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MEASUREMENT OF W-Z INTERFERENCE FROM NEUTRINO-ELECTRON SCATTERING

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ABSTRACT

Neutrino-electron elastic scattering was observed at LAMPF with a 15-ton fine-grained tracking calorimeter exposed to electron-neutrinos from muon decay at rest. The measured $\nu_e e^- \rightarrow \nu_e e^-$ elastic scattering cross section, $10.0 \pm 1.5(stat) \pm 0.9(syst) \times 10^{-45}\mathrm{cm}^2 \times (E_\nu(\mathrm{MeV}))$, gives a model independent measurement of the strength of the destructive interference between the charged and neutral currents, $I = -1.07 \pm 0.21$, that agrees well with the standard model (SM) prediction $I = -1.08$. The agreement between the measured electroweak parameters and SM expectations is used to place limits on neutrino properties, such as neutrino flavor-changing neutral currents and neutrino electromagnetic moments, and on the masses of hypothetical new bosons that would interact with leptons.

INTRODUCTION

Neutrino-electron scattering is a simple and fundamental process with great sensitivity to aspects of the standard model (SM), including dynamic properties of the weak interaction, such as the weak mixing angle $\sin^2\theta_W$ and the interference between charged- and neutral-current amplitudes, and static properties of the neutrino, such as electromagnetic moments and neutrino decay. It is a purely weak, purely leptonic two body reaction which makes both the theoretical cross-section calculations and the experimental signatures straightforward. The history of the field starts with a 1932 paper by Carlson and Oppenheimer [1] on the scattering of a neutrino "...carrying a magnetic moment ... ." A search for such an effect (the first of many upper limits connected with neutrinos!) was made in 1935 by Nahmias [2]; attempts to detect $\nu_e e^-$ scattering continued, leading to the possible observation in 1977 of $\bar{\nu}_e e^-$ scattering [3].

The present program has suceeded [4] in measuring the absolute cross section for $\nu_e e^-$ elastic scattering and the interference term I between $W^\pm$ and Z^0 exchange as tests of the SM, and has set new limits on several neutrino properties that are not contained in the minimal SM. The elastic scattering of electron neutrinos by electrons, $\nu_e e^- \to \nu_e e^-$, occurs through the exchange of both $W^\pm$ and Z^0 bosons as shown by the Feynman diagrams in Fig. 1. Therefore, the cross-section is sensitive to the interference (I) of the weak neutral-current (NC) and weak charged-current (CC) amplitudes [5]. Precise measurements of $\sin^2\theta_W$ now probe the SM at the level of radiative corrections; however,the NC/CC interference present in $\nu_e e^- \to \nu_e e^-$ represents a tree-level prediction that had not been confronted before the present experiment.

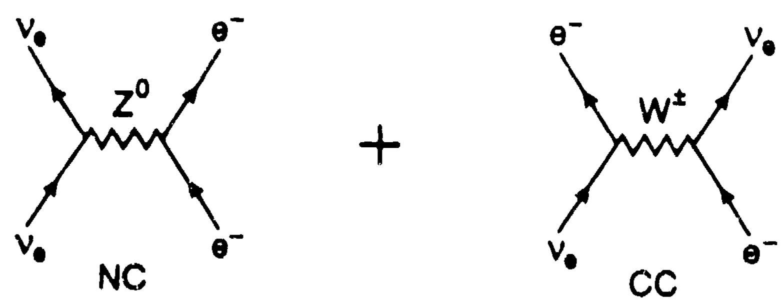

Fig. 1. Feynman diagram for $\nu_e + e^- \to \nu_e + e^-$ showing the weak charged and neutral current amplitudes.

The experiment described here, a collaboration (E225) between UC Irvine, Los Alamos, Argonne and the University of Maryland, and Tel Aviv, utilized the ~~intense~~ flux of ν_e, ν_μ, and $\bar{\nu}_\mu$ neutrinos available at the LAMPF proton beam stop. A fine-grained, 15 ton, tracking detector was used to measure the energy (resolution of 14 %) and track direction (resolution of 8°) of the recoil electrons. The electron from a $\nu_e e^-$ scattering recoiled along the neutrino direction with an angle less than 16°, whereas backgrounds were essentially isotropic. The $\nu_e e^-$ signal is then apparent in the recoil angular distribution as a pronounced peak in the forward direction. The experimentally observed angular distribution, and clear νe^- peak, is shown in Fig. 2.

