Search for pentaquarks at Belle

R. Mizuk

1Institute for Theoretical and Experimental Physics, B.Chemushkinskaya, 25, 117259 Moscow, Russia
E-mail: mizuk@itep.ru
(for the Belle Collaboration)

Abstract

We search for the strange pentaquark $\Theta^+$ using kaon interactions in the material of the Belle detector. No signal is observed in the $pK_S$ final state, while in the $pK^-$ final state we observe $\sim 1.6 \cdot 10^4 \Lambda(1520) \rightarrow pK^-$ decays. We set an upper limit on the ratio of $\Theta^+$ to $\Lambda(1520)$ yields $\sigma(\Theta^+)/\sigma(\Lambda(1520)) < 2\%$ at 90\% CL, assuming that the $\Theta^+$ is narrow. We also report on searches for strange and charmed pentaquarks in $B$ meson decays. These results are obtained from a 155 fb$^{-1}$ data sample collected with the Belle detector near the $\Upsilon(4S)$ resonance, at the KEKB asymmetric energy $e^+e^-$ collider.

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INTRODUCTION

Until recently, all reported particles could be understood as bound states of three quarks or a quark and an antiquark. QCD predicts also more complicated configurations such as glueballs \( gg \), molecules \( q\bar{q}q\bar{q} \) and pentaquarks \( qqq\bar{q} \). Recently, observations of the pentaquark \( \Theta^+ = uudd\bar{s} \) have been reported in the decay channels \( K^+n \) [1] and \( pK_S \) [2]. Many experimental groups have confirmed this observation and the isospin 3/2 members of the same pentaquark multiplet have also been observed [3]. Evidence for the charmed pentaquark \( \Theta^0_c = uudd\bar{c} \) has also been seen [4]. The topic attracts enormous theoretical interest. However the existence and properties of pentaquarks remain a mystery. Some experimental groups do not see the pentaquark signals. The non-observing experiments correspond to higher center-of-mass energies. It has been argued [5] that pentaquark production is suppressed in the fragmentation regime at high energies.

Charged and neutral kaons are copiously produced at Belle. We treat kaons as projectiles and the detector material as a target, and search for strange pentaquark formation, \( KN \rightarrow \Theta^+ \), and production, \( KN \rightarrow \Theta^+X \). The kaon momentum spectrum is soft, with a most probable momentum of only 0.6 GeV/c. Therefore we can search for \( \Theta^+ \) formation in the low energy region.

We also search for strange and charmed pentaquarks in the decays of \( B \) mesons, where the suppression of production observed in \( s \) channel \( e^+e^- \) collisions [6] may be absent. Studies of \( B \) meson decays have proved to be very useful for discoveries of new particles (such as P-wave \( c\bar{q} \) states), therefore it is interesting to search for pentaquarks in \( B \) decays although no firm theoretical predictions for branching fractions exist.

DETECTOR AND DATA SET

These studies are performed using a data sample of 140 fb\(^{-1}\) collected at the \( \Upsilon(4S) \) resonance and 15 fb\(^{-1}\) at an energy 60 MeV below the resonance. The data were collected with the Belle detector [7] at the KEKB asymmetric energy \( e^+e^- \) storage rings [8].

The Belle detector is a large-solid-angle magnetic spectrometer that consists of a three layer silicon vertex detector (SVD), a 50-layer cylindrical drift chamber (CDC), a mosaic of aerogel threshold Cherenkov counters (ACC), a barrel-like array of time-of-flight scintillator counters (TOF), and an array of CsI(Tl) crystals (ECL) located inside a superconducting solenoidal coil that produces a 1.5 T magnetic field. An iron flux return located outside the coil is instrumented to detect muons and \( K_L \) mesons (KLM).

The proton, kaon and charged pion candidates are identified based on the \( dE/dx \), TOF and Cherenkov light yield information for each track. \( K_S \) candidates are reconstructed via the \( \pi^+\pi^- \) decays and must have an invariant mass consistent with the nominal \( K_S \) mass. The \( K_S \) candidate is further required to have a displaced vertex and a momentum direction consistent with the direction from its production to decay vertices.

