Ref.TH.1985-CERN

TESTS OF THE SPACE-TIME PROPERTIES OF NEUTRAL
CURRENTS IN ELECTRON - POSITRON ANNIHILATION

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A B S T R A C T

Electron-positron processes are very valuable for investigating neutral currents. Interference between neutral currents and the electromagnetic current provides unambiguous tests of the space-time properties of neutral currents. We discuss the structure of this interference with particular reference to the process $e^+e^- \rightarrow \text{hadron} + \text{anything}$.

Ref.TH.1985-CERN
24 February 1975

Neutral currents have been observed ¹⁾ in, for example, $\nu + N \rightarrow \nu + \text{anything (X)}$ and $\bar{\nu}_\mu + e \rightarrow \bar{\nu}_\mu + e$ at a level comparable with charged ones. It is of interest to determine the properties of these neutral currents and to consider their effects in other processes; in fact, other neutral currents may exist which do not couple appreciably to the above processes.

Much has been done in discussing ^{*)} possible effects of neutral currents in electron-positron annihilation. This has, however, concentrated on vector (V) or axial-vector (A) type of neutral couplings. Although (V,A) forms are a natural assumption in analogy with the charged weak currents and are, in fact, predicted by some gauge theories, there is no experimental evidence for or against a (V,A) form. Moreover, in contrast with charged currents, no decay processes would seem to provide the necessary information.

Several authors ⁷⁾⁻¹⁰⁾ have discussed the problem of determining the space-time properties of neutral currents in neutrino reactions. However, because neutrinos may be rather special, it is useful to consider other processes also: for instance, scalar (S) and pseudoscalar (P) type couplings are not possible if one is restricted to the two-component neutrino description. Furthermore, for processes involving electrons or muons, there is no doubt about the nature of the interacting leptons whereas in neutrino processes there is some doubt about the initial and the final neutrinos being identical because the final one is not detected. It has been pointed out ¹⁰⁾ that if the two are not identical, one can simulate with V,A currents some such effects ⁹⁾ as would otherwise require S, P or T (tensor) currents. This lends more interest to tests of the space-time properties of neutral currents in, for example, e^+e^- annihilation. There is also the difficulty of obtaining adequate statistics with neutrinos.

This note is devoted to a determination of the space-time structure of neutral currents in e^+e^- annihilation. In contrast to processes like $\nu_\mu + e \rightarrow \nu_\mu + e$ and $\nu + N \rightarrow \nu + X$ proceeding entirely through the weak neutral current, a definite advantage is offered by processes like $\nu_e + e \rightarrow \nu_e + e$, $\mu(\text{or } e) + N \rightarrow \mu(\text{or } e) + X$ and e^+e^- annihilation where the neutral current interferes with another current of known structure. The characteristics of the interference term between the neutral current and the (purely vector) electromagnetic current lead to clear tests of the space-time properties of neutral currents in e^+e^- annihilation. The process $e^+e^- \rightarrow \text{hadron (H)} + X$ where the electron and/or positron are polarized, but the polarization of H is not observed, is discussed in detail below.

*) See, for example, Refs. 2) to 6).

For neutral currents interacting more weakly than the electromagnetic current, the interference term will be larger than the pure neutral current term, except near the mass-shell of the neutral intermediate boson (if it exists). We, therefore, ignore the pure neutral current term. In the analysis of interference terms in e^+e^- annihilation, we consider all non-derivative couplings at a lepton vertex; the hadronic vertex is general.

