LEGIBILITY NOTICE

A major purpose of the Technical Information Center is to provide the broadest dissemination possible of information contained in DOE's Research and Development Reports to business, industry, the academic community, and federal, state and local governments.

Although a small portion of this report is not reproducible, it is being made available to expedite the availability of information on the research discussed herein.

CONF-880364--1

LA-UR--88-892

DE88 007833

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36

TITLE: PRESENT AND FUTURE NEUTRINO PHYSICS RESEARCH AT THE LOS ALAMOS MESON PHYSICS FACILITY

AUTHOR(S): Gary H. Sanders

SUBMITTED TO: Present invited talk to INS International Symposium on Neutrino Mass and Related Topics, Tokyo; visit KAMIOKANDE detector site near Toyama; visit KEK, Tokyo

3/16 - 3/18/88

MASTER

Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

FORM NO 836 R4
ST NO 2629 5/81

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Present and Future Neutrino Physics Research at the Los Alamos Meson Physics Facility

Gary H. Sanders

Los Alamos National Laboratory, Los Alamos, NM 87544 USA

The Los Alamos Meson Physics Facility is currently the site of two neutrino experiments. A measurement of elastic scattering of electron-neutrinos on electrons is providing confirmation of the destructive interference between the weak neutral and charged currents predicted in the standard electroweak theory. A search for the appearance of $\bar{\nu}_e$ is being carried out at the LAMPF beam stop, as well. The status of this experiment is described. A major new initiative is being undertaken to measure neutrino-electron scattering in a large water Čerenkov detector. This measurement will be precise enough to provide, in combination with the measurements to be performed at the new generation of high-energy electron-positron colliders, the first experimental study of the standard electroweak theory at the level of one-loop radiative corrections. The detector will also be a vehicle for neutrino-oscillation searches, measurement of neutrinos from supernovae, and other fundamental physics. The apparatus will consist of a neutrino production target and shield surrounded by a water Čerenkov detector. The fiducial volume of water will be approximately 7000 tons, viewed by approximately 13000 20 cm diameter photomultiplier tubes.

Introduction

The 800 MeV, 1 ma average proton current beam from the linear accelerator at the Los Alamos Meson Physics Facility (LAMPF) is currently being used to complete two major neutrino experiments. In addition, a major new initiative to explore neutrino-electron scattering with a large water Čerenkov detector has begun. The new Large Čerenkov Detector (LCD) will exploit the unique beam characteristics available at LAMPF to carry out a precision test of the standard electroweak theory. This test will be sensitive to the radiative corrections which modify neutrino-electron scattering at the one-loop level.

The proton beam available from the LAMPF linear accelerator is characterized by very high current (< 1 ma) and low duty factor (6-10%). The resulting high beam power facilitates a bright beam stop neutrino source. The low duty factor aids in the suppression of cosmic ray induced backgrounds.

This beam has been used in a study of the nature of muon-number conservation which favored additive muon-number conservation.[1] The beam stop source has been used to measure the rate of electron-neutrino elastic scattering on electrons as a search for interference between the amplitudes of the charged and neutral weak currents.[2] The standard electroweak theory provides a quantitative prediction of destructive interference which reduces the rate at which this scattering is observed. The beam stop is also a source for a current search for oscillation of ν_μ, $\bar{\nu}_\mu$ or ν_e into $\bar{\nu}_e$, often described as an appearance experiment.[3]

The LAMPF accelerator facility includes a new proton storage ring (PSR).[4] The extracted beam from the PSR has an energy of 800 MeV, a design current averaging 100 μA, with a unique, short pulse structure. Typically, pulses 270 ns long, at a repetition rate of 12 Hz, provide the design current. The exceptionally short pulses and low duty factor aid removal of cosmic ray induced backgrounds in a typical neutrino experiment. Even more important, this pulse structure permits a clean time separation of neutrinos produced by pion decay (ν_μ) and those produced by muon decay (ν_e and $\bar{\nu}_\mu$). Thus, two nearly simultaneous, interspersed, but distinguishable neutrino beams are available from a beam stop illuminated by the PSR beam. This capability is unique at LAMPF. It enables the planned study of neutrino-electron scattering with the Large Čerenkov Detector (LCD).

Elastic Scattering of Electron-Neutrinos on Electrons

In the standard model, electron-neutrino scattering on electrons involves the exchange of both charged W bosons and the neutral Z boson and the interference between these two amplitudes. The Feynman diagrams for these two currents are shown in Fig. 1.

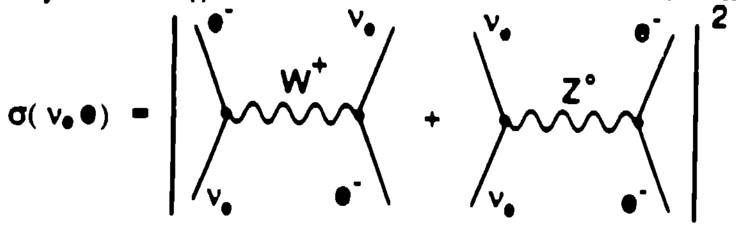

Figure 1. Scattering of electron-neutrinos on electrons proceeds via a mixture of the neutral weak current in which the Z^0 is exchanged, and the charged weak current in which the W^- is exchanged. Interference between these two amplitudes contributes to the observed rate for the scattering.

These reactions are analogous to electron-electron scattering processes in which the exchanged vector particle is the photon. The unique feature of the neutrino scattering process is its purely weak character. The standard model prediction for this rate is

$$\sigma(\nu_e e^-, theory) = 9.2 E_\nu(GeV) \times 10^{-42} cm^2 \quad ,$$

which includes a substantial contribution from destructive interference of the two amplitudes.

The experiment (LAMPF experiment 225), an Irvine-Los Alamos-Maryland collaboration, used a beam stop neutrino source with a well known spectrum of neutrinos from pion and muon decay. The detector was designed to detect the recoiling electron from the scattering process, and eliminate false events from other sources. The detector is shown in Fig. 2. The passive and active anti-coincidence shields are indicated, as is the fine-grained active volume, which serves to record the electron tracks. The active volume was instrumented with layers of plastic scintillators (10 tons) and tracking chambers (4.5 tons) comprised of 208,000 flash chambers.

