Predictions for semileptonic decays of charm baryons. I. SU(4)-symmetry limit

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We review the predictions of SU(4) symmetry and the Glashow-Iliopoulos-Maiani mechanism for the semileptonic decays of $\frac{1}{2}^+$ charm baryons. We use, wherever possible, the experimental masses of charm baryons; for the unknown masses we use the predictions of mass formulas. The q^2 dependence of form factors is taken to be either of monopole or of dipole form. For $\Delta S = \Delta Q = -1$ transitions, very large branching ratios are predicted—of the order of 10%.

I. INTRODUCTION

Semileptonic decays of $\frac{1}{2}^+$ charm baryons should be very interesting to study experimentally and theoretically. On the one hand, the very large mass difference between the charm quark c and the s, u, and d quarks guarantees a big phase space for $\Delta C \neq 0$ decays to occur. This should make their observation easier and high-statistics experiments should be attainable without too much effort. On the other hand, for $\frac{1}{2}^+ \to \frac{1}{2}^+$ decays the transition amplitude involves four relevant form factors when the emitted charged lepton is an electron. Because of the large momentum transfer, the four become almost equally important. Since they are all rich in information about strong interactions, their detailed measurement should give very important guidance to disentangle the theory of strong interactions at low energy, especially with respect to flavor-symmetry breaking which is now expected to be substantially large.

In order to determine such symmetry breaking one must compare the symmetry limit predictions with experiment. It is, therefore, important that such predictions be made available and that they be as accurate as possible. This effort has been tried in the past by Buras[1] and Yamada[2] already several years ago, at a time when only one charm baryon had been discovered. Because the masses of charm baryons were almost all unknown, their predictions necessarily were limited to quote rather wide ranges, covering about 2 orders of magnitude, for the corresponding decay rates. In the meantime, five more charm baryons have been discovered and their masses are known within a certain accuracy. This allows theoretical mass formulas to be parametrized in more reliable ways and, thus, the masses predicted for the still undetected charm baryons are subject to less uncertainties. This leads then to make better calculations for the phase-space coefficients in these decays. Therefore, it is timely to review the theoretical predictions for the semileptonic decays of $\frac{1}{2}^+$ charm baryons.

In this paper we shall study the SU(4)-symmetry-limit predictions, i.e., the extension[3] of the SU(3) Cabibbo theory[4] to cover charm baryons. In the following paper we shall study symmetry breaking as is implemented by some quark and bag models. We shall limit ourselves to $\frac{1}{2}^+ \to \frac{1}{2}^+$ transitions and only to the case when the emitted charged lepton is an electron. The muon modes and the $\frac{1}{2}^+ \to \frac{3}{2}^+$ transition we shall leave for a later occasion.

In Sec. II we shall briefly review the currently accepted extension of SU(4) to semileptonic decays of baryons. The main difficulties we shall find are what values to take for the so-far unknown masses of some charm baryons and how to deal with the four-momentum-transfer (q^2) dependence of the form factors. These questions will be discussed in Sec. III. Then we shall proceed to get the transition rates in terms of coefficients of quadratic products of form factors at $q^2=0$. This is a practical way to deal with the decay rates, because when the q^2 dependence of the form factors is added it goes into changing such coefficients. In Sec. IV we shall list the values of the form factors. Our results will be collected in Sec. V. Finally, we shall reserve Sec. VI to discuss our findings.

II. SU(4) CLASSIFICATION

The formulation of SU(4)-flavor symmetry for baryons, covering the ordinary baryons and the charm ones, has been extensively discussed in the past.[3] Therefore, we can limit ourselves to a short review. The $\frac{1}{2}^+$ baryons are classified in the **20** representation whose SU(3) content is $\mathbf{8}+\mathbf{6}+\mathbf{3}+\mathbf{3}^*$. The ordinary baryons ($C=0$) belong to the **8** and the charm baryons are placed in the **6**, **3***, and **3**, with $C=1$, 1, and 2, respectively. The other quantum numbers, isospin I, its third component I_3, and hypercharge $Y=B+S$, with S the strangeness, are assigned respecting the generalized Gell-Mann–Nishijima rule

$$Q = I_3 + \tfrac{1}{2}Y + \tfrac{1}{2}C \ . \tag{1}$$

This scheme is consistent with the existence of four quarks, u, d, s, and c (which belong to the fundamental representation **4**) and with the decomposition $\mathbf{4}\times\mathbf{4}\times\mathbf{4}=\mathbf{4}+\mathbf{20}+\mathbf{20}+\mathbf{20}'$, corresponding to baryons constituted by three quarks. The $\frac{1}{2}^+$ baryons that we discuss here are in the two 20-plets. All this is summarized in Table I, where we have listed the charm baryons following the nomenclature suggested in Ref. 5.

Within the effective $V-A$ theory, the hadronic vector and axial-vector current operators are classified in the **15** representation of SU(4), with an SU(3) decomposition of $\mathbf{8}+\mathbf{3}+\mathbf{3}^*+\mathbf{1}$. The ordinary currents ($\Delta C=0$) are in the **8**, and the new ones ($\Delta C \neq 0$) are in the **3** and **3***. The

TABLE I. Assignment of SU(3) representation, quantum numbers, and quark content for the $\frac{1}{2}^+$ charm baryons belonging to the representation **20** of SU(4). [,] and { , } denote, respectively, antisymmetric and symmetric quark wave functions.

Baryon	SU(3) representation	Y	C	I	I_3	Quark content
Ξ_{cc}^{++}	**3**	1	2	$\frac{1}{2}$	$+\frac{1}{2}$	ccu
Ξ_{cc}^{+}	**3**	1	2	$\frac{1}{2}$	$-\frac{1}{2}$	ccd
Ω_{cc}^{+}	**3**	0	2	0	0	ccs
Ξ_c^{A+}	**3***	0	1	$\frac{1}{2}$	$+\frac{1}{2}$	$c[s,u]$
Ξ_c^{A0}	**3***	0	1	$\frac{1}{2}$	$-\frac{1}{2}$	$c[s,d]$
Λ_c^{+}	**3***	1	1	0	0	$c[u,d]$
Σ_c^{++}	**6**	1	1	1	1	cuu
Σ_c^{+}	**6**	1	1	1	0	$c\{u,d\}$
Σ_c^{0}	**6**	1	1	1	-1	cdd
Ξ_c^{+}	**6**	0	1	$\frac{1}{2}$	$+\frac{1}{2}$	$c\{s,u\}$
Ξ_c^{0}	**6**	0	1	$\frac{1}{2}$	$-\frac{1}{2}$	$c\{s,d\}$
Ω_c^{0}	**6**	-1	1	0	0	css

flavor-changing neutral currents ($\Delta S \neq 0, \Delta C \neq 0$) are absent because of the Glashow-Iliopoulos-Maiani (GIM) mechanism,[6] and the assumption of exact SU(4) symmetry which requires all quark masses to be the same. This mechanism extended in the manner of Kobayashi and Maskawa[7] (KM) will introduce the KM matrix suppression factors into the transition amplitude. The flavor-conserving neutral currents, contained in the **8** and the **1**, will play only an indirect role in semileptonic decays of charm baryons, through their connection with the electromagnetic current corresponding to the conserved-vector-current (CVC) hypothesis. We are, therefore, left with only eight currents of the **15** representation that are directly relevant in charm-baryon semileptonic decays. These currents are $j_\mu^{\pi^-}$, $j_\mu^{K^-}$, $j_\mu^{D^-}$, $j_\mu^{D_s^-}$, and their Hermitian conjugates. The upper index denotes their quantum numbers, which give rise to important selection rules:

TABLE II. SU(4) Clebsch-Gordan coefficients, change of isospin, and strangeness for all of the $\Delta C=0$ semileptonic decays between $\frac{1}{2}^+$ charm baryons belonging to the representation **20** of SU(4). In the last column the corresponding momentum-transfer parameter $\beta=(M_1-M_2)/M_1$ is included. It will be explained in Sec. III. The values 0.00 for β mean that the third decimal is smaller than 5.