A simplification occurs at the e^+e^- vertex if one drops (as we do hereafter) terms involving the electron mass m_e which are suppressed by a factor m_e/E where E is the centre-of-mass energy of the electron. Then the interference term in the cross-section has the structure

$$\begin{aligned} & \text{Tr} [\not{p}_+(1+\gamma_5 \not{B}_+) \gamma_\mu \not{p}_-(1+\gamma_5 \not{B}_-) \Gamma_i] (\text{Hadronic Tensor})^{\mu i} \\ &= \text{Tr} [(1-\gamma_5 \not{h}_+ + \gamma_5 \not{s}_+) \not{p}_+ \gamma_\mu (1+\gamma_5 \not{h}_- + \gamma_5 \not{s}_-) \not{p}_- \Gamma_i] (\text{Hadronic Tensor})^{\mu i} \quad (1.a) \end{aligned}$$

where the polarization four-vectors $B_\pm$ are written as

$$B_\pm^\mu = \frac{1}{m_e} (h_\pm p_\pm^\mu) + s_\pm^\mu \quad (1.b)$$

and the momentum, longitudinal polarization (at rest) and transverse polarization of the electron and positron are p_- , h_- , s_- and p_+ , h_+ , s_+ , respectively in the centre-of-mass frame, and Γ_i can be leptonic S, P, V, A, T couplings. The expression (1.a) shows that for S, P and T cases, the only terms contributing are linearly proportional to the transverse polarization (with or without a multiplicative longitudinal polarization), but there is no contribution if only longitudinal polarizations occur. For V and A cases, only terms independent of or quadratically dependent on transverse polarizations contribute; the longitudinal polarizations can appear linearly or quadratically, but not along with transverse polarizations.

This complementarity of the types of effects produced by the S, P, T couplings versus the V, A ones is remarkable, and in view of the experimental feasibility of polarized electron-positron beams, is very useful.

For $e^+e^- \rightarrow \mu^+\mu^-$, if muon polarization is not measured, the interference term vanishes for the S, P, T case even for transversely polarized beams, making this process unsuitable for observing these coupling types. For the V, A types, interference effects are present ^{2),5)}. Observation of these

effects would indicate the presence of V, A couplings in the neutral current interaction. Of course, one must distinguish between pure electromagnetic terms (including higher orders) and electromagnetic weak interference effects. Behaviour under parity reflection or charge conjugation helps here; we do not consider such tests ^{2),5)} for this process here.

Therefore, in order to look for the S, P, T couplings and also to investigate the non-leptonic nature of neutral currents, one must look elsewhere. Since we expect to have to go to high energies to suppress the electromagnetic background, exclusive hadronic channels are likely to be strongly damped by form factor effects. The simplest inclusive channel is $e^+e^- \rightarrow \text{hadrons}$ where no details of the hadrons are measured. Here unfortunately, the one photon weak interference term vanishes for the S, P, T types, and the only characteristic weak effect ^{3),11)} (parity violation in this case) produced by (V,A) currents is proportional to $(h_+ - h_-)$. The channel $e^+e^- \rightarrow HX$ offers the advantage that the S, P, T types also give contributions. In view of the rather large experimental cross-section for hadron production in e^+e^- collisions, one expects the cross-section for $e^+e^- \rightarrow HX$ to be comparable to that for $e^+e^- \rightarrow \mu^+\mu^-$.

The effective Lagrangian for the neutral current coupling of the electron field ψ to hadrons is

$$\mathcal{L} = \bar{\psi}\psi J^1 + \bar{\psi}\gamma_5\psi J^2 + \bar{\psi}\gamma^\mu\psi J_\mu^3 + \bar{\psi}\gamma^\mu\gamma_5\psi J_\mu^4 + \bar{\psi}\sigma^{\mu\nu}\psi J_{\mu\nu}^5 \quad (2)$$

where J^1 and J^2 may contain scalar and/or pseudoscalar parts, J_μ^3 and J_μ^4 may contain vector and/or axial vector parts, and $J_{\mu\nu}^5$ transforms as a tensor and/or a pseudotensor. If only the momentum p of the detected hadron is measured, the kinematical forms of the electromagnetic-neutral current interference terms resulting from the Lagrangian (2) are given in the Table for the process $e^+e^- \rightarrow HX$. Each term will, of course, be multiplied by a form factor which depends on the Lorentz invariants formed from the momenta at the hadronic end.

The S, P and T terms are all linearly dependent on transverse polarization, while V and A ones are either independent of or quadratically dependent on the transverse polarization. Experimentally, this is nice since electrons and positrons automatically acquire a transverse polarization in storage rings due to synchrotron radiation. Selective depolarization of one beam would then test for S, P or T versus V or A types by isolating terms linear in transverse polarization.

