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Exotic states of matter in heavy meson decays [1]

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The potential of decays of mesons containing heavy quarks [including B mesons and the $\Upsilon(1S)$] for producing final states of matter with unusual quark configurations, such as $qq\bar{q}\bar{q}$ or $qqqq\bar{q}$, is investigated. The usefulness of antineutron detection in such searches is stressed.

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I. INTRODUCTION

The decays of mesons containing heavy quarks provide carefully controlled environments for production of hadronic states with specific quantum numbers. Copious samples of such mesons accumulated at the BaBar, Belle, and CLEO detectors permit searches for interesting forms of matter, including mesons beyond the usual quark-antiquark and baryons beyond the usual three-quark configurations. Such hadrons (e.g., $qq\bar{q}\bar{q}$ mesons and $qqqq\bar{q}$ baryons) are known as *exotic*. Their existence is not forbidden by quantum chromodynamics (QCD) as long as they maintain color-singlet configurations. They are predicted in a wide variety of schemes.

In the present paper, which follows up some suggestions made in Ref. [1] and presents others, we explore some ways in which the decays of mesons containing heavy (mainly b) quarks can help in the search for exotic hadrons. We focus on states which are manifestly exotic by virtue of their internal quantum numbers, bypassing the question of whether certain recently seen resonances are heavy quarkonium states or molecules of flavored mesons. Our discussion of decays of particles containing charmed (c) quarks will be brief since they are much lighter, thereby probing a much more limited mass range.

We review some of the theoretical framework for exotic states in Section II. We then discuss exotic meson and baryon final states of B decays in Sections III and IV, respectively. Section V is devoted to some specific signatures of a recently discussed candidate for a light $uudd\bar{s}$ baryon. Possibilities for exotic particle observation in $\Upsilon(1S)$ decays are noted in Section VI. Some remarks on charmed particle decays are made in Section VII, while Section VIII summarizes.

II. THEORETICAL SCHEMES

The duality of scattering amplitudes in crossed channels [2] was used [3] to argue in favor of the existence of $qq\bar{q}\bar{q}$ mesons coupling mainly to baryon-antibaryon final states.

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(For a recent review of this work, see Ref. [4].) These arguments are conveniently visualized using quark graphs [5]. Generalizations of the graphical arguments [6] lead to selection rules governing allowed transitions among exotic states.

The properties of $qq\bar{q}\bar{q}$ mesons were analyzed within a particular confinement scheme, known as the MIT Bag Model [7], by Jaffe [8]. Masses and couplings to meson pairs were calculated; there was no particular reason for such states to favor coupling to baryon-antibaryon channels.

A complementary approach investigated the properties of baryon-antibaryon bound states from a standpoint primarily motivated by nuclear physics arguments; see Ref. [9] for a brief historical review. Attempts to describe ordinary mesons such as the pion in terms of such bound states have a long and eminent history [10]. Recently a candidate for such a state near nucleon-antinucleon threshold has been reported in J/ψ decays [11]. Ref. [1] discusses possible interpretations of this state as well as some earlier candidates for nucleon-antinucleon resonances.

Bootstrap-like models of mesons and baryons, which predict properties of excited states by taking account of mesonic rather than quark degrees of freedom, generally do not limit the quantum numbers of states to those of $q\bar{q}$ or qqq. An early example is the strong-coupling theory [12], generalizing Chew and Low's theory of the Δ^{++} isobar [13]. States with $I = J = 1/2,\ 3/2,\ 5/2\ldots$ are predicted in this approach. More recently, chiral soliton models of baryons [14] have taken account of mesonic rather than quark degrees of freedom. In flavor SU(3), several authors noted that these approaches led to an antidecuplet with $J^P = 1/2^+$ lying not far above the $1/2^+$ octet and $3/2^+$ decuplet [15, 16]. The lightest member of this $\overline{\mathbf{10}}$ representation was expected to have strangeness $S = +1$, and a mass of 1530 MeV/c^2 was predicted [16, 17]. As will be noted in Sec. V, the search for this state has taken on new urgency as a result of several claims for its observation. First, however, we note some special features of heavy meson decays that make them particularly useful in the search for exotic mesons and baryons.

III. EXOTIC MESONS IN B DECAYS

We shall be concerned in this Section with the dominant subprocess $\bar{b} \to \bar{c}u\bar{d}$ in B meson decays. The fact that this leads to three quarks of different flavor in the final state provides an immediate advantage in the search for exotic particles. (The favored decays of charm, $c \to su\bar{d}$, share this property.)

If a $\bar{b}$ quark is bound to a u quark in a B^+ meson, the favored nonleptonic final state is then $\bar{c}u\bar{d}u$. This, by itself, is exotic. Thus one means of searching for exotics is simply the study of the missing mass of X_c^+ in $B^+ \to (\gamma, \pi^0, \eta, \eta', \ldots) + X_c^+$. A quark diagram associated with this process is shown in Fig. 1. Another diagram can be drawn in which the final $u\bar{c}\bar{d}$ decay products of $\bar{b}$ are incorporated into the X_c^+ along with a u from $u\bar{u}$ production. Similarly, the subsystem X_c^+ in $B^0 \to \pi^- X_c^+$ will be exotic, also carrying the quantum numbers of $\bar{c}u\bar{d}u$.

A B^+ decay involving $\bar{b} \to u\bar{c}\bar{d}$ can produce an exotic meson consisting entirely of light quarks ($uu\bar{d}\bar{d}$) if the $uu\bar{d}$ system picks up another $\bar{d}$ quark in fragmentation, while the corresponding d quark accompanies the $\bar{c}$ to form a D^- or D^{*-}. This process is shown in Fig. 2. The detection of an exotic final state in the decay $B^+ \to X^{++}D^{(*)-}$ might proceed in several ways.

