Relativistic description of the Ξ_b baryon semileptonic decays

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Semileptonic decays of the Ξ_b baryon are studied in the framework of the relativistic quark-diquark model based on the quasipotential approach. The weak decay form factors are calculated with the comprehensive account of all relativistic effects without employing nonrelativistic and heavy quark expansions. On this basis, differential and total decay rates as well as different asymmetry parameters are calculated for the heavy-to-heavy $\Xi_b \to \Xi_c \ell \nu_\ell$ and heavy-to-light $\Xi_b \to \Lambda \ell \nu_\ell$ semileptonic decays. Predictions for the ratios of such decays involving τ lepton and muon are presented.

I. INTRODUCTION

The investigation of the semileptonic decays of bottom baryons represents a very interesting and important problem. Indeed, their study provides an independent determination of the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements $|V_{cb}|$ and $|V_{ub}|$ and thus can help to better understand the origin of the disagreement of their values determined from inclusive and exclusive B meson decays [1]. Such decays can be also used to verify the lepton flavour universality, indications of which violation were reported in the semileptonic B meson decays governed by the $b \to c$ quark transitions (for a recent review, see [2] and references therein). The discrepancy between predictions of the standard model (SM) and experimental data was observed for the ratios of the branching fractions R_D and R_{D^*} of the semileptonic B meson decays to D and D^* mesons, respectively, involving τ lepton and muon. The combined excess of the measured ratios over the SM prediction is about 3.6σ [2]. Recently the LHCb Collaboration [3] measured the ratio $R_{J/\Psi}$ of semileptonic B_c meson decays to J/Ψ with τ lepton and muon which exceeds the SM prediction by more than 2σ [2,4].

In our paper [5], we comprehensively investigated semileptonic decays of Λ_b baryons in the framework of the relativistic quark-diquark model based on the quasipotential approach. The explicit expressions for the decay form factors were obtained in terms of the overlap integrals over the baryon wave functions. Baryons were treated as quark-diquark composite systems. All relativistic effects including contributions of the intermediate negative-energy states and

wave function transformations from the rest to the moving reference frame were systematically taken into account. To achieve this goal, we do not use either nonrelativistic or heavy quark expansions. As a result the obtained formulas are valid in the whole range of the momentum transfer q^2 both for the heavy-to-heavy ($b \to c$ weak transitions) and heavy-to-light ($b \to u$ weak transitions) semileptonic decays of bottom baryons. The calculated form factors of the Λ_b baryon transitions were used for obtaining predictions for the differential and total decay rates and different asymmetry parameters. Good agreement of theoretical results with experimental data was found.

In the present paper, we extend the previous analysis to the semileptonic decays of the Ξ_b baryon. Such decays are significantly less studied both theoretically and experimentally. However, there are good chances that they will be soon observed at LHC.

II. WEAK DECAY FORM FACTORS

The hadronic matrix elements of the vector and axial vector weak currents for the semileptonic decay $\Xi_b \to \Xi_c(\Lambda)$ are parametrized in terms of six invariant form factors [6]

$$\langle \Xi_c(\Lambda)(p', s') | V^\mu | \Xi_b(p, s) \rangle$$
$$= \bar{u}_{\Xi_c(\Lambda)}(p', s') \left[f_1^V(q^2)\gamma^\mu - f_2^V(q^2)i\sigma^{\mu\nu}\frac{q_\nu}{M_{\Xi_b}} \right.$$
$$\left. + f_3^V(q^2)\frac{q^\mu}{M_{\Xi_b}} \right] u_{\Xi_b}(p, s),$$

$$\langle \Xi_c(\Lambda)(p', s') | A^\mu | \Xi_b(p, s) \rangle$$
$$= \bar{u}_{\Xi_c(\Lambda)}(p', s') \left[f_1^A(q^2)\gamma^\mu - f_2^A(q^2)i\sigma^{\mu\nu}\frac{q_\nu}{M_{\Xi_b}} \right.$$
$$\left. + f_3^A(q^2)\frac{q^\mu}{M_{\Xi_b}} \right] \gamma_5 u_{\Xi_b}(p, s), \tag{1}$$

TABLE I.   Form factors of the weak $\Xi_b \to \Xi_c$ transitions.

	$f_1^V(q^2)$	$f_2^V(q^2)$	$f_3^V(q^2)$	$f_1^A(q^2)$	$f_2^A(q^2)$	$f_3^A(q^2)$
$f(0)$	0.474	0.150	0.081	0.449	−0.030	−0.285
$f(q^2_{\max})$	0.945	0.426	0.161	0.962	−0.104	−0.752
a_0	0.684	0.308	0.121	0.729	−0.078	−0.541
a_1	−5.16	−4.18	−0.315	−7.11	0.775	6.93
a_2	28.0	25.9	−5.81	41.5	0.372	−44.9

TABLE II.   Form factors of the weak $\Xi_b \to \Lambda$ transitions.

