Anti-charmed pentaquark from $B$ decays

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We explore the possibility of observing the anti-charmed pentaquark state from the $\Theta_c \bar{c} \pi^+$ decay of $B$ meson produced at $B$-factory experiments. We first show that the observed branching ratio of the $B^+$ to $\Lambda_c^+ \bar{p} \pi^+$, as well as its open histograms, can be remarkably well explained by assuming that the decay proceeds first through the $\pi^+ D^0$ (or $D^0$) decay, whose branching ratios are known, and then through the subsequent decay of the virtual $D^0$ or $\bar{D}^0$ mesons to $\Lambda_c^+ \bar{p}$, whose strength are calculated using previously fit hadronic parameters. We then note that the $\Theta_c$ can similarly be produced when the virtual $D^0$ or $\bar{D}^0$ decay into an anti-nucleon and a $\Theta_c$. Combining the present theoretical estimates for the ratio $g_{D\Lambda_c}/g_{D\Lambda_0} \sim 13$ and $g_{D^*\Lambda_0} \sim \frac{1}{2} g_{D\Lambda_0}$, we find that the anti-charmed pentaquark $\Theta_c$, which was previously predicted to be bound by several model calculations, can be produced via $B^+ \rightarrow \Theta_c \bar{c} \pi^+$, and be observed from the $B$-factory experiments through the weak decay of $\Theta_c \rightarrow pK^+ \pi^- \pi^-$. 

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The excitement about $\Theta^+$ after its first discovery by the LEPS Collaboration at SPring-8 [1] and its subsequent confirmation by several groups, has recently turned into disappointment and confusion, as increasing number of experiments are reporting negative results with higher statistics [2, 3]. The experimental situation is similarly discouraging for anti-charmed pentaquark, as the initial observation by the H1 collaboration at HERA [4] has not been confirmed by subsequent experiments [3, 4, 5, 6]. While certain processes and energy ranges are ruled out, one can not afford to give up further refined experimental search, because if a pentaquark is found, it will not only provide a major and unique testing ground for QCD dynamics at low energy, but also a basis for investigating many body properties of QCD at higher density.

Given the experimental situation, one should go back and ask what kind of insights theoretical considerations can give us in the search for the $\Theta_c$ or the $\Theta^+$. In this respect, one should first note that the theoretical grounds for the heavy and light pentaquarks are quite different. There are ongoing discussions over the validity of the original prediction for the mass of the $\Theta^+$ based on the SU(3) Skyrme model [10]. On the other hand, many theories consistently predicted that the heavy pentaquark state is heavy and lies below the $DN$ threshold. The pentaquark with one heavy anti-quark was first studied in Ref. [11, 12] in a quark model with color spin interaction, with flavor spin interaction in [13], and Skyrme models [14, 15], and recently in [16, 17, 18, 19, 20], which were motivated by the diquark-quark model [21, 22, 23] and diquark-triquark [24] picture. In the constituent quark model, the existence of a pentaquark state with diquark configuration, crucially depends on how strong the diquark correlation is compared to the quark anti-quark correlation when it recombines into a meson and a nucleon state. Since both correlations are effectively inversely proportional to the constituent quark masses involved, $C \sum_{i>j} \hat{s}_i \cdot \hat{s}_j \frac{1}{m_i m_j}$, the attraction is expected to be more effective for pentaquark state with a heavy anti-quark. As a simplified example, consider the pentaquark picture given in Ref. [21]. The $ud$ diquark will form a color anti-triplet, isospin 0 and spin 0 state. Using the $C$ determined from $M_D - M_N = \frac{3C}{2m_c^2} = 290$ MeV, one finds an attraction of 290 MeV from the two diquarks. This would be identical whether one has a heavy or light anti-quark. On the other hand, assuming the pentaquark recombines into a nucleon and a meson, the attraction expected from the diquark correlation in the spin 1/2 baryon and the quark anti-quark in the spin zero meson would be $\frac{3C}{4m_c^2} - \frac{3C'}{4m_u m_c} = -430$ MeV. Where $C'$ is determined from $M_{K^*} - M_K = \frac{C'}{m_c m_u}$, $C' = 397$ MeV. If $m_u$ is replaced by $m_c$, this will become $-240$ MeV, from $M_{D^*} - M_D = \frac{C}{m_u m_c}$, $C = 137$ MeV. Therefore, comparing this to $-290$ MeV in the pentaquark configuration, one expects a bound pentaquark state only when the anti-quark is heavy. Such simple expectations are explicitly borne out in the constituent quark model calculations, which predict a more stable pentaquark configuration when the antiquark becomes heavy [20, 21, 22, 23]. Similar results are also consistently obtained in the Skyrme model [24] and the QCD sum rule calculations [30]. In this respect, the negative experimental result for the heavy pentaquark from the $DN$ or $D^*N$ final state could be a natural consequence of its stability, and one should search for it from its weak decay.

