LEPTON MASS EFFECTS IN SEMI-LEPTONIC B-MESON DECAYS

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We calculate decay rates, decay spectra and polarization parameters for exclusive semi-leptonic (s.l.) b→c and b→u bottom meson and free bottom quark decays involving the τ-lepton. These are compared to the corresponding observables calculated for the light lepton modes. A surprising feature is a significant scalar current contribution in s.l. B→D and B→π decays which leads to an average positive longitudinal τ-polarization in the B→D mode.

Experimentally the semi-leptonic (s.l.) branching ratios of bottom meson decays are approximately 10% for the two light lepton modes e and μ each. These modes appear to be dominated (≈90%) by the two exclusive s.l. modes B→D and B→D*. Correspondingly one can expect the τ-lepton mode to be dominated by the same two exclusive channels. It is therefore worthwhile and important to theoretically analyze these two exclusive s.l. decay modes also in the τ-sector.

In this letter we calculate decay rates, decay spectra and polarization parameters for exclusive s.l. b→c and b→u bottom meson and free bottom quark decays involving the τ-lepton. These are compared to the corresponding observables calculated in the light lepton sector.

Let us begin by defining a standard set of invariant form factors by writing

\[ \langle D(p_2) | A_\mu + V_\mu | B(p_1) \rangle \]

\[ = F_+ (p_1 + p_2)_\mu + F^- q_\mu, \]

(1a)

\[ \langle D^*(p_2) | A_\mu + V_\mu | B(p_1) \rangle = (F_+ g_{\mu\alpha} + F^- p_1^\alpha p_1) \]

\[ + F_+ q_\mu p_1^\alpha + i F^\nu \epsilon_{\mu\nu\rho\sigma} p_1^\rho p_2^\sigma \epsilon^* (p_2)^\alpha, \]

(1b)

where \( q_\mu = (p_1 - p_2)_\mu \) is the four-momentum transfer and \( q^2 = q_\mu q^\mu \).

Next we calculate helicity form factors by taking the appropriate helicity projections of the covariants in eq. (1) [1]. One has

\[ H_0^B = \frac{2M_1 p}{\sqrt{q^2}} F_+, \]

\[ H_0^D = \frac{1}{\sqrt{q^2}} \left( (M_1^2 - M_2^2) F_+ + q^2 F^\nu \right), \]

(2a)

\[ \frac{1}{2M_2 \sqrt{q^2}} \left( (M_1^2 - M_2^2 - q^2) F_+ + 2M_1^2 p^2 F^\nu \right), \]

\[ H_0^{D^*} = \frac{M_1 p}{M_2 \sqrt{q^2}} \left[ (F_+ + \frac{1}{2}(M_1^2 - M_2^2 + q^2) F^\nu + q^2 F^\mu \right], \]

\[ H_0^{D^*} = F_+ \pm M_1 p F^\nu. \]

(2b)

where \( p \) is the momentum of the D(D*) in the B rest system given by

1 Supported by Bundesministerium für Forschung und Technologie, 05 4HH 92P/3, Bonn, RFG.
\[2M_1 p = (M_1^4 + M_2^4 + q^4 - 2M_1^2M_2^2 - 2M_1^2q^2 - 2M_2^2q^2)^{1/2},\]  
and where \(M_1\) and \(M_2\) are the masses of the B and the D(D*) respectively.

It is instructive to analyze the partial wave structure of the quasi-two-body decays \(B \rightarrow D(D^*) + W_{\text{off-shell}}\) which leads to the pseudo-threshold factors \(p_l\) \((l=0, 1, 2)\) appearing in the helicity amplitudes (2). The \(W_{\text{off-shell}}\) has the spin content \(J^P=0^+, 1^-, 1^+\) for the vector (axial vector) current transitions. Note that the spin 0 (time) components become excited only in decays involving heavy leptons. These involve a lepton–neutrino helicity flip in the decay \(W_{\text{off-shell}} \rightarrow \ell + \nu_\ell\). One has

