SU(4) breaking for semileptonic decays of charmed baryons

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(Received 4 November 1977)

The effects of SU(4) breaking are studied in connection with the semileptonic decays and magnetic moments of the baryons with charm +1. Substantial suppression factors are predicted for the decay in which the final baryon belongs to the decimet. The consequences of a vanishing magnetic moment for the charmed quark are studied in detail.

I. INTRODUCTION

The existence of a fourth quark characterized by a new quantum number, "charm", which was introduced on theoretical grounds,[1] has found experimental support in the discovery of the puzzling J/ψ particle[2] and of other charmonium-like states. Since 1974, it has been confirmed by several experiments on neutrino interactions[3] where dilepton production is commonly viewed as indirect evidence for the production of charmed particles which subsequently decay in a semileptonic way, and by the discovery of charmed mesons.[4] Finally, the peaks which have been observed at 2250 and 2500 MeV/c^2 in the effective-mass distribution of $\bar{\Lambda}(3\pi)$ and $\bar{\Lambda}(4\pi)$, respectively, in photoproduction at Fermilab[5] have been interpreted as charmed antibaryons.[6]

The existence of charmed baryons stable under strong and electromagnetic interactions is indeed expected from the theoretical values[7] of their masses and the measured masses[7] of the already discovered charmed mesons.

The purpose of this paper is the evaluation of the semileptonic decay rates and the magnetic moments of the baryons with charm +1 which are expected to decay weakly. The effects of SU(4)-symmetry breaking, already described[8] in the framework of the transformation from constituent to current quarks,[9,10] are rather large. Therefore our predictions will differ from the ones obtained in the symmetry limit.[11,12]

The expressions for the weak charges and the magnetic-moment operators will be written in Sec. II. Then the predictions for the semileptonic decays and the magnetic moments of the baryons with charm +1 will be derived in Sec. III.

II. THE WEAK CHARGES AND MAGNETIC-MOMENT OPERATORS

The vector and axial-vector charges are obtained from the corresponding SU(8) generators with the unitary transformation[9,10] which connects constituent to current quarks; the unitary operator V applied to the quarks in the ground state transform them according to[8]

$$V\,|\,q_i^\uparrow\,,\text{ ground state}\rangle=\cos\theta_i\,\,|\,q_i^\uparrow\,,\text{ ground state}\rangle+\sin\theta_i\,|\,q_i^\downarrow\,,L_z=+1\rangle\,,\qquad(2.1)$$

$$V\,|q_i^\downarrow,\text{ ground state}\rangle=\cos\theta_i\,\,|q_i^\downarrow\,,\text{ ground state}\rangle+\sin\theta_i\,\,|q_i^\uparrow\,,L_z=-1\rangle\,,$$

where θ_i depends on the flavor index i and the $|L_z=\pm 1\rangle$ state is the same for all the quarks. As a consequence, the matrix elements of the vector and axial-vector charges between the states of the 63 and 120 representations of SU(8) are renormalized with respect to the corresponding generators by the factor $\cos(\theta_i \mp \theta_j)$ in which the upper (lower) sign holds for the vector (axial)charge. The parameters $\theta_{\mathcal{P}_0}=\theta_{\mathfrak{N}_0}$ and θ_{λ_0} are obtained[13] from the semileptonic decays of the ordinary (noncharmed) baryons

$$\theta_{\mathcal{P}_0}=\theta_{\mathfrak{N}_0}=20^\circ,\quad \theta_{\lambda_0}=28^\circ.\qquad(2.2)$$

To determine θ_{c_0}, one assumes also that for the charmed states the magnetic-moment matrix elements are proportional to the ones of the corresponding axial charge. This property holds rather well for ordinary baryons. Indeed from (2.2) this hypothesis implies the following expression for the magnetic moment of the $\underline{35}$ and $\underline{56}$ states of SU(6):

TABLE I. Magnetic moments and transition magnetic moments for baryons [In brackets, the predictions of unbroken SU(4) are reported].

