LA-UR 91-3830

LA-UR--91-3830

DE92 003790

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

DEC 0 3 1991

TITLE: Medium-energy neutrino physics

AUTHOR(S): *D. H. White*

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

SUBMITTED TO: The Proceedings of the symposium on the Future of Muon Physics, Heidelberg, May 7-9, 1991.
(To be Published in Zeitschrift Für Physik C, Particles and Fields)

By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes.

The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy.

LosAlamos Los Alamos National Laboratory
Los Alamos,New Mexico 87545

FORM NO. 836 R4
ST. NO. 2629 5/81

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Medium-energy neutrino physics

D. Hywel White

Medium Energy Physics Division, Los Alamos National Laboratory
Los Alamos, New Mexico 87545

Submitted 22 November 1991

Abstract. A selection of opportunities for neutrino physics from a source generated from pions that decay in flight and at rest is described. The present source at LAMPF has a duty factor of about 6%; improvements in opportunities that emerge from a source using a pulse 0.25 μsec long from a proton storage ring are also described.

In Table I is shown a list of the topics that we have considered in planning a program of low-energy neutrino physics at LAMPF. Neutrinos at LAMPF come from two basic sources, charged pions that decay at rest and those that decay in flight. There are no other particles that are expected to produce neutrinos. Pions are produced in a combination of water and copper targets and subsequently come to rest in materials surrounding the target where they decay to muons and muon neutrinos with a lifetime of 26 ns. In turn, muons decay to electron and muon neutrinos. In practice at LAMPF, positive pions are produced more copiously (~6x) and negative pions are mostly absorbed, so that neutrinos are produced dominantly from the reactions

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \ , \ \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \ . \qquad (1)$$

Notice that at this level of precision $\bar{\nu}_e$ are not produced. Pions can decay in flight before coming to rest and the rate depends in detail on the structure of the target area. In a solid target, rather less than 1% of the pions decay in flight, up to 30% of the pions decay in flight in an open region, which is optimized to produce neutrino flux at a detector. When the decay-in-flight component is significant, muons produced in the primary decay process also decay but at a lower rate, reflecting the muon lifetime. In the decay-in-flight component of the beam, π^- are also present so that $\bar{\nu}_\mu$ exist in this component of the beam although their energy is higher than the decay at rest spectrum. Energy spectra for both components in the beam are shown in Fig. 1.

a. Neutrino-electron scattering

* i. $\sin^2\theta_W$ (and search for 17-keV neutrino)
ii. ν electromagnetic properties
iii. very low energy recoil, Magnetic Moment

* b. Neutrino-proton scattering

c. Inverse beta decay

i. $\nu_e - {}^{12}C \rightarrow e^- + {}^{12}N$ (form factor and normalization)
ii. $\nu_\mu - {}^{12}C \rightarrow \mu^- + {}^{12}N$

d. Threshold cross-section measurement, G_p

$\nu_\mu - p \rightarrow \mu^+ + n$

* e. Neutrino oscillations

i. ν_μ disappearance
ii. ν_e disappearance
iii. $\nu_\mu \rightarrow \nu_e$
iv. $\nu_\mu \rightarrow \bar{\nu}_e$
v. Long baseline disappearance

f. ν - A coherent scattering (bolometric detectors?)

g. ν - ${}^{12}C$ neutral-current inelastic scattering (15.1 MeV)

Table I. In this paper we consider only the topics that are marked with an asterisk.

