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LETTER OF INTENT

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I. Introduction

A long time unanswered question in particle physics has been that of neutrino mass. In the Standard Model of Electroweak Interactions, there are three left handed neutrinos, ν_1, ν_2, and ν_3 corresponding to the three charged leptons, e, μ and τ, and are typically (incorrectly) identified as ν_e, ν_μ, and ν_τ. Attempts to measure the respective neutrino masses use kinematics of the charged lepton decays, but have only yielded upper limits upon the masses, attesting to the smallness of their values.

More recently, experiments have attempted to examine the existence of neutrino masses through the usage of the quantum mechanical concept of mixing of eigenstates in the neutrino sector in a manner similar to that observed in the neutral K system. Because the weak interaction eigenstates can be written as a superposition of mass eigenstates, the time evolution of the overall wave function for neutrinos exhibits a time varying character whose composition changes with time. This phenomenon, referred to as an oscillation, in the case of two neutrino mixing, results in a pure beam of ν_μ leptons at time t = o having a time dependence for its intensity given by

$$I_{\nu_\mu}(t) = I_{\nu_\mu}(o)\left[1 - \sin^2 2\theta \sin^2 \frac{(E_2 - E_1)t}{2}\right]$$

where θ is the mixing angle and E_2 and E_1 are the energies of the states ν_1 and ν_2. Expressed in terms of experimental quantities,

$$I_{\nu_\mu}(t) = 1 - \sin^2 2\theta \sin^2 \frac{1.27 \Delta m^2 L}{E} \qquad (1)$$

where Δm^2 is $m_2^2 - m_1^2$ in $(ev)^2$, L is the distance traversed in m and E is the beam energy in MeV. Because of the stability of the ν's against decay, the reduction in intensity of ν_μ as a function of time is accompanied by an equal increase in the intensity of the second component, i.e., ν_e.

Over the years, beginning with the observation that the $\overline{\nu}_e$ flux from the sun detected here at the earth is less than that expected from calculations of nuclear fusion reactions within the sun, the possibility has arisen that the mechanism previously described is at work. In more recent times, measurements of the flux of ν_μ's from the decay of atmospheric charged pions and muons in underground experiments have yielded fewer ν_μ's than calculated from the incident cosmic ray proton spectrum, particle interactions, and subsequent showering of hadron secondaries. Again, a possible explanation is a decrease in ν_μ because of the oscillation mechanism during the time the neutrinos propagate from source to detector. Finally, an accelerator based experiment (LSND) at Los Alamos has claimed evidence for a ν_e flux in a predominantly ν_μ beam which was several times greater than expected from calculations.

Why then, is the existence of neutrino mass not settled? The answer lies in equation (1) whose prediction is unique., i.e., $I_{\nu_\mu}(t)$ goes as the $\sin^2$ of an angle whose variables are Δm^2, L, and E. None of the experiments to date have convincingly shown this expression to be verified. In the case of the solar experiments, E is not measured and the flux $I_o(t)$ relies totally upon calculation. For the atmospheric neutrino experiments,

$L_\nu(t)$ and L are calculated and integrated and averaged over a wide angular range. In the LSND experiment, potential backgrounds are substantial, yields are low, and integration over E is required. Data which relies more heavily upon measurements and less upon calculations of expectations and for which a sinusoidal time dependent fit might be made, would provide compelling evidence for neutrino mass.

It is with this goal in mind that this letter of intent is being submitted, with the following features being incorporated into the design of the experiment.

1. Good determination of L, the traversed distance of the neutrino from production point to the interaction point.
2. Good determination of the energy of the neutrino in each event from observations of the final state and kinematical fitting.
3. Large event rates to achieve statistically significant results. This requires a powerful accelerator to produce a high intensity neutrino beam.
4. High acceptance of signal events commensurate with low background events. This requires a pure initial beam of well defined momentum, a massive detector with fine angular and energy resolution, and well understood reactions to study.
5. Reasonably uncomplex detector built at low cost. At this stage of exploration, the program should have some capablity of evolving based upon observations. This approach may be more likely be successful in advancing understanding than an investment in a single costly and sophisticated experiment.