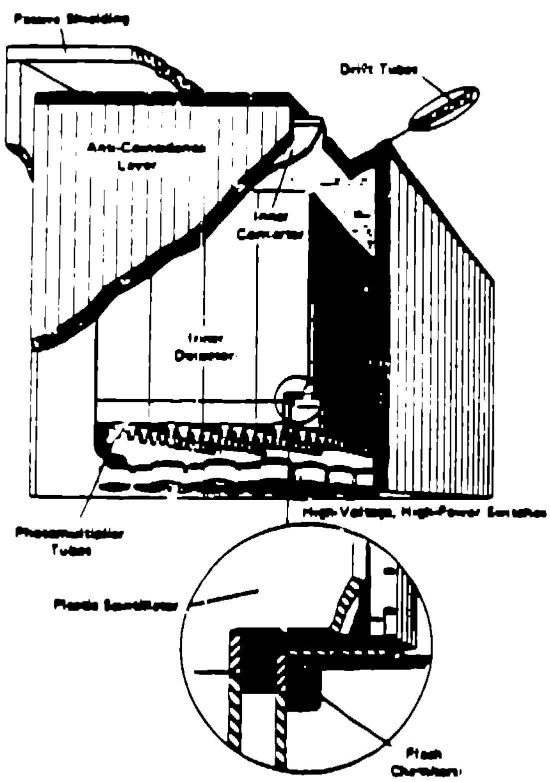

Figure 2. The detector for the measurement of electron-neutrino scattering on electrons. Surrounding the primary detector is a passive shield to reduce cosmic ray induced backgrounds, an active anti-coincidence layer which additionally rejects electrons from muon decays in the passive shield, and an inner converter which rejects photons and beam associated penetrating particles.

The experimental team has completed all data collection and is preparing its final publication. Electron-neutrino scattering on electrons produces recoil electrons in the forward direction. The angular distribution shown in Fig. 3 clearly shows this forward peak. The spectrum includes both muon-neutrino and electron-neutrino scattering and contributions from background processes such as scattering of neutrinos on ^{12}C and ^{13}C and neutron-proton scattering. The Monte Carlo calculation includes all background processes, shown in the solid line histogram. Subtraction of these backgrounds leaves 304 ± 49 events

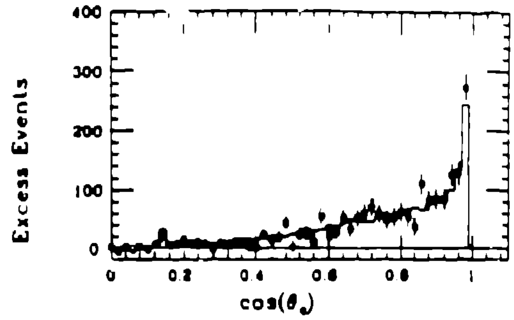

Figure 3. The angular distribution of events recorded in the study of electron-neutrino elastic scattering on electrons. The forward peak is clearly visible. The solid line shows the Monte Carlo prediction of all backgrounds.

assigned to all types of neutrino scattering on electrons. Further subtraction of the portion assigned to $\bar{\nu}_\mu$ and ν_μ scattering on electrons, based upon measured cross-sections from other experiments, leaves 251 $\pm$ 50 events from electron-neutrinos. This agrees well with the standard model prediction. Currently, the team quotes an experimental rate

$$\sigma(\nu_e\, e^-, exp) = 10.7 \pm 2.5 E_\nu(GeV) \times 10^{-42} cm^2 \quad ,$$

which should be compared to the theoretical prediction above. The result is consistent with the destructive interference which results in the standard model, and is nearly five standard deviations away from constructive interference. These results are currently undergoing final corrections.

Search for Neutrino Oscillations (Appearance of $\bar{\nu}_e$)

The LAMPF beam stop is also the site of a search for the appearance of $\bar{\nu}_e$ in a large detector that is exposed only to incoming ν_e, ν_μ, and $\bar{\nu}_\mu$. These neutrino varieties come from π^+ decay in the beam stop, whereas the π^- component is captured, leaving at most a contamination of $\bar{\nu}_e$ below the 10^{-3} level.

The experiment (LAMPF experiment 645) is an Argonne-Caltech-LBL-LAMPF-Louisiana State-Ohio State collaboration. The detector is shown in Fig. 4. It consists of an active cosmic-ray shield made up of liquid scintillators, a passive shield made of lead, a 2000 gm/cm^2 overburden to reduce incoming neutral particles, and a 20-ton active detector made up of liquid scintillators and drift tubes. The central detector is sensitive to $\bar{\nu}_e$ by observing the recoil positron from inverse beta decay [p($\bar{\nu}_e$,e$^+$)n], and has limited neutron detection capability. The detector views the beam stop from a distance of 20 m. In the usual two-component description of oscillations, this experiment has an L/E$_\nu$ = 0.65. Its sensitivity is similar to that of other experiments at higher energy.

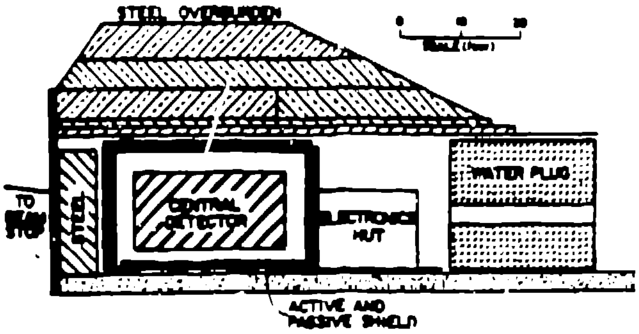

Figure 4. The neutrino detector and cosmic ray shield used in the LAMPF search for the appearance of $\bar{\nu}_e$.

