$\Lambda_c \to \Lambda \ell^+ \nu_\ell$ form factors and decay rates from lattice QCD with physical quark masses†

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The decays $\Lambda_c \to \Lambda \ell^+ \nu_\ell$, where $\ell = e, \mu$, are the most important baryonic $c \to s \ell^+ \nu_\ell$ transitions; their rates are proportional to the CKM matrix element $|V_{cs}|^2$ in the Standard Model. The motivations for studying $\Lambda_c \to \Lambda \ell^+ \nu_\ell$ include the following:

- Taking the precisely determined value of $|V_{cs}|$ from CKM unitarity, a comparison between calculated and measured $\Lambda_c \to \Lambda \ell^+ \nu_\ell$ decay rates provides a stringent test of the methods used to compute the heavy-baryon decay form factors.

- Combining the $\Lambda_c \to \Lambda \ell^+ \nu_\ell$ decay rates from experiment with a lattice QCD calculation of the $\Lambda_c \to \Lambda$ form factors gives a new direct determination of $|V_{cs}|$ and new constraints on physics beyond the Standard Model.

The BES III Collaboration has recently reported precise measurements of the $\Lambda_c \to \Lambda \ell^+ \nu_\ell$ branching fractions[1,2]:

$$\mathcal{B}(\Lambda_c \to \Lambda \ell^+ \nu_\ell) = \begin{cases} 0.0363(38)(20), & \ell = e, \\ 0.0349(46)(27), & \ell = \mu. \end{cases} \quad (1)$$

In the Standard Model, the decay rates depend on six form factors that parametrize the matrix elements $\langle \Lambda(p') | \bar{s} \gamma^\mu c | \Lambda_c(p) \rangle$ and $\langle \Lambda(p') | \bar{s} \gamma^\mu \gamma_5 c | \Lambda_c(p) \rangle$ as functions of $q^2 = (p - p')^2$. These form factors have previously been estimated using quark models and sum rules, giving branching fractions that vary substantially depending on the model assumptions. In this work, the first lattice QCD determination of the $\Lambda_c \to \Lambda$ form factors is reported. The calculation was performed with $2 + 1$ flavors of dynamical domain-wall fermions, using two different lattice spacings and a range of quark masses. Gauge-field ensembles generated by the RBC and UKQCD Collaborations were used, including one ensemble at the physical pion mass. The form factors were extrapolated to the continuum limit and are parametrized using model-independent z-expansions.

The resulting Standard-Model predictions for the $\Lambda_c \to \Lambda \ell^+ \nu_\ell$ differential decay rates, without the factor of $|V_{cs}|^2$, are shown in Fig. 1. The q^2-integrated rates are

$$\frac{\Gamma(\Lambda_c \to \Lambda \ell^+ \nu_\ell)}{|V_{cs}|^2} = \begin{cases} 0.2007(71)(74)\ \mathrm{ps}^{-1}, & \ell = e, \\ 0.1945(69)(72)\ \mathrm{ps}^{-1}, & \ell = \mu, \end{cases} \quad (2)$$

† Condensed from the article in arXiv:1611.09696 (accepted for publication in Phys. Rev. Lett.)

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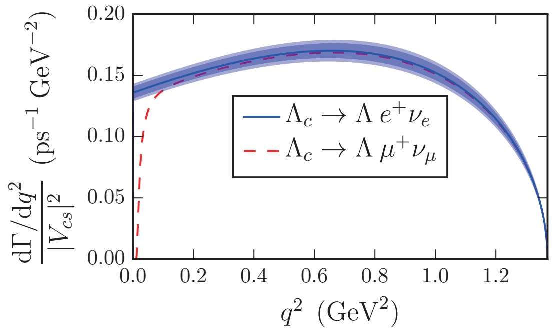

Fig. 1. Predictions for the $\Lambda_c \to \Lambda \ell^+ \nu_\ell$ differential decay rates (divided by $|V_{cs}|^2$) using the form factors from lattice QCD.

where the two uncertainties are from the statistical and total systematic uncertainties in the form factors. The branching fractions obtained from Eq. (2) using $|V_{cs}| = 0.97344(15)$ from a CKM unitarity global fit[3] and $\tau_{\Lambda_c} = 0.200(6)$ ps from experiments[4] are consistent with, and two times more precise than, the BES III measurements shown in Eq. (1). This is a valuable check of the lattice methods which were also used in Refs. 5-6.

Combining instead the BES III measurements (1) and $\tau_{\Lambda_c} = 0.200(6)$ ps with the results in Eq. (2) to determine $|V_{cs}|$ from $\Lambda_c \to \Lambda \ell^+ \nu_\ell$ gives

$$|V_{cs}| = \begin{cases} 0.951(24)_{\rm LQCD}(14)_{\tau_{\Lambda_c}}(56)_{\mathcal{B}}, & \ell = e, \\ 0.947(24)_{\rm LQCD}(14)_{\tau_{\Lambda_c}}(72)_{\mathcal{B}}, & \ell = \mu, \\ 0.949(24)_{\rm LQCD}(14)_{\tau_{\Lambda_c}}(49)_{\mathcal{B}}, & \ell = e, \mu, \end{cases} \quad (3)$$

where the last line is the correlated average over $\ell = e, \mu$. This is the first determination of $|V_{cs}|$ from baryonic decays. The result is consistent with CKM unitarity, and the uncertainty can be reduced further with more precise measurements of the $\Lambda_c \to \Lambda \ell^+ \nu_\ell$ branching fractions.

References

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