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Prospects for pentaquark production at meson factories

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Abstract

Following Rosner [hep-ph/0312269], we consider B-decay production channels for the exotic $I = 0$ and $I = 3/2$ pentaquarks that have been recently reported. We also discuss new search channels for isovector pentaquarks, such as the $\Theta^{*++}(\bar{s}duuu)$, that are generically present in chiral soliton models but were not observed in recent experiments. Furthermore, we argue that weak decays of charmed baryons, such as the Λ_c^+ and Ξ_c^0, provide another clean way of detecting exotic baryons made of light quarks only. We also discuss discovery channels for charmed pentaquarks, such as the isosinglet $\Theta_c^0(\bar{c}udud)$, in weak decays of bottom mesons and baryons. Finally, we discuss prospects for inclusive production of pentaquarks in e^+e^- collisions, with associated production of particles carrying the opposite baryon number.

1. Introduction

Recently a great deal of experimental and theoretical activity has been dedicated to exotic pentaquark baryons. This activity was sparked by observations of a narrow $S = 1$ baryon resonance with a mass of 1540 MeV [1–8]. At present the spin, parity and magnetic moment of this state have not been determined; some groups, e.g., the SAPHIR Collaboration [4], find that the isospin of the Θ^+ is zero. Such a state appears naturally in the rigid rotator approach to the 3-flavor Skyrme model [9–12][1] or in diquark models [21–23]. Both of these approaches produce exotic baryons in the $\overline{\mathbf{10}}$ of $SU(3)$, with positive parity. In the diquark model the $\overline{\mathbf{10}}$ mixes strongly with another exotic multiplet, $\mathbf{8}$ [22,23]; in the chiral soliton model there is also an $\mathbf{8}$ of excited baryons coming from the breathing modes of the Skyrmion, and there is also some mixing between the $\overline{\mathbf{10}}$ and the $\mathbf{8}$ [24]. Therefore, the $SU(3)$ rigid rotator Skyrme model and the diquark models give low-lying pentaquark spectra that are rather similar, although they may be different quantitatively. In particular, both approaches predict the existence of an $I = 3/2$ multiplet of exotics, which are the low-

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[1] The rigid rotator Skyrmion [13] approach to non-exotic baryons is usually justified in the limit of large N_c, where N_c is the number of colors [14,15]. However, the rigid rotator approach to the exotic baryons cannot be justified by large N_c reasoning [16–20]. A study of kaon resonances near a Skyrmion, which is a better approach to the exotics for large N_c, shows that a state with the quantum numbers of Θ^+ does not appear for conventional values of model parameters [19]. However, such a state can be made to appear by large changes in the parameters.

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est strangeness ($S = -2$) members of the antidecuplet.

Quite recently, an experimental boost to these ideas came from the NA49 Collaboration which reported observation of a manifestly exotic member of this quartet, $\Xi^{--}_{3/2}(ssdd\bar{u})$ [25]. For analysis of the theoretical situation in light of this new result, see [23,26]. In spite of the report from NA49, more experimental and theoretical work is clearly needed. The experiments carried out so far are rather difficult, and care needs to be exercised in interpreting the data (see, for instance, [27,28]). A surprising feature of the experimental results is that the ratio of the Θ^+ production cross-section to that of $\Lambda(1520)$ is found to be very high, in the range of 30–50% (however, the experimental consistency of a ratio this high was questioned in [28]). Theoretically, the production cross-section of a 5-quark state is expected to be roughly $O(1\%)$ of that for a 3-quark state.[2]

A further question concerns parity of the pentaquarks. While early quark model approaches predict negative parity (see, for example, [29–32]), it was later pointed out that wave functions with positive parity are energetically preferred for certain model interactions [33]. Soliton and diquark models predict positive parity, while some recent lattice studies instead suggest negative parity [34,35].

