+ angular distribution would be enhanced at backward angles. However, the E559 had no acceptance in that angular region. Furthermore, the beam momentum of 1.2 GeV/c was specifically chosen to maximize the cross sections for the $K^+p \to KN\pi^+$ reactions. However, the Δ^{++} and K^* resonances predominantly fill the phase space in the $K^0p\pi^+$ channel. At this momentum, the expected Θ^+ band intersects with the two resonance bands.

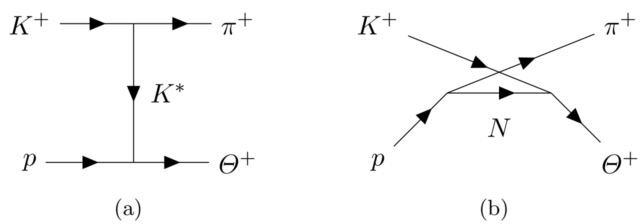
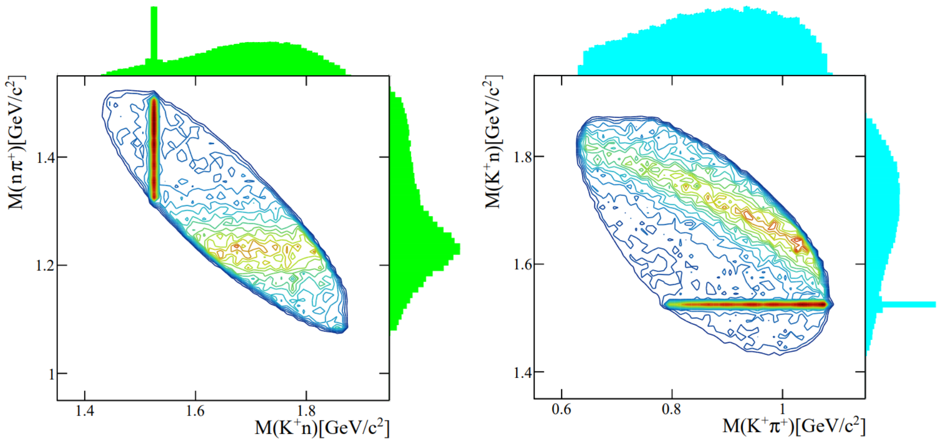


Fig. 3. Feynman diagrams for (a) the t channel and (b) the u-channel processes in the $K^+p \to \Theta^+\pi^+$ reaction.

Therefore, a more definitive conclusion about the existence of the Θ^+ will await further measurements. The $K^+p \to K^+n\pi^+$ reaction at a momentum of 1.5 GeV/c is likely the most promising for the Θ^+ search. This reaction does not involve any background from the K^* production, and only the Δ resonance contributes to the available phase space. Moreover, the beam momentum of 1.5 GeV/c ensures that the Δ resonance band does not overlap with the expected band for the Θ^+, as illustrated in Fig. 4 (a) and (b). The Θ^+ peak appears superimposed on a smooth background shape in the simulated spectrum, which has a mass resolution of 3 MeV. In contrast, in the $K^0p\pi^+$ channel, the K^* band intersects the middle of the Θ^+ band.



(a) (b)

Fig. 4. Dalitz plots of (a) the K^+n *versus* $n\pi^+$ masses and (b) the $K^+\pi^+$ *versus* K^+n masses for the $K^+p \to K^+n\pi^+$ reaction at 1.5 GeV/c.

