Low-mass baryon-antibaryon enhancements in *B* decays

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The nature of low-mass baryon-antibaryon enhancements seen in B decays is explored. Three possibilities include (i) states near threshold as found in a model by Nambu and Jona-Lasinio, (ii) isoscalar states with $J^{PC}=0^{\pm +}$ coupled to a pair of gluons, and (iii) low-mass enhancements favored by the fragmentation process. Ways of distinguishing these mechanisms using angular distributions and flavor symmetry are proposed.

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I. INTRODUCTION

In many decays $B\to\overline{D}^{(*)}N\overline{N}$ [1,2], $B^+\to K^+p\overline{p}$ [3], and $B^0\to\overline{\Lambda}p\pi^-$ [4], the baryon-antibaryon effective mass peaks at very low values. Even more pronounced peaking at a low baryon-antibaryon effective mass has now been observed in the radiative decay $J/\psi\to\gamma p\overline{p}$ [5]. The effective mass distribution in this last process is so sharply peaked near threshold that for an S wave the data can be interpreted in terms of a $p\overline{p}$ bound state with $M=1859^{+3+5}_{-10-25}$ MeV/c^2 and $\Gamma<30$ MeV (90% C.L.). For a P wave a fit [5] yields a state just at the $p\overline{p}$ threshold: $M=1876.4\pm0.9$ MeV/c^2, $\Gamma=4.6\pm1.8$ MeV. There are numerous earlier claims for such states (see, e.g., [6] and [7]), but not much unanimity about their properties. An enhancement near threshold is seen in $p\overline{p}\to e^+e^-$ [8], while various multiparticle production processes such as $e^+e^-\to$ hadrons [9], $e^+e^-\to6\pi$ [10], and diffractive photoproduction of 6π [11] show dips at the $p\overline{p}$ threshold.

Theoretical investigations of baryon-antibaryon bound states date back to the proposal of Fermi and Yang [12] to make the pion out of a nucleon-antinucleon pair. The model of Nambu and Jona-Lasinio [13], which is constructed to give a nearly zero-mass pion as a fermion-antifermion bound state, also has a scalar resonance of twice the fermion mass. Enhancements in the baryon-antibaryon channel near threshold are expected on the basis of duality arguments [14–16] and by comparison with the systematics of resonance formation in meson-meson and meson-baryon channels [17]. A historical survey of bound states or resonances coupled to the nucleon-antinucleon channel is given in Ref. [18]. Gluonic states can couple to baryon-antibaryon channels of appropriate spin and parity. Recent discussions of B decays involving baryon-antibaryon pairs include Refs. [19–23].

In the present note we suggest some tests that may be useful in sorting out the various interpretations of the observed effects near or below the baryon-antibaryon threshold. Gluonic states with $J^{PC}=0^{-+}$ can couple to isoscalar $p\overline{p}$ pairs in a $^1S_0$ state, while those with $J^{PC}=0^{++}$ can couple to such pairs in a $^3P_0$ state. The decays of both such states into $p\overline{p}$ are isotropic. Fragmentation-based effects need not (and, we shall argue, should not) lead to such isotropy. The decays of gluonic states should be flavor symmetric, while fragmentation products need not be. The decay $B^\pm\to p\overline{p}K^\pm$ may occur through a similar mechanism, which gives rise to $B^\pm\to\eta'K^\pm$ and $B^0\to\eta'K^0$, involving the emission of two gluons by a penguin diagram.

We discuss gluonic mechanisms in Sec. II and fragmentation mechanisms in Sec. III. Section IV contains some more general remarks about the possibility of observing baryon-antibaryon and other exotic resonances in B decays, while Sec. V concludes.