Process	C_F	C_D	ΔS	ΔI_3	β
$\Sigma_c^{++}\to\Lambda_c^+$	0	$-\sqrt{2/3}$	0	-1	0.07
$\Xi_c^{A0}\to\Xi_c^+$	0	$-1/\sqrt{3}$	0	$+1$	0.01
$\Sigma_c^0\to\Lambda_c^+$	0	$-\sqrt{2/3}$	0	$+1$	0.07
$\Xi_c^0\to\Xi_c^{A+}$	0	$1/\sqrt{3}$	0	$+1$	0.04
$\Sigma_c^0\to\Sigma_c^+$	$\sqrt{2}$	0	0	$+1$	0.00
$\Xi_c^0\to\Xi_c^+$	1	0	0	$+1$	0.04
$\Xi_{cc}^{++}\to\Xi_{cc}^+$	-1	1	0	-1	0.00
$\Xi_c^{A0}\to\Xi_c^{A+}$	-1	$\frac{2}{3}$	0	$+1$	0.00
$\Sigma_c^+\to\Sigma_c^{++}$	$\sqrt{2}$	0	0	$+1$	0.00
$\Omega_{cc}^+\to\Xi_{cc}^{++}$	-1	1	1	$\frac{1}{2}$	0.05
$\Xi_c^{A0}\to\Lambda_c^+$	1	$-\frac{2}{3}$	1	$\frac{1}{2}$	0.08
$\Xi_c^{A0}\to\Sigma_c^+$	0	$-1/\sqrt{3}$	1	$\frac{1}{2}$	0.01
$\Xi_c^{A+}\to\Sigma_c^{++}$	0	$-\sqrt{2/3}$	1	$\frac{1}{2}$	0.01
$\Xi_c^0\to\Lambda_c^+$	0	$1/\sqrt{3}$	1	$\frac{1}{2}$	0.11
$\Omega_c^0\to\Xi_c^{A+}$	0	$-1/\sqrt{3}$	1	$\frac{1}{2}$	0.10
$\Xi_c^0\to\Sigma_c^+$	1	$-\sqrt{2/3}$	1	$\frac{1}{2}$	0.04
$\Xi_c^+\to\Sigma_c^{++}$	$\sqrt{2}$	0	1	$\frac{1}{2}$	0.00
$\Omega_c^0\to\Xi_c^+$	$\sqrt{2}$	0	1	$\frac{1}{2}$	0.10

TABLE III. SU(4) Clebsch-Gordan coefficients, change of isospin, and strangeness for the $\Delta S=0, \Delta C=-1$ semileptonic decays between $\frac{1}{2}^+$ charm baryons belonging to the representation **20** of SU(4). In the last column the corresponding momentum-transfer parameter $\beta=(M_1-M_2)/M_1$ is included. It will be explained in Sec. III.

Process	C_F	C_D	ΔS	ΔI_3	β
$\Xi_{cc}^{++}\to\Lambda_c^+$	$\sqrt{3}/\sqrt{2}$	$-1/\sqrt{6}$	0	$-\frac{1}{2}$	0.37
$\Xi_{cc}^{++}\to\Sigma_c^+$	$1/\sqrt{2}$	$1/\sqrt{2}$	0	$-\frac{1}{2}$	0.32
$\Xi_{cc}^{+}\to\Sigma_c^0$	1	1	0	$-\frac{1}{2}$	0.32
$\Omega_{cc}^{+}\to\Xi_c^0$	$1/\sqrt{2}$	$1/\sqrt{2}$	0	$-\frac{1}{2}$	0.32
$\Omega_{cc}^{+}\to\Xi_c^{A\,0}$	$-\sqrt{3}/\sqrt{2}$	$1/\sqrt{6}$	0	$-\frac{1}{2}$	0.35
$\Xi_c^0\to\Sigma^-$	$-1/\sqrt{2}$	$1/\sqrt{2}$	0	$-\frac{1}{2}$	0.53
$\Omega_c^0\to\Xi^-$	-1	1	0	$-\frac{1}{2}$	0.52
$\Xi_c^{A\,0}\to\Sigma^-$	$\sqrt{3}/\sqrt{2}$	$1/\sqrt{6}$	0	$-\frac{1}{2}$	0.52
$\Lambda_c^+\to n$	$\sqrt{3}/\sqrt{2}$	$1/\sqrt{6}$	0	$-\frac{1}{2}$	0.59
$\Xi_c^{A\,+}\to\Sigma^0$	$\sqrt{3}/2$	$\sqrt{3}/6$	0	$-\frac{1}{2}$	0.52
$\Xi_c^{A\,+}\to\Lambda$	$-\frac{1}{2}$	$-\frac{1}{6}$	0	$-\frac{1}{2}$	0.55
$\Sigma_c^+\to n$	$1/\sqrt{2}$	$-1/\sqrt{2}$	0	$-\frac{1}{2}$	0.62
$\Xi_c^+\to\Sigma^0$	$-\frac{1}{2}$	$\frac{1}{2}$	0	$-\frac{1}{2}$	0.52
$\Xi_c^+\to\Lambda$	$\sqrt{3}/2$	$-\sqrt{3}/2$	0	$-\frac{1}{2}$	0.55
$\Sigma_c^{++}\to p$	1	-1	0	$-\frac{1}{2}$	0.62

namely,

$$j_\mu^{\pi^\mp}:\ \Delta S=\Delta C=0,\quad \Delta I=1, V_{ud}\ ;$$

$$j_\mu^{K^\mp}:\ \Delta S=\Delta Q=+1,\quad \Delta C=0,\quad \Delta I=\tfrac{1}{2}, V_{us}\ ;$$

$$j_\mu^{D^\pm}:\ \Delta S=0,\quad \Delta C=\Delta Q=-1,\quad \Delta I=\tfrac{1}{2}, V_{cd}\ ;$$

$$j_\mu^{D_s^\pm}:\ \Delta S=\Delta C=\Delta Q=-1,\quad \Delta I=0, V_{cs}\ .$$

In the above we have also included the appropriate KM matrix suppression factor V_{ab}. The hadronic matrix elements of these charged currents between $\frac{1}{2}^+$ baryons can be decomposed in general as

$$\langle B_f | J_\mu^{(j)} | B_i \rangle = C_F F_\mu + C_D D_\mu\ . \tag{2}$$

C_F and C_D are Clebsch-Gordan coefficients which depend on the indices i and f, of the initial and final baryons, and j of the current operator. F_μ and D_μ are reduced matrix elements; they correspond to antisymmetric and symmetric decomposition, respectively. They will be independent of i, f, and j, but they will have a Lorentz

TABLE IV. SU(4) Clebsch-Gordan coefficients, change of isospin, and strangeness for the $\Delta S=\Delta C=-1$ semileptonic decays between $\frac{1}{2}^+$ charm baryons belonging to the representation **20** of SU(4). In the last column the corresponding momentum-transfer parameter $\beta=(M_1-M_2)/M_1$ is included. It will be explained in Sec. III.

Process	C_F	C_D	ΔS	ΔI_3	β
$\Xi_{cc}^{++}\to\Xi_c^{A\,+}$	$\sqrt{3}/\sqrt{2}$	$-1/\sqrt{6}$	-1	0	0.32
$\Xi_{cc}^{++}\to\Xi_c^+$	$1/\sqrt{2}$	$1/\sqrt{2}$	-1	0	0.32
$\Xi_{cc}^{+}\to\Xi_c^0$	$1/\sqrt{2}$	$1/\sqrt{2}$	-1	0	0.29
$\Omega_{cc}^{+}\to\Omega_c^0$	1	1	-1	0	0.28
$\Xi_{cc}^{+}\to\Xi_c^{A\,0}$	$\sqrt{3}/\sqrt{2}$	$-1/\sqrt{6}$	-1	0	0.32
$\Sigma_c^0\to\Sigma^-$	1	-1	-1	0	0.51
$\Xi_c^0\to\Xi^-$	$1/\sqrt{2}$	$-1/\sqrt{2}$	-1	0	0.48
$\Xi_c^{A\,0}\to\Xi^-$	$\sqrt{3}/\sqrt{2}$	$1/\sqrt{6}$	-1	0	0.47
$\Lambda_c^+\to\Lambda$	1	$\frac{1}{3}$	-1	0	0.51
$\Xi_c^{A\,+}\to\Xi^0$	$\sqrt{3}/\sqrt{2}$	$1/\sqrt{6}$	-1	0	0.47
$\Sigma_c^+\to\Sigma^0$	1	-1	-1	0	0.51
$\Xi_c^+\to\Xi^0$	$1/\sqrt{2}$	$-1/\sqrt{2}$	-1	0	0.47
$\Sigma_c^{++}\to\Sigma^+$	1	-1	-1	0	0.51

decomposition into products of Dirac form factors and γ_μ matrices and momentum transfer $q_\mu = p_{1\mu} - p_{2\mu}$.