There were attempts to search for a stable heavy pentaquark with strangeness [31] using high energy pion beam on a nuclear target. But with no realistic estimate on the production cross section of the pentaquark, it is difficult to draw any strong conclusion. Moreover, the QCD sum rule [31] or the skyrmion approach predict the heavy pentaquark state to be stable only when it has
no strangeness\[14\]. Therefore, we propose to search for a stable heavy pen-
taquark without strangeness, and show that the accumulated data at the B-
factory experiments may be sufficient for this purpose. To be precise, we will show,
that the charmed pentaquark can be produced from the $B^+ \rightarrow \Theta_c\bar{n}p\pi^+$ decay, and that with the most conserva-
tive estimate, it can be identified through one of its weak decays, $\Theta_c \rightarrow pK^+\pi^-\pi^-$.

To build up on a reliable method for estimating the decay, we first try to understand the baryonic decay mode
$B^+ \rightarrow \Lambda_c^+ p\pi^+$. The branching ratio for this decay is well measured,
$\mathcal{B}(B^+ \rightarrow \Lambda_c^+ p\pi^+) = 10^{-12}$\[32\] and the branching ratio for the decay $B^+ \rightarrow 
\pi^+\bar{D}^0(D^{*0})$ of $(4.98 \pm 0.29) \times 10^{-3}$ $(4.6 \pm 0.4) \times 10^{-3}$), we find,

\begin{align*}
G_{B^+D} &= 46 \text{ keV}, \\
G_{B^+D^*} &= 43 \text{ keV}.
\end{align*}

Note that these are just phenomenological couplings defined through Eq. \[1\].

Once this coupling is given, the three-body decay rate for the process $B^+ \rightarrow \Lambda_c^- p\pi^+$, represented in Fig. \[1\] is given by,

\begin{equation}
\Gamma_{B^+ \rightarrow \Lambda_c^- p\pi^+} = \frac{1}{2\pi m_{B^+}} \int_{(m_\pi + m_p)^2}^{(m_{B^-} - m_{\Lambda_c})^2} \frac{dp_{\pi^+}^2}{p_{\pi^+}^2} \\
\times \int_{p_{D^-}^{2,\text{min}}}^{p_{D^-}^{2,\text{max}}} \frac{dp_{D^-}^2}{p_{D^-}^2} |F(p_B^*)|^2 |F(p_D^*)|^2,
\end{equation}

where

\begin{align*}
p_B^2 &= \frac{(m_B^2 - (p_D + m_E)^2)(m_B^2 - (p_D - m_E)^2)}{4m_B^2}, \\
p_D^2 &= \frac{p_{D^-}^2 - (m_\Lambda + m_p)^2}{4m_{D^-}^2}.
\end{align*}

The range of integration is given by,

\begin{align*}
p_{D^-}^{2,\text{min, max}} &= (E_p^* + E_{\Lambda_c}^*)^2 \\
&- \left( \sqrt{E_{\pi^+}^2 - m_p^2} \pm \sqrt{E_{\Lambda_c}^2 - m_{\Lambda_c}^2} \right)^2,
\end{align*}

where

\begin{align*}
E_p^* &= \frac{1}{2p_{\pi^+}} (p_{\pi^+}^2 - m_p^2 + m_E^2), \\
E_{\Lambda_c}^* &= \frac{1}{2p_{\pi^+}} (m_B^2 - p_{\Lambda_c}^2 - m_{\Lambda_c}^2).
\end{align*}