For the S, P or T types, no observation of a characteristic weak effect (for example parity violation) is necessary to distinguish it from electromagnetic terms. This is because contributions linearly dependent on transverse polarization (with or without a multiplicative longitudinal polarization) are relatively suppressed in the pure electromagnetic terms by a factor

$$\sim \left[\frac{e^2}{(q^2/M_p^2)} \cdot \frac{m_e}{E} \cdot \frac{1}{G_F M_p^2} \right] \approx 10^{-4}$$

for $4E^2 \equiv q^2 = 10^3 \text{ GeV}^2$, taking $G_F M_p^2$ as the weak neutral coupling. Thus these contributions are a clear signal for the one-photon (S,P,T) interference term.

In contrast, for V, A types, the interference term must be separated from effects due to higher order electromagnetic terms by looking for weak interaction signatures like parity violation or charge conjugation non-invariance. The Table shows that all but one parity odd terms are linearly dependent on longitudinal polarization. Effects persisting when only one beam is longitudinally polarized and the other is unpolarized therefore indicate a V or A parity violating interaction. It is important to check that the other beam has no transverse polarization because effects linear and anti-symmetric in the electron and positron longitudinal polarizations can arise from the S, P, T types also, but these latter effects are directly proportional to the transverse polarization of the "other" beam. The Table also shows that the corresponding angular distributions are different in the various cases. Parity conserving interference terms from $J^{3,4}$ could be tested for their charge conjugation (C) behaviour (see below for C properties in general); possible C odd terms would violate also time reversal invariance, and distinguish the effect from higher order electromagnetic contributions. Tests for V, A types have been already considered ³⁾⁻⁵⁾.

In order to distinguish the S, P types from the T type, one looks at the detailed structure given in the Table. We choose $\vec{p}_-$ along the z axis and take $\vec{p}$ in the (θ, ϕ) direction. Then the terms from J^1 and J^2 are proportional to $\sin\theta$. The first four terms of J^5 have the same form as those from J^1 and J^2 , but multiplied by a factor $\cos\theta$. The final four terms from J^5 are of the same form as for J^1 and J^2 , but with the opposite symmetry under the substitution $\vec{s}_+ \rightleftharpoons \vec{s}_-$; in addition, for a given polarization structure, the corresponding angular distributions are also different. Identification of these features would distinguish between S and P or T types. A convenient way is to choose $\theta = \pi/2$ where the first four terms of J^5 vanish. The separation of S, P from T would then depend on whether the interference term changes sign (as indicated in the Table) when the e^+ instead of the e^- is transversely polarized.

The Table also shows whether the terms are even or odd under parity inversion. Clearly, it is easy to choose (θ, ϕ) so that any term can be looked for, and the presence of parity even or odd neutral currents shown. The charge conjugation behaviour of the various terms is investigated by making the substitutions $+ \rightleftharpoons -$ in the subscripts of the leptonic variables if H is its own antiparticle $\bar{H}$. Since the hadronic form factors depend on only C even quantities, the C properties are those of kinematics, as given in the Table. For $H \neq \bar{H}$, one must consider the cross-section combinations

$$\sigma_{\pm} = \sigma(e^+e^- \rightarrow H(p)X) \pm \sigma(e^+e^- \rightarrow \bar{H}(p)X) \quad (3)$$

for a given leptonic configuration. Then, for σ_+ , the C properties are given in the Table. For σ_- , the C behaviour is opposite to that of σ_+ . Depending on the parity and C properties, the time reversal behaviour is given by CPT invariance for any entry in the Table. But since the final state interactions in $e^+e^- \rightarrow HX$ are unknown, it is not in general possible to predict the form of the time reversal behaviour directly. The Table shows that the C properties of the various terms provide another useful way of distinguishing the different types of neutral current couplings.

