Right-Handed Current Effects in $\Delta S = 1$ Semileptonic Decays

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Some problems encountered in describing the $\Delta S = 1$ semileptonic hyperon decays in terms of the Cabibbo model are considered, and these decays are studied in an $SU(2)_L \otimes SU(2)_R \otimes U(1)$ gauge theory. It is found that a reported discrepancy between the Cabibbo model and experiment in $\Lambda \to pe\bar{\nu}_e$ can be accounted for if right-handed currents exist. The only obstacle to this interpretation is the experimental sign of the electron asymmetry in $\Sigma \to ne\bar{\nu}_e$ which, as in the Cabibbo model, is predicted to be negative.

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The standard description of semileptonic hyperon decays has been based on the Cabibbo Hamiltonian[1] (extended to include six quarks[2])

$$H = (G/\sqrt{2})[\cos\theta_1(\bar{u}\Gamma_L d) + \sin\theta_1 \cos\theta_3(\bar{u}\Gamma_L s)](\bar{l}\Gamma_L \nu_l), \tag{1}$$

where $\Gamma_L = \gamma_\mu(1-\gamma_5)$, $l = e, \mu$,[3] and θ_1, θ_3 are Kobayashi-Maskawa angles.

The matrix elements of the hadronic currents between spin-$\frac{1}{2}$ baryon states have the form

$$\langle B(p')|\bar{u}\Gamma_L Q|A(p)\rangle = \bar{u}(p')(F_1^{BA}\gamma_\mu + F_2^{BA}\sigma_{\mu\nu}iq^\nu/\Sigma + F_3^{BA}q_\mu/\Sigma - G_1^{BA}\gamma_\mu\gamma_5 - G_2^{BA}\sigma_{\mu\nu}\gamma_5 iq^\nu/\Sigma - G_3^{BA}q_\mu\gamma_5/\Sigma)u(p), \tag{2}$$

where $Q = d$ or s, $q = p' - p$, $\Sigma = M_A + M_B$, and the form factors $F_1^{BA}, \ldots, G_3^{BA}$ are functions of q^2. F_3^{BA} and G_3^{BA} can be ignored since their contribution to the decay amplitudes is small, proportional to m_l/Σ. In the limit of SU(3) symmetry $F_3^{BA} = G_2^{BA} = 0$, F_1^{BA} and F_2^{BA} can be expressed in terms of nucleon electromagnetic form factors, and G_1^{BA} is a linear combination of the SU(3) reduced matrix elements F and D.

Detailed comparison of the theory and experiment revealed the following potential difficulties of this description:

(i) If one negelcts G_2 and uses SU(3)-symmetric values of F_2/F_1, the magnitude of the ratio G_1/F_1 deduced from the experimental values of the spin asymmetry coefficients $\alpha_k^{\Lambda p}$ ($k = e$, $\bar{\nu}_e$, and p) in $\Lambda \to pe\bar{\nu}_e$ is different from the value of $|G_1/F_1|$ obtained from the electron-neutrino (e-ν) correlation coefficient $\alpha_{e\nu}^{\Lambda p}$.[4] The latter value agrees with the prediction of the Cabibbo model.

(ii) The Cabibbo value of G_1/F_1 in the decay $\Sigma^- \to ne\bar{\nu}_e$ is $G_1/F_1 = -0.33$ to -0.40,[5,6] while the experimental result,[7]

$$(\alpha_e^{\Sigma n})_{\rm expt} = 0.35 \pm 0.29, \tag{3}$$

favors a positive sign for G_1/F_1.[8]

(iii) Analysis[6] of recent high-statistics experiments on hyperon decay rates indicates that the $D/(F+D)$ ratios in $\Delta S = 0$ and $\Delta S = 1$ sectors are different, contrary to the pattern of symmetry breaking found in calculations based on both a nonrelativistic quark model and the Massachusetts Institute of Technology bag model.[6,9]

