VOLUME 86, NUMBER 19 PHYSICAL REVIEW LETTERS 7 MAY 2001

Pathways to Rare Baryonic B Decays

Wei-Shu Hou[1] and A. Soni[2]
[1]Department of Physics, National Taiwan University, Taipei, Taiwan 10764, Republic of China
[2]Physics Department, Brookhaven National Laboratory, Upton, New York 11973
(Received 9 August 2000)

We point out new ways to search for charmless baryonic B decays and suggest that enhanced baryon production is favored by reduced energy release on the baryon side. Thus $B \to \eta' +$ baryon pairs might be larger than $K\pi/\pi\pi$ modes; the argument may be extended to $B \to \gamma + X_s$, and perhaps to $\ell\nu + X_u$. Guess estimates give some branching ratios in the 10^{-3}–10^{-6} range, with confidence gained from the recent observation of $B \to \bar{D}^* p\bar{n}$, $\bar{D}^* p\bar{p}\pi$ not far below $\bar{D}^*\pi$ and $\bar{D}^*\rho$ rates. Observation of modes proposed here would help clarify the dynamics of weak decays involving baryons, while the self-analyzing prowess of Λ decay can be helpful in CP- and T-violation studies.

DOI: 10.1103/PhysRevLett.86.4247 PACS numbers: 14.20.Mr, 13.25.Hw, 13.60.Rj, 14.40.Nd

Many charmless mesonic B decays have emerged at the 10^{-5} level in recent years, giving evidence for strong $b \to s$ penguins and tree level $b \to u$ transitions. In contrast, rare baryonic modes have yet to emerge. The most recent limits [1] are $B \to \bar{\Lambda}p$, $\bar{\Lambda}p\pi^-$ and $\bar{p}p < 0.26$, 1.3, and 0.7×10^{-5}, respectively, improving previous bounds [2] by more than an order of magnitude, though $p\bar{p}$ mode has a 2.8σ excess. Theoretical work on rare baryonic decay is equally sparse [3–6], but in general they predict $B \to \bar{\mathbf{B}}_{(s)}\mathbf{B}$ ($\mathbf{B}$ stands for baryon) to be below 10^{-5}, oftentimes considerably below. With the advent of B factories, two body baryonic modes should eventually emerge. But one may wonder: Where is the best place to search for charmless baryonic modes?

We suggest that charmless baryon-antibaryon final states in B decays may show up in association with η' and/or γ with sizable branching ratios, i.e., $\approx 10^{-5}$–10^{-6} or more. Although theoretical calculations are very unreliable, the bright side of this is that theory will learn much from experiment once the measurements become available. In particular, we would get important input for understanding the dynamics of weak decays. Furthermore, baryonic final states offer new observables that should be sensitive probes of CP and T violation.

We take cue from the surprise discovery of $B \to \eta' + X$ modes. Without theory guidance, the CLEO Collaboration found that both inclusive [7] $B \to \eta' + X_s$ (where $X_s = K + n\pi$) and exclusive [8] $B \to \eta' K$ modes are very large ($>6 \times 10^{-4}$ and $\simeq 8 \times 10^{-5}$, respectively). Theoretical work done after the fact [9] still falls short of the exclusive rate even with some *ad hoc* tuning of parameters. For the inclusive case, an interesting but still controversial proposal [10,11], based on $b \to sg^*$ followed by the $g^* \to g\eta'$ transition (motivated by the gluon anomaly), can account for the observed m_{X_s} recoil spectrum and rate. In the following, we give two semiquantitative arguments, one from inclusive perspective via anomaly mechanism, the other from exclusive perspective with pole model, that suggest $B \to \eta' \bar{\mathbf{B}}_s \mathbf{B}(\pi)$ [12] may be comparable to the $K\pi$ modes and $\sim 10^{-5}$. Interestingly, our suggestion is supported by the recent observation [13] of $B \to \bar{D}^* p\bar{n}$, $\bar{D}^* p\bar{p}\pi$ modes with rates not far below $B \to \bar{D}^*\pi$, $\bar{D}^*\rho$. Emboldened by this, and since $b \to s\gamma \sim 3 \times 10^{-4}$ [14] and $B \to K^*\gamma \simeq 4 \times 10^{-5}$ [15] are comparable to their η' counterparts, we extend the pole model argument and suggest that $B \to \gamma \bar{\mathbf{B}}_s \mathbf{B}(\pi)$ may also be promising. Similarly, $B \to \ell\nu \bar{\mathbf{B}}\mathbf{B}(\pi)$ should also be searched for, although, in this instance, it is not clear how well the reduced energy release argument would apply. We further comment on the special case of $B \to J/\psi \bar{\mathbf{B}}_s \mathbf{B}$ [16], where phase space is extremely limited.

