SECOND CLASS CURRENT EFFECTS IN TAU LEPTON DECAY?

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INTRODUCTION

About thirty years ago Weinberg\(^1\) classified the weak charged current according to its G-parity transformation properties. One, that we now know is the dominant interaction and that forms the basis of the Standard Model, was called first class (FC). This current behaves under the G parity operation as: \(G V G^{-1} = V\) and \(G A G^{-1} = -A\), where \(V\) and \(A\) stand for the vector and axial vector components of the hadronic weak current. A second possibility was a current that behaved oppositely under the G parity transformation: \(G V G^{-1} = -V\) and \(G A G^{-1} = A\). Such currents were called second class (SC). The corresponding weak form factors would be dominated by the following mesons:

<table>
<thead>
<tr>
<th>Current</th>
<th>Meson</th>
<th>(J^P)</th>
<th>(G)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F.C. V</td>
<td>(\rho)</td>
<td>1(^-)</td>
<td>+</td>
</tr>
<tr>
<td>F.C. A</td>
<td>(a_1(1270))</td>
<td>1(^+)</td>
<td>-</td>
</tr>
<tr>
<td>S.C. V</td>
<td>(a_0(980))</td>
<td>0(^+)</td>
<td>-</td>
</tr>
<tr>
<td>S.C. A</td>
<td>(b_1(1235))</td>
<td>1(^+)</td>
<td>+</td>
</tr>
</tbody>
</table>

Since the axial current is only partially conserved, there is also an induced pseudoscalar form factor that is dominated by the pion pole.

Many experiments\(^2\) in \(B\) decay, in muon captive and in neutrino interactions have searched for evidence of such effects but with no lasting result. The nuclear physics experiments have little sensitivity to the second-class vector current,\(^3\) but give upper limits to the second-class axial current, which corresponds to a tensor form factor, of about 20% of the weak magnetism term. Absolute conservation of the vector current in CVC requires that such a second-class current, which leads to a scalar form factor, be zero, although small isospin breaking effects are expected from a u/d quark mass difference.

NEUTRINO EXPERIMENTS

High sensitivity experiments at high momentum transfer are required to see the effects of SCC since such currents, if they exist, are weaker than the FCC and since they are proportional to momentum transfer. Possibilities of such experiments obviously exist at BNL with the high-intensity neutrino beam. The challenge is to find evidence for the second-class form factors when the

\[ \nu \rightarrow \mu \rightarrow \text{Meson } \rho, a_1, (\pi) (a_0, b_1, \gamma) \]

main experimental features of quasielastic scattering and nucleon resonance production are dominated by the first-class currents and the \( \rho \) and \( a_1 \) poles. One possibility is to measure the nucleon polarization which, as shown in Fig. 2, can change by factors of two at medium \( Q^2 \) for a tensor form factor half as large as the normal axial term.

\[ \text{Fig. 1. Quasielastic and nucleon resonance production in neutrino scattering.} \]

\[ \text{Fig. 2. Predicted nucleon polarization for the reaction } \nu n \rightarrow \mu p \text{ at } 1 \text{ GeV (Ref. 5): Curve (b) is with no SC axial current; curves (a) and (c) are for a SCC with half strength compared to the weak magnetism term.} \]

EVIDENCE FROM TAU LEPTON DECAY

More sensitive searches have become possible in the last few years with the collection of many thousands of examples of tau lepton decay. In this case, the experiment is done in the s channel and the final state meson can be searched for directly as shown in Fig. 3.

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The high tau mass of 1.784 GeV also increases the sensitivity as compared to a typical $Q^2$ of 0.5 GeV$^2$ that dominates the quasielastic neutrino scattering.

