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Search for Baryons in the Radiative Penguin Decay $b \to s\gamma$

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Abstract

We have searched for the baryon-containing radiative penguin decays $B^- \to \Lambda\overline{p}\gamma$ and $B^- \to \Sigma^0\overline{p}\gamma$, using a sample of 9.7×10^6 $B\overline{B}$ events collected at the $\Upsilon(4S)$ with the CLEO detector. We find no evidence for either, and set 90% confidence level upper limits of

$$[\mathcal{B}(B^- \to \Lambda\overline{p}\gamma) + 0.3\mathcal{B}(B^- \to \Sigma^0\overline{p}\gamma)]_{E_\gamma > 2.0 \text{ GeV}} < 3.3 \times 10^{-6} \ ,$$

$$[\mathcal{B}(B^- \to \Sigma^0\overline{p}\gamma) + 0.4\mathcal{B}(B^- \to \Lambda\overline{p}\gamma)]_{E_\gamma > 2.0 \text{ GeV}} < 6.4 \times 10^{-6} \ .$$

From the latter, we estimate

$$\mathcal{B}(B \to X_s\gamma, X_s \ \textit{containing baryons})_{E_\gamma > 2.0 \text{ GeV}} < 3.8 \times 10^{-5} \ .$$

This limit implies upper limits on corrections to CLEO's recent measurement of branching fraction, mean photon energy, and variance in photon energy from $b \to s\gamma$ that are less than half the combined statistical and systematic errors quoted on these quantities.

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The branching fraction for the radiative penguin decay $b \to s\gamma$ has been shown to place significant restrictions on physics beyond the Standard Model (SM) [1]. The photon energy spectrum, in contrast, is insensitive to beyond-SM physics [2], but provides information on the b quark mass and momentum within the B meson, information useful for determining the CKM matrix elements $|V_{ub}|$ and $|V_{cb}|$. Some measurements of $\mathcal{B}(b \to s\gamma)$ [3, 4], including the most precise one to date [5], and the best measurement of the photon energy spectrum [5] include a technique ("pseudoreconstruction") that has reduced sensitivity to those $B \to X_s\gamma$ decays with baryons in the final state. It is therefore important to determine what fraction of $B \to X_s\gamma$ decays lead to baryons, or to place an upper limit on that fraction.

Calculations of the mass distribution of the $s\bar{q}_{spectator}$ system that hadronizes into X_s [2, 6] show 1/3 of the spectrum above 2.05 GeV/c^2, the threshold for $\Lambda\overline{p}$ (the lightest baryon-containing final state), so a sizeable rate for $b \to s\gamma$ with baryons would not be unexpected. Of the spectrum above $\Lambda\overline{p}$ threshold, 2/3 is below 2.5 GeV/c^2, so one expects the baryon-containing final states to be dominated by $\Lambda\overline{N}$ and $\Sigma\overline{N}$. Thus, measurements of the branching fractions for $B \to \Lambda\overline{N}\gamma$ and $B \to \Sigma\overline{N}\gamma$ would help estimate a correction to the $b \to s\gamma$ branching fraction and photon energy spectrum. In addition, the decay $B \to \Lambda\overline{N}\gamma$ provides a method for determining the helicity of the photon in $b \to s\gamma$. For $\Lambda\overline{N}$ systems near threshold (s-wave), or for Λ and $\overline{N}$ near back-to-back to the photon (thus orbital angular momentum perpendicular to the photon), the Λ and γ have the same helicity. A measurement of the Λ helicity, via its decay angle distribution, gives a measurement of the γ helicity. We have therefore conducted searches for $B^- \to \Lambda\bar{p}\gamma$ and $B^- \to \Sigma^0\bar{p}\gamma$ and their charge conjugates.