The above selection rules allow for 60 different decays among the 20 baryons. Of these, 12 correspond to the semileptonic decays between ordinary noncharm baryons described by the Cabibbo theory, which we do not discuss here. The processes $\Lambda_c^+ \to \Sigma^0$ and $\Sigma_c^+ \to \Lambda$ have zero Clebsch-Gordan coefficients, they are forbidden by isospin because Λ_c^+ and Λ are singlets and Σ_c^+ and Σ^0 belong to triplets. We are, thus, left with 46 processes. As a quick reference for the reader, we have listed them in Tables II–IV. There we include the values of the Clebsch-Gordan coefficients[8] and the selection rules that apply.

III. DECAY-RATE COEFFICIENTS

Within the effective $V-A$ theory and taking into account the KM generalization of the GIM mechanism, the transition amplitude for the semileptonic decays of $\frac{1}{2}^+$ charm baryons, $B_i \to B_f e \nu$, is

$$M = \frac{G_\mu}{\sqrt{2}} V_{if} \langle B_f | J_\mu | B_i \rangle \bar{u}_e \gamma_\mu (1+\gamma_5) v_\nu \ . \tag{3}$$

$G_\mu = 1.1664 \times 10^{-5}$ GeV^{-2} is the Fermi constant[5] and V_{ij} is the KM matrix element discussed in the last section. Our metric and γ-matrix conventions are those of Ref. 9. The hadronic part is decomposed using Lorentz covariance as

$$\langle B_f | J_\mu | B_i \rangle = \bar{u}_f \left[f_1 \gamma_\mu - \frac{f_2}{M_1} i \sigma_{\mu\nu} q^\nu \frac{f_3}{M_1} q_\mu + \left[g_1 \gamma_\mu - \frac{g_2}{M_1} i \sigma_{\mu\nu} q^\nu + \frac{g_3}{M_1} q_\mu \right] \gamma_5 \right] u_i \ . \tag{4}$$

Here M_1 is the mass of B_i; the mass of B_f will be denoted by M_2. The form factors f_i and g_i are six scalar functions of q^2.

The decay rate Γ can be expressed[10] as a quadratic function of the form factors at $q^2=0$, with the q^2 dependence of the form factors absorbed into the coefficients. This must be done so, because in order to obtain Γ, the last integration over q^2 requires that it be performed over the form factors. So, we have

$$\Gamma = V_{if}^2 [A_{11} f_1^2(0) + A_{12} f_1(0) f_2(0) + A_{22} f_2^2(0) + A_{13} f_1(0) f_3(0) + A_{33} f_3^2(0) + B_{11} g_1^2(0) + B_{12} g_1(0) g_2(0) + B_{22} g_2^2(0) + B_{13} g_1(0) g_3(0) + B_{33} g_3^2(0)] \ . \tag{5}$$

In order to calculate the coefficients A_{ij} and B_{ij} we must know two things, the masses of the $\frac{1}{2}^+$ baryons and the q^2 dependence of each form factor. Let us discuss the first one first.

Of the twelve charm baryons only five have been observed so far and their masses have been also measured with certain precision. The masses of the other seven are still unknown. In order to be able to proceed we must use theoretical estimates for these latter. Such estimates have been discussed by many authors.[11] Specifically, we shall adopt the predictions given in Ref. 12, except for the mass of Σ_c^+. This mass should be interpolated rather accurately between the masses Σ_c^{++} and Σ_c^0, which have been measured, by assuming that the splitting between these three is in the same proportion as the splitting between the masses of the $\Sigma^+, \Sigma^0, \Sigma^-$ triplet. In Table V we have listed the predictions for the unmeasured masses, along with the experimental values of the masses already measured. It it these 12 masses which we shall use in what follows. In parentheses we have also included the predictions for the measured masses and their percentage deviation. This comparison allows us to gain some confidence on the predicted masses not yet measured; it should be remembered that only the mass of Λ_c^+ was known at the time these estimates were made. The masses of the eight charmless baryons come from Ref. 5. In Tables II–IV we have included the value of the parameter $\beta = (M_1 - M_2)/M_1$ (M_2 being the mass of B_f). This parameter gives a good idea of the phase-space available for the decay.

The other thing we must know is the q^2 dependence of the several form factors. This is an open question which will be resolved when a reliable and detailed theory of strong interactions valid at low energies is available. Nevertheless, it is customary to take a pole-dominance model and to use it either as a monopole or as a dipole q^2 dependence. That is,

TABLE V. Masses employed for the charm baryons with $C=1$ and $C=2$. In parentheses we give the predicted values for the measured masses and their percentage deviation.

Baryon	Mass (GeV)	Ref.
Ξ_{cc}^{++}	3.61	12
Ξ_{cc}^{+}	3.61	12
Ω_{cc}^{+}	3.79	12
Ξ_c^{A+}	2.47	12
Ξ_c^{A0}	2.47	12
Λ_c^+	2.812	13
	(2.26, −1%)	
Σ_c^{++}	2.4486	14
	(2.42, −1%)	
Σ_c^+	2.4528	15
	(2.42, −1%)	
Σ_c^0	2.4594	14
	(2.42, −1%)	
Ξ_c^+	2.459	13,16
	(2.56, +4%)	
Ξ_c^0	2.56	12
Ω_c^0	2.74	13
	(2.73, −0.4%)	

$$f_i(q^2)=\frac{f_i(0)}{\left[1-\frac{q^2}{M_{V_i}^2}\right]^n}, \tag{6}$$

$$g_i(q^2)=\frac{g_i(0)}{\left[1-\frac{q^2}{M_{A_i}^2}\right]^n}, \tag{7}$$

with $n=1$ or 2. We shall consider both these two possibilities, and for comparison purposes we shall also study the case of no q^2 dependence at all, i.e., $n=0$.

The vector and axial-vector meson masses M_{V_i} and M_{A_i} will be the masses of the nearest spin-one mesons with the internal quantum numbers of the hadronic current that effects the transition between B_i and B_f, and with appropriate parity and G parity. For simplicity we shall assume that $M_{V_1}=M_{V_2}=M_{V_3}$ and $M_{A_1}=M_{A_2}=M_{A_3}$; we can then drop the index i in M_{V_i} and M_{A_i}. For the $\Delta C=\Delta S=0$ decays we shall take $M_V=m_\rho=0.77$ GeV and $M_A=m_{a_1}=1.27$ GeV, and for the $\Delta C=0$, $\Delta S=+1$ decays we shall take $M_V=m_{K^*}=0.89$GeV and $M_A-m_{K_1}=1.28$ GeV (Ref. 5). In the $\Delta S=0$, $\Delta C=-1$ decays we can take[5] $M_V=m_{D^*}=2.01$ GeV, but the corresponding axial-vector meson has not yet been established experimentally, only a candidate has been seen[5] at 2.42 GeV. So for the latter we shall assume that this candidate is the corresponding axial vector, and thus $M_A=2.42$ GeV. In the $\Delta S=\Delta C=-1$ decays we must also estimate the corresponding masses. There is a candidate[5] for D_s^* at 2.11 GeV, which we shall assume to give the mass of the vector meson, so $M_V=2.11$ GeV, and for the axial-vector meson we shall take $M_A=2.51$ GeV, which has a 20% increase over the mass of the vector meson, in analogy with the $\Delta S=0, \Delta C=-1$ case.