SEARCH FOR \( \Theta^+ \) USING KAON INTERACTIONS IN THE DETECTOR MATERIAL.

The analysis is performed by selecting \( pK^- \), \( pK^+ \) and \( pK_S \) secondary vertices. The protons and kaons are required not to originate from the region around the run-averaged
interaction point (IP). The proton and kaon candidate are combined and the $pK$ vertex is fitted. The $xy$ distribution of the secondary $pK^-$ vertices is shown in Fig. 1 for the barrel part (left) and for the endcap part (right) of the detector. The double wall beam pipe, three layers of SVD, the SVD cover and the two support cylinders of the CDC are clearly visible. The $xy$ distributions for secondary $pK^+$ and $pK_S$ vertices are similar.

The mass spectra for $pK^-$, $pK^+$ and $pK_S$ secondary vertices are shown in Fig. 2. No significant structures are observed in the $M(pK^+)$ or $M(pK_S)$ spectra, while in the $M(pK^-)$ spectrum a $\Lambda(1520)$ signal is clearly visible. We fit the $pK^-$ mass spectrum to a sum of a $\Lambda(1520)$ probability density function (p.d.f.) and a threshold function. The signal p.d.f. is a

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FIG. 1: The $xy$ distribution of secondary $pK^-$ vertices for the barrel (left) and endcap (right) parts of the detector.

FIG. 2: Mass spectra of $pK^+$ (left), $pK^-$ (right, points with error bars) and $pK_S$ (right, histogram) secondary pairs. The fit is described in the text.
D-wave Breit-Wigner shape convolved with a detector resolution function ($\sigma \sim 2 \text{MeV}/c^2$). The $\Lambda(1520)$ parameters obtained from the fit are consistent with the PDG values [9]. The $\Lambda(1520)$ yield, defined as the signal p.d.f. integral over the 1.48–1.56 GeV/$c^2$ mass interval (2.5Γ), is $15519 \pm 412$ events.

The $pK_S$ mass spectrum is fitted to a sum of a $\Theta^+$ signal p.d.f. and a third order polynomial. The $\Theta^+$ signal shape can be rather complicated because of possible rescattering of particles inside nuclei [10]. In order to compare our result with other experiments we assume that the signal is narrow and its shape is determined by the detector resolution ($\sim 2 \text{MeV}/c^2$). For $m = 1540 \text{MeV}/c^2$ the fit result is $29 \pm 65$ events. Using the Feldman-Cousins method of upper limit evaluation [11] we obtain $N < 94$ events at the 90% CL.

We set an upper limit on the ratio of $\Theta^+$ to $\Lambda(1520)$ yields corrected for the efficiency and branching fractions:

$$\frac{N_{\text{observed}}(\Theta^+)}{N_{\text{observed}}(\Lambda(1520))} \frac{\epsilon(pK^-)}{\epsilon(pK_S)} \frac{\mathcal{B}(\Lambda(1520) \to pK^-)}{\mathcal{B}(\Lambda(1520) \to pK_S)} < 2\% \ (90\% \ \text{CL}).$$

It is assumed that $\mathcal{B}(\Theta^+ \to pK_S) = 25\%$. We take $\mathcal{B}(\Lambda(1520) \to pK^-) = \frac{1}{2} \mathcal{B}(\Lambda(1520) \to N\bar{K}) = \frac{1}{2} (45 \pm 1)\%$ [9]. The ratio of efficiencies for $\Theta^+ \to pK_S$ and $\Lambda(1520) \to pK^-$ of 37% is obtained from the Monte Carlo (MC) simulation. Our limit is much smaller than the results reported by many experiments which observe $\Theta^+$. For example it is two orders of magnitude smaller than the value reported by the HERMES Collaboration [12]. We do not know any physical explanation for such a difference.