The data used for this analysis were taken with the CLEO detector [7] at the Cornell Electron Storage Ring (CESR), a symmetric e^+e^- collider, and consist of 9.1 fb^{-1} on the $\Upsilon(4S)$ resonance (9.7×10^6 $B\overline{B}$ events) and 4.4 fb^{-1} 60 MeV below the resonance. We select hadronic events that contain a $\Lambda \to p\pi^-$, a $\overline{p}$, and a high energy photon (E_γ^{lab} >1.5 GeV), or contain a $\overline{\Lambda}$, a p, and a high energy photon. (Henceforth, charge conjugate modes are implied.) For the $B^- \to \Sigma^0\bar{p}\gamma$ search we *do not* reconstruct the Σ^0, but analyze as if the decay were $B^- \to \Lambda\bar{p}\gamma$, not detecting the soft photon from $\Sigma^0 \to \Lambda\gamma$. The high energy photon must lie in the central region of the calorimeter ($|\cos\theta_\gamma| < 0.7$), must not form a π^0 or η meson with any other photon in the event, and must have a lateral energy distribution in the calorimeter consistent with that for a photon. The Λ requirements involve significance of displacement of vertex from interaction point and consistency of dE/dx and time of flight of the decay proton candidate with expectation. They result in a Λ candidate sample that is 90% pure. The antiproton candidate must pass dE/dx and time of flight requirements and must not form a $\overline{\Lambda}$ with any π^+ candidate in the event.

We compute the standard B reconstruction variables $M_{\rm cand} \equiv \sqrt{E^2_{\rm beam} - P^2_{\rm cand}}$ and $\Delta E \equiv E_{\rm cand} - E_{\rm beam}$, keeping for further analysis events with $M_{\rm cand} > 5.0$ GeV/c^2 and $|\Delta E| <$ 0.5 GeV. P_{cand} and E_{cand} are computed from Λ, $\bar{p}$, and γ only, both for $B^- \to \Lambda\bar{p}\gamma$ and $B^- \to \Sigma^0\bar{p}\gamma$. With this event selection, there is negligible background from other B decay processes, but substantial background from continuum processes: initial state radiation, photons from decays of π^0 or η that have escaped the veto, photons from decays of other hadrons. To suppress the continuum background, we compute twelve event shape variables and apply loose cuts on three of them. The twelve variables are then used as inputs to a neural net. The net is trained to distinguish between signal and continuum background using Monte Carlo samples of each. Monte Carlo samples distinct from those used to train the net are used to determine that cut on neural net output which would give the lowest upper limit on the branching fraction should the branching fraction actually be zero, and also that cut which would allow us to see the smallest possible signal. Those two cuts differ little, and we use their average.

The event shape variables are calculated in two frames of reference, the lab frame and the primed frame, the frame of the system recoiling against the photon. Variables in the primed frame are better at rejecting initial state radiation; those in the lab frame are better at rejecting other continuum events. The twelve input variables to the neural net are 1) $|\cos\theta_{tt}|$, where θ_{tt} is the angle between the thrust axis of the candidate B and the thrust axis of the rest of the event, calculated in the lab frame; 2) $|\cos\theta'_{tt}|$, the same, but calculated in the primed frame; 3) the thrust of the candidate B; 4) the thrust of the rest of the event; 5) R_2, the ratio of second and zeroth Fox-Wolfram [8] moments, calculated in the lab frame; 6) R'_2, the same, but calculated in the primed frame; 7) $|\cos\theta'|$, where θ' is the angle between the photon and the thrust axis of the rest of the event, all calculated in the primed frame; 8) and 9) energies in 20° and 30° cones about the photon direction (excluding the photon energy); 10) the sum of the magnitudes of the component of momentum perpendicular to the thrust axis of the candidate B, for particles more than 45° from this axis, divided by the sum of the magnitudes of momentum for all particles, in both sums excluding particles from the candidate B, in the lab frame; 11) the same, but evaluated in the primed frame; and 12) $\cos\theta_B$, where θ_B is the angle between the beam direction and the direction of the candidate B.

