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QCD EFFECTS IN A MODEL OF NON-LEPTONIC HYPERON DECAYS *

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ABSTRACT

Inclusion of QCD corrections is shown to effect substantial changes in the quark model predictions for non-leptonic hyperon decays.

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The experimentally observed strength of the $\Delta I = \frac{1}{2}$ non-leptonic decays are considerably larger than what one would expect on the basis of a Cabibbo suppressed current-current picture. Calculations on the basis of Wilson's short-distance expansion using QCD as the underlying theory of strong interactions, does indicate some but not enough enhancement 1) of the $\Delta I = \frac{1}{2}$ (or equivalently of the octet) piece of the non-leptonic Lagrangian and some authors have considered this serious enough to introduce right-handed currents 2). Vainshtein, Zakharov and Shifman 3) have indeed obtained right-handed currents essentially on the basis of a more complete calculation along the lines of Ref.1, introducing what have come to be known as "Penguin"diagrams. However, these diagrams give rise to some but not enough enhancement of the $\Delta I = \frac{1}{2}$ non-leptonic decay.

In a somewhat contrasting approach, Schmid 4) followed by Le Yaounac, Oliver, Pene and Raynal 5) and by Riazuddin and Fayyazuddin 6) have sought to explain the $\Delta I = \frac{1}{2}$ non-leptonic decay on the basis of a simple quark model, using PCAC and current algebra techniques without any new currents or short-distance enhancement factors. The results finally depend upon parameters which depend on strong interaction theory and with suitable choice a reasonable fit to the data can be obtained. The purpose of this note is to point out that QCD effects in the context of the model of Refs.4 to 6 effect substantial change in the predictions of the model. The QCD corrections due to soft gluons can be incorporated in the model by including the enhancement factors calculated for the original currents and also by the new currents introduced in Ref.3. The one other essential parameter required for calculations, namely the two-particle quark wave function at zero separation in the baryon, can also be corrected for QCD effects on the basis of QCD based quark model developed by De Rujula, Georgi and Glashow 7).

In the model of Refs.4 to 6, the baryon to baryon matrix element $\langle B_r | H_W^{p.c.} | B_s \rangle$ enter (i) directly in the baryon pole graphs for p waves and (ii) using current algebra in the commutator term for the s wave. With the inclusion of QCD corrections, the effective non-leptonic Hamiltonian is again a four-Fermi structure as follows:

$$H_{eff}^{\Delta S=1} = \sqrt{2}\ \sin\theta_C \cos\theta_C \cdot \left\{ \sum_{i=1}^{6} C_i O_i \right\} , \qquad (1)$$

where

$$O_1 = \bar{d}_L s_L \cdot \bar{u}_L u_L - \bar{d}_L d_L \cdot \bar{u}_L s_L ,$$

$$O_2 = \bar{d}_L s_L \cdot \bar{u}_L u_L + \bar{d}_L u_L \cdot \bar{u}_L s_L + 2\, \bar{d}_L s_L \cdot \bar{d}_L d_L + 2\, \bar{d}_L s_L \cdot \bar{s}_L s_L ,$$

$$O_3 = \bar{d}_L s_L \cdot \bar{u}_L u_L + \bar{d}_L u_L \cdot \bar{u}_L s_L + 2\, \bar{d}_L s_L \cdot \bar{d}_L d_L - 3\, \bar{d}_L s_L \cdot \bar{s}_L s_L ,$$

$$O_4 = \bar{d}_L s_L \cdot \bar{u}_L u_L + \bar{d}_L u_L \cdot \bar{u}_L s_L - \bar{d}_L s_L \cdot \bar{d}_L d_L ,$$

$$O_5 = \bar{d}_L \lambda^\alpha s_L \cdot (\bar{u}_R \lambda^\alpha u_R + \bar{d}_R \lambda^\alpha d_R + \bar{s}_R \lambda^\alpha s_R),$$