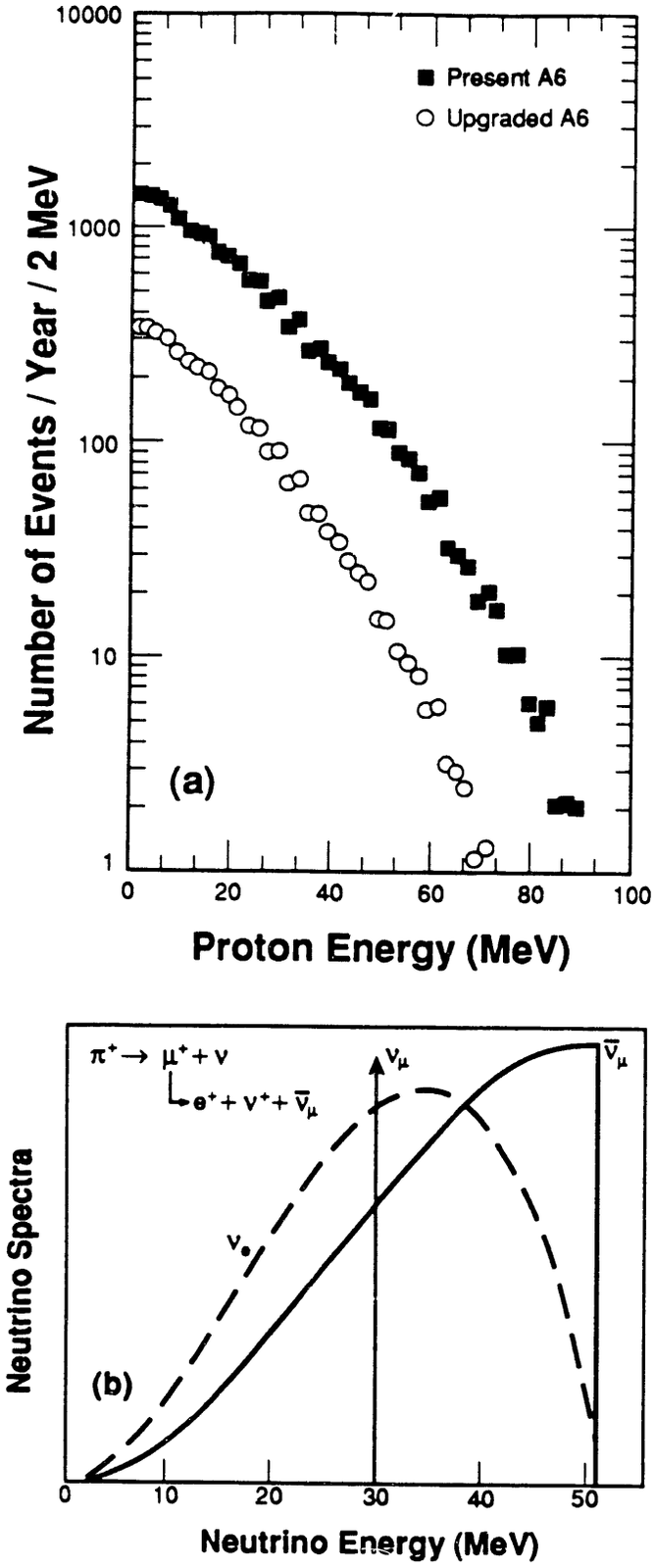

Figure 1. Energy spectra for decay-in-flight neutrinos (ν_μ), and decay at rest (ν_μ, ν_e, $\bar{\nu}_\mu$) are shown. The decay in flight neutrino spectra are for the source as configured at present and for the projected source with improved flux.

Neutrino events at low energy are characterized generally by simple topologies. At the same time, the cross sections are low, even by neutrino standards, so that massive detectors are very much at a premium. We have developed a technique that extends the successes of the Kamioka collaboration in detecting low-energy neutrino events. The essence of the method consists of a homogeneous transparent liquid viewed by a large number of phototubes mounted at the periphery of a containment vessel . A schematic of the detector tank and phototube disposition in the liquid scintillator neutrino detector (LSND) is shown in Fig. 2. These phototubes are capable of detecting single photoelectrons with high efficiency and good timing. Such phototubes have become available from a number of sources in the last few years. Water has been used previously as target medium and radiator for these low-energy neutrino detectors. Combining target mass and radiating medium yields advantages of cost and acceptance. The LSND collaboration is using very pure mineral oil, which has the advantage of lower density, Z, and higher refractive index, low water, reducing multiple scattering and increasing the Cherenkov photon yield. In addition, we have added a small quantity of a scintillating compound so that nonrelativistic particles may also be detected. For most events, electrons only contribute to detectable Cherenkov light and protons produce scintillation light. Pions and muons are mostly nonrelativistic except for cosmic radiation.

It is widely believed that Cherenkov light cannot be observed in liquid scintillator because of the short absorption length that arises when the scintillant and wavelength shifters are added in sufficient quantity to make an efficient scintillator. However, when sufficient phototube coverage is available and a very dilute scintillator is used, light from both sources may be seen simultaneously. In Fig. 3 is shown an angular distribution of light observed from 600-MeV/c electrons in the LAMPF test beam. When ~ 60 ppm of butyl PPD is added, the same angular distribution shows a Cherenkov peak of the same magnitude together with scintillator light giving a uniform angular distribution. This amount of additive gives a desirable ratio of scintillation to Cherenkov light. The absorption length at ~ 400 nm is also adequate.

It has been shown by the Kamioka experiment [1] that with adequate phototube coverage, low-energy electrons may be reconstructed in energy and direction to a precision limited only by multiple scattering and total light acceptance. Expected energy, angle, and position resolutions are shown in Fig. 4 for LSND. Electron-proton separation is also expected to be better than 10^{-3} at about 30 MeV. Some reactions of interest involve low-energy neutrons, which we expected to thermalize in about 200 μsec, giving a 2.2-MeV γ on capture by free protons. The detector is expected to be sensitive to these γs, including the capability to reconstruct the capture position.