	$f_1^V(q^2)$	$f_2^V(q^2)$	$f_3^V(q^2)$	$f_1^A(q^2)$	$f_2^A(q^2)$	$f_3^A(q^2)$
$f(0)$	0.092	0.029	−0.002	0.077	0.007	−0.041
$f(q^2_{\max})$	0.609	0.745	0.290	0.369	−0.528	−1.36
a_0	0.139	0.170	0.098	0.122	−0.175	−0.292
a_1	0.136	−0.368	−0.323	0.016	0.865	0.554
a_2	−0.845	−0.180	0.059	−0.470	−0.947	0.630

where M_B and $u_B(p, s)$ are masses and Dirac spinors of the B baryons (Ξ_b, Ξ_c, Λ), $q = p' - p$.

The expressions for these form factors as the overlap integrals of baryon wave functions with the systematic account of the relativistic effects are given in Ref. [5]. They were obtained without employing the heavy quark expansion both for initial and final baryons. Therefore we can apply them for the calculation of the heavy-to-heavy $\Xi_b \to \Xi_c \ell \nu_\ell$ and heavy-to-light $\Xi_b \to \Lambda \ell \nu_\ell$ decay form factors. For the numerical calculations we use the baryon wave functions obtained while studying their spectroscopy [7,8].

We found that the numerically calculated form factors can be approximated with high accuracy by the following analytic expression

$$f(q^2) = \frac{1}{1 - q^2/M_{\text{pole}}^2} \{a_0 + a_1 z(q^2) + a_2 [z(q^2)]^2\}, \quad (2)$$
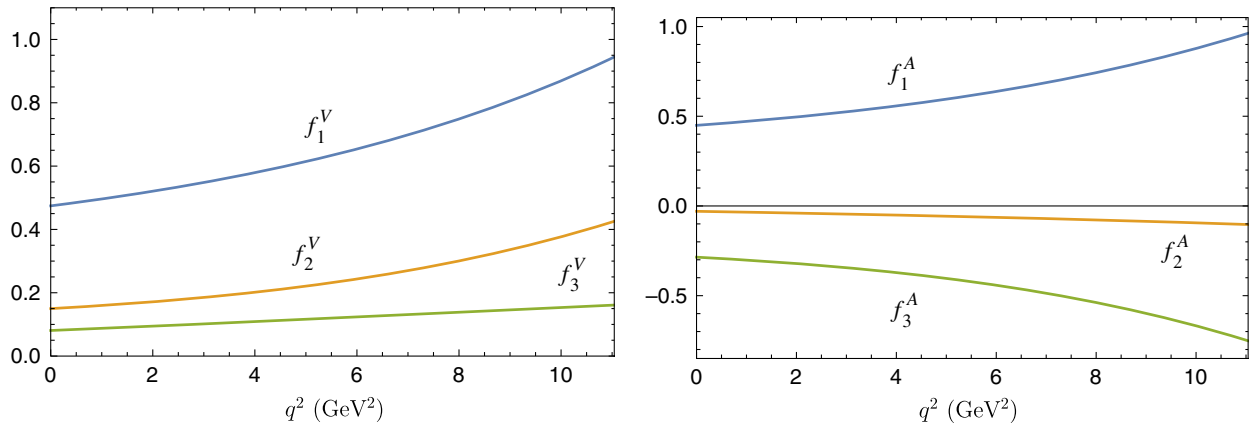
where the variable

$$z(q^2) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}}, \quad (3)$$

here $t_+ = (M_B + M_\pi)^2$ and $t_0 = q^2_{\max} = (M_{\Xi_b} - M_{\Xi_c(\Lambda)})^2$. The pole masses have the following values:
(a) for $\Xi_b \to \Xi_c$ transitions
    $M_{\text{pole}} \equiv M_{B_c^*} = 6.333$ GeV for $f_{1,2}^V$; $M_{\text{pole}} \equiv M_{B_{c1}} = 6.743$ GeV for $f_{1,2}^A$;
    $M_{\text{pole}} \equiv M_{B_{c0}} = 6.699$ GeV for f_3^V; $M_{\text{pole}} \equiv M_{B_c} = 6.275$ GeV for f_3^A;
(b) for $\Xi_b \to \Lambda$ transitions
 $M_{\text{pole}} \equiv M_{B^*} = 5.325$ GeV for $f_{1,2}^V$; $M_{\text{pole}} \equiv M_{B_1} = 5.723$ GeV for $f_{1,2}^A$;
    $M_{\text{pole}} \equiv M_{B_0} = 5.749$ GeV for f_3^V; $M_{\text{pole}} \equiv M_B = 5.280$ GeV for f_3^A.

