A SEARCH FOR THE $\Theta^{+++}$ PENTAUQUARK IN $B^{\pm} \rightarrow p\bar{p}K^{\pm}$

The BABAR Collaboration

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Abstract

We report the results of a search for the $\Theta^{+++}$ pentaquark in the decay $B^{\pm} \rightarrow \Theta^{+++}\bar{p}$ where $\Theta^{+++} \rightarrow pK^{\pm}$ using 81 fb$^{-1}$ of data collected on the $\Upsilon(4S)$ resonance with the BABAR detector at PEP-II. We find an upper limit on the branching fraction of $B^{+} \rightarrow \Theta^{+++}\bar{p}$ where $\Theta^{+++} \rightarrow pK^{+}$ to be $1.5 \times 10^{-7}$ for $1.43 < m(\Theta^{+++}) < 1.85$ GeV/$c^2$, $2.4 \times 10^{-7}$ for $1.85 < m(\Theta^{+++}) < 2.00$ GeV/$c^2$ and $3.3 \times 10^{-7}$ for $2.00 < m(\Theta^{+++}) < 2.36$ GeV/$c^2$, at 90% confidence level. All results are preliminary.

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1 INTRODUCTION

Recently several experimental groups have reported observations of a new, manifestly exotic baryon resonance, called the Θ⁺(1540) \(^1\), with an unusually narrow width (Γ < 8 MeV/c\(^2\)). These results have prompted a surge of pentaquark searches in experimental data of many kinds \(^2\). In this paper we will concentrate on the exclusive search for pentaquarks in the decay of B mesons. Following the observation of the decay \(B^+ \rightarrow p\bar{p}K^+\)\(^6\) \(^3\) \(^4\) it was suggested that this decay might include events of the form \(B^+ \rightarrow \Theta^{*++}\bar{p}\) where \(\Theta^{*++}\) is an \(I = 1, I_3 = 1\) pentaquark \(^5\). \(\Theta^{*++}\) would be a member of the baryon 27-plet with quark content \(uuud\bar{s}\). It has been predicted to lie in the region 1.43 – 1.70 GeV/c\(^2\) in the \(pK^+\) invariant mass of \(B^+ \rightarrow p\bar{p}K^+\) candidates and to have a width of 37 – 80 MeV \(^6\). The \(pK^+\) cross section is nearly purely elastic in the region of interest so a resonance would follow the Breit-Wigner form, with a peak cross section of about 25 mb if the resonance is at 1.7 GeV/c\(^2\) and even larger if the mass is less. The cross section is measured to be about 12 mb at center-of-mass energies spaced by about 15 MeV \(^7\), so its width would need to be considerably less than 15 MeV to have escaped detection. Our limits will not depend on the \(\Theta^{*++}\) width in any significant fashion. We will search for \(\Theta^{*++}\) in the mass region up to 2.36 GeV/c\(^2\).

2 THE \textit{BaBar} DETECTOR AND DATASET

We use data collected on the \(\Upsilon(4S)\) resonance with the \textit{BaBar} detector at PEP-II to search for \(\Theta^{*++}\). The data sample contains 89 million \(\bar{B}B\) pairs, corresponding to an integrated luminosity of 81 fb\(^{-1}\) on the \(\Upsilon(4S)\) resonance. An additional 9 fb\(^{-1}\) of data, collected 40 MeV below the resonance peak (referred to as off-peak data), are used to study the background from light-quark and \(c\bar{c}\) production.

A detailed description of the \textit{BaBar} detector can be found elsewhere \(^8\); only detector components relevant to this analysis are mentioned here. Charged-particle trajectories are measured by a five-layer double-sided silicon vertex tracker (SVT) and a 40-layer drift-chamber (DCH), operating in the magnetic field of a 1.5-T solenoid. Charged particles are identified by combining the measurements of ionization energy loss \((dE/dx)\) in the DCH and SVT for \(p_T < 0.7\) GeV/c or the measured Cherenkov angle and the number of photons observed in the DIRC for \(p_T > 0.7\) GeV/c.

