

Rare $B^- \rightarrow \Lambda \bar{p} \nu \bar{\nu}$ decay

 C. Q. Geng^{1,2} and Y. K. Hsiao²
¹*Department of Physics, National Tsing Hua University, Hsinchu, Taiwan 300, Republic of China*
²*Physics Division, National Center for Theoretical Sciences, Hsinchu, Taiwan 300, Republic of China*
 (Received 1 December 2011; revised manuscript received 11 April 2012; published 18 May 2012)

We study the four-body semileptonic baryonic decay of $B^- \rightarrow \Lambda \bar{p} \nu \bar{\nu}$ in the standard model. We find that the decay branching ratio is $(7.9 \pm 1.9) \times 10^{-7}$. Similar to the rare decays of $B^- \rightarrow K^{(*)-} \nu \bar{\nu}$, this baryonic decay of $B^- \rightarrow \Lambda \bar{p} \nu \bar{\nu}$ is also sensitive to new physics and accessible to the future B factories.

DOI: 10.1103/PhysRevD.85.094019

PACS numbers: 13.20.He, 13.15.+g, 14.60.Lm

I. INTRODUCTION

Since the inclusive flavor-changing neutral-current processes of $b \rightarrow s \nu \bar{\nu}$ and $b \rightarrow d \nu \bar{\nu}$ in the standard model (SM) can only be induced through box and electroweak penguin diagrams, the corresponding exclusive ones, such as $B \rightarrow K^{(*)} \ell \bar{\ell}$ ($\ell = e, \mu, \tau, \nu$), are highly suppressed as rare decays. Experimental searches for these rare decays could shed light to find new physics. For example, as the current experimental upper bound on the decay branching ratio of $B^- \rightarrow K^- \nu \bar{\nu}$ is 14×10^{-6} [1,2], while its SM prediction is $(4.5 \pm 0.7) \times 10^{-6}$ [3], there would exist some kind of new physics [3–7] between the sandwiched area. Moreover, for the decay of $B \rightarrow K^* \nu \bar{\nu}$ with an on shell $K^* \rightarrow K \pi$, some physical observables [8] are also available to test T -violating effects beyond the SM. When the experimental sensitivities are gradually improved, even the decays of $B^- \rightarrow (\pi^-, \rho^-) \nu \bar{\nu}$ via $b \rightarrow d \nu \bar{\nu}$ with an additional suppression of $|V_{td}/V_{ts}|^2$ can also function as probes for new physics.

In this report, we propose to use the baryonic modes of $B^- \rightarrow \Lambda \bar{p} \ell \bar{\ell}$ ($\ell = e, \mu, \tau, \nu$) as a new type of the exclusive B decays via $b \rightarrow s \ell \bar{\ell}$ to examine flavor-changing neutral currents. To simplify our discussions on the baryonic form factors, we will concentrate on the four-body semileptonic baryonic decay of $B^- \rightarrow \Lambda \bar{p} \nu \bar{\nu}$. In particular, we will study its decay branching ratio in the SM. It is interesting to note that the $B^- \rightarrow \Lambda \bar{p} \nu \bar{\nu}$ can be well reconstructed experimentally, since the charged \bar{p} along with $p \pi^-$ from Λ can be easily detected.

The decay of $B^- \rightarrow \Lambda \bar{p} \nu \bar{\nu}$ has several interesting features. First, as a four-body decay, the observables for angular distribution asymmetries can be constructed as a probe to right-handed vector as well as (pseudo)-scalar currents beyond the SM. Second, by keeping the Λ spin \vec{s}_Λ , we are able to construct a T -odd observable $\vec{s}_\Lambda \cdot (\vec{p}_\Lambda \times \vec{p}_{\bar{p}})$ with the $\Lambda(\bar{p})$ momentum $\vec{p}_{\Lambda(\bar{p})}$ to test time-reversal violation. As the basis to study new physics, $\mathcal{B}(B^- \rightarrow \Lambda \bar{p} \nu \bar{\nu})$ in the SM can be naively estimated to be of order 10^{-6} – 10^{-7} . This is in comparison with the $B^- \rightarrow p \bar{p} \ell^- \bar{\nu}$ via $b \rightarrow u \ell^- \bar{\nu}$ being 100 times bigger than $b \rightarrow s \nu \bar{\nu}$, while the predicted $\mathcal{B}(B^- \rightarrow p \bar{p} \ell^- \bar{\nu})$ is of order 10^{-4} to 10^{-5} [9]. In order to precisely calculate the decay, a knowledge of the matrix