The detector is located about 25 m from the beam stop at LAMPF in a shielded area shown in Fig. 5. An

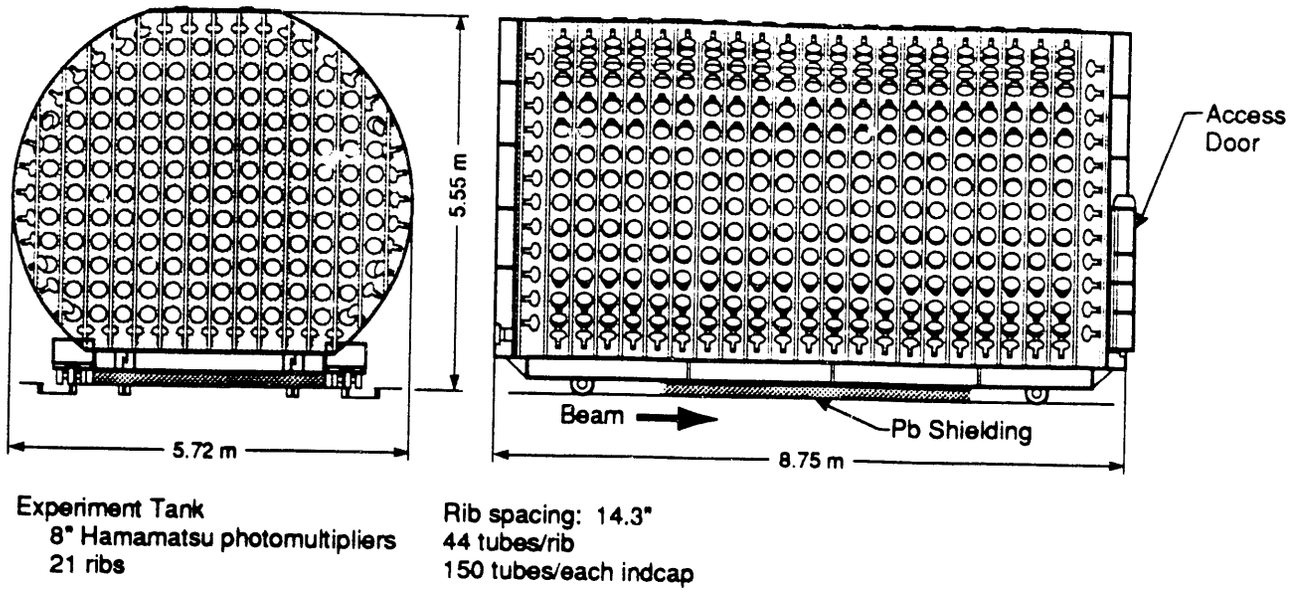

Figure 2. Schematic diagram of the Liquid Scintillator Neutrino Detector (LSND). The tank contains a dilute liquid scintillator viewed by 1250 phototubes.

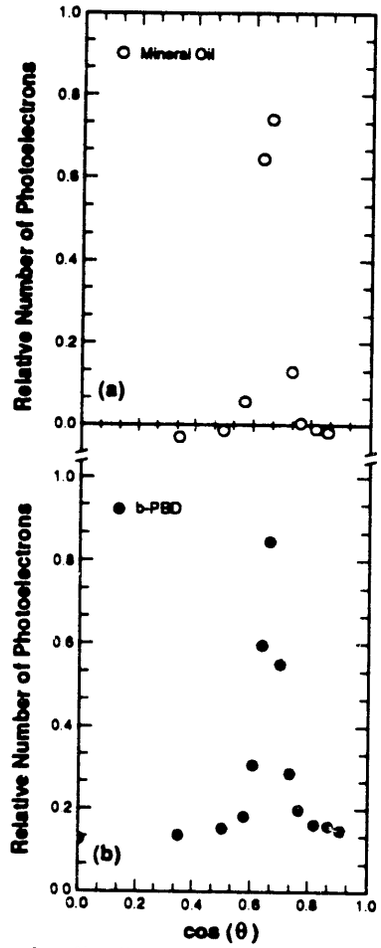

Figure 3. Angular distributin of light from a dilute mixture of mineral oil and butyl PBD. This mixture allows the observation of Cherenkov and Scintillator light simultaneously, a requirement for LSND.

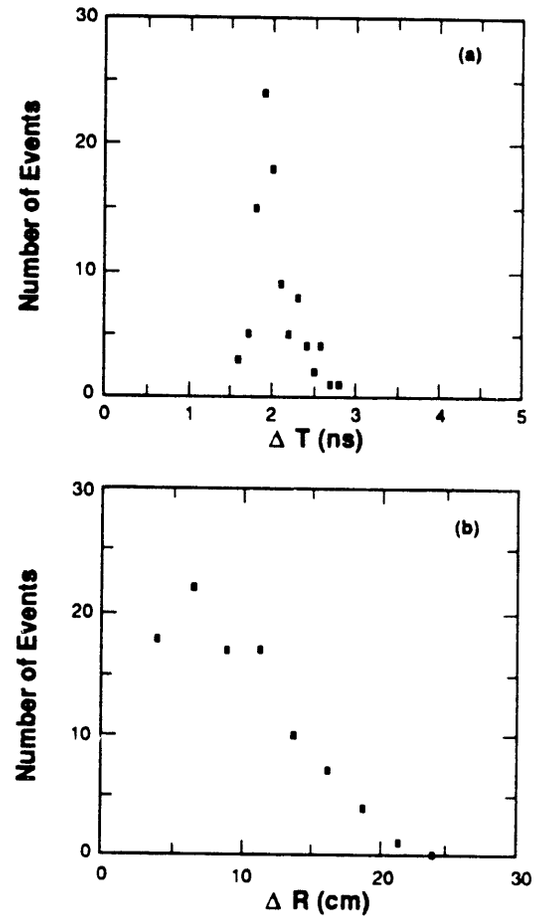

Figure 4. Resolution of the detector in time and position of the event vertex.