Let us understand why $B \to \bar{\mathbf{B}}_{(s)}\mathbf{B}(\pi)$ modes are so suppressed. Baryon formation in B decays is more difficult than the mesonic case, as reflected in model calculations. In pole models [3,4], the strong $B \to \bar{\mathbf{B}}_b \mathbf{B}_1$ transition ($\mathbf{B}_b$ is a b baryon) is followed by a $\bar{\mathbf{B}}_b \to \bar{\mathbf{B}}_2$ weak transition, where the large imbalance in mass is the main source of uncertainty. The estimate of transitions to final states involving spin 3/2 baryons [4] seems to be ruled out by experiment already [1]. Another intuitive picture involves diquarks, which we denote generically as $\mathbf{D}$. The $b \to \mathbf{D}_1 \bar{q}$ weak decay [5], together with the spectator quark, gives a $\mathbf{D}_1 \bar{\mathbf{D}}_2$ pair. Further creation of $\bar{q}q$ pairs leads to a $\bar{\mathbf{B}}\mathbf{B}$ final state. However, since the energy release in B decays is so much larger than the argued color $\bar{3}$ diquark binding scale ~ 1 GeV, the approach is dubious for charmless two body final states. Finally, the QCD sum rules approach [6] tries to evaluate directly the B-$\bar{\mathbf{B}}_{(s)}$-$\mathbf{B}$ three point function, and it is the only method that has studied penguin effects so far. One may question the applicability of sum rules to B decay to light hadrons, and one again relies on a soft $\bar{q}$-q pair creation model. Hence, it seems better suited for $B \to \bar{\mathbf{B}}_c \mathbf{B}$ processes where the energy release is lower.

We can now understand why $B \to \bar{\mathbf{B}}_{(s)}\mathbf{B}$ modes are suppressed compared to $B \to M_{(s)}\bar{M}$: Baryons are more complex than the "atomic" mesons and harder to form. The weak Hamiltonian induces $\bar{b} \to \bar{d}q\bar{q}$ and $\bar{s}q\bar{q}$ transitions that lead to final states already containing two $q\bar{q}$ pairs, typically with matching color, that project easily onto $M_{(s)}\bar{M}$ final states. In contrast, not all the ingredients are present for the $B \to \bar{\mathbf{B}}_{(s)}\mathbf{B}$ case. The need for an extra $q\bar{q}$ pair leads to suppression either by a strong coupling or by the intrinsic softness of nonperturbative pair creation against the rather hard weak decay.

Applying the diquark model to penguin processes serves to illustrate the point. The process $b \to s\bar{\mathbf{D}}\mathbf{D}$ is not on the same footing as $b \to s\bar{q}q$ because, while quarks are fundamental, diquarks are quark-quark correlations at best up to some typical hadronic scale; $g^* \to \bar{\mathbf{D}}\mathbf{D}$ is suppressed by some form factor with respect to $g^* \to q\bar{q}$ since the g^* virtuality in two body penguin transitions is well above this scale. The smallness of $B \to \bar{\mathbf{B}}_{(s)}\mathbf{B}$ modes is thus rooted in the large energy release.

We have gained some insight into where charmless baryonic B decays may be larger: *One has to reduce the energy release and at the same time allow for baryonic ingredients to be present in the final state.* A natural starting point is the inclusive $B \to \eta' + X_s$ decay, where a large rate of $\simeq 6 \times 10^{-4}$ is observed for $p_{\eta'} > 2.0$ GeV. Much energy is already carried away by the η' while the signal is established by requiring a cut [7] on recoil system mass $m_{X_s} < 2.35$ GeV. The observed m_{X_s} spectrum is so far accounted for only by the anomaly mechanism [10,11], namely $b \to sg^*$ followed by $g^* \to g\eta'$ with effective coupling motivated by the gluon anomaly. It has been argued that the anomaly coupling should be form factor suppressed [17] since the g^* is rather virtual ($\sqrt{q^2} \sim 3$ GeV). However, the problem is interestingly nontrivial [11] because of high glueball scale in the $G_{\mu\nu}\tilde{G}_{\mu\nu}$ channel, which has no analog in the $\gamma^* \to \gamma\pi$ case. At any rate, we take this as a model that is effective in producing fast η' and consider the transition $\bar{b}q \to \eta' + \bar{s}gq$, where $\bar{s}gq$ forms a color singlet.