elements for the $B^- \rightarrow \Lambda \bar{p}$ transition is needed, which is difficult to obtain in QCD. However, since $B^- \rightarrow \Lambda \bar{p} \nu \bar{\nu}$ is considered to associate with the three-body baryonic \bar{B} decays of $\bar{B} \rightarrow p \bar{p} (\bar{K}^{(*)}, \pi, \rho)$ [10–15] and $\bar{B}^0 \rightarrow p \bar{p} D^{(*)0}$ [16,17] via the $\bar{B} \rightarrow \mathbf{B} \bar{\mathbf{B}}'$ transitions, the solution can be simply made. The parametrizations for the $\bar{B} \rightarrow \mathbf{B} \bar{\mathbf{B}}'$ transitions in [18–24] can be reliably adopted, as the theoretical studies of $\mathcal{B}(\bar{B} \rightarrow \Lambda \bar{\Lambda} \bar{K})$ [22], $\mathcal{B}(\bar{B}^0 \rightarrow \Lambda \bar{\Lambda} D^0)$ and $\mathcal{B}(B^- \rightarrow \Lambda \bar{p} D^{(*)0})$ [23] relating the $\bar{B} \rightarrow \mathbf{B} \bar{\mathbf{B}}'$ transitions are approved to agree with the data [25,26]. In addition, with the $B^- \rightarrow p \bar{p}$ transition, the CP violation for $B^- \rightarrow p \bar{p} K^{*-}$ [24] is found to be nearly 20% of the world average [27,28] even though it is still inconclusive experimentally due to the data errors.

The paper is organized as follows. In Sec. II, we provide the formalism, which involves the decay amplitude and rate of $B^- \rightarrow \Lambda \bar{p} \nu \bar{\nu}$ based on the form factors in the parametrizations for the matrix elements of the $\bar{B} \rightarrow \mathbf{B} \bar{\mathbf{B}}'$ transitions. We give our numerical results and discussions in Sec. III. In Sec. IV, we present the conclusions.

II. FORMALISM

The effective Hamiltonian for the inclusive mode of $b \rightarrow s \nu_\ell \bar{\nu}_\ell$ is given by [29]

$$\mathcal{H}(b \rightarrow s \nu_\ell \bar{\nu}_\ell) = \frac{G_F}{\sqrt{2}} \frac{\alpha_{\text{em}}}{2\pi \sin^2 \theta_W} \lambda_t D(x_t) \bar{s} \gamma_\mu (1 - \gamma_5) \times b \bar{\nu}_\ell \gamma^\mu (1 - \gamma_5) \nu_\ell, \quad (1)$$

with $\lambda_t = V_{ts}^* V_{tb}$, $x_t \equiv m_t^2/m_W^2$, and $\nu_\ell = \nu_e$ or ν_μ or ν_τ , where $D(x_t)$ is the top-quark loop function [30,31]. From Fig. 1, via the effective Hamiltonian in Eq. (1) the amplitude of $B^- \rightarrow \Lambda \bar{p} \nu_\ell \bar{\nu}_\ell$ can be factorized as

$$\mathcal{A}(B^- \rightarrow \Lambda \bar{p} \nu_\ell \bar{\nu}_\ell) = \frac{G_F}{\sqrt{2}} \frac{\alpha_{\text{em}}}{2\pi \sin^2 \theta_W} \lambda_t D(x_t) \langle \Lambda \bar{p} | \bar{s} \gamma_\mu \times (1 - \gamma_5) b | B^- \rangle \bar{\nu}_\ell \gamma^\mu (1 - \gamma_5) \nu_\ell, \quad (2)$$

where the explicit form of the matrix element for $B^- \rightarrow \Lambda \bar{p}$ depends on the parametrization, which has been studied in three-body baryonic \bar{B} decays. With Lorentz

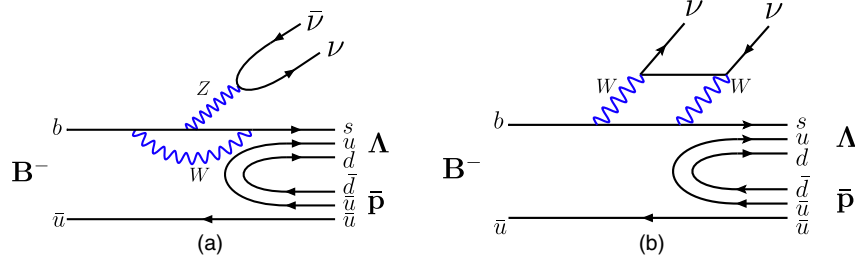


FIG. 1 (color online). Contributions to the $B^- \rightarrow \Lambda \bar{p} \nu \bar{\nu}$ decay from (a) penguin and (b) box diagrams.