(i) \(B \rightarrow D\)
\[V: B(0^-) \rightarrow D(0^-) + W(1^-) \quad \text{p-wave},\]
\[B(0^-) \rightarrow D(0^-) + W(0^+) \quad \text{s-wave},\]  

(ii) \(B \rightarrow D^*\)
\[V: B(0^-) \rightarrow D^*(1^-) + W(1^-) \quad \text{p-wave},\]
\[A: B(0^-) \rightarrow D^*(1^-) + W(1^+) \quad \text{s,d-wave},\]
\[B(0^-) \rightarrow D^*(1^-) + W(0^-) \quad \text{p-wave}.\]  

The fact that one has an s-wave scalar current excitation with its accompanying pseudo-threshold enhancement in decays involving heavy leptons in the \(B \rightarrow D\) (or \(B \rightarrow \pi\)) case leads to interesting consequences, in particular for the semi-leptonic \(B \rightarrow D\) decay involving the \(\ell\)-lepton as we shall show in the following.

The double decay distribution for the decays \(B(b) \rightarrow D(c) (D^*(c)) + \ell^- + \nu_\ell\) reads [1,2]
\[
\frac{d\Gamma}{dq^2 dE_\ell} = \frac{G^2}{48\pi^3} |V_{bc}|^2 \frac{q^2 - \mu^2}{M_1^2} \times \left[ \frac{1}{8} \left( (1 + \cos^2 \theta) \hat{H}_U + \frac{1}{2} \sin^2 \theta \hat{H}_L + \frac{1}{2} \cos \theta \hat{H}_P \right) + \frac{\mu^2}{2q^2} \left( \frac{1}{4} \sin^2 \theta \hat{H}_U + \frac{1}{2} \cos^2 \theta \hat{H}_L \right) + \frac{3}{4} \hat{H}_S \right],
\]  
where \(E_\ell\) is the lepton energy in the B rest system and \(\mu\) is the lepton mass. \(\theta\) is the polar angle between the D(D*) and the lepton \(\ell^-\) in the \((\ell^- - \nu_\ell)\) CM system and is given by
\[
\cos \theta = \frac{(M_1^2 - M_2^2 + q^2)(q^2 + \mu^2) - 4q^2M_1E_\ell}{2M_1 p(q^2 - \mu^2)}.
\]  
The hadron tensor components \(\hat{H}_i\) appearing in the decay distribution (5) can be expressed in terms of the helicity amplitudes and are given by
\[
\hat{H}_U = |H_+|^2 + |H_-|^2 \quad \text{unpolarized-transverse},
\]
\[
\hat{H}_L = |H_0|^2 \quad \text{longitudinal},
\]
\[
\hat{H}_P = |H_+|^2 - |H_-|^2 \quad \text{parity-odd},
\]
\[
\hat{H}_S = 3|H_1|^2 \quad \text{scalar},
\]
\[
\hat{H}_{SL} = \text{Re}(H_L H_S^* \right) \quad \text{scalar-longitudinal-interference}.
\]

The \(E_\ell\) (or \(\cos \theta\)) integration in eq. (5) can easily be done and results in the differential \(q^2\)-distribution
\[
\frac{d\Gamma}{dq^2} = \frac{d\Gamma_{U+L}}{dq^2} + \frac{d\Gamma_{U+L}}{dq^2} + \frac{d\Gamma_{S}}{dq^2},
\]  
where \(\Gamma_{U+L} = \Gamma_U + \Gamma_L\), and where we have defined partial helicity rates according to
\[
\frac{d\Gamma_i}{dq^2} = \frac{G^2}{(2\pi)^3} |V_{bc}|^2 \frac{(q^2 - \mu^2)^2 p}{12M_1^2q^2} \hat{H}_i,
\]  
\(i = U, L, P\)  