Treating the gluon as a parton in the final state, the $\bar{s}gq$ system gives an m_{X_s} recoil mass spectrum in good agreement with data [7] and peaks roughly at 2.3 GeV. Although $\bar{s}gq$ clearly can evolve into $K + n\pi$, it is instructive to visualize how it may feed a single kaon. In Ref. [11] an effective $m_g = 0.5$ GeV was used in final state phase space to remove "soft" gluons (below constituent $q\bar{q}$ threshold). Since there are no infrared singularities, it was pointed out that the m_{X_s} region covered by $m_g \lesssim 0.5$ GeV might be swept under the kaon, and could by itself account for the observed size of $B \to \eta' K$. Such "$|\bar{s}gq\rangle$ Fock component" contributions to $B \to \eta' K$ have not been taken into account in the usual approach [9]. Here we extend the picture and exploit $g^* \to \bar{\mathbf{D}}\mathbf{D}$ diquark pair creation to construct baryonic final states.

We illustrate the $\bar{b}q \to \eta' + \bar{s}gq$ transition and $\bar{s}gq \to \bar{s}\bar{\mathbf{D}}\mathbf{D}q$ evolution in Figs. 1(a) and 1(b), respectively. Although the g-$\bar{\mathbf{D}}$-$\mathbf{D}$ coupling can be quantified, we refrain from introducing further model dependence in forming baryons from, say, $\mathbf{D}q$. Rather, we exploit mainly kinematic arguments, by taking m_g as an effective mass in final state phase space to correspond to $\bar{q}q$ or $\bar{\mathbf{D}}\mathbf{D}$ formation thresholds. For $m_g \lesssim 0.6$ GeV $\lesssim 2m_q$, where m_q is the constituent quark mass [18], the gluon has "no place to go," and hence could end up only in the K meson, as argued earlier. For 0.6 GeV $\lesssim m_g \lesssim 1.1$ GeV $\lesssim 2m_s \sim 2m_{\mathbf{D}}$ (we treat m_s and $m_{\mathbf{D}}$ as roughly equal), the gluon can split into only $u\bar{u}$ and $d\bar{d}$, and one has nonresonant formation of $K\pi$, $K2\pi$, etc., or the formation of $|K_g\rangle = |\bar{s}gq\rangle$ hybrid mesons. For $m_g \gtrsim 1.1$ GeV, $s\bar{s}$ and $\bar{\mathbf{D}}\mathbf{D}$ also become open. Until effective m_g becomes very massive, say, beyond 1.8 GeV (could be a bit higher or lower), diquark pair formation is on similar footing with $q\bar{q}$ and is not form factor suppressed, i.e., diquarks remain as correlated quark-quark pairs.

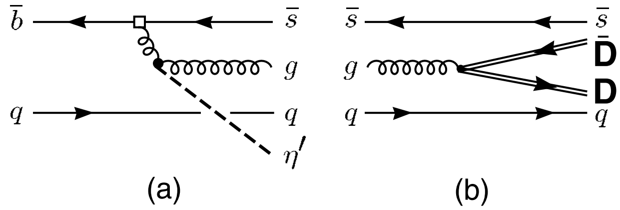

FIG. 1. Baryon formation via (a) $\bar{b}q \to \eta' + \bar{s}gq$ transition, followed by (b) $\bar{s}gq \to \bar{s}\bar{\mathbf{D}}\mathbf{D}q$ evolution, where $\mathbf{D}$ is a diquark.