We can now proceed to compute the coefficients of Eq. (5). First, let us notice[4] that for electron mode decays, $B_i \to B_f e$, the coefficients A_{13} and B_{13} are proportional to m_e/M_1 and the coefficients A_{33} and B_{33} are proportional to $(m_e/M_1)^2$. This means that they will be 10^{-4} and 10^{-7} smaller than the other coefficients, respectively. We can, therefore, safely neglect them; only six of ten coefficients of Eq. (5) will be relevant for these modes. Second, let us emphasize that in Eq. (5) the effect of the q^2 dependence of the form factors is absorbed into the A_{ij} and B_{ij} coefficients. The results of the calculation of the relevant coefficients of this equation are collected in Tables VI–XII.

A few remarks are in order. For the $\Delta C=0$ decays we have given only the coefficients for $q^2=0$ dependence of the form factors in Table VI; the effects of monopole and dipole q^2 dependences are negligible—they amount to an increase of 0.5% in A_{11} and B_{11} at most. These decays have very small coefficients and will have very small decay rates; only eight of them with coefficients 10^5-10^7 $\sec^{-1}$ may have a chance of being observed, if at all possible. Notice that only three coefficients count A_{11}, B_{11}, and B_{12}; this means that g_2 could give some noticeable contribution compared to those of f_1 and g_1. In contrast, in the $\Delta S=0, \Delta C=-1$ decays in Tables VII–IX the coefficients are big corresponding to substantial decay rates and the q^2 dependence of the form factors is very important and none of the six coefficients can be ignored. The dipole q^2 dependence amounts to almost a 90% increase of the coefficients compared to the $q^2=0$ case. The induced form factors will play a very important role; in particular, the interference between g_1 and g_2 has a coefficient B_{12} which is larger than the A_{11} of f_1^2. All these last remarks apply equally well for the $\Delta S=\Delta C=-1$ decays in Tables X–XII, except that the increase of the coefficients due to the dipole q^2 dependence is typically around 40–60%. Again the induced form factors will play very important roles. Although the coefficients of Tables VI–XII should be recalculated when the masses involved in their computation are firmly established, in the meantime they can help the interested reader to obtain a fast estimation of the decay rates, when values of the form factors at $q^2=0$ different from the ones used here are chosen.

IV. EVALUATION OF FORM FACTORS

As we remarked in the preceding section, the contributions to the decay rate of the induced scalar and pseudoscalar form factors f_3 and g_3, in electron mode decays, is just too small and should be ignored. We shall, therefore, not concern ourselves anymore with f_3 and g_3. We shall assume that there are no second-class hadronic currents under G parity. This means, in the limit of exact flavor-SU(4) symmetry that the pseudotensor form factor g_2 is zero. We are thus left with only two vector form factors, f_1 and f_2, and with one axial-vector one, g_1.

The Lorentz index μ in the reduced matrix decomposition of Eq. (2) is taken care of in the hadronic part of the transition amplitude in Eq. (4). This means that we have for the form factors two scalar reduced matrix elements: namely,

$$f_1=C_F F_1+C_D D_1 , \tag{8}$$

$$f_2=C_F F_2+C_D D_2 , \tag{9}$$

and

$$g_1=C_F F+C_D D . \tag{10}$$

The Clebsch-Gordan coefficients are given in Tables II–IV.

The assumption of the validity of the CVC hypothesis at the level of SU(4) fixes F_i and D_i, $i=1,2$, in terms of the electric charges and the magnetic moments of the neutron and the proton. Specifically, we have $F_1=1$, $D_1=0$, $F_2=(\mu_p+\mu_n/2)/2$, and $D_2=-3\mu_n/4$. $\mu_p=1.7928$ and $\mu_n=-1.9130$ are the anomalous magnetic moments of the proton and the neutron.[5]

F and D are fixed in the semileptonic decays of noncharm baryons. We shall take the values of Ref. 4: namely, $F=0.451$ and $D=0.794$. These last values were multiplied by $1/\sqrt{6}$ and $-\sqrt{3/10}$, respectively, to account for the difference in conventions in the Clebsch-

TABLE VI. Transition-rate coefficients without any q^2 dependence in the form factors for all the $\Delta C=0$ decays.

$B_1\to B_2 e\nu$	A_{11}	A_{22}	A_{12}	B_{11}	B_{22}	B_{12}	Units ($\sec^{-1}$)
$\Sigma_c^{++}\to\Lambda_c^+$	13.6	0.22	0.14	40	0.66	−9.1	10^6
$\Xi_c^{A\,0}\to\Xi_c^+$	56.3	0.01	0.00	170	0.04	−5.0	10^1
$\Sigma_c^0\to\Lambda_c^+$	13.0	0.21	0.13	39	0.62	−8.6	10^6
$\Xi_c^0\to\Xi_c^{A\,+}$	62.2	0.28	0.17	187	0.86	−22.4	10^4
$\Sigma_c^0\to\Sigma_c^+$	0.2	0	0	0.6	0	0	10^{-3}
$\Xi_c^0\to\Xi_c^+$	18.3	0.13	0.08	55	0.39	−8.2	10^5
$\Omega_{cc}^+\to\Xi_{cc}^{++}$	19.5	0.36	0.14	58.6	1.10	−14.1	10^6
$\Xi_c^{A\,0}\to\Lambda_c^+$	23.8	0.48	0.31	71	1.40	−17.9	10^6
$\Xi_c^{A\,0}\to\Sigma_c^+$	396	0.10	0.06	1200	0.29	−32.5	10^0
$\Xi_c^{A\,+}\to\Sigma_c^{++}$	386	0.09	0.06	1200	0.27	−31.0	10^0
$\Xi_c^0\to\Lambda_c^+$	15.8	0.70	0.44	47.3	2.10	−17.6	10^7
$\Omega_c^0\to\Xi_c^{A\,+}$	13.7	0.57	0.33	41	1.70	−14.7	10^7
$\Xi_c^0\to\Sigma_c^+$	171	1.20	0.71	514	3.58	−75.7	10^4
$\Xi_c^+\to\Sigma_c^{++}$	0.1	0	0	0.2	0	0	10^{-3}
$\Omega_c^0\to\Xi_c^+$	20	0.98	0.56	60	2.90	−23.3	10^7

Gordan coefficients.

Using the above values of the reduced form factors and the Clebsch-Gordan coefficients of Tables II–IV, we get the numerical values of the relevant form factors. The results are quoted in Tables XIII–XV. There is a subtlety in Eq. (9) that must be pointed out. The above F_2 and D_2 assume that f_2 is in units of the proton mass M_p, i.e., f_2 should be divided by M_p and not by M_1 as it is in Eq. (4). Therefore, in order to use the f_2 of Tables XIII–XV in the decay rate formula Eq. (5), with the coefficients of Tables VI–XII, it must first be multiplied by the factor M_1/M_p.

Before closing this section we want to point out that this SU(4) extension of the Cabibbo theory reproduces several features of the ordinary SU(3) Cabibbo theory. In Tables XIII we can observe that many processes are predicted to be purely axial-vector decays such as $\Sigma^\pm\to\Lambda e^\pm\nu$, because $f_1=0$ and f_2 plays practically no role due to smallness of the A_{12} and A_{22} coefficients in Table VI. We have marked with an asterisk those decays in Tables XIII–XV that, being initially $V-A$, are effectively turned into $V+A$ because the relative sign between f_1 and g_1 (positive for $V-A$ in our convention) is reversed by the SU(4) symmetry. These decays are predicted to behave like $\Sigma^-\to ne\nu$ in SU(3); they are rather extreme predictions of the symmetry limit.

