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NON-LEPTONIC DECAYS OF CHARMED BARYONS
IN THE MIT BAG MODEL

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ABSTRACT

Non-leptonic decays of lower mass charmed baryons are calculated by employing the QCD corrected weak Hamiltonian of the Weinberg-Salam model and wave functions of the MIT bag model. The results are compared with quark model predictions.

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The choice of realistic models for hadron wave functions is obviously very important for analyzing non-leptonic weak decays of hadrons, and may help to understand weak interactions. A particularly convenient framework for doing so is the MIT-bag model ¹⁾ which manifestly allows the confinement of relativistic quarks inside hadrons. This model has been successfully applied to the calculation of the low-lying hadron mass spectrum and of static hadronic parameters, and later on, to a study of non-leptonic hyperon decays ^{2),3)}. Encouraged by these results and the fact that first data on Λ_c^+ decay already exist ^{4),5)}, we shall use the bag model to study some typical non-leptonic weak decays of the lower mass charmed baryons $\Lambda_c^+(c[u,d])$, $\Lambda_c^{+(0)}(c[s,u(d)])$ and $T^0(css)$. These baryons are expected to be stable under strong and electromagnetic interactions. Among them the Λ_c^+ has recently been detected at the CERN SPS hyperon beam ⁶⁾.

As the bulk of non-leptonic charm decays consists of Cabibbo favoured channels, we shall consider here $\Delta C = \Delta S = 1$ decays only. For definiteness, let us choose the processes $\Lambda_c^+ \rightarrow (p\bar{K}^0, \Xi^0 K^+, \Sigma^0 \pi^+)$, $\Lambda_c^{+(0)} \rightarrow \Xi^0 \pi^+$, $\Lambda_c^0 \rightarrow \Xi^- \pi^+$ and $T^0 \rightarrow \Xi^0 \bar{K}^0$. Finally, we shall then compare our bag model estimates with the quark model results of Körner et al. ⁷⁾ and with experiments.

The starting point of our analysis is the charm-changing part of the QCD corrected effective weak Hamiltonian of the Weinberg-Salam model ⁸⁾

$$H_w = \frac{G}{\sqrt{2}} \cos^2 \theta_c (f_- O^- + f_+ O^+) \quad (1)$$

$$O^\mp = \frac{1}{2} \left\{ (\bar{s}c)_L (\bar{u}d)_L \mp (\bar{s}d)_L (\bar{u}c)_L \right\}$$

where $f_- = 1.96$, $f_+ = 0.64$, and $(\bar{s}c)_\pm$ is a shorthand notation for $(\bar{s}c)_L = \bar{s}^i \gamma_\mu (1 + \gamma_5) c^i$ (the operators $O^\pm$ are understood to be normal ordered; colour indices are henceforth suppressed). The matrix element for baryon decay processes $B^c \rightarrow B' + \mathcal{M}_k$ takes the form

$$\langle \mathcal{M}_k(q) B' | H_w | B^c \rangle = i \bar{u}_{B'} [A + B \gamma_5] u_{B^c} \varphi_{\mathcal{M}_k} \quad (2)$$

where A, B are the (parity violating) S wave and (parity conserving) P wave amplitudes, respectively. The untractable three-hadron matrix element of the weak Hamiltonian may be reduced to tractable baryon to baryon transition elements by applying standard soft-meson techniques ⁹⁾. The relevant formula reads

$$\langle \mathcal{M}_k(q) B' | H_w | B^c \rangle \approx \frac{-i\eta_k}{\sqrt{2}F_k} \langle B' | [Q_k^5, H_w] | B^c \rangle + P(q) + R(q) \quad (3)$$

Here Q_k^5 is the axial generator associated with the meson $\mathcal{M}_k$, F_k is the pseudoscalar meson decay constant ($F_\pi = 93$ MeV, $F_K = 1.27 F_\pi$), and η_k is a phase factor (-1 for $\mathcal{M}_k = \pi^+, K^+, \bar{K}^0$; +1 for $\mathcal{M}_k = \pi^-, K^-, \text{etc.}$). Besides the commutator term, the matrix element in Eq. (3) contains contributions from possible pole diagrams denoted by $P(q)$ and from quark decay diagrams denoted by $R(q)$. The latter term takes the form of a factorizable product of two current matrix elements when inserting vacuum intermediate states. As usual, we shall assume in the following that Eq. (3) which was derived in the soft-meson limit $q \rightarrow 0$, is approximately valid for $q \neq 0$, too.