Let us consider the situation in Λ decay in more detail and in the light of presently available data. The experimental values (world averages)[10] $\alpha_e^{\Lambda p} = 0.125 \pm 0.066$, $\alpha_\nu^{\Lambda p} = 0.821 \pm 0.060$, and $\alpha_p^{\Lambda p} = -0.508 \pm 0.065$ imply, respectively,

$$(G_1/F_1)_{q^2=0} = 0.28^{+0.35}_{-0.11}, \tag{4a}$$

$$(G_1/F_1)_{q^2=0} = 0.42^{+0.07}_{-0.06}, \tag{4b}$$

$$(G_1/F_1)_{q^2=0} = 0.33^{+0.11}_{-0.07}. \tag{4c}$$

In obtaining (4) I have neglected G_2, used SU(3)-symmetric values of F_2/F_1, and adopted the usual dipole formulas $F_1(q^2) = F_1(0)(1 - q^2/m_v^2)^{-2}$ and $G_1(q^2) = G_1(0)(1 - q^2/m_a^2)^{-2}$, with $m_v = 0.97$ GeV and $m_a = 1.25$ GeV.[11] The quoted errors correspond to an increase in χ^2 by one unit. Note that $\alpha_k^{\Lambda p}$ are parity-nonconserving observables. Under the same assumptions, the values of $|G_1/F_1|$ derived from parity-conserving observables (the e-ν correlation coefficient, the corresponding integrated quantity $\alpha_{e\nu}^{\Lambda p}$, and the electron and proton energy distributions) are consistent with each other, and have an average value of[12]

$$|G_1/F_1|_{q^2=0} = 0.703 \pm 0.019. \tag{5}$$

In the average value (5) I have included the value obtained from a recent high-statistics study of

$\Lambda \to pe\bar{\nu}_e$,[13]

$$|G_1/F_1|_{q^2=0} = 0.734 \pm 0.031, \quad (6)$$

which takes into account both radiative corrections and the q^2 dependence of the form factors.

The difference between (4) and (5) [or (6)] is significant, because radiative corrections to $\alpha_k^{\Lambda p}$ are negligible (of order 10^{-3}),[14,15] and the sensitivity to the choice of m_v and m_a is small {since the effect of the q^2 dependence on $\alpha_k^{\Lambda p}$ and on the value (5) [or (6)] is only a few percent[13]}. The values (5) and (6) are consistent with $G_1/F_1 = 0.70$ to 0.73, obtained from a standard fit in the Cabibbo model.[5,6]

The question arises whether the difference between the values (4) and (5) [or (6)] could be due to SU(3) breaking. Like García,[4] I performed a four-parameter (G_1/F_1, F_2/F_1, G_2/G_1, and $\sin\theta_1 \cos\theta_3$) fit to Λ-decay data.[16] I find $G_1/F_1 = 0.32 \pm 0.08$, $G_2/G_1 = -11 \pm 4$, $F_2/F_1 = -1 \pm 1$, and $|\sin\theta_1 \cos\theta_3| = 0.268 \pm 0.007$ (with $\chi^2 = 1.4$ for one degree of freedom). These values appear to be too far from the SU(3)-symmetric ones [$G_1/F_1 = 0.70$ to 0.73,[5,6] $F_2/F_1 = 1.79$, $G_2/G_1 = 0$, and $|\sin\theta_1 \cos\theta_3| = 0.219 \pm 0.003$ (Ref. 5)] to be able to attribute them to effects of SU(3) breaking.[17]

I conclude that if the present experimental situation in Λ decay persists, we must seek an explanation for the problem outside of the Cabibbo model, and thus beyond the standard $SU(2)_L \otimes U(1)$ gauge theory[18] of the electroweak interactions. The purpose of this Letter is to consider the semileptonic decays of hyperons in the framework of extended electroweak models, based on the gauge group $SU(2)_L \otimes SU(2)_R \otimes U(1)$.[19] In these theories the charged electroweak interactions contain right-handed (RH) currents, in addition to the usual left-handed (LH) ones.

Neglecting CP-nonconserving phases, W_L-W_R mixing, and mixing in the leptonic sector, the effective Hamiltonians for $\Delta S = 0$ and $\Delta S = 1$ semileptonic processes are given by[20]

$$H_{\Delta S=0} = (g_L^2/8m_L^2)\cos\theta_1^L[(\bar{u}\Gamma_L d)(\bar{l}\Gamma_L \nu_l) + a\lambda(\bar{u}\Gamma_R d)(\bar{l}\Gamma_R \nu_l')], \quad (7)$$

$$H_{\Delta S=1} = (g_L^2/8m_L^2)\sin\theta_1^L\cos\theta_3^L[(\bar{u}\Gamma_L s)(\bar{l}\Gamma_L \nu_l) + b\lambda(\bar{u}\Gamma_R s)(\bar{l}\Gamma_R \nu_l')], \quad (8)$$