The loose cuts are $R_2 < 0.5$, $R'_2 < 0.3$, $|\cos\theta_{tt}| < 0.8$. Having obtained substantial suppression of background with the loose cuts and the cuts on the net output, our final selection is from the $2D$ distribution in $M_{\rm cand} - \Delta E$ space. We define a "signal box" $|\Delta E| < 84$ MeV, $|M_{\rm cand} - M_B| < 8$ MeV$/c^2$, which, based on Monte Carlo simulation, should contain $\sim$90% of the $B^- \to \Lambda\bar{p}\gamma$ signal events and (0.75 ± 0.15)% of the background events. We use the yield of events in the large $M_{\rm cand} - \Delta E$ region (excluding the signal box), $M_{\rm cand} > 5.0$ GeV$/c^2$, $|\Delta E| < 0.5$ GeV, to predict the background in the signal box. For $B^- \to \Sigma^0\bar{p}\gamma$, we shift the signal box by 114 MeV to negative ΔE, compensating for the missing soft photon from $\Sigma^0 \to \Lambda\gamma$. The shifted signal box should contain $\sim$80% of the $B^- \to \Sigma^0\bar{p}\gamma$ signal events.

The $2D$ distributions in $M_{\rm cand} - \Delta E$ space, On-4S resonance and Below-resonance, are shown in Fig. 1. There are 84 events On-resonance, and 43 events Below-resonance (with $\sim$ half the luminosity), leading to a background prediction of 0.6 events On, 0.3 events Below, in either signal box. In the $B^- \to \Lambda\bar{p}\gamma$ signal box, we observe zero events On and one event Below. In the $B^- \to \Sigma^0\bar{p}\gamma$ signal box, we observe one event On and zero events Below. The one On event has a B rest frame photon energy of 2.18 GeV, estimated by imposing the constraints that the undetected $\Sigma^0 \to \Lambda\gamma$ decay photon brings ΔE to zero, and combines with the Λ to give the Σ^0 mass. Thus, we have no evidence for $B^- \to \Lambda\bar{p}\gamma$, and have a 90% confidence level upper limit on its true mean of 2.30 events. For $B^- \to \Sigma^0\bar{p}\gamma$, with one event observed and a background of 0.6 events expected, we also have no evidence of signal. We use the pre-Feldman-Cousins PDG procedure[9] for calculating upper limits. We allow for a systematic error in background by conservatively using only half the expected background in the upper limit calculation. That gives a "conservative 90% confidence level" upper limit of 3.64 events. With the additional requirement that the B rest frame photon energy be greater than 2.0 GeV, the background in the large $M_{cand} - \Delta E$ region drops to 27 events On and 15 events Below, with 0.21 background events predicted for the $B^- \to \Sigma^0\bar{p}\gamma$ signal box. This leads to an upper limit of 3.80 events for $E_\gamma > 2.0$ GeV.