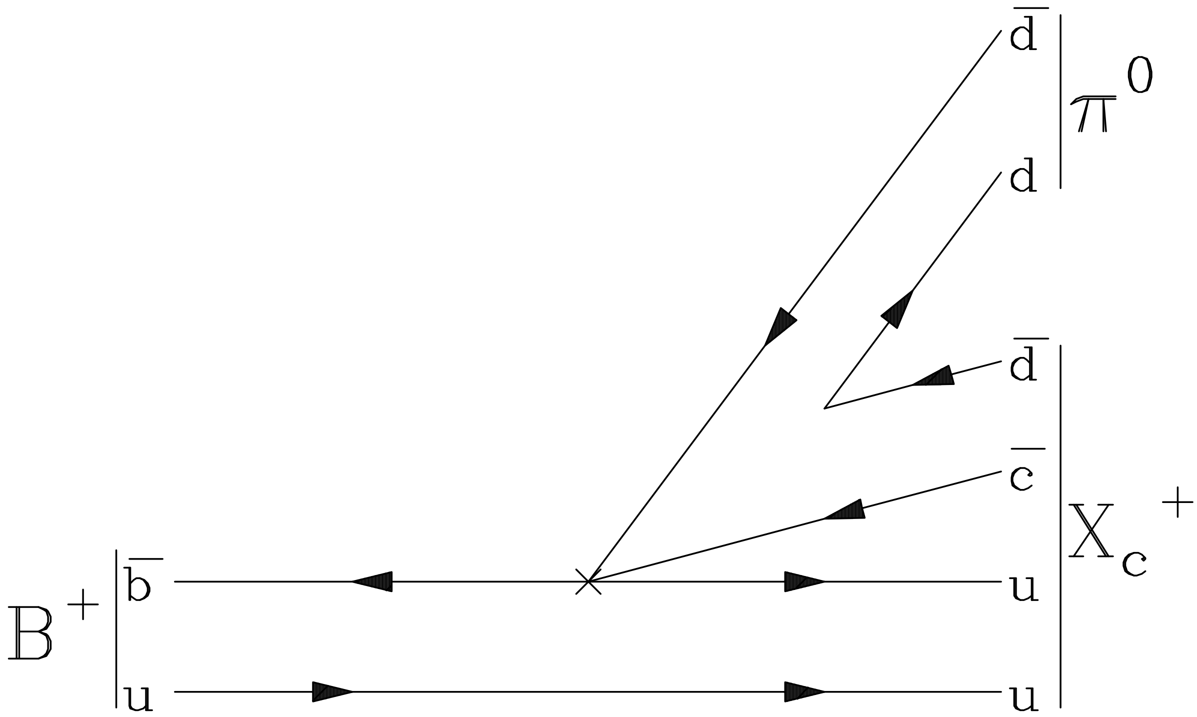

Figure 1: Production of an exotic meson $X_c^+ = uu\bar{c}\bar{d}$ in B^+ decays. The π^0 could also be a photon or any other neutral particle. Here and subsequently the weak vertex is denoted by $\times$.

(1) One could study the missing mass opposite the $D^{(*)-}$, if the energy and momentum of the B^+ are known. Such information might be provided by reconstructing the opposite-side B^- in the decay $\Upsilon(4S) \to B^+B^-$.

(2) One could look for a mass peak in the decay products of X^{++}. If X^{++} indeed decays predominantly to baryon-antibaryon final states, as proposed in some schemes (e.g., [3]), one could look for $X^{++} \to \Delta^{++}\bar{\Delta}^0 \to p\pi^+\bar{p}\pi^+$.

(3) One could use a combination of methods (1) and (2) if some of the decay products of X^{++} are difficult to observe, as in $X^{++} \to \Delta^{++}\bar{n}$. Here one might look for annihilation of the $\bar{n}$ in the detector. Such a signal has attracted attention as a possible background to $b \to s\gamma$ [18], and was utilized in a study of $B^0 \to D^{*-}p\bar{n}$ [19]. While the energy of the $\bar{n}$ might not be well-measured, one could use information about the remaining particles in the event to constrain it.

It is possible that X^{++} does not decay predominantly to baryon-antibaryon final states, for example if it lies in the below-threshold mass range predicted in Ref. [8]. One final state which has not been thoroughly explored for exotic mesons, and which is observable by modern detectors such as BaBar, Belle, and CLEO, is $\rho^+\rho^+$. An $I = 2$ meson with favored coupling to $\rho\rho$ and mass 1.4–1.6 GeV/c^2 could help to explain the predominance of $\gamma\gamma \to \rho^0\rho^0$ over $\gamma\gamma \to \rho^+\rho^-$ near threshold [20].

A strange exotic meson can be formed if the final $uu\bar{d}$ state picks up an anti-strange $\bar{s}$ quark, so that the recoil system is (for example) D_s^-. This process is shown in Fig. 3.