II. GLUONIC MECHANISMS

The decays of the form $B\to K+X$ receive an important contribution from a “flavor-singlet penguin” amplitude. Here the fundamental subprocess is $\overline{b}\to\overline{s}+g+g$, where $g+g$ stands for a pair of gluons or a nonperturbative structure with vacuum quantum numbers. The need for this amplitude was anticipated [24,25] before it appeared experimentally in the decays $B\to\eta'K$ [26]. The η', being largely a flavor-singlet meson, couples strongly to a pair of gluons with $J^{PC}=0^{-+}$. A flavor-singlet penguin contribution that boosts that of the ordinary penguin amplitude by as little as 50% suffices to explain the observed decay rate [27,28]. Taking account of interference with the ordinary penguin amplitude (whose importance is considerable; see the arguments by Lipkin [29]), the branching ratio of B^+ to $\eta'K^+$ due to the singlet penguin (sp) alone was estimated to be [28]

$$\mathcal{B}(B^+\to\eta'K^+)|_{\rm sp}\geqslant1.1\times10^{-5}. \tag{1}$$

The inequality becomes an equality if the singlet and ordinary penguin interfere constructively. We shall use this result to estimate the value of $\mathcal{B}(B^+\to p\overline{p}K^+)$ due to a gluonic mechanism.

The decays $B^+\to p\overline{p}K^+$ and $J/\psi\to\gamma p\overline{p}$ both appear to be dominated by a $p\overline{p}$ bound state whose mass we shall take to be that for the 0^{-+} (S-wave) fit presented in Ref. [5], or 1859 MeV/c^2. We shall denote this state by E. We assume

$$\frac{\mathcal{B}(B^+\to EK^+)|_{\rm sp}}{\mathcal{B}(B^+\to\eta'K^+)|_{\rm sp}}=\frac{\mathcal{B}(J/\psi\to\gamma E)}{\mathcal{B}(J/\psi\to\gamma\eta')} \tag{2}$$

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modulo phase space corrections. Since E is assumed to be spinless, the $B^+ \to EK^+$ and $B^+ \to \eta' K^+$ decays are characterized by S-wave kinematic factors proportional to the first power of the center-of-mass (c.m.) momenta p^*, with $p^*_{B^+\to EK^+} = 2282$ MeV/c and $p^*_{B^+\to\eta' K^+} = 2528$ MeV/c, respectively. The magnetic dipole ($M1$) J/ψ decays contain kinematic factors proportional to p^{*3}, with $p^*_{J/\psi\to\gamma E} = 990$ MeV/c and $p^*_{J/\psi\to\gamma\eta'} = 1400$ MeV/c. We use the branching ratios [30]

$$\mathcal{B}(J/\psi \to \gamma p\bar{p}) = (3.8 \pm 1.0) \times 10^{-4},$$

$$\mathcal{B}(J/\psi \to \gamma\eta') = (4.31 \pm 0.30) \times 10^{-3}, \tag{3}$$

whose ratio is 0.088 ± 0.024, to calculate

$$\frac{\mathcal{B}(B^+ \to EK^+)|_{\rm sp}}{\mathcal{B}(B^+ \to \eta' K^+)|_{\rm sp}} = \frac{2282}{2528}\left(\frac{1400}{990}\right)^3 (0.088 \pm 0.024)$$

$$= 0.23 \pm 0.06, \tag{4}$$

or, combining this result with Eq. (1),

$$\mathcal{B}(B^+ \to EK^+)|_{\rm sp} \geqslant (2.5 \pm 0.7) \times 10^{-6}. \tag{5}$$

This lower bound is to be compared with the observed branching ratio [3]

$$\mathcal{B}(B^+ \to p\bar{p}K^+) = (4.3^{+1.1}_{-0.9} \pm 0.5) \times 10^{-6}. \tag{6}$$

Thus, the singlet penguin amplitude is expected to provide a fair fraction of the observed final state. Reasons for a shortfall could be that (1) the singlet penguin amplitude is larger than its lower bound based on Eq. (1); (2) there could be some additional contribution from another $p\bar{p}$ partial wave, such as ${}^3P_0$ ($J^{PC} = 0^{++}$); (3) there could be a contribution from the fragmentation mechanism to be discussed in the next section.

The angular distribution of the photon in $J/\psi \to p\bar{p}\gamma$ is found to be compatible with the $1 + \cos^2\theta^*$ expected if the $p\bar{p}$ system is in a state with $J^{PC} = 0^{-+}$ [5]. Here θ^* is measured with respect to the beam direction in the e^+e^- c.m. The same angular distribution is expected for a 0^{++} (${}^3P_0$) $p\bar{p}$ state. The two possibilities could be distinguished from one another by measuring the photon polarization, e.g., in the Dalitz process $J/\psi \to p\bar{p}e^+e^-$.