The unexpectedly small width of the pentaquark resonances is also a puzzle. Measurements of the width have been largely limited by the experimental resolution. Careful analysis of some experiments indicates a width as small as 1 MeV [36–40]. This poses a challenge for all presently available theoretical models, although there are some ideas on why the width is considerably smaller than a typical $\mathcal{O}(100)$ MeV width expected of a strongly interacting state this much above threshold [12,41–45].

Another important question concerns pentaquarks with $I = 1$ and $I = 2$. On general grounds, if the isosinglet $\bar{s}udud$ pentaquark has been found, then one suspects that the $\bar{s}uduu$ and $\bar{s}uuuu$ may be discovered as well, with somewhat higher masses. In chiral soliton models one indeed finds that the existence of the $I = 1$ and $I = 2$ pentaquarks is tied to the existence of the $I = 0$ one [18,19,46,47]. In the $SU(3)$ rigid rotator model the $I = 1$ and $I = 2$ exotics belong to the **27** and the **35**, respectively. Their origin is more general, however: all that is needed to construct exotic states of higher isospin is an $SU(2)$ collective coordinate [19] whose existence can be argued on large N_c grounds [18]. In the simplest diquark model, where all diquarks are assumed to be antisymmetric in color, spin and flavor, such states are absent [22,23]. If, however, one also assumes the presence of quark pairs symmetric in flavor (pairs of quarks with such quantum numbers are present in decuplet baryons), then the $I = 1$ pentaquark states of $J = 3/2$ and $J = 1/2$ appear, just as in the chiral soliton models, and restore agreement with large N_c considerations. The $I = 1$ states are typically predicted to lie in the range 1600–1680 MeV [18,19,46,47] and should be sufficiently narrow to be observable. The highest charge member of this multiplet, Θ^{*++}, should be observable through decay into pK^+. There is no evidence for such a resonance in available pK^+ scattering data [37,48]; recent photoproduction experiments also did not find evidence for this state [3,4,49]. In this Letter we propose further searches for Θ^{*++}.

Beyond the pentaquarks made of the light flavors, it is important to search for heavy flavored pentaquarks, such as the $\Theta^0_c(\bar{c}udud)$. A natural description of such objects in chiral soliton models is provided by the bound state approach [50] where they are described by bound states or resonances of flavored mesons and solitons. In this approach the exotic baryons are distinguished from the conventional ones by the Wess–Zumino term, which attracts D mesons, but repels $\bar{D}$ mesons. Heavy quark symmetry was incorporated into the bound state approach in [51]. As the mass of the meson increases, so does the tendency to bind, and the Θ^0_c is typically predicted to lie below the $\bar{D}N$ threshold [52] (see also [19,53,54]). The bottom flavored pentaquark, $\Theta^+_b(\bar{b}udud)$, is even more likely to be bound.[3] In the quark model approaches of [22,33] the heavy flavored pentaquarks are also predicted to be bound (in [22] the Θ^0_c is estimated to lie ~ 100 MeV below the $\bar{D}N$ threshold, in rough agreement with bound state approach estimates [52]).

[2] We thank G. Farrar for pointing this out to us.

[3] However, the effective Lagrangian for heavy mesons near a Skyrmion is not known precisely; appreciable changes of parameters can make heavy flavored pentaquarks unbound.

If the Θ_c^0 lies below the threshold, then it has only weak decay modes, such as $\Theta_c^0 \to pK^0\pi^-$. If, however, it lies above the threshold, as predicted by other models [55,56], then it should appear as a narrow $D^- p$ resonance. One should keep in mind that some earlier charmed pentaquark searches, such as the Fermilab E791 searches for $\bar{c}suud$ through its weak decays into $\phi\pi^- p$ or $K^{*0}K^- p$, were not successful [57].