The \(B\) candidate is formed from the proton, the anti-proton and the kaon candidates. Two kinematic variables are used to isolate the \(B^+ \rightarrow ppK^+\) signal taking advantage of the kinematic constraints of \(B\) mesons produced at the \(\Upsilon(4S)\). The first is the beam-energy-substituted mass, \(m_{ES} = [(E_{CM}^2/2 + \mathbf{p}_i \cdot \mathbf{p}_B)^2/E_i^2 - \mathbf{p}_B^2]^{1/2}\), where \(E_{CM}\) is the total center-of-mass energy of the \(e^+e^-\) \(^6\)Charge-conjugates are assumed throughout the paper.
collision. Here, the four-momentum of the initial $e^+e^-$ system is $(E_i, \mathbf{p}_i)$ and $\mathbf{p}_B$ is the momentum of the reconstructed $B$ candidate, both measured in the laboratory frame. The second variable is $\Delta E = E^*_B - E_{CM}/2$, where $E^*_B$ is the $B$-candidate energy in the center-of-mass frame.

Several topological variables provide discrimination between the large continuum background ($e^+e^- \rightarrow q\bar{q}$, where $q = u, d, s, c$), which tends to be collimated along the original quark direction, and more spherical $B\bar{B}$ events. In order to suppress the dominant continuum background we use a linear combination (a Fisher discriminant) of the following four event-shape variables: $\cos \theta^B_{thr}$, the cosine of the angle between the thrust axis of the reconstructed $B$ and the beam axis in the center-of-mass frame; $\cos \theta^B_{mom}$, the cosine of the angle between the momentum of the reconstructed $B$ and the beam axis in the center-of-mass frame; and zeroth- and second-order Legendre polynomial momentum moments, $L_0 = \sum_i |p_i^{(s)}|$ and $L_2 = \sum_i |p_i^{(s)}|[(3 \cos^2 \theta_{thr,B,i} - 1)/2]$, where $p_i^{(s)}$ are the center-of-mass momenta for the tracks and neutral clusters that are not associated with the $B$ candidate, and $\theta_{thr,B,i}$ are the angles between $p_i^{(s)}$ and the thrust axis of the $B$ candidate. We optimize the Fisher discriminant coefficients for the best background and $B^+ \rightarrow p\bar{p}K^+$ signal separation using off-resonance data and $B^+ \rightarrow p\bar{p}K^+$ simulated events that are distributed uniformly in phase-space ($B^+ \rightarrow p\bar{p}K^+$ signal Monte Carlo). These event topology requirements retain 67% of $B^+ \rightarrow p\bar{p}K^+$ signal while removing 94% of continuum background. We expect 94% of the combinatoric background to come from continuum events and the remaining 6% from $B\bar{B}$ events.

The Fisher discriminant, $m_{ES}$, and $\Delta E$ cuts are optimized to maximize the statistical sensitivity of the $B^+ \rightarrow p\bar{p}K^+$ signal, defined as $S/\sqrt{S+B}$, with $S$ and $B$ being estimated numbers of $B^+ \rightarrow p\bar{p}K^+$ signal and background yields in the Monte Carlo simulation respectively. We assumed the $B^+ \rightarrow p\bar{p}K^+$ signal branching fraction of $(5.66^{+0.57}_{-0.62} \pm 0.62) \times 10^{-6}$ in the optimization. The $B^+ \rightarrow p\bar{p}K^+$ signal region is defined to be $5.276 < m_{ES} < 5.286 \text{ GeV}/c^2$ and $|\Delta E| < 0.029 \text{ GeV}$ (signal box) and the $m_{ES}$ sideband region is taken to be $5.20 < m_{ES} < 5.26 \text{ GeV}/c^2$ and $|\Delta E| < 0.029 \text{ GeV}$ for the combinatoric background studies.