V. DECAY RATES AND BRANCHING RATIOS

After having obtained the coefficients of the decay rate formula and the values of the relevant form factors, the only parameters that we must determine in order to make predictions are the KM suppression factors. In principle, these must be determined experimentally.[17] Of the four we need, only V_{ud} and V_{us} are accurately known, within the ranges (0.973,0.976) and (0.217,0.223), respectively, while V_{cd} is determined within a rather lax range of (0.16,0.23) and V_{cs} is even less well determined within

TABLE VII. Transition-rate coefficients without any q^2 dependence in the form factors for the $\Delta S=0, \Delta C=-1$ decays. All of the coefficients are in units of $10^{11}\ \sec^{-1}$.

$B_1\to B_2 e\nu$	A_{11}	A_{22}	A_{12}	B_{11}	B_{22}	B_{12}
$\Xi_{cc}^{++}\to\Lambda_c^+$	2.554	0.1935	0.3518	7.231	0.5547	−3.522
$\Xi_{cc}^{++}\to\Sigma_c^+$	1.386	0.0801	0.1420	3.989	0.2327	−1.696
$\Xi_c^+\to\Sigma_c^0$	1.351	0.0772	0.1368	3.891	0.2244	−1.645
$\Omega_{cc}^+\to\Xi_c^0$	1.868	0.1107	0.1965	5.370	0.3210	−2.311
$\Omega_{cc}^+\to\Xi_c^{A\,0}$	2.555	0.1738	0.3126	7.286	0.5010	−3.362
$\Xi_c^0\to\Sigma^-$	2.174	0.3334	0.6623	5.619	0.8875	−3.908
$\Omega_c^0\to\Xi^-$	2.729	0.3976	0.7836	7.130	1.068	−4.831
$\Xi_c^{A\,0}\to\Sigma^-$	1.593	0.2299	0.4525	4.168	0.6182	−2.811
$\Lambda_c^+\to n$	1.818	0.3348	0.6853	4.482	0.8567	−3.420
$\Xi_c^{A\,+}\to\Sigma^0$	1.618	0.2352	0.4634	4.228	0.6318	−2.862
$\Xi_c^{A\,+}\to\Lambda$	2.049	0.3320	0.6652	5.230	0.8745	−3.740
$\Sigma_c^+\to n$	3.147	0.6316	1.313	7.542	1.577	−6.009
$\Xi_c^+\to\Sigma^0$	1.555	0.2244	0.4415	4.071	0.6034	−2.745
$\Xi_c^+\to\Lambda$	1.974	0.3178	0.6359	5.047	0.8381	−3.587
$\Sigma_c^{++}\to p$	3.117	0.6255	1.300	7.472	1.562	−5.952

TABLE VIII. Transition-rate coefficients with monopole q^2 dependence in the form factors for the $\Delta S=0, \Delta C=-1$ decays. All of the coefficients are in units of 10^{11} $\sec^{-1}$.

$B_1 \to B_2 e\nu$	A_{11}	A_{22}	A_{12}	B_{11}	B_{22}	B_{12}
$\Xi_{cc}^{++} \to \Lambda_c^+$	3.481	0.3108	0.5643	10.08	0.8372	−5.236
$\Xi_{cc}^{++} \to \Sigma_c^+$	1.729	0.1126	0.1993	5.084	0.3143	−2.266
$\Xi_{cc}^{+} \to \Sigma_c^0$	1.680	0.1080	0.1911	4.943	0.3020	−2.189
$\Omega_{cc}^{+} \to \Xi_c^0$	2.412	0.1638	0.2907	7.094	0.4533	−3.222
$\Omega_{cc}^{+} \to \Xi_c^{A0}$	3.463	0.2770	0.4976	10.11	0.7517	−4.969
$\Xi_c^0 \to \Sigma^-$	3.040	0.5522	1.093	7.942	1.366	−5.919
$\Omega_c^0 \to \Xi^-$	3.958	0.6957	1.366	10.45	1.718	−7.636
$\Xi_c^{A0} \to \Sigma^-$	2.112	0.3519	0.6908	5.601	0.8936	−4.008
$\Lambda_c^+ \to n$	2.515	0.5437	1.108	6.232	1.295	−5.087
$\Xi_c^{A+} \to \Sigma^0$	2.151	0.3615	0.7103	5.695	0.9160	−4.093
$\Xi_c^{A+} \to \Lambda$	2.853	0.5456	1.089	7.347	1.337	−5.626
$\Sigma_c^+ \to n$	4.928	1.228	2.534	11.70	2.733	−10.19
$\Xi_c^+ \to \Sigma^0$	2.056	0.3417	0.6708	5.452	0.8686	−3.898
$\Xi_c^+ \to \Lambda$	2.730	0.5169	1.031	7.046	1.271	−5.370
$\Sigma_c^{++} \to p$	4.870	1.212	2.500	11.57	2.700	−10.07

(0.65,0.98). If it is assumed that only three generations of quarks and leptons exist, these last two ranges are substantially reduced, by the unitarity of the KM matrix, to (0.217,0.223) and (0.973,0.975), respectively. Restricting ourselves to this assumption, the four ranges become very narrow and then we see that they can be quite well parametrized by only one angle Θ_C. This means that the effect of the other KM angles on these four parameters is expected to be small and, for our purposes, can be ignored. In other words, we can limit ourselves to the original GIM mechanism with the assurance that the error introduced by ignoring the other KM angles is appreciably smaller than the uncertainties in the masses or the q^2 dependence of the form factors. We then have $V_{ud}=V_{cs}=\cos\Theta_C$ and $V_{us}=V_{cd}=\sin\Theta_C$. The numerical values we shall use are close to the central values of the above first two ranges: namely, $\cos\Theta_C=0.9748$ and $\sin\Theta_C=0.220$. These values are consistent with the ones used to obtain F and D in Ref. 4, as it should be.

We can now obtain the predictions for the decay rates. The results are displayed in columns 2–4 of Tables XVI–XVIII. It should be noted that some rates of the $\Delta S=\Delta C=0$ decays in Table XVI, although small, are not negligible. They compare very favorably with, for example, the widths of $\Sigma^- \to ne\nu$ and $\Lambda \to pe\nu$ which are[4,5] of the order of 10^6 $\sec^{-1}$. The same applies to the $\Delta S \neq 0, \Delta C=0$ decays. This means that many of these decays could be measured without investing an unreasonable amount of effort. The rates of the $\Delta S=0, \Delta C=-1$ and $\Delta S=\Delta C=-1$ decays in Tables XVII and XVIII are predicted to be much larger, 3–5 orders of magnitude bigger, of the order of $10^{11}-10^{12}$ $\sec^{-1}$ which means that they should be rather easily observable.

There is another way to appreciate the magnitudes of these semileptonic partial decay rates predicted by SU(4) symmetry. This is to quote branching ratios. Unfortunately, the lifetimes of each one of the 12 charm baryons should be known and so far only two have been measured, the one of Λ_c^+ and the one[13,16], of Ξ_c^+. Nevertheless, we can quote an order-of-magnitude estimate,

TABLE IX. Transition-rate coefficients with dipole q^2 dependence in the form factors for the $\Delta S=0, \Delta C=-1$ decays. All of the coefficients are in units of 10^{11} $\sec^{-1}$.

$B_1 \to B_2 e\nu$	A_{11}	A_{22}	A_{12}	B_{11}	B_{22}	B_{12}
$\Xi_{cc}^{++} \to \Lambda_c^+$	5.045	0.5295	0.9600	14.56	1.298	−8.006
$\Xi_{cc}^{++} \to \Sigma_c^+$	2.222	0.1628	0.2880	6.600	0.4306	−3.072
$\Xi_{cc}^{+} \to \Sigma_c^0$	2.151	0.1554	0.2747	6.395	0.4120	−2.956
$\Omega_{cc}^{+} \to \Xi_c^0$	3.243	0.2523	0.4473	9.605	0.6521	−4.581
$\Omega_{cc}^{+} \to \Xi_c^{A0}$	4.980	0.4672	0.8384	14.52	1.158	−7.547
$\Xi_c^0 \to \Sigma^-$	4.567	0.9783	1.930	11.68	2.169	−9.255
$\Omega_c^0 \to \Xi^-$	6.277	1.325	2.592	16.08	2.870	−12.55
$\Xi_c^{A0} \to \Sigma^-$	2.943	0.5646	1.105	7.745	1.321	−5.847
$\Lambda_c^+ \to n$	3.718	0.9392	1.905	8.993	2.013	−7.795
$\Xi_c^{A+} \to \Sigma^0$	3.008	0.5827	1.142	7.900	1.359	−5.991
$\Xi_c^{A+} \to \Lambda$	4.256	0.9570	1.903	10.73	2.106	−8.731
$\Sigma_c^+ \to n$	8.816	2.701	5.345	19.42	4.991	−18.26
$\Xi_c^+ \to \Sigma^0$	2.851	0.5449	1.067	7.510	1.278	−5.661
$\Xi_c^+ \to \Lambda$	4.033	0.8950	1.778	10.21	1.984	−8.259
$\Sigma_c^{++} \to p$	8.678	2.652	5.435	19.14	4.915	−17.98

TABLE X. Transition-rate coefficients without any q^2 dependence in the form factors for the $\Delta S=\Delta C=-1$ decays. All of the coefficients are in units of 10^{11} sec^{-1}.