and
\[
\frac{d\Gamma_i}{dq^2} = \frac{\mu^2}{2q^2} \frac{d\Gamma_i}{dq^2}, \quad i = U, L, S, SL.
\]  
As the angular distribution (5) is evaluated in the \((\ell^- - \nu_\ell)\) CM system the rates \(d\Gamma_i/dq^2\) and \(d\hat{\Gamma}_i/dq^2\) can be seen to correspond to the neutrino–lepton spin no-flip and flip contributions, respectively, in that system [1]. The flip contributions \(d\hat{\Gamma}_i/dq^2\) involve the characteristic flip factor \(\mu^2/2q^2\) which vanishes when \(\mu \rightarrow 0\). Since the massless antineutrino has positive helicity the flip/no-flip composition determines the longitudinal polarization \(P_L\) of the heavy lepton in the \((\ell^- - \nu_\ell)\) CM system via
\[
P_L = \frac{d\hat{\Gamma}_U - d\hat{\Gamma}_P}{d\hat{\Gamma}_U + d\hat{\Gamma}_P}.
\]  
In the following we shall investigate rates and decay spectra involving the \(\ell\)-lepton and \(\ell\)-polarization

\[\text{Note that the longitudinal polarization evaluated in the} \quad (\ell^- - \nu_\ell) \quad \text{CM system differs from the longitudinal polarization evaluated in the B rest system as e.g. in ref. [3].}\]
spectra for the free quark decay model (FQD) and the helicity matching model of exclusive s.l. B decays introduced in ref. [4]. For reasons of brevity the latter model will be referred to as the KS-model.

The FQD model is specified in terms of its hadron tensor components $\hat{H}_i$, which are given by

\begin{align}
\hat{H}_U &= 8(m_1^2 + m_2^2 - q^2), \\
\hat{H}_L &= 4(m_1^2 + m_2^2 - q^2 + 4m_1^2 p^2/q^2), \\
\hat{H}_F &= -16m_1p, \\
\hat{H}_S &= 3\hat{H}_L, \\
\hat{H}_{SL} &= 8m_1p(m_1^2 - m_2^2)/q^2,
\end{align}

where $m_1$ and $m_2$ refer to the masses of the heavy and light quark.

In the KS model of exclusive s.l. $B \to D(D^*)$ and $B \to \rho(\pi)$ decays the particle helicity amplitudes are matched to the free quark decay helicity amplitudes at $q^2 = 0$, assuming that the spectator quark is spin-inert.

Thus one has

\begin{align}
H^D_0(D^*) &= \langle D(D^*)|J_0|B\rangle \\
&\approx \frac{1}{2}I(\langle c\bar{t}|J_0|b\rangle + (-)\langle c\bar{t}|J_0|b\rangle), \\
H^D_1(D^*) &= \langle D(D^*)|J_1|B\rangle \\
&\approx \frac{1}{2}I(\langle c\bar{t}|J_1|b\rangle + (-)\langle c\bar{t}|J_1|b\rangle), \\
H^D_{-\pm}(D^*) &= \langle D^*(\pm)|J_{-\pm}|B\rangle \\
&\approx \frac{1}{\sqrt{2}}I\langle c\bar{t}|J_{-\pm}|b\rangle|b\rangle(1),
\end{align}

where $I$ is an overlap factor between the initial and final meson. To be definite we take $I_{bc} = 0.7$ and $I_{bu} = 0.33$ as in ref. [5].

Solving the matching conditions (12) to first order in $q^2$ one arrives at $q^2 = 0$ form factor values which are then continued to $q^2 > 0$ by using pole-type form factors with a power behaviour given by the QCD power counting rules [6]. The KS invariant form factors are then given by

\begin{align}
F^V(q^2) &= I(1-q^2/m^2)^{-1}, \\
F^V_-(q^2) &= -\frac{M_1 - M_2}{M_1 + M_2} I(1-q^2/m^2)^{-1}, \\
F^V_+(q^2) &= F^V_-(q^2) = -F^V_-(q^2) = -\frac{2}{M_1 + M_2} I(1-q^2/m^2)^{-2}.
\end{align}

For the sake of simplicity we work only with one effective form factor pole mass $m_{FF}$ in each of the $b\to c$ and $b\to u$ cases, for which we take $B^* (6.34)$ and $B^* (5.33)$, respectively.