The main source of $B\bar{B}$ backgrounds is the $b \rightarrow c\bar{s}s$ transitions, where $B^+ \rightarrow X_{cc\bar{K}}$, $X_{cc} \rightarrow p\bar{p}$ and $X_{cc} = \eta_c$, $J/\psi$, $\psi(2S)$, $\chi_{c0,1,2}$ (so-called “charmonium background”). We expect $72 \pm 10$ events of this type in the signal box region. To check for additional $B\bar{B}$ backgrounds that might peak in the $B^+ \rightarrow p\bar{p}K^+$ signal region, we study generic $B\bar{B}$ Monte Carlo as well as a set of samples of exclusive $B$ decay simulated events for potential charmoniumless backgrounds. The expected $B\bar{B}$ “charmoniumless” background contribution is less than one event in the signal box region.

## 4 SYSTEMATIC STUDIES

Systematic uncertainties in the analysis are described below and are summarized in Table 1. The $B^+ \rightarrow \Theta^{++}(pK^+)\bar{p}$ signal efficiency is computed with $B^+ \rightarrow p\bar{p}K^+$ simulated events, reconstructed and selected using the same procedure as for the data. We apply small corrections determined from data to the efficiency calculation to account for the overestimation of the tracking and particle-identification systems performance. The resulting efficiency, as a function of $m_{pK^+}$, is shown in Fig. 9. A systematic uncertainty is assigned to each correction to account for the limited size and purity of the control sample used in computing that correction. For example, for the kaon identification, we correct the simulation using a pure sample of $D^{*+} \rightarrow \pi^+D^0$ decays with $D^0 \rightarrow K^-\pi^+$ and for the proton identification we use a sample of $\Lambda \rightarrow p\pi^-$. Conservatively, we take the size of the correction applied as our systematic error.

In addition, after all the corrections, we compare our $B^+ \rightarrow p\bar{p}K^+$ signal simulation to a control sample with similar kinematics and final state topology ($B^+ \rightarrow J/\psi(e^+e^-)K^+$), in order
Table 1: Systematic uncertainties for the branching fraction of $B^+ \rightarrow \Theta^{*++}(pK^+)\bar{p}$ without(with) background subtraction.

| Type                     | % BF |
|--------------------------|------|
| $B$-counting             | 1.1  |
| Tracking                 | 2.4  |
| PID                      | 6.0  |
| Event Shape              | 2.0  |
| Signal Box Cut           | 2.5  |
| Monte Carlo Statistics   | 1.1  |
| Background subtraction   | (1.1)|
| Total                    | 7.4(7.5)|

to quantify the ability of the simulation to model the kinematic and event-shape variables used in the event selection. The small residual differences in the efficiencies at the cut value are assigned as systematic uncertainties affecting the selection procedure.

For the calculation of the systematic error due to the background subtraction we decrease the $B$-backgrounds by the uncertainties in their branching fractions \(^7\). The change in the upper limit for the new background estimation is 1.1\% which we take as a systematic error.

The systematic error also comprises the uncertainties from the determination of the number of $B\bar{B}$ pairs. We assume that the branching fraction of the $\Upsilon(4S)$ into $B\bar{B}$ is 100\%, with an equal admixture of charged and neutral $B$ final states. We do not include any additional uncertainty due to these assumptions.

5 RESULTS

The distribution of events in the $m_{ES} - \Delta E$ plane is shown in Fig. 2. We see 212 events in the signal box region. To extract the number of $B^+ \rightarrow p\bar{p}K^+$ signal events we loosen signal box cuts on $\Delta E$ and fit the $\Delta E$ projection for $5.276 < m_{ES} < 5.286 \text{GeV}/c^2$ and $|\Delta E| < 400 \text{MeV}$ with a single-Gaussian distribution for $B^+ \rightarrow p\bar{p}K^+$ signal and a first-order polynomial for the background. From that fit we estimate that the 212 total events comprise 40±2 combinatoric background events and 188±17 $B^+ \rightarrow p\bar{p}K^+$ signal events, including 68±10 events originating from charmonium decays to $p\bar{p}$.