The One-Prong Anomaly in Tau Decay

The principal decay modes of the tau are quite well known, as shown in Table I - which was compiled for the Berkeley conference. The branching ratio of $6.4 \pm 0.4$ for the $\pi^+\pi^-\pi^0$ final state is taken to be equal to that measured for

\begin{table}[h]
\centering
\begin{tabular}{lrcc}
\hline
Decay Mode & Dominant Resonance & Branching Fraction \% & \\
$\tau^- +$ & & One-Prong & Three-Prong \\
\hline
e$^-\nu_e\tau$ & & 17.9 & 17.9 \\
$\mu^-\nu_\mu\tau$ & & 17.5 & 17.5 \\
$\pi^-\nu_\tau$ & $\pi^-$ & 10.9 & 10.9 \\
$\pi^-\pi^0\nu_\tau$ & $\rho^-$ & 22.1 & 22.1 \\

$3\pi^\pm\nu_\tau$ & $a_1$ & & 6.4 \\
$\pi^-2\pi^0\nu_\tau$ & $a_1$ & (6.4) & (6.4) \\
$3\pi^\pm\pi^0\nu_\tau$ & & & 5.2 \\
$K^-\nu_\tau$ & & 0.7 & 0.7 \\
$(K\pi)^-\nu_\tau$ & $K^*(890)$ & 1.1 & 1.1 \\
$(KK\pi)^-\nu_\tau$ & & 0.22 & 0.22 \\
$(KK\pi)^-\pi^0\nu_\tau$ & & 0.22 & 0.22 \\

Total & & 76.6 & 12.7 \\
\hline
\end{tabular}
\end{table}

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6 P. Burchat, Santa Cruz preprint SCIPP 86/72.
the $\pi^- \pi^+ \pi^-$ final state by isospin invariance since the three-charged final state is dominated by the $a_1(1270)$ resonance. The decay modes involving $K$ mesons are small as expected from the Cabibbo angle.

The topological branching ratios for the tau decay are well measured\(^7\) and are: $B_1 = 86.6 \pm 0.3\%$; $B_3 = 13.2 \pm 0.3\%$; $B_5 = (10.2 \pm 2.9) \times 10^{-4}$; $B_7 < 1.9 \times 10^{-4}$. The value of $B_3 = 13.2 \pm 0.3\%$ agrees with the sum of the individual three-prong decays of $12.7 \pm 0.7\%$, given in Table I, but this is not the case for the one-prong topology where there is a deficit of decays that have not been identified amounting to $10 \pm 1.5\%$. This is a large anomaly, particularly since the measured modes agree well with simple theoretical expectations.

A number of recent experiments have addressed this missing one-prong issue. The TPC collaboration\(^8\) reports a branching ratio of $(13.9 \pm 2.0 + 1.9)^\%$ for the decays $\tau^- + \pi^- \nu_\tau + \text{multiple neutrals}$. The data can be interpreted as a weighted sum of the three modes: $B_{\pi^- 2 \pi^0} = 1.6B_{\pi^- 3 \pi^0} + 1.1B_{\pi^- \pi^0 \eta}$, where $B_{\pi^- \pi^0 \eta} = B_{\pi^- \pi^0 \eta} + \text{neutrals}$. A similar analysis by the MARK II collaboration\(^9\) gives the individual values: $B_{\pi^- 2 \pi^0} = 6.2 \pm 0.6\%$, $B_{\pi^- 3 \pi^0} = 0 \pm 1.4\%$ and $B_{\pi^- \eta \pi^0} = 4.2 \pm 0.7\%$. If $B_{\pi^- 2 \pi^0}$ is set to $6.4 \pm 0.4\%$ deduced from the three-charged particle decay of the $a_1$, then the TPC data gives $1.6 B_{\pi^- 3 \pi^0} + 1.1 B_{\pi^- \pi^0 \eta} = 7.5 \pm 2.8\%$.

