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NON-DIAGONAL NEUTRAL CURRENTS AND THE SCATTERING OF
NEUTRINOS AND ANTINEUTRINOS BY ELECTRONS

G.V. Dass *)
CERN - Geneva
and
Rutherford Laboratory, Chilton

A B S T R A C T

Non-diagonal currents arise if the initial and final neutrinos in neutral current interactions are not identical. Implications of non-diagonal neutral currents for the scattering of neutrinos and antineutrinos by electrons are considered within a general vector and axial vector description. Several observable relations can test for the presence of the non-diagonal pieces.

*) On attachment from (and address after 15 May 1975) the Rutherford Laboratory, Chilton, Didcot, Oxon, OX11 0QX, England.

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Within a description with vector (V) and axial vector (A) currents, non-diagonal neutral currents have been introduced ¹⁾ to account for the possibility that the final neutrino in neutral current interactions may not be the same as the initial one. This allows antihermitian currents which are the neutral current analogues of second class charged currents. For hadronic processes, it has been pointed out ¹⁾ that if the initial and final neutrinos be not identical, one can simulate with V, A currents some effects which would otherwise require scalar (S), pseudoscalar (P) or tensor (T) currents. This simulation uses antihermitian currents which are as natural as the corresponding hermitian pieces, once one introduces non-diagonality; the hermitian (antihermitian) currents are symmetric (anti-symmetric) under interchange of the two neutrinos.

Since the $\bar{\nu}_\mu e^-$ interaction has been observed ²⁾, it is interesting to consider whether non-diagonal neutral currents can be detected in the scattering of neutrinos and antineutrinos by electrons. To this end, we restrict to (V,A) non-derivative currents and assume the additive lepton conservation laws, as in Refs. 1), 3), 4). We also consider the consequences of μe universality.

Some of our relations can clearly test for the presence of hermitian [e.g., Eqs. (12), (20) below] and antihermitian (e.g., the new observable correlations, below) non-diagonal neutral currents. Some of our tests are useful for both low and high energy experiments, e.g., (10) to (12) expressed in terms of the observable coefficients A_i, B_i . Other tests [(17) to (21)] are useful for only low energy experiments. Some of the relations between observables are shown to be insensitive to the presence of non-diagonal neutral currents, and provide interesting generalisations of the existing ^{3),4)} relations derived by retaining only diagonal neutral currents. We have considered non-diagonal neutral currents generated by an arbitrary number n of neutrinos ν_i^n different from the incident ones which are taken to arise from charged current interactions.

A neutrino identity test relating different coefficients in the electron recoil energy spectrum, but crucially involving terms of order (m/E_ν) where m is the electron mass and E_ν the laboratory neutrino energy has been proposed ⁵⁾ for $\bar{\nu}_e e^-$ scattering at very low energies for the case when only one extra neutrino is present. Our corresponding results

are included in relations (17) to (19) below. Some new low energy tests for non-diagonal currents are also considered in (20) and (21) ; these help to make the ones in (17) to (19) definitive. All the tests are generalized to an arbitrary number of extra neutrinos ν^n .

For this leptonic system, antihermitian currents imply time-reversal non-invariant ^{*}) couplings. The new observable introduced by these couplings is hard to detect experimentally ; it involves time-reversal and parity-non-invariant correlations like $\vec{p} \cdot (\vec{s}_1 \times \vec{s}_2)$ where $\vec{p}$ is the initial or final electron momentum and $\vec{s}_{1,2}$ are the transverse polarisations of the two electrons. However, the presence of (hermitian) non-diagonal currents can be detected even in high energy integrated cross sections, Eq. (12) below. We keep interactions general, and do not assume time-reversal invariance ; we point out where the antihermitian currents appear crucially [e.g., (17) to (19) below] ; see also remark 1 at the end.