We take the masses of the excited B_c and B mesons from our previous study of their spectroscopy [9,10]. The fitted values of the parameters a_0, a_1, a_2 as well as the values of form factors at maximum $q^2 = 0$ and zero recoil $q^2 = q^2_{\max}$ are given in Tables I and II. The difference of the fitted form factors from the calculated ones does not exceed 0.5%. Our model form factors are plotted in Figs. 1 and 2. We roughly estimate the total uncertainty of our form factor calculation to be about 5%.

III. SEMILEPTONIC $\Xi_b \to \Xi_c \ell \nu_\ell$ AND $\Xi_b \to \Lambda \ell \nu_\ell$ DECAYS

Now we can use the obtained form factors for the calculation of the differential and total semileptonic decay rates, different asymmetry parameters and other observables. To achieve this goal it is convenient to use the helicity formalism [6,11]. The helicity amplitudes are

FIG. 1.   Form factors of the weak $\Xi_b \to \Xi_c$ transitions.
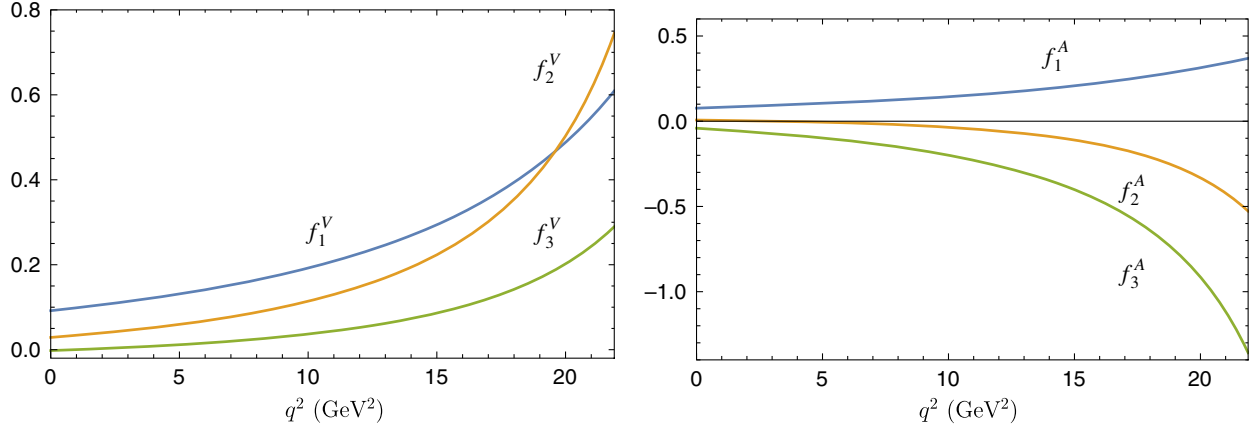
FIG. 2.　Form factors of the weak $\Xi_b \to \Lambda$ transitions.

expressed through the decay form factors by the following relations:

$$H^{V,A}_{+\frac{1}{2}0} = \frac{\sqrt{(M_{\Xi_b} \mp M_{\Xi_c(\Lambda)})^2 - q^2}}{\sqrt{q^2}}$$
$$\times \left[(M_{\Xi_b} \pm M_{\Xi_c(\Lambda)}) f^{V,A}_1(q^2) \pm \frac{q^2}{M_{\Xi_b}} f^{V,A}_2(q^2) \right],$$

$$H^{V,A}_{+\frac{1}{2}+1} = \sqrt{2[(M_{\Xi_b} \mp M_{\Xi_c(\Lambda)})^2 - q^2]}$$
$$\times \left[f^{V,A}_1(q^2) \pm \frac{M_{\Xi_b} \pm M_{\Xi_c(\Lambda)}}{M_{\Xi_b}} f^{V,A}_2(q^2) \right],$$

$$H^{V,A}_{+\frac{1}{2}t} = \frac{\sqrt{(M_{\Xi_b} \pm M_{\Xi_c(\Lambda)})^2 - q^2}}{\sqrt{q^2}}$$
$$\times \left[(M_{\Xi_b} \mp M_{\Xi_c(\Lambda)}) f^{V,A}_1(q^2) \pm \frac{q^2}{M_{\Xi_b}} f^{V,A}_3(q^2) \right]. \quad (4)$$