The rate for the decay $\tau^- + \pi^- 3 \pi^0 \nu_\tau$ has been estimated by Gilman and Rhie\(^10\) from the $e^+e^-$ annihilation cross sections to four charged pions in the $\tau$ mass energy region. Specifically, CVC gives the following relationship:

$$\frac{\Gamma(\tau^- + \pi^- 3 \pi^0 \nu_\tau)}{\Gamma(\pi^- + e^- \nu \nu_\tau)} = \frac{3m_\tau^2}{2\pi^2 m_\tau^8} \int_{Q^2}^2 \left(\frac{Q^2}{m_\tau^2 - Q^2}\right)^2 (m_\tau^2 + 2Q^2) dQ^2 \frac{\sigma(e^+e^- + 2\pi^+ 2\pi^-)}{2}.$$

\(^7\) See, for example, C. Akerlof et al., Phys. Rev. Lett. 55, 570 (1985).
The cross section for $e^+e^- + 2\pi^+\pi^-$ is well measured from threshold up to the $\tau$ mass, as shown in Fig. 4(a), and these results give $\Gamma(\tau^- + \pi^-\pi^0\nu_\tau)/\Gamma(\tau^- + e^-\nu_e\nu_\tau) = 0.055$, or a branching ratio for $\tau^- + \pi^-\pi^0\nu_\tau$ of slightly less than 1%. The TPC measurement then implies $B_{\pi^-\pi^0\eta} = 7.6 \pm 2.8\%$, in agreement with the value of $4.2 \pm 1.2\%$ given by the MARK II group.

Both of these analyses were done ignoring more complicated final states such as $\pi^-\eta\nu_\tau$, $\pi^-\pi^0\pi^0\nu_\tau$. The low values for the five-prong decay modes, measured by the HRS collaboration\textsuperscript{11} of $B_{\pi^\pm\pi^0} = (5.1 \pm 2.0) \times 10^{-4}$ and

$$B_{\pi^\pm\pi^0} = (5.1 \pm 2.2) \times 10^{-4},$$

severely limit the branching ratios for these higher multiplicity final states.\textsuperscript{12} Because of the $\eta + \pi^+\pi^-\pi^0$ decay, an upper limit to $B_{\pi^-\eta\eta}$ of $0.3 \pm 0.2\%$ can be estimated since only three of the six events of $5\pi^+\pi^0$ observed by the HRS group have two $\pi^+\pi^-$ mass combinations below 415 MeV. In a similar way, an upper limit to $B_{\pi^-\eta\pi^0\pi^0}$ of $0.18 \pm 0.08\%$

can be estimated since isospin conservation predicts $B_{\pi^-\eta\eta^0\eta^0} \lesssim B_{\pi^-\eta\eta^+\eta^-}$.

We conclude that MARK II and TPC experiments give indirect indications of a substantial branching ratio for the decay $\tau^{-} + \pi^- \eta\eta^0 \nu_{\tau}$, which goes far to solving the one-prong anomaly.

**Direct Observations of $\eta$ Meson Production in Tau Decay**

Two experiments have presented direct evidence for $\eta$ meson production in tau decay by the observation of a peak in the $YY$ effective mass. The HRS experiment, done at $\sqrt{s} = 29$ GeV, has an integrated luminosity of $300 \text{ pb}^{-1}$. The selection of $\tau$ pair events is quite straightforward at this energy. The standard cuts yielded 4004 events in the 1-1 topology and 2553 events in the 1-3 topology.

The analysis depends on reconstructing $\eta + YY$ decays via measurement of electromagnetic showers in the barrel shower counter. Each of the 40 wedge-shaped modules consists of three sections: a $3\times\pi$ Pb-scintillator sandwich, a single-layer, 14-wire proportional chamber (PWC) in which the wires are aligned along the $e^+e^-$ beam direction and finally an $8\times\pi$ Pb-scintillator sandwich. The PWC plane is at a radius of 2.03 m from the interaction point. Each of the two scintillator sections is read out by two phototubes, one at each end of the approximately 3 m long modules. The energy resolution is $\frac{q_E^2}{E} = 0.16^2 + 0.06^2$ with $E$ in GeV. The positions of the electromagnetic showers along the beam direction, $z$, were measured by current division in the PWC wires to an accuracy of $\sim 2.5$ cm.