The team had a short run in 1986, which revealed a large neutral background. This was traced to a surprising forgotten beam pipe that viewed the beam stop. In a long 1987 data run, the background problems were solved and the data set is undergoing the last corrections in the analysis. They are sensitive to oscillations at the 1% level. They observe a beam-associated excess of electron tracks at a level consistent with backgrounds from scattering of ν_e on ^{12}C and on electrons. At this point, they are claiming no evidence for an oscillation and are expected to present a final statement very soon.

The Large Čerenkov Detector

During the next 5-10 years, the new high-energy electron-positron colliders will measure the mass of the W and Z bosons to very high precision. This measurement will provide an accurate determination of the electroweak mixing angle θ_W of the electroweak theory. However, only when combined with a sufficiently accurate measure of this angle at low energies can the predictions of the electroweak theory be verified at the level of one-loop radiative corrections.[5] The high-energy measurements address only the first-order "tree-level" contributions. Deviations from the standard model predictions are a signature of new physics.

A low-energy measurement of the electroweak parameter based upon neutrino-electron scattering is particularly clean because of the simplicity of the neutrino-Z vertex. The value obtained from neutrino-electron scattering at LAMPF energies can differ from the collider value by as much as 7%, due to the energy-dependent radiative corrections. Furthermore, only the beam properties at LAMPF make this measurement possible at the required precision. The precision proposed for the LAMPF Large Čerenkov Detector is better than 1%.

In the standard model, it can be shown that the ratio of scattering cross-sections

$$R = \frac{\sigma(\nu_\mu e)}{\sigma(\nu_e e) + \sigma(\bar{\nu}_\mu e)}$$

can be written in terms of the mixing angle as, if $s = \sin^2 \theta_W$,

$$R = \frac{3}{4} \quad \frac{1 - 4s^2 + \frac{16}{3}s^4}{1 + 2s^2 + 8s^4}$$

By measuring the ratio R to better than 2% precision, the mixing angle is determined to better than 1% precision. It is this measurement of neutrino-electron scattering that will be carried out with the new Large Čerenkov Detector at LAMPF, by a Los Alamos-Irvine-UCLA-Colorado-CEBAF-New Mexico-Pennsylvania-Temple-William and Mary-Riverside collaboration.

The conventional way to measure this ratio would be to employ two different neutrino beams, one rich in ν_μ and a second beam rich in ν_e and $\bar{\nu}_\mu$, in sequence. The first species is produced in pion decay, the second in muon decay. Changing over from a pion rich to muon rich beam might be done in alternate months of running, for example. Carrying out a precision experiment in this manner would be very difficult. The time structure of the LAMPF beam, as prepared by the new Proton Storage Ring, is a 270 ns long pulse repeated 12 times per second. Since pion decay and muon decay are characterized by such widely differing lifetimes, neutrinos observed in the first several hundred nanoseconds are those in the numerator of the expression defining R. The muon decays occur over several microseconds, yielding the cross-sections in the denominator. Thus every PSR pulse yields a neatly time-separated neutrino beam. Figure 5 shows this neutrino yield as a function

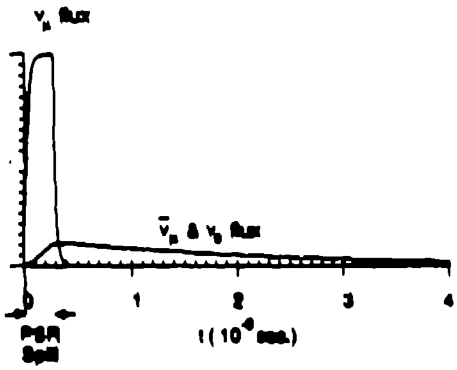

Figure 5. Time distribution of neutrinos from each pulse into the Large Čerenkov Detector beam stop.

of time from each PSR pulse. By recording the of time of each recoiling electron from a neutrino scatter, the ratio which determines R can be unfolded by fitting the time-dependence of the data set.

The Large Čerenkov Detector system is shown in an isometric drawing in Fig. 6. The PSR beam is transported in a 100 m long beam-line that features very low losses and a superconducting dipole that bends the beam 90° down into the LCD beam stop. The target is surrounded by a massive 15 m diameter iron shield designed to reduce all backgrounds from neutrons to an acceptable level. The neutrinos exit the shield into a cylindrical water tank 32.2 m in diameter and filled with water to a depth of 15.6 m. The outer veto region of the water is typically 1.5 m thick, and the fiducial volume contains approximately 7000 tons of water. Viewed by about 13000 photomultipliers, each approximately 20 cm diameter, the photocathodes cover nearly 20% of the tank surface. This fine grained imaging counter should achieve a 10 MeV threshold with 27 photoelectrons in a minimum of 20 phototubes as a primary trigger.

In a 625 day run, at 100 μA average beam current, there will be 12 events per day from $\nu_\mu e$ and 101 events per day from $\bar{\nu}_\mu e$ and $\nu_e e$, for a total of 7500 and 63,400 events, respectively. The total statistical error on R is about 1.6% from counting statistics, PSR pulse shape variations, cosmic ray and neutron induced background subtractions, and ν_e-oxygen scattering. Systematic errors total 1.86% in R. The combined total error in $\sin^2\theta_W$ is then 0.89%. Systematic errors come from decay in flight, cosmic rays, photons and $\pi^\pm$ from neutron interactions, threshold energy uncertainties and non-uniform efficiency.

The Large Čerenkov Detector will be capable of addressing several other fundamental topics at the same time the standard model study is carried out. These include several types of neutrino oscillation searches, searches for neutrino structure such as a charge radius or magnetic moment, observation of neutrino bursts from supernovae, searches for upward going muons, lepton number violation and heavy neutrinos or axions.

Neutrino oscillations can be detected in departures of the ratio R from the standard model predictions, observation of radial oscillations in the cylindrical detector volume and observation of a contribution to the ν_e-oxygen signal with a monoenergetic signature. Since the $\nu_e e$ cross-section is seven times larger than the other $\nu_\ell e$ cross-sections, LCD can search for the processes $\nu_e \longleftrightarrow \nu_\mu$ [6,7] and $\nu_e \longleftrightarrow \nu_\tau$ by measuring an increase in R. Disappearance experiments ($\nu_\mu \rightarrow \bar{\nu}_\mu$(sterile), $\nu_e \rightarrow \bar{\nu}_e$(sterile)) also show up as changes in R.

