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Implications of second-class currents for neutral weak currents and gauge models*

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Exploiting the Hermiticity of hadronic neutral weak currents, we investigate implications of second-class charged currents for hadronic neutral weak currents. The main result is that if second-class charged currents exist, the isospin $I = 1$ axial-vector neutral current must be a "new" current, or it must contain a "new" $I = 1$ piece. Another result is that if the $I = 1$ axial-vector neutral current is "old" (that is, it is proportional to the third component of the charged current), then the proportionality constant is real. In this case second-class charged currents are excluded. *CP* invariance is assumed throughout the discussion.

I. INTRODUCTION

The evidence for neutral weak current reactions, which have been discovered at Gargamelle[1] and NAL,[2] has further stimulated interest in neutral currents. The first interesting question to be faced, once neutral-current effects are at all established, will have to do with the spatial (V, A) and isotopic structure of the hadronic neutral currents J_μ^Z.

In a recent paper Pais and Treiman[3] raised the question (among other questions), whether J^Z (we omit the Lorentz index) contains "new" currents. Restricting ourselves to $I = 1$ (isospin) and 0 currents we can express the general form of J^Z as

$$J^Z = V^{Z0} + A^{Z0} + V^{Z3} + A^{Z3}, \tag{1}$$

where V^{Z0} (V^{Z3}) is an $I = 0$ ($I = 1$) neutral vector current and A^{Z0} (A^{Z3}) is an $I = 0$ ($I = 1$) neutral axial-vector current. Then the question above can be stated as follows: Are V^{Z0}, V^{Z3}, A^{Z0}, and A^{Z3} related to charged currents (via isospin rotation), or are they members of different isomultiplets (new currents)?

If V^{Z0} and A^{Z0} exist, they are surely new currents, because charged currents have no $I = 0$ pieces. As for V^{Z3} and A^{Z3} the situation is not so simple, although all published gauge models (among those which feature neutral currents at all) imply that V^3 and A^3 are not new currents, that is, they are proportional to the third component of the charged currents (or $A^{Z3} = 0$).

In the following we restrict ourselves to A^{Z3} and will use the concept of first- and second-class charged current to decide (experimentally) whether A^{Z3} is "new" or not.

The only input for A^{Z3} in our discussion is its Hermiticity.

Throughout our discussion we assume *CP* invariance of weak interactions (at least of semileptonic reactions).

II. NOTATION

Let

$$J_+ = V_+ - A_+, \tag{2}$$

where V_+ (A_+) is charged $I = 1$, $I_3 = 1$ vector (axial-vector) current. Denoting by T^+, T^3, T^- the infinitesimal generators of the isospin group, we define

$$\begin{aligned} A_3 &\equiv -\tfrac{1}{2}[T^-, A_+], \\ A_- &\equiv [T^-, A_3]. \end{aligned} \tag{3}$$

Thus, A_+, A_3, A_- belong to an isotriplet. We denote the Hermitian conjugate of J_+ by $(J_+)^{\mathrm{Hc}}$ and define

$$\begin{aligned} J'_- &\equiv (J_+)^{\mathrm{Hc}}, \\ A'_- &\equiv (A_+)^{\mathrm{Hc}}, \\ A'_3 &\equiv -\tfrac{1}{2}[T^+, A'_-], \\ A'_+ &\equiv -[T^+, A'_3], \end{aligned} \tag{4}$$

where A'_+, A'_3, and A'_- belong to an isotriplet.

As long as we do not assume $A_3 = A'_3$, the two triplets (A_+, A_3, A_-) and (A'_+, A'_3, A'_-) are not the same. But the following relation holds:

$$(A_3)^{\mathrm{Hc}} = A'_3. \tag{5}$$

III. SECOND-CLASS CURRENTS

The classification of hadronic strangeness-conserving but charge-changing weak currents into first- and second-class was introduced by Weinberg[4] using G parity:

$$\left.\begin{aligned} G^{-1}VG &= +V \\ G^{-1}AG &= -A \end{aligned}\right\} \text{first-class current}, \tag{6}$$

$$\left.\begin{aligned} G^{-1}VG &= -V \\ G^{-1}AG &= +A \end{aligned}\right\} \text{second-class current}. \tag{7}$$

V (A) is the vector (axial-vector) current. With CP invariance the following definition[5] is equivalent to that of (6) and (7):

$$J'_- \equiv J_+^{\mathrm{Hc}} = -\tfrac{1}{2}[T^-,[T^-,J_+]]\,, \quad \text{first class} \tag{8}$$

$$J'_- \equiv J_+^{\mathrm{Hc}} = \tfrac{1}{2}[T^-,[T^-,J_+]]\,, \quad \text{second class.} \tag{9}$$

It is easily seen from (8) and (9) that if $J_3 = -\frac{1}{2}[T^-,J_+]$ is Hermitian (anti-Hermitian), then J_+ is a first- (second-) class current. This classification was introduced by Hertel[6]:

$$J_3^{\mathrm{Hc}} = +J_3, \quad \text{first-class current} \tag{10}$$

$$J_3^{\mathrm{Hc}} = -J_3, \quad \text{second-class current.} \tag{11}$$

For our discussion we will use the definition (10) and (11).