CROSS SECTION AND INTERFERENCE

The rate for $\nu_e e^-$ scattering is obtained by subtracting the $(\nu_\mu + \bar{\nu}_\mu)e^-$ events, and yields an absolute cross section, for a mean energy $\langle E_{\nu_e} \rangle = 31.7$ MeV, of $\sigma(\nu_e e^-)/E_\nu = 10.0 \pm 1.5 \pm 0.9 \times 10^{-45} cm^2/MeV$. The interference term is measured directly, and in a model independent manner, by the difference between the measured elastic scattering total cross-section and the sum of the two 'conventional' contributions, $\sigma^I = \sigma^{tot} - \sigma^{CC} - \sigma^{NC}$, where the conventional terms, σ^{CC} and σ^{NC}, have been measured in muon-decay and in $\nu_\mu e^- \to \nu_\mu e^-$ scattering. The experimental result is $I = -1.07 \pm 0.21$. For $\sin^2\theta_W = 0.23$, the SM predicts that $I = -1.08$; the agreement between experiment and the SM is (dismayingly?) excellent.

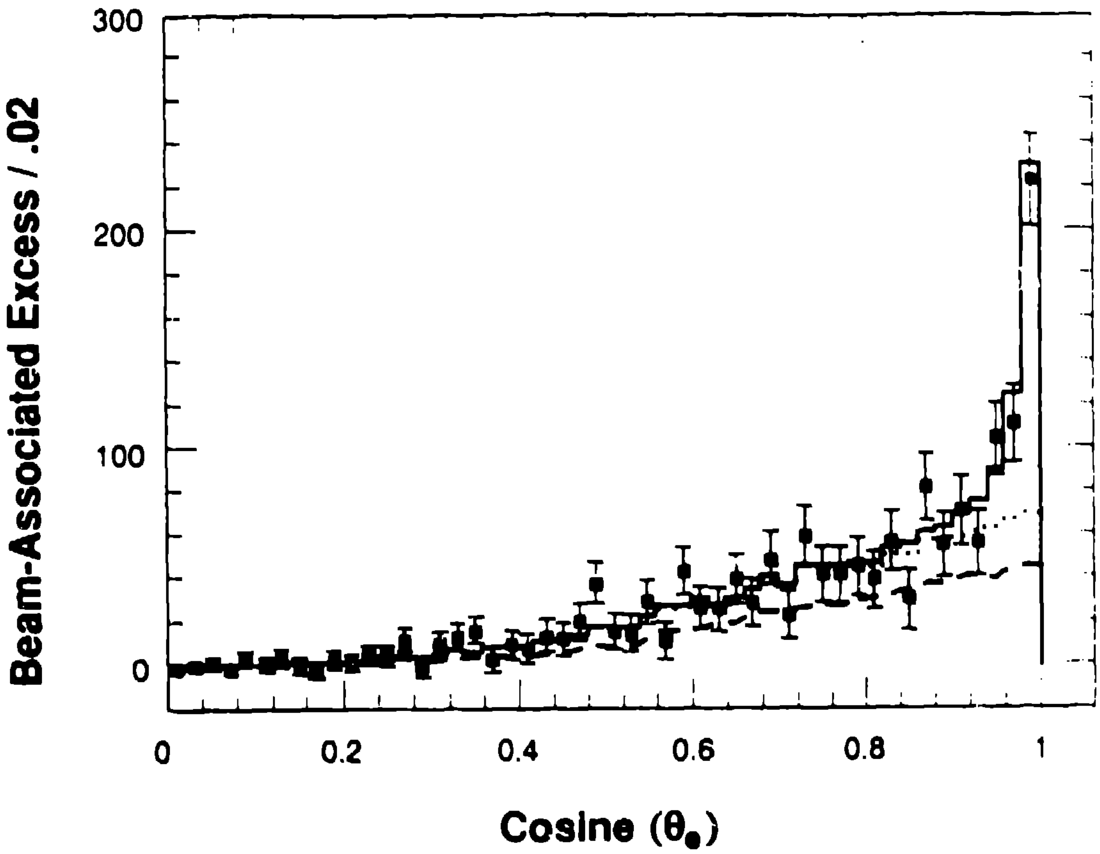

Fig. 2. The observed angular distribution of the beam-associated recoil electrons. Here, $\theta_{e\nu}$ is the angle between the incident neutrino and the reconstructed recoil electron. The solid line indicates the fit to the Monte Carlo distributions for the expected signal and backgrounds. The dotted line indicates the total background, while the dashed line indicates the neutrino induced background only.