Theory	Experiment
$\mu_p = \mu_0 \cos 2\theta_{\mathcal{P}_0} = 2.79$	2.79
$\mu_n = \mu_0(-\frac{2}{3})\cos 2\theta_{\mathcal{P}_0} = -1.86$	-1.91
$\mu_{\Sigma^+} = \mu_0 \frac{1}{9}(8\cos 2\theta_{\mathcal{P}_0} + \cos 2\theta_{\lambda_0}) = 2.71(2.79)$	2.62 ± 0.41
$\mu_{\Sigma^0} = \mu_0 \frac{1}{9}(2\cos 2\theta_{\mathcal{P}_0} + \cos 2\theta_{\lambda_0}) = 0.84(0.93)$	
$\mu_{\Sigma^-} = \mu_0 \frac{1}{9}(-4\cos 2\theta_{\mathcal{P}_0} + \cos 2\theta_{\lambda_0}) = -1.01(-0.93)$	-1.48 ± 0.37
$\mu_{\Lambda} = \mu_0(-\frac{1}{3})\cos 2\theta_{\lambda_0} = -0.68(-0.93)$	-0.67 ± 0.06
$\mu_{\Xi^0} = \mu_0(-\frac{2}{9})(\cos 2\theta_{\mathcal{P}_0} + 2\cos 2\theta_{\lambda_0}) = -1.52(-1.86)$	
$\mu_{\Xi^-} = \mu_0 \frac{1}{9}(\cos 2\theta_{\mathcal{P}_0} - 4\cos 2\theta_{\lambda_0}) = -0.59(-0.93)$	-1.85 ± 0.75
$\mu_{T^0} = \mu_0(-\frac{2}{9})(2\cos 2\theta_{\lambda_0} + \cos 2\theta_{c_0}) = -0.91(-1.86)$	
$\mu_{C_0^+} = \mu_0 \frac{2}{3}\cos 2\theta_{c_0} = 0(1.86)$	
$\mu_{A^+} = \mu_0 \frac{2}{3}\cos 2\theta_{c_0} = 0(1.86)$	
$\mu_{A^0} = \mu_0 \frac{2}{3}\cos 2\theta_{c_0} = 0(1.86)$	
$\mu_{C_0^+ C_1^+} = \mu_0\left(-\frac{1}{\sqrt{3}}\right)\cos 2\theta_{\mathcal{P}_0} = 1.62$	
$\mu_{A^+ S^+} = \mu_0\left(-\frac{1}{3\sqrt{3}}\right)(2\cos 2\theta_{\mathcal{P}_0} + \cos 2\theta_{\lambda_0}) = -1.45(-1.62)$	
$\mu_{A^0 S^0} = \mu_0\left(\frac{1}{3\sqrt{3}}\right)(\cos 2\theta_{\mathcal{P}_0} - \cos 2\theta_{\lambda_0}) = 0.14(0).$	

$$\vec{\mu} = \mu_p \left[\tfrac{2}{3}\vec{S}_{\mathcal{P}_0} - \tfrac{1}{3}\vec{S}_{\mathcal{N}_0} - \tfrac{0.73}{3}\vec{S}_{\lambda_0}\right]. \qquad (2.3)$$

A comparison of Eq. (2.3) with experiment is performed in Table I.

For the hadrons containing charmed quarks, Eq. (2.3) should be generalized by adding the term $\mu_p(\frac{2}{3})(\cos 2\theta_{c_0}/\cos 2\theta_{\mathcal{P}_0})\vec{S}_{c_0}$. A measure of $\cos 2\theta_{c_0}$ can be obtained by considering the decay rate $\psi_c \to \eta_c + \gamma$; assuming $m_{\eta_c} = 2800$ MeV one finds[14]

$$\Gamma(\psi_c \to \eta_c + \gamma) = \frac{1}{3\pi}\,\mu_{VP}^2 k^3 = 887\,\frac{\cos^2 2\theta_{c_0}}{\cos^2 2\theta_{\mathcal{P}_0}}\ \text{keV}.$$

Since $\Gamma_{\text{Total}}(\psi_c) = 67 \pm 12$ keV and the channel $\eta_c\gamma$ has a small branching ratio,[15] we conclude that

$$\theta_{c_0} = 45°. \qquad (2.4)$$

A confirmation that the contribution of the charmed quarks to the hadronic magnetic moment is negligible may be achieved from the measured branching ratio[16]

$$\Gamma(D^{*0} \to D^0 + \gamma)/\Gamma(D^{*0} \to D^0 + \pi^0) = 1.0 \pm 0.3.$$