For $D$ intermediate state, the matrix element is given as

\begin{equation}
|M_{D^+}\rangle = \frac{2g_{D^+\Lambda_c} G_{B^+D}}{m_{D^+}^2 - (m_p + m_{\Lambda_c})^2} \frac{p_D^2 - (m_{D^+} + m_{\lambda})^2}{(p_D^2 - m_{D^+}^2)^2},
\end{equation}

and for $D^*$ as,

\begin{equation}
|M_{D^*}\rangle = \frac{4g_{D^*\Lambda_c} G_{B^+D^*}}{(2m_B^2 + 2m_{D^*}^2 - m_{B^+}^2, (p_{D^*}^2 - m_{D^*}^2))^2} \frac{1}{(2p_{\pi^+}^2 + p_{D^*}^2 - m_{D^*}^2)} \\
\times \left( 2p_{\pi^+}^2 + p_{D^*}^2 - m_{D^*}^2 \right) \\
\times \left( m_{B^+}^2 + m_{\Lambda_c}^2 \right) \\
+ \left( m_{B^+}^2 + m_{\Lambda_c}^2 \right) \left( m_{D^*}^2 + m_{\lambda}^2 - p_{D^*}^2 \right),
\end{equation}

where for simplicity, we have assumed here and in ob-
taining Eq. \[5\] that the polarization sums for the $D^*$
quite remarkable. In Fig. 3, we also show the histogram of theoretical form factors and couplings were similar to those in a totally different reaction, the agreement is quite remarkable. In Fig. 3, we also show the histogram of theoretical event rates are obtained from our differential formula as in Eq. (4) multiplied by the total number of 152 million $B^+$, used in ref. [32]. The solid line is the sum of the contributions from $D$ and $D^*$. Noting that the theoretical form factors and couplings were similar to those used in the previous calculation on the open histogram of the $B^+ \rightarrow \Lambda^- p\pi^+$ decay as a function of $M(\Lambda^- p)$, requiring $M(\Lambda^- \pi) > 2.6$ GeV/c^2 and $M(p\pi^+) > 1.6$ GeV/c^2.

are just proportional to $g_{\mu\nu}$. Using $g_{D\Lambda_c} = 13.5$ and $g_{D^*\Lambda_c} = -4$ [33] and Eq. (9), we find,

$$\Gamma_{B^+ \rightarrow \Lambda^- p\pi^+}/\Gamma_{B^+} = (2.05 \pm 0.51) \times 10^{-4}, \tag{10}$$

where the first(second) number come the $D(D^*)$ intermediate state. This lies within the experimental measurement of $(2.1 \pm 0.7) \times 10^{-4}$. In Fig 2 we compare our calculation for the open histogram as a function of $p_D = M(\Lambda^- p)$ to the experimental result in ref. [32]. The theoretical event rates are obtained from our differential formula in Eq. (4) multiplied by the total number of 152 million $B^+$, used in ref. [32]. The solid line is the sum of the contributions from $D$ and $D^*$. Noting that the theoretical form factors and couplings were similar to those used in the previous calculation on the open histogram of the $B^+ \rightarrow \Lambda^- p\pi^+$ decay as a function of $M(\Lambda^- p)$, requiring $M(\Lambda^- \pi) > 2.6$ GeV/c^2 and $M(p\pi^+) > 1.6$ GeV/c^2.

FIG. 3: Similar to Fig. 2 but as a function of $M(p\pi^+)$, requiring $M(\Lambda^- \pi) > 2.6$ GeV/c^2 and $M(\Lambda^- p) > 3.5$ GeV/c^2.

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in $p_{\pi p} = M(\pi^+ p)$. Apart from the peak in 1.6 GeV [32], which should come from the $\Delta(1600)$ intermediate state that we did not include, the other structure and magnitude is again well reproduced. We conclude from our fit that the $D$ and $D^*$ intermediate state contributions are important part of the baryonic decay $B^+ \rightarrow \Lambda^- p\pi^+$, and explains much of the detailed histogram of its decay. We note that such contributions have to be subtracted out from the data before extracting any information about baryon resonance mediated decay [34].

