Semileptonic decays of charmed and beauty baryons with sterile neutrinos in the final state

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Abstract

We obtain tree-level estimates of various differential branching ratios of heavy baryon decays with massive sterile neutrinos $\nu_x$ in the final state. Heavy sterile neutrinos can be searched for in heavy baryon decays with missing mass as a signature as well as in fixed target experiments, where heavy baryon decays contribute to sterile neutrino production, with sterile neutrino decays as a signature. Generally, charmed baryons are found to be less promising than charmed mesons, in contrast to $b$-hadrons. In the latter case, branching ratios of beauty mesons and baryons into sterile neutrinos are of the same order. As a consequence, at high energies beauty baryons give contribution to sterile neutrino production comparable to the contribution of beauty mesons (up to about 15%). Experimental limits on active-to-sterile mixing are quite strong for neutrinos lighter than D-meson but for heavier neutrinos they are weaker. As an example, for neutrino masses in the range $2 \text{ GeV} \lesssim m_{\nu_x} \lesssim 2.5 \text{ GeV}$, current data imply that the bounds on $\Lambda_b$-hyperon branching ratios into sterile neutrinos are $\text{Br}(\Lambda_b \to \Lambda_c + e^- + \nu_x) \lesssim 1.3 \cdot 10^{-5} - 1.7 \cdot 10^{-6}$ and $\text{Br}(\Lambda_b \to \Lambda_c + \mu^- + \nu_x) \lesssim 3.9 \cdot 10^{-7} - 1.4 \cdot 10^{-7}$.

1 Introduction

Sterile neutrinos are introduced in particle physics to explain neutrino oscillations: they provide the active neutrino sector with masses and mixing. The inferred mass and mixing patterns in the active neutrino sector are severely constrained by neutrino experiments whereas resulting limits on parameters of the sterile neutrino sector are strongly model-dependent. In particular, sterile neutrino masses can be in the GeV range and this fact does not necessarily imply very small values of mixing angles $\theta$. In this case sterile neutrinos can be searched for in particle physics experiments, and here we discuss in detail sterile neutrino production in baryon decays.

For this study we assume that some sterile neutrinos have masses in the GeV range, and consider active-to-sterile mixing angles as free parameters constrained from direct searches for sterile neutrinos. This model-independent approach yields most conservative constraints on the sterile neutrino production rates. While chosen ad hoc, the GeV range for sterile neutrino masses can be preferred in some models, with $\nu$MSM \cite{2,3} serving as an example.

The richest source of sterile neutrinos of masses in the range we consider are weak decays of heavy mesons created in beam-beam and beam-target collisions. Recently, these decays
were revised in Ref. [4]. If sufficiently light, sterile neutrinos are produced mostly in π- and K-meson decays. For heavier neutrinos, leptonic and semileptonic decays of charmed mesons are the most relevant sources of sterile neutrino production. Finally, in models with neutrinos heavier than D-mesons but still in the GeV range, decays of B-mesons dominate. In all cases additional contribution comes from decays of baryons. For relatively heavy neutrinos the largest contribution from this baryon channel is due to semileptonic decays of charmed and beauty baryons, among which the most promising are Λ_c and Λ_b-hyperons because of the largest statistics collected.

In this paper we present explicit formulas for differential branching ratios of baryon semileptonic decays with massive sterile neutrinos in the final state. These formulas can be used to estimate the contribution of the baryon channel to the spectrum of sterile neutrinos produced in fix-target experiments, where sterile neutrino decays can be searched for. Likewise, the obtained formulas are relevant for searches of heavy baryon decays into sterile neutrinos which can be performed at operating and future B-factories, Tevatron and LHC.