invariance, the most general forms of the $\bar{B} \rightarrow \mathbf{B}\bar{\mathbf{B}}'$ transition form factors are given by [23]

$$\begin{aligned} \langle \mathbf{B}\bar{\mathbf{B}}' | \bar{q}' \gamma_\mu b | \bar{B} \rangle &= i\bar{u}(p_{\mathbf{B}})[g_1 \gamma_\mu + g_2 i \sigma_{\mu\nu} p^\nu + g_3 p_\mu \\ &\quad + g_4 q_\mu + g_5 (p_{\bar{\mathbf{B}}'} - p_{\mathbf{B}})_\mu] \gamma_5 v(p_{\bar{\mathbf{B}}'}), \\ \langle \mathbf{B}\bar{\mathbf{B}}' | \bar{q}' \gamma_\mu \gamma_5 b | \bar{B} \rangle &= i\bar{u}(p_{\mathbf{B}})[f_1 \gamma_\mu + f_2 i \sigma_{\mu\nu} p^\nu + f_3 p_\mu \\ &\quad + f_4 q_\mu + f_5 (p_{\bar{\mathbf{B}}'} - p_{\mathbf{B}})_\mu] v(p_{\bar{\mathbf{B}}'}), \end{aligned} \quad (3)$$

with $q = p_{\mathbf{B}} + p_{\bar{\mathbf{B}}'}$ and $p = p_{\bar{B}} - q$, for the vector and axial-vector quark currents, respectively. For the momentum dependences, the form factors f_i and g_i ($i = 1, 2, \dots, 5$) are taken to be [19]

$$f_i = \frac{D_{f_i}}{t^3}, \quad g_i = \frac{D_{g_i}}{t^3}, \quad (4)$$

with $t \equiv q^2 \equiv m_{\mathbf{B}\bar{\mathbf{B}}'}^2$, where D_{f_i} and D_{g_i} are constants to be determined by the measured data in $\bar{B} \rightarrow p\bar{p}M$ decays. Note that $1/t^3$ arises from three hard gluons as the propagators to form a baryon pair in the approach of the perturbative quantum chromodynamics counting rules [18,32–34], where two of them attach to valence quarks in $\mathbf{B}\bar{\mathbf{B}}'$, while the third one kicks and speeds up the spectator quark in \bar{B} . It is worth to note that, due to $f_i, g_i \propto 1/t^3$, the dibaryon invariant mass spectrum peaks at the threshold area and flattens out at the large energy region. Hence, this so-called threshold effect measured as a common feature in $\bar{B} \rightarrow p\bar{p}M$ decays should also appear in the $B^- \rightarrow \Lambda \bar{p} \nu \bar{\nu}$ decay. To integrate over the phase space for the amplitude squared $|\bar{\mathcal{A}}|^2$, which is obtained by assembling the required elements in Eqs. (2)–(4) and summing over all fermion spins, the knowledge of the kinematics for the four-body decay is needed. For this reason, we use the partial decay width [35–37]

$$d\Gamma = \frac{|\bar{\mathcal{A}}|^2}{4(4\pi)^6 m_{\bar{B}}^3} X \beta_{\mathbf{B}} \beta_{\mathbf{L}} ds dt d\cos\theta_{\mathbf{B}} d\cos\theta_{\mathbf{L}} d\phi, \quad (5)$$

where

$$\begin{aligned} X &= \left[\frac{1}{4} (m_{\bar{B}}^2 - s - t)^2 - st \right]^{1/2}, \\ \beta_{\mathbf{B}} &= \frac{1}{t} \lambda^{1/2}(t, m_{\mathbf{B}}^2, m_{\bar{\mathbf{B}}'}^2), \quad \beta_{\mathbf{L}} = \frac{1}{s} \lambda^{1/2}(s, m_{\nu}^2, m_{\bar{\nu}}^2), \end{aligned} \quad (6)$$

with $\lambda(a, b, c) = a^2 + b^2 + c^2 - 2ab - 2bc - 2ca$, and $t, s \equiv (p_\nu + p_{\bar{\nu}})^2$, $\theta_{\mathbf{B}}$, $\theta_{\mathbf{L}}$, and ϕ are five variables in the phase space. As seen from Fig. 2, the angle $\theta_{\mathbf{B}(\mathbf{L})}$ is between $\bar{p}_{\mathbf{B}}(\bar{p}_{\nu})$ in the $\mathbf{B}\bar{\mathbf{B}}'$ ($\nu\bar{\nu}$) rest frame and the line of flight of the $\mathbf{B}\bar{\mathbf{B}}'$ ($\nu\bar{\nu}$) system in the rest frame of the \bar{B} , while the angle ϕ is between the $\mathbf{B}\bar{\mathbf{B}}'$ plane and the $\nu\bar{\nu}$ plane, which are defined by the momenta of the $\mathbf{B}\bar{\mathbf{B}}'$ pair and the momenta of the $\nu\bar{\nu}$ pair, respectively, in the rest frame of \bar{B} . The ranges of the five variables are given by

$$\begin{aligned} (m_\nu + m_{\bar{\nu}})^2 &\leq s \leq (m_{\bar{B}} - \sqrt{t})^2, \\ (m_{\mathbf{B}} + m_{\bar{\mathbf{B}}'})^2 &\leq t \leq (m_{\bar{B}} - m_\nu - m_{\bar{\nu}})^2, \quad 0 \leq \theta_{\mathbf{L}}, \\ \theta_{\mathbf{B}} &\leq \pi, \quad 0 \leq \phi \leq 2\pi. \end{aligned} \quad (7)$$

