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LOW-ENERGY PHOTON PRODUCTION IN NEUTRINO NEUTRAL-CURRENT INTERACTIONS

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ABSTRACT

The search for $\nu_\mu \to \nu_e$ oscillations by the MiniBooNE Collaboration at Fermilab has revealed a low-energy signal which could be due either to electrons produced by ν_e or photons produced by the interaction of the weak neutral current on the target nucleus. One contribution to the latter is a Wess-Zumino-Witten anomaly leading to a term in the Lagrangian proportional to $\epsilon^{\mu\nu\kappa\lambda} Z_\mu \omega_\nu F_{\kappa\lambda}$. This term is normalized with the help of the known rates for the processes $f_1 \to \rho\gamma$ and $\tau \to \nu_\tau a_1$. A rate of about 1/4 of that employed in several previous estimates is obtained. As the anomaly term had already been found to play a subdominant role in photon production (e.g., in comparison with Δ excitation and decay), the present estimate reduces its strength even further.

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I INTRODUCTION

The search for $\nu_\mu \to \nu_e$ oscillations by the MiniBooNE Collaboration at Fermilab [1] has revealed a low-energy signal which could be due either to electrons produced by ν_e or photons produced by the interaction of the weak neutral current on the target nucleus [2–4]. One proposed source of the latter is an interaction between the Z, ω meson, and photon [5] due to a Wess-Zumino-Witten anomaly [6–8], whose strength has been calculated in Refs. [9–11]. It was concluded in Ref. [12, 13] that the anomaly contribution was not enough to account for a photon signal. Although neutral-current nucleon excitation followed by photon emission was originally suggested as a source of the signal, it was found insufficient as well in Refs. [14–19]. A comprehensive review of neutrino-induced quasi-elastic scattering and single photon production is given in a workshop summary [20].

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The imminent operation of the MicroBooNE Experiment at Fermilab [21] will be able to distinguish final-state photons from electrons. Hence it is timely to present an independent estimate of the strength of the anomaly-mediated interaction. In this paper we perform such an estimate based on dominance of the Z–ω–γ interaction by the a_1 pole in the neutral current. The a_1 decay constant is obtained from the observed rate for $\tau \to a_1 \nu_\tau$, while the a_1–ω–γ coupling is obtained from the observed decay rate for $f_1 \to \gamma\rho$, which involves a coupling constant identical to $g_{a_1 \omega\gamma}$ if f_1 contains only nonstrange quarks. This interaction was overlooked in an otherwise successful description of light meson radiative decays based on the quark model [22, 23].

In Sec. II we review the consequence for the MiniBooNE experiment of the assumed Z–ω–γ interaction. We then (Sec. III) derive the consequence of assuming a_1 dominance of the weak neutral current. The a_1 decay constant which arises in this derivation is evaluated with the help of the rate for $\tau \to a_1 \nu_\tau$ in Sec. IV, while the decay rate for $f_1 \to \gamma\rho$ is employed to evaluate the a_1–ω–γ coupling in Sec. V. Section VI contains predictions for the rates for $a_1^0 \to \omega\gamma$ and $a_1 \to \rho\gamma$ (all charge states). We sum up in Sec. VII.

II NEW INTERACTION AND MINIBOONE

The MiniBooNE experiment [1] at Fermilab was conceived to check a signal for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation observed at the LSND detector [24] operating at Los Alamos National Laboratory. The oscillation signature would be the appearance of electrons. Initially signals were restricted to an electromagnetic energy deposit greater than 475 MeV. An excess of events below this cutoff was observed, attributable either to electrons or to photons.