With $m_{D^{*0}} = 2005$ MeV and $m_{D^0} = 1867$ MeV one finds

$$\Gamma(D^{*0} \to D^0 + \gamma) = 24\ \ 1 + \left(\frac{\cos 2\theta_{c_0}}{\cos 2\theta_{\mathcal{P}_0}}\right)^2\ \text{keV},$$

while

$$\Gamma(D^{*0} \to D^0 + \pi^0) = \frac{1}{24\pi F_\pi^2}\, q^3_{\pi^0\,\text{c.m.}} \cos^2 2\theta_{\mathcal{P}_0}$$
$$= 15.4\ \text{keV}.$$

A further check on this hypothesis could be obtained from the study of the D^{*+} decays. In fact, one obtains

$$\Gamma(D^{*+} \to D^+ + \gamma) = 6\left(1 - 2\,\frac{\cos 2\theta_{c_0}}{\cos 2\theta_{\mathcal{P}_0}}\right)^2\ \text{keV},$$

compared to the rate

$$\Gamma(D^{*+} \to D + \pi) = 54.8\ \text{keV}$$

obtained with $m_{D^{*+}} = 2010$ MeV and $m_{D^+} = 1872$ MeV. Of course, the pionic rates depend critically on the masses of the charmed mesons.

From (2.2) and (2.4) one can get the following expression for the effective weak current of the constituent quarks, in the ground state, involving the charmed quark:

$$\bar{c}_0\gamma_\mu[\cos\theta_{\text{Cabibbo}}(0.96 - 0.29\gamma_5)\lambda_0 - \sin\theta_{\text{Cabibbo}}(0.91 - 0.42\gamma_5)\mathcal{N}_0], \qquad (2.5)$$

where the Glashow-Iliopoulous-Maiani (GIM) form[1] has been taken for the weak Lagrangian.

III. PREDICTIONS FOR SEMILEPTONIC DECAYS OF CHARMED +1 BARYON STATES

According to Reference 7, the $C=1$ baryons, stable under strong and electromagnetic interactions, are the isospin singlet of the $\underline{6}$ representation of SU(3), T^0 (with quark content $\overline{C}\lambda\lambda$) and all the states of the $\underline{\overline{3}}$, the isospin singlet $C_0^+(c\mathcal{P}\mathfrak{N})$, and the doublet $A^{+,0}$ ($\overline{c}\lambda\mathcal{P}$ or $c\lambda\mathfrak{N}$). The states of the $\underline{\overline{3}}$ are not coupled by the charm-changing currents, which behave as a $\underline{3}$ representation of SU(3), to the $\frac{3}{2}^+$ decouplet ($\underline{3}\otimes\underline{\overline{3}}=\underline{1}\oplus\underline{8}$). Their $\Delta S=1$ and $\Delta S=0$ decays are, respectively,

$$\left.\begin{matrix} C_0^+\to\Lambda \\ A^{+,0}\to\Xi^{0,-}\end{matrix}\right\}+e^++\nu_e \quad\text{and}\quad \left.\begin{matrix} C_0^+\to n \\ A^+\to\Lambda \\ A^{+,0}\to\Sigma^{0,-}\end{matrix}\right\}+e^++\nu_e\,.$$

From (2.5) one finds the corresponding values of the weak-charge matrix elements

$$-\langle\Lambda\,|Q_{(5)}^{13+i14}|\,C_0^+\rangle=+\left(\frac{2}{3}\right)^{1/2}\langle\Xi^{0,-}\,|Q^{13+i14}|\,A^{+,0}\rangle =0.96\ (0.29) \tag{3.1a}$$

for the $\Delta S=1$ transitions, and

$$\left(\frac{2}{3}\right)^{1/2}\langle n\,|\,Q_{(5)}^{11+i12}\,|C_0^+\rangle=\left(\frac{2}{3}\right)^{1/2}\langle\Sigma^-\,|Q_{(5)}^{11+i12}\,|A^0\rangle = \frac{2}{\sqrt{3}}\langle\Sigma^0\,|Q_{(5)}^{11+i12}\,|\,A^+\rangle = -2\langle\Lambda\,|Q_{(5)}^{11+i12}\,|A^+\rangle = 0.91\ \ (0.42) \tag{3.1b}$$

for the $\Delta S=0$ transitions. We put into brackets the renormalization factors corresponding to the axial-vector charges $Q_5^{m+i(m+1)}$. The proportionality between the vector and axial-vector charge matrix elements is a consequence of the fact that in the $\underline{\overline{3}}$, the ordinary-quark spins couple to zero,

