Semileptonic decays of heavy baryons to negative-parity baryons

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Simplest semileptonic decays: $J^P=1/2^+$ ground states

Charged current decays:
- $\Lambda_b \rightarrow \Lambda_c \ell^- \bar{\nu}_\ell$
- $\Lambda_b \rightarrow p \ell^- \bar{\nu}_\ell$
- $\Lambda_b \rightarrow \Lambda \ell^+ \nu_\ell$
- $\Lambda_b \rightarrow n \ell^+ \nu_\ell$

Neutral current (rare) decays:
- $\Lambda_b \rightarrow \Lambda \ell^+ \ell^-$
- $\Lambda_b \rightarrow n \ell^+ \ell^-$
- $\Lambda_b \rightarrow p \ell^+ \ell^-$
## Next simplest decays?

<table>
<thead>
<tr>
<th>Name</th>
<th>$J^P$</th>
<th>Mass [MeV]</th>
<th>Width [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda^*(1520)$</td>
<td>$\frac{3}{2}^-$</td>
<td>1519.42(19)</td>
<td>15.73(26)</td>
</tr>
<tr>
<td>$\Lambda_c^*(2595)$</td>
<td>$\frac{1}{2}^-$</td>
<td>2592.25(28)</td>
<td>2.6(6)</td>
</tr>
<tr>
<td>$\Lambda_c^*(2625)$</td>
<td>$\frac{3}{2}^-$</td>
<td>2628.11(19)</td>
<td>$\leq 0.97$</td>
</tr>
</tbody>
</table>
Experimental Situation

- LHCb has large $\Lambda_b \rightarrow \Lambda_c^*(2595, 2625)\mu^-\bar{\nu}_\mu$ # of samples and can measure $R(\Lambda_c^*)$ ratios

- LHCb is planning an analysis of $\Lambda_b \rightarrow \Lambda^*(1520) (\rightarrow p^+K^-) \ell^-\ell^+$ [Y. Amhis et al., arXiv:2005.09602/EPJP 2021]

- BESIII has measured the inclusive semileptonic branching fraction [arXiv:1805.09060/PRL 2018]

\[
B(\Lambda_c \rightarrow Xe^+\nu_e) = (3.95 \pm 0.34 \pm 0.09) \times 10^{-2}
\]
Related theoretical work

- Quark-model studies of $\Lambda_b \to \Lambda_c^* \ell^- \bar{\nu}_\ell$, $\Lambda_b \to p^* \ell^- \bar{\nu}_\ell$, $\Lambda_b \to \Lambda^* \ell^+ \ell^-$, $\Lambda_c \to \Lambda^* \ell^+ \nu_\ell$, $\Lambda_c \to n^* \ell^+ \nu_\ell$
  
  T. Gutsche et al., arXiv:1807.11300/PRD 2018
  Y.-S. Li, X. Liu, F.-S. Yu, arXiv:2104.04962

- $\Lambda_b \to \Lambda_c^*(2595, 2625)\mu^- \bar{\nu}_\mu$ in HQET up to $O(\alpha_s, 1/m_b)$
  
  P. Böer et al., arXiv:1801.08367/JHEP 2018
  M. Papucci, D. Robinson, arXiv:2105.09330
Related theoretical work

- $\Lambda_c \rightarrow \Lambda^*(1405)\ell^+\nu_\ell$ in chiral unitary approach

- Angular distribution of $\Lambda_b \rightarrow \Lambda^*(1520) \rightarrow p^+K^- \ell^-\ell^+$

- $\Lambda_b \rightarrow \Lambda^*(1520)\ell^+\ell^-$ in HQET up to $O(\alpha_s) \text{ or } O(1/m_b)$
  M. Bordone, arXiv:2101.12028/Symmetry 2021

- LHCb sensitivity study of $\Lambda_b \rightarrow \Lambda^*(1520) \rightarrow p^+K^- \ell^-\ell^+$

- Endpoint symmetries of baryon helicity amplitudes at $q^2 = q^2_{\text{max}}$
Our lattice calculations

- $\Lambda_b \rightarrow \Lambda^*(1520)\ell^+\ell^-$

- $\Lambda_b \rightarrow \Lambda^*_c(2595)\ell^-\bar{\nu}_\ell$ and $\Lambda_b \rightarrow \Lambda^*_c(2625)\ell^-\bar{\nu}_\ell$