We shall show in the succeeding sections how the above features can be incorporated into the design of the proposed experiment.

II. Physics Considerations

The reactions we have chosen to study are limited in number and complexity and rely upon essentially two body kinematics. They are listed below:

1. $\nu_\mu + n \rightarrow \mu^- + p$
2. $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$
3. $\nu_e + n \rightarrow e^- + p$
4. $\bar{\nu}_e + p \rightarrow e^+ + n$
5. $\nu_\mu + e^- \rightarrow e^- + \nu_\mu$
6. $\nu_\mu + e^- \rightarrow e^- + \bar{\nu}_\mu$
7. $\nu_e + e^- \rightarrow e^- + \bar{\nu}_e$
8. $\bar{\nu}_e + e^- \rightarrow e^- + \bar{\nu}_e$

Notice that the emphasis is upon using ν_μ and $\bar{\nu}_\mu$ incident beams to produce charged current interactions with nucleons and combinations neutral and charged current interactions with electrons. For reactions 1-4, the identity of the neutrino type is deduced from its observed lepton. For reactions 5-8, the presence of both charged and neutral currents in reaction 7 results in constructive interference in the scattering amplitude which results in a large enhancement in cross section over the other reactions which can proceed only via neutral currents.

Restriction to two body kinematics has obvious advantages over other multi-body processes which are inelastic. Measurement of the energy and angle of the outgoing lepton is sufficient to determine entirely the kinematics for the event. The all important neutrino energy may be deduced, event by event or, if the incident neutrino momentum is well defined in constraining the event. Another feature of the reactions is that only two types of leptons are to be detected, i.e., electrons and muons. Discriminating between these two as well as separating from charged and neutral pions may be more easily achieved at low energies.

While maximal sensitivity to small mass difference oscillations arises from the appearance of ν_e induced events, measurement of the disappearance of ν_μ events either as a function of L or E provides an investigation into the high mass difference region should that difference be due to $\Delta m \equiv (m_\mu - m_\tau)$. The low momentum of the ν_μ beam does not energetically allow the quasi elastic τ production process to occur.

Neutral current reactions on nucleons will have a single outgoing nucleon in the final state if the neutrino momentum is low enough and a Δ baryon if the neutrino energy is above the threshold momentum of about 400 MeV/c. At 500 MeV/c, this cross section is less than 20 percent of the quasi elastic charged current cross section. Considering that the outgoing state of $\nu N\pi$, obeys three body kinematics, we believe this contamination to the two body charged current processes should be in the few percent or less range.

III. Experimental Details

A. Neutrino Beam

The neutrino beam needs to be a reasonably monochromatic beam of low momentum. We are, therefore, considering a sign selected quadrupole triplet π focused beam. To achieve a mean neutrino momentum of 500$\pm$ 100 MeV/c, a π beam with a momentum of about 1.5 GeV/c is required. Judging from the results of the 12 GeV Argonne ZGS proton beam yielding a neutrino beam of mean momentum of 0.7 GeV/c, we believe the proton beam from the 8 GeV Booster at Fermilab would be ideally matched to achieving the desired neutrino beam. Further, the anticipated intensity of about 5×10^{13} protons/sec is probably the most intense source of protons in this energy range in the world.

We do not have a design for the π beam line at this time and would need to work together with Fermilab personnel to optimize a design. We have assumed ν fluxes per proton to be those in the ANL neutrino beam.