$B_1\to B_2 e\nu$	A_{11}	A_{22}	A_{12}	B_{11}	B_{22}	B_{12}
$\Xi_{cc}^{++}\to\Xi_c^{A\,+}$	1.296	0.0728	0.1286	3.736	0.2116	−1.565
$\Xi_{cc}^{++}\to\Xi_c^{+}$	1.353	0.0774	0.1371	3.897	0.2249	−1.648
$\Xi_{cc}^{+}\to\Xi_c^{0}$	0.8958	0.0428	0.0746	2.600	0.1250	−1.004
$\Omega_{cc}^{+}\to\Omega_c^{0}$	0.9165	0.0398	0.0688	2.670	0.1165	−0.9824
$\Xi_{cc}^{+}\to\Xi_c^{A\,0}$	1.296	0.0728	0.1286	3.736	0.2116	−1.565
$\Sigma_c^{0}\to\Sigma^-$	1.533	0.2196	0.4318	4.019	0.5914	−2.700
$\Xi_c^{0}\to\Xi^-$	1.471	0.1886	0.3650	3.931	0.5161	−2.497
$\Xi_c^{A\,0}\to\Xi^-$	1.043	0.1240	0.2376	2.818	0.3425	−1.724
$\Lambda_c^{+}\to\Lambda$	1.034	0.1470	0.2886	2.715	0.3962	−1.817
$\Xi_c^{A\,+}\to\Xi^0$	1.067	0.1283	0.2461	2.880	0.3538	−1.771
$\Sigma_c^{+}\to\Sigma^0$	1.521	0.2184	0.4296	3.985	0.5878	−2.680
$\Xi_c^{+}\to\Xi^0$	1.022	0.1216	0.2330	2.761	0.3358	−1.689
$\Sigma_c^{++}\to\Sigma^+$	1.513	0.2176	0.4281	3.963	0.5856	−2.668

which may help to better visualize, so to speak, the importance of the semileptonic decay mode. We shall compute the branching ratios with respect to $\tau_{\Lambda_c^+}$, the lifetime of Λ_c^+. We shall use the average quoted in Ref. 5: namely, $\tau_{\Lambda_c^+}=(1.79^{+0.23}_{-0.17})\times 10^{-13}$ sec. The latest value of the Ξ_c^+ lifetime[16] is $(4^{+1.8+1.2}_{-1.0-1.0})\times 10^{-13}$ sec. Since this latter still has large error bars and its central value is larger than the one of $\tau_{\Lambda_c^+}$ it is more conservative to use $\tau_{\Lambda_c^+}$ to estimate the branching ratios. Using the central value we obtain the predictions in columns 5–7 of Tables XVI–XVIII. It should be kept in mind that these branching ratios, normalized to the Λ_c^+ lifetime, are not proper branching ratios.

Let us comment on these results. It should be noticed that in the $\Delta S=\Delta C=-1$ case, the semileptonic mode is predicted to be very substantial, of the order of 10%; in the case of $\Omega_{cc}^+\to\Omega_c^0$ an impressive 20% is predicted. This should be contrasted to the $\Sigma^-\to ne\nu$ and $\Lambda\to pe\nu$ branching ratios which are around 0.1%. In the case of $\Delta S=0, \Delta C=-1$ decays many branching ratios are quite appreciable, around 2%. It should be mentioned that it is these decays that are the more energetically favored, but the suppression due to V_{cd} overruns this advantage and makes their rates and branching ratios smaller, typically by a factor of 3, than those of the less favored $\Delta S=\Delta C=-1$ decays. At any rate, these decay modes should also be easily observable. Finally, the $\Delta C=0$ decays have very small branching ratios, but many of them have decay rates comparable and even bigger than those of $\Sigma^-\to ne\nu$ and $\Lambda\to pe\nu$. Their measurement may be difficult but not necessarily hopeless, although admittedly there is little chance that they can be measured in the forseeable future.

VI. DISCUSSION

Semileptonic decays of charm baryons show very interesting features, which are subdued in SU(3) baryon semileptonic decays. These can be appreciated best by going through the decay rate coefficients in Tables VI–XII. In the $\Delta S=0, \Delta C=-1$ and the $\Delta S=\Delta C=-1$ decays the coefficients of the terms with induced form factors f_2 and g_2 are comparable, if not equal, to those of the lead-

TABLE XI. Transition-rate coefficients with monopole q^2 dependence in the form factors for the $\Delta S=\Delta C=-1$ decays. All of the coefficients are in units of 10^{11} sec^{-1}.

$B_1\to B_2 e\nu$	A_{11}	A_{22}	A_{12}	B_{11}	B_{22}	B_{12}
$\Xi_{cc}^{++}\to\Xi_c^{A\,+}$	1.569	0.0976	0.1724	4.638	0.2766	−2.027
$\Xi_{cc}^{++}\to\Xi_c^{+}$	1.645	0.1045	0.1849	4.859	0.2958	−2.146
$\Xi_{cc}^{+}\to\Xi_c^{0}$	1.049	0.0546	0.0952	3.114	0.1564	−1.246
$\Omega_{cc}^{+}\to\Omega_c^{0}$	1.073	0.0507	0.0878	3.198	0.1458	−1.219
$\Xi_{cc}^{+}\to\Xi_c^{A\,0}$	1.569	0.0976	0.1724	4.638	0.2766	−2.027
$\Sigma_c^{0}\to\Sigma^-$	1.961	0.3184	0.6246	5.245	0.8246	−3.718
$\Xi_c^{0}\to\Xi^-$	1.860	0.2691	0.5199	5.080	0.7103	−3.397
$\Xi_c^{A\,0}\to\Xi^-$	1.269	0.1672	0.3198	3.501	0.4488	−2.236
$\Lambda_c^{+}\to\Lambda$	1.269	0.2001	0.3922	3.392	0.5233	−2.375
$\Xi_c^{A\,+}\to\Xi^0$	1.302	0.1736	0.3325	3.587	0.4652	−2.305
$\Sigma_c^{+}\to\Sigma^0$	1.944	0.3163	0.6206	5.196	0.8188	−3.688
$\Xi_c^{+}\to\Xi^0$	1.241	0.1635	0.3128	3.423	0.4390	−2.187
$\Sigma_c^{++}\to\Sigma^+$	1.933	0.3149	0.6181	5.165	0.8151	−3.668

TABLE XII. Transition-rate coefficients with dipole q^2 dependence in the form factors for the $\Delta S=\Delta C=-1$ decays. All of the coefficients are in units of 10^{11} sec^{-1}.