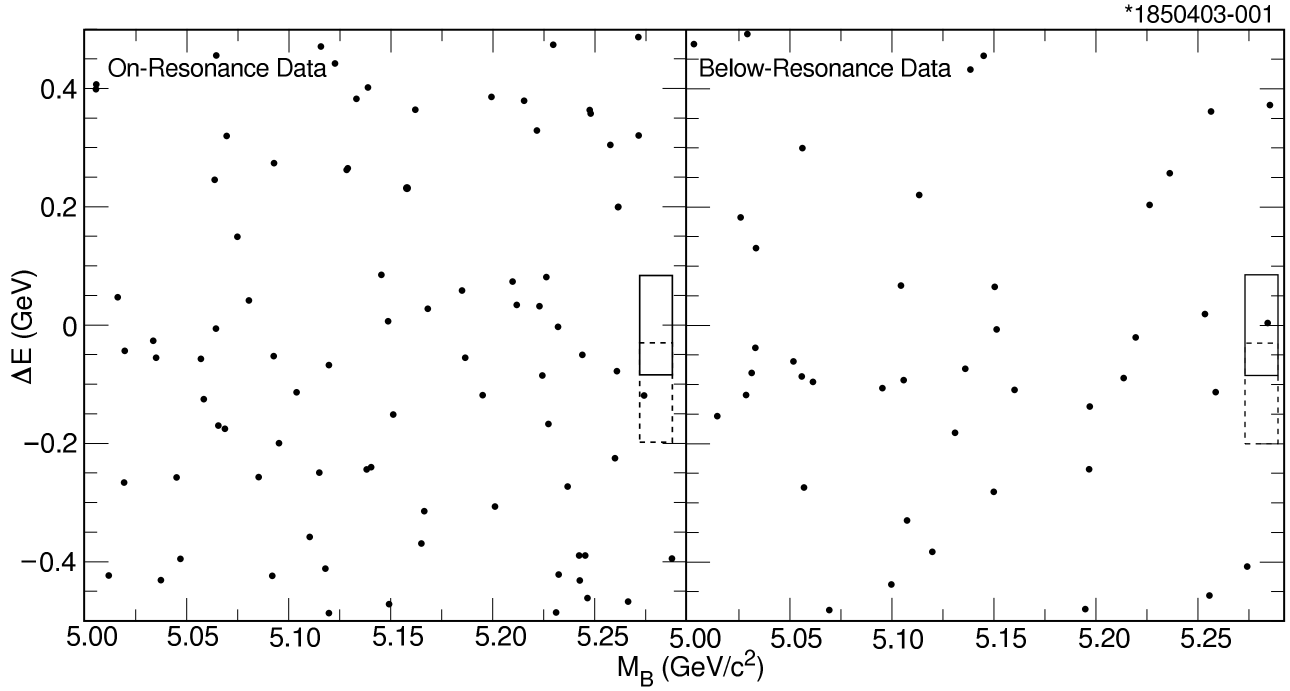

FIG. 1: $M_B - \Delta E$ for On and Below resonance data and photons with $E_\gamma^{lab} > 1.5$ GeV. The solid box shows the tight signal box ($5.272 < M_B < 5.288$ GeV/c^2, $|\Delta E| < 0.084$ GeV) used for determining the $B^- \to \Lambda\overline{p}\gamma$ yield. The dashed box is shifted downward in ΔE by 114 MeV and is used for determining the $B^- \to \Sigma^0\overline{p}\gamma$ yield.

The upper limit on the branching fraction will be those upper limits on the number of signal events, divided by the number of charged B's, by the $\Lambda \to p\pi^-$ branching fraction, and by the detection efficiency.

We assume equal number of charged and neutral B's, noting that a correction for this assumption can be applied at such time as the B^+B^- to $B^0\overline{B^0}$ ratio in $\Upsilon(4S)$ decays has been well determined. Thus, we have 9.7 million charged B's. We assign a $\pm 2\%$ uncertainty to that number.

We use Monte Carlo simulation to determine the efficiency for detecting $B^- \to \Lambda\overline{p}\gamma$, and $B^- \to \Sigma^0\bar{p}\gamma$. The Standard Model predicts left-handed photons and s quarks in $b \to s\gamma$, and thus the Λ's in $B^- \to \Lambda\bar{p}\gamma$ will tend to be left-handed. This tendency decreases the number of pions from $\Lambda \to p\pi^-$ that decay against the Λ boost direction. Such pions are soft and more difficult to detect. Thus, SM decays will have a detection efficiency *higher than* that of unpolarized Λ's. For an upper limit, we conservatively assume unpolarized Λ's. For $B^- \to \Sigma^0\bar{p}\gamma$, we also assume unpolarized Λ's.

The efficiency as a function of $\Lambda\bar{p}$ mass is shown in Fig. 2. The sharp fall-off near 3.5 GeV/c^2 is caused by the photon energy requirement, $E_\gamma^{lab} > 1.5$ GeV. The gentler decrease from 2.4 to 3.4 GeV/c^2 is caused by the background suppression requirements. Similar results are obtained for $\Sigma^0\overline{p}$. We assume a $\Lambda\bar{p}$ mass distribution ($\Sigma^0\bar{p}$ mass distribution) given by the parton-level hadronic mass distribution [2, 6] times a phase space factor P/M, P being the momentum of Λ or $\bar{p}$ (Σ^0 or $\bar{p}$) in the $\Lambda\bar{p}$ ($\Sigma^0\bar{p}$) rest frame, for that value of $\Lambda\bar{p}$ ($\Sigma^0\bar{p}$) mass M. We have also used a weighting P^3/M, appropriate for a p-wave system.