Clearly, further experimental input on pentaquarks is crucial at this point. It is important to find pentaquark production mechanisms that give clean and unambiguous signatures. One possibility first suggested by Rosner [58] is to search for pentaquarks by using baryonic B decays.[4] Although B decays into a baryon and antibaryon typically have branching ratios $< 10^{-4}$, the large numbers of events accumulated at the B-factories offer excellent opportunities for pentaquark detection that are distinct from photoproduction or kaon scattering that have been used so far. In this Letter we make further suggestions along the lines of [58], and also propose other production mechanisms involving decays of heavy flavored baryons. Since the experimental detection of charged particles is typically easier than that of neutral particles, we will focus on signatures that do not require the detection of an antineutron (or neutron) and that lead to final states with charged particles only.

2. Pentaquarks in B decays

One of the suggestions in [58] is that $\Theta^+(1540)$ may be observable through the decay sequences

$$B^0 \to \Theta^+ \bar{p} \to p\bar{p}K^0, \tag{2.1}$$

$$\bar{B}^0 \to \bar{\Theta}^- p \to p\bar{p}\bar{K}^0. \tag{2.2}$$

In practice one observes K_S instead of K^0. The existence of the Θ^+ and its antiparticle may be confirmed either by examining both the pK_S and $\bar{p}K_S$ invariant mass combinations or by using flavor-tagging. The Θ^+ pentaquark can also appear in a weak decay of the meson $\bar{B}_s^0$, which consists of $b\bar{s}$ quarks. If the b quark decays weakly into $du\bar{u}$ then we may find

$$\bar{B}_s^0 \to \Theta^+ \bar{p} \to p\bar{p}K^0. \tag{2.3}$$

Similarly, one can search for the $I = 1$, $I_3 = 1$ pentaquark Θ^{*++} in the decay

$$B^+ \to \Theta^{*++} \bar{p} \to p\bar{p}K^+ \tag{2.4}$$

by examining the pK^+ invariant mass. Another possibility is

$$B^0 \to \Theta^{*++} \bar{p}\pi^- \to p\bar{p}K^+\pi^-, \tag{2.5}$$

where again we should examine the pK^+ invariant mass. On the other hand, examination of the $\bar{p}K^+$ invariant mass should reveal a peak corresponding to the antiparticle of $\Lambda(1520)$, which provides a useful normalization. The first of these modes seems most promising as far as statistics are concerned. For example, Belle finds $96.4^{+11.2}_{-10.5}$ $p\bar{p}K^+/78\ \mathrm{fb}^{-1}$ versus $11.3^{+4.1}_{-3.4}$ $p\bar{p}K_S/78\ \mathrm{fb}^{-1}$ [62]. Belle also finds $14.5^{+4.6}_{-4.0}$ $p\bar{p}K^{*+}/78\ \mathrm{fb}^{-1}$ where $K^{*+} \to K_S\pi^+$ [62]. However, searches for peaks in the pK spectra are not reported in [62]. The final state $p\bar{p}K_S\pi^+$ is one suggested by Rosner. This final state is flavor-specific (allowing one to distinguish pK_S and $p\bar{K}_S$); however, the signal to background is marginal.

To produce the $I = 0$ charmed pentaquark Θ_c^0 in a B-decay, there are modes involving the dominant weak process $\bar{b} \to \bar{c}u\bar{d}$ [58]:

$$B^+ \to \Theta_c^0 \bar{\Delta}^+, \tag{2.6}$$

$$B^0 \to \Theta_c^0 \bar{p}\pi^+. \tag{2.7}$$

If the Θ_c is below the $\bar{D}N$ threshold, then it will decay weakly into $pK^0\pi^-$. Otherwise, it will decay strongly into $\bar{D}^0 n$ or $D^- p$. Since CLEO reported a large signal for $B^0 \to D^{*-}p\bar{p}\pi^+$ (32.3 ± 6.0 events/ $9.1\ \mathrm{fb}^{-1}$) [65], we should expect a large signal for $B^0 \to D^- p\bar{p}\pi^+$ as well. This mode can be used to search for $D^- p$ resonances.