Let us first calculate the commutator terms which, as is well known, contribute only to the S wave amplitude A. In the bag model their contribution is given by ^{*)}

$$A^{com}(B^c \rightarrow B' + \mathcal{M}_k) = \eta_k \int G/F_k \cos^2 \theta_c (a_1 I_1 + a_2 I_2). \quad (4)$$

Here I_1, I_2 are dynamical four-quark overlap integrals and a_1, a_2 are coefficients depending on the specific decay mode under consideration. We have

$$\begin{aligned} I_1 &= \int_{bag} d^3r (u_u^2 + v_u^2)(u_s u_c + v_s v_c) = 2.76 \cdot 10^{-3} \text{ GeV}^3 \\ I_2 &= \int_{bag} d^3r (v_u u_s - u_u v_s)(u_u v_c - v_u u_c) = -0.05 \cdot 10^{-3} \text{ GeV}^3 \end{aligned} \quad (5)$$

where u_i, v_i are the usual large and small Dirac components of the quark spinor in the bag. To get the numerical estimates (5), we used a set of parameters for the quark masses m_i , frequencies $\omega_{1,-1}(i)$ and the inverse bag radius R^{-1} which is similar to the one used in Ref. 2): $m_u = 44$ MeV, $m_s = 300$ MeV, $m_c = 1529$ MeV, $\omega_{1,-1}(u) = 2.148$, $\omega_{1,-1}(s) = 2.864$, $\omega_{1,-1}(c) = 7.79$ and $R^{-1} = 211.9$ MeV. The values (5) are rather stable against variations of these parameters. Finally, let us quote the numerical values of the various coefficients (a_1, a_2) referring to the decay processes indicated in the Table. We have :

*) The O^+ operator does not contribute because of its symmetry property. Recall also that the so-called Penguin operators are Cabibbo suppressed.

$$\left\{ (\sqrt{3/2}, 2\sqrt{2/3}); (0, -\sqrt{2/3}); (-\sqrt{3}, -4/\sqrt{3}); (\sqrt{3/2}, \sqrt{2/3}); (-\sqrt{3/2}, -\sqrt{2/3}); (3/2, 3/2) \right\}.$$

The pole terms contribute only to the B amplitude and are given by the standard formula ⁹⁾

$$B^P(B_i^c \rightarrow B_j' + M_k) = \eta_k \frac{g_A^{B_i^c B_k} g_A^{B_k B_j'}}{\sqrt{2} F_k} \frac{(M_i + M_j')}{(M_k'' - M_j')} \langle B_j' | H_w^{P.C.} | B_k'' \rangle + \eta_k \frac{g_A^{B_j' B_k} g_A^{B_k B_i^c}}{\sqrt{2} F_k} \frac{(M_i + M_j')}{(M_k'' - M_i)} \langle B_k'' | H_w^{P.C.} | B_i^c \rangle \quad (6)$$

where M_i, M_j', M_k'' denote baryon masses, and g_A are axial-vector form factors at zero momentum transfer discussed below. The various sets of baryon intermediate states B_k'' contributing to the six processes listed in the Table are: $\{\Sigma^+; (S^0, \Sigma^+); (\Sigma_c^0, \Sigma^+); A^0; \Xi^0; (S^0, A^0)\}$. The matrix elements appearing in Eq. (6) can then be read off from the relations

$$\begin{aligned} \langle \Lambda_c^+ | 0^- | \Sigma^+ \rangle &= -\langle \Sigma_c^0 | 0^- | \Lambda \rangle = \langle \Xi^0 | 0^- | A^0 \rangle + \sqrt{2/3} I_2 = \\ &= \frac{1}{\sqrt{3}} \langle \Xi^0 | 0^- | S^0 \rangle + \frac{1}{\sqrt{6}} I_2 = \sqrt{3/2} I_1 + 2\sqrt{2/3} I_2; \\ \langle \Sigma^0 | 0^- | \Sigma_c^0 \rangle &= \langle \Sigma^+ | 0^- | \Sigma_c^+ \rangle = \frac{3}{\sqrt{2}} I_1 + \frac{4}{3} \sqrt{2} I_2. \end{aligned} \quad (7)$$

We shall use the following values of the baryon masses, $M_{\Lambda_c^+} = 2282$ MeV ⁴⁾, $M_{\Sigma_c} = 2450$ MeV ⁴⁾ and $M_{A^+} = 2460$ MeV ⁶⁾. The values of the T^0 and S^0 masses are taken from the quark mass formulae of Ref. 7).