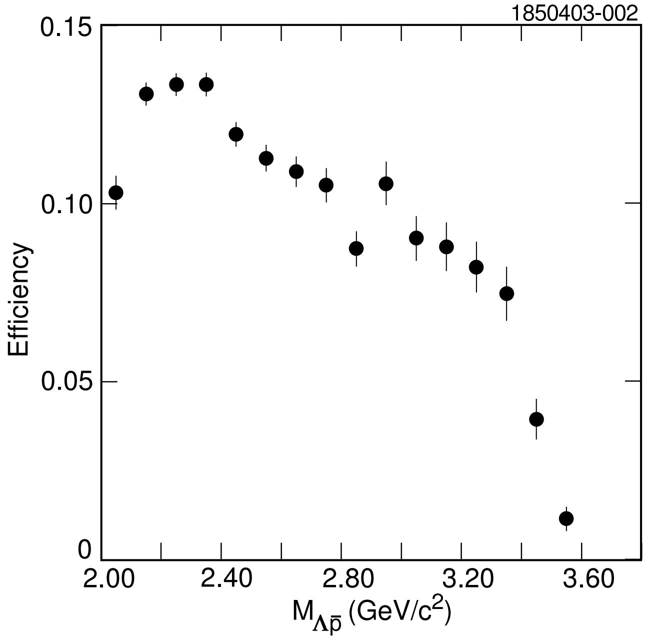

FIG. 2: Efficiency as a function of $M_{\Lambda\bar{p}}$, for signal Monte Carlo, with all cuts applied.

As we are primarily interested in decays with a high energy photon, we compute the efficiency for the subset of events with B rest frame photon energy $E_\gamma > 1.5$ GeV ($M_{\Lambda\bar{p}} < 3.5$ GeV/c^2), and with $E_\gamma > 2.0$ GeV ($M_{\Lambda\bar{p}} < 2.6$ GeV/c^2). For $B^- \to \Lambda\bar{p}\gamma$, for events with $E_\gamma > 1.5$ GeV we find efficiencies of 11.6% (for P/M) and 10.5% (for P^3/M); for events with $E_\gamma > 2.0$ GeV we find an efficiency of 12.4% in both cases. For the $E_\gamma > 1.5$ GeV case, we conservatively use the smaller efficiency. For $B^- \to \Sigma^0\bar{p}\gamma$, for events with $E_\gamma > 1.5$ GeV we find efficiencies of 9.4% (for P/M) and 8.2% (for P^3/M); for events with $E_\gamma > 2.0$ GeV we find an efficiency of 10.6% in both cases.

There are also systematic errors in the efficiency from uncertainty in the simulation of the detector performance (track-finding, photon-finding, vertex-finding, resolutions) and an uncertainty in the modeling of the other B. We estimate these at $\pm 8.2\%$.

We obtain a conservative 90% confidence level upper limit on the branching fraction by using unpolarized Λ's, using the P^3/M option for the $\Lambda\bar{p}$ ($\Sigma^0\bar{p}$) mass distribution, and then increasing the limit so obtained by 1.28 times the quadratic sum of the two remaining systematic errors, $\pm 2\%$ from number of B's and $\pm 8.2\%$ from detector simulation and modeling of the other B.

While our specific goal in the first search was $B^- \to \Lambda\overline{p}\gamma$, we also have sensitivity to the decay $B^- \to \Sigma^0\overline{p}\gamma$, $\Sigma^0 \to \Lambda\gamma$ in that analysis. Our efficiency for the latter decay is 0.3 times that of the former. Similarly, while our specific goal in the second search was $B^- \to \Sigma^0\bar{p}\gamma$, we also have sensitivity to $B^- \to \Lambda\bar{p}\gamma$, 0.4 that for $B^- \to \Sigma^0\bar{p}\gamma$. Hence, our primary results can be written

$$[\mathcal{B}(B^- \to \Lambda\overline{p}\gamma) + 0.3\mathcal{B}(B^- \to \Sigma^0\overline{p}\gamma)]_{E_\gamma > 1.5\ \mathrm{GeV}} < 3.9 \times 10^{-6}\ ,$$

$$[\mathcal{B}(B^- \to \Lambda\overline{p}\gamma) + 0.3\mathcal{B}(B^- \to \Sigma^0\overline{p}\gamma)]_{E_\gamma > 2.0\ \mathrm{GeV}} < 3.3 \times 10^{-6}\ ,$$