In table 1 we list our results for the no-flip and flip partial rates $\Gamma_i$ and $\bar{\Gamma}_i$ appearing in the decay distribution (5) for $b\to c$ transitions in the electron and $\tau$-case \(^3\). We also list the total decay rate (for notational simplicity we use $U_i = \bar{T}_i$ and $\bar{U}_i = \bar{T}_i$ etc.)

\begin{equation}
\Gamma_{tot} = U + L + \bar{U} + \bar{L} + S,
\end{equation}

and the average longitudinal polarization of the lepton

\begin{equation}
\langle P_L \rangle = \frac{\bar{U} + \bar{L} + S - U - L}{\bar{U} + \bar{L} + S + U + L}.
\end{equation}

\(^3\) Results for the s.l. modes involving the $\mu$-lepton differ only insignificantly from the e-lepton case [1].

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|c|c|c|}
\hline
Decay & $U$ & $L$ & $P$ & $\bar{U}$ & $\bar{L}$ & $S$ & $\bar{S}$ & $\Gamma$ & $\langle P_L \rangle$ & $\alpha$ \\
\hline
$B \to D(e)$ & - & 8.3 & - & - & - & - & - & 8.3 & -1 & - \\
$B \to D^*(e)$ & 12.7 & 13.1 & -6.9 & - & - & - & - & 25.8 & -1 & 1.1 \\
b$\to c(e)$ & 12.4 & 24.8 & -7.6 & - & - & - & 37.2 & -1 & - \\
$B \to D(\tau)$ & - & 0.72 & - & - & - & - & 0.17 & 1.26 & 0.26 & 2.15 & 0.33 & - \\
$B \to D^*(\tau)$ & 3.03 & 1.95 & -1.39 & 0.64 & 0.43 & 0.46 & 0.25 & 6.50 & -0.53 & 0.55 \\
b$\to c(\tau)$ & 2.24 & 2.01 & -1.14 & 0.51 & 0.49 & 1.47 & 0.43 & 6.72 & -0.26 & - \\
\hline
\end{tabular}
\caption{Partial rates, total rates and polarization parameters for s.l. $b\to c$ transitions in the e- and $\tau$-sectors. We take $m_b = 4.73$ GeV and $m_c = 1.55$ GeV. Rates are in units of $|V_{tb}|^2 \times 10^{12}$ s$^{-1}$.}
\end{table}
Table 1 also contains the value of the asymmetry parameter $\alpha$ which determines the polar angle decay distribution $W(\theta^*) = 1 + \alpha \cos^2 \theta^*$ in the cascade decay $D^* \rightarrow D \pi (\rho \rightarrow \pi \pi)$, where $\theta^*$ is the polar angle of the $D$ (or $\pi$) in the $D^*(\rho)$ rest system. The asymmetry parameter is given by [1]

$$\alpha = \frac{2L+2\bar{L}-U-\bar{U}+2\bar{S}}{U+\bar{U}}.$$  (16)

Table 1 shows a rate reduction from the $e$-modes to the $\tau$-modes which is largest for the FQD with 18%, 25% for $B \rightarrow D^*$ and smallest for $B \rightarrow D$ with 26%. In fact, the sum of the $D$ and $D^*$ rates now exceeds the FQD rate. The strongest rate reduction occurs in the longitudinal no-flip rates which are 8.6%, 14.8% and 8.1% for $B \rightarrow D$, $B \rightarrow D^*$ and $b \rightarrow c$, respectively, of the corresponding $e$-rates whereas the transverse no-flip rates contributing to $B \rightarrow D^*$ and $b \rightarrow c$ are down less and occur at $O(25\%)$. That the total $B \rightarrow D$ rate reduction is comparable to the $B \rightarrow D^*$ and $b \rightarrow c$ cases can be seen to result from the fact that one has a strong scalar current contribution from $\bar{S}$ in the $\tau$-mode. This contribution is large because there is no pseudo-threshold factor to dampen the enhancement resulting from the time-like form factors at large $q^2$ as explained after (4). For the same reason the average longitudinal polarization has undergone a drastic change from the value $-1$ in the $e$-mode to a positive value of 0.33 in the $\tau$-mode, which again results from the large scalar current contribution. In the $B \rightarrow D^*$ and $b \rightarrow c$ cases the flip rates $\bar{U}, \bar{L}$ and $\bar{S}$ occur at only $O(10\%)$ of the total rate which explains why the average polarization is still negative in these cases. One notes also that the alignment polarization of the $D^*$ measured by the asymmetry parameter $\alpha$ is smaller in the $\tau$-mode than in the $e$-mode. This results from the relatively strong suppression of the longitudinal contribution in the $\tau$-mode.