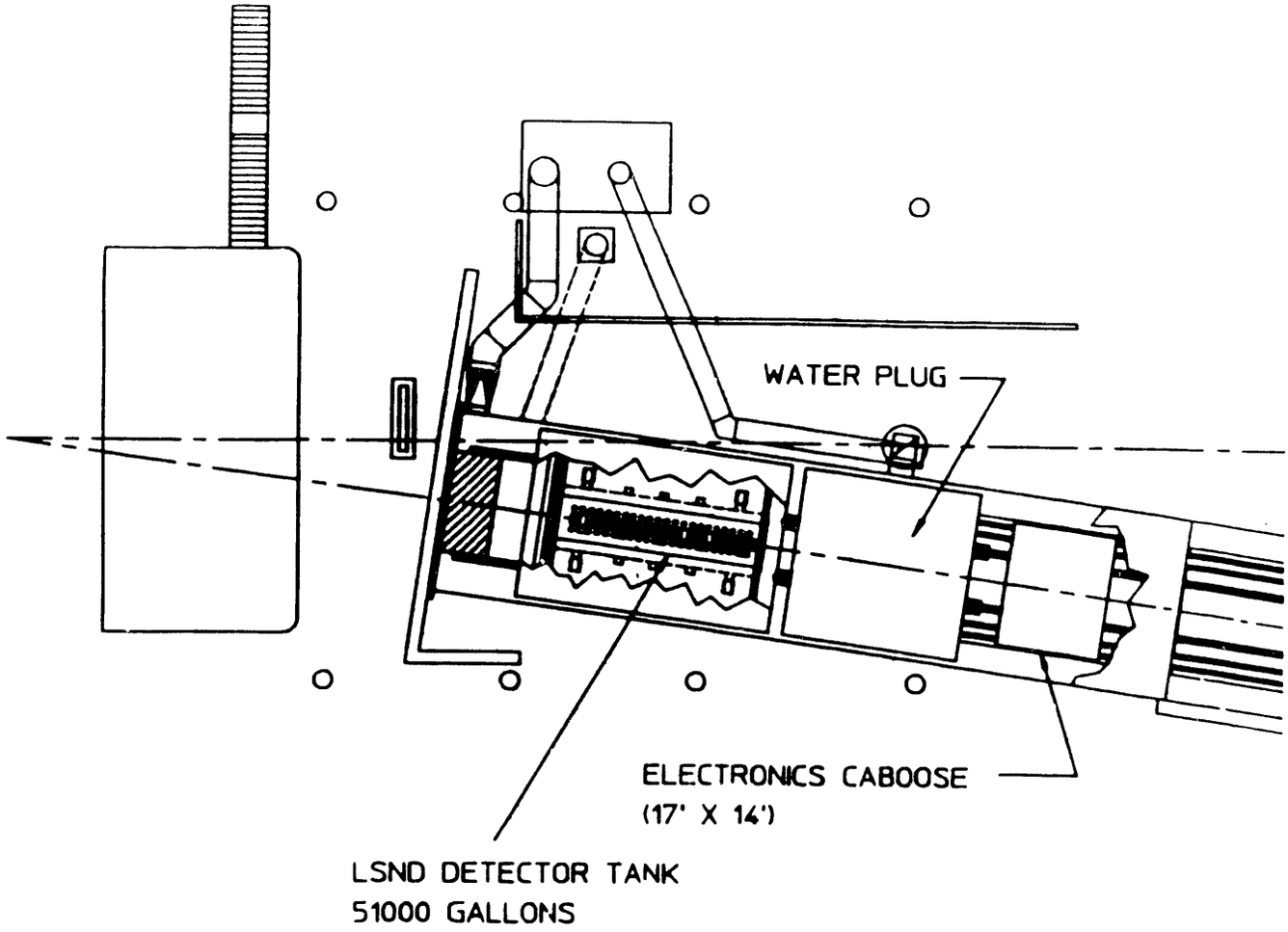

Figure 5. Plan of the experimental area in which the detector is located.

overburden of about 2.5 kg/cm^2 serves to filter out the hadronic component of cosmic rays. Cosmic rays that traverse the detector are excluded in a trigger, cosmic rays which stop in the target medium are likely to decay giving an electron which can mimic a neutrino interaction unless a correlation is made both in the position of the muon track end and the two microseconds characteristic of muon decay. A primary source of background for low-energy neutrino events comes from those muons that stop close to the detector in nearby material and either decay or are captured. Decay muons generate breamsstrahlung photons from electrons and captured μ^- generate neutrons , both of which may penetrate the shielding into the detector. The closest layer of material always becomes the primary source of these events, so that adding more shielding does not help. In order to remove this background, it is necessary to veto cosmic-ray muons in a counter outside a shielding layer. Such a system, in which liquid scintillator is used outside a thickness of lead to veto this secondary background, has been used successfully in a previous experiment at LAMPF and will be reused.