The momentum spectrum of the produced $\Lambda(1520)$ is shown in Fig. 3 (left). This spectrum is obtained from fitting $M(pK^-)$ in momentum bins and correcting for the efficiency obtained from MC. The $K^-$ should have a 440 MeV/c momentum to produce $\Lambda(1520)$ on a proton at rest. Even in the presence of Fermi motion with a typical momentum of 150 MeV/c, $\Lambda(1520)$ produced in the formation channel should be contained in the first momentum bin, 0.4 to 0.6 GeV/c$^2$. Therefore most of the $\Lambda(1520)$ are produced in the production channel. The projectiles that can produce $\Lambda(1520)$ are $K^-, K_S, K_L, \Lambda$. The momentum spectra
of $K^-$ and $K^+$ are given in Fig. 3 (right). The spectra are corrected for efficiency and for contamination from other particle species. It is not likely that $\Lambda(1520)$ production is dominated by interactions induced by $\Lambda$ projectiles, because the $\Lambda(1520)$ momentum spectrum is too soft. Even at the threshold of the $\Lambda N \rightarrow \Lambda(1520)p$ reaction the $\Lambda(1520)$ momentum is $\sim 1.1 \text{ GeV}/c$.

To demonstrate that non-strange particles do not produce $\Lambda(1520)$ we study the $pK^-$ vertices accompanied by a $K^+$ tag. The distance from the $pK^-$ vertex to the nearest $K^+$ is plotted in Fig. 4 as a dashed histogram. For comparison the distance to any track is plotted as a solid histogram. The peak at zero corresponds to the vertices with additional tracks.

![Distance plot](image)

**FIG. 4:** Distance from $pK^-$ secondary vertex to the nearest track (solid histogram) and to the nearest $K^+$ (dashed histogram).

The much smaller peak at zero for the $K^+$ tagged vertices leads us to the conclusion that most $\Lambda(1520)$ are produced by strange projectiles.

**SEARCH FOR PENTAUQUARKS IN $B$ MESON DECAYS**

In this analysis we search for $\Theta^+$ and $\Theta^{*+}$ (an isovector pentaquark predicted in some models [13]) in the decays $B^0 \rightarrow \Theta^+\bar{p}$ followed by $\Theta^+ \rightarrow pK_S$, and $B^+ \rightarrow \Theta^{*+}\bar{p}$ followed by $\Theta^{*+} \rightarrow pK^+$, respectively (inclusion of charge conjugated modes is implied throughout this section). We also search for $\Theta_c^0$ in the decay $B^0 \rightarrow \Theta_c^0\bar{p}\pi^+$ followed by $\Theta_c^0 \rightarrow D^{(*)-}p$, and $\Theta_c^{*+}$ (the charmed analogue of $\Theta^{*+}$) in the decay $B^0 \rightarrow \Theta_c^{*+}\bar{p}$ followed by $\Theta_c^{*+} \rightarrow D^0\bar{p}$. We reconstruct $D$ mesons in the decay modes $D^{*+} \rightarrow D^0\pi^+$, $D^0 \rightarrow K^-\pi^+$ and $D^- \rightarrow K^-\pi^+\pi^+$. The dominant background arises from the continuum $e^+e^- \rightarrow q\bar{q}$ process. It is suppressed using event shape variables (the continuum events are jet-like, while the $B\bar{B}$ events are spherically symmetric).

The $B$ decays are identified by their CM energy difference, $\Delta E = (\sum_i E_i) - E_{\text{beam}}$, and the beam constrained mass, $M_{bc} = \sqrt{E_{\text{beam}}^2 - (\sum_i \vec{p}_i)^2}$, where $E_{\text{beam}}$ is the beam energy and $\vec{p}_i$ and $E_i$ are the momenta and energies of the decay products of the $B$ meson in the CM frame. The $\Delta E$ distribution (with $M_{bc} > 5.27 \text{ GeV}/c^2$) and $M_{bc}$ distribution (with $|\Delta E| < 0.05 \text{ GeV}/c^2$) for the $B^0 \rightarrow p\bar{p}K_S$ and $B^+ \rightarrow p\bar{p}K^+$ decays are shown in Fig. 5. The
signal yields are extracted by performing unbinned maximum likelihood fits to the sum of signal and background distributions in the two dimensional \((M_{bc}, \Delta E)\) space. The signal distributions are determined from MC, whereas the background distributions are determined from the \(\Delta E\) and \(M_{bc}\) sideband data samples. The fits give \(28.6^{+6.5}_{-5.8}\) and \(216.5^{+17.3}_{-16.6}\) signal yields for the \(p\bar{p}K_S\) and \(p\bar{p}K^+\) modes, respectively. For the region \(1.53 \text{ GeV}/c^2 < M_{pK_S} < 1.55 \text{ GeV}/c^2\), corresponding to the reported \(\Theta^+\) mass, we find no signal. Since there is only a theoretical conjecture for the \(\Theta^{++}\), we check the \(1.6 \text{ GeV}/c^2 < M_{pK^+} < 1.8 \text{ GeV}/c^2\) region and find no signal. Assuming both states are narrow, we set the upper limits