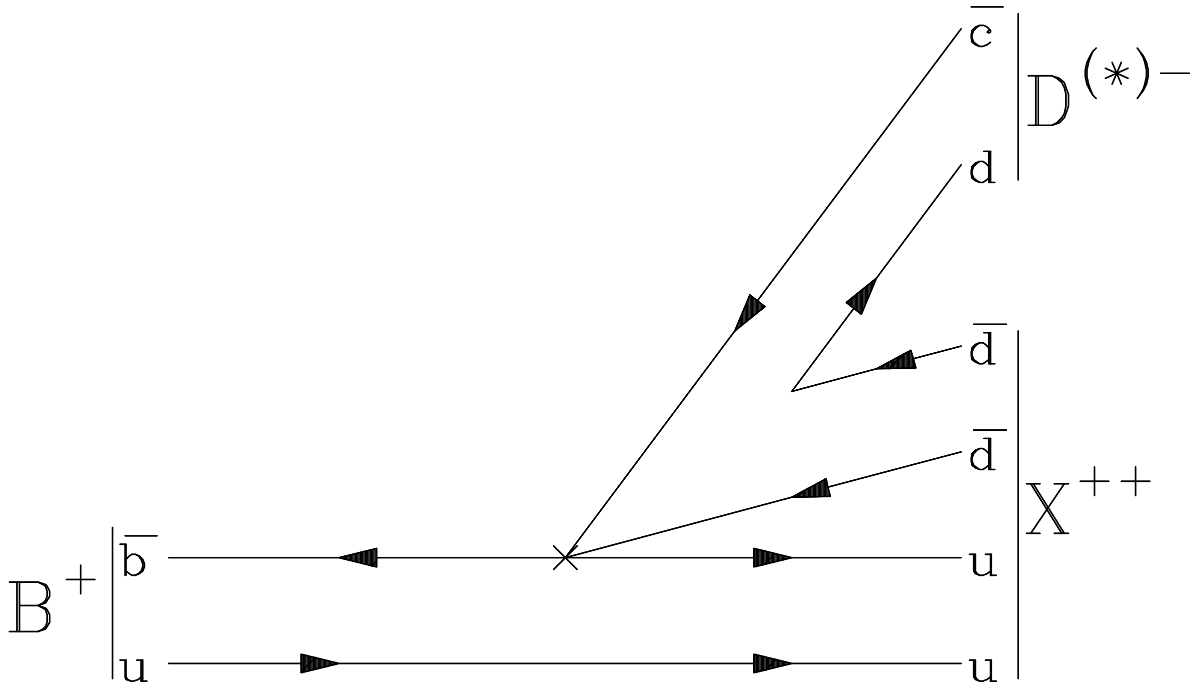

Figure 2: Production of an exotic meson $X^{++} = uu\bar{d}\bar{d}$ in B^+ decays. If the recoiling charmed meson is a D^{*-}, identification may be easier through the decay $D^{*-} \to \pi^- \bar{D}^0$.

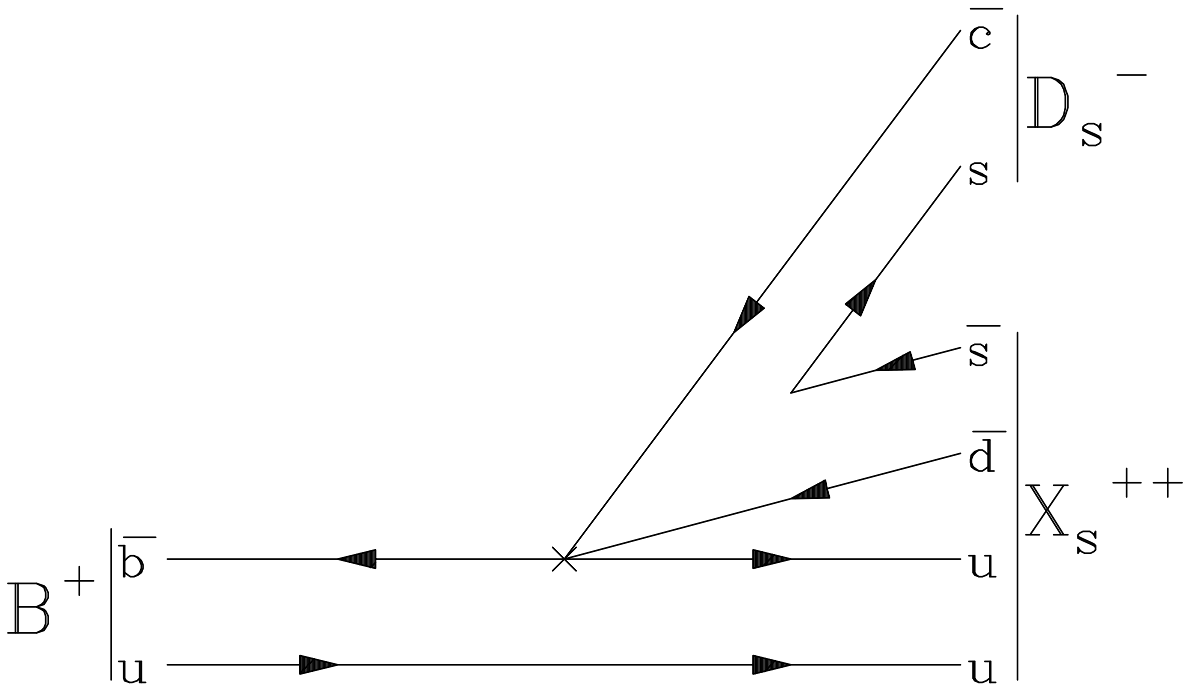

Figure 3: Production of a strange exotic meson $X^{++} = uu\bar{d}\bar{s}$ in B^+ decays.