Neutrino-Electron Scattering

The ratio of neutrino electron scattering cross sections,

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

is sensitive to the weak mixing angle $\sin^2\theta_W = s$ through the relation,

$$R = \frac{3}{4}\frac{1 - 4s^2 + 16/3s^4}{1 + 2s^2 + 8s^4} = 0.144 ,$$

at the tree level in standard electroweak theory.

A measurement of R to 2% yields a measure of $\sin^2\theta_W$ to about 1% because of a favorable derivative between R and $\sin^2\theta_W$. Extraordinarily precise measurements of the Z mass at LEP, have concentrated interest on the effect of radiative corrections, both within and outside of the standard model. These radiative corrections depend on the overall structure of the standard model, for example the magnitude of the top quark mass has a major impact on radiative corrections to the Z mass. In the ratio R the effects on

numerator and denominator largely cancel, leaving R rather insensitive to the top quark mass so that different measures of $\sin^2\theta_W$ through different processes can provide a critical test of the overall structure of the theory. Conversely, a Z' would affect the numerator, leaving the denominator, which is dominated by charged current amplitudes, unchanged. This ratio, along with other measurements like high-energy neutrino neutral current interactions and parity violation in atoms, forms an array of critical tests of the standard electroweak theory and its constituents.

Neutrinos that contribute to the numerator come from pion decay; those in the denominator from muon decay. Pion decay neutrinos that decay in flight preserve the fine time structure of the LAMPF beam, pulses less than 1 ns wide separated by 5 ns. Pions that decay at rest do so with a lifetime of 25 ns, which is reflected in a modulation of events between pulses with a slope reflecting this lifetime. Events from muon decay do so nearly uniformly in time. Neutrino electron scattering is identified by the angular distribution of the recoil electrons, which are sharply peaked in the forward direction. The ratio is derived from the time distribution. In three years of data taking, rather more than 500 events are expected in the numerator with 1000 in the denominator, leading to a statistical error on R of 6% and a precision of $\sin^2\theta_W$ of ±0.006.

Neutrino-Proton Elastic Scattering

Neutrino-proton scattering is identified by a recoil particle in which no Cherenkov light is observed and no decay products correlated in time. The direction of this recoil cannot be determined, but multiple interactions such as might be observed from neutrons can be excluded. The neutron background in the experiment location has been measured and a signal to background in excess of three to one is expected after the time correlation of the neutrino events with the beam line structure has been used. The cross section for ν_μ elastic scattering on protons is given by

$$\frac{d\sigma}{dQ^2} \approx A \pm BW/m_p^2 + CW^2/m_p^4 \,. \qquad (2)$$

with $W = Q^2 + 2\, m_p E_\nu$.

The three terms

$$A = Q^2 (G_A^2 - F_1^2 + F_2^2 Q^2 / 4m_p^2)$$

$$B = Q^2 G_A (F_1 + F_2)$$

$$C = 0.25 (G_A^2 + F_1^2 + F_2^2 Q^2 / 4m_p^2) \,.$$

The differential cross section for selected ν energies is shown in Fig. 6. This cross section becomes particularly simple in form at low Q^2 because $F_1(0) = 1 - 4 \sin^2\theta_W$ is small and the F_2 terms involve a power of Q^2 and are also not important. The cross section is dominated by the axial

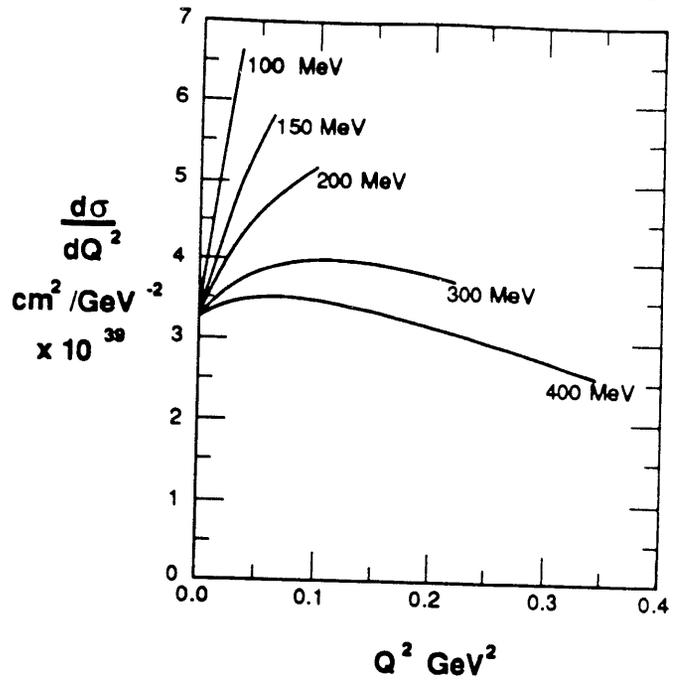

Figure 6. Cross section vs. Q^2 for ν_μ - p elastic scattering.

form factor G_A with small corrections from vector terms. The hadronic current may be written schematically as

$$\frac{1}{2}\,\bar{u}u - \frac{1}{2}\,\bar{d}d - \frac{1}{2}\,\bar{s}s \,,$$

with numerical coefficients reflecting the axial charge of the relevant quark. The first two terms are just those responsible for neutron decay so that any deviation from $G_A = 1.26$ is directly attributable to strange quark contributions in the proton. The cross section is measured absolutely by comparing with the reaction

$$\nu_\mu + {}^{12}C \rightarrow \mu^+ + {}^{12}N \,,$$

the magnitude of which is related to β decay. This cross section is known to a 7% uncertainty which comes from lack of knowledge of the Q^2 dependence of some form factors in the reaction.