The effective Lagrangian (with or ⁴) without intermediate bosons) is

$$\begin{aligned} \mathcal{L} = & -\frac{G}{\sqrt{2}} \left[\bar{\nu}_e \gamma_\alpha (1-\gamma_5) e \cdot \bar{e} \gamma^\alpha (1-\gamma_5) \nu_e + \right. \\ & + \bar{\nu}_e \gamma_\alpha (1-\gamma_5) \nu_e \cdot \bar{e} \gamma^\alpha (d_V - d_A \gamma_5) e + \sum_n \left\{ \bar{\nu}_e'^n \gamma_\alpha (1-\gamma_5) \nu_e \cdot \right. \\ & \cdot \bar{e} \gamma^\alpha (D_V^n - D_A^n \gamma_5) e + \bar{\nu}_e \gamma_\alpha (1-\gamma_5) \nu_e'^n \cdot \bar{e} \gamma^\alpha (D_V^{n*} - D_A^{n*} \gamma_5) e \left. \right\} + \\ & + \bar{\nu}_\mu \gamma_\alpha (1-\gamma_5) \nu_\mu \cdot \bar{e} \gamma^\alpha (z_V - z_A \gamma_5) e + \sum_n \left\{ \bar{\nu}_\mu'^n \gamma_\alpha (1-\gamma_5) \nu_\mu \cdot \right. \\ & \cdot \bar{e} \gamma^\alpha (Z_V^n - Z_A^n \gamma_5) e + \bar{\nu}_\mu \gamma_\alpha (1-\gamma_5) \nu_\mu'^n \cdot \bar{e} \gamma^\alpha (Z_V^{n*} - Z_A^{n*} \gamma_5) e \left. \right\} \left. \right] \end{aligned} \quad (1)$$

where the first term is the conventional charged current (obtained by applying μe universality to μ decay) with Fermi constant G , the terms with couplings $d_{V,A}$ and $z_{V,A}$ are the conventional (diagonal) neutral currents,

^{*}) At present, the space-time structure of neutral currents is not established, nor does one know the relative strength of the diagonal and non-diagonal pieces. It seems, therefore, as natural to allow time-reversal non-invariance as it is to allow parity violation for non-diagonal neutral currents.

the non-diagonal terms in curly brackets arise for interactions of the neutrino field $\nu_{e,\mu}^{'n}$ different from $\nu_{e,\mu}$; the superscripts n refer to the n^{th} neutrino field $\nu^{'n}$. Equivalently,

$$\begin{aligned} \mathcal{L} = & -\frac{G}{\sqrt{2}} \left[\bar{\nu}_e \gamma_\alpha (1-\gamma_5) \nu_e \cdot \bar{e} \gamma^\alpha (d'_V - d'_A \gamma_5) e + \right. \\ & + \bar{\nu}_\mu \gamma_\alpha (1-\gamma_5) \nu_\mu \cdot \bar{e} \gamma^\alpha (z_V - z_A \gamma_5) e + \sum_n \left\{ [\bar{\nu}_e^{'n} \gamma_\alpha (1-\gamma_5) \nu_e + \right. \\ & + \bar{\nu}_e \gamma_\alpha (1-\gamma_5) \nu_e^{'n}] \cdot \bar{e} \gamma^\alpha (g_V^n - g_A^n \gamma_5) e + [\bar{\nu}_e^{'n} \gamma_\alpha (1-\gamma_5) \nu_e - \\ & - \bar{\nu}_e \gamma_\alpha (1-\gamma_5) \nu_e^{'n}] \cdot i \bar{e} \gamma^\alpha (f_V^n - f_A^n \gamma_5) e \left. \right\} + \\ & + \sum_n \left\{ [\bar{\nu}_\mu^{'n} \gamma_\alpha (1-\gamma_5) \nu_\mu + \bar{\nu}_\mu \gamma_\alpha (1-\gamma_5) \nu_\mu^{'n}] \cdot \bar{e} \gamma^\alpha (G_V^n - G_A^n \gamma_5) e + \right. \\ & + [\bar{\nu}_\mu^{'n} \gamma_\alpha (1-\gamma_5) \nu_\mu - \bar{\nu}_\mu \gamma_\alpha (1-\gamma_5) \nu_\mu^{'n}] \cdot i \bar{e} \gamma^\alpha (F_V^n - F_A^n \gamma_5) e \left. \right\} \end{aligned} \quad (2)$$

