The Current × Current Hypothesis and the $\Delta S = \Delta Q$ Rule

Except for the admittedly still undigested matter of *CP* violation in neutral *K*-meson decay, the overall structure of the weak interactions has given the appearance for some time now of being very coherent and tight. The lepton pairs (e, ν_e) and (μ, ν_μ) couple to each other (μ-meson decay) in current × current form; and they couple separately to the hadrons, in identical ways so far as we know, again in vector–axial-vector form: hadron current × lepton current. Classified with respect to the symmetries of the strong interactions, the vector and axial-vector hadron currents each decompose in good approximation into very simple pieces: a strangeness-conserving piece, which transforms like the charged component of a pure isovector; and a strangeness-changing piece ($|\Delta S| = 1$) which transforms like the charged ($|\Delta Q| = 1$) component of a pure isodoublet, with $\Delta S = +\Delta Q$. The vector strangeness-conserving current, moreover, is simply related to the isovector part of the ordinary electromagnetic current (CVC hypothesis); and, finally, the diverse pieces of the hadronic weak currents are all tied to one another through the connections provided by Gell-Mann's algebra of equal-time current commutators.

This disposes of the purely leptonic and semileptonic interactions!

For the nonleptonic, strangeness-changing weak interactions, where strangeness changes by one unit only, the picture is rounded out economically on the model which couples *together* the $\Delta S = 0$ and $\Delta S = 1$ hadronic currents already invoked for the semileptonic reactions. So no new elements are needed here.

Still more comprehensive is the master current × current picture of Feynman and Gell-Mann,[1] in which a single master current, composed of a lepton part $[(e, \nu_e) + (\mu, \nu_\mu)]$ and a hadron part, interacts with itself. This picture does more than merely codify the initial input, for it entails the existence of such purely leptonic processes as $e + \nu_e \rightarrow e + \nu_e$ and $\mu + \nu_\mu \rightarrow \mu + \nu_\mu$, with structure similar to that for μ-meson decay; and it leads qualitatively to the expectation of parity violation in strangeness-*preserving* nonleptonic reactions, with strength comparable to that for the usual strangeness-changing reactions. Direct evidence bearing on the reaction $e+\nu_e \rightarrow e+\nu_e$ cannot be anticipated for the near future. But weak parity violation in nuclear processes has recently been reported. The situation has been summarized in this journal in the admirable article by L. B. Okun.[2]

The occurrence of nonleptonic $\Delta S=1$ and $\Delta S=0$ (parity violating) reactions is naturally incorporated in the master current × current picture; but in itself this is not what is distinctive about the model. What is distinctive, rather, is that the nonleptonic couplings are supposed to be built up out of the very same hadronic currents that arise in connection with the semileptonic weak interactions, i.e., it is this feature of theoretical *economy* that is special. No theoretical way has yet been found, however, to decisively test this special structure of the nonleptonic interactions; that is, to distinguish the current × current structure from alternative forms of interaction that can freely be invented. Partial tests are provided by the application of current algebra ideas to nonleptonic $\Delta S=1$ reactions, where one employs the commutation relations suggested by the current × current structure.[3] There has been some success here, but the situation is still murky and the theoretical challenge remains.

It is one thing to decisively confirm a theoretical picture, and another to make troubles for it. A standard and familiar difficulty for the current × current model is that it fails to account, in a natural way, for the $\Delta I=\frac{1}{2}$ rule that appears in excellent approximation to describe the strangeness-changing nonleptonic reactions. According to the rule, the effective nonleptonic interaction Hamiltonian transforms like the neutral component of an isotopic doublet. But in a picture in which this interaction is built up as a product of the charged semileptonic currents $(\Delta I=1,\ \Delta S=0)\times(\Delta I=\frac{1}{2},\ \Delta S=1)$ one expects to find in addition to $\Delta I=\frac{1}{2}$ also a $\Delta I=\frac{3}{2}$ piece. Again, current algebra ideas have gone part way to explaining the effective simulation of $\Delta I=\frac{1}{2}$, but only part way.[3] The empirical rule would appear to hold too well and too widely to rest on such a partial and only approximate foundation.[4] The introduction of products of neutral currents could be arranged to provide a firm basis for the $\Delta I=\frac{1}{2}$ rule, but there is no evidence for weak lepton coupling to neutral hadronic currents and the elegance of the current × current picture would thereby be lost.