Just like the Θ^+, the charmed pentaquark may have counterparts with $I = 1$ and $I = 2$. The antiparticle of a member of the $I = 1$ multiplet, $\Theta_c^{*+}(\bar{c}uuud)$, may be produced through

$$\bar{B}^0 \to \bar{\Theta}_c^{*-} p \to D^0 \bar{p}p, \tag{2.8}$$

where we assumed that it lies above the DN threshold. This decay mode has been observed (Belle finds $\sim$

[4] For other recent pentaquark search proposals see, for example, [59–61].

92 ± 11.5 $D^0 p\bar{p}/29$ fb^{-1} and $\sim 19 \pm 5$ $D^{*0} p\bar{p}/29$ fb^{-1}) [63], and now the spectrum of invariant mass of $\bar{p}D^0$ needs to be analyzed.

One may also try to observe pentaquarks containing a $\bar{c}$ quark and an s-quark. It is natural to suppose that the lightest such states are the $\Theta^0_{cs}(\bar{c}sudu)$ and $\Theta^-_{cs}(\bar{c}sddu)$, which form an $I = 1/2$ doublet [32,33]. They could be produced, for example, in decays of $B^0_s(\bar{b}s)$:

$$B^0_s \to \Theta^0_{cs}\bar{p}\pi^+, \tag{2.9}$$

$$B^0_s \to \Theta^-_{cs}\bar{\Delta}^+. \tag{2.10}$$

In the Skyrme model, such states could emerge as bound states or resonances of D^-_s near a Skyrmion. If these states are above the $D_s N$ threshold of ≈ 2910 MeV, then they could be detected through strong decays, such as $\Theta^0_{cs} \to D^-_s p$, $\Theta^0_{cs} \to D^-\Sigma^+$, and $\Theta^-_{cs} \to \bar{D}^0\Sigma^-$. Otherwise only their weak decays are allowed (however, earlier searches for such states through weak decays have not been successful [57]).

3. Pentaquarks in baryon decays

Another promising way of producing pentaquarks is through weak decays of heavy flavored baryons. Consider, for example, Cabibbo suppressed decays of the $\Lambda^+_c(cud)$. If instead of the dominant mode $c \to su\bar{d}$ we consider Cabibbo suppressed modes that proceed through $c \to su\bar{s}$, then we find the following possible decay modes where only one additional $q\bar{q}$ pair is produced:

$$\Lambda^+_c \to \Theta^+\bar{K}^0 \to pK^0\bar{K}^0, \tag{3.1}$$

$$\Lambda^+_c \to \Theta^{*++}K^- \to pK^+K^-. \tag{3.2}$$

Belle published a signal for $\Lambda_c \to pK^+K^-$ with 676 ± 89 events/78 fb^{-1} [64]. No signal was shown for $\Lambda_c \to pK_S\bar{K}_S$. Rough scaling leads one to expect $\mathcal{O}(90-100)$ $pK_S\bar{K}_S$ events/78 fb^{-1}. The signal to background should be excellent.

Another good opportunity is provided by decays of $\Xi^+_c(csu)$ and $\Xi^0_c(csd)$. Using the dominant mode $c \to su\bar{d}$, we may have

$$\Xi^0_c \to \Xi^{--}_{3/2}\pi^+\pi^+ \to \Xi^-\pi^-\pi^+\pi^+. \tag{3.3}$$

This is a large mode, and a sample of events $\Xi^0_c \to \Xi^-\pi^-\pi^+\pi^+$ was already obtained by Belle for the study of excited Ξ^*_c. This, or another possible mode

$$\Xi^0_c \to \Xi^{--}_{3/2}\pi^+\pi^+ \to \Sigma^-K^-\pi^+\pi^+, \tag{3.4}$$

provide good opportunities to confirm the discovery [25] of the $\Xi^{--}_{3/2}(1860)$.