$$[\mathcal{B}(B^- \to \Sigma^0\overline{p}\gamma) + 0.4\mathcal{B}(B^- \to \Lambda\overline{p}\gamma)]_{E_\gamma > 1.5 \text{ GeV}} < 7.9 \times 10^{-6} \ ,$$

$$[\mathcal{B}(B^- \to \Sigma^0\overline{p}\gamma) + 0.4\mathcal{B}(B^- \to \Lambda\overline{p}\gamma)]_{E_\gamma > 2.0 \text{ GeV}} < 6.4 \times 10^{-6} \ .$$

From these upper limits, we would like to obtain an upper limit on the branching fraction for $b \to s\gamma$ leading to baryons. Our first step in this direction uses isospin considerations. The parton-level final states, $s\bar{u}$ and $s\bar{d}$, form an isospin doublet, and the hadronization process should conserve isospin. This gives $\mathcal{B}(B^- \to \Lambda\bar{p}\gamma) = \mathcal{B}(\bar{B}^0 \to \Lambda\bar{n}\gamma)$, and $\mathcal{B}(B^- \to \Sigma^0\bar{p}\gamma) = \mathcal{B}(\bar{B}^0 \to \Sigma^0\bar{n}\gamma) = 1/2\mathcal{B}(B^- \to \Sigma^-\bar{n}\gamma) = 1/2\mathcal{B}(\bar{B}^0 \to \Sigma^+\bar{p}\gamma)$. Thus $\mathcal{B}(B \to \Sigma\bar{N}\gamma) = 3\mathcal{B}(B^- \to \Sigma^0\bar{p}\gamma)$, and $\mathcal{B}(B \to (\Lambda \ or \ \Sigma)\bar{N}\gamma) = 3\mathcal{B}(B^- \to \Sigma^0\bar{p}\gamma) + \mathcal{B}(B^- \to \Lambda\bar{p}\gamma)$. Multiplying the last upper limit given above by 3, we have $[\mathcal{B}(B \to \Sigma\overline{N}\gamma) + 1.2\mathcal{B}(B \to \Lambda\overline{N}\gamma)]_{E_\gamma > 2.0 \text{ GeV}} < 1.9 \times 10^{-5}$, which we use as our limit on $\mathcal{B}(B \to (\Lambda \ or \ \Sigma)\overline{N}\gamma)$.

The above branching fraction limit is for both baryon and antibaryon in the lowest lying baryon SU(3) octet. We must also consider decays with one of the baryons in the decuplet (i.e., $B \to \Sigma\bar{\Delta}\gamma$ and $B \to \Sigma(1385)\bar{N}\gamma)$, decays involving higher-mass octet and decuplet members, and non-resonant decays such as $B \to (\Lambda \ or \ \Sigma)(\bar{N} \ or \ \bar{\Delta})\pi\gamma$. The requirement that E_γ(B rest frame) be greater than 2.0 GeV translates into an upper limit on the mass of the baryon-antibaryon system of 2.60 GeV/c^2. The various mass thresholds are: $\Lambda\bar{N}$, 2.05 GeV/c^2; $\Sigma\bar{N}$, 2.13 GeV/c^2; $\Sigma\bar{\Delta}$, 2.43 GeV/c^2; $\Sigma(1385)\bar{N}$, 2.32 GeV/c^2. Thus, phase space will suppress the octet-decuplet rates relative to the octet-octet rates. Combining this with the falling parton-level hadronic mass distribution given by the spectator model [6], or the calculation of Kagan and Neubert [2], we estimate a suppression of a factor of ~4. This is partially compensated by the factor of 2 more spin states available in the octet-decuplet combination. A plausible assumption is that the octet-decuplet contribution would be ~1/2 that of the octet-octet contribution. Octet-decuplet pairs with an excited member are above the 2.60 GeV/c^2 cutoff imposed by the 2.0 GeV photon energy requirement, and octet-octet pairs with excited members have thresholds very close to the cutoff. Non-resonant $(\Lambda \ or \ \Sigma)(\bar{N} \ or \ \bar{\Delta})\pi$ states will have thresholds below the cutoff, but will be phase-space-suppressed relative to $(\Lambda \ or \ \Sigma)\bar{N}$. From all this, we take as our working assumption $\mathcal{B}(b \to s\gamma, \ with \ baryons)_{E_\gamma > 2.0 \text{ GeV}} = 2\mathcal{B}(B \to (\Lambda \ or \ \Sigma)\bar{N}\gamma)_{E_\gamma > 2.0 \text{ GeV}}$, and hence $\mathcal{B}(b \to s\gamma, \ with \ baryons)_{E_\gamma > 2.0 \text{ GeV}} < 3.8 \times 10^{-5}$.