where $\lambda = g_R^2 m_L^2/g_L^2 m_R^2$, $a = \cos\theta_1^R/\cos\theta_1^L$, and $b = \sin\theta_1^R\cos\theta_3^R/\sin\theta_1^L\cos_3^L$. $g_{L,R}$ are the coupling constants associated with the subgroups $SU(2)_{L,R}$, $m_{L,R}$ are the masses of the corresponding charged gauge bosons, and $\theta_{1,3}^L, \theta_{1,3}^R$ are mixing angles in the Kobayashi-Maskawa matrices for the LH and RH sectors. The RH neutrino will be assumed to be sufficiently light to participate in the decay. If the neutrinos are Dirac particles, $\nu_l = \nu_l'$. The Cabibbo Hamiltonian (1) is a special case of (7) and (8), corresponding to $a\lambda = b\lambda = 0$.

Beall, Bander, and Soni[21] find that for equal LH and RH angles and $g_L = g_R$, the experimental value of the mass difference Δm_K between K_L and K_S imposes the bound $\lambda \equiv m_L^2/m_R^2 = 3 \times 10^{-3}$. As a consequence, the effects of RH currents in all leptonic and semileptonic decays are expected to be in this case negligible. However, as noted in Ref. 20, for unequal LH and RH angles Δm_K does not rule out large effects in leptonic and semileptonic processes, since the constraint from Δm_K takes the form

$$|ab|\lambda \leq 3 \times 10^{-3}. \quad (9)$$

Let us consider the decay $\Lambda \to pe\bar{\nu}_e$ using the interaction (8). For parity-conserving observables the contribution of RH currents affects only the overall coupling constant

$$(g_L^2/8m_L^2)\sin\theta_1^L\cos\theta_3^L \to (g_L^2/8m_L^2)\sin\theta_1^L\cos\theta_3^L(1+b^2\lambda^2)^{1/2},$$

so that $|G_1/F_1|$ derived from parity-conserving observables retains its value given by (5) [or (6)]. Parity-nonconserving observables, however, change as

$$(\alpha_k^{\Lambda p})_{V-A} \to [(1-b^2\lambda^2)/(1+b^2\lambda^2)](\alpha_k^{\Lambda p})_{V-A}. \quad (10)$$

If we use $(\alpha_k^{\Lambda p})_{V-A}$ calculated with the value (5) [or (6)] and the Cabibbo-favored positive sign, and take the same q^2 dependence for the form factors as used in (4), the experimental results for $\alpha_k^{\Lambda p}$ imply for the quantity $n = (1-b^2\lambda^2)/(1+b^2\lambda^2)$

$$n = 5.5 \pm 3.7 \quad (16 \pm 32), \quad (11a)$$

$$n = 0.844 \pm 0.062 \quad (0.838 \pm 0.061), \quad (11b)$$

$$n = 0.86 \pm 0.11 \quad (0.87 \pm 0.11), \quad (11c)$$

for $k = e$, $\bar{\nu}_e$, and p, respectively. The values in parentheses are obtained if (6) rather than (5) is used. A fit by (11a)–(11c) yields

$$|b|\lambda = 0.284 \pm 0.055, \quad (12a)$$

$\chi_{min}^2 = 1.6$ for two degrees of freedom,

$$|b|\lambda = 0.289 \pm 0.054, \quad (12b)$$

$\chi_{min}^2 = 0.3$ for two degrees of freedom, for G_1/F_1 given by (5) and (6), respectively. (If we allow for two standard deviations from the central value in the data, the values are $|b|\lambda = 0.28 \pm 0.11$ and 0.29 ± 0.11, respectively.) Inclusion of SU(3)-breaking effects, using the results of Ref. 9, changes the values of $|b|\lambda$ in (12) by less than 2%.[22] Hence I conclude that present data on $\Lambda \to pe\bar{\nu}_e$ decay indicate the presence of RH currents.

Turning to the problem in $\Sigma^- \to ne\bar{\nu}_e$, I have fitted the form-factor ratios G_1/F_1, G_2/G_1, and F_2/F_1 to the experimental data,[7,8,11,23] assuming $b\lambda = 0$. The solutions deviate significantly from the values obtained from the SU(3)-symmetric Cabibbo model.[24] Considering Σ^- decay with the Hamiltonian (8) and using for $|b|\lambda$ the value (12a) [or (12b)] deduced from Λ decay, I predict for $\alpha_e^{\Sigma n}$

$$\alpha_e^{\Sigma n} = -0.58^{+0.10}_{-0.08}. \quad (13)$$

While the magnitude of (13) is consistent with the experimental result (3), the signs of (13) and (3) are opposite.[25] It should be noted that new data[26] seem to indicate a negative sign for $\alpha_e^{\Sigma n}$, consistent with the presence of RH currents.