If the $p\bar{p}$ system is in a $J = 0$ final state (whether 0^{-+} or 0^{++}), the band for the low-mass $p\bar{p}$ enhancement in the Dalitz plot for $J/\psi \to p\bar{p}\gamma$ should be uniformly populated. A similar remark holds for the $p\bar{p}$ system in $B^+ \to p\bar{p}K^+$ if the singlet penguin mechanism is dominant. In such a case one expects the c.m. momentum distributions of p and $\bar{p}$ to be identical. As we shall argue, this is not necessarily the case in a fragmentation picture.

When the $p\bar{p}$ system is produced through a pair of gluons (or any such flavorless state), one should expect isospin symmetry to give the same production rate for an $n\bar{n}$ system. This prediction is difficult to test. In the limit of flavor-SU(3) symmetry one would also expect the same rate for $B_8\bar{B}_8$, where B_8 is any member of the baryon octet, but SU(3) breaking could alter this prediction considerably. For example, the proposed $p\bar{p}$ bound state at 1859 MeV is far below the $\Lambda\bar{\Lambda}$, $\Sigma\bar{\Sigma}$, or $\Xi\bar{\Xi}$ threshold, reducing the likely branching ratios when $p\bar{p}$ is replaced by a hyperon-antihyperon pair. Some nucleon-antinucleon bound states proposed to exist near or below threshold have $I = 1$ [7], and could not be identified with the gluonic effect we are proposing.

III. FRAGMENTATION MECHANISMS

The gluonic mechanism of the previous section is unlikely for certain B decays involving low-mass $p\bar{p}$ states. A singlet penguin mechanism cannot account for such decays as $B^0 \to \bar{D}^0 p\bar{p}$ and $B^0 \to \bar{\Lambda} p \pi^-$. Instead, a fragmentation picture is appealing; this may also play a role in $B^+ \to K^+ p\bar{p}$.

Let us consider the example of $B^0 \to \bar{D}^0 p\bar{p}$. Imagine that the quark subprocess is $\bar{b}d \to (\bar{c}u)_{\bar{D}^0}\bar{d}d$, with subsequent fragmentation of $\bar{d}d$ into $\bar{p}p$ through the creation of two additional $\bar{u}u$ pairs. The fragmentation rate for $\bar{d}d$ into $\bar{p}p$ may differ from that into $\bar{n}n$ and other $B_8\bar{B}_8$ pairs. Moreover, the fact that the d is a spectator quark while $\bar{d}$ was produced in the weak decay can lead to kinematic asymmetries. The Dalitz plot need no longer be uniform along the low-mass $p\bar{p}$ band. Since both the $\bar{D}^0$ and $\bar{d}$ are produced in the weak decay, they are correlated, leading one to expect the inequalities $\langle M(\bar{D}^0\bar{p})\rangle < \langle M(\bar{D}^0 p)\rangle$ between the average effective masses of pairs and $\langle p^*_{\bar{p}}\rangle < \langle p^*_p\rangle$ between average c.m. momenta.

As has been pointed out elsewhere (see in particular Fig. 2 of the last of Refs. [22]), there are other subprocesses contributing to $B^0 \to \bar{D}^0 p\bar{p}$. One involves the exchange process $\bar{b}d \to \bar{c}u$, followed by the fragmentation of $\bar{c}u$ to $\bar{D}^0 p\bar{p}$. Such processes are expected to be suppressed in other B decays (see, e.g., [31]) and there is no reason to expect them to play a major role here.

Another color-suppressed mechanism involves the quark subprocess $\bar{b} \to \bar{c}u\bar{d}$ in which the u is incorporated into a baryon while the $\bar{d}$ is incorporated into an antibaryon. This process is not expected to lead to a low-mass baryon-antibaryon enhancement. Its relative importance is hard to estimate without a detailed flavor-symmetry analysis.