The amplitudes for negative values of the helicities can be obtained using the relation

$$H^{V,A}_{-\lambda',-\lambda_W} = \pm H^{V,A}_{\lambda',\lambda_W}.$$

The total helicity amplitude for the $V - A$ current is given by

$$H_{\lambda',\lambda_W} = H^V_{\lambda',\lambda_W} - H^A_{\lambda',\lambda_W}. \quad (5)$$

The helicity structures entering the differential decay rates and angular distributions are expressed in terms of the total helicity amplitudes (5) by

$$\mathcal{H}_U(q^2) = |H_{+1/2,+1}|^2 + |H_{-1/2,-1}|^2,$$
$$\mathcal{H}_L(q^2) = |H_{+1/2,0}|^2 + |H_{-1/2,0}|^2,$$
$$\mathcal{H}_S(q^2) = |H_{+1/2,t}|^2 + |H_{-1/2,t}|^2,$$
$$\mathcal{H}_{SL}(q^2) = \mathrm{Re}(H_{+1/2,0} H^\dagger_{+1/2,t} + H_{-1/2,0} H^\dagger_{-1/2,t}),$$
$$\mathcal{H}_P(q^2) = |H_{+1/2,+1}|^2 - |H_{-1/2,-1}|^2,$$
$$\mathcal{H}_{L_P}(q^2) = |H_{+1/2,0}|^2 - |H_{-1/2,0}|^2,$$
$$\mathcal{H}_{S_P}(q^2) = |H_{+1/2,t}|^2 - |H_{-1/2,t}|^2. \quad (6)$$

Then the differential decay rate can be presented by [6]

$$\frac{d\Gamma(\Xi_b \to \Xi_c(\Lambda) \ell \bar{\nu}_\ell)}{dq^2} = \frac{G_F^2}{(2\pi)^3} |V_{qb}|^2 \frac{\lambda^{1/2}(q^2 - m_\ell^2)^2}{48 M^3_{\Xi_b} q^2} \mathcal{H}_{\mathrm{tot}}(q^2), \quad (7)$$

where G_F is the Fermi constant, V_{qb} is the CKM matrix element $(q = c, u)$, $\lambda \equiv \lambda(M^2_{\Xi_b}, M^2_{\Xi_c(\Lambda)}, q^2) = M^4_{\Xi_b} + M^4_{\Xi_c(\Lambda)} + q^4 - 2(M^2_{\Xi_b} M^2_{\Xi_c(\Lambda)} + M^2_{\Xi_c(\Lambda)} q^2 + M^2_{\Xi_b} q^2)$, and m_ℓ is the lepton mass $(\ell = e, \mu, \tau)$,

$$\mathcal{H}_{\mathrm{tot}}(q^2) = [\mathcal{H}_U(q^2) + \mathcal{H}_L(q^2)]\left(1 + \frac{m_\ell^2}{2q^2}\right) + \frac{3m_\ell^2}{2q^2} \mathcal{H}_S(q^2). \quad (8)$$

It is plotted in Fig. 3 for the $\Xi_b \to \Xi_c \ell \nu_\ell$ (left) and $\Xi_b \to \Lambda \ell \nu_\ell$ (right) semileptonic decays.

Many important observables are expressed in terms of the helicity structures (6) (see [6] for details):
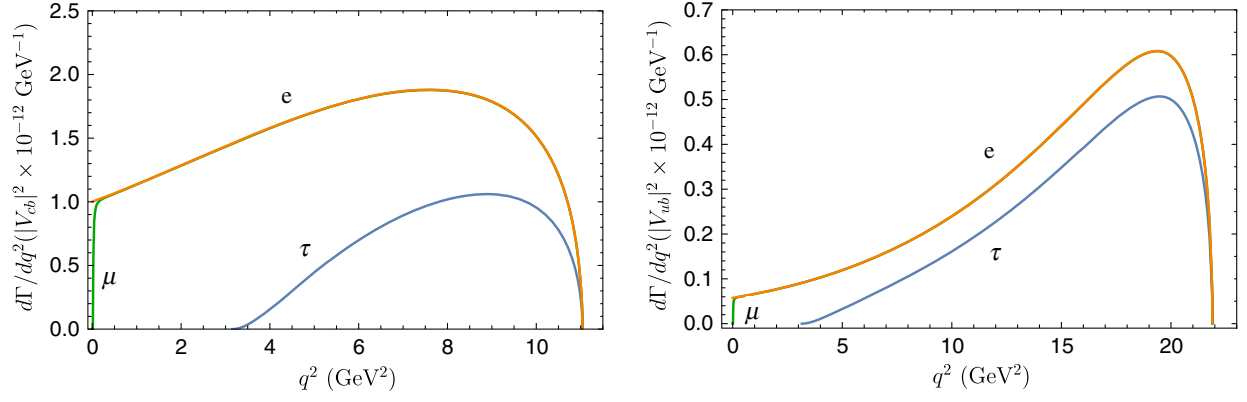
FIG. 3.   The differential decay rates of the $\Xi_b \to \Xi_c \ell \nu_\ell$ (left) and $\Xi_b \to \Lambda \ell \nu_\ell$ (right) semileptonic decays.