$$O_6 = \bar{d}_L s_L \cdot (\bar{u}_R u_R + \bar{d}_R d_R + \bar{s}_R s_R),$$

where $\bar{d}_L s_L \equiv \bar{d}^i_L \gamma_\mu s^i_L$ and so on. The suffix i represents the colour index and λ's are the Gell-Mann SU(3) matrices. The values of the constants c_i's are (with the strong coupling constant normalized to $\alpha_s = 1$ around 1 GeV) $c_1 = -2.5$, $c_2 = 0.11$, $c_3 = 0.08$, $c_4 = 0.4$, $c_5 = -0.06$ and $c_6 = -0.01$. Their values when the strong interaction is turned off are $c^0_1 = -1$, $c^0_2 = +0.2$, $c^0_3 = 0.13$, $c^0_4 = 0.67$, $c^0_5 = c^0_6 = 0$. If we consider the matrix element of the parity-conserving part of the above Hamiltonian between baryon states in the non-relativistic quark model, the operator O_3 and O_4 belonging to the 27-plet does not contribute. The two octet operators' contribution is parametrized as usual [8)]

$$\langle B_s | (H_w)^{pc}_{\Delta S=1} | B_r \rangle = 2\sqrt{2}\ \bar{u}_s (i f_{6rs} F + d_{6rs} D) . \qquad (2)$$

It is easy to see from Eq.(2) that the ratio D/F equals $5c_2/c_1$ and hence equals -0.22 compared with the value -1 in the free quark model. With this value of D/F, the absolute magnitude of F can be worked out by considering Λ decay to yield

$$F = \left(\frac{c_1}{c_1^0}\right) \cdot \left(\frac{3}{2\cdot 78}\right) \cdot G_F \cos\theta_c \sin\theta_c \langle \psi^S | \delta^3(\vec{r}_{12}) | \psi^S \rangle , \qquad (3)$$

where ψ^S represents the space wave function of the three systems. We shall, following Ref.5, relate the quantity $\langle \psi^S | \delta^3(\vec{r}_{12}) | \psi^S \rangle$ to the electromagnetic mass splitting of baryons. The mass splitting however is now assumed to be due to both electromagnetic interactions and to intrinsic mass difference of the constituent quarks, the latter making itself felt directly as well as through a Breit-Fermi colour hyperfine interaction [7)]. The electromagnetic interaction between the quarks is

$$H_{e.m.} = \alpha_{em} \sum_{i<j} \frac{e_i e_j}{e^2} \left[\frac{1}{r_{ij}} - \frac{8\pi}{3} \cdot \frac{\vec{S}_i \cdot \vec{S}_j}{m_i m_j} \cdot \delta^3(\vec{r}_{ij}) \right] , \qquad (4)$$

where e_i, $\vec{S}_i$ and m_i denote, respectively, the charge, spin and mass of the i^{th} quark. The colour hyperfine interaction introduced by De Rujula, Georgi and Glashow [7)] is

$$H_{Col} = \sum_{i<j} \frac{16\pi\alpha_s}{9 m_i m_j} (\vec{S}_i \cdot \vec{S}_j) \ \delta^3(\vec{r}_{ij}) . \qquad (5)$$

Using (4) and (5), the difference in the electromagnetic splitting of nucleons and the Σ's turns out to be [9)]

$$(m_p - m_n) - (m_{\Sigma^+} - m_{\Sigma^-}) = \frac{2\pi\alpha_{em}}{9 m_u^2} \left(1 + 2\frac{m_u}{m_s} \right) \cdot \langle \delta^3(\vec{r}_{12}) \rangle_0$$

$$+ \frac{5}{24} \cdot \frac{\delta m}{m} \cdot \frac{8\pi\alpha_s}{3 m_u^2} \left(0.5 + \frac{m_u}{m_s} \right) \cdot \langle \delta^3(\vec{r}_{12}) \rangle_0 , \qquad (6)$$

where $\delta m \equiv m_d - m_u$.