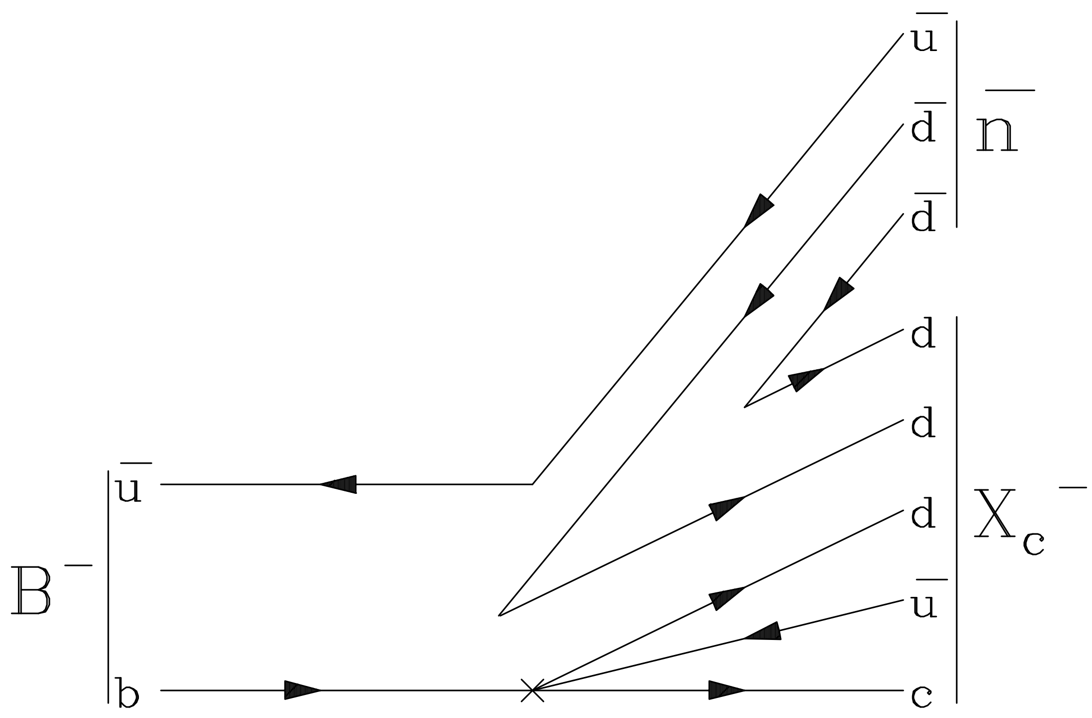

Figure 4: Production of a charmed exotic baryon $X_c^- = cddd\bar{u}$ in B^- decays.

The recoil D_s^- could be replaced by a $\bar{K}\bar{D}$ system. The X_s^{++} can decay, for example, to $\bar{\Lambda}p\pi^+$ if baryon-antibaryon channels are favored, or to $K^+\pi^+(m\pi^0)$ or $K^+\pi^+(m\pi^+m\pi^-)$ ($m = 0, 1, 2, \ldots$) if the lighter exotics of Ref. [8] are favored.

If the final $uu\bar{d}$ state picked up a $\bar{u}$ during fragmentation, we would not be able to tell the exotic nature of the final product. That is why we have focused on fragmentation mechanisms involving $\bar{d}$ or $\bar{s}$.

The presence of baryon-antibaryon pairs in B decays is well-documented. Channels which have been seen include $B \to \bar{D}^{(*)}N\bar{N}$ [19, 21], $B^+ \to K^+p\bar{p}$ [22], $B^0 \to \bar{\Lambda}p\pi^-$ [23], $B^+ \to p\bar{p}\pi^+$, $p\bar{p}K^0$, and $p\bar{p}K^{*+}$ [24], and $B \to \Lambda_c^+\bar{p}(m\pi)$ ($m = 0, 1, 2, 3$) [25, 26]. Theoretical investigations of such decays include [1, 27, 28, 29, 30]. The decays being considered here may involve somewhat higher multiplicities than those reported so far.

IV. EXOTIC BARYONS IN *B* DECAYS

As in exotic meson production, several fragmentation mechanisms can produce exotic baryons in B decays. One, leading to an exotic charmed baryon, is illustrated in Fig. 4 for a non-strange charmed baryon $X_c^- = cddd\bar{u}$ and in Fig. 5 for a strange charmed baryon $X_{cs}^- = cdds\bar{u}$. Here the baryon contains all three quarks produced in the decay $b \to c\bar{u}d$ as well as two more quarks (e.g., dd or ds) picked up during fragmentation. (If a u quark were picked up during fragmentation, we would not be able to tell that the state was exotic.)

A state composed of $cddd\bar{u}$ has the same quantum numbers as $\Sigma_c^0\pi^-$ or $\Lambda_c^+\pi^-\pi^-$. In Fig. 4 this state is shown recoiling against an antineutron, the importance of whose

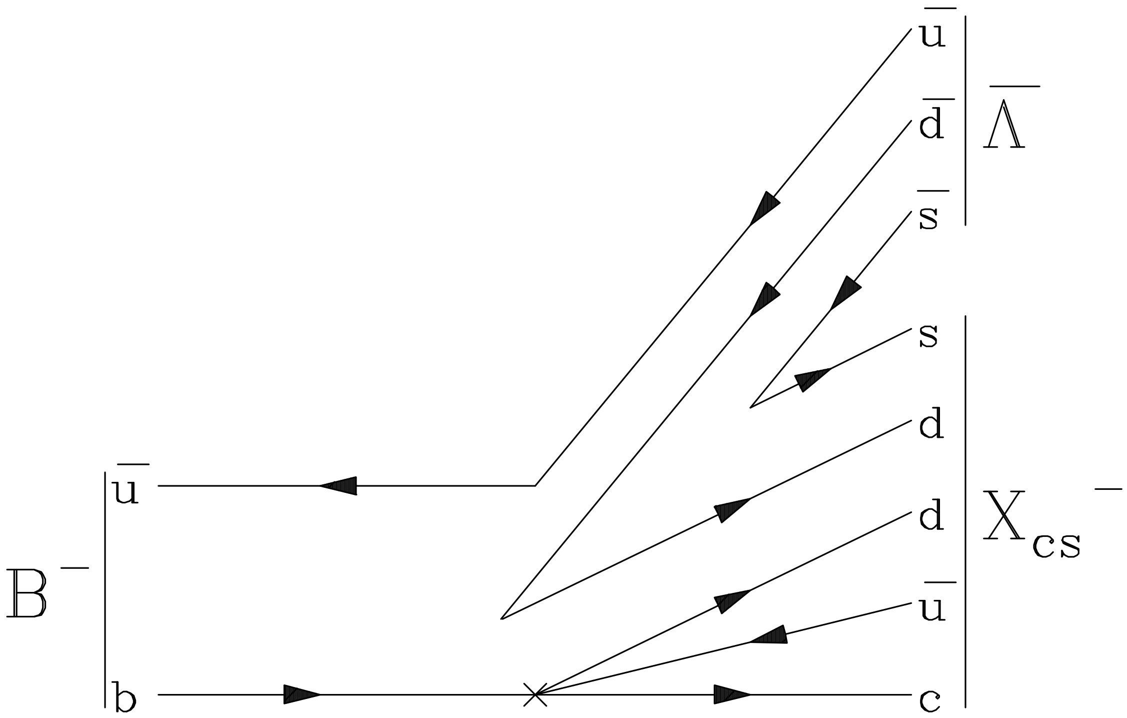

Figure 5: Production of a charmed-strange exotic baryon $X^-_{cs} = cdds\bar{u}$ in B^- decays.