In fig. 1 we show the $x (=p/p_{\text{max}})$ hadron momentum spectrum of the $b \rightarrow c$ transitions (full lines) and $b \rightarrow c(\tau)$ (dashed lines). In the $e$-mode the spectra rise to their highest values at $x = 1$ for $B \rightarrow D$ and $b \rightarrow c$, whereas the $B \rightarrow D^*$ spectrum is softer and shows a shoulder around $x = 0.6$ as also seen in the data [7]. In the $\tau$-mode the heavy lepton kinematics forces the spectra to go to zero at $x = 1$. Consequently the spectra become softer in the $\tau$-modes. The same behaviour is observed to a lesser degree in the $y (=p_\ell/p_{\text{max}})$ lepton momentum spectra, where the spectra become slightly softer going from the $e$-mode to the $\tau$-mode (see fig. 2).

In fig. 3 we show the $y$-behaviour of the longitudinal polarization of the $e$ and $\tau$ in $b \rightarrow c$ transitions.
nal polarization $P_L(y)$ of the $\tau$ in the three decay modes $B \rightarrow D(\tau)$, $B \rightarrow D^*(\tau)$ and $b \rightarrow c(\tau)$ (in the e-mode the longitudinal polarization is obviously equal to $-1$). In all three cases the longitudinal polarization decreases uniformly from its highest (positive) value at $y=0$ to its lowest (negative) value at $y=1$. That $P_L(y=0)=1$ for $B \rightarrow D$ is due to spin kinematics as there are only spin flip contributions to $B \rightarrow D$ in this limit. The longitudinal polarization of the $\tau$ is positive for the cases $B \rightarrow D^*$ and $b \rightarrow c$ close to $y=0$ where the transverse and parity-odd no-flip contributions $U$ and $P$ add destructively. That $P_L(B \rightarrow D) > P_L(b \rightarrow c) > P_L(B \rightarrow D^*)$ over the whole $y$-range reflects the relative strength of flip and no-flip contributions as evidenced by the partial rates in table 1.

In table 2 we list our predictions for the $b \rightarrow u$ transitions. When comparing the exclusive $B \rightarrow \pi$ and $B \rightarrow \rho$ modes with the FQD modes one has to take the theoretical uncertainty in the calculation of the overlap factor $I_{bu}$ into account which could easily deviate from its value of $I_{bu}=0.33$ used in this calculation by $\pm 25\%$. For this reason we limit our discussion to the qualitative features of the two exclusive $b \rightarrow u$ decay modes.

The total decay rates are generally reduced going from the e- to the $\tau$-mode. The reduction, however, is not as strong as in the corresponding $b \rightarrow c$ transitions. The $\tau$-rates are $52\%$, $58\%$ and $34\%$ of the corresponding e-rates in the $B \rightarrow \pi$, $B \rightarrow \rho$ and $b \rightarrow u$ cases, respectively. In the $\tau$-mode the two decay channels $B \rightarrow \pi$ and $B \rightarrow \rho$ almost saturate the FQD rate. The flip rates are generally small except again for the scalar current contribution in the $B \rightarrow \pi$ case which occurs at a level of $28\%$ compared to the total rate. That the scalar current contribution is not as strong as in the $B \rightarrow D$ case discussed earlier is due to the fact that there is a strong cancellation of the $F_{\pi}$ and $F_{\rho}$ contributions to the scalar helicity amplitude $H_1^s$ (with $F_{\pi}/F_{\rho} = -(M_1-M_2)/(M_1+M_2) \rightarrow -1$ as $M_2/M_1 \rightarrow 0$) which partially compensates for the s-wave enhancement. The average longitudinal polarization is negative for all three cases $B \rightarrow \pi$, $B \rightarrow \rho$ and $b \rightarrow u$. The largest reduction from the left-handed value $P_L=-1$ in the e-mode occurs for the $B \rightarrow \pi$ case with $P_L=-0.25$ which is mainly due to the strength of the scalar current contribution $S$. The alignment polarization of the $\rho$ as measured by the asymmetry parameter $\alpha$ is small for both the e- and the $\tau$-modes.