The quantity $\alpha_s \langle \delta^3(\vec{r}_{12}) \rangle_0$ is estimated by relating this to the Δ-nucleon mass difference [7)]

$$\frac{8\pi\alpha_s}{3 m_u^2} \langle \delta^3(\vec{r}_{12}) \rangle_0 = (m_\Delta - m_N) . \qquad (7)$$

Substituting numbers and using $(m_d - m_u) = 6$ meV [9)], we finally get

$$\langle \delta^3(\vec{r}_{12}) \rangle_0 = 0.47 \times 10^{-2}\ (\mathrm{GeV})^3 , \qquad (8)$$

which is considerably less than the estimate of Ref.5 and a value of

$$F = 3.1 \times 10^{-5}\ \mathrm{meV} . \qquad (9)$$

Using this value of F and a D/F ratio of -0.22, the PCAC and current algebra predictions for the s-wave and p-wave amplitudes (denoted, respectively, by A and B) can be worked out following standard formulae [8)]. The results are shown in Table I, indicating a reasonable fit for the s-wave but total disagreement for the p-wave amplitudes. The inclusion of a K^* pole (or equivalently of "one-quark" decay in the langauge of Ref.4) has very little effect on the amplitudes. Typically, for example, the s-wave Σ^-_- amplitude is, including now the QCD suppression factor for the d-type octet Hamiltonian:

$$\begin{aligned} S(\Sigma^-_-)\Big|_{K^*\cdot\text{pole}} &\simeq \frac{G_F}{\sqrt{2}}\ (0.11)\cdot \cos\theta_c\ \sin\theta_c\ \ f_\pi\ \ (m_\Sigma - m_N) \\ &\simeq 3\times 10^3\ \ (m_\pi\ \ \text{Sec.})^{-1/2}, \end{aligned} \tag{10}$$

which is two orders of magnitude less than the commutator terms. A p-wave contribution cannot be obtained in the framework of "one-quark" decay model. Instead, if we consider the p-wave contribution coming from a K^*_A pole 10), then the contribution can be estimated similarly. We again include the Cabibbo suppression and also the QCD suppression factor for the d-type K^*_A-π coupling. Typically, the p-wave contribution to Λ^-_0 decay comes out to be

$$\begin{aligned} P(\Lambda^0_-)\Big|_{K^*_A\cdot\text{pole}} &\simeq -\frac{G_F}{\sqrt{2}}\ \cos\theta_c\ \sin\theta_c\cdot(0.11)\cdot f_\pi\cdot(m_\Lambda - m_N)\ \frac{\sqrt{3}}{\sqrt{2}} \\ &\simeq 3\times 10^3\ \ (m_\pi\ \ \text{Sec.})^{-1/2}, \end{aligned} \tag{11}$$

which again is two orders of magnitude less than the baryon pole contribution and hence cannot remedy the disagreement between theory and experiment. We finally consider the contribution of the operators O_5 and O_6 in Eq.(1). However, with the subtraction point chosen around 1 GeV, their contributions, shown separately in Table I, are quite small compared to the current algebra and baryon pole contribution.

Our conclusion is that a simple constituent quark model with QCD effects taken into account while agreeing reasonably with s-wave non-leptonic hyperon decay, fails to reproduce the quantitative details of the p-wave decay. A possible resolution may lie in the inclusion of right-handed currents 2) or estimation of "hard" gluon effects in QCD for which however no known methods exist so far.

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Table I

Decay	A			B		
	Theory	Experiment	Penguin contribution	Theory	Experiment	Penguin contribution
$\Sigma^- \to n\pi^-$	1.82	1.93	0.37	-6.8	-0.65	0.61
$\Sigma^+ \to n\pi^+$	0	0.06	0	3.3	19.05	0
$\Sigma^+ \to p\pi^0$	-1.30	-1.48	-0.28	7.2	12.04	0.83
$\Lambda^0 \to p\pi^-$	1.69	1.48	0.33	17.7	10.17	1.67
$\Xi \to \Lambda\pi$	-1.98	-2.04	-0.38	-5.2	6.73	-0.63

All entries are in units of $10^5\ (m_\pi\,\mathrm{sec})^{-1/2}$. A and B represent the s- and p-wave amplitudes as defined in Ref. 8. The experimental data is from Ref. 11. The entries in the "Theory" column are the contributions calculated from the left-handed octet currents. The contribution from the currents O_5 and O_6 are shown separately as "Penguin" contributions.

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