The decay branching ratio of $\mathcal{B}(B^- \rightarrow \Lambda \bar{p} \nu \bar{\nu})$ depends on the integration in Eqs. (5)–(7), where we have to sum over the three neutrino flavors since they are indistinguishable. We can also define the integrated angular distribution asymmetries, given by

$$\mathcal{A}_{\theta_i} \equiv \frac{\int_0^1 \frac{d\mathcal{B}}{d\cos\theta_i} d\cos\theta_i - \int_{-1}^0 \frac{d\mathcal{B}}{d\cos\theta_i} d\cos\theta_i}{\int_0^1 \frac{d\mathcal{B}}{d\cos\theta_i} d\cos\theta_i + \int_{-1}^0 \frac{d\mathcal{B}}{d\cos\theta_i} d\cos\theta_i}, \quad (i = B, L). \quad (8)$$

III. NUMERICAL RESULTS AND DISCUSSIONS

For the numerical analysis, we take the values of G_F , α_{em} , $\sin^2\theta_W$ and $V_{is}^*V_{ib}$ in the PDG [38] as the input parameters. In the large t limit, the approach of the

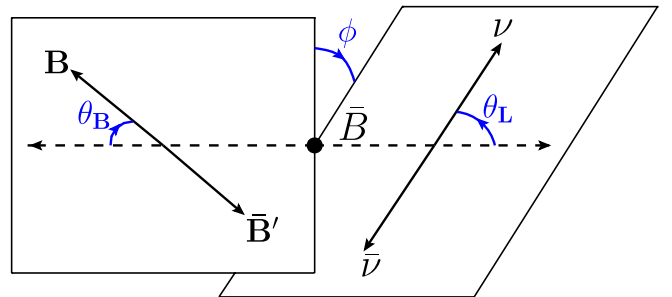


FIG. 2 (color online). Three angles $\theta_{\mathbf{B}}$, $\theta_{\mathbf{L}}$, and ϕ in the phase space for the four-body $\bar{B} \rightarrow \mathbf{B}\bar{\mathbf{B}}' \nu \bar{\nu}$ decay.

perturbative quantum chromodynamics counting rules allows the vector and axial-vector currents to be incorporated as two chiral currents. As a result, D_{g_i} and D_{f_i} from the vector currents can be related by the another set of constants D_{\parallel} and DD_{\parallel} from the chiral currents, and the 10 constants for $B^- \rightarrow \Lambda \bar{p}$ are reduced as [23]

$$D_{g_1} = D_{f_1} = -\sqrt{\frac{3}{2}}D_{\parallel}, \quad D_{g_j} = -D_{f_j} = -\sqrt{\frac{3}{2}}D_{\parallel}^j, \quad (9)$$

with $j = 2, 3, \dots, 5$. We note that the reduction is first developed in Refs. [32–34] for the spacelike $\mathbf{B} \rightarrow \mathbf{B}'$ baryonic form factors, and extended to deal with the timelike $0 \rightarrow \mathbf{B}\mathbf{B}'$ baryonic form factors and the $\bar{B} \rightarrow \mathbf{B}\mathbf{B}'M$ transition form factors in the studies of the $\bar{B} \rightarrow \mathbf{B}\mathbf{B}'M$ decays [18–23,39–43]. For $D_{\parallel}^{(j)}$ and $D_{\parallel}^{(j)}$, we adopt the values, given by [23]

$$\begin{aligned} (D_{\parallel}, D_{\parallel}) &= (67.7 \pm 16.3, -280.0 \pm 35.9) \text{ GeV}^5, \\ (D_{\parallel}^2, D_{\parallel}^3, D_{\parallel}^4, D_{\parallel}^5) &= (-187.3 \pm 26.6, -840.1 \pm 132.1, \\ &\quad -10.1 \pm 10.8, -157.0 \pm 27.1) \text{ GeV}^4, \end{aligned} \quad (10)$$

extracted from the measured data of the total branching ratios, invariant mass spectra, and angular distributions in the $\bar{B} \rightarrow p \bar{p} M$ decays. By using the various inputs, we obtain the numerical results for the branching ratio and angular distribution asymmetries of $B^- \rightarrow \Lambda \bar{p} \nu \bar{\nu}$ in Table I, where the values of $B^- \rightarrow p \bar{p} e^- \bar{\nu}_e$ are taken from Ref. [9]. The invariant mass spectra and angular distributions for $B^- \rightarrow \Lambda \bar{p} \nu \bar{\nu}$ are shown in Fig. 3, where the shaded areas represent the theoretical uncertainties from the form factors and Cabibbo-Kobayashi-Maskawa (CKM) mixings. Note that the errors of the integrated angular asymmetries $\mathcal{A}_{\theta_{B,L}}$ in Table I are relatively small compared to those in Fig. 3(b). The reason is that $\mathcal{A}_{\theta_{B,L}}$ depend on the ratios as shown in Eq. (8), which reduce the uncertainties.