We depict in Fig. 2 the regions separated by $m_g = 0.6$, 1.1, and 1.8 GeV. Counting spin degrees of freedom only, we estimate that $\sim 1/13$ and up to $3/7$ (depending on scalar or vector diquark nature) of the rate in the 1.1 GeV $\lesssim m_g \lesssim 1.8$ GeV domain corresponds to $\bar{s}\bar{\mathbf{D}}\mathbf{D}q$ final state. For $m_{X_s} < 2.3$ GeV (the recoil peak in anomaly model), phase space and kinematic considerations suggest that this final state would preferentially end up in two body $\bar{\mathbf{B}}_s\mathbf{B}$ final states, given that the $\bar{\Lambda}p$ threshold is at 2.05 GeV. It is likely that one would receive threshold enhancement since diquark pairs are already produced to the right of

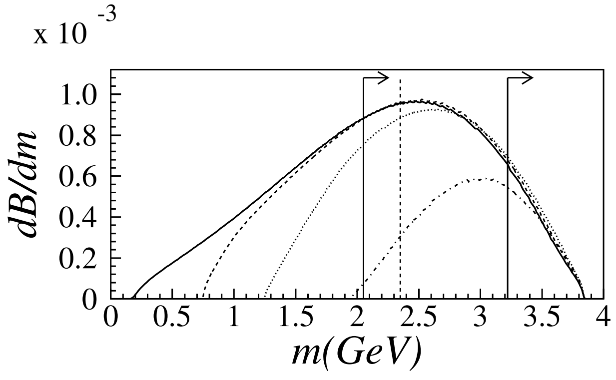

FIG. 2. Phase space argument of $\eta' +$ baryon-pair formation via the mechanism of Fig. 1. Solid, dashed, dotted, and dot-dashed curves correspond to taking $m_g = 0$, 0.6, 1.1, 1.8 GeV in phase space. The "gluon mass" of 0.6 (1.1) GeV marks the opening of $u\bar{u}$, $d\bar{d}$ ($s\bar{s}$, $\bar{\mathbf{D}}\mathbf{D}$) thresholds, while beyond 1.8 GeV, diquark pair formation may suffer from form factors. The dotted vertical line indicates the experimental cut on $m \equiv m_{X_s}$ in $B \to \eta' + K + n\pi$ search, while the two solid vertical lines to the left and right correspond to the $\bar{\Lambda}N$ and $\Lambda_c^+\bar{N}$ thresholds of 2.05 and 3.22 GeV, respectively.

the $m_g \simeq 1.1$ GeV curve. The modes to search for are therefore $B \to \eta'\bar{\Lambda}N$ and similar low lying $\bar{\mathbf{B}}_s\mathbf{B}$ states accompanying a relatively fast η'. We stress that the reconstruction of $\eta'\bar{\mathbf{B}}_s\mathbf{B}$ modes should be easy and with little background, since the $\Lambda_c^+\bar{N}$ threshold does not open up until 3.22 GeV. It therefore may offer an important probe into the higher mass m_{X_s} spectrum not afforded by $X_s = K + n\pi$ modes. One can in principle pursue the inclusive study of $B \to \eta'\bar{\Lambda}N + n\pi(\gamma)$, where γ could come from, e.g., $\Sigma \to \Lambda\gamma$.

The picture outlined above bears some similarity to the explanation for the low $p_{J/\psi}$ "bump" in the feed-down subtracted inclusive primary J/ψ momentum spectrum seen by CLEO [19]. The excess for $p_{J/\psi} < 0.6$ GeV is suggested [16] to be $B \to J/\psi\bar{\Lambda}p$ where there is only 128 MeV available kinetic energy. It is known that $B \to J/\psi + X$ decay has a large $\bar{c}c$ color octet contribution. Although the excess color could be shed by more than one gluon, kinematic arguments were also used to argue for $\bar{\Lambda}p$ in the final state. The enhancement may come about because nonperturbative effects are operative for such low kinetic energy. It should be noted that, because of the latter, the detection of the $\bar{\Lambda}p$ system recoiling against J/ψ would not be easy. In the anomaly model mechanism for explaining fast η' production in B decays as we outlined above, the X_s recoil system has m_{X_s} peaked at 2.3 GeV. On the one hand, this is not far above $\bar{\Lambda}p$ threshold so one again does not expect the opening of many channels. On the other hand, the $\bar{\Lambda}$ and p baryons have considerable kinetic energy since they are recoiling against an energetic η', the energy of which is (conjectured to be) fed by the $g^*g\eta'$ vertex. Thus, discovery of $B \to \eta'\bar{\mathbf{B}}_s\mathbf{B}$ modes with energetic η' may be more straightforward than detecting $B \to J/\psi\bar{\Lambda}p$, which may also give credence to the anomaly mechanism itself.