The cross section is needed on free protons, of course, so the "background" from protons bound in ^{12}C is a problem. The extrapolation to $Q^2 = 0$ will help, together with the possibility of running the detector with a pseudocumene fill ($CH_{1.2}$), as well as the normal mineral oil fill so that a subtraction may be made for the contribution from bound protons.

Neutrino Oscillations

Neutrino oscillations and the possibility of a finite neutrino mass have received impetus from a number of observations

in the last few years. The solar neutrino problem has a plausible solution through the Mikhail-Smirnov-Wolfenstein [2] effect producing matter oscillations (MSW). We do not wish to discuss this problem here, but only take note of the fact that the event rate seen in the Chlorine experiment [3], together with the rate of neutrino electron scattering in Kamioka [1], shows very interesting indications of finite neutrino mass and generation mixing. Initial indications from the Soviet-American Gallium Experiment (SAGE) are also supportive of this idea. If this hypothesis is correct, then the product of mass difference squared of electron neutrino and muon neutrino and the vacuum mixing between them is given by

$$\Delta m^2 \sin^2 2\theta \sim 10^{-8}\ \mathrm{eV}^2 \ .$$

The center of the allowed range for these two parameters from solar neutrino experiments gives $\sin^2 2\theta \sim 10^{-2}$ so that a continuation with this somewhat speculative reasoning gives a mass for the muon neutrino of 10^{-3} eV with a much smaller mass for the electron neutrino. Moreover, extending the seesaw mechanism leads us to believe that the tau neutrino mass might be in the range 0.1-10 eV. We do not pretend that this reasoning is other than a small contribution to the motives for searching for neutrino oscillations in this mass range.

The 17-keV neutrino observed first by Simpson and Hime [4] is still controversial but also influences the motives of experimenters with low-energy neutrinos. Langacker and Caldwell [5] have produced an analysis of the relevant data and have suggested two solutions, one that ν_μ and ν_τ form an almost degenerate doublet with both masses near 17 keV; a second possibility identifies the 17-keV neutrino with the tau and the muon neutrino has a mass between 180 and 270 keV. The lower limit is given by the limit on $\nu_\mu \rightarrow \nu_e$ oscillations from an experiment at BNL [6]. LSND [7] was designed to search for such oscillations and because of the low probability for finding ν_e in the LAMPF beam above 30 MeV, such a search has the potential for being extremely sensitive. In fact, as is shown in Fig. 7, the second solution of Langacker-Caldwell would either yield an observation of $\nu_\mu \rightarrow \nu_e$ or be eliminated in a year of data taking.

The MSW-motivated possibilities, as well as Langacker-Caldwell, lead us to consider ν_μ disappearance. The reaction that is most promising to sample ν_μ flux is

$$\nu_\mu + {}^{12}C \rightarrow \mu^- + {}^{12}N \ .$$

As we have remarked, the cross section is well known. If oscillations occur between two flavor states with mass difference squared $\Delta m^2 = m_1^2 - m_2^2$, then the probability of finding neutrinos of type 1 in a beam initially pure is

$$P = 1 - \sin^2 2\theta \sin^2[1.27\ \Delta m^2\ L(E_\nu)] \ ,$$

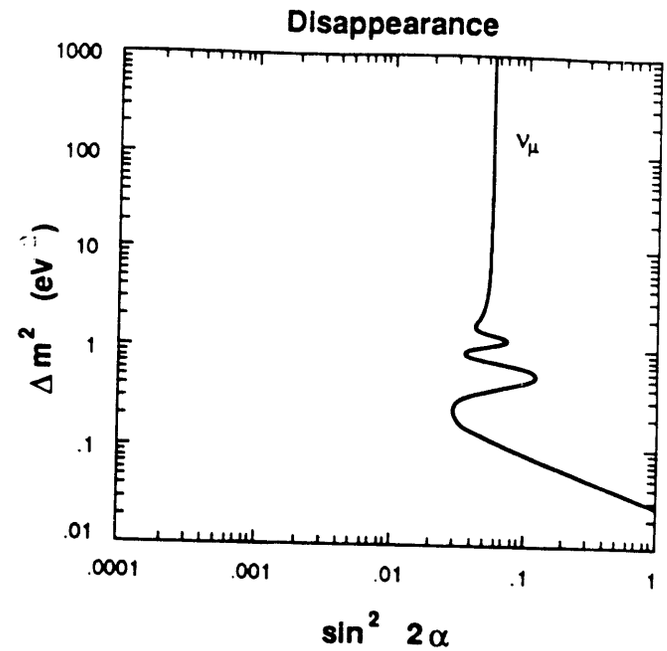

Figure 7. Expected neutrino oscillation limits for $\nu_\mu \rightarrow \nu_e$ using the LSND detector.