From Fig. 3(a), we see that $\mathcal{B}(B^- \rightarrow \Lambda \bar{p} \nu \bar{\nu})$ receives the dominant contribution near the threshold of $m_{\Lambda \bar{p}} \rightarrow m_{\Lambda} + m_{\bar{p}}$, when the curve sharply peaks in the invariant mass spectrum. This reflects the fact of $1/t^3$ as the momentum dependence in the $B^- \rightarrow \Lambda \bar{p}$ transition form factors. In

TABLE I. Numerical results for \mathcal{B} and \mathcal{A}_{θ_i} ($i = B, L$) for $B^- \rightarrow \Lambda \bar{p} \nu \bar{\nu}$ and $B^- \rightarrow p \bar{p} e^- \bar{\nu}_e$ [9], respectively, where the theoretical errors are mainly from the uncertainties in the form factors and CKM mixings.

| | $B^- \rightarrow \Lambda \bar{p} \nu \bar{\nu}$ | $B^- \rightarrow p \bar{p} e^- \bar{\nu}_e$ [9] |
|--------------------------|---|---|
| \mathcal{B} | $(7.9 \pm 1.9) \times 10^{-7}$ | $(1.04 \pm 0.29) \times 10^{-4}$ |
| \mathcal{A}_{θ_B} | 0.01 ± 0.02 | 0.06 ± 0.02 |
| \mathcal{A}_{θ_L} | 0.56 ± 0.02 | 0.59 ± 0.02 |

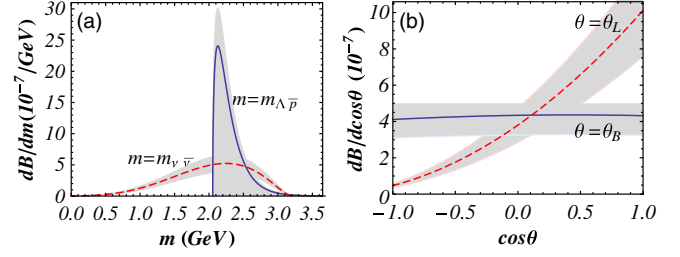


FIG. 3 (color online). Invariant mass spectra as functions of the invariant masses $m_{\Lambda \bar{p}}$ and $m_{\nu \bar{\nu}}$ and angular distributions as functions of $\cos \theta_{B,L}$ for $B^- \rightarrow \Lambda \bar{p} \nu \bar{\nu}$, respectively, where the shaded areas represent the theoretical uncertainties from the form factors and CKM mixings.

contrast, the curve in the $m_{\nu \bar{\nu}}$ spectrum is associated with the total energy of the $\nu \bar{\nu}$ pair. This is due to the helicity structure of $\bar{\nu} \gamma^\mu (1 - \gamma_5) \nu$ in the amplitude, formed as $(E_\nu + E_{\bar{\nu}}) \varepsilon^\mu(p)$ with $\varepsilon^\mu(p)$ the left-handed polarization. Moreover, the fact that $\varepsilon^\mu(p)$ couples to the left-handed helicity state of the virtual Z boson results in a factor of $(1 + \cos \theta_L)^2$ to explain the angular distribution for $\theta = \theta_L$ in Fig. 3(b). As a duplicate case, $B^- \rightarrow p \bar{p} e^- \bar{\nu}_e$ has the same helicity structure for the lepton pair to couple to the left-handed helicity state of the virtual weak boson W^{*-} . As a result, it is reasonable to have $\mathcal{A}_{\theta_L}(B^- \rightarrow \Lambda \bar{p} \nu \bar{\nu}) \simeq \mathcal{A}_{\theta_L}(B^- \rightarrow p \bar{p} e^- \bar{\nu}_e)$ in Table I. On the other hand, since $\mathcal{B}(B^- \rightarrow \Lambda \bar{p} \nu \bar{\nu})$ can be traced back to the tensor terms $f_2(g_2)$ in the $B^- \rightarrow \Lambda \bar{p}$ transition, which give the main contributions, $f_1 \bar{u} \gamma_\mu \gamma_5 \nu$ and $g_1 \bar{u} \gamma_\mu \nu$ are too small to provide factors of $(1 \pm \cos \theta_B)^2$ as apparent angular dependent terms, as given in Fig. 3(b) for $\theta = \theta_B$ and Table I for \mathcal{A}_{θ_B} .