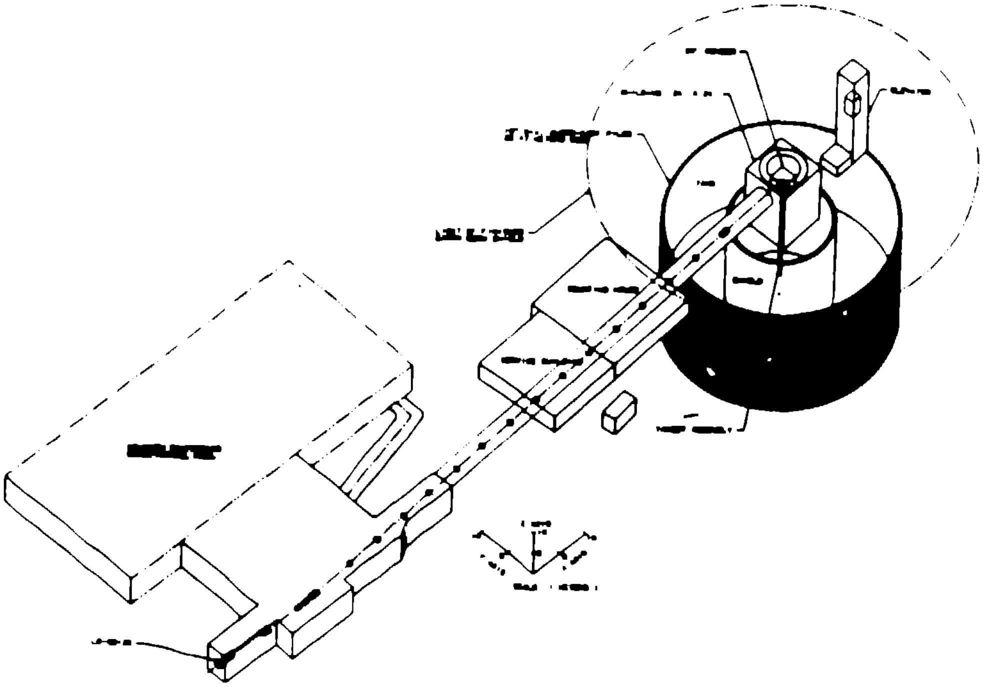

Figure 6. Isometric view of the Large Čerenkov Detector.

By unfolding the radial dependence of the events, oscillations that occur with a wavelength close to the tank radius are detectable, particularly in the prompt signal from the monoenergetic ν_μ, or in the ν_e-oxygen event radial distributions. Since the LCD beam stop produces monoenergetic ν_μ, the process $\nu_\mu \rightarrow \nu_e$ will result in prompt ν_e-oxygen events which are monoenergetic.

The best sensitivity will likely be achieved in the search for the process $\bar{\nu}_\mu \longleftrightarrow \bar{\nu}_e$, the same process sought in the current LAMPF experiment. In the LCD case, the signal is the inverse beta decay, which is observable above the leading background from ν_e-oxygen events. In the usual two-component oscillation description, LCD should achieve limits on the quantity $\sin^2 2\alpha$ of about 2×10^{-4}. Detailed sensitivities for these and other oscillation processes are presented in the full proposal.[8]

If the electron or muon neutrino has a sufficiently large magnetic moment or charge radius, then LCD will observe an anomalous value of R and an anomalous y distribution ($y = E_e/E_\nu$). A non-zero magnetic moment (or electric moment) increases the neutrino-electron cross section and makes the y distribution peaked toward $y = 0$. LCD would achieve sensitivity comparable to or better than limits derived from terrestrial or astrophysical considerations.[9,10,11] A non-zero charge radius can increase or decrease the cross section and has the effect of flattening the y distribution. LCD limits on such unexpected compositeness fall in the 10^{-33} cm^2 range, better than existing limits by an order of magnitude.

LCD is similar to IMB or KAMIOKANDE II in its ability to detect neutrinos, muons, and electrons from supernovae. Due to its thin overburden, it has significantly higher cosmic ray related back grounds. Nevertheless, electron neutrinos from the prompt collapse phase and delayed high-energy muon neutrinos can be detected.

LCD requires only a small enhancement to its data acquisition electronics to make this possible. Our estimate for the LCD response to another SN1987A is 35 events, or if this supernova were in our galaxy, 750 events. The range of our estimates for high multiplicity electrons reaches as high as 16000 events in 10 seconds.[8] For a modest addition to the hardware, this detector, easily maintainable for a decade because it is on-site at a large, national laboratory, offers an attractive capability in neutrino astronomy.

Separate experiments at LAMPF on lepton number conservation, electron neutrino scattering on electrons and searches for oscillations have set the stage for the next decade of LAMPF research with neutrinos using the Large Čerenkov Detector.

References

1. S. E. Willis et al, Neutrino Experiment to Test the Nature of Muon-Number Conservation, Physical Review Letters 44, 25 February 1980, 522-524.
2. Michael Ernest Potter, Study of Neutrino-Electron Scattering at LAMPF, PhD. thesis, Department of Physics, University of California at Irvine, Irvine, CA 92717, UC-34, January 1988.
3. S. J. Freedman, A Search for Neutrino Oscillations at LAMPF, X. Workshop on Particles and Nuclei, Max-Planck-Institut fuer Kernphysik, Heidelberg, West Germany, October, 1987.
4. G. P. Lawrence, Performance of the Los Alamos Proton Storage Ring, Proceedings of the 1987 I.E.E.E. Particle Accelerator Conference, Washington, D.C., March 1987, 825-830.
5. U. Amaldi et al, Comprehensive analysis of data pertaining to the weak neutral current and the intermediate-vector-boson masses, Physical Review D **36**, 1385 (1987).
6. W. Marciano, Proceedings of Brookhaven National Laboratory Neutrino Workshop, BNL 52079 (1987).
7. C. Lim. Proceedings of Brookhaven National Laboratory Neutrino Workshop, BNL 52079 (1987).
8. A Proposal for a Precision Test of the Standard Model by Neutrino Electron Scattering, Los Alamos Meson Physics Facility, Mail Stop H846, Los Alamos, NM 87545 USA, March, 1988.
9. R. C. Allen et al., Physical Review Letters 22, 2401 (1985).
10. K. Abe et al., Physical Review Letters 58, 636 (1987).
11. F. Sutherland et al., Physical Review D13, 2700 (1976).