2 Probabilities of baryon decays

We start with the semileptonic decay of Λ_c-hyperon. Λ_c-hyperon weakly decays into Λ-hyperon, positron and electron neutrino (as well as positive muon and muon neutrino). Let sterile neutrino ν_x mix with electron neutrino ν_e or muon neutrino ν_μ and θ_{lx} (l = e, μ) is the corresponding mixing angle. Then the amplitude of the process Λ_c → Λ + l^+ + ν_x can be written as follows,

\[ M = \frac{G}{\sqrt{2}} V_{cs} \sin \theta_{lx} \times \bar{\Lambda}(P) \left[ f_1 \gamma_\nu + i f_2 \frac{\sigma_{\nu\mu} q^\mu}{M_{\Lambda_c}} q_\nu - \left( g_1 \gamma_\nu + i g_2 \frac{\sigma_{\nu\mu} q^\mu}{M_{\Lambda_c}} q_\nu + \frac{g_3}{M_{\Lambda_c}} q^\nu \right) \gamma_5 \right] \Lambda_c (P - q) \times \bar{\nu}_x \gamma^\nu (1 - \gamma_5) l, \]  

where \( P \) and \( (P - q) \) are 4-momenta of Λ- and Λ_c-hyperons, \( M_\Lambda \) and \( M_{\Lambda_c} \) are their masses, \( G \) is the Fermi constant, \( V_{cs} \) is the element of the Cabibbo–Kobayashi–Maskawa matrix. The dimensionless form factors \( f_1, f_2, g_1, g_2, g_3 \) entering Eq. (1) parametrize the matrix element of the relevant hadronic current \( j^h_\nu = \bar{c} \gamma_\nu (1 - \gamma_5) s \) between real Λ- and Λ_c-hyperons. These form factors are functions of \( q^2 \).

The differential decay rate is given by

\[ d\Gamma = \frac{|\tilde{M}|^2}{2M_{\Lambda_c}} d\Phi, \]  

where

\[ d\Phi = (2\pi)^4 \delta(q + k_\nu + k_l) \frac{d\tilde{P}}{(2\pi)^3 2E_\Lambda} \frac{d\tilde{k}_\nu}{(2\pi)^3 2E_\nu} \frac{d\tilde{k}_l}{(2\pi)^3 2E_l}, \]
\( \vec{P}, \vec{k}_{\nu_e}, \vec{k}_l \) denote the 3-momenta of \( \Lambda \)-hyperon, sterile neutrino and charged lepton, respectively, \( E_\Lambda, E_{\nu_e}, E_l \) are their energies, \( |\mathcal{M}|^2 \) is the squared amplitude, averaged over spins of the initial baryon and summed over spins of final particles.

The direct calculation gives the following expression for \(|\tilde{\mathcal{M}}|^2\):

\[
|\mathcal{M}|^2 = 8G^2|V_{cs}|^2 \sin^2 \theta_{lx} \left[ (f_1^2 + g_1^2)(4Pk_{\nu_e}Pk_l - 2P_{k_{\nu_e}}qk_l - 2Pk_lq_{k_{\nu_e}}) - 2(f_1^2 - g_1^2)M_\Lambda M_{\Lambda_e}k_{\nu_e}k_l - 2M_\Lambda^2(f_1f_2 + g_1g_2)(k_{\nu_e}k_l(Pq - q^2) + q_{k_{\nu_e}}(Pk_l - qk_l) + q_{k_l}(Pk_{\nu_e} - q_{k_{\nu_e}})) - 2(f_1f_2 - g_1g_2)(Pk_lq_{k_{\nu_e}} + Pk_{\nu_e}qk_l + Pqk_{k_{\nu_e}}k_l) - f_2^2 + g_2^2(4Pk_{\nu_e}Pk_lq^2 - 4Pq(Pk_lq_{k_{\nu_e}} + Pk_{\nu_e}qk_l) - 2k_{\nu_e}k_l(2(Pq)^2 - q^2M_\Lambda^2 - Pq q^2) + 2q_{k_{\nu_e}}qk_l(Pq + M_\Lambda^2) - 3M_\Lambda^2q^2k_{\nu_e}k_l + 4(Pq)^2k_{\nu_e}k_l - Pq q^2k_{\nu_e}k_l) - M_\Lambda M_{\Lambda_e}(f_2^2 - g_2^2)(q^2k_{\nu_e}k_l + 2q_{k_{\nu_e}}qk_l) + M_\Lambda M_{\Lambda_e}(f_1f_3 + g_1g_3)M_\Lambda M_{\Lambda_e}(2q_{k_{\nu_e}}(Pk_l - qk_l) + 2qk_l(Pk_{\nu_e} - q_{k_{\nu_e}}) - 2k_{\nu_e}k_l(Pq - q^2)) + (f_1f_3 - g_1g_3)(2Pk_lq_{k_{\nu_e}} + 2P_{k_{\nu_e}}qk_l - 2Pqk_{k_{\nu_e}}k_l) + 2f_2f_3 + g_2g_3q^2(Pk_lq_{k_{\nu_e}} + Pk_{\nu_e}qk_l) - f_3^2M_{\Lambda_e}^2(2qk_{\nu_e}qk_l - q^2k_{\nu_e}k_l)(Pq - M_\Lambda(M_{\Lambda_e} + M_\Lambda)) - g_3^2M_{\Lambda_e}^2(2qk_{\nu_e}qk_l - q^2k_{\nu_e}k_l)(Pq + M_\Lambda(M_{\Lambda_e} - M_\Lambda)) + 4(Pk_lq_{k_{\nu_e}} - Pk_{\nu_e}qk_l) \times \left( g_1f_1 + g_2f_2(2Pq - q^2) + f_1g_2 \left( 1 - \frac{M_\Lambda}{M_{\Lambda_e}} \right) + f_2g_1 \left( 1 + \frac{M_\Lambda}{M_{\Lambda_e}} \right) \right) \right].
\]