An alternative approach offers complementary support from a different perspective. Using simple pole model ideas, the $B \to \eta'\bar{\Lambda}p$ decay is seen [Fig. 3(a)] as occurring in two steps: $B \to \eta' +$ "K", followed by "K" $\to \bar{\Lambda}p$, where "K" denotes an off-shell kaon. The first vertex can be normalized to the observed rate for $B \to \eta'K$, but it is very difficult to make reliable statements about the strength of the dimensionless K-p-Λ effective coupling, $g_{b\mathrm{eff}}$. The crude approximation of $g_{b\mathrm{eff}}^2/4\pi \approx 0.3$ gives $\Gamma(B \to \eta'\bar{\Lambda}p)/\Gamma(B \to \eta'K) \approx 0.3$, comparable to the estimate made above through diquark arguments.

Although the pole model ideas are far from reliable, interestingly, some of the latest results from CLEO support the above number. Following a suggestion by Dunietz [20], the first exclusive B decays to nucleons have just been observed, with [13] $B^0 \to D^{*-}p\bar{n}$, $D^{*-}p\bar{p}\pi^+ \approx 1.45 \times 10^{-3}$, 6.6×10^{-4}, respectively, which is not far below $B^0 \to D^{*-}\pi^+$, $D^{*-}\rho^+ \approx 2.8 \times 10^{-3}$, 6.7×10^{-3}. As illustrated in Fig. 3(b), with effective couplings analogous to the K-p-Λ case above, one easily attains order of magnitude understanding of the strength of $D^{*-}N\bar{N}(\pi)$ modes. By analogy, CLEO's observation of sizable exclusive $B \to \bar{D}^*N\bar{N}(\pi)$ decays as compared to $B \to \bar{D}^*\pi$ gives strong support to our argument that $B \to \eta'\bar{\Lambda}N(\pi)$ may not be far lower than $B \to \eta'K$.

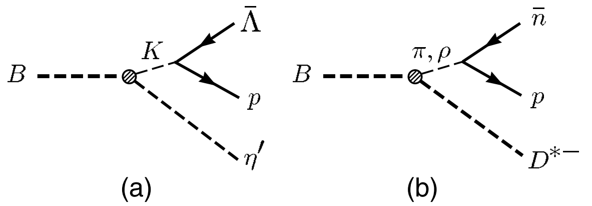

FIG. 3. Pole model diagrams for (a) $B \to \eta'\bar{\Lambda}p$ and (b) $B \to D^{*-}\bar{n}p$ mediated by K, and π, ρ, respectively.

We stress that this data-inspired argument is complementary to our suggestion inspired by the anomaly mechanism for the η' mode. The situation with regard to $B \to \bar{\Lambda}p\gamma$ is quite similar in the pole model picture, except K is replaced by K^*. Similar estimates as above again give $\Gamma(B \to \bar{\Lambda}p\gamma)/\Gamma(B \to K^*\gamma) \approx 0.1$–$0.3$. These estimates place the baryonic branching ratios with η' and γ in the range of 10^{-5}–10^{-6} and therefore within reach of the luminosities of the B factories. As in the $\eta'\bar{\Lambda}p$ case, we stress that the final states $\gamma\bar{\Lambda}p(\pi)$, with energetic photon characteristic of $b \to s\gamma$, are reconstructible, are clean, and have little background.

It is tempting to extend the pole model picture further to $B \to \ell^+\nu$ plus baryon pairs. However, it is not clear if the argument for reduced energy release is applicable when baryon pairs accompany semileptonic decays. In fact, charmed baryon production in semileptonic B decays, where one has reduced energy release, is relatively suppressed [21]. In particular, $B \to \Lambda_c^- pe^+\nu < 0.0015$ [21] which is 30 times smaller than $B \to D^*\ell\nu$, suggesting that $B \to \ell^+\nu + \bar{\mathbf{B}}_c\mathbf{B}(\pi)$ may be less promising than in association with fast η' or γ. But perhaps semileptonic B decays involving charmed baryons may be suppressed by too small an energy release and/or by a smaller $D^{(*)}$-Λ_c-N coupling, although for the Cabibbo-suppressed $b \to u$ case, $B \to \ell^+\nu + \bar{\mathbf{B}}\mathbf{B}(\pi)$ may still be at the 10^{-5}–10^{-6} level.