- $\Lambda_c \rightarrow \Lambda^*(1520)\ell^+\nu_\ell$

Also, in arXiv:2107.13140 we also improve the analysis on $\Lambda_b \rightarrow \Lambda^*(1520)$ and $\Lambda_b \rightarrow \Lambda^*_c(2595,2625)$ form factors enforcing exactly endpoint relations during the fits. Any results shown for these two processes are using this improved analysis.
Our lattice calculations

- We work on the baryon rest frame to allow the exact projection to \( J^P = 1/2^- \) or \( 3/2^- \) (\( G_{1u} \) or \( H_u \) irreps).
- We use an interpolating field with derivatives to obtain an \( L=1 \) quantum number, that is,

\[
(O_{\Lambda^*})_{j\gamma} = \epsilon^{abc} (C_{\gamma 5})_{\alpha \beta} \left( \frac{1 + \gamma_0}{2} \right)_{\gamma \delta} \left[ \tilde{z}_\alpha^a \tilde{d}_\beta^b (\tilde{\nabla}_j \tilde{u})^c_\delta - \tilde{z}_\alpha^a \tilde{u}_\beta^b (\tilde{\nabla}_j \tilde{d})^c_\delta + \tilde{u}_\alpha^a (\tilde{\nabla}_j \tilde{d})^b_\beta \tilde{s}^c_\delta - \tilde{d}_\alpha^a (\tilde{\nabla}_j \tilde{u})^b_\beta \tilde{s}^c_\delta \right]
\]
Our lattice calculations

- We use helicity-based definitions of the form factors

<table>
<thead>
<tr>
<th>Transition</th>
<th>Current</th>
<th>Form factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{1}{2}^+ \rightarrow \frac{1}{2}^-$</td>
<td>Vector</td>
<td>$f_{0}^{(\frac{1}{2}^-)}$, $f_{+}^{(\frac{1}{2}^-)}$, $f_{\perp}^{(\frac{1}{2}^-)}$</td>
</tr>
<tr>
<td></td>
<td>Axial vector</td>
<td>$g_{0}^{(\frac{1}{2}^-)}$, $g_{+}^{(\frac{1}{2}^-)}$, $g_{\perp}^{(\frac{1}{2}^-)}$</td>
</tr>
<tr>
<td></td>
<td>Tensor</td>
<td>$h_{+}^{(\frac{1}{2}^-)}$, $h_{\perp}^{(\frac{1}{2}^-)}$, $\tilde{h}<em>{+}^{(\frac{1}{2}^-)}$, $\tilde{h}</em>{\perp}^{(\frac{1}{2}^-)}$</td>
</tr>
<tr>
<td>$\frac{1}{2}^+ \rightarrow \frac{3}{2}^-$</td>
<td>Vector</td>
<td>$f_{0}^{(\frac{3}{2}^-)}$, $f_{+}^{(\frac{3}{2}^-)}$, $f_{\perp}^{(\frac{3}{2}^-)}$, $f_{\perp}^{(\frac{3}{2}^-)}$</td>
</tr>
<tr>
<td></td>
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<td>$g_{0}^{(\frac{3}{2}^-)}$, $g_{+}^{(\frac{3}{2}^-)}$, $g_{\perp}^{(\frac{3}{2}^-)}$, $g_{\perp}^{(\frac{3}{2}^-)}$</td>
</tr>
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<td></td>
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<td>$h_{+}^{(\frac{3}{2}^-)}$, $h_{\perp}^{(\frac{3}{2}^-)}$, $\tilde{h}<em>{+}^{(\frac{3}{2}^-)}$, $\tilde{h}</em>{\perp}^{(\frac{3}{2}^-)}$, $\tilde{h}<em>{\perp}^{(\frac{3}{2}^-)}$, $\tilde{h}</em>{\perp}^{(\frac{3}{2}^-)}$</td>
</tr>
</tbody>
</table>

\[ w(q^2) = v \cdot v' = \frac{m_{\Lambda_b}^2 + m_{\Lambda^*}^2 - q^2}{2m_{\Lambda_b}m_{\Lambda^*}} \]
Our lattice calculations

- We use RBC/UKQCD ensembles with 2+1 flavors of domain-wall fermions

<table>
<thead>
<tr>
<th>Label</th>
<th>$N_s^3 \times N_t$</th>
<th>$a$ [fm]</th>
<th>$m_\pi$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>C01</td>
<td>$24^3 \times 64$</td>
<td>0.1106(3)</td>
<td>0.4312(13)</td>
</tr>
<tr>
<td>C005</td>
<td>$24^3 \times 64$</td>
<td>0.1106(3)</td>
<td>0.3400(11)</td>
</tr>
<tr>
<td>F004</td>
<td>$32^3 \times 64$</td>
<td>0.0828(3)</td>
<td>0.3030(12)</td>
</tr>
</tbody>
</table>