Present and Future Neutrino Physics Research at the Los Alamos Meson Physics Facility

Gary H. Sanders

Los Alamos National Laboratory, Los Alamos, NM 87544 USA

The Los Alamos Meson Physics Facility is currently the site of two neutrino experiments. A measurement of elastic scattering of electron-neutrinos on electrons is providing confirmation of the destructive interference between the weak neutral and charged currents predicted in the standard electroweak theory. A search for the appearance of $\bar{\nu}_e$ is being carried out at the LAMPF beam stop, as well. The status of this experiment is described. A major new initiative is being undertaken to measure neutrino-electron scattering in a large water Čerenkov detector. This measurement will be precise enough to provide, in combination with the measurements to be performed at the new generation of high-energy electron-positron colliders, the first experimental study of the standard electroweak theory at the level of one-loop radiative corrections. The detector will also be a vehicle for neutrino-oscillation searches, measurement of neutrinos from supernovae, and other fundamental physics. The apparatus will consist of a neutrino production target and shield surrounded by a water Čerenkov detector. The fiducial volume of water will be approximately 7000 tons, viewed by approximately 13000 20 cm diameter photomultiplier tubes.

Introduction

The 800 MeV, 1 ma average proton current beam from the linear accelerator at the Los Alamos Meson Physics Facility (LAMPF) is currently being used to complete two major neutrino experiments. In addition, a major new initiative to explore neutrino-electron scattering with a large water Čerenkov detector has begun. The new Large Čerenkov Detector (LCD) will exploit the unique beam characteristics available at LAMPF to carry out a precision test of the standard electroweak theory. This test will be sensitive to the radiative corrections which modify neutrino-electron scattering at the one-loop level.

The proton beam available from the LAMPF linear accelerator is characterized by very high current (< 1 ma) and low duty factor (6-10%). The resulting high beam power facilitates a bright beam stop neutrino source. The low duty factor aids in the suppression of cosmic ray induced backgrounds.

This beam has been used in a study of the nature of muon-number conservation which favored additive muon-number conservation.[1] The beam stop source has been used to measure the rate of electron-neutrino elastic scattering on electrons as a search for interference between the amplitudes of the charged and neutral weak currents.[2] The standard electroweak theory provides a quantitative prediction of destructive interference which reduces the rate at which this scattering is observed. The beam stop is also a source for a current search for oscillation of ν_μ, $\bar{\nu}_\mu$ or ν_e into $\bar{\nu}_e$, often described as an appearance experiment.[3]

The LAMPF accelerator facility includes a new proton storage ring (PSR).[4] The extracted beam from the PSR has an energy of 800 MeV, a design current averaging 100 μA, with a unique, short pulse structure. Typically, pulses 270 ns long, at a repetition rate of 12 Hz, provide the design current. The exceptionally short pulses and low duty factor aid removal of cosmic ray induced backgrounds in a typical neutrino experiment. Even more important, this pulse structure permits a clean time separation of neutrinos produced by pion decay (ν_μ) and those produced by muon decay (ν_e and $\bar{\nu}_\mu$). Thus, two nearly simultaneous, interspersed, but distinguishable neutrino beams are available from a beam stop illuminated by the PSR beam. This capability is unique at LAMPF. It enables the planned study of neutrino-electron scattering with the Large Čerenkov Detector (LCD).

Elastic Scattering of Electron-Neutrinos on Electrons

In the standard model, electron-neutrino scattering on electrons involves the exchange of both charged W bosons and the neutral Z boson and the interference between these two amplitudes. The Feynman diagrams for these two currents are shown in Fig. 1.

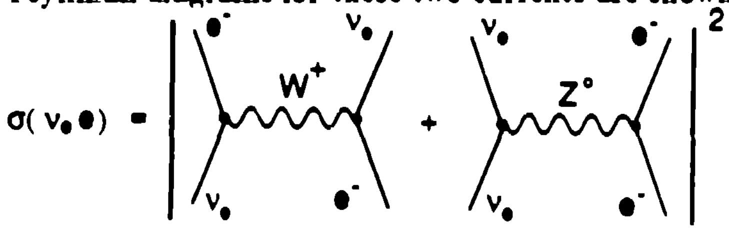

Figure 1. Scattering of electron-neutrinos on electrons proceeds via a mixture of the neutral weak current in which the Z^0 is exchanged, and the charged weak current in which the W^- is exchanged. Interference between these two amplitudes contributes to the observed rate for the scattering.

These reactions are analogous to electron-electron scattering processes in which the exchanged vector particle is the photon. The unique feature of the neutrino scattering process is its purely weak character. The standard model prediction for this rate is

$$\sigma(\nu_e e^-, theory) = 9.2 E_\nu(GeV) \times 10^{-42} cm^2 \quad ,$$

which includes a substantial contribution from destructive interference of the two amplitudes.

The experiment (LAMPF experiment 225), an Irvine-Los Alamos-Maryland collaboration, used a beam stop neutrino source with a well known spectrum of neutrinos from pion and muon decay. The detector was designed to detect the recoiling electron from the scattering process, and eliminate false events from other sources. The detector is shown in Fig. 2. The passive and active anti-coincidence shields are indicated, as is the fine-grained active volume, which serves to record the electron tracks. The active volume was instrumented with layers of plastic scintillators (10 tons) and tracking chambers (4.5 tons) comprised of 208,000 flash chambers.