The Dalitz plots for the events in the signal box (212 events) and the sideband region (368 events) are shown in Fig. 3. Note that the relative phase-space, or the fraction of Fig. 3(bottom) in the signal box, is 0.104. The distributions in Fig. 3 are not efficiency-corrected. The Dalitz plot for the events in the signal box (Fig. 3) shows a threshold enhancement in the $p\bar{p}$ mass spectrum, as well as three clear bands corresponding to $\eta_c$, $J/\psi$ and $\psi(2S)$ events. The background events tend to lie on the edges of the Dalitz plot because they are dominated by inclusion of random soft tracks.

As we are interested only in the low $m_{pK^+}$ region the following figures will be limited to $m_{pK^+}$ up to 3.4 GeV/$c^2$ or the total of 75 events in the signal box region. It is convenient to represent data in two different ways: in Fig. 4 we separate the events into those inside the charmonium
Figure 1: The $B^+ \rightarrow p\bar{p}K^+$ signal reconstruction efficiency (left) and the detector resolution (right) as functions of $m_{pK^+}$.

Figure 2: $m_{ES} - \Delta E$ distribution of on-peak data reconstructed in the $B^+ \rightarrow p\bar{p}K^+$ mode. The small box (blue) is “signal” box: $5.276 < m_{ES} < 5.286$ GeV/$c^2$ and $|\Delta E| < 29$ MeV; and the large box (red) is “sideband”: $5.20 < m_{ES} < 5.26$ GeV/$c^2$ and $|\Delta E| < 29$ MeV.
Figure 3: Dalitz plot of on-peak data reconstructed in $B^+ \rightarrow ppK^+$ mode. Events in the signal box region (top), sideband region (bottom). Note that these distributions are not efficiency-corrected.
Figure 4: The $m_{pK^+}$ distribution for data events in $B^+ \rightarrow p\bar{p}K^+$ signal box: events in the charmonium region $2.85 < m_{\bar{p}p} < 3.15$ GeV/c$^2$ (solid), events outside the charmonium region (dashed). Note that these distributions are not efficiency-corrected.

Figure 5: The $m_{pK^+}$ distributions for data reconstructed as $B^+ \rightarrow p\bar{p}K^+$ (dots), $m_{ES}$ sideband (empty squares) and, Monte Carlo, $B^+ \rightarrow \eta_c(p\bar{p})K^+$ (dashed line) and $B^+ \rightarrow J/\psi(p\bar{p})K^+$ (solid line). Note that these distributions are not efficiency-corrected.
Figure 6: Upper Limit on the branching fraction of $B^+ \rightarrow \Theta^{++}(pK^+)\bar{p}$ at 90% confidence level with the assumption of no background (dashed), with background as determined from data and Monte Carlo (solid). The systematic error correction is included in the limits.

window and those outside, where as in Fig. 5 we emphasize the different background contributions to the data.

We search for $\Theta^{++}$ pentaquark in the $pK^+$ mass spectrum, shown in Fig. 4. The binning corresponds to $4 \cdot \sigma_{pK^+}$, where $\sigma_{pK^+}$ is the detector resolution shown in Fig. 1(right). The average $B^+ \rightarrow \Theta^{++}(pK^+)\bar{p}$ signal efficiency is $(17.0 \pm 0.2)$% for $1.43 < m_{pK^+} < 2.40\text{GeV}/c^2$. We observe no events for $m_{pK^+} < 1.85\text{GeV}/c^2$.