There is, potentially, another difficulty looming on the horizon, one which is of the greatest interest in its own right. In our cozy introduction, it was implied that the semileptonic currents are well understood and about as simple in quantum-number structure as can be; in particular, it was implied that the strangeness-changing leptonic currents obey the rule $\Delta S=+\Delta Q$. At a phenomenological level, nothing disastrous would befall if $\Delta S = -\Delta Q$ pieces were also to be found (for these one would of course have $|\Delta I| = \frac{3}{2}$). But such pieces would find no ready home in the algebra-of-currents workshop; and they would also make trouble for the master current × current picture of the weak, non-leptonic interactions: the product of $(\Delta S = +\Delta Q)$ and $(\Delta S = -\Delta Q)$ currents would lead to a net interaction with $\Delta S = 2$ not observed!

On the more affirmative side, however, if $\Delta S = -\Delta Q$ semileptonic interactions were to be confirmed, then in view of their awkwardness with respect to other aspects of the weak interactions, one might be tempted to link them with that other awkward phenomenon, *CP* violation.[5]

Evidence for the existence of $\Delta S = -\Delta Q$ semileptonic interactions would be provided by the discovery of such processes as $\Sigma^+ \to l^+ + n + \nu$ ($l = \mu$ or e) or $K^+ \to 2\pi^+ + l^- + \nu$. A very small number of isolated $\Sigma^+ \to l^+ + n + \nu$ events have been reported over the years, but in view of alternative, though improbable, experimental interpretations, their significance is still debatable. No $K^+ \to 2\pi^+ + l^- + \nu$ events have been reported. The $\Delta S = +\Delta Q$ analogues, $\Sigma^- \to l^- + n + \nu$, $K^+ \to \pi^+ + \pi^- + l^+ + \nu$ are on the other hand seen in abundance. The ratio of $\Delta S = -\Delta Q$ and $\Delta S = +\Delta Q$ amplitudes in each case is bounded by a fairly small number, of order 10–15 percent. One also looks for evidence of $\Delta S = -\Delta Q$ couplings in neutral K_{l_3} processes, $K^0 \to l^+ + \pi^- + \nu$, $\overline{K^0} \to l^- + \pi^+ + \nu$, corresponding to $\Delta S = +\Delta Q$; $K^0 \to l^- + \pi^+ + \nu$, $\overline{K^0} \to l^+ + \pi^- + \nu$, corresponding to $\Delta S = -\Delta Q$. Owing to the well-known coherence properties of neutral *K*-meson decay, there is the possibility here of detecting the two kinds of processes in interference, so that the relative amplitude x for $\Delta S = -\Delta Q$ and $\Delta S = +\Delta Q$ analogues is experimentally accessible. This is especially welcome, since the phase φ of this amplitude ratio bears on *CP* invariance, this invariance principle requiring that $\sin\varphi = 0$ (apart from electromagnetic effects, presumably small).

The earliest experiments on the subject indicated a very large value for the magnitude $|x|$. The claim was reduced in subsequent studies. But a nonvanishing effect appears to persist in recent measurements,[6] accompanied by a nonvanishing value for $\sin\varphi$. The latest measurement[7] gives the results

$$|x| \cos\varphi = 0.17 \pm 0.10, \qquad |x| \sin\varphi = 0.20 \pm 0.10,$$

corresponding to $\varphi = 50^{\circ}{}^{+25^{\circ}}_{-27^{\circ}}$. Like other "two or three standard deviation" phenomena in the past, the effects here may eventually go away. If they don't—and new experiments are under way—we will be in for some real excitement.

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