The $B \rightarrow \pi$, $B \rightarrow \rho$ and $b \rightarrow u$ hadron momentum spectra are shown in fig. 4. In the e-mode the spectra rise to their highest values at $x=1$ for $B \rightarrow \pi$ and $b \rightarrow u$. The $B \rightarrow \rho$ spectrum shows a shoulder around $x=0.3$ at a lower $x$-value than in the corresponding $B \rightarrow D$ case. This is due to the time-like form factor effect – the $\rho$ prefers to be produced at low momentum where $q^2$ is largest. In the $\tau$-mode all spectra become slightly

![Fig. 4. x (p/p_{max}) hadron momentum spectra of b→u(e) transitions (full lines) and b→u(\tau) transitions (dashed lines).](image-url)

Table 2

Partial rates, total rates and polarization parameters for s.l. b→u transitions in the e- and $\tau$-sectors. $m_q=4.73$ GeV and $m_u=0.3$ GeV.

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<th>Decay</th>
<th>$U$</th>
<th>$L$</th>
<th>$P$</th>
<th>$U$</th>
<th>$L$</th>
<th>$S$</th>
<th>$SL$</th>
<th>$\Gamma$</th>
<th>$\langle P_L \rangle$</th>
<th>$\alpha$</th>
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<tr>
<td>B→\pi(e)</td>
<td>26.1</td>
<td>52.2</td>
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<tr>
<td>B→\pi(\tau)</td>
<td>11.9</td>
<td>4.6</td>
<td>10.1</td>
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<tr>
<td>b→u(e)</td>
<td>9.1</td>
<td>9.8</td>
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<tr>
<td>b→u(\tau)</td>
<td>9.1</td>
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softer which is due to the fact that the spectra go to zero at $x = 1$ in the $\tau$-mode.

The $y (= p_e/P_{e\text{max}})$ lepton momentum spectra shown in fig. 5 remain practically unchanged for the $B \rightarrow \pi$ case and become slightly softer for $B \rightarrow \rho$ and slightly harder for $b \rightarrow u$ when going from the $e$- to the $\tau$-mode.

Fig. 6 finally shows the $y$-dependence of the longitudinal polarization. As in the corresponding $b \rightarrow c$ transitions the flip contributions dominate at lower $y$-values whereas the no-flip contributions dominate at higher $y$-values leading to positive and negative values of $P_L$ at lower and higher $y$-values. The dominance of the respective contributions is, however, more pronounced than in the $b \rightarrow c$ transitions with $P_L(y = 0) \approx +1$ and $P_L(y = 1) \approx -1$ in all three cases.

In conclusion, we have pointed out some interesting physics features in the exclusive semi-leptonic decays of the $B$-meson involving the heavy $\tau$-lepton. The $\tau$-rates occur at $\approx 25\%$ and $\approx 50\%$ of the $e$-rates for $B \rightarrow D(D^*)$ and $B \rightarrow \pi(\rho)$, respectively. There is a significant scalar current (lepton spin-flip) contribution in the $B \rightarrow D$ and $B \rightarrow \pi$ cases which is strong enough to change the average longitudinal polarization from $-1$ to $0.33$ and $-0.25$, respectively. It would be interesting to experimentally confirm these polarization predictions by analyzing the $\tau$'s subsequent decay distributions.

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