IV. IMPLICATION OF SECOND-CLASS CHARGED CURRENTS FOR NEUTRAL CURRENTS

The question, whether second-class charged currents exist or not, is still open. (In the following we omit the word "charged" in "second-class charged current," if there is no danger of confusion with second-class neutral currents which many gauge models imply.[7]) What, however, will be the implication for J_μ^Z, if A_+ (or A'_-) contains second-class components? The answer is obvious:

If A_+ contains second-class components, then A^{Z3} of Eq. (1) cannot be the third component of A_+.

$$A^{Z3}\ \textit{is a new current.} \tag{12}$$

Due to (11) A_3 has a non-Hermitian component, whereas A^{Z3} is Hermitian. So the conclusion (12) follows.

This conclusion (12) does not correspond to any of the published gauge models. Here the question arises, whether gauge models can be constructed which do contain new isovector currents and which do meet the usual requirements, including the constraint imposed by the $\pi^0 \to 2\gamma$ rate. The answer is affirmative as pointed out in Ref. 3. Maybe the main part of A^{Z3} is "old" and the "new" piece is just a small correction.

V. $A^{Z3} = CA^3$

If A^{Z3} is proportional to A^3, what can we say about the proportionality factor C, and what consequence does it imply for second-class charged currents?

First, we show that C must be real. Because of the Hermiticity of A^{Z3} it is clear that C must be either real or imaginary. In order to see that C cannot be imaginary, let us consider the reactions

$$\nu + n \to l^- + p\,, \tag{13}$$

$$\nu + n \to \nu + n\,. \tag{14}$$

The matrix element of A^+ for the reaction (13) is

$$\langle p|A_\mu^+|n\rangle = N\,\bar{u}(p')(g_A\gamma_\mu + ig_T\sigma_{\mu\nu}q_\nu + if_A q_\mu)\gamma_5 u(p)\,, \tag{15}$$

and the matrix element of A^{Z3} for the reaction (14) is

$$\langle n|A_\mu^{Z3}|n\rangle = N'\bar{u}(p')(g_A^Z\gamma_\mu + ig_T^Z\sigma_{\mu\nu}q_\nu + if_A^Z q_\mu)\gamma_5 u(p)\,, \tag{16}$$

where N, N' are normalization factors.

Due to $A^{Z3} = CA^3$ the following relations hold:

$$\begin{aligned} g_A^Z &= \tfrac{1}{2}Cg_A\,,\\ g_T^Z &= \tfrac{1}{2}Cg_T\,,\\ f_A^Z &= \tfrac{1}{2}Cf_A\,. \end{aligned} \tag{17}$$

Now we assume that C is imaginary. Then A^3 is anti-Hermitian. According to (11) A^+ is a second-class current. Therefore g_A and f_A vanish. On the other hand, g_T^Z vanishes because of the Hermiticity of A^{Z3} (and CP invariance). Thus all form factors of (17) vanish. This surely contradicts experimental results.

The conclusion is that

$$C\ \textit{must be real.} \tag{18}$$

It is obvious that in this case A_+ is a first-class current. Note that this conclusion (18) is a general one, assuming only the Hermiticity of the neutral current. So any model which implies that A^{Z3} is proportional to A^3 must satisfy (18).

Now let us look at some gauge models. One can represent the neutral hadronic currents of most of the published gauge models as follows:

$$J^Z = \rho(V_3 + V_0) + \lambda(V_3 - A_3)\,, \tag{19}$$

$$J^Z = \rho' V_3 + \lambda'(V_3 - A_3) + V^{Z0} + A^{Z0}\,. \tag{20}$$

V_3 is the $I = 1$ part and V_0 is the $I = 0$ part of the hadronic electromagnetic current, and ρ, ρ', λ, λ' are real constants.

The Weinberg model[8] and the model of Bég and Zee[9] belong to the type of Eq. (19), whereas the model of Glashow, Iliopoulos, and Maiani,[10] one version of the three-triplet model,[11] and the $O(4) \times U(1)$ spinor model[12] belong to the type of Eq. (20).

We see that all these models contain no new $I = 1$ neutral currents; they are proportional to the third component of the charged currents, and the proportionality factor is real as the conclusion (18) implies. An obvious consequence is that these gauge models exclude second-class charged currents.

VI. SUMMARY

We have discussed the implication of second-class charged currents for hadronic neutral axial-vector currents. We found that if second-class charged currents exist, then the neutral axial-vector currents must contain "new" $I=1$ current.

Another result of our discussion is that if the neutral current is "old," that is, if it is proportional to the third component of the charged currents, then the proportionality constant must be real. In this case the second-class charged currents are excluded. This (second) result corresponds to most of the published gauge models.

Summarizing, we should like to stress that experimental tests for second-class charged currents will be very important also for gauge theories. With high-energy neutrino beams available now at NAL and Gargamelle, there are several experimental possibilities for testing second-class currents. We refer the reader to Ref. 13. Of particular interest is neutrino- and antineutrino-induced production of 3-3 resonance Δ production on proton and neutron.[14] Here the lepton mass may be neglected with impunity, in contrast to the quasielastic scattering of neutrinos by nucleons, where in the limit of vanishing lepton mass all first-class-current–second-class-current interference effects vanish from the differential cross section unless one measures the polarization of the recoil nucleon.

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