TABLE II. Semileptonic decay widths and partial lifetimes for charmed $\frac{1}{2}^+$ baryons into $\frac{1}{2}^+$ and $\frac{3}{2}^+$ noncharmed states. We neglected the weak-magnetism contributions to the rates since we expect them to be depressed by the factors $\cos(\theta_c+\theta_{\mathcal{P}})/\cos 2\theta_{\mathcal{P}}$ and $\cos(\theta_c+\theta_\lambda)/\cos 2\theta_{\mathcal{P}}$. In parentheses are the predictions without symmetry breaking.

Decaying baryons	Baryons in final state	Cabibbo factor	Decay width (MeV)	Partial lifetime (sec)	Buras' partial lifetime (sec)
C_0^+	Λ^0	$\cos\theta$	0.63×10^{-10}	8.5×10^{-12}	5×10^{-12}–3×10^{-14}
(2200 MeV)			(1.48×10^{-10})		
	n	$\sin\theta$	0.14×10^{-10}		
			(0.29×10^{-10})		
A^+	Λ^0	$\sin\theta$	0.03×10^{-10}	5.5×10^{-12}	10^{-11}–3×10^{-14}
(2420 MeV)			(0.064×10^{-10})		
	Σ^0	$\sin\theta$	0.07×10^{-10}		
			(0.14×10^{-10})		
	Ξ^-	$\cos\theta$	1.1×10^{-10}		
			(2.67×10^{-10})		
A^0	Σ^-	$\sin\theta$	0.14×10^{-10}	5.3×10^{-12}	10^{-11}–3×10^{-14}
(2420 MeV)			(0.28×10^{-10})		
	Ξ^-	$\cos\theta$	1.1×10^{-10}		
			(2.67×10^{-10})		
T^0	Ξ^-	$\sin\theta$	0.11×10^{-10}	13×10^{-12}	10^{-13}–10^{-13}
(2680 MeV)			(0.15×10^{-10})		
	Ω^-	$\cos\theta$	0.36×10^{-10}		
			(2.66×10^{-10})		
	Ξ^{*-}	$\sin\theta$	0.036×10^{-10}		
			(0.12×10^{-10})		

and the total spin coincides with the spin of the charmed quark. Therefore the action of the SU(8) generators corresponding to the vector and axial charges is the same. However, the renormalization factors are different.

For the T^0 particle, one expects the following semileptonic decays:

$$\left.\begin{array}{l} T^0 \to \Omega^- \\ T^0 \to \Xi^- \\ T^0 \to \Xi^{*-} \end{array}\right\} + e^+ + \nu_e \ ,$$

and the relevant matrix elements are

$$\begin{aligned} \langle \Omega^- \,|Q_5^{13+i14}\,|\, T^0\rangle &= -2\left(\frac{2}{3}\right)^{1/2} \times 0.29\,, \\ \langle \Xi^{*-}\,|Q_5^{11+i12}\,|\,T^0\rangle &= -2\,\frac{\sqrt{2}}{3} \times 0.42\,, \\ \langle \Xi^-\,|Q_5^{11+i12}\,|\,T^0\rangle &= -\tfrac{1}{3} \times 0.42\,, \\ \langle \Xi^-\,|Q_5^{11+i12}\,|\,T^0\rangle &= 0.91 \end{aligned} \qquad (3.2)$$

The rates derived from (3.1) and (3.2) are written in Table II.