Kingsley et al.⁹⁾ have classified currents into first or second rank according to whether or not the corresponding operators can be constructed, assuming time reversal invariance, from a single quark multiplet. The second rank interactions appear for only the S, P, T types, and involve a net parity violation in the amplitude; these would correspond to the parity odd entries in the Table for $J^{1,2,5}$. It is interesting that, as mentioned above, the observation of the S, P, T types does not require the characteristic weak signature of parity violation, since one may possibly believe that somehow second rank interactions are relatively suppressed.

Estimates of the expected size of the neutral current effects for the V, A types can be made in, for example, the gauge model of Weinberg and Salam, as done by McDonald⁵⁾. For the S, P, T types, one makes (plausible ?) assumptions. We assume the observed $\nu p \rightarrow \nu X$ to be wholly of these types, and that their coupling in $e^+e^- \rightarrow HX$ is comparable. Since the neutral current couplings seen at NAL energies are comparable to or less than those seen at Gargamelle, a reasonable assumption is that no big enhancement or suppression occurs in continuing to high timelike momenta. Then, the interference term will be enhanced relative to the one-photon term by an inverse power of the photon propagator :

$$\frac{\text{Interference Term}}{\text{1 Photon Term}} \approx \left(\frac{M_p^2 G_F}{e^2} \right) \cdot \left(\frac{q^2}{M_p^2} \right) \approx 10^{-4} q^2 / M_p^2. \quad (4)$$

Thus for $q^2 = 10^3 \text{ GeV}^2$, effects of order 10% of the background could be present.

Neutral currents can, of course, be simulated by conventional charged currents in second order. Since such effects involve an integral over a loop momentum, some model for the high energy behaviour is necessary to estimate their size. In gauge models, this behaviour is specified, and a final neutral current of order $G_F \alpha$ is expected ¹²⁾. Even at $q^2 = 1000 \text{ GeV}^2$, such contributions would be too small to observe.

We would like to thank J.S. Bell for reading the manuscript and for useful remarks.

Hadronic current	Kinematic structure in c.m. frame	R	C
J^1	$p \cdot (h_+ s_- - h_- s_+)$	+	-
	$p \cdot (K \times [s_+ + s_-])$	+	-
J^2	$p \cdot (s_+ - s_-)$	-	-
	$p \cdot (K \times [h_- s_+ + h_+ s_-])$	-	-
J^3	$1 - h_- h_+$	+	+
	$(h_- - h_+) p \cdot K$	-	+
	$(1 - h_- h_+ + s_- \cdot s_+) (p \cdot p K \cdot K - p \cdot K p \cdot K) - 2 p \cdot s_- p \cdot s_+$	+	+
J^4	$h_- - h_+$	-	-
	$(h_- - h_+) (p \cdot p K \cdot K - p \cdot K p \cdot K)$	-	-
	$(1 - h_- h_+) p \cdot K$	+	-
	$p \cdot s_+ p \cdot (K \times s_-) + p \cdot s_- p \cdot (K \times s_+)$	-	-
J^5	$p \cdot K p \cdot (h_+ s_- - h_- s_+)$	+	+
	$p \cdot K p \cdot (K \times [s_+ + s_-])$	+	+
	$p \cdot K p \cdot (s_+ - s_-)$	-	+
	$p \cdot K p \cdot (K \times [h_- s_+ + h_+ s_-])$	-	+
	$p \cdot (h_+ s_- + h_- s_+)$	+	+
	$p \cdot (K \times [s_+ - s_-])$	+	+
	$p \cdot (s_+ + s_-)$	-	+
	$p \cdot (K \times [h_- s_+ - h_+ s_-])$	-	+

TABLE : Kinematic structure of the weak electromagnetic interference terms for the process $e^+e^- \rightarrow HX$ for the currents $J^1, \dots, 5$ of Eq. (2). The symbols p, p_+, p_-, s_+, s_- are all three-vectors, $2K = p_- - p_+$. The last two columns give the behaviour under parity inversion (R) and for charge conjugation (C); odd and even are denoted - and + respectively. The column for C refers to the case $H = \bar{H}$ or to σ_+ ; for σ_- , the behaviour is opposite to that for σ_+ .

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