Similar arguments apply to the decay $B^0 \to \bar{\Lambda} p \pi^-$. Since strangeness-changing charmless B decays appear to be dominated by the $\bar{b} \to \bar{s}$ penguin amplitude, we assume that to be the case here, so the expected quark subprocess is $\bar{b}d \to \bar{s}d$ followed by fragmentation of $\bar{s}d$ into $\bar{\Lambda}p\pi^-$. A graph for this process, reading from top to bottom, involves the following subprocesses.

The $\bar{s}$ antiquark is "dressed" by a $\overline{ud}$ antidiquark to form a $\bar{\Lambda}$. The antidiquark is produced with a ud diquark, which is dressed by a u quark to form a proton. The u quark is produced with a $\bar{u}$ antiquark which forms a π^- with the spectator d quark.

In this process the $\bar{\Lambda}$ and the proton are neighbors in the fragmentation chain. One thus expects their effective mass to be low, as is seen. Since the p and π^- are also neighbors, one expects their average effective mass $\langle M(p\pi^-)\rangle$ to be less than the average effective mass $\langle M(\bar{\Lambda}\pi)\rangle$.

The observed branching ratio [4]

$$\mathcal{B}(B^0\to\bar{\Lambda}p\pi^-)=(3.97^{+1.00}_{-0.80}\pm0.56)\times10^{-6} \qquad (7)$$

is quite similar to that for $B^+\to K^+p\bar{p}$ quoted in Eq. (6). Thus, one might expect at least some contribution to this last process from fragmentation. Here the quark subprocess is expected to be $\bar{b}u\to\bar{s}u$, followed by $\bar{s}u$ fragmentation into the final state. Reading again from top to bottom in the diagram, the $\bar{s}$ is dressed with a u to form a K^+. The u is produced in a pair with a $\bar{u}$. The $\bar{u}$ is dressed with $\bar{u}\bar{d}$ to form a $\bar{p}$. The $\bar{u}\bar{d}$ is produced with a ud, which combine with the spectator u to form a proton.

In the fragmentation picture for $B^+\to K^+p\bar{p}$, the Dalitz plot need not be uniform along the low-$p\bar{p}$-mass band. One expects the fact that the K^+ and $\bar{p}$ are neighbors along the fragmentation chain to result in $\langle M(K^+\bar{p})\rangle<\langle M(K^+p)\rangle$ and $\langle p^*_{\bar{p}}\rangle<\langle p^*_p\rangle$. The $\bar{p}p$ system in this case has been formed by fragmentation of a $\bar{u}u$ pair, which is not a flavor singlet, so there are no simple relations for production of other baryon-antibaryon pairs.

A further example that may shed light on the fragmentation process is the decay $B^+\to\pi^+\bar{\Lambda}_cp$ [32,33]. This process has a color-suppressed contribution which can be visualized as involving the intermediate state $\bar{\Lambda}_c\Delta^{++}$ (treated recently in [34]), but more importantly a color-favored contribution involving the subprocess $\bar{b}\to\pi^+\bar{c}$. The $\bar{c}$ and the spectator u quark then fragment into a $\bar{\Lambda}_cp$ final state. Simple kinematic arguments then favor low $M(\bar{\Lambda}_cp)$, as is apparently observed [35].

A similar discussion applies to the decay $B^0\to\pi^+\pi^-\bar{\Lambda}_cp$ [32,33]. Here the $\bar{c}$ produced in the color-favored subprocess $\bar{b}\to\pi^+\bar{c}$ combines with a spectator d to produce $\pi^-\bar{\Lambda}_cp$. This system should have a low effective mass, as should its $\bar{\Sigma}_c^{--}p$ component. Another mechanism for the decay $B^0\to\pi^+\pi^-\bar{\Lambda}_cp$ is $B^0\to\bar{\Sigma}_c^{--}\Delta^{++}$, which proceeds only via W exchange [34] and thus is expected to be highly suppressed.

Some baryon production processes in B decays, such as $B^0\to D^{*-}p\bar{p}\pi^-$ and $B^0\to D^{*-}p\bar{n}$ [1], occur with much larger branching ratios $[\mathcal{O}(10^{-3})]$ than penguin-mediated processes such as Eq. (6) or Eq. (7). In these, it appears that the charged weak current is fragmenting into a nucleon-antinucleon system (plus possible additional pions) [21,22]. Nucleon form factors then favor low effective masses for these subsystems.