where

$$D_{V,A}^n = g_{V,A}^n + i f_{V,A}^n; \quad Z_{V,A}^n = G_{V,A}^n + i F_{V,A}^n; \quad d'_{V,A} = 1 + d_{V,A};$$

the coupling constants $g_{V,A}^n, f_{V,A}^n, G_{V,A}^n, F_{V,A}^n, d_{V,A}, z_{V,A}$ are all real: a Fierz transformation has been applied to the charged current term of Eq. (1). Time-reversal non-invariant terms (with couplings $f_{V,A}^n, F_{V,A}^n$) are a characteristic of the new non-diagonal contributions because both the combinations $[\nu^{'n} \gamma_\alpha (1-\gamma_5) \nu \pm \bar{\nu} \gamma_\alpha (1-\gamma_5) \nu^{'n}]$ are equally natural to retain. The unknown relative phase of the ν_e and $\nu_e^{'n}$ states may be exploited to "transform away" the non-zero phase of D_V^n (or equivalently D_A^n), but $\text{Im}(D_V^{n*} D_A^n)$ cannot be so eliminated; similarly, $\text{Im}(Z_V^{n*} Z_A^n)$ is a characteristic prediction. These produce the above-mentioned corrections like $\vec{p} \cdot (\vec{s}_1 \times \vec{s}_2)$. In general, the couplings $d_{V,A}$ (and $z_{V,A}$) of the diagonal currents need not be related to the couplings $g_{V,A}^n$ (and $G_{V,A}^n$) of the hermitian non-diagonal currents; these two types of currents may be dynamically different simply because the neutrinos $\nu^{'n}$ differ from ν .

Neglecting ^{*)} terms proportional to m , the centre-of-mass differential cross-section is

$$\frac{d\sigma_i}{d\cos\theta} = \frac{\sigma_0}{2} \left[A_i + \left(\frac{1+\cos\theta}{2} \right)^2 B_i \right], \quad \sigma_0 = \frac{G^2}{4\pi} (\text{Total C.M. Energy})^2 \quad (3)$$

where θ is the angle between the two electrons; the subscripts $i=1,2,3,4$ refer to the four reactions $\nu_e e^- \rightarrow f_e e^-$, $\bar{\nu}_e e^- \rightarrow \bar{f}_e e^-$, $\nu_e e^- \rightarrow f_{\mu} e^-$, $\bar{\nu}_e e^- \rightarrow \bar{f}_{\mu} e^-$ respectively, the symbols $f_{e,\mu}$ represent the final neutrino (see next paragraph); also,

$$A_i, B_i \geq 0. \quad (3')$$

The corresponding integrated cross-sections are

$$\sigma_i = \sigma_0 \left(A_i + \frac{1}{3} B_i \right); \quad (4)$$

we henceforth drop the unit σ_0 in which σ_i are measured.

Assuming the charged current contribution to be always present for $i=(1,2)$, we shall consider all the three possible hypotheses for the neutral current contributions $f_{e,\mu}^0$ to $f_{e,\mu}$ (of course, $f_{\mu}^0 \equiv f_{\mu}$):

- a) $f_{e,\mu}^0$ are mixtures of the incident neutrinos $\nu_{e,\mu}$ and the new neutrinos $\nu_{e,\mu}^{in}$ [i.e., both diagonal and non-diagonal neutral currents are present; all couplings in (1) are non-vanishing];
- b) $f_{e,\mu}^0$ are purely the new neutrinos $\nu_{e,\mu}^{in}$ [i.e., diagonal neutral currents are absent; $d_{V,A} = z_{V,A} = 0$; other couplings in (1) are non-vanishing]; and
- c) $f_{e,\mu}^0$ are purely the incident neutrinos $\nu_{e,\mu}$ [i.e., non-diagonal neutral currents are absent; $D_{V,A}^n = Z_{V,A}^n = 0$; other couplings in (1) are non-vanishing].