Integrating Eq. (2) over 3-momenta of sterile neutrino and charged lepton and over all possible directions of the outgoing baryon, one gets for the differential decay rate

\[
\frac{d\Gamma}{dE_\Lambda} = \frac{G^2|V_{cs}|^2 \sin^2 \theta_{lx} \sqrt{E_\Lambda^2 - M_\Lambda^2}}{64\pi^3 q^4} \sqrt{q^4 - 2q^2(m_{\nu_e}^2 + m_l^2) + (m_{\nu_e}^2 - m_l^2)^2} q^4 \times \left[ \frac{1}{3}(2q^4 - q^2(m_{\nu_e}^2 + m_l^2) - (m_{\nu_e}^2 - m_l^2)^2)((f_1^2 + g_1^2)(4M_\Lambda^2q^2 - 12Pq q^2 + 8(Pq)^2) \right]
\]

3
\[
-12(f_1^2 - g_1^2)M_\Lambda M_{\Lambda_c} q^2 + 24 \frac{M_\Lambda}{M_{\Lambda_c}} (f_1 f_2 + g_1 g_2)(Pq - q^2)q^2 - 24(f_1 f_2 - g_1 g_2)Pq q^2
\]
\[
- \frac{f_2^2 + g_2^2}{M_{\Lambda_c}^2}(12Pq q^4 - 8(Pq)q^2 + 4M_\Lambda^2 q^4) - 6 \frac{M_\Lambda}{M_{\Lambda_c}} (f_2 - g_2)q^4
\]
\[
+ ((m_1^2 - m_{\nu_e}^2)^2 - q^2(m_\nu_e^2 + m_\nu_s^2))(f_1^2 + g_1^2)(4M_\Lambda^2 q^2 + 4Pq q^2 - 8(Pq)^2)
\]
\[
- 4(f_1^2 - g_1^2)q^2 M_\Lambda M_{\Lambda_c} - 8 \frac{M_\Lambda}{M_{\Lambda_c}} (f_1 f_3 + g_1 g_3)Pq q^2 - 8(f_1 f_3 - g_1 g_3)Pq q^2
\]
\[
+ 4 \frac{f_3^2}{M_{\Lambda_c}^2} q^2 (Pq - M_\Lambda(M_{\Lambda_c} + M_\Lambda)) + 4 \frac{g_3^2}{M_{\Lambda_c}^2} q^2 (Pq + M_\Lambda(M_{\Lambda_c} - M_\Lambda))
\]
where \(Pq\) and \(q^2\) are functions of \(E_\Lambda\):
\[
Pq = M_\Lambda^2 - E_\Lambda M_{\Lambda_c}
\]
and
\[
q^2 = M_\Lambda^2 + M_{\Lambda_c}^2 - 2M_\Lambda E_\Lambda.
\]

Semileptonic decays of any other baryons \((B_1 \to B_2 + l + \nu)\) are described by similar formulas with obvious replacements: \(M_{\Lambda_c} \to M_{B_1}, M_\Lambda \to M_{B_2}, |V_{cs}|^2 \to |V_{ij}|^2\), where \(V_{ij}\) is the relevant element of the Cabibbo–Kobayashi–Maskawa matrix.