where L is the distance from the source in meters and E_ν is the neutrino energy in MeV. For a neutrino energy of 150 MeV and a $\Delta m^2 = 1\ \mathrm{eV}^2$, the oscillation wavelength is 370 m. At the higher end of the Δm^2 range the event distribution will show a modulation within the detector length of 9 m. For lower Δm^2 (~10) moving the detector to ~50 m will give good sensitivity. In Fig. 7 is shown the limits established by existing experiments.

Experiments that rely on measuring the ν flux as a function of distance from the target have systematic error problems stemming mostly from uncertainty in the characteristics of the source. For flavor oscillations, LSND has a major advantage, namely the simultaneous measurement of ν_μ - p elastic scattering, which is flavor independent. The traditional methods of simulating the source and the neutrino flux are subject to a very substantial set of constraints, namely the angular and distance distributions of elastic scattering events. It seems likely that a significant improvement in systematic error can be achieved. With LSND, a statistically limited exclusion area is shown in Fig. 8.

All this is in the relatively near future. LSND is under construction, and it is expected that data taking with beam will commence in 1993. Much will be learned about this new technique for neutrino physics at these low energies. In another paper, the pulsed lepton source for LAMPF (PLS) is described with emphasis on the source rather than the physics program.

An outline of the facility is shown in Fig. 9. The extracted proton beam will be shared continuously between

LANSCE, the neutron facility, and the pulsed lepton source. A single muon beam is shown schematically to indicate the general location in which muon beams might be built. With sufficient funds both sides of the target could be instrumented. Our present thinking is to use two targets close together for muons and neutrinos to provide sufficient flexibility. The upstream target would be relatively thin and provide a source tailored for a surface muon beam, for example. The primary neutrino target would be enclosed in the pion focusing structure. The shield is of the right thickness to provide adequate shielding for the neutrino detectors from neutrons from this target system and a typical neutrino detector size is indicated.

A question remains, what does the PLS do for neutrino physics? The answer is relatively simple. First with 200 μA of protons at the facility, the flux of neutrinos per second is about the same as at Area A when an optimized decay-in-flight source is used. Improvements in source efficiency offset the reduction in proton current. The big change is in the duty factor from about 10% to 10^{-4}. This makes it feasible to abandon the veto shield and allows the prospect of much larger detectors. A second advantage emerges from the use of pion focusing, which becomes feasible at this duty cycle. As the focusing is particle sign specific, the purity of the decay-in-flight component of each sign selected beam is enhanced, improving event identification.

A detector of 2000 tons mass would have about twenty times the counting rate of LSND at Area A. At the same

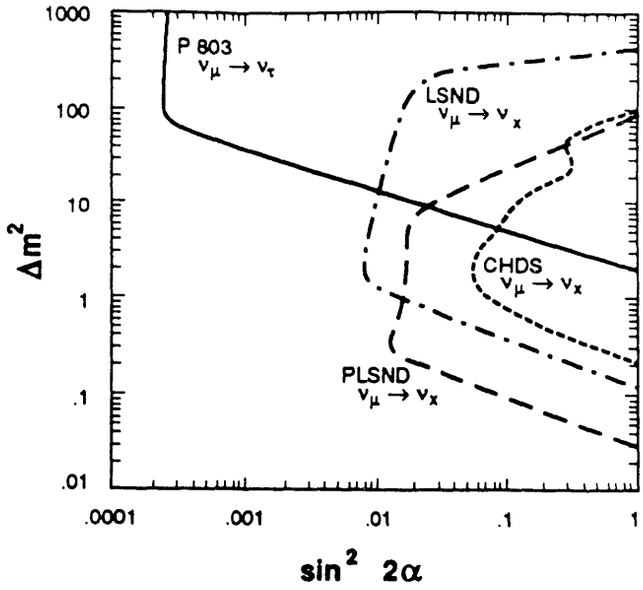

Figure 8. Limits for ν_μ disappearance using LSND using statistical errors only.

