Addendum to "Overview of Λ_c decays"

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An earlier analysis of observed and anticipated Λ_c decays [M. Gronau and J. L. Rosner, Phys. Rev. D **97**, 116015 (2018)] is provided with a table of inputs and a figure denoting branching fractions. This addendum is based on the compilation by M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018) and employs a statistical isospin model to estimate branching fractions for as-yet-unseen decay modes.

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The decays of the charmed baryon Λ_c [1] appear to be within about 10% of fully mapped out [2] when a statistical isospin model [3,4] is used to estimate branching fractions for as-yet-unseen decay modes. In this addendum to Ref. [2] we display graphically the modes which have been seen and those anticipated. Part of the ~10% shortfall may be composed of decay modes such as $\Lambda_c \to \Lambda^* \ell^+ \nu_\ell$, where Λ^* is an excited resonance, or may be due to a shortcoming in the statistical isospin model. Cabibbo-suppressed modes appear to be less well represented by known or anticipated decays, and are worthy of more experimental study. In order for this analysis to serve as a model-independent counterpart to a Particle Data Group analysis of D_s decays [5], measurements of inclusive branching fractions of Λ_c decays need to be undertaken. [An example is the result from BESIII [6], $\mathcal{B}(\Lambda_c \to \Lambda + X) = (38.2^{+2.8}_{-2.2} \pm 0.8)\%$.]

Λ_c branching fractions and their sources are listed in Tables I and II. These serve as inputs to Fig. 1, in which the branching fractions are indicated by the areas of the boxes. Shaded areas correspond to processes not represented by observed decays, but whose rates are anticipated using a

TABLE I. Branching fractions of CF Λ_c decays.

Mode	Value (%)	Source
$p\bar{K}^0$	3.16 ± 0.16	[1][a]
$pK^-\pi^+$	6.23 ± 0.33	[1]
$n\bar{K}^0\pi^+$	3.64 ± 0.50	[1][a]
$p\bar{K}^0\pi^0$	3.92 ± 0.26	[1][a]
$p\bar{K}^0\eta$	1.6 ± 0.4	[1][a]
$pK^-\pi^+\pi^0$	4.42 ± 0.31	[1]
$p\bar{K}^0\pi^+\pi^-$	3.18 ± 0.24	[1][a]
Other $N\bar{K}2\pi$	5.28 ± 0.39	[2][b,c]
$pK^-2\pi^+\pi^-$	0.14 ± 0.09	[1]
Other $N\bar{K}3\pi$	0.70 ± 0.36	[2][b,c,d]
$\Lambda\pi^+$	1.29 ± 0.07	[1]
$\Lambda\pi^+\pi^0$	7.0 ± 0.4	[1]
$\Lambda 2\pi^+\pi^-$	3.61 ± 0.29	[1]
$\Lambda\pi^+ 2\pi^0$	2.41 ± 0.13	[2][b,c]
$\Lambda 2\pi^+\pi^0\pi^-$	2.2 ± 0.8	[1]
$\Lambda\pi^+ 3\pi^0$	0.55 ± 0.2	[2][b,c,d]
$\Sigma^0\pi^+$	1.28 ± 0.07	[1]
$\Sigma^+\pi^0$	1.24 ± 0.10	[1]
$\Sigma^-\pi^+\pi^+$	1.86 ± 0.18	[1]
$\Sigma^0\pi^+\pi^0$	3.03 ± 0.23	[1]
$\Sigma^+\pi^+\pi^-$	4.41 ± 0.20	[1]
$\Sigma^+\pi^0\pi^0$	1.23 ± 0.12	[1]
$\Sigma^0 2\pi^+\pi^-$	1.10 ± 0.30	[1]
$\Sigma^- 2\pi^+\pi^0$	2.1 ± 0.4	[1]
Other $\Sigma 3\pi$	4.1 ± 0.5	[2][b,c,e]
$\Sigma^+\eta$	0.69 ± 0.23	[1]

(Table continued)

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TABLE I. *(Continued)*

Mode	Value (%)	Source
$\Sigma^+\omega$	1.69 ± 0.21	[1]
$\Lambda K^+\bar{K}^0$	0.56 ± 0.11	[1]
$\Sigma^+K^+K^-$	0.34 ± 0.04	[1]
Other $\Sigma K\bar{K}$	0.68 ± 0.34	[2][b,c]
Ξ^0K^+	0.55 ± 0.07	[1,7][f]
$\Xi^-K^+\pi^+$	0.62 ± 0.06	[1]
Other $\Xi K\pi$	1.24 ± 0.12	[2][b,c,d]
$\Lambda e^+\nu_e$	3.63 ± 0.43	[8]
$\Lambda\mu^+\nu_\mu$	3.49 ± 0.53	[9]
Total	83.17 ± 4.92	

[a]Branching fractions for modes with $\bar{K}^0$ are obtained by doubling those quoted for K_S.
[b]Isospin statistical model [2].
[c]Subtraction of known modes from estimated total.
[d]Total estimated assuming equal branching fractions for each charge state.
[e]$\Sigma^+\omega$ quoted separately.
[f]PDG value averaged with new value from [7].

statistical isospin model [2]. The figures show only central values; errors are quoted in the tables.