The lifetime of 1.5 GeV/c pions being about 280 nanoseconds means that in a decay length of about 30m, about 30 percent of the pions will have decayed to a muon and a muon type neutrino. This decay length is purposely kept short to keep $\frac{\Delta L}{L}$ to about 0.25 so as not to wash out the oscillation. The main sources of electron type neutrinos in the beam should be from K_{e_3} decay and μ decay, both of which should be in the 1 percent range or less. In the former case the K/π ratio at production is about 10^{-2} and the ratio of K_{e_3}/K_{μ_2} decay is 0.12 while for the latter case, the factor of 85 increase for the muon lifetime over that of the pion and a 3 body decay, result in a low decay rate as well as a softer spectrum of ν_e's.

After 30m, the π beam would be steered away through an angle of about 30 degrees to a dump where it would come to rest, thereby eliminating ν_e's from muons at rest from the main beam. The muon type neutrinos produced by π decay in the decay volume would traverse about 50m of shielding and then be detected in a neutrino detector of about 80m length. If neutrino oscillations occur, differences in yields from the front and back parts of the detector my be detected, thereby testing the anticipated time dependence (Equation 1).

B. Detector

The neutrino detector is designed to match the neutrino beam and to have a number of important characteristics listed below:

1. The detector must be totally active.
2. The detector must have good particle identification.
3. The detector must have good tracking ability.
4. The detector must have good energy determination.
5. The detector must have large mass.
6. The detector must be inexpensive.
7. The detector should be easily expandable.
8. The detector should have the potential of observing an oscillation within the detector volume itself.

The design we have developed is one which uses a modular hybrid design consisting of water tubes interspersed with glass resistive plate tracking chambers. The water tubes act as the primary interaction volume for the neutrinos and are instrumented with photomultiplier tubes at the two ends to detect Cerenkov light from electrons and higher energy muons. Electrons will emit Cerenkov light until the end of their range while muons will yield less light both because β is less than 1 and no light is emitted when $\beta_\mu <$ 3/4. The resistive plate chambers provide large fast unamplified electronic signals and will be read out with 1cm wide strips which measure the time of arrival of hits and their location in space to good accuracy. Angular resolutions will be dominated by multiple scattering and not by the resolution of the order of detector.

A schematic of the set-up is shown in Figure 1. One hundred layers of 20cm thick H_2O tubes and 2cm thick double chamber RPC planes will be spaced over a distance of 80m, making the detector equal in length to the distance L traversed by the neutrinos before striking the detector. Each layer constitutes of about 23gms of material, or about 0.64 of a radiation length. A 200 MeV/c muon will have a range of about 2 layers while a 400 MeV/c muon will have a range of about 6 layers. Range is used to determine muon energy while the sum of Cerenkov light from the various tubes determines the energy of the electrons.

The exact transverse dimensions of the RPC planes have not been specified, but 3m × 3m is a distinct possibility. This would yield a mass for the detector of about 200 tons and a fiducial volume of about 160 tons if the outer 15cm is used to reject cosmic rays. An anti coincidence shield of RPC's will be employed if necessary. With this volume and an average neutrino charge current cross section of 0.3×10^{-38} cm^2 and a neutrino flux of 0.3×10^8/sec, an interaction rate of the order of one per second might be anticipated.

The cost of the detector components is remarkably low. The 8″ × 8″ H_2O Cerenkov detectors would be made of extruded PVC and cost about $75 each. The main costs of that part of the detector are the photomultipliers and bases which might average about $600/detector. Double gap glass RPC of 3m × 3m cross sectional area cost about $2000 each. Readout electronics costs would be kept to a minimal cost because of the present availability of several thousand channels of Fastbus ADC's and TDC's previously used in other experiments and because of the possibility of multiplexing large sections of the detector.

C. <u>Sensitivity and Resolution</u>

The question of prime importance is the sensitivity of the proposed experiment to the existence of neutrino mass. The answer depends upon a number of assumptions, some of which are listed below. What follows is basically an exercise to develop a feel of what the experiment is capable of achieving and is not meant to constitute firm results which will require detailed Monte Carlo calculations.