The background contributions are shown in Fig. 5. The $m_{pK^+}$ distribution of the combinatoric background is obtained from the events in the data $m_{ES}$ sideband region and is scaled to the expected number of the combinatoric background events in the signal box. The shape and amount of $B^+ \rightarrow \eta_c(p\bar{p})K^+$ and $B^+ \rightarrow J/\psi(p\bar{p})K^+$ background contributions are determined from the simulation and scaled by their respective branching fractions [7]. There is no contribution to the background from $B^+ \rightarrow \eta_c(p\bar{p})K^+$ for $m_{pK^+} < 1.80\text{GeV}/c^2$ and $B^+ \rightarrow J/\psi(p\bar{p})K^+$ for $m_{pK^+} < 1.75\text{GeV}/c^2$.

To set an upper limit at 90% confidence level on the branching fraction of $B^+ \rightarrow \Theta^{++}(pK^+)\bar{p}$ we count events in each of the $m_{pK^+}$ mass bins in Fig. 4 assuming that all the events observed are $B^+ \rightarrow \Theta^{++}(pK^+)\bar{p}$ signal events. To simplify the presentation of the upper limit on the branching fraction as a function $m_{pK^+}$ we assume that number of events in each of the bins in $m_{pK^+}$ is equal to the maximum number of events per bin for each of the $m_{pK^+}$ regions (see Table 2).

We use two methods to determine the upper limit. In the first one we assume that there is no background contribution. We calculate from Table 31.3 [7] the Bayesian upper limit for 90% confidence level as a function of $m_{pK^+}$ assuming Poisson-distributed events in the absence of background. The resulting values are shown in Fig. 6 and given in Table 2. To account for systematic errors we increase the upper limit by the total systematic error (7.5%).
Table 2: The upper limit for the branching fraction of $B^+ \rightarrow \Theta^{*++}(pK^+)\bar{p}$ as a function $m_{pK^+}$ without(with) background subtraction.

| Mass Region, GeV/c^2 | Maximum Events Observed in any $m_{pK^+}$ bin | BF UL (10^{-7}) @ 90% CL without bkg | BF UL (10^{-7}) @ 90% CL with bkg |
|----------------------|-----------------------------------------------|--------------------------------------|--------------------------------------|
| 1.43 < $m_{pK^+}$ < 1.85 | 0                                             | 1.63                                 | 1.49                                  |
| 1.85 < $m_{pK^+}$ < 2.00 | 1                                             | 2.76                                 | 2.40                                  |
| 2.00 < $m_{pK^+}$ < 2.36 | 2                                             | 3.78                                 | 3.28                                  |

To calculate the upper limit in the presence of background we use a tool described in [9]. It uses toy Monte Carlo technique to calculate an upper limit in presence of uncertainties on the efficiency and the number of expected background events. We assume all the systematic errors but the systematics on background and $B$-counting to contribute to the uncertainty on the efficiency (7.3%). To estimate the number of expected background events we fit a first-order polynomial to the $pK^+$ mass spectrum of the combinatoric background events as well as $B^+ \rightarrow \eta_c(\bar{p}p)K^+$ and $B^+ \rightarrow J/\psi(\bar{p}p)K^+$ Monte Carlo events (so-called peaking $B$-background). The uncertainty on the background comes from the statistical error on the fit as well as the systematic error on the background. The resulting values of the upper limit as a function of $m_{pK^+}$ increased by the systematic error on $B$-counting (1.1%) are given in Table 2 and shown in Fig. 6.

6 SUMMARY

Using 81 fb^{-1} of on-peak data accumulated by the BABAR detector, we set an upper limit at 90% confidence level on the branching fraction of $B^+ \rightarrow \Theta^{*++}(pK^+)\bar{p}$ to be $1.49 \times 10^{-7}$ for $1.43 < m(\Theta^{*++}) < 1.85$ GeV/c^2, $2.40 \times 10^{-7}$ for $1.85 < m(\Theta^{*++}) < 2.00$ GeV/c^2 and $3.28 \times 10^{-7}$ for $2.00 < m(\Theta^{*++}) < 2.36$ GeV/c^2.

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