$B_1 \to B_2 e\nu$	A_{11}	A_{22}	A_{12}	B_{11}	B_{22}	B_{12}
$\Xi_{cc}^{++} \to \Xi_c^{A+}$	1.941	0.1337	0.2361	5.842	0.3658	−2.655
$\Xi_{cc}^{++} \to \Xi_c^{+}$	2.045	0.1442	0.2551	6.153	0.3935	−2.827
$\Xi_{cc}^{+} \to \Xi_c^{0}$	1.248	0.0707	0.1232	3.769	0.1973	−1.559
$\Omega_{cc}^{+} \to \Omega_c^{0}$	1.276	0.0657	0.1137	3.871	0.1839	−1.526
$\Xi_{cc}^{+} \to \Xi_c^{A0}$	1.941	0.1337	0.2361	5.842	0.3658	−2.655
$\Sigma_c^{0} \to \Sigma^-$	2.602	0.4781	0.9356	7.008	1.171	−5.217
$\Xi_c^{0} \to \Xi^-$	2.431	0.3956	0.7644	6.706	0.9941	−4.700
$\Xi_c^{A0} \to \Xi^-$	1.581	0.2304	0.4400	4.415	0.5950	−2.937
$\Lambda_c^{+} \to \Lambda$	1.595	0.2790	0.5458	4.307	0.6998	−3.144
$\Xi_c^{A+} \to \Xi^0$	1.627	0.2403	0.4596	4.538	0.6190	−3.038
$\Sigma_c^{+} \to \Sigma^0$	2.576	0.4742	0.9284	6.936	1.161	−5.168
$\Xi_c^{+} \to \Xi^0$	1.542	0.2246	0.4291	4.308	0.5806	−2.864
$\Sigma_c^{++} \to \Sigma^+$	2.560	0.4717	0.9237	6.889	1.155	−5.137

ing form factor f_1. In addition, the q^2 dependence of the several form factors is very important; it may amount to more than a 60–80% increase in many decays. All this comes from the fact that the available phase space, characterized by the parameter β displayed in Tables II–IV, is very sizable, up to around 0.6; in SU(3) semileptonic decays it is at most 0.22. This also means that the branching ratios, displayed in Tables XVI–XVIII, will be comparatively very large, around several percent compared to a few hundredths of a percent in SU(3) decays; this should make their high-statistics measurement a lot easier. All put together, this indicates that the $\Delta S=0, \Delta C=-1$ and $\Delta S=\Delta C=-1$ decays will give very important information both on the induced form factors and on the detailed q^2 dependence of all four form factors. This leads us to comment on SU(4)-symmetry-breaking effects.

How badly is SU(4) broken in these decays is something that must be established experimentally. For this to happen it is necessary to have reliable predictions for the symmetry limit and accurate measurements. The former is what we have attempted here; the latter will surely come in the next few years. It is expected that, owing to the big mass difference between the c and the s, u, and d quarks, SU(4) will be very broken. This breaking should be established not only in decay rates, but in detailed measurements of form factors as well. In this sense an important form factor is g_2, which here has been kept at zero as required by G parity and the symmetry limit restriction. It will be very important that this form factor be accurately measured. As we just mentioned the $\Delta S=0, \Delta C=-1$ and $\Delta S=\Delta C=-1$ decays will be very appropriate for this. The $\Delta C=0, \Delta S=+1$, some of which have small but not necessarily negligible branching ratios as can be seen in Table XVI, may play a useful role in determining f_1 and g_1 because they do remain leading form factors.

The main limitation of our results lies in our present

TABLE XIII. SU(4)-symmetry-limit predictions for the form factors of all of the $\Delta C=0$ decays. Asterisks indicate initial $V-A$ decays effectively turned into $V+A$ because the relative sign between f_1 and g_1 is reversed by SU(4) symmetry.

$B_1 \to B_2 e\nu$	f_1	f_2	g_1
$\Sigma_c^{++} \to \Lambda_c^{+}$	0	−1.17	−0.65
$\Xi_c^{A0} \to \Xi_c^{+}$	0	−0.83	−0.46
$\Sigma_c^{0} \to \Lambda_c^{+}$	0	−1.17	−0.65
$\Xi_c^{0} \to \Xi_c^{A}$	0	0.83	0.46
$\Sigma_c^{0} \to \Sigma_c^{+}$	1.41	0.59	0.64
$\Xi_c^{0} \to \Xi_c^{+}$	1	−0.42	0.45*
$\Omega_{cc}^{+} \to \Xi_{cc}^{++}$	−1	1.02	0.34*
$\Xi_c^{A0} \to \Lambda_c^{+}$	1	−0.54	−0.08*
$\Xi_c^{A0} \to \Sigma_c^{+}$	0	−0.83	−0.46
$\Xi_c^{A+} \to \Sigma_c^{++}$	0	−1.17	−0.65
$\Xi_c^{0} \to \Lambda_c^{+}$	0	0.83	0.46
$\Omega_c^{0} \to \Xi_c^{A+}$	0	−1.17	−0.65
$\Xi_c^{0} \to \Sigma_c^{+}$	1	0.42	0.45
$\Xi_c^{+} \to \Sigma_c^{++}$	1.41	0.59	0.64
$\Omega_c^{0} \to \Xi_c^{+}$	1.41	0.59	0.64

TABLE XIV. SU(4)-symmetry-limit predictions for the form factors of the $\Delta S=0, \Delta C=-1$ decays. Asterisks are as defined in Table XIII.

$B_1 \to B_2 e$	f_1	f_2	g_1
$\Xi_{cc}^{++} \to \Lambda_c^{+}$	0.86	−0.22	0.07
$\Xi_{cc}^{++} \to \Sigma_c^{+}$	0.71	1.31	0.88
$\Xi_{cc}^{+} \to \Sigma_c^{0}$	1	1.85	1.25
$\Omega_{cc}^{+} \to \Xi_c^{0}$	0.71	1.31	0.88
$\Omega_{cc}^{+} \to \Xi_c^{A0}$	−1.22	0.07	−0.23*
$\Xi_c^{0} \to \Sigma^-$	−0.71	0.72	0.24
$\Omega_c^{0} \to \Xi^-$	−1	1.02	0.34*
$\Xi_c^{A0} \to \Sigma^-$	1.22	1.10	0.88
$\Lambda_c^{+} \to n$	1.22	1.10	0.88*
$\Xi_c^{A+} \to \Sigma^0$	0.87	0.78	0.62
$\Xi_c^{A+} \to \Lambda$	−0.50	−0.45	−0.36
$\Sigma_c^{+} \to n$	0.71	−0.72	−0.24
$\Xi_c^{+} \to \Sigma^0$	−0.50	0.51	0.17
$\Xi_c^{+} \to \Lambda$	0.86	−0.88	−0.30*
$\Sigma_c^{++} \to p$	1	−1.02	−0.34*

TABLE XV. SU(4)-symmetry-limit predictions for the form factors of the $\Delta S = \Delta C = -1$ decays. Asterisks are as defined in Table XIII.

$B_1 \to B_2 e\nu$	f_1	f_2	g_1
$\Xi_{cc}^{++} \to \Xi_c^{A\,+}$	1.22	−0.07	0.23
$\Xi_{cc}^{++} \to \Xi_c^{+}$	0.71	1.31	0.88
$\Xi_{cc}^{+} \to \Xi_c^{0}$	0.71	1.31	0.88
$\Omega_{cc}^{+} \to \Omega_c^{0}$	1	1.85	1.25
$\Xi_{cc}^{+} \to \Xi_c^{A\,0}$	1.22	−0.07	0.23
$\Sigma_c^{0} \to \Sigma^{-}$	1	−1.02	−0.34*
$\Xi_c^{0} \to \Xi^{-}$	0.71	−0.72	−0.24*
$\Xi_c^{A\,0} \to \Xi^{-}$	1.22	1.10	0.88
$\Lambda_c^{+} \to \Lambda$	1	0.90	0.72
$\Xi_c^{A\,+} \to \Xi^{0}$	1.22	1.10	0.88
$\Sigma_c^{+} \to \Sigma^{0}$	1	−1.02	−0.34*
$\Xi_c^{+} \to \Xi^{0}$	0.71	−0.72	−0.24*
$\Sigma_c^{++} \to \Sigma^{+}$	1	−1.02	−0.34*

ignorance of the masses of seven of the charm baryons. We chose not to vary these masses to quote ranges for the decay rates as was done in Refs. 1 and 2, but still the predicted values we used may change. A 5–10 % variation in the masses might easily happen. Since the expression for the decay rate is roughly proportional to β^5, we may expect our results to be uncertain by 30–60 %. This should be kept in mind and, whenever those masses are established, the SU(4)-symmetry-limit prediction should be refined.