The domination of the tensor terms $f_2(g_2)$ in the $B^- \rightarrow \Lambda \bar{p}$ transition can be realized. The terms $f_3(g_3)$ disappear due to $\varepsilon^\mu(p)$ with $p = p_\nu + p_{\bar{\nu}}$, leading to the coupling of $\varepsilon_\nu \cdot p = 0$. Because of the relatively small value of $|D_{\parallel}^4| \simeq 10 \text{ GeV}^4$, the terms $f_4(g_4)$ are negligible. The suppression for $f_5(g_5)$ is in accordance with the limit of $(p_{\bar{p}} - p_\Lambda)_\mu = (E_{\bar{p}} - E_\Lambda, \vec{p}_{\bar{p}} - \vec{p}_\Lambda) \rightarrow (0, \vec{0})$ as the invariant mass $m_{\Lambda \bar{p}}$ approaches the threshold area to receive the main contribution for $\mathcal{B}(B^- \rightarrow \Lambda \bar{p} \nu \bar{\nu})$ (see Fig. 3(a)). Moreover, with an additional p in $f_2(g_2) \sigma_{\mu\nu} p^\nu$, the ratio of $|f_2(g_2) p|^2$ to $|f_1(g_1)|^2$, which is equal to $D_{f_2(g_2)}^2 |p|^2 / D_{f_1(g_1)}^2 \simeq 8 |p|^2$, can be enhanced by $|p| \rightarrow m_{\bar{B}} - (m_\Lambda + m_{\bar{p}})$ around the threshold area. This explains why $f_2(g_2)$ prevail over the other terms in the $B^- \rightarrow \Lambda \bar{p} \nu \bar{\nu}$ decay. Since the decays of $B^- \rightarrow p \bar{p} e^- \bar{\nu}_e$ and $B^- \rightarrow \Lambda \bar{p} \nu \bar{\nu}$ are similar four-body decays, we suggest a relation, given by

$$R(|\bar{\mathcal{A}}|^2) \equiv \frac{|\bar{\mathcal{A}}(B^- \rightarrow \Lambda \bar{p} \nu \bar{\nu})|^2}{|\bar{\mathcal{A}}(B^- \rightarrow p \bar{p} e^- \bar{\nu}_e)|^2} = 3R(\text{Const}^2) \frac{1/m_{p\bar{p}}^{12}}{1/m_{\Lambda\bar{p}}^{12}}, \quad (11)$$

where the factor 3 comes from the three neutrino flavors and $R(\text{Const}^2) = 0.012$ is due to the constants of their own

Hamiltonian and the form factor for $f_2(g_2)$. When the invariant masses $m_{p\bar{p}}$ and $m_{\Lambda\bar{p}}$ are close to 1.877 and 2.054 GeV² for $B^- \rightarrow p\bar{p}e^-\bar{\nu}_e$ and $B^- \rightarrow \Lambda\bar{p}\nu\bar{\nu}$, respectively, the curves are drawn to be at the top in the spectra. Thus, we obtain $R(|\bar{\mathcal{A}}|^2) \simeq R(\text{Const}^2)$, which agrees with the numerical result $R(\mathcal{B}) \equiv \mathcal{B}(B^- \rightarrow \Lambda\bar{p}\nu\bar{\nu})/\mathcal{B}(B^- \rightarrow p\bar{p}e^-\bar{\nu}_e) = 0.012$. It is interesting to point out that the measurement for $R(\mathcal{B})$ can be a test of $1/t^3$ as the momentum dependence of the $\bar{B} \rightarrow \mathbf{B}\bar{\mathbf{B}}'$ transition form factors in Eqs. (3) and (4).