- The charm and bottom quarks were simulated using “RHQ” (anisotropic clover) action
Extracting the form factors from ratios of 3pt and 2pt functions

In simple terms:
- Project to desired parity and spin at source and sink
- Project to desired FF at the current

Advantages:
- Overlap factors cancel out
- Time dependence cancels out at infinite time

\[ R_f(p, t) \rightarrow |f(p)|^2 \text{ at large } t \]
Extracting the form factors from ratios of 3pt and 2pt functions
Extracting form factors from ratios of 3pt functions

Schematically:
- Determine FF’s using 3pt/2pt ratios
- Choose reference FF
- Determine all other FF’s relative magnitudes and signs using 3pt/3pt

Advantages:
- Same source and sink, so reduced noise
- Don’t have to determine FF’s phase separately
Extracting form factors from ratios of 3pt functions

\[ F_{A}^{\perp'} \]
Extracting form factors from ratios of 3pt functions

\[
X_{g_{\perp}}^2
\]

<table>
<thead>
<tr>
<th>3pt/2pt ratio</th>
<th>3pt/3pt ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.010</td>
<td>0.000</td>
</tr>
<tr>
<td>-0.005</td>
<td>0.005</td>
</tr>
<tr>
<td>0.000</td>
<td>0.010</td>
</tr>
<tr>
<td>0.005</td>
<td>0.015</td>
</tr>
<tr>
<td>0.010</td>
<td>0.015</td>
</tr>
<tr>
<td>0.015</td>
<td></td>
</tr>
</tbody>
</table>

4 6 8 10 12 14
Sample form-factor results: $\Lambda_b \rightarrow \Lambda^*(1520)$

We have data for two different $\Lambda_b$ momenta, $p/L = (0, 0, 2), (0, 0, 3)$

\[ g^\left(\frac{3}{2}^-, +\right) \]

\[ a = 0, \quad m_\pi = 135 \text{ MeV} \]
Sample form-factor results: $\Lambda_b \rightarrow \Lambda_c^*(2595, 2625)$

We have data for two different $\Lambda_b$ momenta, $p/2\pi = (0, 0, 2), (0, 0, 3)$

\[ g_{\frac{3}{2}^-}^{(3)} \]
Sample form-factor results: $\Lambda_c \rightarrow \Lambda^*(1520)$

We have data for four different $\Lambda_c$ momenta, $p/\frac{2\pi}{L} = (0, 0, 1), (0, 1, 1), (1, 1, 1), (0, 0, 2)$

We also enforce $q^2 = 0$ endpoint relations

$g_{3/2}^{(3^-)}$
$\Lambda_b \rightarrow \Lambda^*(1520)\mu^+\mu^-$ differential branching fraction near $q_{\text{max}}$

\[ \Lambda_b \rightarrow \Lambda^* (1520) (\rightarrow pK^-) \mu^+ \mu^- \] differential branching fraction near \( q_{\text{max}} \)

\( \Lambda_b \rightarrow \Lambda^*(1520)(\rightarrow pK^-)\mu^+\mu^- \) differential branching fraction near \( q_{\text{max}} \)

**O(1/m_b, \alpha_s) HQET fit to our 2020 \Lambda_b \to \Lambda^*(1520) lattice results**

The fit to the V & A form factors has good quality [M. Bordone, arXiv:2101.12028/Symmetry 2021]

In gray are lattice results and in red are HQET
$O(1/m_b, \alpha_s)$ HQET fit to our 2020 $\Lambda_b \rightarrow \Lambda^*(1520)$ lattice results

However, tensor form factors (not included in fit) show deviations
\[ \Lambda_b \rightarrow \Lambda_c^{(*)} \mu^- \overline{\nu}_\mu \] differential decay rates near \( q^2_{\text{max}} \) from lattice QCD

The relative size of \( \frac{1}{2}^- \) and \( \frac{3}{2}^- \) differential decay rates is opposite to the expectation from LO HQET.
\[ \Lambda_b \rightarrow \Lambda_c^{(*)}\ell^- \bar{n} \nu_\ell \] angular observables near \( q^2_{\text{max}} \) from lattice QCD

LO HQET would predict the angular observables for the \( \frac{1}{2}^- \) and \( \frac{3}{2}^- \) cases to be equal.
$\Lambda_b \rightarrow \Lambda_c^{(*)}\ell^-\overline{\nu}_\ell$: HQET results

- HQET including only $O(1/m, \alpha_s)$ corrections does not allow a good fit to the lattice results for the $\Lambda_b \rightarrow \Lambda_c^{*}(2595, 2625)$ form factors. In particular, the results for the spin-1/2 final state $\Lambda_c^{*}(2595)$ imply very large $1/m_c^2$ corrections.