(a) The forward-backward asymmetry of the charged lepton

$$A_{\rm FB}(q^2) = \frac{\frac{d\Gamma}{dq^2}({\rm forward}) - \frac{d\Gamma}{dq^2}({\rm backward})}{\frac{d\Gamma}{dq^2}}$$

$$= -\frac{3}{4}\frac{\mathcal{H}_P(q^2) + 2\frac{m_\ell^2}{q^2}\mathcal{H}_{SL}(q^2)}{\mathcal{H}_{\rm tot}(q^2)}. \qquad (9)$$

(b) The convexity parameter

$$C_F(q^2) = \frac{3}{4}\left(1 - \frac{m_\ell^2}{q^2}\right)\frac{\mathcal{H}_U(q^2) - 2\mathcal{H}_L(q^2)}{\mathcal{H}_{\rm tot}(q^2)}. \qquad (10)$$

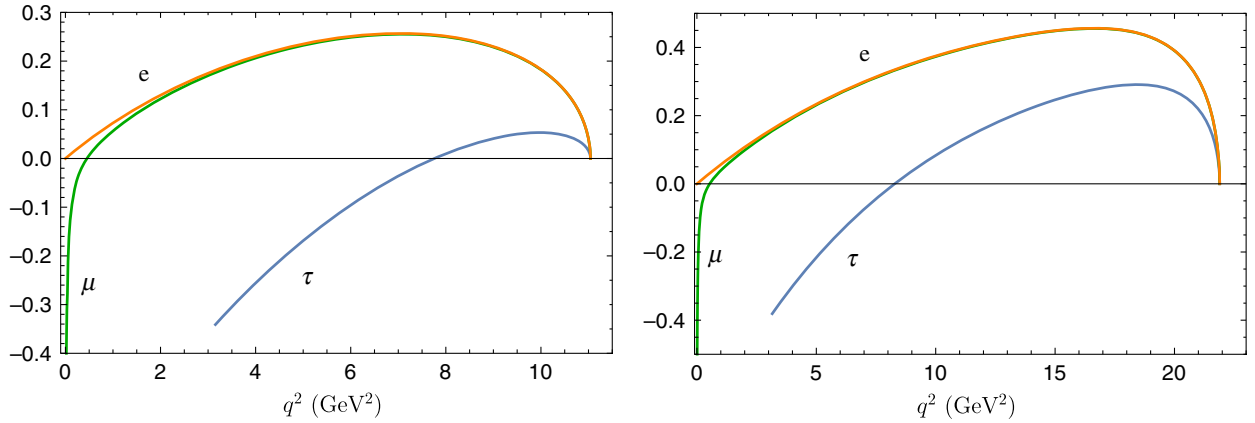(c) The longitudinal polarization of the final baryon $\Xi_c(\Lambda)$

$$P_L(q^2) = \frac{[\mathcal{H}_P(q^2) + \mathcal{H}_{L_P}(q^2)](1 + \frac{m_\ell^2}{2q^2}) + 3\frac{m_\ell^2}{2q^2}\mathcal{H}_{S_P}(q^2)}{\mathcal{H}_{\rm tot}(q^2)}. \qquad (11)$$

(d) The longitudinal polarization of the charged lepton ℓ

$$P_\ell(q^2) = -\frac{\mathcal{H}_U(q^2) + \mathcal{H}_L(q^2) - \frac{m_\ell^2}{2q^2}[\mathcal{H}_U(q^2) + \mathcal{H}_L(q^2) + 3\mathcal{H}_S(q^2)]}{\mathcal{H}_{\rm tot}(q^2)}. \qquad (12)$$

We plot these observables in Figs. 4–7 for heavy-to-heavy $\Xi_b \to \Xi_c \ell \nu_\ell$ and heavy-to-light $\Xi_b \to \Lambda \ell \nu_\ell$ semileptonic decays. Our predictions for the decay rates, branching fractions and asymmetry parameters are given in Table III. The decay rates are calculated using the CKM values $|V_{cb}| = (3.90 \pm 0.15) \times 10^{-2}$, $|V_{ub}| = (4.05 \pm 0.20) \times 10^{-3}$ extracted from our previous analysis of the heavy B and B_s meson decays [12]. The average