A possible source of photons in this experiment was identified by J. A. Harvey, C. T. Hill, and R. J. Hill [4]. A Wess-Zumino-Witten anomaly [6, 7] gives rise to a term

$$\delta\mathcal{L} = \frac{N_c}{48\pi^2} \frac{e g_\omega g_2}{\cos\theta_W} \epsilon_{\mu\nu\rho\sigma} \omega^\mu Z^\nu F^{\rho\sigma} \ . \tag{1}$$

Here $N_c = 3$ is the number of quark colors, $e = \sqrt{4\pi\alpha} = 0.3028$ is the proton charge, g_ω is a coupling constant of the ω meson to baryon number whose value needs to be specified, g_2 is the electroweak SU(2) coupling constant, θ_W is the electroweak mixing angle, and $F^{\rho\sigma}$ is the photon field-strength tensor. The contribution of this term to the coherent process $\nu A \to \nu\gamma A$, where A denotes a nucleus of atomic number A, is illustrated in Fig. 1(a). The induced decay $f_1 \to \gamma\rho$ is shown in Fig. 1(b), while a related WZW anomaly [6, 7] leads to a $K\bar{K}\omega$ coupling responsible for $K_L \to K_S$ coherent regeneration [Fig. 1(c)] [25, 26].

The term (1) leads to a cross section per nucleon N in the zero-recoil limit [4]:

$$\sigma(\nu N \to \nu\gamma N) = \frac{\alpha g_\omega^4 G_F^2}{480\pi^6 m_\omega^4} E_\nu^6 = 2.6 \times 10^{-41} \ E_\nu^6(\mathrm{GeV})(g_\omega/10.0)^4 \mathrm{cm}^2 \ . \tag{2}$$

in the limit of E_ν below a few hundred MeV. The E_ν^6 behavior can only be valid below threshold for nucleon excitation; contributions of Compton-like scattering and Δ excitation

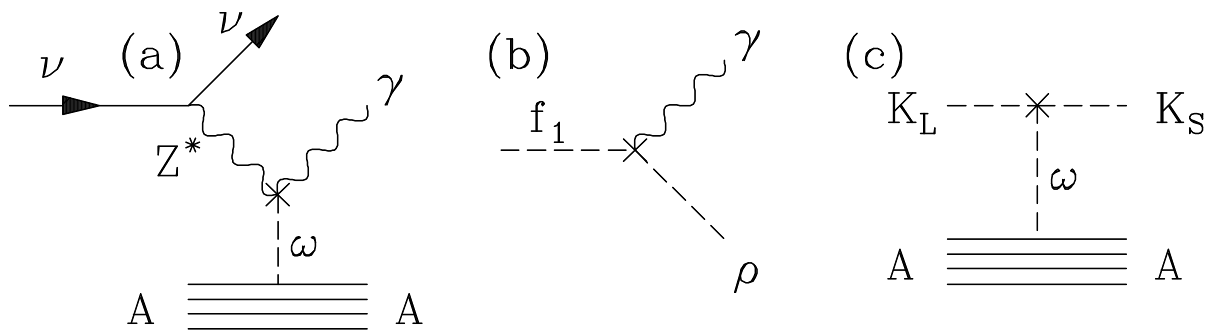

Figure 1: Processes sensitive to WZW anomalies: (a) Coherent reaction $\nu A \to \nu\gamma A$ on a nucleus of atomic number A ; (b) Induced $f_1 \to \gamma\rho$ decay; (3) Coherent $K_L \to K_S$ regeneration on a nucleus of atomic number A.

are more important in this regime [12,13]. (For $E_\nu \simeq 20$ GeV, upper limits on neutral-current photon production contradict (2) [27].) For production on a nucleus of atomic number A, the right-hand side of Eq. (2) is to be multiplied by a factor less than A [12].

Ref. [4] quoted considerable uncertainty in the value of g_ω but noted that the nominal value $g_\omega = 10$ agreed roughly with the MiniBooNE signal interpreted as photons. This was found [12, 13] to be an overestimate, as a result of form factor and recoil effects, with Δ excitation and decay providing a dominant photon source, but the nominal value $g_\omega = 10$ was retained. Corrections for efficiency [17, 19] further reduced the expected signal. We shall use a_1 dominance of the weak neutral current to find an independent extimate of g_ω, finding a value close to 7. This strengthens the conclusions of Refs. [9–15, 17–19] that if the MiniBooNE signal is indeed found to be photons, the WZW anomaly is unlikely to be their dominant source.