By integrating Eq. (1) over the final baryon energy one obtains the decay rate \(\Gamma\) as the function of sterile neutrino mass \(m_{\nu_s}\). The corresponding branching ratios of the decays \(\Lambda_c \to \Lambda + l^+ + \nu_s\) and \(\Lambda_b \to \Lambda_c + l^- + \nu_s\) are presented in Fig.1. Charged lepton is considered to be massless (electron or positron). Results of numerical calculations for the differential branching ratios, which give differential spectrum of outgoing baryons, are presented in Fig.2.

In all numerical calculations we use the form factors in the dipole approximation [5]:
\[
f_i(q^2) = \frac{f_i(0)}{(1 - \frac{q^2}{m_i^2})^2}, \quad (5)
\]
\[
g_i(q^2) = \frac{g_i(0)}{(1 - \frac{q^2}{m_i^2})^2}, \quad (6)
\]
where for charmed baryons \(m_V = 2.11\) GeV, \(m_A = 2.54\) GeV, and for beauty baryons \(m_V = 6.34\) GeV, \(m_A = 6.73\) GeV. Values of \(f_i(0)\) and \(g_i(0)\) for the transitions \(\Lambda_b \to \Lambda_c\) and \(\Lambda_c \to \Lambda\) are taken from Ref. [4]. They are summarized in Table 1. Values of \(f_2(0), f_3(0), g_2(0), g_3(0)\) have the opposite sign as compared to Ref. [5] because of the different parametrization of matrix element [1].
Table 1: Form factors for the transitions $\Lambda_c \to \Lambda$ and $\Lambda_b \to \Lambda_c$ adopted from Ref. [5] and used in numerical calculations.

| Form factors | $\Lambda_b \to \Lambda_c$ | $\Lambda_c \to \Lambda$ |
|--------------|--------------------------|--------------------------|
| $f_1(0)$     | 0.53                     | 0.29                     |
| $f_2(0)$     | 0.12                     | 0.14                     |
| $f_3(0)$     | 0.02                     | 0.03                     |
| $g_1(0)$     | 0.58                     | 0.38                     |
| $g_2(0)$     | 0.02                     | 0.03                     |
| $g_3(0)$     | 0.13                     | 0.19                     |

Figure 1: Branching ratios $\frac{Br}{\sin^2\theta_{lx}}$ for baryon decays: a) $\Lambda_c \to \Lambda + l^+ + \nu_x$; b) $\Lambda_b \to \Lambda_c + l^- + \nu_x$.

The differential rate $\frac{d\Gamma}{dE_l}$, describing the differential spectrum of outgoing charged leptons, is obtained by integrating Eq. (2) over $\vec{P}, \vec{k}_{\nu_x}$. The final expression is:

$$\frac{d\Gamma}{dE_l} = \frac{1}{64\pi^3M_{\Lambda_c}}\sqrt{E_l^2 - m_l^2} \sqrt{\frac{(p^2 + 4\Lambda^2 - m_{\nu_x}^2)^2}{4p^4} - \frac{M_{\Lambda_c}^2}{p^2}} \int |\tilde{M}|^2 \sin \theta d\theta,$$

where

$$p^2 = M_{\Lambda_c}^2 + m_l^2 - 2M_{\Lambda_c}E_l,$$

$\theta$ is the angle between charged lepton and outgoing baryon in the center-of-mass frame of sterile neutrino and outgoing baryon. The results of numerical calculation are presented in Fig. 3. Differential spectrum (7) can be used in searches of heavy baryon decays with sterile neutrinos in the final state.