detection we have discussed above. Of course, one could replace $\bar{n}$ by $\bar{p}\pi^+$, looking at the missing mass X^- in $B^- \to \bar{p}\pi^+X^-$. Indeed, the decay $B^- \to \Lambda_c^+\bar{p}\pi^+\pi^-\pi^-$, permitting the study of this final state, has been reported by the CLEO Collaboration [25].

The corresponding charmed-strange state composed of $cdds\bar{u}$ has the same quantum numbers as $\Xi_c^0\pi^-$, and is shown in Fig. 5 recoiling against a $\bar{\Lambda}$. Thus, a useful missing-mass search involves the decay $B^- \to \bar{\Lambda}X^-$.

Another type of fragmentation involves a baryon containing only a subset of the quarks in the final state of $\bar{b} \to \bar{c}u\bar{d}$. An example in which the baryon contains the $\bar{c}u$, a spectator u from the decaying B^+, and two additional d quarks picked up during fragmentation, is shown in Fig. 6.

In the example shown here, the exotic baryon recoils against $\bar{d}\bar{d}\bar{d} = \bar{\Delta}^+$ which decays to $\bar{n}\pi^+$. If one $d\bar{d}$ pair in fragmentation is replaced by an $s\bar{s}$ pair, the exotic baryon recoils against $\bar{d}\bar{d}\bar{s} = \bar{\Sigma}^+$ (or $\bar{\Lambda}\pi^+$), while if both $d\bar{d}$ pairs are replaced by $s\bar{s}$, the exotic baryon recoils against $\bar{d}\bar{s}\bar{s} = \bar{\Xi}^+$. It may be easier to look directly for decay products of the $\Theta_c^0 = uudd\bar{c}$, which could be pD^- if the state is above that threshold. If the state decays weakly via $\bar{c} \to \bar{s}d\bar{u}$, the quantum numbers will be the same as those of $dddu\bar{s}$, i.e., $I_3 = -1,\ S = 1$. This is still manifestly exotic. Karliner and Lipkin [31] have predicted such a state to have a mass of 2985 ± 50 MeV$/c^2$ and to show up as a narrow peak in $\bar{D}^0n$ and D^-p spectra. The decay $D^{*-}p$, which has certain advantages for identification, also may be kinematically allowed. If the mass is light enough, a weak decay can occur involving a detached proton vertex [32].

Our examples have clearly not exhausted nearly all the possibilities for exotic mesons

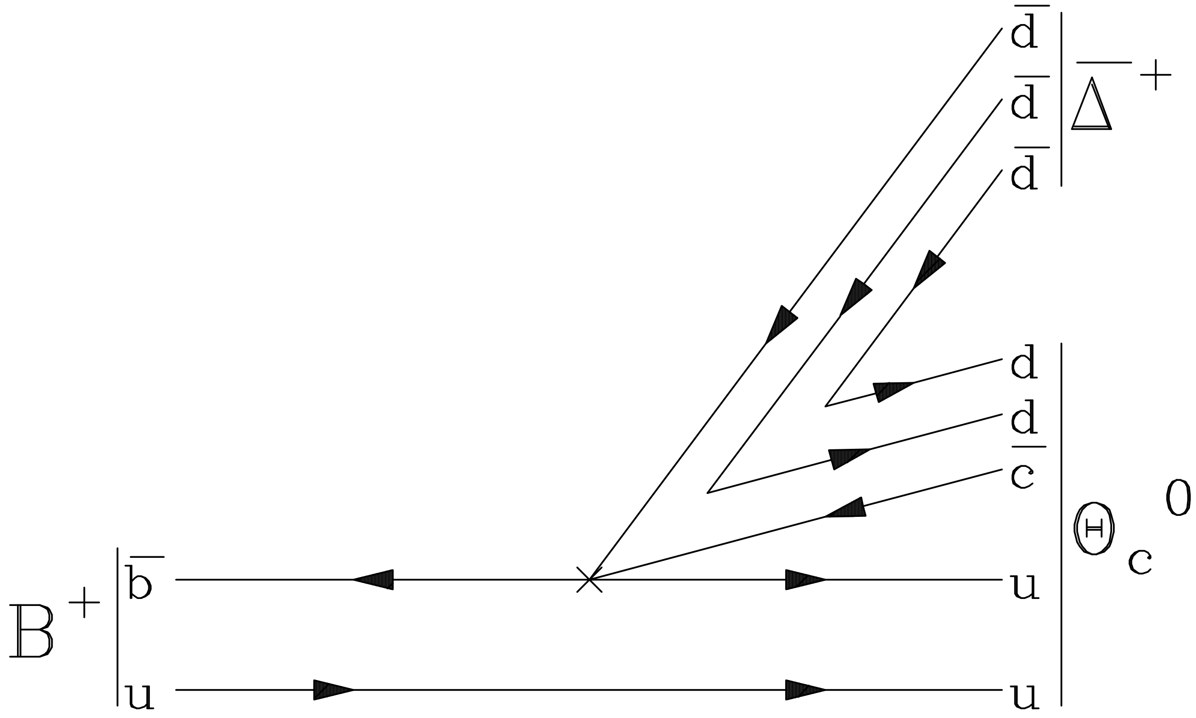

Figure 6: Production of a charmed exotic baryon $\Theta_c^0 = uudd\bar{c}$ in B^+ decays.

and baryons in B decays. Those will be determined as much by experimental opportunities as by a systematic listing of decay and recoil modes. Now, however, we turn our attention to a state which has been the subject of much recent interest.