To get the decay rates for the $\frac{1}{2}^+ \to \frac{1}{2}^+ + e^+ + \nu_e$, we used the formula

$$\Gamma_{A\to B+e^+ +\nu_e} = \frac{G^2C^2}{384\pi^3}\,\frac{1}{M_A{}^3}\,(A_1F_V{}^2 + A_2F_A{}^2) \quad (3.3)$$

where C is the Cabibbo factor, F_V and F_A the matrix elements of the vector and axial-vector charges, respectively, and the A_i are given by

$$\begin{aligned} A_1 &= \int_0^{\Delta^2} \frac{2\,[(\Delta^2 - s)(\Sigma^2 - s)]^{1/2}}{(1 - s/m^{*2})^2} \\ &\qquad \times (\Sigma^2 + 2s)(\Delta^2 - s)ds\,, \\ A_2 &= \int_0^{\Delta^2} \frac{2[(\Delta^2 - s)(\Sigma^2 - s)]^{1/2}}{(1 - s/m^{*2})^2} \\ &\qquad \times (\Delta^2 + 2s)(\Sigma^2 - s)ds\,, \end{aligned} \qquad (3.4)$$

where $\Delta = M_A - M_B$, $\Sigma = M_A + M_B$, and m^* is the mass of the charmed vector meson (i.e., F^* and D^* for $\Delta S = 1$ and $\Delta S = 0$ transitions, respectively), and the lepton mass has been neglected.

In the limit $\Delta \ll \Sigma, m^*$ (which is the case for the semileptonic decays of noncharmed baryons) one obtains

$$A_2 = 3A_1 = \tfrac{12}{5}\,\Delta^5\Sigma^3\,.$$

However, for the charmed baryons the above inequalities are not well satisfied since $\Delta \sim \frac{1}{2} m^* \sim \frac{1}{3}\Sigma$. So the A_1 and A_2 given by (3.4) are larger by a factor ~1.25 for $\Delta S = 1$ decays and ~1.4 for $\Delta S = 0$ ones.

A similar, albeit more complicated, expression holds for the $\frac{1}{2}^+ \to \frac{3}{2}^+$ decays.[11]

Let us conclude this section with some discussion about the magnetic moments. From Eqs. (2.3) and (2.4), one deduced that the states of the $\overline{3}$ have no magnetic moment (the only quark with nonvanishing spin projection of the hadron spin is the charmed one), while the symmetry prediction is $\frac{2}{3}\,\mu_p$ for all of them.

As for the transition magnetic moments, the only ones which can be measured indirectly while evaluating the branching ratio of the radiative decay with respect to the pionic one are $\mu_{C_1^+C_0^+}$ and $\mu_{S^{+,0}A^{+,0}}$, which does not change $(\mu_{C_1^+C_0^+})$, or changes very little (μ_{SA}) from the symmetry value,[17] cf. Table I.

IV. CONCLUSION

The effect of symmetry breaking is such that it reduces by a factor 2.5 (2) the Cabibbo-favored (-disfavored) $\Delta S = 1$ $(= 0)$ decays of the charmed states of the $\overline{3}$. This changes slightly the branching ratios into the different channels, with respect to the predictions of SU(4).[11] A stronger effect concerns the T^0 decays, where the Ξ^- final state is expected to occur rather frequently (22% instead of 5%). Also the spectrum of the baryon final state is predicted to be different with respect to the symmetry limit: The dominance of the vector-current contribution implies a larger amount of energy transfer to the final baryon.

Should the pattern proposed here for the renormalization of the weak charm-changing charges be confirmed by experiment, rather interesting implications would arise concerning the transformation from consituent to current quarks: Indeed the understanding[10] of this transformation as a consequence of the relativistic motion of quarks inside the hadrons would rather bring a decreasing (instead of increasing) value for the θ_i going from lower- to higher-mass quarks.[18] A typical feature of the scheme presented here is the property of renormalizing more the $\Delta C = \Delta S = 1$ axial-vector charges than the $\Delta C = 1$, $\Delta S = 0$ axial-vector charges.

ACKNOWLEDGMENTS

One of us (P.S) would like to thank J. Donohue and C. Quigg for discussions, D. Duke for his assistance in numerical programming, and the Theoretical Physics Group of Fermilab for their kind hospitality. The work of P.S. was supported in part by the NSF.

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†Operated by Universities Research Association Inc. under contract with the Energy Research and Development Administration.

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