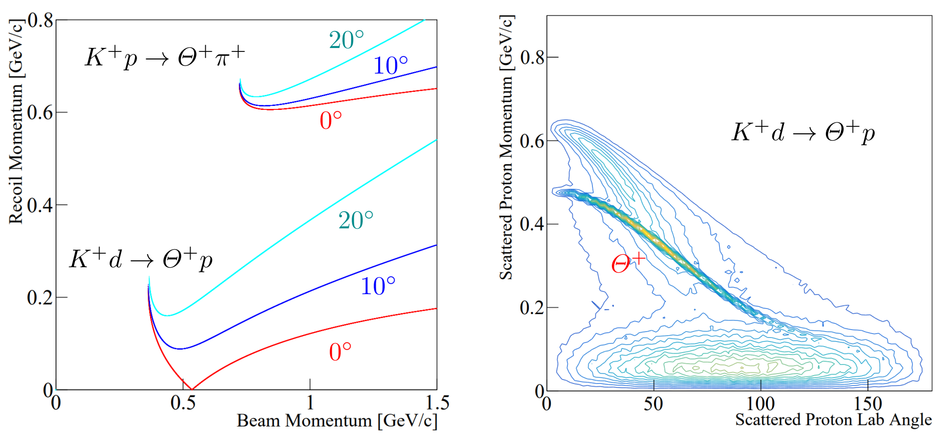
The experiment for the $K^+p \to K^+n\pi^+$ reaction can be conducted using a 1.5 GeV/c K^+ beam in conjunction with the Hyperon Spectrometer at J-PARC. The neutron can be reconstructed by detecting the outgoing K^+ and π^+ tracks using the HypTPC. The excellent separation of π and K provided by the HypTPC will help in identifying the $K^+p \to K^+n\pi^+$ reaction. Additionally, the HypTPC can also reconstruct the $K^0p\pi^+$ and $K^+p\pi^0$ channels.

This experiment can provide crucial information on the spin and parity of the Θ^+. The conservation of parity in the $K^+p \to \Theta^+\pi^+$ reaction requires that the relative angular momentum L must be even. If the Θ^+ has a spin of 1/2, then L must be zero. Conversely, in the $K^+d \to \Theta^+p$ reaction, the opposite parity between the initial and final states requires that the relative angular momentum L be odd, and specifically $L = 1$ for the $J = 1/2^+\Theta^+$. The value of L determines the angular distribution of the outgoing particle. If the final state $\Theta^+\pi^+$ exhibits relative angular momentum zero, the spin-parity of the Θ^+ could also be $D5/2+$ ($L = 2$) [15]. However, the production of the Θ^+ competes with other strong background processes involving Δ and K^* resonances, making the unpolarized angular distributions insufficient to clarify the quantum numbers of the Θ^+ [16]. Since the meson beams are unpolarized, utilizing target polarization can help determine the quantum number of the Θ^+.

3. K^+d reactions

A direct formation of the Θ^+ can occur through both the $K_{\rm L}p \to K^+n$ and $K^+n \to K^0p$ reactions. The $K_{\rm L}p \to K^+n$ reaction will be investigated using the KLF facility at Jefferson Lab [17] and the details of this experiment will be presented in another review of this volume [18]. The $K^+n \to K^0p$ reaction can also be realized through the $K^+d \to K^0pp$ reaction, using a liquid deuterium target. Previous bubble chamber experiments have provided data with limited statistics near the mass of the Θ^+, although a few data points that deviate from a smooth trend have attracted attention.

The $K^+d \to \Theta^+p$ reaction can produce a recoilless Θ^+ at a scattering angle of 0°, as illustrated in Fig. 5 (a). This magic momentum is approximately 0.5 GeV/c, which is suitable for the Θ^+ search experiment. This ideal momentum allows the K^0 and p to emerge in a back-to-back configuration. In contrast, the $K^+p \to \Theta^+\pi^+$ reaction has a minimum recoil momentum of about 0.6 GeV/c. A clear signal is expected from this reaction due to the two-body kinematical correlation between the production angle and momentum, as shown in Fig. 5 (b).



(a) (b)

Fig. 5. (a) Momentum transferred to Θ^+ in the $K^+d \to \Theta^+p$ and $K^+p \to \Theta^+\pi^+$ reactions at lab scattering angles of 0°, 10°, and 20°; (b) a scatter plot of the momentum and lab scattering angle for the scattered protons in the $K^+d \to \Theta^+p$ reaction.