^{*)} The case when these terms are not neglected is considered in (15). It is only the relations between the cross-sections and A_i, B_i that are subject to electron mass corrections. The expressions for the various coefficients given in the Tables, and all our relations involving only the coefficients A_i and/or B_i and/or C_i [of (15)] are exact. See also remark 7 at end.

Apart from the stated restrictions, the couplings are assumed to be general. Hypothesis c) has been dealt with already ⁴⁾, apart from our new results (20) and (21). We include it here for comparison with the other two hypotheses. Distinguishing c) from a) and b) is needed to indicate the presence of non-diagonal currents ; hence one must study all the three hypotheses. The three together give information on the comparison between diagonal and non-diagonal neutral currents. Some results will turn out to hold for all the three hypotheses, and thus provide generalisations of the results of hypothesis c). Some results can distinguish the three hypotheses clearly ; others not so clearly. We turn to these results now.

For all the three hypotheses, the form ^{*)} (3) holds, and we also have the consequences

$$B_1 = A_2, \quad B_2 = A_1, \quad B_3 = A_4, \quad B_4 = A_3 ; \quad (5)$$

and

$$\frac{1}{3} \leq u \leq 3, \quad u = \frac{\sigma_2}{\sigma_1} \text{ OR } \frac{\sigma_4}{\sigma_3}. \quad (6)$$

The coefficients A_i are listed in Table I ; we at first restrict the sum over n to only a single term ($n=1$) and drop the superscripts n in (1) and (2). Later, we shall include the sum over n ; remark 2 at the end. Because of (5), we shall concentrate on the coefficients A_i , referring to B_i only occasionally.

In general, there are no further relations between the four σ_i because of the four independent A_i of Table I ; (4) and (5) give ^{**)}

$$8 A_i = 9 \sigma_i - 3 \sigma_{i+1}, \quad i=1,3 ;$$

$$8 A_i = 9 \sigma_i - 3 \sigma_{i-1}, \quad i=2,4. \quad (7)$$

^{*)} This may be said also when terms proportional to m are retained ; for example, the corresponding form (15) for the electron energy spectrum.

^{**)} Because of (7), constraints on A_i are expressible as constraints on σ_i ; we concentrate on A_1 .

However, with μe universality, $Z_{V,A} = D_{V,A}$ and $z_{V,A} = d_{V,A}$, giving

$$A_2 = A_4 \quad (8)$$

which, using (7) for $i = 2, 4$ gives

$$\sigma_1 - \sigma_3 = 3(\sigma_2 - \sigma_4). \quad (9)$$

Consider constraints on the observable coefficients A_i and B_i of Eq. (3). From Table I, one can show, using (4), that

$$|\sqrt{\sigma_1}| + |\sqrt{\sigma_3}| > |\sqrt{A_1}| + |\sqrt{A_3}| = 2h \quad (10)$$

or, using (5),

$$|\sqrt{3\sigma_2}| + |\sqrt{3\sigma_4}| > |\sqrt{B_2}| + |\sqrt{B_4}| = 2h \quad (11)$$

In (10) and (11), $h > 1$ for hypotheses a) and b) and $h \geq 1$ for hypothesis c), providing some distinction between the three hypotheses. Apart from this distinction, the results so far are generalisations of the corresponding results ⁴⁾ for the unique neutrino case.

With μe universality, a relation which provides a clear distinction between the three hypotheses is

$$\frac{1}{16}(A_1 - A_3 - 4)^2 = x A_3 \quad (12)$$

where $x < 1$ for hypothesis a), $x = 0$ for hypothesis b) and $x = 1$ for hypothesis c). This test is useful for both low energy and high energy experiments. Using (7), the test (12) can be trivially written also in terms of integrated (high energy) cross-sections. For hypothesis b), the implications are quite simple : (12) gives [using (5), (8) for second part]

$$A_1 = A_3 + 4 ; \quad \sigma_1 = \sigma_3 + 4 , \quad \sigma_1 \geq 4 \quad (13)$$

implying, because of (5), (9),

$$B_2 = B_4 + 4 ; \quad \sigma_2 = \sigma_4 + \frac{4}{3} , \quad \sigma_2 \geq \frac{4}{3} . \quad (14)$$

Also, using (3'), (14) gives $B_2 \geq 4$ which ^{*)} can be used ⁵⁾ to eliminate hypothesis b). Correspondingly, the cross-sections σ_1 and σ_2 must not be less than their charged current values of 4 and 4/3, respectively, if hypothesis b) holds. Like (13) and (14), $B_2 \geq 4$ results from the incoherence of the charged current contribution with the neutral one. Of course, $A_1 = B_2 \geq 4$ for hypothesis b) does not use μe universality ; Table I.