  [M. Papucci, D. Robinson, arXiv:2105.09330]

- The spin-1/2 $\Lambda_c^{*}(2595)$ may may have an exotic structure and may correspond to two poles similar to the strange $\Lambda_c^{*}(1405)$.

\( \Lambda_c \rightarrow \Lambda^*(1520)e^+\nu_e \) observables comparison: lattice vs quark model

\[ \frac{d\Gamma}{dq^2} \text{[ps}^{-1}\text{GeV}^{-2}] \]

\[ F_0 \text{ vs } q^2 \text{[GeV}^2]\]

\[ A_{FB} \text{ vs } q^2 \text{[GeV}^2]\]

$\Lambda_c \rightarrow \{\Lambda, n, \Lambda^*(1520)\} \ell^+ \nu_\ell$ differential decay rates from lattice QCD

The form factors for transitions to $n$ and $\Lambda$ were taken from S. Meinel, arXiv:1611.09696/PRL 2017; arXiv:1712.05783/PRD 2018
\[ \Lambda_c \rightarrow \{ \Lambda, n, \Lambda^*(1520) \} \ell^+ \nu_\ell \] angular observables from lattice QCD

The form factors for transitions to \( n \) and \( \Lambda \) were taken from S. Meinel, arXiv:1611.09696/PRL 2017; arXiv:1712.05783/PRD 2018
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The form factors for transitions to \( n \) and \( \Lambda \) were taken from S. Meinel, arXiv:1611.09696/PRL 2017; arXiv:1712.05783/PRD 2018
Bounding $\mathcal{B}(\Lambda_c \rightarrow \Lambda^*(1405)e^+\nu_e)$

BESIII has measured the inclusive branching fraction [arXiv:1805.09060/PRL 2018]

$$\mathcal{B}(\Lambda_c \rightarrow Xe^+\nu_e)_{\text{BESIII}} = 3.95(0.34)(0.09)\%$$

Using lattice QCD we predict

$$\left[\mathcal{B}(\Lambda_c \rightarrow \Lambda e^+\nu_e) + \mathcal{B}(\Lambda_c \rightarrow ne^+\nu_e) + \mathcal{B}(\Lambda_c \rightarrow \Lambda^*(1520)e^+\nu_e)\right]_{\text{LQCD}} = 4.32(0.23)(0.07)\%$$

Subtracting this to the BESIII result, we obtain an upper bound on the branching fraction to all other hadrons:

$$\mathcal{B}(\Lambda_c \rightarrow Xe^+\nu_e)_{X\neq\Lambda,n,\Lambda^*(1520)} \leq 0.15\% \text{ at 68\% CL, using Feldman-Cousins}$$

Summary

- We have updated our results for $\Lambda_b \to \Lambda_c^*(2595)$, $\Lambda_b \to \Lambda_c^*(2625)$, and $\Lambda_b \to \Lambda^*(1520)$ form factors enforcing $q_{\text{max}}^2$ endpoint relations. Angular observables now take the exact values predicted by rotational symmetry. The old results remain consistent within 1-2 sigma.

- Our $\Lambda_b \to \Lambda_c^*$ results are not very well described by HQET up to $O(1/m_b, \alpha_s)$. In particular, results for spin-1/2 particle, $\Lambda_c(2625)$, imply very large $1/m_c^2$ corrections. Some authors have suggested $\Lambda_c^*(2625)$ has a two pole structure like the strange $\Lambda^*(1405)$.

- We have performed the first lattice-QCD determination of the $c \to^* (1520)(J^P = 3/2^-)$ form factors. These results do cover the entire kinematic range.

- Using the $\Lambda_c$ inclusive branching fraction from BESIII and subtracting lattice results for $\Lambda_c \to \Lambda$, $\Lambda_c \to n$ and $\Lambda_c \to \Lambda^*(1520)$. With this we have put an upper limit on $\Lambda_c \to \Lambda^*(1405)$. Quark-model results slightly exceed this upper limit.