A new experiment is being discussed to search for the Θ^+ in the $K^+d \to K^0pp$ reaction at a momentum of 0.5 GeV/c at J-PARC [19]. This experiment was initially designed to exclusively measure the decay products K^0p of the Θ^+ along with a spectator proton. The Θ^+ can be produced via impulse scattering (Fig. 6 (a)), two-step processes involving a primary $K^+n \to K^0p$ reaction followed by a secondary $K^0p \to K^0p$ reaction (Fig. 6 (b)) and the other with a proton first involved in the primary reaction (Fig. 6 (c)).

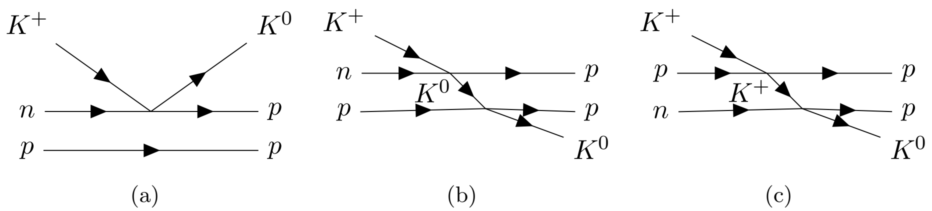


Fig. 6. The production processes of Θ^+ in the $K^+d \to K^0pp$ reaction include; (a) a direct one-step process (impulse scattering), two-step processes involving (b) a charge-exchange reaction followed by elastic scattering, and (c) *vice versa*.

However, the use of an 80 mm thick cylindrical liquid deuterium target poses a challenge, as it limits the detection of spectator protons that emerge slowly from the target. Additionally, the intensity of the K^+ beam decreases significantly at low momenta. To address this issue, an alternative approach is being considered, which involves using a high-momentum beam equipped with a graphite degrader. This approach can increase statistics since higher momentum beams provide greater intensity [20].

Nonetheless, this alternative means that the original goal of conducting a complete kinematic analysis in the search for the Θ^+ cannot be achieved because the exact beam momentum would remain unknown. In this case, the K^0p mass resolution will entirely depend on the momentum and angular resolutions in reconstructing the $K_S \to \pi^+\pi-$ decay and a fast proton. The expected K^0p mass spectra are demonstrated in Fig. 7 (a) and (b), assuming 3 MeV of the mass resolution for $\sigma_\Theta = 500$ μb and 100 μb, respectively. The enhanced lineshape could only be recognized when the Θ^+ production cross section exceeds 100 μb.

To effectively address this challenge, a reliable solution is to change the shape of the target cell from a cylinder to a long, thin slab. This adjustment would allow low-energy spectator protons to escape more easily from the target at large angles. Furthermore, the cross-section measurement for the $K^+d \to K^0pp$ reaction is crucial, as it provides important information about the center-of-mass energy for the KN system, particularly near the mass of the Θ^+.

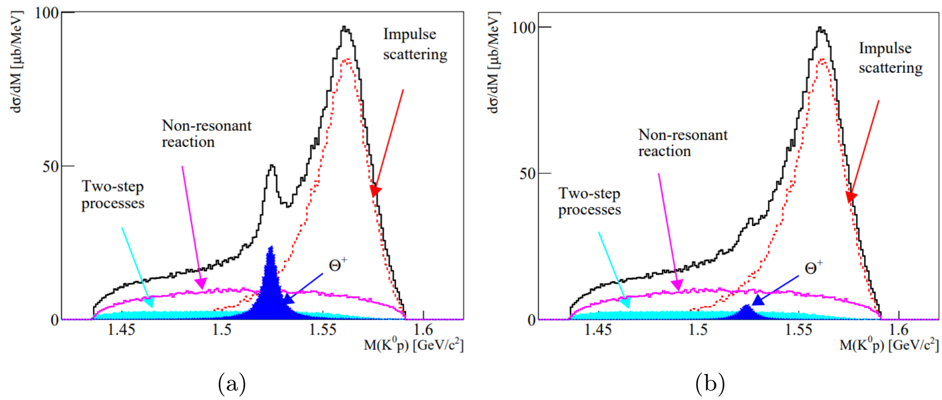


Fig. 7. Expected K^0p mass spectra for the $K^+d \to K^0pp$ reactions at 0.5 GeV/c, assuming the Θ^+ production cross section is (a) 500 μb and (b) 100 μb, respectively. A 3 MeV mass resolution is taken into account.