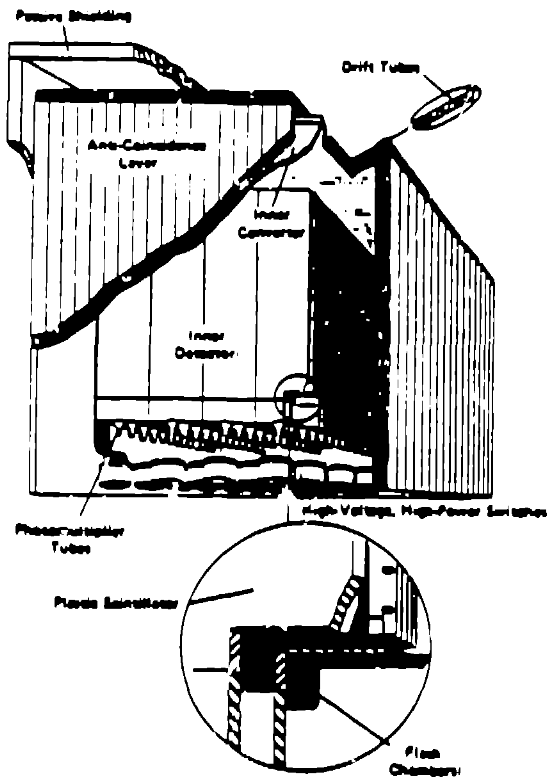

Figure 2. The detector for the measurement of electron-neutrino scattering on electrons. Surrounding the primary detector is a passive shield to reduce cosmic ray induced backgrounds, an active anti-coincidence layer which additionally rejects electrons from muon decays in the passive shield, and an inner converter which rejects photons and beam associated penetrating particles.

The experimental team has completed all data collection and is preparing its final publication. Electron-neutrino scattering on electrons produces recoil electrons in the forward direction. The angular distribution shown in Fig. 3 clearly shows this forward peak. The spectrum includes both muon-neutrino and electron-neutrino scattering and contributions from background processes such as scattering of neutrinos on ^{12}C and ^{13}C and neutron-proton scattering. The Monte Carlo calculation includes all background processes, shown in the solid line histogram. Subtraction of these backgrounds leaves 304 $\pm$ 49 events

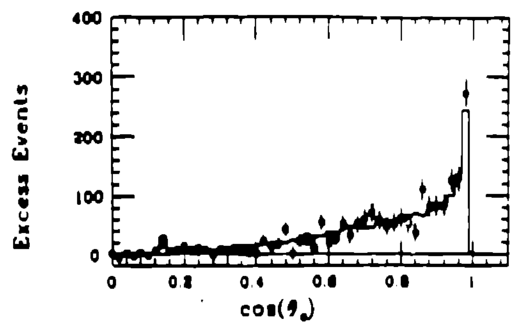

Figure 3. The angular distribution of events recorded in the study of electron-neutrino elastic scattering on electrons. The forward peak is clearly visible. The solid line shows the Monte Carlo prediction of all backgrounds.

assigned to all types of neutrino scattering on electrons. Further subtraction of the portion assigned to $\bar{\nu}_\mu$ and ν_μ scattering on electrons, based upon measured cross-sections from other experiments, leaves 251 ± 50 events from electron-neutrinos. This agrees well with the standard model prediction. Currently, the team quotes an experimental rate

$$\sigma(\nu_e\, e^-, exp) = 10.7 \pm 2.5 E_\nu(GeV) \times 10^{-42} cm^2 \quad ,$$

which should be compared to the theoretical prediction above. The result is consistent with the destructive interference which results in the standard model, and is nearly five standard deviations away from constructive interference. These results are currently undergoing final corrections.

Search for Neutrino Oscillations (Appearance of $\bar{\nu}_e$)

The LAMPF beam stop is also the site of a search for the appearance of $\bar{\nu}_e$ in a large detector that is exposed only to incoming ν_e, ν_μ, and $\bar{\nu}_\mu$. These neutrino varieties come from π^+ decay in the beam stop, whereas the π^- component is captured, leaving at most a contamination of $\bar{\nu}_e$ below the 10^{-3} level.

The experiment (LAMPF experiment 645) is an Argonne-Caltech-LBL-LAMPF-Louisiana State-Ohio State collaboration. The detector is shown in Fig. 4. It consists of an active cosmic-ray shield made up of liquid scintillators, a passive shield made of lead, a 2000 gm/cm^2 overburden to reduce incoming neutral particles, and a 20-ton active detector made up of liquid scintillators and drift tubes. The central detector is sensitive to $\bar{\nu}_e$ by observing the recoil positron from inverse beta decay [$p(\bar{\nu}_e, e^+)n$], and has limited neutron detection capability. The detector views the beam stop from a distance of 26 m. In the usual two-component description of oscillations, this experiment has an L/E_ν = 0.65. Its sensitivity is similar to that of other experiments at higher energy.

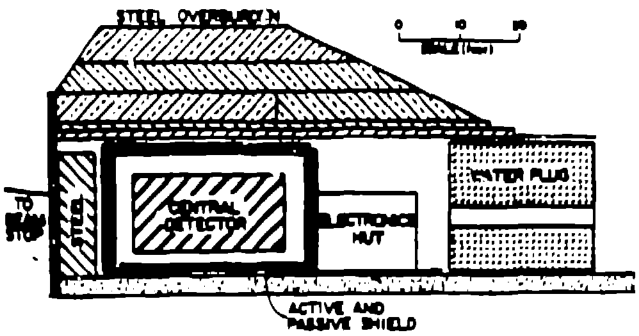

Figure 4. The neutrino detector and cosmic ray shield used in the LAMPF search for the appearance of $\bar{\nu}_e$.

The team had a short run in 1986, which revealed a large neutral background. This was traced to a surprising forgotten beam pipe that viewed the beam stop. In a long 1987 data run, the background problems were solved and the data set is undergoing the last corrections in the analysis. They are sensitive to oscillations at the 1% level. They observe a beam-associated excess of electron tracks at a level consistent with backgrounds from scattering of ν_e on ^{12}C and on electrons. At this point, they are claiming no evidence for an oscillation and are expected to present a final statement very soon.

