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# Study of semileptonic $\bar{B}^* \to P\ell\bar{\nu}_\ell$ decays

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**Abstract**

In anticipation of abundant $B^*$ data samples at high-luminosity heavy-flavor experiments in the future, the tree-dominated semileptonic $\bar{B}^*_{u,d,s} \to P\ell^-\bar{\nu}_\ell$ $(P = D\,, D_s\,, \pi\,, K)$ decays are studied within the Standard Model. After a detailed calculation of the helicity amplitudes, the theoretical predictions for branching fraction (decay rate), lepton spin asymmetry, forward–backward asymmetry and ratio $R_D^{*(L)}$ are firstly presented. It is found that the CKM-favored $\bar{B}^* \to D\ell^-\bar{\nu}_\ell$ decays have relatively large branching fractions of $\mathcal{O}(10^{-9})\sim\mathcal{O}(10^{-7})$, and are in the scope of running LHC and forthcoming SuperKEKB/Belle-II experiments.



## 1. Introduction

The semileptonic $B$ meson decays induced by the tree-level $b \to p\ell\bar{\nu}_\ell$ $(p = u\,, c)$ transition provide an ideal ground for testing the Standard Model (SM) and probing possible hints of new physics (NP). For instance, (i) such decays offer ways of extracting the magnitudes of the CKM matrix element $V_{cb}$ and $V_{ub}$. Moreover, the extractions from exclusive vs. inclusive semileptonic decays exhibit a long-standing $\sim 2.5\sigma$ discrepancy [1,2]; (ii) The measurements of

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ratios $R_{D^{(*)}} \equiv \frac{\mathcal{B}(\bar{B}\to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}\to D^{(*)}\ell'^-\bar{\nu}_{\ell'})}$ ($\ell' = \mu\,, e$) reported by BaBar [3,4], Belle [5–7] and LHCb [8] collaborations exhibit significant deviations from the SM expectations at $> 3\sigma$ level [9–13], which are the so-called "$R_{D^{(*)}}$ puzzles". A lot of efforts have been made for possible solutions within various NP models, for instance, new four fermion operators, two-Higgs-doublet models, R-parity violating supersymmetry models, leptoquark models, Alternative Left–Right Symmetric Model and so on [14–34]. In addition to $B$ mesons, some other hadrons, such as $\Lambda_b$ and $B^*$, could also decay through $b \to c\ell\bar{\nu}_\ell$ transition at quark level, and therefore, these decay modes would play a similar role as semileptonic $B$ decays mentioned above.

The $\bar{B}_q^*$ meson with quantum number of $n^{2s+1}L_J = 1^3S_1$ and $J^P = 1^-$ is the partner of $B$ meson in the heavy-meson doublet of $(b\bar{q})$ system [35–38]. Its decay occurs mainly through the electromagnetic process $\bar{B}_q^* \to \bar{B}_q\gamma$, and the weak decay modes are generally very rare. Until now, there is no available experimental information for $\bar{B}_q^*$ weak decays due to the limited center-of-mass energy and integrated luminosity in the previous experiments of heavy flavor physics. Fortunately, such situation is expected to be improved by the upcoming SuperKEKB/Belle-II experiment [39], which has started test operations and succeeded in circulating and storing beams in the electron and positron rings recently. For instance, using the target annual integrated luminosity 13 ab$^{-1}$/year [39], the cross section of $\Upsilon(5S)$ production $\sigma(e^+e^- \to \Upsilon(5S)) = 0.301$ nb [40] and the branching fractions of $\Upsilon(5S)$ decays into $B^*$ final states [41], one can find that about $\sim 4 \times 10^9$ $(B^*_{u,d} + \bar{B}^*_{u,d})$ and $\sim 2 \times 10^9$ $(B_s^* + \bar{B}_s^*)$ samples could be collected per year, which implies that the $B^*$ decays with branching fractions $> \mathcal{O}(10^{-9})$ are possible to be observed by Belle-II.

In addition, the running LHC may also provide some experimental information for $B^*$ decays, such as $B_s^* \to l^+l^-$ decay analyzed in Ref. [42], due to the much large beauty production cross section of $pp$ collision compared with $e^+e^-$ collision [43–45]. Thanks to the rapid development of heavy flavor physics experiments, the theoretical studies of $B^*$ weak decays, which could provide some useful suggestions and references for the measurements, are urgently required. Recently, a few theoretical evaluations of $B^*$ weak decays have been done, for instance, the studies of the semileptonic $B_c^*$ decays within the QCD sum rules [46–48], the pure leptonic $\bar{B}_s^* \to \ell\ell$ and $\bar{B}^*_{u,c} \to \ell\bar{\nu}_\ell$ decays [42], the impact of $\bar{B}^*_{s,d} \to \mu\mu$ on $\bar{B}_{s,d} \to \mu\mu$ decays [49], and the nonleptonic $\bar{B}^{*0}_{d,s} \to D^+_{d,s}M^-$ ($M = \pi\,, K\,, \rho$ and $K^*$) decays [50,51]. In this paper, we will pay attention to the charged $b \to (u,c)\ell\bar{\nu}_\ell$ transitions induced $\bar{B}^*_{u,d,s} \to P\ell\bar{\nu}_\ell$ ($P = D\,, D_s\,, \pi\,, K$) decays within the SM. Especially, the $\bar{B}^* \to D\ell\bar{\nu}_\ell$ decays are suppressed neither by CKM factors (compared to other $\bar{B}^*$ decays) nor by loop factors, and thus expected to be observed with relatively large branching fractions.

Our paper is organized as follows. In section 2, the theoretical framework and calculations of $\bar{B}^* \to P\ell\bar{\nu}_\ell$ decays are presented in detail. Section 3 is devoted to the numerical results and discussion. Finally, we give our conclusions in section 4.

## 2. Theoretical framework and calculation

### 2.1. Effective Hamiltonian and amplitude

Within the SM, the quark-level $b \to p\ell^-\bar{\nu}_\ell$ ($p = u\,, c$ and $\ell = \tau\,, \mu\,, e$) transitions occur through $W$-exchange and could be described by the effective low-scale $\mathcal{O}(m_b)$ Hamiltonian

$$\mathcal{H}_{\rm eff}(b \to p\ell^-\bar{\nu}_\ell) = \frac{G_F}{\sqrt{2}} \sum_{p=u\,,c} V_{pb} \sum_{\ell=\tau\,,\mu\,,e} [\bar{p}\gamma_\mu(1-\gamma_5)b][\bar{\ell}\gamma^\mu(1-\gamma_5)\nu_\ell]\,, \tag{1}$$