Additionally, it is essential to emphasize that a high-precision measurement of the $d(K^+,p)\Theta^+$ reaction has been proposed [21]. This proposal can be improved by introducing a new approach to suppress background processes related to elastic and charge exchange reactions using the HypTPC [22].

There is a clear need in the near future for a new combined $I = 0$ and $I = 1$ partial-wave analysis using all the new K^+n data in combination with $I = 1$ partial waves from the K^+p data.

4. π^-p reactions

The π^-p reaction can produce the Θ^+ associated with K^-. Unlike the γp reaction, it can produce it with a proton target. Additionally, it can proceed only with a K^* exchange in the t channel, while the γp reaction can have both K- and K^*-exchange processes in the t channel. The Θ^+ production in π^-p reactions can also occur through N^* resonances in the s channel above a threshold momentum of 1.7 GeV/c, as illustrated in Fig. 8 (a) and (b). However, the lack of observed Θ^+ production in the $K^+p \to \Theta^+\pi^+$ reaction indicates that the t-channel process via the K^* exchange is relatively small [23]. Thus, it is likely that the s-channel contribution predominates in the $\pi^-p \to \Theta^+K^-$ reaction.

In the $\pi^-p \to \Theta^+K^-$ reaction, the Θ^+ is produced with high momentum, as illustrated in Fig. 9 (a). The J-PARC E19 experiment conducted a high-resolution and high-statistics measurement to search for the Θ^+ in the (π^-,K^-) reaction at 1.92 [24] and 2.01 GeV/c [25]. The mass resolutions

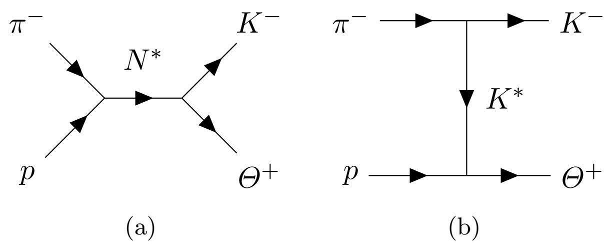


Fig. 8. (a) Feynman diagrams for Θ^+ production in (a) the s channel and (b) t channel.

were 1.72 and 2.13 MeV/c^2 (FWHM). No peak structure was observed in the missing mass spectra at scattering angles ranging from 2° to 15° in the laboratory frame. As a result, the upper limit on the forward production cross section for the possible Θ^+ mass region was found to be less than 0.28 μb/sr at a 90% C.L.