NEUTRINO PROPERTIES

It is the comparison of the measured $\nu_e e^-$ strength to that predicted by the electroweak SM that places limits on non standard physics. A listing of neutrino properties, and of the new results from LAMPF, are displayed in Table 1. A neutrino magnetic moment would be manifest as an excess of elastic scattering events. From a fit to the experimental angular distribution we find $11 \pm 35(stat) \pm 25(syst)$ events above expectations from the minimal SM. Including systematic and statistical uncertainties, the observed event limit for a

Type	Property	Value	New Limit
ν_e	Mass	< 9 eV	
	Charge	0	
	Spin	1/2	
	μ_ν	$< 7 \times 10^{-10}\ \mu_{Bohr}$	$< 10.8 \times 10^{-10}\ \mu_{Bohr}$
	r	?	$< 2.3 \times 10^{-16}\ cm$
	$1 - f_{ee}$	?	< 0.35
	$\tau / m_{\bar{\nu}_e}$	$> 5 \times 10^3\ sec/eV$	
ν_μ	Mass	$< 270\ keV$	
	Charge	0	
	Spin	1/2	
	μ_ν	$< 8.5 \times 10^{-10}\ \mu_{Bohr}$	$< 7.4 \times 10^{-10}\ \mu_{Bohr}$
	$\lvert r \rvert$	$< 1.6 \times 10^{-16}\ cm$	
	$1 - f_{\mu\mu}$	?	
	τ / m_{ν_μ}	$> 0.11\ sec/eV$	$>$ [illegible] sec/eV

Table 1: Properties of ν_e and ν_μ neutrinos. The present values and limits are listed in the third column. New limits from E225 are given in the final column.

possible magnetic moment scattering is $N_{obs}^{mag} < 68$ events at 90 % confidence level; this translates to 90 % confidence limits on the neutrino magnetic moments of $\mu_{\nu_e} < 10.8 \times 10^{-10} \mu_{Bohr}$ and $\mu_{\nu_\mu} < 7.4 \times 10^{-10} \mu_{Bohr}$. The upper limit obtained for for μ_{ν_e} is consistent with that for $\mu_{\bar{\nu}_e}$ from a reactor experiment, while the bounds on μ_{ν_μ} are more restrictive than previous results.

In contrast with the magnetic dipole moment, the neutrino charge radius is not gauge invariant, nevertheless, a measureable neutrino charge-radius form factor can be defined for low q^2 laboratory interactions as an additive correction to the effective weak neutral-current vector coupling, g_V. A non zero charge radius shifts g_V from its uncorrected value to $g_V = -\frac{1}{2} + 2(\sin^2\theta_W + \delta)$ where $\sin^2\theta_W$ is the weak mixing angle measured in non neutrino interactions and $\delta = (\sqrt{2}\pi\alpha/3G_F)\langle r^2\rangle = 2.39 \times 10^{30}\mathrm{cm}^{-2}\langle r^2\rangle$. From the LAMPF experiment we find the radiative correction to be $-0.170 < 2\delta < 0.260$. This leads immediately to the 90% confidence limits, $-3.56 \times 10^{-32}\mathrm{cm}^2 < \langle r^2\rangle < 5.44 \times 10^{-32}\mathrm{cm}^2$. Thus, the ν_e charge radius is $\lvert r \rvert < 2.2 \times 10^{-16}$ with 90 % confidence, which represents a new upper bound on the dimensions of internal structure of the electron neutrino. This result can also be interpreted directly as an upper limit against a possible ν_e anapole moment. Although these limits represent the first laboratory limits on the size of internal structure of the electron neutrino, the experimental precision on g_V must

Coupling	Charge	Mass Limit
T	Neutral	$105 GeV$
S,P	Neutral	$47 GeV$
Higgs (S)	Charged	$87 GeV$
Left-handed (V,A)	Neutral	$119 GeV$
"	Charged	$240 GeV$

Table 2: Limits on new gauge boson masses for S,P,T,V and A couplings.

be improved by more than an order of magnitude to be sensitive to the expected SM radiative corrections, and so to provide a definitive test of the SM radiative correction scheme.