If all of the above processes are shown to be compatible with a fragmentation process, what does one learn? First of all, one would then have established the phenomenological observation that fragmentation into baryon-antibaryon pairs leads to low effective masses for those pairs. This feature should be taken into account in any simulation which seeks to describe baryon production. Second, one would have established another feature of low-energy quantum chromodynamics for which any nonperturbative approach (such as lattice gauge theory) is obliged to provide an explanation.

IV. EXOTIC RESONANCES IN *B* DECAYS

The fact that some B decays lead to low-mass baryon-antibaryon enhancements encourages the reopening of an old question which has never been satisfactorily addressed: If such enchancements *do* exist, are they limited to the ordinary quantum numbers of the $q\bar{q}$ system? Some arguments based on duality [14–16] or the systematics of resonance formation [17] suggest instead that baryon-antibaryon enhancements are possible in all systems with the quantum numbers of *two* quarks and *two* antiquarks. If such resonances exist, why are they not seen in ordinary meson-meson channels? A consistent set of selection rules was proposed [36] to forbid such mesonic couplings. B decays offer a new opportunity to test such rules.

Let us consider the decay of a B^+ at the quark level: $\bar{b}u\to\bar{c}u\bar{d}u$. The final state is "exotic" in the sense that it does not share flavor quantum numbers with any quark-antiquark state. Now let the charmed antiquark $\bar{c}$ fragment into a D^- by dressing itself with a d quark. This is produced in a pair with a $\bar{d}$, so that in addition to the D^- we have a meson with the quark content $\bar{d}\bar{d}uu$. This is an exotic meson.

We thus suggest that in the decay $B^+\to D^-X^{++}$ the missing mass of X^{++} be studied. If the selection rules of Ref. [36] are valid, any resonances in the X^{++} channel should decay to baryon-antibaryon pairs. Such pairs might be $p\bar{\Delta}^+$, $\Delta^{++}\bar{n}$, or $\Delta^{++}\bar{\Delta}^0$. The last final state has the property that $p\bar{p}\pi^+\pi^+$ is one of its decay products; the others involve antineutrons and thus might be tricky to observe.

If the $\bar{c}$ quark instead fragments to a D_s^- by dressing itself with an s quark, the remaining meson has the quark content $\bar{s}\bar{d}uu$. Thus in $B^+\to D_s^-X^{++}$ if the missing mass of X^{++} displays peaks, one should see whether such resonances decay to baryon-antibaryon pairs such as $\bar{\Lambda}p\pi^+$.

The selection rules of Ref. [36] also imply that the $\bar{c}\bar{d}uu$ system produced by a B^+ decay can fragment into an exotic antibaryon (composed of four antiquarks and a quark) and a baryon. All one needs is the production of two extra pairs $\bar{q}_1\bar{q}_2q_1q_2$, where neither q_1 nor q_2 is a u quark. Then the exotic antibaryon is $\bar{c}\bar{d}\bar{q}_1\bar{q}_2u$, while the baryon is uq_1q_2. If $q_1=q_2=d$, the baryon is a neutron. The system X^+ in $B^+\to X^+n$ is exotic, but the neutron is difficult to detect. If $q_1=d$ and $q_2=s$, the baryon can be a Λ (easier to see). The system X^+ in $B^+\to X^+\Lambda$ again is exotic; a missing-mass plot would be interesting. Depending on the relative masses of exotic baryons and exotic mesons, such a state might be forced to decay via a violation of the selection rules of Ref. [36].

V. CONCLUSIONS

The observation of low-mass baryon-antibaryon enhancements in B decays has opened a range of interesting possibilities. Some of these enhancements may be associated with coupling to flavorless states of two or more gluons, and may be related to the enhanced branching ratios for $B \to \eta' K$ and $B \to \eta' X$. If they are associated with spinless versions of such states, specific features of the Dalitz plots for three-body decays are expected. Other enhancements may be associated with details of the fragmentation picture, suggesting a short-range correlation between baryons and antibaryons in the fragmentation chain. The possibility that exotic mesons and baryons may be observable in the decays of charged B mesons is a further outcome of the recent experimental observations.

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