V. A $uudd\bar{s}$ STATE IN B DECAYS

A narrow $S = 1$ baryon resonance was observed recently in photoproduction from the neutron on ^{12}C [33] and deuterium [34] targets, and in photoproduction from the proton [35]. It was also reported in K^+ collisions with Xe nuclei [36], in neutrino interactions as a $K_S p$ resonance [37], and in the mass spectrum recoiling against Σ^+ in $pp \to pK^0\Sigma^+$ [38, 39]. It has figured prominently in a recent conference devoted to multiquark hadrons, where further references may be found [40]. The state has been dubbed Θ^+. Its minimal quark content would be $uudd\bar{s}$.

The mass of the reported state (around 1540 MeV/c^2) is close to that anticipated from chiral soliton models [16, 17] for a $J^P = 1/2^+$ state. (The prediction of Ref. [16] relies to some extent on identification of an SU(3) partner of the state with an observed $1/2^+$ nucleon resonance at 1710 MeV/c^2.) A $J^P = 1/2^+$ quark configuration is proposed in Ref. [41]. Another (in which the state involves two $I = 0$ ud diquarks bound to an $\bar{s}$ quark with total $J^P = 1/2^+$) appears in [42]; see [4] for other references. The state appears to have zero isospin, showing up only in the $K^0 p$ and $K^+ n$ final states. Its spin and parity are not yet known [43] (see also [39]), and a lattice QCD calculation [44] (see also [45]) predicts negative parity. The direct examination of K^+ charge-exchange and total cross sections on xenon and deuterium, however, shows that if such a resonance exists, its total width must be less than of the order of an MeV [46], considerably less than the value of 15 MeV predicted in Ref. [16]. (See Ref. [47] for a recent discussion of the width prediction.) Partial-wave analyses of K^+N data [48] also exclude a resonance more than a few MeV wide, and other analyses come to similar conclusions [49]. The suggestion has been made that the observed effect may be a kinematic reflection [50].

Part of the difficulty in pinning down such a resonance comes from its decay products. Direct observation of a decay to K^+n requires detection of the neutron, while direct observation of a decay to K^0p is difficult since one only sees the K_S decay mode of K^0. The potential for confusion with the non-exotic $\bar{K}^0p$ channel thus exists. (On the other hand, there is no known evidence for a $\bar{K}^0p$ resonance [a Σ^*] at 1540 MeV/c^2.)

Another potential source of a low-mass kinematic enhancement in the K^+n channel occurs in K^+K^- photoproduction on nuclei. While this mechanism does not apply to all the channels mentioned above, it is a source of concern for some claims for a $\Theta(1540)$.

If the photoproduction of K^+K^- pairs is dominated by a virtual transition in which the pair is kicked into a low-$M(K^+K^-)$ state (e.g., the ϕ) by diffraction, the K^+ and K^- will tend to have equal velocities v with respect to the nucleus. Neglecting nuclear Fermi momentum, the center-of-mass (c.m.) energy of each kaon with respect to each nucleon in the nucleus is roughly the same. The K^- can form a prominent resonance $\Lambda(1520)$ of spin-parity $J^P = 3/2^-$ with any proton in the nucleus. This resonance decays approximately 45% of the time back to $\bar{K}N$ [51], and is quite prominent in the K^-p mass spectra in the aforementioned photoproduction experiments. The emerging K^- from decay of this resonance can have a quite different direction in the c.m. from the initial one, so it no longer will form a state of low effective mass with the K^+.

Meanwhile the K^+, having approximately the same velocity in the laboratory frame as the K^-, is *necessarily forced to have the same effective mass in combination with any other nucleon in the nucleus* as the K^- with the proton. The argument is simplest for the deuteron, in which the binding energy is particularly small. Thus, when $M(K^-p) \simeq 1520$ MeV/c^2, one will necessarily have a low-mass peak in $M(K^+n)$ near the same value. A more explicit calculation should be performed to see whether this is indeed a problem for deuterium or other nuclei.

B meson decays provide a potentially useful source of kaons and baryons whose final-state interactions may be examined for evidence of the Θ^+. (See Ref. [52] for the suggestion that this state be looked for in nucleon-antinucleon interactions.) We consider charmless decays, in which a $\bar{b} \to \bar{s}$ penguin amplitude appears to play a large role. Several examples illustrate the power of these decays in searches.

Consider, for example, the process $B^0 \to p\bar{p}K^0$ reported in Ref. [24]. If one were able to flavor-tag the B^0 so as to be sure it was not a $\bar{B}^0$, one would have an indication of the strangeness of the neutral kaon, since B^0 decays generally lead to $S = 1$ and not $S = -1$ states. One could then examine the K^0p effective-mass spectrum for a low-mass peak.

No flavor tagging would be needed if one were to observe $B^0 \to K^+n\bar{p}$. Given an observation of the neutron, one could then directly plot the K^+n effective mass. However, neutrons are elusive in all detectors.

The charge-conjugate mode $\bar{B}^0 \to K^-\bar{n}p$ produces an antineutron whose annihilation in the calorimeter of the detector may provide enough of a constraint to permit kinematic

Table I: Possible decay modes of a $\Theta^+ = uudd\bar{s}$ observable in B decays. Decay products of the Θ^+ are indicated in square brackets.

Decaying particle	Mode	Comments
B^+	$[K^0p]\bar{n}$	See $\bar{n}$ annihilate
	$[K^0p]\bar{p}\pi^+$	Full reconstruction
	$[K^+n]\bar{p}\pi^+$	Only missing neutron
B^-	$[\bar{K}^0\bar{p}]n$	Only missing neutron
	$[\bar{K}^0\bar{p}]p\pi^-$	Full reconstruction
	$[K^-\bar{n}]p\pi^-$	See $\bar{n}$ annihilate
B^0	$[K^0p]\bar{p}$	Need to flavor tag
	$[K^+n]\bar{p}$	Only missing neutron
$\bar{B}^0$	$[\bar{K}^0\bar{p}]p$	Need to flavor tag
	$[K^-\bar{n}]p$	See $\bar{n}$ annihilate

reconstruction, especially if the opposite-side B^0 is reconstructed as well. One then would search the $K^-\bar{n}$ effective-mass spectrum for evidence of the $\bar{\Theta}^-$.