The test (12) involves neutrino couplings to only left-handed (LH) electrons, and is insensitive to neutrino interactions with right-handed (RH) ones. This is because the charged current is purely LH, and x in (12) merely determines how neutral currents mix with the charged current. The corresponding RH contributions are not useful in this sense ; they are incoherent sums of different neutral currents for all i ; Table I.

So far, the only relations that distinguish among the three hypotheses invoke μe universality. Tests for the presence of non-diagonal currents without invoking μe universality can be possible if terms proportional to m are retained, as is appropriate for very low energy experiments. Unfortunately, the corresponding tests [(17) to (19) below] turn out not to be definitive. Keeping terms proportional to m , the distribution in the electron laboratory kinetic energy E is

$$\frac{d\sigma_i}{dE} = \frac{m G^2}{2\pi} \left[A_i + B_i \left(1 - \frac{E}{E_\nu}\right)^2 - C_i \frac{mE}{E_\nu^2} \right] \quad (15)$$

where, for the new coefficients C_i , the relations

$$C_1 = C_2 ; \quad C_4 = C_3 \quad (16)$$

*) Our coefficients A_i and B_i are four times the corresponding coefficients of Ref. 5).

hold for all the three hypotheses. We now consider only the independent coefficients C_2 and C_3 (listed in Table II). In practice, relations involving C_i are useful for $i=2$ (the reactor experiment) and will hopefully become useful also for the other i values at meson factories. From the Tables, the relations

$$C_i^2 < A_i \cdot B_i, \quad i = 2, 3; \quad (17a)$$

$$C_2^2 < A_2(B_2 - 4), \quad C_3^2 < A_3 B_3, \quad (17b)$$

$$C_i^2 = A_i \cdot B_i, \quad i = 2, 3 \quad (17c)$$

can be shown to hold for hypotheses a), b), c), respectively, again generalizing (17c) for ⁴⁾ case c). Specializing to the case of only hermitian non-diagonal currents ($f_{A,V} = F_{A,V} = 0$), the results for hypotheses a), b) become

$$C_i^2 \leq A_i \cdot B_i, \quad i = 2, 3; \quad (18a)$$

$$C_2^2 = A_2(B_2 - 4), \quad C_3^2 = A_3 \cdot B_3 \quad (18b)$$

respectively. If in addition to taking $f_{A,V} = F_{A,V} = 0$, one specializes to the case in which the dynamical structure of diagonal and non-diagonal currents is identical ($d_A/d_V = g_A/g_V$; $z_A/z_V = G_A/G_V$), the result for hypothesis a) becomes

$$C_2^2 = A_2(B_2 - 4 + 4y^2), \quad C_3^2 = A_3 \cdot B_3 \quad (19a)$$

where y is the overlap of the neutral current component $\bar{f}_e^0$ of the final antineutrino $\bar{f}_e$ with the initial antineutrino $\bar{\nu}_e$; $0 < y < 1$. The results (18b) and (19a) were deduced ^{*}) in Ref. 5) for C_2 . However, for general non-diagonal currents, the result is (17). While (17a,b,c) do distinguish c) from a) and b), (17a) and (17b) are not completely non-overlapping and do not always distinguish between the a) and b) hypotheses; the ambiguities due to (18) and (19) make the situation worse [even for distinguishing

^{*}) I am thankful to L.M. Sehgal for correspondence concerning his paper ⁵⁾.

out c)] ; see also remarks 2, 3 below. It would, of course, help to check (17) for both ν_μ (or $\bar{\nu}_\mu$) and ν_e (or $\bar{\nu}_e$) beams because the forms (17b) differ for the two.