Since the expected momentum spectrum of $\eta$ mesons is hard and since photons from high $\pi^0$ decays almost always hit the same shower counter module, we show in Fig. 5(a) the $YY$ mass spectrum for combinations where: (i) the photons hit separate modules, (ii) $E_\gamma > 1$ GeV for both clusters, and (iii) no other photon shared the same module. A significant signal is seen both at the $\pi^0$ and at the $\eta$ mass.

The data have been further divided into a low and a high energy sample with $E_\gamma_1 + E_\gamma_2$ less than or greater than 4.5 GeV. As expected, the $\eta$ signal persists in the $YY$ mass plot for the high energy data of Fig. 5(c), but is less prominent in the low energy spectrum of Fig. 5(b). The $\pi^0$ production populates the latter spectrum primarily because of the requirement that the two-photon clusters occur in separate modules: a module spans an azimuthal angle of $9^0$.

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To study whether the one-prong $\tau$-decay events come from the $\pi^+\eta^0\nu$ or $\pi^+\eta^0\nu$ final states, the data of Fig. 5(a) were subdivided into 229 events with two and only two neutral clusters (Fig. 5(d)) and 145 $\gamma\gamma$ combinations from 113 events with three or more neutral clusters (Fig. 5(e)). A minimum energy cut of 100 MeV was applied in defining a separate cluster. The enhancement of the $\eta$ mass in the inclusive data persists in the events with only two photons, whereas there is no significant signal for $n_{\gamma} > 3$ selections. Photons from the $\pi^+\eta^0\nu$ final state can be missed either because

Fig. 5. Effective mass of $\gamma\gamma$ system for events with $E_{\gamma_1}, E_{\gamma_2} > 1$ GeV and having the photons in separate modules: (a) all combinations; (b) combinations with $E_{\gamma_1} + E_{\gamma_2} < 4.5$ GeV; (c) combinations with $E_{\gamma_1} + E_{\gamma_2} > 4.5$ GeV; (d) events with two and only two photon clusters; (e) events with three or more photon clusters. The lines show fits to a smooth background function, plus contributions at the $\pi^0$ and $\eta$ masses.
they hit the cracks between modules or because they are coalesced with other photons in the event. Monte Carlo and other studies indicate that such effects are small— at about the 7% level. The 2Y data of Fig. 5(d) is therefore evidence that the π⁻π⁺νν final state is being observed. The corresponding decay branching ratio is $(5.1 \pm 1.0 \pm 1.2)\%$.

The CRYSTAL BALL (CB) collaboration has presented evidence\(^\text{14}\) for inclusive π production in tau decay using data taken at the DORIS storage ring at about $\sqrt{s} = 10$ GeV. Figure 6 shows the YY mass spectrum after removal of photons that are within 3σ of the π⁰ mass. There is a peak at $550 \pm 4.3$ MeV with a width of $20 \pm 4.1$ MeV that shows π production at a significance level of 5.5σ. If the final state is assumed to be $π⁻π⁺τ⁻ντ⁻$, then the corresponding branching ratio is $(7.5 \pm 1.2 \pm 2.5)\%$. The events observed in the CB seem to have additional photon activity so the two direct observations are not obviously compatible, although they do agree that π production in τ decay is substantial.

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\textbf{Fig. 6.} Effective mass of the YY system in the CRYSTAL BALL experiment.

The quantum numbers of the π⁻π in the π⁻π⁺ντ final state are $G = -$ and $J^P = 0^+$, 1⁻ so the decay manifestly occurs through a second-class current. For the $τ⁻ + π⁻π⁺ντ$ decay, the $G$ parity is even but many $J^P$ combinations are possible. However, the final hadronic state, consisting of a $π$ and an $π$ in a relative p wave can have $J^P = 1^-$ that corresponds to the allowed FCC. Such a decay could proceed through the intermediary of the $ρ(1600)$ resonance. However, a photoproduction experiment\(^\text{15}\) shows no evidence for this decay and gives a limit for the branching ratio of $(ρ(1600) + π⁻π⁺/ρ(1600) + \text{all})$ of less than 2%.