Finally, the factorizable contributions to the S and P wave amplitudes are estimated as follows ^{*)}

$$\begin{aligned} A^{fac} &= -\frac{1}{3} \eta_k G F_k \cos^2 \theta_c [2f_+ \pm f_-] (M_{B^c} - M_{B'}) g_v^{B' B^c} \\ B^{fac} &= \frac{1}{3} \eta_k G F_k \cos^2 \theta_c [2f_+ \pm f_-] (M_{B^c} + M_{B'}) g_A^{B' B^c} \end{aligned} \quad (8)$$

) Possible q^2 dependences of current matrix elements have been neglected here. In fact, there are q^2 dependent terms of the form $(1 - q^2/m_{D^, F^*}^2)^{-1}$ or $(1 - q^2/m_{D, F}^2)^{-1}$ when one includes F^*, D^* or F, D meson poles in the vector or axial vector form factors. Including such terms or the analogous dipole-like form factors of Ref. 7) would yield at most a correction of order of 10% to the partial rates.

where the $+$ ($-$) sign in the bracket refers to π^+ ($\bar{K}^0$) emission. The vector and axial vector form factors appearing in Eqs. (6) and (8) are given by the two-quark integrals

$$g_{V(A)} = C_{V(A)} \int_{\text{bag}} d^3r (u_i u_j + r_{V(A)} v_i v_j) \quad (9)$$

with $r_V = 1$, $r_A = -1/3$. The indices i, j label the flavour of the quarks in the corresponding transition currents. Here the coefficients $c_{V(A)}$ are pure SU(4) vector or axial vector couplings as defined, for example, by the weak hadron current in chiral SU(4) theories¹⁰⁾, whereas the integrals in Eq. (9) give an additional renormalization due to the bag structure. The form factors needed in our calculations are estimated as follows :

$$\begin{aligned} g_V^{P\Lambda_c^+} &= \sqrt{3/2} g_V^{\Xi^0\pi^0} = \sqrt{3/2} 0.89 \\ g_A^{P\Lambda_c^+} &= -3\sqrt{3/2} g_A^{\Xi^0\pi^0} = \sqrt{3/2} 0.78 \\ g_{V(A)}^{\Xi^0\Lambda_c^+} &= g_{V(A)}^{\Xi^0\Lambda^0} = \sqrt{3/2} 0.95 \left(\sqrt{3/2} 0.86 \right) \\ g_A^{P\Sigma^+} &= -\frac{1}{2\sqrt{2}} g_A^{S^0\pi^0} = \frac{1}{\sqrt{6}} g_A^{A^0\pi^0} = \frac{1}{\sqrt{3}} g_A^{S\Lambda_c^+} = \frac{1}{5} g_A^{\Xi^0\Sigma^+} = \frac{1}{3} 0.72 \\ g_A^{\Sigma^0\Lambda_c^+} &= -g_A^{\Lambda\Sigma^+} = \sqrt{3/2} g_A^{Z^0\Sigma^+} = -\sqrt{6} g_A^{\Xi^0\Xi^0} = \sqrt{3/2} 0.68 \\ g_{V(A)}^{\Sigma^0\Lambda_c^+} &= g_{V(A)}^{\Sigma^0\Lambda^0} = g_A^{A^0\Lambda_c^+} = g_A^{A^0\Lambda^0} = 0 \end{aligned} \quad (10)$$

The Table contains the estimates for the commutator terms, pole contributions and factorizable terms contributing to the A and B amplitudes, and the bag model predictions for the partial widths.

Let us compare our bag model predictions with the calculations of Körner et al.⁷⁾ using a quark model approach with U(2,2) wave functions. As we find, their decay rate for the process $\Lambda_c^+ \rightarrow p\bar{K}^0$ comes out by about a factor of six larger than our prediction, which is close to the experimental value $\Gamma(\Lambda_c^+ \rightarrow p\bar{K}^0) = (1.00 \pm_{0.78}^{0.86}) \times 10^{11} \text{ sec}^{-1}$ ⁴⁾. On the other hand, our rate $\Gamma(A^0 \rightarrow \Xi^-\pi^+)$ is by about a factor of four larger than their quark model rate, whereas the values for $\Gamma(T^0 \rightarrow \Xi^0\bar{K}^0)$ differ even by an order of magnitude. As it turns out, our predictions are generally closer to their current algebra estimates. Also in the latter case, there remain, however, some