1. Number of Events

Neutrino Flux $2 \times 10^6 \nu/cm^2/second$

Momentum 500 + 100 MeV/c

Detector Volume

200 tons total

150 tons fiducial

p - 85 tons = 5.0×10^{31}

n - 65 tons n° = 4.0×10^{31}

Cross Sections

$\sigma(\nu_\mu + n \rightarrow \mu^- + p) = 0.6 \times 10^{-38}$ cm^2

$\sigma(\nu_e + n \rightarrow e^- + p) = 0.6 \times 10^{-38}$ cm^2

$\sigma(\overline{\nu}_\mu + p \rightarrow \mu^+ + n) = 0.2 \times 10^{-38}$ cm^2

$\sigma(\nu_\mu + p \rightarrow \mu^- + \Delta^{++}) = 0.1 \times 10^{-38}$ cm^2

$\sigma(\nu_\mu + e^- \rightarrow e^- + \nu_\mu) = 0.6 \times 10^{-42}$ cm^2

$\sigma(\nu_e + e^- \rightarrow e^- + \nu_e) = 5 \times 10^{-42}$ cm^2

Detection Efficiency 50%

Running Time 2×10^7 seconds (1 year)

Rates

$\nu_\mu + n \rightarrow \mu^- + p \sim 3.5 \times 10^6 \pm 2 \times 10^3$

$\overline{\nu}_\mu + p \rightarrow \mu^+ + n \sim 10^6 \pm 10^3$

Sensitivities

$$\frac{I(\nu_\mu)}{I_o(\nu_\mu)} = 1 - \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{E}$$

a.) For disappearance of ν_μ to 10^{-2} level, limits are

$(\sin^2 2\theta)$ min $= 10^{-2}$

$$\sin^2 \frac{\Delta m^2 L}{E} = 10^{-2} \Rightarrow \Delta m^2 = 0.5(ev)^2.$$

b.) For ν_e charge current appearance, a 4 standard deviation signal above background requires about 600 ± 150 net events over the background of 20,000 events If $\phi \frac{\nu_e}{\nu_\mu} = 5 \times 10^{-2}$ in ν beam. The limits in this case are

$$\sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{E} = \frac{6 \times 10^2}{3.5 \times 10^6} = 1.7 \times 10^{-4}$$

or, $(\sin^2 2\theta)_{min} = 2 \times 10^{-4}$ and $(\Delta m^2) = 0.07(ev)^2$.

Conservatively, limits of $\sin^2 2\theta$ equal to 10^{-3} and $\Delta m^2 = 10^{-1}$ are reasonable values. Clearly the appearance of ν_e charge current quasi elastic events is a more sensitive test of ν_μ - ν_e oscillations, than the disappearance experiment.

c.) For $\nu_e + e^-$ appearance, we assume the dominate background is the scattering of ν_μ from electrons. However, since the ratio

$\frac{\sigma(\nu_e + e^- \rightarrow \nu_e + e^-)}{\sigma(\nu_\mu + e^- \rightarrow \nu_\mu + e^-)}$ is about nine, a large enhancement in the appearance of ν_e results even for small ν_μ disappearance.

With $3.3 \times 10^3 \pm 60$ background events expected from $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$, a four standard deviation effect requires an excess of about 240 events over background. This requires that 4×10^{-4} of the ν_μ have oscillated into ν_e. The limits now become $\sin^2 2\theta = 10^{-3}$ and $\sin^2 \frac{\Delta m^2 L}{E} = 4 \times 10^{-4} \Rightarrow \Delta m^2 = 2 \times 10^{-2}\,(\text{ev})^2$.

These anticipated regions of sensitivity cover the regions of sensitivity from atmospheric neutrinos and the LSND experiment. The anticipated sensitivities have been predicated upon integrated results over the entire detector, and do not include the possibility of observing the more sensitive time dependent effects within the detector.