The differential rates $\frac{d\Gamma}{dE_{\nu_x}}$ are given by the same expression with obvious replacement: $\nu_x \leftrightarrow l$; $\theta$ is now the angle between neutrino and outgoing baryon in the center-of-mass frame.
Figure 2: Differential branching ratios \( \frac{d(Br/\sin^2 \theta_{\nu_x})}{d(E_{\Lambda}/\text{GeV})} \) as functions of final baryon energy for baryon decays: a) \( \Lambda_c \rightarrow \Lambda + l^+ + \nu_x \), various plots correspond to various sterile neutrino masses: from top to bottom \( m_{\nu_x} = 0, 0.2, 0.4, 0.6, 0.8, 1.0 \) GeV; b) \( \Lambda_b \rightarrow \Lambda_c + l^- + \nu_x \); \( m_{\nu_x} = 0, 0.5, 1.0, 1.5, 2.0, 2.5 \) GeV.

Figure 3: Differential branching ratios \( \frac{d(Br/\sin^2 \theta_{\nu_x})}{d(E_l/\text{GeV})} \) as functions of charged lepton energy for baryon decays: a) \( \Lambda_c \rightarrow \Lambda + l^+ + \nu_x \); b) \( \Lambda_b \rightarrow \Lambda_c + l^- + \nu_x \). Sterile neutrino masses are the same as in Fig. 2. Larger branching ratios correspond to smaller neutrino masses.

of lepton and outgoing baryon. The numerical results are presented in Fig. 4 and are relevant for searches of sterile neutrinos in baryon decays, since \( \frac{d\Gamma}{dE_{\nu_x}} \) describes the spectrum of produced neutrinos.
Figure 4: Differential branching ratios \( \frac{d(Br/\sin^2 \theta_{\nu_x})}{d(E_{\nu_x}/\text{GeV})} \) as functions of sterile neutrino energy for baryon decays: a) \( \Lambda_c \rightarrow \Lambda + l^+ + \nu_x \); b) \( \Lambda_b \rightarrow \Lambda_c + l^- + \nu_x \). Sterile neutrino masses are the same as in Fig. 2. Larger branching ratios correspond to smaller neutrino masses.

3 Discussion

Our results for the baryon branching ratios into sterile neutrinos can be compared to similar results for heavy meson decays, presented in Ref. [4]. In the case of charmed hadrons the general conclusion is that baryon branching ratios are always significantly lower than branching ratios of charmed mesons. As an example, for \( m_K \lesssim m_{\nu_x} \lesssim 1 \text{ GeV} \), where \( m_K \) is K-meson mass, one estimates \( \frac{Br(D \rightarrow K^0 + l + \nu_x)}{Br(\Lambda_c \rightarrow \Lambda + l^+ + \nu_x)} \approx 10 \). Branching ratios of leptonic meson decays are even larger. Hereafter, meson branching ratios are calculated with the use of formulas presented in Ref. [4] and form factors presented in Ref. [6]. Hence, charmed baryons are less promising for sterile neutrino searches in comparison with charmed mesons, since larger statistics is required to reach the same level of statistical sensitivity to active-to-sterile mixing angles. From the analyses of baryon and meson decay modes, presented in this work and in Ref. [4], respectively, and with account of baryon fraction in c-quark hadronization [7] one can estimate the contribution of baryon channel to sterile neutrino production in proton beam-beam and beam-target collisions at the level of 2%.