The Large Čerenkov Detector

During the next 5-10 years, the new high-energy electron-positron colliders will measure the mass of the W and Z bosons to very high precision. This measurement will provide an accurate determination of the electroweak mixing angle θ_W of the electroweak theory. However, only when combined with a sufficiently accurate measure of this angle at low energies can the predictions of the electroweak theory be verified at the level of one-loop radiative corrections.[5] The high-energy measurements address only the first-order "tree-level" contributions. Deviations from the standard model predictions are a signature of new physics.

A low-energy measurement of the electroweak parameter based upon neutrino-electron scattering is particularly clean because of the simplicity of the neutrino-Z vertex. The value obtained from neutrino-electron scattering at LAMPF energies can differ from the collider value by as much as 7%, due to the energy-dependent radiative corrections. Furthermore, only the beam properties at LAMPF make this measurement possible at the required precision. The precision proposed for the LAMPF Large Čerenkov Detector is better than 1%.

In the standard model, it can be shown that the ratio of scattering cross-sections

$$R = \frac{\sigma(\nu_\mu e)}{\sigma(\nu_e e) + \sigma(\bar{\nu}_\mu e)}$$

can be written in terms of the mixing angle as, if $s = \sin^2 \theta_W$,

$$R = \frac{3}{4} \frac{1 - 4s^2 + \frac{16}{3}s^4}{1 + 2s^2 + 8s^4}$$

By measuring the ratio R to better than 2% precision, the mixing angle is determined to better than 1% precision. It is this measurement of neutrino-electron scattering that will be carried out with the new Large Čerenkov Detector at LAMPF, by a Los Alamos-Irvine-UCLA-Colorado-CEBAF-New Mexico-Pennsylvania-Temple-William and Mary-Riverside collaboration.

The conventional way to measure this ratio would be to employ two different neutrino beams, one rich in ν_μ and a second beam rich in ν_e and $\bar{\nu}_\mu$, in sequence. The first species is produced in pion decay, the second in muon decay. Changing over from a pion rich to muon rich beam might be done in alternate months of running, for example. Carrying out a precision experiment in this manner would be very difficult. The time structure of the LAMPF beam, as prepared by the new Proton Storage Ring, is a 270 ns long pulse repeated 12 times per second. Since pion decay and muon decay are characterized by such widely differing lifetimes, neutrinos observed in the first several hundred nanoseconds are those in the numerator of the expression defining R. The muon decays occur over several microseconds, yielding the cross-sections in the denominator. Thus every PSR pulse yields a neatly time-separated neutrino beam. Figure 5 shows this neutrino yield as a function

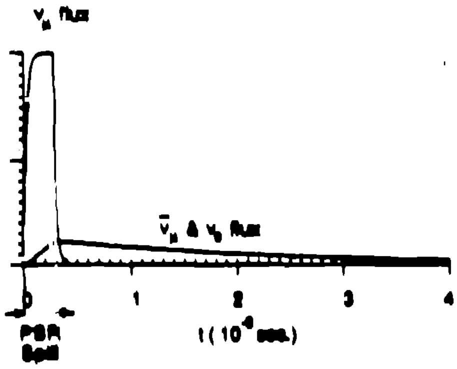

Figure 5. Time distribution of neutrinos from each pulse into the Large Čerenkov Detector beam stop.

of time from each PSR pulse. By recording the of time of each recoiling electron from a neutrino scatter, the ratio which determines R can be unfolded by fitting the time-dependence of the data set.

The Large Čerenkov Detector system is shown in an isometric drawing in Fig. 6. The PSR beam is transported in a 100 m long beam-line that features very low losses and a superconducting dipole that bends the beam 90° down into the LCD beam stop. The target is surrounded by a massive 15 m diameter iron shield designed to reduce all backgrounds from neutrons to an acceptable level. The neutrinos exit the shield into a cylindrical water tank 32.2 m in diameter and filled with water to a depth of 15.6 m. The outer veto region of the water is typically 1.5 m thick, and the fiducial volume contains approximately 7000 tons of water. Viewed by about 13000 photomultipliers, each approximately 20 cm diameter, the photocathodes cover nearly 20% of the tank surface. This fine grained imaging counter should achieve a 10 MeV threshold with 27 photoelectrons in a minimum of 20 phototubes as a primary trigger.

In a 625 day run, at 100 μA average beam current, there will be 12 events per day from $\nu_\mu e$ and 101 events per day from $\bar{\nu}_\mu e$ and $\nu_e e$, for a total of 7500 and 63,400 events, respectively. The total statistical error on R is about 1.6% from counting statistics, PSR pulse shape variations, cosmic ray and neutron induced background subtractions, and ν_e-oxygen scattering. Systematic errors total 1.86% in R. The combined total error in $\sin^2\theta_W$ is then 0.89%. Systematic errors come from decay in flight, cosmic rays, photons and $\pi^\pm$ from neutron interactions, threshold energy uncertainties and non-uniform efficiency.

The Large Čerenkov Detector will be capable of addressing several other fundamental topics at the same time the standard model study is carried out. These include several types of neutrino oscillation searches, searches for neutrino structure such as a charge radius or magnetic moment, observation of neutrino bursts from supernovae, searches for upward going muons, lepton number violation and heavy neutrinos or axions.

Neutrino oscillations can be detected in departures of the ratio R from the standard model predictions, observation of radial oscillations in the cylindrical detector volume and observation of a contribution to the ν_e-oxygen signal with a monoenergetic signature. Since the $\nu_e e$ cross-section is seven times larger than the other $\nu_\ell e$ cross-sections, LCD can search for the processes $\nu_e \longleftrightarrow \nu_\mu$ [6,7] and $\nu_e \longleftrightarrow \nu_\tau$ by measuring an increase in R. Disappearance experiments ($\nu_\mu \rightarrow \bar{\nu}_\mu$(sterile), $\nu_e \rightarrow \bar{\nu}_e$(sterile)) also show up as changes in R.