Because of the rich spin structure in the final state, the baryonic decay of $B^- \rightarrow \Lambda\bar{p}\nu\bar{\nu}$ is clearly quite different from the mesonic one of $B^- \rightarrow (K\pi)^-\nu\bar{\nu}$. The spin effect is sensitive to some new physics. For example, the angular distributions in $B^- \rightarrow \Lambda\bar{p}\nu\bar{\nu}$ can be used to probe for right-handed and (pseudo)-scalar currents beyond the SM. In Ref. [6], the invisible scalar (S) decay has been studied for the mesonic decays of $\bar{B} \rightarrow K^*SS$ and $\bar{B} \rightarrow K^{(*)}\nu\bar{\nu}$. Similar studies can be extended to the baryonic modes here. In particular, we would like to emphasize that to test the invisible scalar pair SS from the $b \rightarrow sSS$ via the (pseudo)-scalar couplings, $B^- \rightarrow \Lambda\bar{p}\nu\bar{\nu}$ can be more beneficial than $\bar{B} \rightarrow K^{(*)}\nu\bar{\nu}$. As shown in Ref. [44], the angular distributions in $\bar{B} \rightarrow K^*(\rightarrow K\pi)SS$ and $\bar{B} \rightarrow K^{(*)}(\rightarrow K\pi)\nu\bar{\nu}$ are both angular-symmetric, so one cannot distinguish them from the angular analysis. However, the situation for the baryonic decays are different. Recall that the large angular asymmetry observed to be 60% in the $B^- \rightarrow p\bar{p}K^-$ decay [10] has been attributed to the $\bar{B} \rightarrow \mathbf{B}\bar{\mathbf{B}}'$ transition via the (pseudo)-scalar couplings [19]. Since the decay of $B^- \rightarrow \Lambda\bar{p}SS$ through $b \rightarrow sSS$ has the same type of the $\bar{B} \rightarrow \mathbf{B}\bar{\mathbf{B}}'$ transition, we expect it to be largely angular-asymmetric, whereas $\mathcal{A}_{\theta_B}(B^- \rightarrow \Lambda\bar{p}\nu\bar{\nu})$ is pre-

dicted to be as small as 1%. If the integrated angular asymmetry in $B^- \rightarrow \Lambda\bar{p}SS$ is 50%, to measure it at the $n\sigma$ level, about $5 \times 10^8 nB^\pm$ are required, which should be accessible to the future B factories.

Finally, we remark that in $B^- \rightarrow \Lambda\bar{p}\nu\bar{\nu}$, as the spins and momentums may not be on the same plane, similar to the cases in the $\bar{B} \rightarrow \mathbf{B}\bar{\mathbf{B}}'M$ decays [45], T -odd triple product correlations, such as $\vec{p}_{\nu_e} \cdot (\vec{p}_\Lambda \times \vec{p}_{\bar{p}})$ and $\vec{s}_\Lambda \cdot (\vec{p}_\Lambda \times \vec{p}_{\bar{p}})$ with \vec{s}_Λ denoting the Λ spin, can be generated. In the SM, since the decay depends on $\lambda_t = V_{ts}^*V_{tb}$, which contains no CP phase, these T -odd observables are expected to be vanishingly small. However, they can be used to test direct T violating effects from new particles.

IV. CONCLUSIONS

We have studied the four-body semileptonic baryonic decay of $B^- \rightarrow \Lambda\bar{p}\nu\bar{\nu}$ based on the effective Hamiltonian for $b \rightarrow s\nu\bar{\nu}$, arising from electroweak penguin and box diagrams in the SM. We have calculated the decay branching ratio and angular distribution asymmetries for the decay. Explicitly, we have found that $\mathcal{B}(B^- \rightarrow \Lambda\bar{p}\nu\bar{\nu}) = (7.9 \pm 1.9) \times 10^{-7}$. We have also obtained a useful relation between the decays of $B^- \rightarrow \Lambda\bar{p}\nu\bar{\nu}$ and $B^- \rightarrow p\bar{p}e^-\bar{\nu}_e$. Similar to the rare mesonic decays of $B^- \rightarrow K^{(*)-}\nu\bar{\nu}$, the experimental search for the rare baryonic decay of $B^- \rightarrow \Lambda\bar{p}\nu\bar{\nu}$ in the current as well as future B factories is useful to test the SM and limit new physics.

ACKNOWLEDGMENTS

The work was supported in part by National Center of Theoretical Science and National Science Council (NSC-98-2112-M-007-008-MY3) of R.O.C.

-
- [1] B. Aubert *et al.* (BABAR Collaboration), *Phys. Rev. Lett.* **94**, 101801 (2005).
 - [2] B. Aubert *et al.* (BABAR Collaboration), *Phys. Rev. Lett.* **99**, 221801 (2007).
 - [3] W. Altmannshofer, A.J. Buras, D.M. Straub, and M. Wick, *J. High Energy Phys.* **04** (2009) 022.
 - [4] P. Colangelo, F. De Fazio, R. Ferrandes, and T.N. Pham, *Phys. Rev. D* **73**, 115006 (2006).
 - [5] T.M. Aliev, A.S. Cornell, and N. Gaur, *J. High Energy Phys.* **07** (2007) 024.
 - [6] C.S. Kim, S.C. Park, K. Wang, and G. Zhu, *Phys. Rev. D* **81**, 054004 (2010).
 - [7] A. Arhrib and W.S. Hou, *J. High Energy Phys.* **07** (2006) 009.
 - [8] C.H. Chen and C.Q. Geng, *Nucl. Phys.* **B636**, 338 (2002).
 - [9] C.Q. Geng and Y.K. Hsiao, *Phys. Lett. B* **704**, 495 (2011)
 - [10] M.Z. Wang *et al.* (BELLE Collaboration), *Phys. Lett. B* **617**, 141 (2005).
 - [11] M.Z. Wang *et al.* (BELLE Collaboration), *Phys. Rev. Lett.* **92**, 131801 (2004).
 - [12] B. Aubert *et al.* (BABAR Collaboration), *Phys. Rev. D* **72**, 051101 (2005).
 - [13] J.T. Wei *et al.* (BELLE Collaboration), *Phys. Lett. B* **659**, 80 (2008).
 - [14] B. Aubert *et al.* (BABAR Collaboration), *Phys. Rev. D* **76**, 092004 (2007).
 - [15] J.H. Chen *et al.* (BELLE Collaboration), *Phys. Rev. Lett.* **100**, 251801 (2008).
 - [16] K. Abe *et al.* (BELLE Collaboration), *Phys. Rev. Lett.* **89**, 151802 (2002).
 - [17] B. Aubert *et al.* (BABAR Collaboration), *Phys. Rev. D* **74**, 051101 (2006).
 - [18] C.K. Chua, W.S. Hou, and S.Y. Tsai, *Phys. Rev. D* **66**, 054004 (2002).
 - [19] C.Q. Geng and Y.K. Hsiao, *Phys. Rev. D* **74**, 094023 (2006).