If one can identify an antineutron in $B^+ \to K^0p\bar{n}$, one can plot the K^0p effective mass with reasonable confidence that the neutral kaon is not a $\bar{K}^0$, since a B^+ charmless decay is much more likely to yield an anti-strange $\bar{s}$ quark than an s quark. If one replaces the $\bar{n}$ in this case with $\bar{p}\pi^+$, the reconstruction of the decay is much more straightforward.

We summarize some decay modes of B mesons useful for searching for the Θ^+ in Table I. Examples of quark diagrams associated with the production of Θ^+ in B decays are given in Figs. 7 and 8. The weak subprocess of interest is $\bar{b} \to \bar{s}q\bar{q}$, where $q = u, d$.

These figures are clearly very similar to those associated with the production of the charmed exotic baryon depicted in the previous Section. There may be some differences associated with differences in the structure of the corresponding weak vertices. In particular, in the penguin diagrams it is not clear how directly the light $q\bar{q}$ pair can be associated with the weak vertex; it may arise as a result of rescattering from the $\bar{b} \to \bar{s}c\bar{c}$ subprocess, in which case Figs. 7 and 8 may represent an oversimplification.

VI. SPECIAL FEATURES OF $\Upsilon(1S)$ DECAYS

The decays of $\Upsilon(1S)$ lead to large numbers of baryons in the final state [53], and even (anti)deuterons have been observed [54]. Thus, it is reasonable to expect $\Upsilon(1S)$ decay products to include multi-quark states beyond $q\bar{q}$ and qqq if they exist.

The neutral light-quark quantum numbers (isospin and strangeness) of the $\Upsilon(1S)$ are an asset in searching for exotic states via missing-mass techniques. One simply looks for a decay $\Upsilon(1S) \to X + Y$, reconstructing all particles in Y and plotting the missing mass in X. If desired, X or Y may be selected for the presence of a baryon or a baryon-antibaryon pair. Or, one may simply plot a mass of the appropriate subsystem.

Suppose one is looking for an exotic meson with quark content $X = uu\bar{d}\bar{d}$. One can reconstruct the subsystem Y in any of a number of ways, such as $\rho^-\rho^-$ or $p\bar{p}\pi^-\pi^-$,

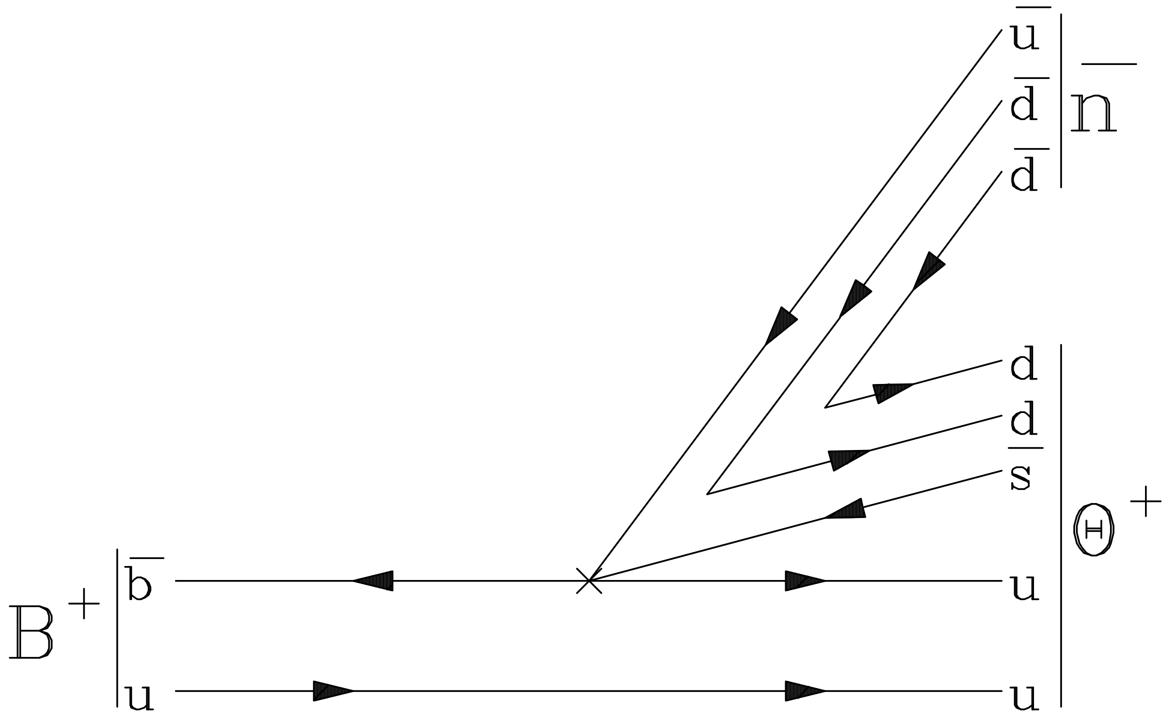

Figure 7: Production of an exotic baryon $\Theta^+ = uudd\bar{s}$ in B^+ decays.