III a_1 DOMINANCE OF NEUTRAL CURRENT

In the contribution (1) to the Lagrangian, the weak neutral current carried by the Z may be viewed as dominated by the $a_1(1260)$ meson. The matrix element between Z and a_1 may be written as $m_a f_a$, where [28] $m_a = 1230 \pm 40$ MeV and the neutral a_1 decay constant is to be determined. The interaction between a Z and a fermion-antifermion pair $f\bar{f}$ is

$$\mathcal{L}Zf\bar{f} = \frac{g_2}{\cos\theta_W}\bar{f}\gamma_\mu Z^\mu[(1-\gamma_5)a_L + (1+\gamma_5)a_R]f \ , \tag{3}$$

where the coupling constants a_L and a_R are listed in Table I.

The axial vector coupling is then

$$\mathcal{L}^{\rm axial}_{Zf\bar{f}} = \frac{g_2}{\cos\theta_W}\bar{f}\gamma_m u\gamma_5 Z^\mu(a_R - a_L)f \ , \tag{4}$$

Table I: Coupling constants of $f\bar{f}$ to the Z. Here $x_W \equiv \sin^2\theta_W$.

$f\bar{f}$ pair	a_L	a_R
$\nu\bar{\nu}$	$\frac{1}{4}$	0
$\ell\bar{\ell}$	$\frac{1}{2}\left(-\frac{1}{2}+x_W\right)$	$\frac{1}{2}x_W$
$u\bar{u}$	$\frac{1}{2}\left(\frac{1}{2}-\frac{2}{3}x_W\right)$	$\frac{1}{2}\left(-\frac{2}{3}x_W\right)$
$d\bar{d}$	$\frac{1}{2}\left(-\frac{1}{2}+\frac{1}{3}x_W\right)$	$\frac{1}{2}\left(\frac{1}{3}x_W\right)$

where

$$(a_R - a_L)(u\bar{u}) = -\frac{1}{4} \ , \quad (a_R - a_L)(d\bar{d}) = \frac{1}{4} \ . \tag{5}$$

The quark content of a_1 is $(d\bar{d} - u\bar{u})/\sqrt{2}$, so the Z–a_1^0 coupling may be written as

$$g_{Za_1{}^0} = \frac{g_2 f_a m_a}{2\sqrt{2}\cos\theta_W} \ . \tag{6}$$

Assuming a_1 dominance of the weak neutral current, Eq. (1) then may be written as

$$\delta\mathcal{L} = \frac{f_a}{2\sqrt{2}m_a}\epsilon_{\mu\nu\rho\sigma}\omega^\mu Z^\nu F^{\rho\sigma} \ g_{a\omega\gamma} \ . \tag{7}$$

Equating coefficients of equal terms in Eqs. (1) and (7) and taking $N_c = 3$, we find

$$g_{a\omega\gamma} = \frac{e g_\omega}{4\sqrt{2}\pi^2} \ \frac{m_a}{f_a} \ . \tag{8}$$

We shall evaluate f_a in the next Section.

IV EVALUATION OF f_{a_1}

The decays $\tau^- \to \pi^- \nu_\tau$ and $\tau^- \to \rho^- \nu_\tau$ are described by simple expressions involving the pion and rho decay constants, respectively (see, e.g., Ref. [29].) The corresponding expression for the decay $\tau^- \to a_1^- \nu_\tau$, in terms of the decay constant f_a linking the Z and the neutral a_1, is

$$\Gamma(\tau^- \to a_1^- \nu_\tau) = \frac{G_F^2 m_\tau^3 f_a^2}{8\pi}|V_{ud}|^2 \left(1 + \frac{2m_a^2}{m_\tau^2}\right)\left(1 - \frac{m_a^2}{m_\tau^2}\right)^2 \ . \tag{9}$$

