T-violating triple product asymmetries in $\Lambda_b \to \Lambda \pi^+ \pi^-$ decay

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We study the decay $\Lambda_b \to \Lambda \pi^+ \pi^-$. The branching fraction is predicted to be about 4.4×10^{-8}. Within the standard model, we compute the T-odd triple product asymmetries to be about 1.4, 4.3, 6.5, and 7.2 %, respectively, due to $\vec{s}_{\Lambda_b,\Lambda}\cdot(\vec{p}_\Lambda \times \vec{p}_\pi)$ and $\vec{p}_{\Lambda,\pi}\cdot(\vec{s}_\Lambda \times \vec{s}_{\Lambda_b})$.

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In this paper, we consider $\Lambda_b \to \Lambda \pi^+ \pi^-$ decay and study T-odd triple product correlations (TPC's). As discussed in [1–4], the presence of a nonzero TPC of the form $\vec{v}_1\cdot(\vec{v}_2 \times \vec{v}_3)$, where the $\vec{v}_i$'s are spin or momentum, is given by

$$A_T=\frac{\Gamma(\vec{v}_1\cdot(\vec{v}_2\times\vec{v}_3)>0)-\Gamma(\vec{v}_1\cdot(\vec{v}_2\times\vec{v}_3)<0)}{\Gamma(\vec{v}_1\cdot(\vec{v}_2\times\vec{v}_3)>0)+\Gamma(\vec{v}_1\cdot(\vec{v}_2\times\vec{v}_3)<0)}, \tag{1}$$

where Γ is the decay rate in question. In order to see that the TPC is indeed caused by the weak phase, it is expressed in comparison with that of the corresponding conjugate mode $\overline{A}_T$ as a triple product asymmetry (TPA):

$$\mathcal{A}_T=\frac{1}{2}(A_T-\overline{A}_T)$$
$$\sim \sin\phi\cos\delta, \tag{2}$$

where ϕ (δ) is the weak (strong) phase. Thus, the TPA is maximal in the vanishing limit of the strong phase. In $\Lambda_b \to pP(V)$ where $P(V)$ is the pseudoscalar (vector) meson, T-odd triple correlations give rise to an asymmetry of about $O(10\%)$ in certain decays while in some the asymmetry is at $O(1\%)$ [3]. However, in beyond the standard model scenarios the TPA is about 50% or so [5,6]. Thus Λ_b decays provide a better opportunity to study CP or T violating effects. For instance, the Λ_b spin and the final state baryon spin are observable, in terms of which physics of the standard model and beyond can be investigated. In the two-body decay mode, i.e., $\Lambda_b \to pP$, TPC's necessarily involve the polarization of both baryons, whereas in a three-body final state such as the one we consider, TPC's are constituted by either of the baryon polarizations (in addition to cases involving both). This is more feasible experimentally, despite the size being smaller, than the one with two polarizations. On the other hand, with most of the b quark polarization being carried by the Λ_b baryon, polarization of final state baryons alone can be considered in the search for CP violating effects. Hopefully, at the future colliders BTeV and CERN Large Hadron Collider (LHC-b), production of about 10^{10} $\Lambda_b\overline{\Lambda}_b$ pairs will facilitate such studies. In this work, we describe the decay using factorization and obtain the branching ratio. Then we look for the following TPC's: $\vec{s}_{\Lambda_b,\Lambda}\cdot(\vec{p}_\Lambda\times\vec{p}_\pi)$ and $\vec{p}_{\Lambda,\pi}\cdot(\vec{s}_\Lambda\times\vec{s}_{\Lambda_b})$. The effective Hamiltonian for $b\to u\bar{u}s$ which underlies the decay $\Lambda_b\to\Lambda\pi^+\pi^-$ (see [7] for other modes) is

$$\mathcal{H}_{eff}=\frac{G_f}{\sqrt{2}}\{V_{ub}V_{us}^*a_2-2V_{tb}V_{ts}^*(a_3-a_5)\}$$
$$\times[\overline{s}_\alpha\gamma_\mu(1-\gamma_5)b_\alpha][\overline{u}_\beta\gamma^\mu(1-\gamma_5)u_\beta], \tag{3}$$

where of the Wilson coefficients a_i, a_2 comes from tree level operators and $a_{3,5}$ from QCD penguins [8]. The invariant amplitude for the hadronic process $\Lambda_b\to\Lambda\pi^+\pi^-$ is, then,

$$M=(X+Y)q^\mu\langle\Lambda|\overline{s}\gamma_\mu(1-\gamma_5)b|\Lambda_b\rangle, \tag{4}$$

where

$$X=\frac{G_f}{\sqrt{2}}F^{\pi\pi}(q^2)V_{ub}V_{us}^*a_2, \tag{5}$$

$$Y=-2\frac{G_f}{\sqrt{2}}F^{\pi\pi}(q^2)V_{tb}V_{ts}^*(a_3-a_5), \tag{6}$$

with $a_2\equiv c_2^{eff}+c_1^{eff}/N_c$, $a_{3(5)}\equiv c_{3(5)}^{eff}+c_{4(6)}^{eff}/N_c$, and $F^{\pi\pi}(q^2)=[1-q^2/m_{\pi\pi}^2+i\Gamma_\sigma/m_{\pi\pi}]^{-1}$. In the following, we take the Wilson coefficients a_i in the limit $N_c\to\infty$ and for numerical values we follow the work of [9]; and for the form factor $F^{\pi\pi}(q^2)$, we use $m_{\pi\pi}\approx m_\sigma=0.7$ GeV and $\Gamma_\sigma=0.2$ GeV. The matrix elements between baryons are parametrized in heavy quark effective theory as