With μe universality, one gets useful supplements to (17) ; for example,

$$|C_2 - C_3| = 2x |\sqrt{A_2}| \quad (20)$$

where $x < 1$ for hypothesis a), $x=0$ for b) and $x=1$ for case c) ; this provides a rather clear low energy test complementary to the test (12) which is interesting also for high energies ; A_2 in (20) may preferably be determined from a low energy experiment depending on (15). The C_i are an interference between neutrino couplings to LH and to RH electrons. If the whole coupling is purely LH or purely RH, tests like (17) become null identities because the C_i then vanish. The pure LH nature of the charged currents is the reason why the incoherent contribution of charged currents drops out for hypothesis b), giving $x=0$ in (20). Further relations between C_2 and C_3 may help to distinguish between the three hypotheses :

$$(C_2 + C_3)^2 < 2 A_2 (A_1 + A_3 - 2) \quad (21a)$$

for hypothesis a), where $<$ becomes $\leq$ if antihermitian currents are postulated to be absent. For hypothesis b), there is just one independent C_i ; (16), (20). For hypothesis c),

$$C_2 + C_3 = A_2 (A_1 - A_3) / (C_2 - C_3). \quad (21c)$$

Some Remarks

1. The coefficients A_i of Table I and B_i [because of (5)] involve non-diagonal contributions in the combinations $|D_V \pm D_A|^2$, $|Z_V \pm Z_A|^2$. For the coefficients C_i of Table II, the corresponding quantities are $|D_V|^2 - |D_A|^2$ and $|Z_V|^2 - |Z_A|^2$. None of these observable coefficients directly involve $\text{Im}(D_V^* D_A)$ and $\text{Im}(Z_V^* Z_A)$, the characteristics of antihermitian currents. Since

$$|D_V + D_A|^2 |D_V - D_A|^2 - 4 [\text{Im}(D_V^* D_A)]^2 = (|D_V|^2 - |D_A|^2)^2,$$

relations between C_i^2 and $A_i B_i$ can test for the presence of antihermitian currents ; compare (17) and (18). Relations among only the coefficients A_i and/or B_i do not involve antihermitian currents in an essential way.

2. In generalizing to include a sum over an arbitrary number n of new neutrinos ν^n , one has to insert the superscripts n on couplings $Z_{V,A}$, $D_{V,A}$ and replace contributions like $|D_V \pm D_A|^2$ by $\sum_n |D_V^n \pm D_A^n|^2$ for hypotheses b) and a). All our results remain unchanged [except for replacing $=$ by $\leq$ in (18b)], thus further generalizing the existing constraints on neutrino and antineutrino scattering by electrons.

While our results are more general than the existing ones, it may be remembered that in general such V,A descriptions all violate unitarity asymptotically, unless one specializes ³⁾ to a particular gauge model. Since one does not in general know how and when unitarity modifications to these descriptions set in, the optimist's attitude is to utilize the eventual failure of such descriptions for obtaining clues about these modifications. In fact, these modifications for the four processes ($i=1$ to 4) may be quite different.

3. The low energy test (17) does not always distinguish between the three hypotheses, in addition to the ambiguities implied by (18) and (19). Useful help is offered by results (10) to (14), (20) and (21). Unfortunately, all these latter ones use μe universality because they relate ($i=1,2$) to ($i=3,4$), while (17) to (19) for a given i do not. At present, there is no direct experimental evidence for or against μe universality for neutral currents. In fact, if in (12) and (20), experimentally, $x > 1$, this universality would probably be the first assumption to relax.

4. For hypothesis c), $C_1^2 = A_1 B_1$, (17c). Generalizing to a) and b), we got $C_1^2 \leq A_1 B_1$, but not $C_1^2 > A_1 B_1$. It would be nice to check this general consequence of (V,A) descriptions. This, of course, makes no reference to μ e universality.