Some qualifying remarks are in order. The $pK^-\pi^+$ decay mode, frequently used to normalize others, is not firmly pinned down yet, with an S-value of 1.4 [1]. The statistical isospin model is poorly obeyed for the $N\bar{K}\pi$ and $\Sigma 3\pi$ modes but well obeyed for the $\Sigma 2\pi$ modes [2], possibly indicating the need to take into account the resonant substructure. Nevertheless, one can draw some general conclusions.

(1) We see a shortfall of about 10% in accounting for all Λ_c decays. This could be filled in part by semileptonic decays to excited final states, but a measurement $\mathcal{B}(\Lambda_c \to \Lambda e^+\nu_e + X) = (3.95 \pm 0.34 \pm 0.09)\%$ by the BESIII Collaboration [12] limits this possibility.

(2) The Cabibbo-suppressed (CS) modes are not as well represented as the Cabibbo-favored (CF) ones, though the anticipated totals are not far from the expected ratio $|V_{cd}/V_{cs}|^2$, where V_{ij} are elements of the Cabibbo-Kobayashi-Maskawa matrix.

(3) Modes involving neutrons, η, and η' are under-represented.

(4) There is sufficient phase space to accommodate higher-multiplicity modes, such as $\Sigma 4\pi$ and $N5\pi$, but no evidence for them has been presented so far.

TABLE II. Branching fractions of CS Λ_c decays, in percent.

Mode	Value (%)	Source
$p\pi^0$	0.008	Theory [10]
$n\pi^+$	0.027	Theory [10]
$p\eta$	0.124 ± 0.030	[1]
$p\pi^+\pi^-$	0.42 ± 0.04	[1]
Other $N\pi\pi$	0.84 ± 0.08	[2][a]
$N3\pi$	1.22 ± 0.30	[2][b]
$p2\pi^+2\pi^-$	0.22 ± 0.14	[1]
Other $N4\pi$	0.88 ± 0.56	[2][a]
pK^+K^-	0.10 ± 0.04	[1]
Other NK^+K^-	0.20 ± 0.08	[2][a]
ΛK^+	0.06 ± 0.012	[1]
Σ^0K^+	0.051 ± 0.008	[1]
Σ^+K^0	0.051 ± 0.008	[2][a]
$\Sigma^+K^+\pi^-$	0.21 ± 0.06	[1]
Other $\Sigma K\pi$	0.84 ± 0.24	[2][a]
$ne^+\nu_e$	0.41 ± 0.03	Lattice QCD [11]
$n\mu^+\nu_\mu$	0.40 ± 0.03	Lattice QCD [11]
Total	6.06 ± 0.84	

[a]Total estimated assuming equal branching fractions for each charge state.
[b]Branching ratio to $p\pi^+\pi^0\pi^-$ taken as $(0.304 \pm 0.076)\%$ (geometric mean of $p\pi^+\pi^-$ and $p2\pi^+2\pi^-$ modes) multiplied by 4 for the total number of charge states.

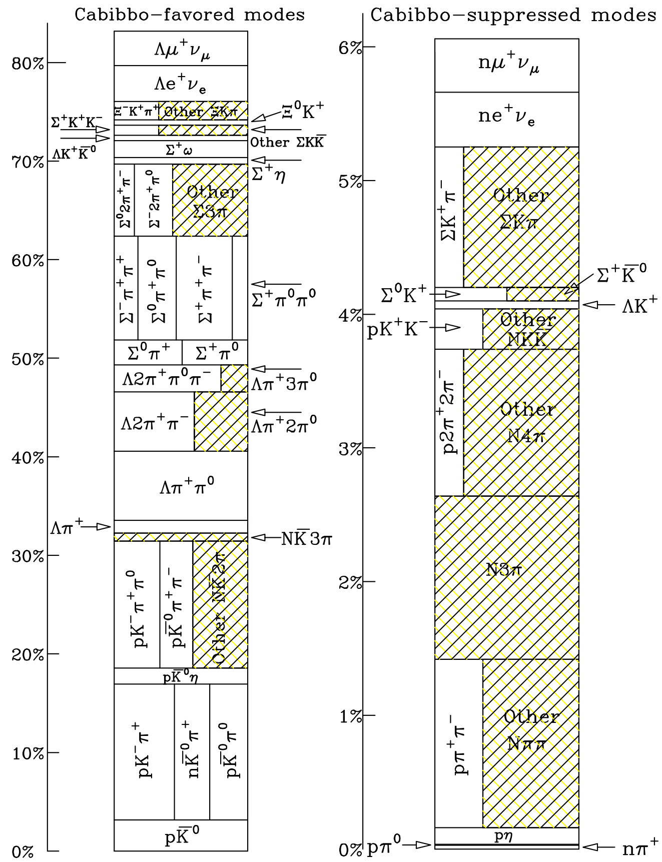

FIG. 1. Branching fractions of Λ_c decays. Left: Cabibbo-favored (CF), governed by weak transition $c \to sW^*$. Right: Cabibbo-suppressed (CS), governed by weak transition $c \to dW^*$.

(5) The statistical isospin model itself may be at fault. Inclusive branching fractions in Λ_c decays would be very helpful in anticipating as-yet-unseen modes without the help of models, as has been done for D_s decays [5].

We urge more studies of Λ_c decay modes containing neutrons, η, and η'; greater investigation of the singly-Cabibbo-suppressed and higher-multiplicity modes; and inclusive studies. Determination of resonant substructure is a crucial ingredient in filling gaps only partially addressed by an imperfect statistical isospin model.

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