The Particle Data Group does not give a branching fraction for this decay. However, assuming that the quoted branching fractions [28]

$$\mathcal{B}(\tau^- \to \pi^-\pi^0\pi^0\nu_\tau) = (9.30 \pm 0.11)\% \ , \quad \mathcal{B}(\tau^- \to \pi^-\pi^+\pi^-\nu_\tau) = (8.99 \pm 0.06)\% \tag{10}$$

are dominated by the a_1, one obtains $\mathcal{B}(\tau^- \to a_1^- \nu_\tau) = (18.29 \pm 0.13)\%$. Using the values $G_F = 1.16638 \times 10^{-5}$ GeV^{-2}, $m_\tau = 1776.82 \pm 0.16$ MeV, $|V_{ud}| = 0.97425 \pm 0.00022$, $m_a = 1230 \pm 40$ MeV, and $\tau_\tau = 290.3 \pm 0.5$ fs quoted in [28], we find a decay constant $f_a = (164.6 \pm 7.3)$ MeV, where the error is dominated by uncertainty in m_a. In our convention f_a refers to the *neutral* current, whereas most authors quote a value which in our notation would be $\sqrt{2} f_a$. Our value is consistent with several others obtained theoretically or extracted from data [30, 31]. The resulting decay constant may now be used in Eq. (8) to obtain the result $g_{a\omega\gamma} = (0.0405 \pm 0.0005) g_\omega$.

V EVALUATION OF $g_{a\omega\gamma}$ USING $f_1 \to \gamma\rho$ RATE

The coupling constants $g_{a\omega\gamma}$ and $g_{f\rho\gamma}$ both involve the isovector photon coupling to an isovector and isosinglet, and are equal by U(3) symmetry as long as f_1 contains no strange quarks: $g_{f\rho\gamma} = g_{a\omega\gamma}$. The rate for $f_1 \to \gamma\rho$ is given (see also Appendix C of Ref. [11]) by

$$\Gamma(f_1 \to \gamma\rho) = \frac{g_{f\rho\gamma}^2}{3\pi} \frac{E_\gamma^3}{m_\rho^2} \left(1 + \frac{m_\rho^2}{m_f^2}\right) = (26.6 \pm 0.7) g_\omega^2 \text{ keV} , \tag{11}$$

where we have used $m_\rho = (775.25 \pm 0.25)$ MeV, $m_f = (1281.9 \pm 0.5)$ MeV, and $E_\gamma = (m_f^2 - m_\rho^2)/(2m_f) = (406.5 \pm 0.4)$ MeV. The first and second terms in large parentheses correspond to longitudinal and transverse ρ polarizations, respectively, so longitudinal ρ polarization is dominant [22, 33], in contradiction to the result found in Ref. [32].

The experimental partial width for $f_1 \to \gamma\rho$ is the product of the total f_1 width and the corresponding branching fraction [28]:

$$\Gamma(f_1 \to \gamma\rho) = \Gamma(f_1)\mathcal{B}(f_1 \to \rho\gamma) = (24.2 \pm 1.1) \text{ MeV})(0.055 \pm 0.013) = (1.33 \pm 0.32) \text{ MeV} . \tag{12}$$

When combined with Eq. (11) this yields $g_\omega = 7.07 \pm 0.86$, where the error is dominated by the experimental error in Eq. (12). This value is lower than the nominal one of 10 taken in [4, 12], and leads to an anomaly contribution only about 1/4 of that previously estimated, thanks to the quartic power of g_ω in Eq. (2).