Consideration of weak neutral currents has been central to the development of the SM of electro-weak interactions. Much of the formal structure of the SM derives from the necessity to eliminate flavor-changing neutral currents (FCNC) at the tree-level since such currents have not been observed experimentally. The interference effect in $\nu_e e^-$ scattering requires the outgoing neutrino to be the same type, i.e. ν_e, as the incoming neutrino; thus $\nu_e e^-$ is sensitive to FCNC's. A convenient way to search for such a phenomena would be to compare the measured value of the weak-mixing angle from $\nu_e e^-$ scattering, $\bar{\theta}_W$, with that extracted from non-neutrino processes. A framework in which to discuss FCNC in neutrino-lepton currents begins with the introduction by Okun' of purely phenomenological couplings f_{ee}, $f_{e\mu}$, and $f_{e\tau}$ where $1 = f_{ee}^2 + f_{e\mu}^2 + f_{e\tau}^2$ and the SM is recovered by setting $f_{e\mu} = f_{e\tau} = 0$. If we label the weak-mixing angle extracted from $\nu_e e^-$ elastic scattering as $\bar{\theta}_W$, and the weak-mixing angle derived from the $W^{\pm}$ and Z^0 masses as θ_W, we have $1 - f_{ee} = (\sin^2\bar{\theta}_W - \sin^2\theta_W)[1 + \frac{4}{3}(\sin^2\theta_W + \sin^2\bar{\theta}_W)][(1 - 2\sin^2\theta_W)]^{-1}$. Explicit limits from this experiment give the mean value $f_{ee} = 0.93$, and the 90% confidence limit for an off-diagonal, flavor-changing coupling, as $1 - f_{ee} < 0.35$. Alternatively, through use of the normalization relation, we have a limit on the total strength of flavor-changing transitions of $f_{e\mu}^2 + f_{e\tau}^2 < 0.58$ (90% CL)

NEW BOSONS

Finally, we can place limits on the cross section for exchange of scalar, vector or tensor bosons which are not included in the SM. The observed νe^- elastic scattering rate, 295 ± 35, is to be compared to the SM prediction of 284 ± 26. Therefore, at 90 % confidence level, anomalous (beyond the SM) interactions contribute fewer than 78 events. Schematically, the strength of any new interaction ($\Delta\sigma$), after accounting for experimental detection efficiency ϵ_{new} for the proposed differential cross sections, must be small enough to fall within the bound $\Delta\sigma < \frac{\epsilon_{SM}}{\epsilon_{new}} \cdot \frac{74}{223}\sigma_{SM}$.

with $\epsilon_{SM} = 0.164$ and $\sigma_{SM} = 2.20\ \sigma_0$. If terms proportional to m_e/E_ν are ignored, then the differential cross section for *any* interaction composed of the sum of S, P, T, V, A components can be expressed as $d\sigma/dy \propto A + B(1-y) + C(1-y)^2$ and the total cross section is simply $\sigma = (A + B/2 + C/3)\sigma_0$. We can extract general limits on the mass/couplings ratios for scalar and tensor interactions, as listed in Table 2.

As an example, for the case of a purely spin-2 T interaction ($S = P = 0$), we find that $T = 2(\eta_T M_W)/(gM_Z) < 0.379$. If the tensor boson couples with same strength as the weak charged-current ($\eta_T = g$), this limit would imply that the neutral tensor boson must be heavier than $M_T > 1.15 M_Z \approx 105$ GeV. In general, limits obtained here on the mass of hypothetical bosons are similiar to limits obtained by direct searches for such bosons in collider experiments. However, limits from neutrino-electron scattering would be important for ruling out particular extensions of the SM which involve bosons that couple mainly, or only, to leptons, or weak interactions that only couple fermions within the same weak isodoublet.

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