Another uncertainty, but this time coming from our theoretical ignorance, lies in the q^2 dependence of the form factors. Whether it is a monopole or a dipole or whether such simplified analytical shapes are correct are open questions at present. Changes in the values of M_V and M_A affect the predictions of the rates very importantly. Compare, for example, with Ref. 18. All these questions require very detailed theoretical and experimental analyses. As we shall see in the following paper, in charm-baryon decays these uncertainties turn out to be much more important than expected at first.

TABLE XVI. SU(4)-symmetry-limit predictions for the rates Γ and branching ratios B of all the $\Delta C = 0$ decays. Only the results without q^2 dependence of form factors are displayed. The effect of monopole or dipole q^2 dependence amounts to an increase smaller than 0.5%.

$B_1 \to B_2 e\nu$	Γ_0	$(\sec^{-1})$	B_0	Unit
$\Sigma_c^{++} \to \Lambda_c^{+}$	0.18	10^8	3.22	10^{-6}
$\Xi_c^{A\,0} \to \Xi_c^{+}$	0.34	10^3	6.13	10^{-11}
$\Sigma_c^{0} \to \Lambda_c^{+}$	0.18	10^8	3.14	10^{-6}
$\Xi_c^{0} \to \Xi_c^{A\,+}$	0.39	10^6	6.97	10^{-8}
$\Sigma_c^{0} \to \Sigma_c^{+}$	0.61	10^{-5}	1.09	10^{-16}
$\Xi_c^{0} \to \Xi_c^{+}$	0.28	10^7	5.05	10^{-7}
$\Omega_{cc}^{+} \to \Xi_{cc}^{++}$	0.15	10^7	2.76	10^{-7}
$\Xi_c^{A\,0} \to \Lambda_c^{+}$	0.12	10^7	2.15	10^{-7}
$\Xi_c^{A\,0} \to \Sigma_c^{+}$	0.12	10^2	2.20	10^{-12}
$\Xi_c^{A\,+} \to \Sigma_c^{++}$	0.24	10^2	4.40	10^{-12}
$\Xi_c^{0} \to \Lambda_c^{+}$	0.66	10^7	1.18	10^{-6}
$\Omega_c^{0} \to \Xi_c^{A\,+}$	0.12	10^8	2.08	10^{-6}
$\Xi_c^{0} \to \Sigma_c^{+}$	0.13	10^6	2.40	10^{-8}
$\Xi_c^{+} \to \Sigma_c^{++}$	0.14	10^{-4}	2.43	10^{-18}
$\Omega_c^{0} \to \Xi_c^{+}$	0.33	10^8	5.94	10^{-6}

Finally we would like to mention how the predictions found can be contrasted with the experiment in order to explore the possibility for the existence of a fourth generation.[18]

According to Table XVIII we can cast our predictions for the $\Lambda_c \to \Lambda$ decay in terms of the V_{cs} parameter. Using the published data[5] we obtain

$$V_{cs} = 0.36 \pm 0.14 \quad \text{(monopole)} ,$$

$$V_{cs} = 0.32 \pm 0.11 \quad \text{(dipole)} .$$

We conclude that the SU(4)-symmetry-limit predic-

TABLE XVII. SU(4)-symmetry-limit predictions for the decay rates Γ (in units of $10^{11}\ \sec^{-1}$) and branching ratios B (in percent) without q^2 dependence, with monopole, and with dipole q^2 dependence in the form factors for decays $\Delta S = 0, \Delta C = -1$.

$B_1 \to B_2 e\nu$	Γ_0	Γ_{mon}	Γ_{dip}	B_0	B_{mon}	B_{dip}
$\Xi_{cc}^{++} \to \Lambda_c^{+}$	0.20	0.27	0.39	0.35	0.48	0.69
$\Xi_{cc}^{++} \to \Sigma_c^{+}$	0.31	0.41	0.55	0.55	0.73	0.99
$\Xi_{cc}^{+} \to \Sigma_c^{0}$	0.60	0.79	1.06	1.07	1.41	1.90
$\Omega_{cc}^{+} \to \Xi_c^{0}$	0.43	0.60	0.86	0.77	1.07	1.54
$\Omega_{cc}^{+} \to \Xi_c^{A\,0}$	0.20	0.27	0.38	0.35	0.48	0.69
$\Xi_c^{0} \to \Sigma^{-}$	0.09	0.13	0.20	0.15	0.22	0.35
$\Omega_c^{0} \to \Xi^{-}$	0.23	0.35	0.59	0.41	0.63	1.05
$\Xi_c^{A\,0} \to \Sigma^{-}$	0.44	0.62	0.92	0.79	1.12	1.65
$\Lambda_c^{+} \to n$	0.52	0.78	1.23	0.94	1.39	2.20
$\Xi_c^{A\,+} \to \Sigma^{0}$	0.23	0.32	0.47	0.40	0.57	0.85
$\Xi_c^{A\,+} \to \Lambda$	0.10	0.15	0.24	0.18	0.27	0.43
$\Sigma_c^{+} \to n$	0.12	0.20	0.39	0.22	0.36	0.69
$\Xi_c^{+} \to \Sigma^{0}$	0.03	0.04	0.06	0.05	0.07	0.10
$\Xi_c^{+} \to \Lambda$	0.11	0.16	0.25	0.20	0.29	0.44
$\Sigma_c^{++} \to p$	0.24	0.39	0.74	0.43	0.71	1.32

TABLE XVIII. SU(4)-symmetry-limit predictions for the decay rates Γ (in units of 10^{11} $\sec^{-1}$) and branching ratios B (in percent) without q^2 dependence, with monopole, and with dipole q^2 dependence in the form factors for decays $\Delta S = \Delta C = -1$.

$B_1 \to B_2 e$	Γ_0	Γ_{mon}	Γ_{dip}	B_0	B_{mon}	B_{dip}
$\Xi_{cc}^{++} \to \Xi_c^{A\,+}$	2.0	2.4	3.0	3.6	4.3	5.3
$\Xi_{cc}^{++} \to \Xi_c^{+}$	5.8	7.5	9.9	10.5	13.4	17.6
$\Xi_c^{+} \to \Xi_c^{0}$	3.6	4.4	5.5	6.5	7.9	9.8
$\Omega_{cc}^{+} \to \Omega_c^{0}$	7.4	9.1	11.3	13.3	16.3	20.1
$\Xi_{cc}^{+} \to \Xi_c^{A\,0}$	2.0	2.4	3.0	3.6	4.3	5.3
$\Sigma_c^{0} \to \Sigma^{-}$	2.3	3.0	4.1	4.1	5.4	7.4
$\Xi_c^{0} \to \Xi^{-}$	1.1	1.5	2.0	2.0	2.6	3.5
$\Xi_c^{A\,0} \to \Xi^{-}$	5.3	6.8	8.8	9.5	12.1	15.7
$\Lambda_c^{+} \to \Lambda$	3.6	4.6	6.0	6.4	8.2	10.8
$\Xi_c^{A\,+} \to \Xi^{0}$	5.5	7.0	9.1	9.8	12.5	16.3
$\Sigma_c^{+} \to \Sigma^{0}$	2.3	3.0	4.1	4.1	5.3	7.3
$\Xi_c^{+} \to \Xi^{0}$	0.8	0.9	1.2	1.4	1.7	2.1
$\Sigma_c^{++} \to \Sigma^{+}$	2.3	3.0	4.0	4.0	5.3	7.2

tions definitely predict the existence of a fourth generation of quarks. But as just mentioned, these predictions should be improved by incorporating SU(4)-breaking effects. As we shall see at the end of the following paper, the quark-model predictions reduce considerably the discrepancy between the symmetry-limit prediction and this experimental value for the Λ_c semileptonic branching ratio. However, there does remain ample room for an appreciable effect of the existence of a fourth generation through the value of V_{cs}.

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