FIG. 4.   Predictions for the forward-backward asymmetries $A_{\rm FB}(q^2)$ in the $\Xi_b \to \Xi_c \ell^- \nu_\ell$ (left) and $\Xi_b \to \Lambda \ell^- \nu_\ell$ (right) semileptonic decays.
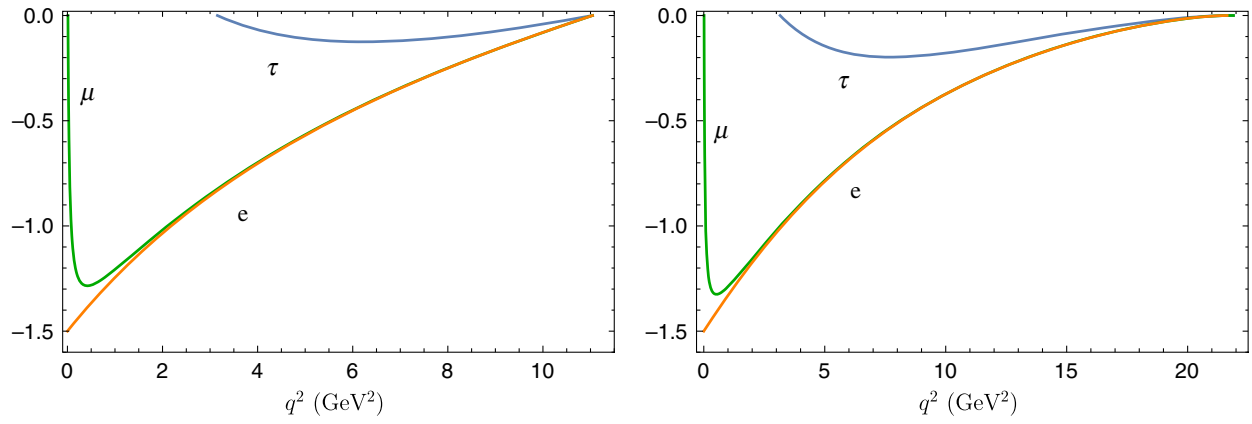
FIG. 5. Predictions for the convexity parameter $C_F(q^2)$ in the $\Xi_b \to \Xi_c \ell \nu_\ell$ (left) and $\Xi_b \to \Lambda \ell \nu_\ell$ (right) semileptonic decays.
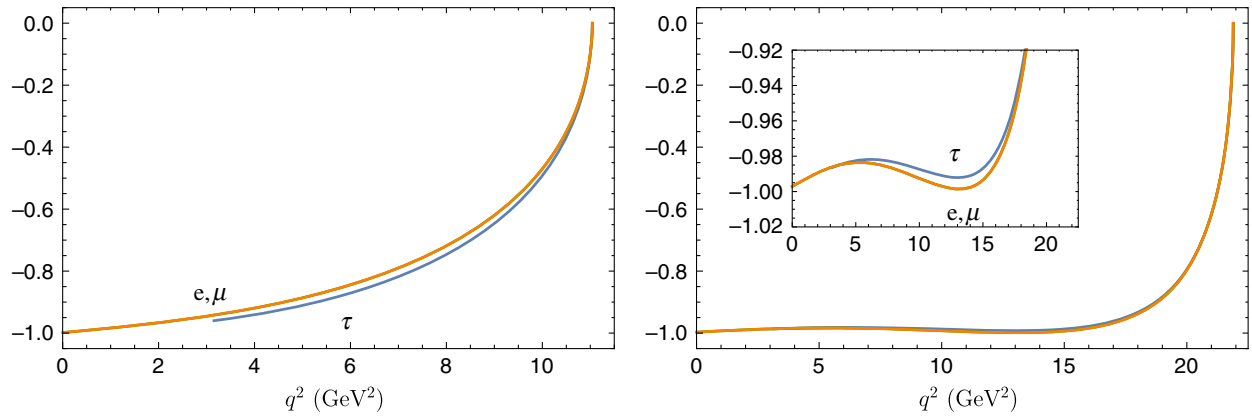