It is interesting that the same events could be used to search for another manifestly exotic member of the $I = 3/2$ quartet, $\Xi^+_{3/2}(ssuu\bar{d})$, which is a state not yet observed by NA49 [25]. Indeed, the following decay sequence is available:

$$\Xi^0_c \to \Xi^+_{3/2}\pi^- \to \Xi^-\pi^-\pi^+\pi^+, \tag{3.5}$$

and $\Xi^+_{3/2}$ could appear as a peak in the distribution of the invariant mass of $\Xi^-\pi^+\pi^+$. Another possible decay sequence is

$$\Xi^0_c \to \Xi^+_{3/2}\pi^- \to \Sigma^+\bar{K}^0\pi^-, \tag{3.6}$$

but it is not reported as "seen" by the PDG [66]. Perhaps it is also possible to observe

$$\Xi^0_c \to \Xi^+_{3/2}\pi^- \to \Xi^0\pi^+\pi^- \to \Lambda\pi^0\pi^+\pi^-, \tag{3.7}$$

where the Ξ^0 decays weakly into $\Lambda\pi^0$.

Charm pentaquarks, such as the Θ^0_c may be produced in weak decays of the $\Lambda_b(bud)$. Using a Cabibbo suppressed mode $b \to cd\bar{c}$, we may find

$$\Lambda_b \to \Theta^0_c D^0 \tag{3.8}$$

or

$$\Lambda_b \to \Theta^{*-}_c D^+, \tag{3.9}$$

where $\Theta^{*-}_c(\bar{c}uddd)$ is the $I = 1$, $I_3 = -1$ state. Using instead the dominant mode $b \to cs\bar{c}$, we may find, e.g.,

$$\Lambda_b \to \Theta^0_{cs}D^0, \tag{3.10}$$

or

$$\Lambda_b \to \Theta^-_{cs}D^+. \tag{3.11}$$

4. Pentaquarks in quarkonium decays or in e^+e^- continuum production

As suggested in [58], another possible way of observing the Θ^+ is through the inclusive reaction

$$J/\psi \to \Theta^+ + X. \tag{4.1}$$

However, there is little phase space available since $m(J/\psi) \approx 3097$ MeV, while the minimum mass of X is $m_N + m_K \approx 1435$ MeV. It may be better to study instead excited charmonium states, such as the $\psi(2S)$ whose mass is 3686 MeV. Millions of its decays have been observed at BES. The typical branching fraction for a $\psi(2S)$ decay to a baryon–antibaryon pair is $\mathcal{O}(10^{-4})$ [66], thus perhaps it is possible to observe the decay

$$\psi(2S) \to \Theta^+ + X \to pK^0 + X. \tag{4.2}$$

Similar events could be expected in the decay of $b\bar{b}$ mesons, such as the $\Upsilon(1S)$ (millions of its decays have been recorded by CLEO [67]). It is heavy enough that it can decay into charmed pentaquarks. For example, one could carry out an inclusive search for events of the type

$$\Upsilon(1S) \to \Theta_c^0 + X \to pD^- + X. \tag{4.3}$$

Even if the Θ_c^0 is slightly below the DN threshold, there could be some indication for it from a pD^- spectrum rising toward the threshold. Otherwise, the decay sequence is

$$\Upsilon(1S) \to \Theta_c^0 + X \to pK^0\pi^- + X. \tag{4.4}$$

Finally we mention perhaps the most obvious way of producing pentaquarks: through $e^+e^- \to q\bar{q}$ with subsequent production of four light quark–antiquark pairs during fragmentation (this was briefly discussed in [68]). While this method is possible off any resonance, a particularly convenient data set involves the vast number of $e^+e^- \to q\bar{q}$ events accumulated by the B-factories at the $\Upsilon(4S)$ resonance. This method seems particularly well-suited for production of pentaquarks containing a $\bar{c}$ quark, such as in the inclusive reactions

$$e^+e^- \to \Theta_c^0 + X \to pD^- + X, \tag{4.5}$$

if the Θ_c^0 is above the $\bar{D}N$ threshold, or

$$e^+e^- \to \Theta_c^0 + X \to pK^0\pi^- + X, \tag{4.6}$$

if the Θ_c^0 is below the $\bar{D}N$ threshold. In these cases, due to the hard fragmentation of the charm quark, one can apply a tight momentum requirement, e.g., $p_P^* > 2.5$ GeV, (where p_P^* is the momentum of the pentaquark candidate in the center of mass frame), to reduce backgrounds in the search.