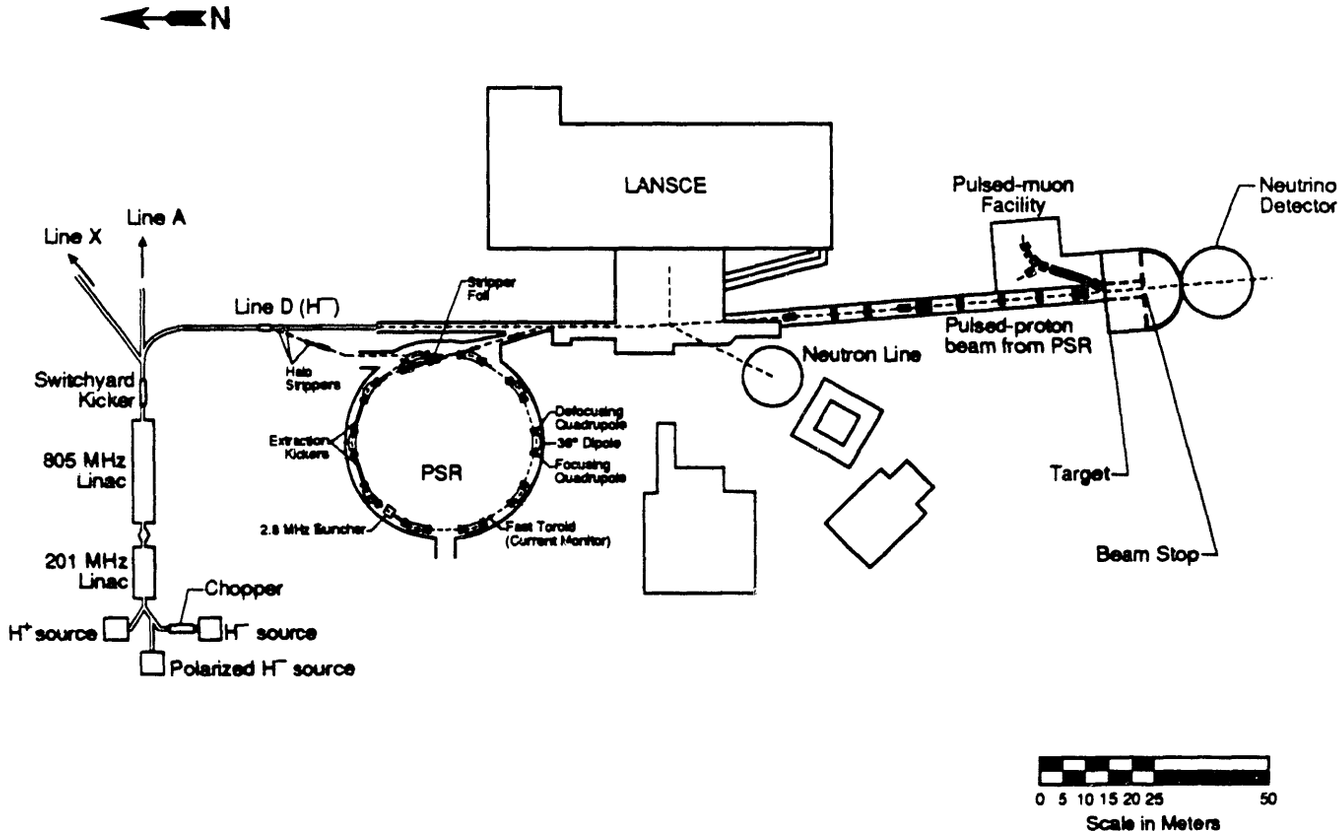

Figure 9. Plan of the pulsed lepton source area.

phototube coverage, this would require nearly 4000 phototubes at a cost of about 7M$ scaling from LSND costs. Of course, the possibilities of other neutrino detectors and experiments are considerable, given freedom from constructing an elaborate veto shield for each one. For example, a detector capable of detecting very low-energy electrons would extend the region in which small values of neutrino magnetic moment could be observed.

A major opportunity would exist at PLS for a long baseline ν_μ disappearance experiment. Assume that the 2000-ton detector alluded to above could be placed at an appropriate distance, and that a systematic limit of 1% can be achieved using both charged current

$$\nu_\mu + {}^{12}C \rightarrow \mu^- + {}^{12}N \quad ,$$

together with flavor-independent νp elastic scattering. Then the distance that the detector is placed should roughly balance systematic and statistical errors. For a four-year data-taking cycle, this puts the detector at 500 m. Putting the detector closer to the target will not help appreciably because the systematic limit will inhibit improvement in sensitivity. Putting the detector further away improves the sensitivity at low Δm^2 at the expense of sensitivity to low mixing angles. Of course, any hint of specific Δm^2 determines the optimum detector position.

The neutrino program at PLS gains from the flexibility that follows independence from elaborate veto requirements. Sign-selected beams are also advantageous. Such a facility shows remarkable promise in a field where developments are coming rapidly.

References

1. K. S. Hirata et al., Phys. Rev. Lett. 65(1990)1297
2. J. N. Bahcall, Neutrino Astrophysics, Chapter 7, University Press, Cambridge, 1989
3. R. Davis, Jr., in Proceedings of the 21st International Cosmic-Ray Conference, Adelaide, Australia
4. J. J. Simpson, Phys. Rev. Lett. 54(1985)1891
5. D. Caldwell and P. Langacker, preprints UCSB-HEP-91-02 and UPR-0469T
6. L. A. Ahrens et al., Phys. Rev. D31(1985)2732
7. Proposal to search for neutrino oscillations in the appareance channels $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, Los Alamos National Laboratory report LA-11842-P (1989)

END

DATE FILMED

01/08/92