5. Numerical coefficients like 2 in (10), (11) and 4 in (12) to (14), (17) to (19) depend crucially on the form of the charged current in (1). While that form is the standard prejudice derived by applying μ e universality on μ decay, there is no direct experimental evidence for or against it.

Also, the new neutrinos have been introduced for only neutral currents because one wanted non-diagonal neutral ¹⁾ currents. The charged current neutrinos $\nu_{e,\mu}$ may themselves be superpositions of many states $s_{e,\mu}$; all that characterizes the new neutrinos $\nu_{e,\mu}'^n$ is that they are different from those superpositions. If all the states $s_{e,\mu}$ were not of sufficiently low mass, this could lead to threshold effects in charged current contributions in our analysis, and in other processes. It may be of interest to look for such energy-dependent effects.

6. Since the incident neutrinos $\nu_{e,\mu}$ originating from charged currents are left-handed and since V, A couplings conserve helicity, only left-handed neutrinos $\nu_{e,\mu}'^n$ (similarly, right-handed antineutrinos) participate in the Lagrangian (1). The presence or absence of the opposite helicity components does not matter.

7. Lepton masses were dropped in (3). If some of the neutrinos $\nu_{e,\mu}'^n$ have masses comparable to the beam energy, this would modify (3). For (15), lepton masses are even more important, and even neutrino masses of the order of m would change it; neutrinos were taken strictly massless for (15).

8. Neutral currents have been postulated to be pure ⁶⁾ V, pure ⁷⁾ A, and also ⁸⁾ V-A. In all these cases, simplifications occur and further testable relations between observables hold.

Finally, since neutral currents could have components of the remaining types ⁹⁾, one may ask if one could distinguish between our three hypotheses if the S, P, T currents are also included (or present by themselves); of course, one uses four-component neutrino fields for the types S, P, T.

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i	Hypothesis →	a)	b)	c)
	↓ Reaction			
1	$\nu_e e^- \rightarrow f_e e^-$	$ D_V + D_A ^2 + (d_V + d_A + 2)^2$	$ D_V + D_A ^2 + 4$	$(d_V + d_A + 2)^2$
2	$\bar{\nu}_e e^- \rightarrow \bar{f}_e e^-$	$ D_V - D_A ^2 + (d_V - d_A)^2$	$ D_V - D_A ^2$	$(d_V - d_A)^2$
3	$\nu_\mu e^- \rightarrow f_\mu e^-$	$ Z_V + Z_A ^2 + (z_V + z_A)^2$	$ Z_V + Z_A ^2$	$(z_V + z_A)^2$
4	$\bar{\nu}_\mu e^- \rightarrow \bar{f}_\mu e^-$	$ Z_V - Z_A ^2 + (z_V - z_A)^2$	$ Z_V - Z_A ^2$	$(z_V - z_A)^2$

TABLE I - The coefficients A_i of Eqs. (3), (4) for the four cross-sections of neutrino and antineutrino scattering by electrons. The corresponding coefficients B_i are given by Eq. (5). The final neutrinos $f_{e,\mu}$ have different compositions for the three hypotheses a), b) and c) defined in the text.

i	a)	b)	c)
2	$(D_V ^2 - D_A ^2) + [(d_V + 1)^2 - (d_A + 1)^2]$	$ D_V ^2 - D_A ^2$	$(d_V + 1)^2 - (d_A + 1)^2$
3	$(Z_V ^2 - Z_A ^2) + (z_V^2 - z_A^2)$	$ Z_V ^2 - Z_A ^2$	$z_V^2 - z_A^2$

TABLE II - The coefficients C_i occurring in the laboratory electron energy spectrum (15) for $i=2$ ($\bar{\nu}_e e^- \rightarrow \bar{f}_e e^-$) and $i=3$ ($\nu_\mu e^- \rightarrow f_\mu e^-$); the corresponding coefficients for $i=1$ ($\nu_e e^- \rightarrow f_e e^-$) and $i=4$ ($\bar{\nu}_\mu e^- \rightarrow \bar{f}_\mu e^-$) are given by Eq. (16). The final neutrinos $f_{e,\mu}$ have different compositions for the three hypotheses a), b) and c) defined in the text.

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