Before we conclude, let us review, in descending order of inclusive rate, the processes to be studied for charmless baryonic B decays. While $B \to J/\psi + X \sim 1\%$, one has very limited phase space for $X = \bar{\Lambda}p$ (the *only* possibility). A distortion or bump at low J/ψ momentum indicates that $B \to J/\psi\bar{\Lambda}p$ could be of order 4%–5% of $B \to J/\psi + X$ rate. But this mode is not easy to reconstruct because of the very slow proton. For semileptonic $B \to \ell^+\nu + X_u \sim 10^{-3}$, one faces a bound on charm baryon content of $B \to \ell^+\nu + X_c < 1.5\%$ of semileptonic rate. However, if charm and light baryon formation are different, charmless baryon content of semileptonic decays may still be promising. For $B \to \eta' + X_s \sim 10^{-3}$, we expect X_s to be $\sim$10% or more composed of $\bar{\mathbf{B}}_s\mathbf{B}(\pi)$, by both anomaly mechanism and pole model arguments,

TABLE I. Estimates of branching ratios of some final states with baryon-antibaryon pairs. $\bar{B} \to D^* N \bar{N}$ data indicate that the optimistic estimate may well be realized. The semileptonic case is less certain.

Mode	Inclusive	Exclusive	Source
$D^* N \bar{N}$	$>10^{-3}$	$\sim 10^{-3}$	Expt.
$J/\psi \Lambda \bar{p}$	$\cdots$	few$\times 10^{-4}$	Ref. [16]
$\eta' \Lambda \bar{p}$	10^{-4}–10^{-5}	10^{-5}–10^{-6}	Our estimate
$\gamma \Lambda \bar{p}$	10^{-4}–10^{-5}	10^{-5}–10^{-6}	Our estimate
$\ell \nu B_c \bar{B}$	$<3.2 \times 10^{-3}$	$<1.5 \times 10^{-3}$	Expt.
$\ell \nu B \bar{B}$	10^{-4}–10^{-5}	10^{-5}–10^{-6}	Our estimate

which is strengthened by newly observed $B \to D^* N \bar{N}(\pi)$ modes. For $B \to \gamma + X_s \sim 3 \times 10^{-4}$, the pole model argument suggests that baryonic recoil could again be 10% or more. These considerations lead us to summarize the expected hierarchy of baryonic modes as in Table I.

It should be stressed that, besides yielding useful information about the dynamics of weak decays, the observation of baryonic final states suggested here could open up a new direction of studies. It is well known that Λ decay self-analyzes its spin, which can be important for studying CP or T violation. In particular, one can construct T_N-odd observables such as $\vec{s}_{\bar{\Lambda}} \cdot (\vec{p}_p \times \vec{p}_{\bar{\Lambda}}) \equiv \kappa_{\bar{\Lambda}}$ and similarly $\kappa_\Lambda \equiv \vec{s}_\Lambda \cdot (\vec{p}_{\bar{p}} \times \vec{p}_\Lambda)$ for the conjugate decay. Combining information from B and $\bar{B}$ decays, one can form $\Delta_{\text{odd,even}} = \kappa_{\bar{\Lambda}} \mp \kappa_\Lambda$ which is CP-odd, even. Now, unlike the partial rate asymmetry (PRA), a very commonly used CP-odd, T_N-even observable, Δ_{odd} is driven by the dispersive part of the Feynman amplitude; hence it probes genuine CP-violating triple correlation asymmetry. One may learn about final state interaction phases through Δ_{even} since it is T_N-odd, and such information may help improve our ability to quantitatively predict the PRA between these conjugate modes.