The systematic errors that we are able to identify tend to decrease g_ω by a modest amount. We have taken $\mathcal{B}(\tau \to a_1 \nu_\tau)$ to be as large as possible when ascribing all the $3\pi\nu_\tau$ decays to a_1. If $\mathcal{B}(\tau^- \to a_1^- \nu_\tau)$ is smaller, f_a is smaller, the coefficient of g_ω is larger in Eq. (8), so g_ω is smaller. We have also assumed the anomaly to fully account for the $f_1 \to \rho\gamma$ decay rate, whereas a small quark model contribution of 150 keV was predicted in Ref. [22]. It is not clear whether the decay amplitude for longitudinal ρ production predicted in Ref. [22] should be added coherently to that predicted here.

Table II: Photon energies, predicted decay rates, and range of predicted branching fractions for the decays $a_1 \to \gamma\omega$ and $a_1 \to \gamma\rho$.

Final state f	E_γ (MeV)	Γ_f	$\mathcal{B}_f$
$\gamma\omega$	366	(0.98 ± 0.24) MeV	$(1.2\text{–}4.9)\times10^{-3}$
$\gamma\rho$	371	(115 ± 28) keV	$(1.4\text{–}5.7)\times10^{-4}$

VI RATES FOR $a_1^0 \to \gamma\omega$ AND $a_1 \to \gamma\rho$

The decay $f_1 \to \gamma\rho$ is related by U(3) symmetry to the decays $a_1 \to \gamma\omega$ and $a_1 \to \gamma\rho$:

$$g^2_{a\omega\gamma} = 9g^2_{a\rho\gamma} = g^2_{f\rho\gamma} = 0.082 \pm 0.020 \ , \tag{13}$$

where we have used the experimental value (12) in the expression (11) for the $f_1 \to \gamma\rho$ rate. The corresponding formulae for the a_1 radiative decay widths are

$$\Gamma(a_1^0 \to \gamma\omega) \ = \ \frac{g^2_{a\omega\gamma}}{3\pi}\frac{E_\gamma^3}{m_\omega^2}\left(1 + \frac{m_\omega^2}{m_a^2}\right) \ , \tag{14}$$

$$\Gamma(a_1 \to \gamma\rho) \ = \ \frac{g^2_{a\rho\gamma}}{3\pi}\frac{E_\gamma^3}{m_\rho^2}\left(1 + \frac{m_\rho^2}{m_a^2}\right) \ , \tag{15}$$

where the photon energies, predicted rates, and range of predicted branching fractions (using $\Gamma_{\rm tot}(a_1) = 250$ to 600 MeV [28]) are shown in Table II. We have used $m_\omega = (782.65 \pm 0.12)$ MeV. The expression (15) holds for all a_1 charge states.

The branching fractions in Table II are quite small because of the large a_1 total width. Nevertheless, it may be possible to see the decay $a_1^- \to \gamma\rho^-$ in the final state of $\tau^- \to a_1^-\nu_\tau$. The subprocess $a_1^0 \to \gamma\omega$ may be observable through coherent photoproduction of a_1^0 on a heavy nucleus $a = A$: $\gamma A \to a_1^0 A \to \pi^+\pi^-\pi^0 A$, proceeding via ω exchange.

VII SUMMARY

A neutral-current interaction based on the Z–ω–γ interaction depicted in Fig. 1(a) is predicted [4] on the basis of a Wess-Zumino-Witten anomaly [6,7]. This interaction is calibrated with the help of the decay $\tau \to a_1\nu$. It leads to a prediction for the low-energy signal in the MiniBooNE experiment [1], if interpreted in terms of photons rather than electrons or positrons, which is about a fourth of that previously estimated, which already was below the needed magnitude. (One proposed source of photons is the decay of a quasi-sterile neutrino with mass between 40 and 80 MeV [34, 35].)

For the future one looks forward to tests of the predicted rates for $a_1 \to \gamma\omega$ and $a_1 \to \gamma\rho$, to a more precise estimate of f_a, and to an experimental distinction between electrons or positrons and photons in the final state studied by MiniBooNE. The MicroBooNE experiment [21], soon to begin operation at Fermilab, should resolve the question.

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