CLEO's recent study [5] of $b \to s\gamma$ reported a branching fraction for $E_\gamma > 2.0$ GeV, corrected for the $b \to d\gamma$ contribution, of $(2.94 \pm 0.39 \pm 0.25) \times 10^{-4}$. Our upper limit on the branching fraction for $b \to s\gamma$ leading to baryons, with $E_\gamma > 2.0$ GeV, 3.8×10^{-5}, is 13% of that number. The recent study [5] had an efficiency for detecting $B \to$ *baryons* γ that was 1/2 of that for modes not involving baryons. That implies an upper limit on the correction needed for the branching fraction reported there of 6.5%, less than half the combined reported statistical (±13%) and systematic (±8%) errors.

CLEO's recent study [5] of $b \to s\gamma$ also reported information on the photon energy spectrum: an average energy $\langle E_\gamma \rangle = (2.346 \pm 0.032 \pm 0.011)$ GeV, and a variance $\langle (E_\gamma - \langle E_\gamma \rangle)^2 \rangle = (0.0226 \pm 0.0066 \pm 0.0020)$ GeV^2. Both averages were taken *only for photons above 2.0 GeV*. The average energy of B rest frame photons from events with baryons (averaging only for photons above 2.0 GeV) is ~2.1 GeV, 250 MeV lower than the published mean. The upper limit on the correction to the first moment is thus 6.5% of 250 MeV, i.e. 16 MeV (compared with the published statistical and systematic errors of 32 MeV and 11 MeV, respectively). The limit on the correction to the variance is 0.0025 GeV^2, which is 36% of the combined quoted statistical and systematic errors on the variance.

In conclusion, we have conducted searches for the exclusive radiative penguin decays $B^- \to \Lambda\overline{p}\gamma$, and $B^- \to \Sigma^0\overline{p}\gamma$, found no evidence for either, and placed upper limits on them of

$$[\mathcal{B}(B^- \to \Lambda\overline{p}\gamma) + 0.3\mathcal{B}(B^- \to \Sigma^0\overline{p}\gamma)]_{E_\gamma > 1.5 \text{ GeV}} < 3.9 \times 10^{-6} \ ,$$

$$[\mathcal{B}(B^- \to \Lambda\overline{p}\gamma) + 0.3\mathcal{B}(B^- \to \Sigma^0\overline{p}\gamma)]_{E_\gamma > 2.0 \text{ GeV}} < 3.3 \times 10^{-6} \ ,$$

$$[\mathcal{B}(B^- \to \Sigma^0\overline{p}\gamma) + 0.4\mathcal{B}(B^- \to \Lambda\overline{p}\gamma)]_{E_\gamma > 1.5 \text{ GeV}} < 7.9 \times 10^{-6} \ ,$$

$$[\mathcal{B}(B^- \to \Sigma^0\overline{p}\gamma) + 0.4\mathcal{B}(B^- \to \Lambda\overline{p}\gamma)]_{E_\gamma > 2.0 \text{ GeV}} < 6.4 \times 10^{-6} \ .$$

With plausible assumptions, this leads to the conclusion that $b \to s\gamma$ decays with baryons in the final state and $E_\gamma > 2.0$ GeV constitute at most 13% of all $b \to s\gamma$ decays with $E_\gamma > 2.0$ GeV. With that limit, the upper limit on corrections to our recent measurement [5] of the $b \to s\gamma$ branching fraction, the mean energy of the photon, and the variance in the photon energy, are less than half of the combined quoted statistical and systematic errors.

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