FIG. 6. Predictions for the longitudinal polarization $P_L(q^2)$ of the final baryon in the $\Xi_b \to \Xi_c \ell \nu_\ell$ (left) and $\Xi_b \to \Lambda \ell \nu_\ell$ (right) semileptonic decays.
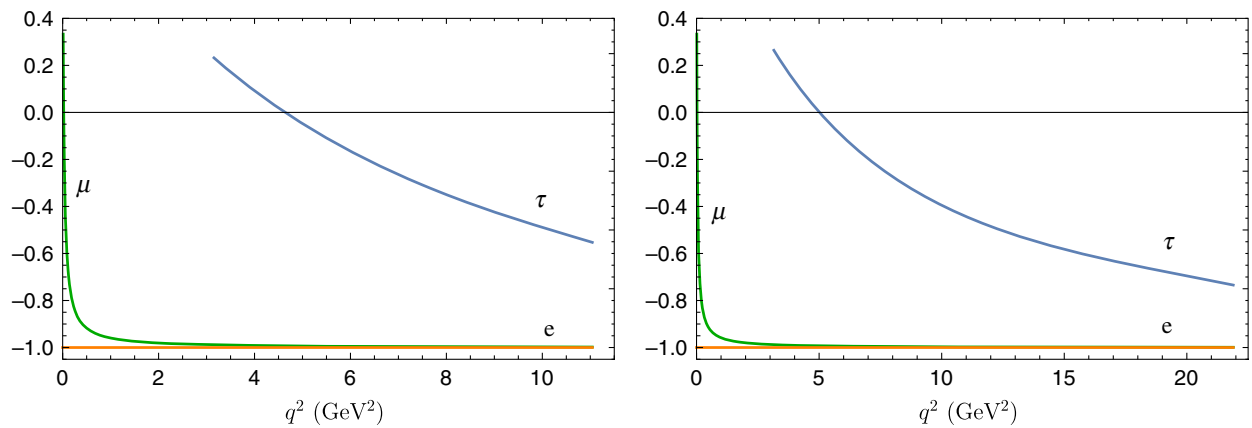

FIG. 7. Predictions for the longitudinal polarization $P_\ell(q^2)$ of the charged lepton in the $\Xi_b \to \Xi_c \ell \nu_\ell$ (left) and $\Xi_b \to \Lambda \ell \nu_\ell$ (right) semileptonic decays.

TABLE III. Ξ_b semileptonic decay rates, branching fractions and asymmetry parameters.

Decay	Γ (ns^{-1})	$\Gamma/|V_{qb}|^2$ (ps^{-1})	Br (%)	$\langle A_{FB}\rangle$	$\langle C_F\rangle$	$\langle P_L\rangle$	$\langle P_\ell\rangle$
$\Xi_b \to \Xi_c e\nu_e$	39.1	25.7	6.15	0.199	−0.540	−0.794	−1
$\Xi_b \to \Xi_c \mu\nu_\mu$	39.0	25.6	6.13	0.194	−0.525	−0.794	−0.985
$\Xi_b \to \Xi_c \tau\nu_\tau$	12.7	8.4	2.00	−0.018	−0.087	−0.703	−0.324
$\Xi_b \to \Lambda e\nu_e$	0.164	10.0	0.026	0.384	−0.226	−0.919	−1
$\Xi_b \to \Lambda \mu\nu_\mu$	0.164	9.99	0.026	0.382	−0.223	−0.919	−0.996
$\Xi_b \to \Lambda \tau\nu_\tau$	0.117	7.17	0.018	0.213	−0.073	−0.903	−0.579

values of the forward-backward asymmetry of the charged lepton $\langle A_{FB}\rangle$, the convexity parameter $\langle C_F\rangle$ and the longitudinal polarization of the final baryon $\langle P_L\rangle$ and the charged lepton $\langle P_\ell\rangle$ are calculated by separately integrating the numerators and denominators over q^2.

Since the discrepancy between predictions of the standard model and experimental data in heavy meson semileptonic decays is observed for the ratio of branching ratios of decays involving τ and a muon or electron [1,2], it is important to investigate similar decays of the heavy baryons. Using our results, we get the following predictions for the ratios of the Ξ_b baryon branching fractions ($l = e, \mu$):

$$R_{\Xi_c} = \frac{\text{Br}(\Xi_b \to \Xi_c \tau\nu_\tau)}{\text{Br}(\Xi_b \to \Xi_c l\nu_l)} = 0.325 \pm 0.010,$$

$$R_\Lambda = \frac{\text{Br}(\Xi_b \to \Lambda \tau\nu_\tau)}{\text{Br}(\Xi_b \to \Lambda l\nu_l)} = 0.717 \pm 0.021. \qquad (13)$$

Note that part of the theoretical uncertainties cancels in these ratios and we roughly estimate them to be about 3%. The values of these ratios are slightly larger than the corresponding values $R_{\Lambda_c} = 0.313$ and $R_p = 0.649$ calculated previously for the semileptonic Λ_b decays [5]. Any significant deviations from these results, if observed, can be interpreted as a signal of the new physics contributions.