numerical differences which are at least partly related to additional symmetry breaking effects due to quark masses when calculating $g_A(v)$ in the bag model. In addition, let us notice that our ratio of partial widths for the $\Sigma^0 \pi^+$ and $p \bar{K}^0$ channels, $\Gamma(\Lambda_c^+ \rightarrow \Sigma^0 \pi^+) / \Gamma(\Lambda_c^+ \rightarrow p \bar{K}^0) = 0.99$, is consistent with recent data on Λ_c^+ decays obtained with the Fermilab bubble chamber ^{5),*)}. Finally, let us comment on a suggestion of Bigi ¹⁴⁾ that there might be some analogy concerning the relative role of quark decay and annihilation mechanisms for charmed baryon and meson isodoublets A^+, A^0 and D^+, D^0 , respectively. From the Table, one sees that the ratio of the partial rates of A^+, A^0 decays considered here is $\Gamma(A^0 \rightarrow \Xi^- \pi^+) / \Gamma(A^+ \rightarrow \Xi^0 \pi^+) = 3.2$. Recall that the ratio of total rates of D^0, D^+ mesons is $\Gamma(D^0) / \Gamma(D^+) = (2.4 \pm_{0.6}^{0.8})$ ¹⁵⁾. Although suggestive, this numerical similarity is, of course, not conclusive and could be an accident. In fact, one should compare the corresponding total rates which requires analyzing all other decay channels of the A^+, A^0 baryons, too. Investigation of this question is under way.

Clearly, before drawing final conclusions about the success of the MIT bag approach to charmed baryon decays, one has to wait for more detailed data with better statistics. Nevertheless, we believe that our results are interesting and that the bag approach, including also the use of more sophisticated models like the cloudy bag model ¹³⁾, deserves further study. A more complete list of various possible charmed baryon decays will be given elsewhere.

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*) We have also calculated the decay rate for $\Lambda_c^+ \rightarrow \Lambda \pi^+$ which unfortunately comes out in the MIT bag model too large by a factor of 3-5 when compared with experiment ⁴⁾ [see also Ref. 11)]. For this process the commutator term vanishes and the factorizable term seems to be overestimated. The question whether excited $(70, 1^-)$ or $(168, 1^-)$ baryon intermediate states, as proposed in Ref. 12), may yield the needed suppression in the S wave is presently under investigation. Alternatively, there could be additional suppression effects from $g_A(q^2)$ due to large meson momenta, as suggested by the cloudy bag model ¹³⁾.

TABLE : Numerical estimates of the various terms (commutator terms, pole terms and factorizable terms) contributing to the S and P wave amplitudes for different decay processes. In the last column the numerical predictions for the partial rates calculated from the A and B amplitudes are given in units of 10^{11} sec^{-1} .

Amplitude $\times 10^6$	Bag contribution (commutator or pole terms)	Factorizable terms	Total	$\Gamma(\text{bag})$
$A(\Lambda_c^+ \rightarrow p \bar{K}^0)$	-0.61	-0.44	-1.05	1.40
$A(\Lambda_c^+ \rightarrow \Xi^0 K^+)$	$-7.49 \cdot 10^{-3}$	0	$-7.49 \cdot 10^{-3}$	0.06
$A(\Lambda_c^+ \rightarrow \Sigma^0 \pi^+)$	1.09	0	1.09	1.39
$A(\Lambda_c^+ \rightarrow \Xi^0 \pi^+)$	-0.78	1.49	0.71	2.91
$A(\Lambda_c^0 \rightarrow \Xi^- \pi^+)$	0.78	1.49	2.27	9.35
$A(T^0 \rightarrow \Xi^0 \bar{K}^0)$	-1.50	-0.38	-1.88	4.58
$B(\Lambda_c^+ \rightarrow p \bar{K}^0)$	0.43	0.91	1.34	
$B(\Lambda_c^+ \rightarrow \Xi^0 K^+)$	1.12	0	1.12	
$B(\Lambda_c^+ \rightarrow \Sigma^0 \pi^+)$	-0.49	0	-0.49	
$B(\Lambda_c^+ \rightarrow \Xi^0 \pi^+)$	0	-4.42	-4.42	
$B(\Lambda_c^0 \rightarrow \Xi^- \pi^+)$	-0.58	-4.42	-5.00	
$B(T^0 \rightarrow \Xi^0 \bar{K}^0)$	1.07	-0.31	0.76	

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