$$\langle\Lambda|\overline{s}\gamma_\mu(1-\gamma_5)b|\Lambda_b\rangle$$
$$=\overline{u}_\Lambda[F_1+\not{v}F_2]\gamma_\mu(1-\gamma_5)u_{\Lambda_b} \tag{7}$$

where $v=p_{\Lambda_b}/m_{\Lambda_b}$, $F_1=0.473$, and $F_2=-0.117$ as predicted in QCD sum rule analysis [10], satisfying the bound [11] $F_2/F_1\approx-0.25$ [12]. The invariant amplitude squared with all spins averaged, letting the pion mass vanish and using Eq. (7), from Eq. (4) is

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$$|MM^{\dagger}|=\frac{G_f^2}{2}[F^{\pi\pi}(q^2)]^2\{|V_{ub}V_{us}^{*}|^2a_2^2+4|V_{tb}^{*}V_{ts}|^2(a_3-a_5)^2-4|V_{ub}V_{us}V_{tb}^{*}V_{ts}|a_2(a_3-a_5)\}\times[F_1^2+F_1F_2(1+m_\Lambda/m_{\Lambda_b})+F_2^2]\times(m_{\Lambda_b}+m_\Lambda)^2(m_{\Lambda_b}-m_\Lambda)^2. \tag{8}$$

On performing the integration using RAMBO,[1] the prediction for the branching ratio is

$$BR(\Lambda_b\to\Lambda\pi^+\pi^-)\equiv 4.4\times10^{-8}. \tag{9}$$

Like *CP* asymmetry, TP asymmetry does arise when two amplitudes interfere, provided their weak phases are different from one another. The size of the TPA depends on the relative magnitudes of the coefficients X and Y in Eqs. (5) and (6). On looking for TPC's in this process, we obtain from Eq. (4) the following:

$$|MM^{\dagger}|_1^{T\ odd}=16\xi F_2^2[(m_{\Lambda_b}-m_\Lambda)^2m_\Lambda E_\pi+(m_{\Lambda_b}-m_\Lambda)m_{\Lambda_b}m_\Lambda E_\pi]\hat{\mathbf{p}}_{\boldsymbol{\pi}}\cdot(\hat{\mathbf{s}}_{\boldsymbol{\Lambda}}\times\hat{\mathbf{s}}_{\boldsymbol{\Lambda}_{\mathbf{b}}}), \tag{10}$$

$$|MM^{\dagger}|_2^{T\ odd}=3\xi(2F_2^2-F_1F_2)(m_{\Lambda_b}-m_\Lambda)^2m_{\Lambda_b}m_\Lambda\times\hat{\mathbf{p}}_{\boldsymbol{\Lambda}}\cdot(\hat{\mathbf{s}}_{\boldsymbol{\Lambda}}\times\hat{\mathbf{s}}_{\boldsymbol{\Lambda}_{\mathbf{b}}}), \tag{11}$$

$$|MM^{\dagger}|_3^{Todd}=12\xi F_2^2(m_{\Lambda_b}-m_\Lambda)m_{\Lambda_b}m_\Lambda E_\pi\hat{\mathbf{s}}_{\boldsymbol{\Lambda}}\cdot(\hat{\mathbf{p}}_{\boldsymbol{\pi}}\times\hat{\mathbf{p}}_{\boldsymbol{\Lambda}}), \tag{12}$$

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$$|MM^{\dagger}|_4^{T\ odd}=-4\xi F_2^2(m_{\Lambda_b}-m_\Lambda)m_{\Lambda_b}m_\Lambda E_\pi\times\hat{\mathbf{s}}_{\boldsymbol{\Lambda}_{\mathbf{b}}}\cdot(\hat{\mathbf{p}}_{\boldsymbol{\pi}}\times\hat{\mathbf{p}}_{\boldsymbol{\Lambda}}), \tag{13}$$

where the subscripts label the amplitude squared, referring to the TPC in the right hand side, and

$$\xi=2G_f^2a_2(a_3-a_5)[F^{\pi\pi}(q^2)]^2\mathrm{Im}[V_{ub}V_{us}^{*}V_{tb}^{*}V_{ts}e^{i\delta}]. \tag{14}$$

We find the magnitude of the TPA's corresponding to each of the TPC's:

$$\mathcal{A}_T^1=7.2\%, \tag{15}$$

$$\mathcal{A}_T^2=6.5\%, \tag{16}$$

$$\mathcal{A}_T^3=4.3\%, \tag{17}$$

$$\mathcal{A}_T^4=1.4\%, \tag{18}$$

where we have assumed $\delta=0$ and expressed the weak phase in terms of Wolfenstein parameters and one of them is $\eta=0.35$. We can now see that the TPA corresponding to a TPC involving two polarization vectors is larger in magnitude, as expected, than the one involving single polarization. In conclusion, we have found the branching ratio of the decay $\Lambda_b\to\Lambda\pi^+\pi^-$ and computed the TPA in $\Lambda_b\to\Lambda\pi^+\pi^-$ decays. We earlier [4] pointed out that Λ spin constituted TPC's appear within the standard model. The same is expected to hold in this decay. The present predictions for TPA except the one in Eq. (18) are accessible in a collider with 10^{10} $\Lambda_b\overline{\Lambda}_b$ pair production.

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