For the semileptonic Λ_b decays the LHCb Collaboration measured the ratio of the heavy-to-heavy and heavy-to-light decays [13]. If we consider the similar ratio for the Ξ_b semileptonic decays, we get the following results:

$$R^l_{\Xi_c\Lambda} = \frac{\text{Br}(\Xi_b \to \Lambda l\nu_l)}{\text{Br}(\Xi_b \to \Xi_c l\nu_l)} = (0.389 \pm 0.012)\frac{|V_{ub}|^2}{|V_{cb}|^2}$$
$$= (4.2 \pm 0.5) \times 10^{-3}, \qquad (l = e, \mu),$$

$$R^\tau_{\Xi_c\Lambda} = \frac{\text{Br}(\Xi_b \to \Lambda \tau\nu_\tau)}{\text{Br}(\Xi_b \to \Xi_c \tau\nu_\tau)} = (0.854 \pm 0.025)\frac{|V_{ub}|^2}{|V_{cb}|^2}$$
$$= (9.2 \pm 1.2) \times 10^{-3}. \qquad (14)$$

The measurement of such ratios can provide an additional determination of the ratio of the CKM matrix elements $|V_{ub}|$ and $|V_{cb}|$. The final value was obtained for our preferred CKM values and the error bar includes combined theoretical uncertainties in the ratio of decay branching

TABLE IV.   Comparison of theoretical predictions for the $\Xi_b \to \Xi_c \ell\nu_\ell$ semileptonic decay rates, branching fractions and asymmetry parameters. The superscript corresponds to the lepton type e or τ.

Observable	This paper	[14]	[15]	[16]
$\Gamma^e/|V_{cb}|^2$ (ps^{-1})	25.7	29.6(2.5)	31	
Br^e (%)	6.15		7.4	9.22
Br$^\tau$ (%)	2.00			2.35
R_{Ξ_c}	0.325			0.255
$\langle A^e_{FB}\rangle$	0.199			0.163
$\langle A^\tau_{FB}\rangle$	−0.018			−0.042
$\langle C^e_F\rangle$	−0.540			−0.697
$\langle C^\tau_F\rangle$	−0.087			−0.103
$\langle P^e_L\rangle$	−0.794	−0.820(4)	−0.802	
$\langle P_e\rangle$	−1			−1
$\langle P_\tau\rangle$	−0.324			−0.317

fractions as well as the uncertainties in the ratio of the CKM values.

In Table IV, we compare our results for the semileptonic decay $\Xi_b \to \Xi_c \ell\nu_\ell$ with other calculations [14–16].[1] The previous investigations [14–16] employed heavy quark effective theory to study this heavy-to-heavy baryon transition. Both the infinitely heavy quark limit and the first order $1/m_Q$ corrections were considered. In our present calculations, we perform all calculations without application of the nonrelativistic or heavy quark expansions. We find our total decay rates and branching ratios to be somewhat lower and slight deviations in other observables. Note that the central value of our ratio R_{Ξ_c} is approximately 1.3 times larger than in Ref. [16]. This can be attributed to the completely relativistic treatment of the decays in our study.

IV. CONCLUSION

The form factors of the heavy-to-heavy $\Xi_b \to \Xi_c$ and heavy-to-light $\Xi_b \to \Lambda$ weak transitions were calculated in the relativistic quark-diquark picture with the comprehensive account of the relativistic effects. The relativistic

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[1]The results and references of the earlier predictions can be found in Ref. [15].

baryon wave functions were used for the evaluation of the corresponding form factors. The form factor momentum transfer q^2 dependence was explicitly determined in the whole accessible kinematical range without extrapolations or additional model assumptions. It was found that the analytic approximation for these form factors (2) accurately reproduces their q^2 behaviour with the parameters listed in Tables I and II. The helicity formalism was used for the calculation of the differential and total semileptonic decay rates and other useful observables which are given in Table III. The ratios R_{Ξ_c} and R_Λ (13) of the semileptonic Ξ_b to Ξ_c and Λ decay rates involving τ and electron are

obtained. Their measurement can serve as an additional test of the lepton flavour universality. The measurement of the ratio (14) of heavy-to-light $\Xi_b \to \Xi_c \ell \nu_\ell$ to heavy-to-heavy $\Xi_b \to \Xi_c \ell \nu_\ell$ semileptonic decays can provide the independent determination of the CKM ratio $|V_{ub}|/|V_{cb}|$. To our knowledge this is the first detailed study of the CKM suppressed semileptonic $\Xi_b \to \Lambda \ell \nu_\ell$ decays.

ACKNOWLEDGMENTS

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