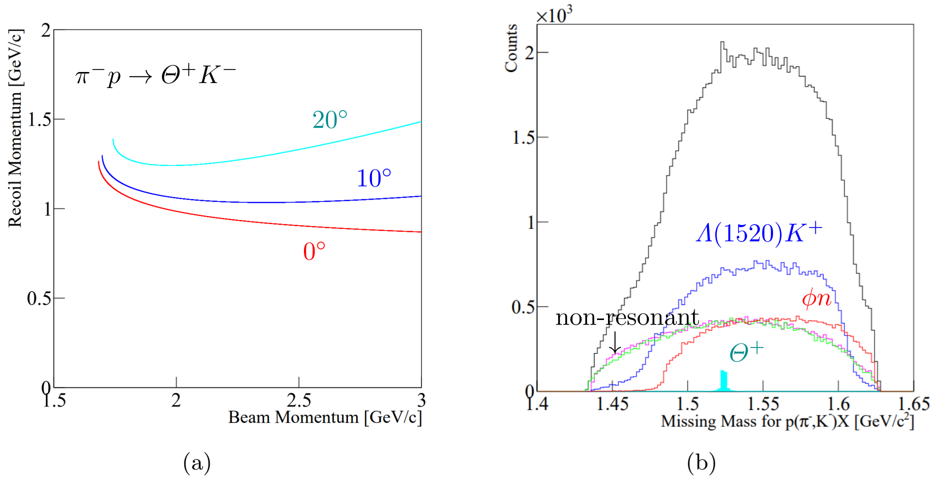


Fig. 9. (a) Momentum transferred to the Θ^+ in the $\pi^- p \to \Theta^+ K^-$ reaction for different lab angles of K^- as a function of beam momentum and (b) simulated missing-mass spectra for the $\pi^- p \to \Theta^+ K^-$ reaction at 1.92 GeV/c.

The (π^-, K^-) reaction includes background processes such as ϕ and $\Lambda(1520)$ production reactions. Although the E19 is accounted for these background contributions in the missing-mass spectrum, there remains the potential for interference effects among the resonances. The simulated missing-mass spectra for the $\pi^- p \to \Theta^+ K^-$ reaction at 1.92 GeV/c are shown in Fig. 9 (b). This simulation assumes a Θ^+ production cross section of 0.1 μb with flat angular distributions for all processes. It also considers the acceptance of the HypTPC, which is nearly 3π. The Θ^+ peak is represented as an incoherent sum of all amplitudes in Fig. 9 (b). If the Θ^+ production amplitude interferes destructively with other amplitudes, it could diminish the visibility of the Θ^+ signal. Therefore, it is essential to measure all final-state particles to investigate the interference pattern in the Dalitz plot, particularly near the Θ^+ mass.

The two $\pi^- p \to K^0 K^- p$ and $\pi^- p \to K^+ K^- n$ reactions are associated with the Θ^+ production. The first reaction is linked to $\Lambda(1520)$, while the second is related to the ϕ production. Figure 10 (a) and (b) show the simulated mass distributions for these two reactions at 1.92 GeV/c. This simulation assumes a Θ^+ production cross section of 3.5 μb, which highlights a distinct peaking structure.

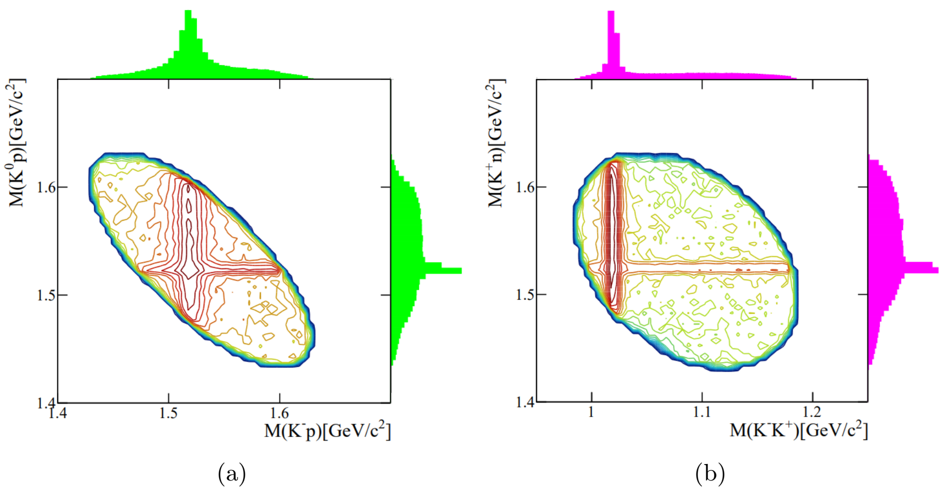


Fig. 10. Simulated scatter plots for the (a) $K^- p$ *versus* $K^0 p$ mass distributions and (b) $K^- K^+$ *versus* $K^+ n$ mass distributions for the (π^-, K^-) reactions at 1.92 GeV/c.