In beauty sector the situation is quite the opposite: baryon branching ratios are somewhat larger than branching ratios of mesons. As an example, for \( 2 \text{ GeV} \lesssim m_{\nu_x} \lesssim 3 \text{ GeV} \) we obtain \( \frac{Br(B \rightarrow D^* + l + \nu_x)}{Br(\Lambda_b \rightarrow \Lambda_c + l^- + \nu_x)} \approx 0.5 \). Note that \( B \rightarrow D^* + l + \nu_x \) dominates the sterile neutrino production in meson channel. Thus, one expects that searches for sterile neutrinos in baryon decays should be competitive with similar searches in meson decays. From the analyses of baryon and meson decay modes, presented in this work and in Ref. [4], respectively, and with account of baryon fraction in b-quark hadronization [8] one can estimate the contribution of baryon channel to sterile neutrino production in proton beam-beam and beam-target collisions at the level of 15%.
The absolute values of baryon branching ratios into sterile neutrinos are proportional to squared values of corresponding active-to-sterile mixing angles. The latter are limited from above due to negative results of direct searches for sterile neutrinos. For mixing with electron neutrinos, the strongest limits are $|\theta_{\text{ex}}|^2 \lesssim 3 \cdot 10^{-6} - 3 \cdot 10^{-7}$ for $m_K \lesssim m_{\nu_x} \lesssim 1$ GeV from BEBC experiment [9], $|\theta_{\text{ex}}|^2 \lesssim 10^{-7}$ for 1.5 GeV $\lesssim m_{\nu_x} \lesssim 2$ GeV from CHARM [10] and $|\theta_{\text{ex}}|^2 \lesssim 1 \cdot 10^{-3} - 1 \cdot 10^{-4}$ for 2 GeV $\lesssim m_{\nu_x} \lesssim 3$ GeV from HRS [11]. For mixing with muon neutrinos the limits are $|\theta_{\mu x}|^2 \lesssim 5 \cdot 10^{-7} - 1 \cdot 10^{-7}$ for $m_K \lesssim m_{\nu_x} \lesssim 1$ GeV, $|\theta_{\mu x}|^2 \lesssim 6 \cdot 10^{-8} - 1 \cdot 10^{-7}$ for 1.5 GeV $\lesssim m_{\nu_x} \lesssim 2$ GeV from NuTeV [12], $|\theta_{\mu x}|^2 \lesssim 3 \cdot 10^{-5} - 4 \cdot 10^{-5}$ for 2 GeV $\lesssim m_{\nu_x} \lesssim 2.5$ GeV from CHARM II experiment [13] and $|\theta_{\mu x}|^2 \lesssim 5 \cdot 10^{-4} - 1 \cdot 10^{-4}$ from HRS experiment [11].

Consequently, in models with sterile neutrino mass ranging within $m_K \lesssim m_{\nu_x} \lesssim 1$ GeV one estimates from Fig. 1 and the above limits:

$$\text{Br}(\Lambda_c \rightarrow \Lambda + e^+ + \nu_x) \lesssim 2.1 \cdot 10^{-8},$$
$$\text{Br}(\Lambda_c \rightarrow \Lambda + \mu^+ + \nu_x) \lesssim 3.5 \cdot 10^{-9}.$$  

In models with 1.5 GeV $\lesssim m_{\nu_x} \lesssim 2$ GeV:

$$\text{Br}(\Lambda_b \rightarrow \Lambda_c + e^- + \nu_x) \lesssim 2.8 \cdot 10^{-9} - 1.3 \cdot 10^{-9},$$
$$\text{Br}(\Lambda_b \rightarrow \Lambda_c + \mu^- + \nu_x) \lesssim 1.7 \cdot 10^{-9} - 1.3 \cdot 10^{-9},$$

where larger value on the right hand side corresponds to smaller value of $m_{\nu_x}$ and vice versa. In models with 2 GeV $\lesssim m_{\nu_x} \lesssim 2.5$ GeV:

$$\text{Br}(\Lambda_b \rightarrow \Lambda_c + e^- + \nu_x) \lesssim 1.3 \cdot 10^{-5} - 1.7 \cdot 10^{-6},$$
$$\text{Br}(\Lambda_b \rightarrow \Lambda_c + \mu^- + \nu_x) \lesssim 3.9 \cdot 10^{-7} - 1.5 \cdot 10^{-7}.$$  

Finally, in models with heavy sterile neutrinos in the range 2.5 GeV $\lesssim m_{\nu_x} \lesssim 3$ GeV:

$$\text{Br}(\Lambda_b \rightarrow \Lambda_c + e^- + \nu_x) \lesssim 1.7 \cdot 10^{-6},$$

and the same limit for the process $\Lambda_b \rightarrow \Lambda_c + \mu^- + \nu_x$.

Thus, to search for sterile neutrinos, one has to collect statistics of at least a few million heavy baryons.

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