A further test of the presence of RH currents in the $\Delta S = 1$ sectors could be obtained by precise measurements of the muon polarization in $K \to \mu\nu_\mu$. If we neglect radiative corrections, which are expected to be small, the muon longitudinal polarization $P_{K\mu}$ in the rest frome of K is given (neglecting neutrino mass) by

$$P_{K\mu} = -(1 - b^2\lambda^2)/(1 + b^2\lambda^2). \quad (14)$$

Substituting either of the values (12a) or (12b) for $|b|\lambda$, I predict

$$P_{K\mu} = -0.85 \pm 0.06. \quad (15)$$

[The result allowing for two standard deviations in $(\alpha_k^{\Lambda p})_{expt}$ is $P_{K\mu} = -0.85 \pm 0.11$.] The present average experimental value is[27]

$$(P_{K\mu})_{expt} = -0.97 \pm 0.07. \quad (16)$$

Finally I note that the inclusion of the $b\lambda$ term does not alter the situation regarding the hyperon decay rates [described above under (iii)]: The $b\lambda$ term changes only the overall coupling constant; the ratio $D/(F + D)$ remains unchanged. Further work on SU(3) breaking may shed light on this problem.

An immediate consequence of the nonzero value of $|b|\lambda$ is that RH-current effects must be present in leptonic reactions, particularly in the standard decay of the muon. For muon decay, the magnitude of the effects at low energies is characterized by $2\lambda^2$.

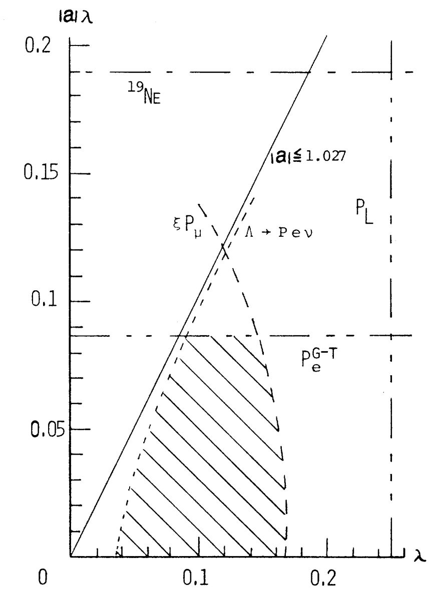

FIG. 1. Allowed region (hatched region) for λ and $|a|\lambda$ (two-standard-deviation limits). The limits are obtained from the asymmetry parameter in ^{19}Ne β decay (^{19}Ne), the electron polarization in Gamow-Teller β decay (P_e^{G-T}), the product (ξP_μ) of the polarization parameter ξ describing muon decay and the polarization P_μ of a μ^+ from π^+ decay at rest (see Ref. 28 for more details), and the positron longitudinal polarization (P_L) in muon decay (Ref. 29). The constraint from $\Lambda \to pe\bar{\nu}_e$ decays is also shown. Here we use $|\cos\theta_1^L| = 0.974$ and $|\sin\theta_1^L \cos\theta_3^L| = 0.219$ (Ref. 5) (since the effects of RH currents on these angles are small, about 1% for $\cos\theta_1^L$ and 5% for $\sin\theta_1^L \cos\theta_3^L$, if $|b|\lambda = 0.29$ and $\lambda = 0.1$ are taken).

Since $|b| \leq 4.57$, the values in (12) imply that these effects should be of the order of 3×10^{-3} or larger. Figure 1 shows the present experimental constraints on the parameters λ and $|a|\lambda$ (two-standard-deviation limits) from the data on μ decay and $\Delta S = 0,1$ semileptonic decays.[28,29] The constraint (9) obtained from the K_L-K_S mass difference (not shown in Fig. 1) suggests that RH-current effects in $\Delta S = 0$ semileptonic processes, governed by $2a^2\lambda^2$, should be of the order of 2×10^{-5} or less, and thus too small to be observable.

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ries from the $\Delta S=1$ semileptonic sector, and for the numerous helpful discussions and suggestions.

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