Both plots depict how the Θ^+ band intersects with the bands for ϕ and $\Lambda(1520)$ resonances. This overlap necessitates the isolation of the background resonances by reconstructing all final-state particles. Notably, the crossing between the $\Lambda(1520)$ and Θ^+ bands is broader than the crossing between the ϕ and Θ^+ bands, which could lead to a more pronounced interference effect.

The Θ^+ band starts to diverge from the ϕ and $\Lambda(1520)$ bands at 2.2 GeV/c, where no interference effects are observed, as shown in Fig. 11 (a) and (b). There may be other resonances in the high-mass region, such as $\Sigma(1670)$ and $f_2(1270)$, but these are weakly coupled to the $K^- p$ and $K^+ K^-$ channels. The measurement of the $\pi^- p \to \Theta^+ K^-$ reaction will be available in the $\pi 20$ beam line at J-PARC.

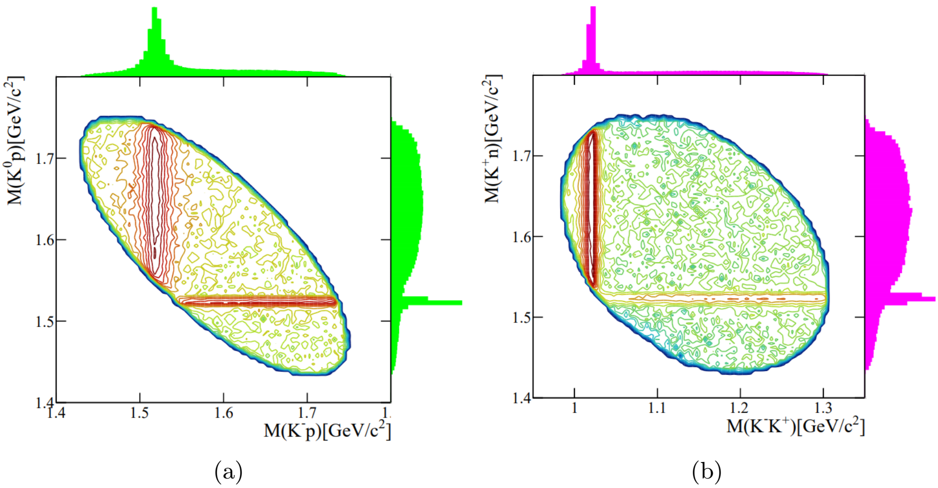


Fig. 11. Simulated scatter plots for the (a) $K^- p$ *versus* $K^0 p$ mass distributions and (b) $K^- K^+$ *versus* $K^+ n$ mass distributions for the (π^-, K^-) reactions at 2.2 GeV/c.

5. Hidden-strangeness pentaquarks

Hidden-strangeness pentaquarks are considered siblings to $P_{c\bar{c}}$ states that were observed in the decays of $\Lambda_b \to J/\psi p K^-$ at the LHCb. A new antidecuplet, formed by combining vector mesons with baryon octet members, includes an isospin doublet of $P_{s\bar{s}}$ states and a singlet $P_{\bar{s}}$ state. If we assume a similar mass splitting between $P_{\bar{s}}$ and $P_{s\bar{s}}$ states, we find that $P_{\bar{s}}$ has a mass of 1.91 GeV. This state can be searched for in photoproduction and hadron-induced reactions.

The search for the $P_{s\bar{s}}^+$ state was conducted in the Cabbibo-suppressed decays of $\Lambda_c^+ \to \phi p \pi^0$ at Belle [26] and BESIII [27]. Due to limited statistics, the results provided only an upper limit on the combined branching ratio of $\mathcal{B}(\Lambda_c^+ \to P_{s\bar{s}}^+ \pi^0)\, \mathcal{B}(P_{s\bar{s}}^+ \to \phi p)$ to be 8.3×10^{-5} at 90% C.L. Although the Λ_c^+ can decay to $\phi p \pi^0$ decay with a sufficient phase space of approximately 100 MeV, this decay is significantly suppressed.