Let us now consider a process where a $\Theta_c$ can be produced. The process is shown in Fig. 4. We use the same formula as in Eq. (4) with masses replaced to those shown in Fig. 4. We take the $m_\Theta = 2800$ MeV, which is slightly below the $DN$ threshold, and assume it to have spin 1/2 and positive parity. To estimate the coupling $g_{\Lambda_c\Theta_c}$, we use an analogy to the $\Theta^+$. The particle data book puts the width of $\Theta^+$ to be $0.9 \pm 0.3$ MeV [32]. Such a small width is necessary if the existence of the resonance is to be consistent with the previous $KN$ scattering data. Moreover, all the experiments reporting positive signal quote the width to be smaller than their experimental resolution, which are typically of 10 MeV. Now assuming the width of $\Theta^+$ to be 1 MeV, which is dominated by its $KN$ decay, one finds that the coupling to be $g_{KN\Theta^+} = 1$ [37]. Noting that $g_{\Lambda_c\Theta_c}$ is estimated to be similar in magnitude to $g_{KN\Theta^+}$, we will also take $g_{\Lambda_c\Theta_c} = 1$. Such a small coupling is also expected if the pentaquark wave function is composed of strongly correlated diquarks with small spatial overlap with the $DN$ states [21]. Moreover, we will take $g_{\Lambda_c\Theta_c}/g_{\Lambda_c\Theta_c} = g_{\Lambda_c\Theta_c}/g_{\Lambda_c\Theta_c} \sim 1/3$. With this coupling, we find the branching ratio for $B^+ \rightarrow \Theta_c\pi^+$ to be $14.4 \times 10^{-7}$, which roughly comes from $(g_{\Lambda_c\Theta_c}/g_{\Lambda_c\Theta_c})^2 \times \Gamma_{B^+ \rightarrow \Lambda^- p\pi^+}/\Gamma_{B^+}$. Once $\Theta_c$ is produced, and if it is unbound, it can decay into either $D^- p$ and $D^0 n$, and be directly observed. However, if it is bound, it will only be observed via weak decays. The dominant decay would be through $\Theta_c \rightarrow pK^+\pi^-\pi^-$, which has a branching ratio of $(9.2 \pm 0.6)\%$ [32].

To account for experimental acceptance and efficiency,
we take 70% as a rough estimate of track-finding efficiency including particle identification, for each charged particle. Then, the total efficiency to correctly find all 4 charged tracks for a \( \Theta_c \) decay would be \((0.7)^4\). Combining the two \( B \)-factory experiments, Belle and BABAR, we are close to accumulating \( 10^9 \) \( B^+/B^- \) pairs. Therefore, the total number of expected events for \( B^+ \rightarrow \pi^+ n\Theta_c \) and subsequently \( \Theta_c \rightarrow pK^+\pi^-\pi^- \), would be,

\[
(10^9)(14.4 \times 10^{-7})(0.092)(0.7)^4 = 32 \text{ events.} \tag{11}
\]

In a sense, this can be regarded as a lower limit, since the contribution from other possible production processes have been neglected and a very conservative estimate for \( B_{DN\Theta_c} \) has been taken. The main uncertainty of this number comes from our uncertainty in the overall fit of Fig 2 and Fig. 3. If \( m_{\Theta_c} = 3100 \text{MeV} \) and unbound, the branching ratio will only change slightly to \( 15.5 \times 10^{-7} \), and its existence could be observed through strong decay into \( DN \) or \( D^*N \) final states with event rates larger than that given in Eq. (11), depending on what additional final states will be used to identify the on shell D meson.

Considering the fact that each \( B \)-Factory experiment will accumulate at least \( 1 \times 10^8 \) \( B^+ \)'s every year, adding the already accumulated data of about \( 0.5 \times 10^9 \), the prospect of observing a charmed pentaquark state in this channel from analyzing the existing and upcoming data at each factory is quite promising.

We have shown that the baryonic decay modes of \( B^+ \) can be sensibly estimated with previously determined hadronic parameters. Starting from such methods and previous estimates on the coupling of the pentaquark to the \( DN \) states, we find that the pentaquark can be produced in the baryonic decay of the \( B^+ \). Estimates show that in both cases, where the pentaquark is unbound or bound, the pentaquark can be observed realistically through the \( DN \) or weak decay final states respectively, from the accumulated data at \( B \)-Factories. Previous searches on the charmed pentaquark were not combined with a realistic estimate of the cross section, and therefore it was not clear what to conclude even from a null result. Since we present a definite lower bound on the counting rate with which the pentaquark should be observed, the experimental search would be able to provide a final conclusion on the existence of the charmed pentaquark.

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