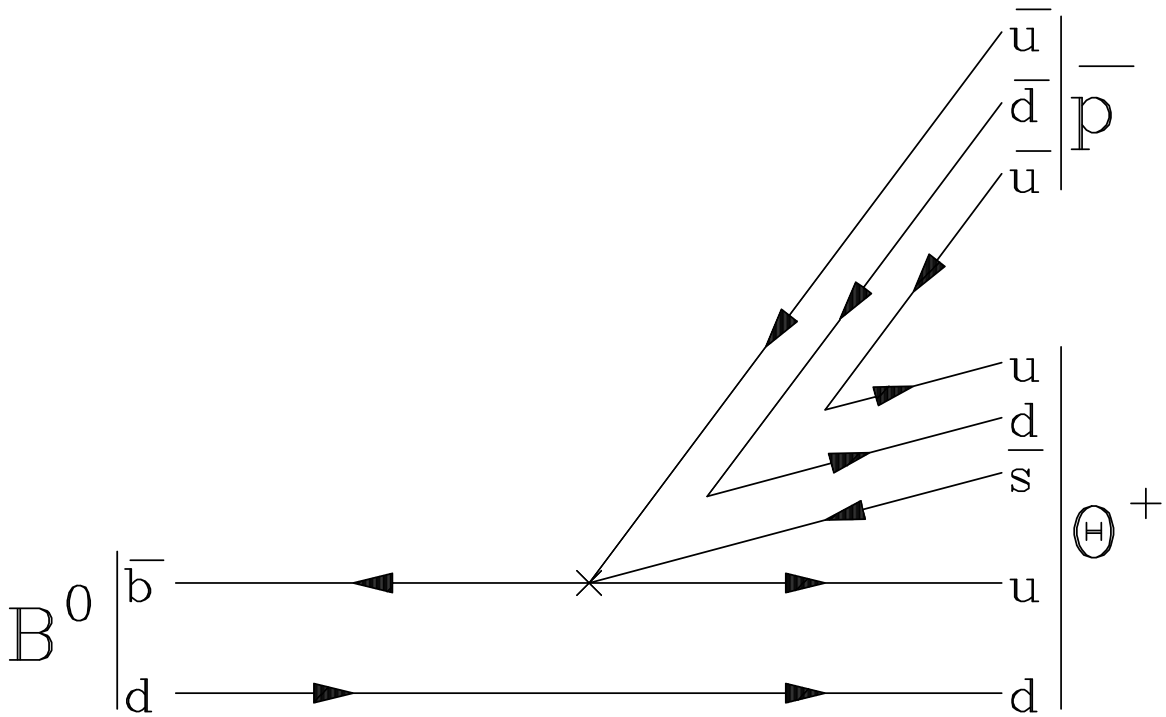

Figure 8: Production of an exotic baryon $\Theta^+ = uudd\bar{s}$ in B^0 decays.

and plot the missing mass in X, or one can directly plot $M(\rho^+\rho^+)$ or $M(p\bar{p}\pi^+\pi^+)$. In searching for $X_s = uu\bar{s}\bar{d}$ one can choose Y to be (e.g.) $\Lambda\bar{p}\pi^-$ or $K^-\pi^-(m\pi^0)$ ($m = 0, 1, 2, \ldots$). One can select for a system X with strangeness $S = 1$, baryon number $B = 1$, and charge $Q = 1$ (the quantum numbers of the reputed Θ^+) by choosing the subsystem Y to have $S = -1$, $B = -1$, and $Q = -1$, for instance by taking $Y = \bar{p}K^-\pi^+$.

The CLEO Collaboration has recently amassed a sample of 21 million $\Upsilon(1S)$ decays, far exceeding that available previously [55]. With the enhanced particle identification capabilities and excellent neutral particle detection of the CLEO-III Detector, this sample should be an excellent one in which to search for exotic systems with internal quantum numbers beyond those of $q\bar{q}$ and qqq.

VII. POSSIBILITIES WITH CHARM

The Cabibbo-favored decays of a charmed quark, $c \to su\bar{d}$, lead to a state with three quarks of distinct flavor. The decay $D^+ = c\bar{d} \to su\bar{d}\bar{d}$ leads to an exotic state. The weakness of final-state interactions in such states may be one reason why the lifetime of the D^+ is longer than that of the D^0 or D_s^+, for which the Cabibbo-favored final states are not exotic [56].

One can then look directly for exotic final states in the decays $D^+ \to X^0 + Y^+_{S=-1}$, where $X^0 = \gamma,\ \pi^0, \ldots$ is used to measure the missing mass of the strange subsystem $Y^+_{S=-1}$. One has to ensure that Y^+ has negative strangeness since if it is non-strange, it will not be exotic. Similarly, the decay $D^0 \to \pi^- Y^+_{S=-1}$ can be used to probe the missing mass of the subsystem Y. Although D decays do not involve enough energy to produce exotic resonances decaying to baryon-antibaryon pairs, they should be able to populate the lighter mass ranges proposed in Ref. [8].

Decay of the J/ψ into light-quark states may allow probes of the lower mass range for exotic systems, using techniques mentioned in the previous Section. Even the decay $J/\psi \to \Theta^+\bar{\Theta}^-$ would be just barely kinematically allowed for a Θ of mass 1540 MeV/c^2. A search for the Θ in J/ψ and $\psi(2S)$ decays has revealed no evidence for the state so far [57].

VIII. SUMMARY

Systems containing heavy quarks are potentially a rich source of information on exotic mesons and baryons containing lighter quarks. We have shown how such information may be obtained from B, $\Upsilon(1S)$, and charm decays. Both B decays and $\Upsilon(1S)$ provide unique advantages in searching for the $\Theta^+(1540)$ recently reported in several experiments, since the final states of interest – K^0p or K^+n – can be easily identified under some cirumstances. For example, B decays favor a particular strangeness (b quarks give rise to s quarks, while $\bar{b}$ quarks give rise to $\bar{s}$ quarks). The nearly hermetic detectors constructed to study B physics have some sensitivity to antineutrons, allowing the study of the $K^-\bar{n}$ final state. (Note added: The reader's attention should also be drawn to the recent Refs. [58, 59, 60] which cite the present work and offer further suggestions.)

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