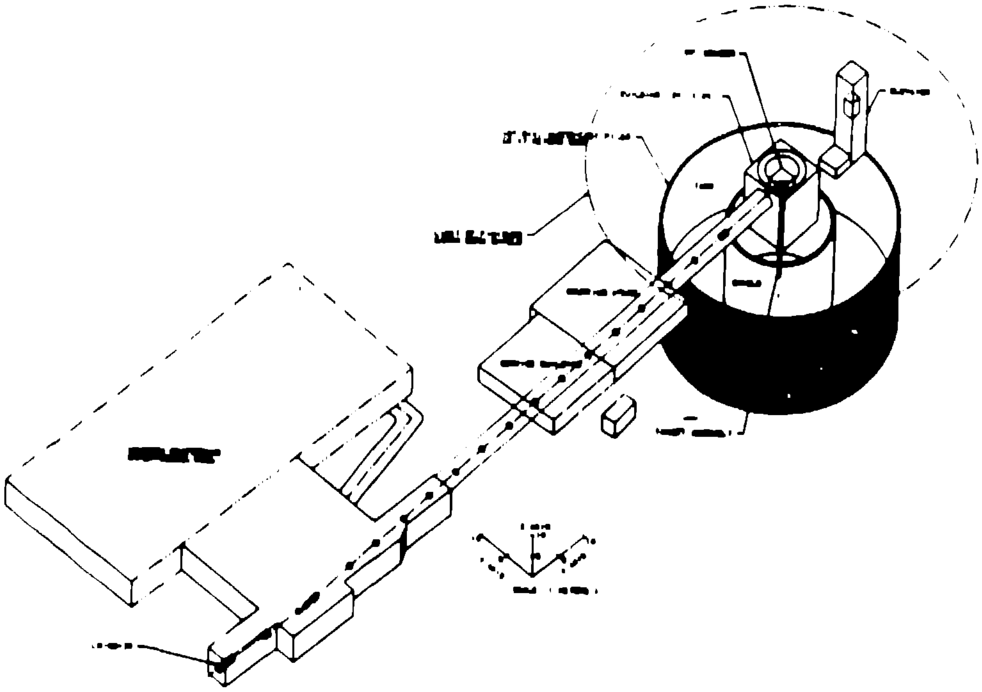

Figure 6. Isometric view of the Large Čerenkov Detector.

By unfolding the radial dependence of the events, oscillations that occur with a wavelength close to the tank radius are detectable, particularly in the prompt signal from the monoenergetic ν_μ, or in the ν_e-oxygen event radial distributions. Since the LCD beam stop produces monoenergetic ν_μ, the process $\nu_\mu \rightarrow \nu_e$ will result in prompt ν_e-oxygen events which are monoenergetic.

The best sensitivity will likely be achieved in the search for the process $\bar{\nu}_\mu \longleftrightarrow \bar{\nu}_e$, the same process sought in the current LAMPF experiment. In the LCD case, the signal is the inverse beta decay, which is observable above the leading background from ν_e-oxygen events. In the usual two-component oscillation description, LCD should achieve limits on the quantity $\sin^2 2\alpha$ of about 2×10^{-4}. Detailed sensitivities for these and other oscillation processes are presented in the full proposal.[8]

If the electron or muon neutrino has a sufficiently large magnetic moment or charge radius, then LCD will observe an anomalous value of R and an anomalous y distribution ($y = E_e/E_\nu$). A non-zero magnetic moment (or electric moment) increases the neutrino-electron cross section and makes the y distribution peaked toward $y = 0$. LCD would achieve sensitivity comparable to or better than limits derived from terrestrial or astrophysical considerations.[9,10,11] A non-zero charge radius can increase or decrease the cross section and has the effect of flattening the y distribution. LCD limits on such unexpected compositeness fall in the 10^{-33} cm^2 range, better than existing limits by an order of magnitude.

LCD is similar to IMB or KAMIOKANDE II in its ability to detect neutrinos, muons, and electrons from supernovae. Due to its thin overburden, it has significantly higher cosmic ray related back grounds. Nevertheless, electron neutrinos from the prompt collapse phase and delayed high-energy muon neutrinos can be detected.

LCD requires only a small enhancement to its data acquisition electronics to make this possible. Our estimate for the LCD response to another SN1987A is 35 events, or if this supernova were in our galaxy, 750 events. The range of our estimates for high multiplicity electrons reaches as high as 16000 events in 10 seconds.[8] For a modest addition to the hardware, this detector, easily maintainable for a decade because it is on-site at a large, national laboratory, offers an attractive capability in neutrino astronomy.

Separate experiments at LAMPF on lepton number conservation, electron neutrino scattering on electrons and searches for oscillations have set the stage for the next decade of LAMPF research with neutrinos using the Large Čerenkov Detector.

References

1. S. E. Willis et al, Neutrino Experiment to Test the Nature of Muon-Number Conservation, Physical Review Letters 44, 25 February 1980, 522-524.
2. Michael Ernest Potter, Study of Neutrino-Electron Scattering at LAMPF, PhD. thesis, Department of Physics, University of California at Irvine, Irvine, CA 92717, UC-34, January 1988.
3. S. J. Freedman, A Search for Neutrino Oscillations at LAMPF, X. Workshop on Particles and Nuclei, Max-Planck-Institut fuer Kernphysik, Heidelberg, West Germany, October, 1987.
4. G. P. Lawrence, Performance of the Los Alamos Proton Storage Ring, Proceedings of the 1987 I.E.E.E. Particle Accelerator Conference, Washington, D.C., March 1987, 825-830.
5. U. Amaldi et al, Comprehensive analysis of data pertaining to the weak neutral current and the intermediate-vector-boson masses, Physical Review D 36, 1395 (1987).
6. W. Marciano, Proceedings of Brookhaven National Laboratory Neutrino Workshop, BNL 52079 (1087).
7. C. Lim, Proceedings of Brookhaven National Laboratory Neutrino Workshop, BNL 52079 (1987).
8. A Proposal for a Precision Test of the Standard Model by Neutrino Electron Scattering, Los Alamos Meson Physics Facility, Mail Stop H846, Los Alamos, NM 87545 USA, March, 1988.
9. R. C. Allen et al., Physical Review Letters 22, 2401 (1985).
10. K. Abe et al., Physical Review Letters 58, 636 (1987).
11. F. Sutherland et al., Physical Review D13, 2700 (1976).