This suppression can be attributed to the dominance of the triangular singularity diagram in the $\Lambda_c^+ \to \phi p \pi^0$ decay via $\Sigma^{*+} K^{*0}$ [28]. The Σ^{*+} decays into $\Sigma^+ \pi^0$, and the Σ^+ then interacts with K^{*0} to produce ϕ and p. In this scenario, the available phase space for the $\Lambda_c^+ \to \Sigma^{*+} K^{*0}$ decay is limited to just a few MeV, which results in a highly-suppressed branching ratio.

The ϕp bump structure could be interpreted as a ΣK^* molecular state ($J^P = 3/2^-$). This interpretation explains the $\Sigma^+ K^{*0} \to \phi p$ reaction in the $\Lambda_c^+ \to \phi p \pi^0$ decay, as well as the near-threshold $\gamma p \to \phi p$ reaction [29]. In addition, the measured parity spin asymmetry in the $\gamma p \to K^{*0}\Sigma^+$ reaction supports the dominance of a natural-parity exchange process, which shares characteristics with the Pomeron exchange [30].

In the $\gamma p \to \phi p$ reaction, the t-channel process dominates, while in the $\pi^- p \to \phi n$ reaction, the s channel is more significant. The $\pi^- p$ reaction specifically investigates the $P^0_{s\bar{s}}$, which is an isospin partner of $P^+_{s\bar{s}}$. A measurement of the $\pi^- p \to \phi n$ reaction has been proposed using a secondary π^- beam with momentum ranging from 1.6 to 2.4 GeV/c, delivered by the π20 beam line [31]. In this reaction, only the production processes of ϕ and $\Sigma(1775)$ can contribute to the final state K^+K^-n. This new proposal, referred to as J-PARC P95, also aims to measure the production of $K^*\Lambda$, $K\Lambda^*$, $K^*\Sigma$, and $K\Sigma^*$. These processes are likely to have a strong coupling to the ϕp channel.

In addition, the $P_{s\bar{s}}$ production reactions using hadron beams can also be explored. The $\pi^- p \to \pi^- p\phi$ reaction is available above a threshold momentum of 1.86 GeV/c. In the $K^+ p \to K^+ p\phi$ reaction, the only background comes from $K^*(1680)$, which is just below the $K^*\Sigma$ threshold [32]. Therefore, this reaction is one of the most promising reactions to investigate the existence of the $P_{s\bar{s}}$.

The $P_{\bar{s}}$ is located at the top corner of the antidecuplet triangle, sharing the same location as the Θ^+ in the antidecuplet multiplet formed by the combination of pseudoscalar mesons and baryon octet members. An observation of the $f_1(1285)$ meson has been reported in the $\pi^- K^+ \bar{K}^0$ channel in the $\gamma p \to pK^+\pi^-\bar{K}^0$ reactions using the CLAS detector at JLab [33]. Within the same dataset, there may be a hint of the $P_{\bar{s}}$ signal, if it indeed exists.

This state could also be investigated in the decay channels involving K^*N through the $\gamma p \to P_{\bar{s}}(1910)\bar{K}^0$ reactions, which occurs above a threshold energy of 2.65 GeV, and $\pi^- p \to P_{\bar{s}}(1910)^+ K^-$, which takes place above a threshold momentum of 2.6 GeV/c.

6. Summary

The Θ^+ search should continue until its existence is definitely ruled out in hadron-induced reactions, such as $K^+ p \to \Theta^+\pi^+$, $K^+ d \to K^0 pp$, and $\pi^- p \to \Theta^+ K^-$. New measurements need to be designed to reconstruct all final states at energies where the Θ^+ band does not overlap with background resonance bands. A direct formation of Θ^+ in the $K^+ n \to K^0 p$ reaction using a deuterium target would provide a straightforward way to confirm the existence of the Θ^+; however, the final-state interaction between pp and the measurement of spectator protons presents significant challenges.

To provide conclusive evidence for either the existence or exclusion of the Θ^+, a new experimental approach must achieve a sensitivity that is two orders of magnitude higher than previous Θ^+ searches. This unprecedented experiment will put an end to the Θ^+ controversy.

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