\[
\frac{\mathcal{B}(B^0 \to \Theta^+ \bar{p}) \times \mathcal{B}(\Theta^+ \to pK_S^0)}{\mathcal{B}(B^0 \to p\bar{p}K_S^0)} < 22\% \quad (90\% \text{ CL}) \quad \text{and} \quad \frac{\mathcal{B}(B^+ \to \Theta^{++} \bar{p}) \times \mathcal{B}(\Theta^{++} \to pK^+)}{\mathcal{B}(B^+ \to p\bar{p}K^+)} < 2\% \quad (90\% \text{ CL}).
\]
FIG. 6: $\Delta E$ and $M(D^{(*)}p)$ distributions for $B^0 \to D^- p\bar{p}\pi^+$ (left), $B^0 \to D^{*-} p\bar{p}\pi^+$ (middle) and $\bar{B}^0 \to D^0 p\bar{p}$ (right) decays. The hatched histogram in $\Delta E$ distributions corresponds to the $D$ meson sidebands, while the hatched histogram in $M(D^{(*)}p)$ distributions corresponds to the $\Delta E$ sidebands (shown with vertical lines on the $\Delta E$ plots). The vertical line in the $M(D^{(*)}p)$ distributions shows the H1 $\Theta^0_c$ mass, 3.099 GeV/$c^2$.

The $\Delta E$ and corresponding $M(D^{(*)}p)$ plots for the decays $B^0 \to D^- p\bar{p}\pi^+$, $B^0 \to D^{*-} p\bar{p}\pi^+$ and $\bar{B}^0 \to D^0 p\bar{p}$ are shown in Fig. 6. From the fit to $\Delta E$ spectra the numbers of reconstructed $B$ decays are $303 \pm 21$, $60 \pm 8$ and $66 \pm 9$ for the three modes, respectively. No signal of $\Theta^0_c$ or $\Theta^{*+}_c$ is found in the $M(D^{(*)}p)$ spectra. We set the following upper limits on the fractions of the final state proceeding via $\Theta^0_c$ and $\Theta^{*+}_c$:

$$\frac{\mathcal{B}(B^0 \to \Theta^0_c p\bar{p}) \times \mathcal{B}(\Theta^0_c \to D^- p)}{\mathcal{B}(B^0 \to D^- p\bar{p} \pi^+)} < 1.2\% \ (90\% \ CL),$$
$$\frac{\mathcal{B}(B^0 \to \Theta^{*+}_c p\bar{p}) \times \mathcal{B}(\Theta^{*+}_c \to D^{*-} p)}{\mathcal{B}(B^0 \to D^{*-} p\bar{p} \pi^+)} < 11\% \ (90\% \ CL),$$
$$\frac{\mathcal{B}(B^0 \to \Theta^{*+}_c p\bar{p}) \times \mathcal{B}(\Theta^{*+}_c \to \bar{D}^0 p)}{\mathcal{B}(\bar{B}^0 \to \bar{D}^0 p\bar{p})} < 5.9\% \ (90\% \ CL).$$

We assume here that the charmed pentaquark mass is 3.099 GeV/$c^2$ and that the signal p.d.f. is determined by the detector resolution ($\sim 3.5$ MeV/$c^2$) [4]. Our limits can be compared with the H1 claim that about 1% of $D^{*+}$ mesons originate from $\Theta^0_c$ decays. The branching fraction for $\Theta^0_c$ decays to $D$ mesons is expected to be even larger because of the larger phase
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