Interestingly, several studies have emphasized the possibility of large PRAs in exclusive (mesonic) and inclusive B decays with final states containing η' [22]. This is especially so for $B \to \eta' \pi$ wherein tens of percents of asymmetries are predicted in model calculations [22]. It is, therefore, very reasonable that baryonic final states under discussion here should also have appreciable asymmetries; in particular, modes such as $B \to \eta' p \bar{p}$ and $\eta' \Lambda \bar{\Lambda}$ should both be promising candidates for PRAs, and the latter one should also be sensitive to CP-violating triple correlation asymmetries. Furthermore, since η' and photonic modes are dominantly loop induced, they may turn out to be very useful as sensitive probes of new physics.

In conclusion, we point out that $B \to \eta' + \bar{\mathbf{B}}_s \mathbf{B}(\pi)$ could be the most promising charmless baryonic modes. The η' should still be fast, and for m_{X_s} that is not far above $\bar{\Lambda} p$ threshold, the baryonic recoil system is simple and of low multiplicity. These modes not only could be the first charmless baryonic modes to be detected, their detection could strengthen the anomaly picture, and provide new probes for CP and T violation by bringing in the powerful self-analyzing Λ spin observable. Though the argument gets a bit less compelling, a parallel program should also be started to reconstruct baryonic modes in the recoil system against the photon in $B \to \gamma + X_s$. The traditional search for two body $B \to \bar{\mathbf{B}}_{(s)} \mathbf{B}$ modes, of course, should continue, but observation of rare charmless baryonic B decays proposed here could open a new program for the study of the interplay of weak and strong dynamics, and offer very important probes of new CP and T violation observables.

This work is supported in part by Grants No. NSC 89-2112-M-002-036 of R.O.C. and No. DE-AC02-98CH10886(BNL) of U.S. DOE. We thank Jim Alexander, Tom Browder, Tony Rubiera, and John Yelton for discussions.

[1] T. E. Coan *et al.,* Phys. Rev. D **59**, 111101 (1999).
[2] Particle Data Group, C. Caso *et al.,* Eur. Phys. J. C. **3**, 1 (1998).
[3] N. Deshpande, J. Trampetic, and A. Soni, Mod. Phys. Lett. **3A**, 749 (1988).
[4] M. Jarfi *et al.,* Phys. Lett. B **237**, 513 (1990); Phys. Rev. D **43**, 1599 (1991).
[5] P. Ball and H. G. Dosch, Z. Phys. C **51**, 445 (1991).
[6] V. Chernyak and I. Zhitnitsky, Nucl. Phys. **B345**, 137 (1990).
[7] T. E. Browder *et al.,* Phys. Rev. Lett. **81**, 1786 (1998).
[8] B. Behrens *et al.,* Phys. Rev. Lett. **80**, 3710 (1998).
[9] A. Ali, G. Kramer, and C. D. Lü, Phys. Rev. D **58**, 094009 (1998); Y. H. Chen *et al., ibid.* **60**, 094014 (1999).
[10] D. Atwood and A. Soni, Phys. Lett. B **405**, 150 (1997).
[11] W. S. Hou and B. Tseng, Phys. Rev. Lett. **80**, 434 (1998).
[12] The π in the parentheses is to serve as a reminder that the reaction can occur at an exclusive (no π) and also at an inclusive ($n\pi$) level.
[13] S. Anderson *et al.,* hep-ex/0009011.
[14] M. S. Alam *et al.,* Phys. Rev. Lett. **74**, 2885 (1995).
[15] T. E. Coan *et al.,* Phys. Rev. Lett. **84**, 5283 (2000).
[16] S. J. Brodsky and F. S. Navarra, Phys. Lett. B **411**, 152 (1997).
[17] A. L. Kagan and A. A. Petrov, hep-ph/9707354.
[18] As we aim at low energy release on the baryonic side, this makes the use of constituent quark masses tenable.
[19] R. Balest *et al.,* Phys. Rev. D **52**, 2661 (1995).
[20] I. Dunietz, Phys. Rev. D **58**, 094010 (1998).
[21] G. Bonvicini *et al.,* Phys. Rev. D **57**, 6604 (1998).
[22] M. R. Ahmady and E. Kou, Phys. Rev. D **59**, 054014 (1999); A. S. Dighe, M. Gronau, and J. L. Rosner, Phys. Rev. Lett. **79**, 4333 (1997). See also Ref. [11] and D. Atwood and A. Soni, Phys. Rev. Lett. **79**, 5206 (1997).