- [20] Y. K. Hsiao, *Int. J. Mod. Phys. A* **24**, 3638 (2009).
- [21] C. Q. Geng, Y. K. Hsiao, and J. N. Ng, *Phys. Rev. D* **75**, 094013 (2007).
- [22] C. Q. Geng and Y. K. Hsiao, *Phys. Lett. B* **619**, 305 (2005).
- [23] C. H. Chen, H. Y. Cheng, C. Q. Geng, and Y. K. Hsiao, *Phys. Rev. D* **78**, 054016 (2008).
- [24] C. Q. Geng, Y. K. Hsiao, and J. N. Ng, *Phys. Rev. Lett.* **98**, 011801 (2007).
- [25] Y. W. Chang *et al.* (BELLE Collaboration), *Phys. Rev. D* **79**, 052006 (2009).
- [26] P. Chen *et al.* (BELLE Collaboration), *Phys. Rev. D* **84**, 071501 (2011).
- [27] B. Aubert *et al.* (BABAR Collaboration), *Phys. Rev. D* **76**, 092004 (2007).
- [28] J. H. Chen *et al.* (BELLE Collaboration), *Phys. Rev. Lett.* **100**, 251801 (2008).
- [29] T. Inami and C. S. Lim, *Prog. Theor. Phys.* **65**, 297 (1981); **65**, 1772(E) (1981).
- [30] G. Belanger and C. Q. Geng, *Phys. Rev. D* **43**, 140 (1991).
- [31] G. Buchalla and A. J. Buras, *Nucl. Phys.* **B400**, 225 (1993).
- [32] G. P. Lepage and S. J. Brodsky, *Phys. Rev. Lett.* **43**, 545 (1979); **43**, 1625(E) (1979).
- [33] G. P. Lepage and S. J. Brodsky, *Phys. Rev. D* **22**, 2157 (1980).
- [34] S. J. Brodsky, G. P. Lepage, and S. A. A. Zaidi, *Phys. Rev. D* **23**, 1152 (1981).
- [35] A. Pais and S. B. Treiman, *Phys. Rev.* **168**, 1858 (1968).
- [36] C. L. Y. Lee, M. Lu, and M. B. Wise, *Phys. Rev. D* **46**, 5040 (1992).
- [37] H. Y. Cheng, C. Y. Cheung, W. Dimm, G. L. Lin, Y. C. Lin, T. M. Yan, and H. L. Yu, *Phys. Rev. D* **48**, 3204 (1993).
- [38] K. Nakamura *et al.* (Particle Data Group), *J. Phys. G* **37**, 075021 (2010).
- [39] H. Y. Cheng and K. C. Yang, *Phys. Rev. D* **66**, 014020 (2002).
- [40] H. Y. Cheng and K. C. Yang, *Phys. Rev. D* **66**, 094009 (2002).
- [41] C. K. Chua, W. S. Hou, and S. Y. Tsai, *Phys. Rev. D* **65**, 034003 (2002).
- [42] C. K. Chua and W. S. Hou, *Eur. Phys. J. C* **29**, 27 (2003).
- [43] C. Q. Geng and Y. K. Hsiao, *Phys. Rev. D* **75**, 094005 (2007).
- [44] W. Altmannshofer, A. J. Buras, D. M. Straub, and M. Wick, *J. High Energy Phys.* 04 (2009) 022.
- [45] C. Q. Geng and Y. K. Hsiao, *Phys. Rev. D* **72**, 037901 (2005); *Int. J. Mod. Phys. A* **21**, 897 (2006); **23**, 3290 (2008).