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\(^{14}\) M. Gilchrise, Review talk given at Berkeley meeting (1986) and S. Keh et al. (CRYSTAL BALL Collaboration) (to be published).

\(^{15}\) M. Atkinson et al., Z. Phys. C30, 531 (1986).
Comparison with $e^+e^- + \pi^+\pi^-\eta$

The conserved vector current again allows an estimate of the branching ratio for the allowed $\tau^- + \pi^-\eta\pi^0\nu_\tau$ decay to a $J^P = 1^-$ final state from the measured cross section for $e^+e^- + \pi^+\pi^-\eta$. Figure 4(b) shows the data for this $e^+e^-$ cross section in the appropriate energy range. The corresponding value for $B_{\pi^-\eta\pi^0}$ is $\sim 0.25\%$, much lower than the inferred results from the TPC and MARK II groups, and from the direct measurement of the CRYSTAL BALL collaboration. This comparison indicates a strong violation of CVC as does the HRS observation of the forbidden decay $\tau^- + \pi^-\eta\nu_\tau$.

Search for Second-Class Axial Currents

The ARGUS collaboration\textsuperscript{17} has studied the decay $\tau^- + \pi^-\pi^+\pi^-\pi^0\nu_\tau$; their value of $(4.2 \pm 0.5 \pm 0.9)\%$ for $B_{2\pi^-\pi^+\pi^0}$ is lower than, but in agreement with, $5.2 \pm 0.5\%$ given in Table I. The $\pi^+\pi^-\pi^0$ mass spectrum, shown in Fig. 7(a) has a strong $\omega^0$ signal corresponding to $B_{\pi^-\omega^0} = (1.5 \pm 0.3 \pm 0.3)\%$.

![Mass spectrum](image)

**Fig. 7.** (a) Effective mass of $\pi^+\pi^-\pi^0$ system for $\tau^- + \pi^-\pi^+\pi^-\pi^0\nu_\tau$. (b) Distributions of normal to $W$ decay plane with respect to the bachelon pion as compared to the expectation for different $J^P$ values of $WW$ system.

This \( \pi^+ \pi^- \pi^0 \) mass spectrum shows no evidence for the decay \( \tau^- + \pi^- \eta \nu_\tau \rightarrow \pi^+ \pi^- \pi^0 \) which, on the face of it, is in disagreement with the HRS result. However, in the latter experiment, the detection efficiency is a strong function of \( 3\pi \) mass being about six times lower at 550 MeV than at 785 MeV. The acceptance depends on the details of the experimental equipment and so a limit on \( \tau^- + \pi^- \eta \nu_\tau \) from the data of Fig. 7(a) can only be given by the ARGUS collaboration themselves.

The CRYSTAL BALL measurement can also be checked by the ARGUS data.

To establish the spin-parity of the \( \pi^- \omega \) system, it is necessary to measure the distribution in the angle \( \psi \), which is that between the normal to the \( \omega \) decay plane and the batchelor pion in the \( \omega \) rest frame. The result, which is shown in Fig. 7(b) is completely consistent with \( J^P = 1^- \) although up to 50% of \( 1^+ \), which corresponds to the second-class axial current, is allowed by the data.

**Conclusions**

Since the establishment of a second-class vector current would be a major contribution to physics\(^\text{18}\) and could be an indication of the so-far unexplored scalar (Higgs) sector, it is necessary that several experiments report the same results. This is not the case so far in the measurement reviewed here. However, several groups are actively pursuing this issue, and we can look forward to an experimental clarification over the next several months. If it turns out that CVC is upheld and inclusive \( \eta \) production is no more than a fraction of a percent of tau decays, then the major mystery of the missing one-prongs will require further detective work.

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