5. Conclusion

There is strong motivation to search for the pentaquarks in decays of heavy hadrons or in e^+e^- collisions, as suggested in [58,68] and in this Letter. Possible signatures are given in Tables 1, 2, and 3. Besides confirming the existence of the pentaquarks, these methods promise a precise determination of their widths and quantum numbers (spin and parity). Based on experience so far, their widths are expected to be narrow, much less than the 100 MeV width that one might naively expect for a strongly decaying resonance. Some heavy flavored pentaquarks may even have weak lifetimes.

One uncertainty for all searches is the lack of a good understanding of the pentaquark production

Table 1
Pentaquark signatures in B meson decay

Pentaquark	Mode	Experimental signature
$\Theta^+(1540)$	$B^0 \to p\bar{p}K_S$	$M(pK_S)$
$\Theta^+(1540)$	$B^+ \to p\bar{p}K_S\pi^+$	$M(pK_S)$
Θ^{*++}	$B^+ \to p\bar{p}K^+$	$M(pK^+)$
Θ^{*++}	$B^0 \to p\bar{p}K^+\pi^-$	$M(pK^+)$
Θ_c^0	$B^0 \to D^- p\bar{p}\pi^+$	$M(D^- p)$
$\bar{\Theta}_c^{*-}$	$\bar{B}^0 \to D^0\bar{p}p$	$M(D^0\bar{p})$

Table 2
Pentaquark signatures in charmed baryon decay

Pentaquark	Mode	Experimental signature
$\Theta^+(1540)$	$\Lambda_c^+ \to pK_S\bar{K}_S$	$M(pK_S)$
Θ^{*++}	$\Lambda_c^+ \to pK^+K^-$	$M(pK^+)$
$\Xi_{3/2}^{--}(1860)$	$\Xi_c^0 \to \Xi^-\pi^-\pi^+\pi^+$	$M(\Xi^-\pi^-)$
$\Xi_{3/2}^{--}(1860)$	$\Xi_c^0 \to \Sigma^-K^-\pi^+\pi^+$	$M(\Sigma^-K^-)$
$\Xi_{3/2}^{+}$	$\Xi_c^0 \to \Xi^-\pi^-\pi^+\pi^+$	$M(\Xi^-\pi^+\pi^+)$
$\Xi_{3/2}^{+}$	$\Xi_c^0 \to \Sigma^+\bar{K}_S\pi^-$	$M(\Sigma^+\bar{K}_S)$

Table 3
Pentaquark signatures in B_s^0 and Λ_b decay

Pentaquark	Mode	Experimental signature
$\Theta^+(1540)$	$\bar{B}_s^0 \to p\bar{p}K_S$	$M(pK_S)$
Θ_{cs}^0	$B_s^0 \to D_s^- p\bar{p}\pi^+$	$M(D_s^- p)$
Θ_c^0	$\Lambda_b \to D^- pD^0$	$M(D^- p)$
Θ_{cs}^0	$\Lambda_b \to D_s^- pD^0$	$M(D_s^- p)$
Θ_{cs}^-	$\Lambda_b \to \bar{D}^0\Sigma^- D^+$	$M(\bar{D}_0\Sigma^-)$

cross-sections. Cross-sections for known non-exotic resonances, such as the $\Lambda(1520)$, should be measured first for calibration. One then expects pentaquark cross-sections to be at least of order a percent of that.

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