D. Particle Identification

Good particle separation and identification is necessary if the experiment is to have the sensitivities previously estimated. In addition to electrons and muons arising from charged interactions, protons and pions from neutral current interactions need to be rejected with high accuracy.

The detector is designed to measure the Cerenkov radiation of charged particles as they pass through the $H_2 0$ volumes and to measure the position and angles of particle tracks from their production point to their stopping point with the use of glass RPC detector planes with 1cm strip readout. The usage of Cerenkov light, range, multiple scattering and the requirement of two body kinematics represents a powerful combination of criteria in selecting the desired charged current events of ν–e elastic scattering events.

At the energies of this experiment, only electrons will always have $\beta > 0.75$, the threshold β for producing Cerenkov light in H_20 in contrast to pions with momentum less than 160 MeV/c and muons with momentum below 125 MeV/c having a $\beta < 0.75$. Total Cerenkov light from higher momenta pions and muons of about 500 MeV/c will be about 50 - 60 percent of the light from electrons of the same momentum. In the case of electrons, the Cerenkov light collected will be the same in each layer to the end of the electron's range whereas in the pion and muon cases, the light intensity will decrease smoothly as the particles slow down with no light being emitted in the layer before the end of the particle's range. The integrated light over all layers should be proportional to the electron's total energy even if radiation occurs.

Pions and muons of a few hundred MeV/c momentum have ranges of the order of 100 - 200 g/cm^2 in H_20 and differences in range of about 20g cm^2. Pions will have a high probability of scattering or interacting before the end of their range because of the high cross section for Δ production at T_π=175 MeV, whereas muons remain undeflected except for multiple scattering. Range measurement provides the energy of the muon.

As a further check on the identity of the outgoing lepton and subsequently the incident neutrino, a kinematical fit to the hypothesis of quasi elastic charge current reactions will be made to verify the validity of the particle's identity.

Probably one of the more serious backgrounds to electron identification is the possibility of photons from π°'s produced in neutral current reactions which decay into two photons followed by may Compton scattering or conversion into an electron-positron pair. The energies recorded for these photons will tend to be less than one half that of electrons produced in charged current events because of the three body nature of $\pi N\nu$ events and the fact that the π^0 energy is split between 2 photons. Also, since the NC cross section is only about 20 percent of the charge current cross section at these energies, the number of these events may be manageable.

E. Costs

Although the detector was designed to optimize its technical abilities and to maximize the sensitivity of the experiment, attention was given to keeping costs low and manageable.

The usage of glass RPC chambers for tracking and timing is ideally suited to low rate neutrino experiments. The devices themselves are inherently simple, consisting of two glass electrodes separated by a 2mm gap across which a 8 Kv potential difference is applied. A detector consisting of 100 layers of RPC planes of 3m × 3m cross sectional area is estimated to cost about $300,000 dollars. Signal readout of 60,000 strips each 1cm wide can be accomplished through multiplexing of signals and the use of Fastbus ADCs and TDC's which is presently available to the group. Incidental electronics is estimated to cost about $200,000. The H_20 tubes of PVC would cost about $150,000 and the associated photomultiplier tubes would cost about $750,000. Other incidental expenses such as circulating pumps, power supplies, on line computers and peripherals, materials, and incidental labor might add another $200,000. With a 25 percent contingency, we believe the detector could be prepared at a cost of approximately 2.0 million dollars.

IV. Summary and Conclusions

In concluding this letter of intent, we wish to emphasize a number of important points.

1. The Fermilab 8 GeV Booster with a beam intensity of 5×10^{13} protons 1sec. has the potential for producing a copious number of low energy neutrinos. Operating the Booster for this program can be achieved without limiting the performance of the rest of the Fermilab program.

2. Low energy (few hundred MeV/c) neutrino beams are ideal for observing small mass differences and couplings in neutrino generation mixing. The reactions of low energy neutrinos with protons, neutrinos, and electrons are kinematically analyzable. Since the cross sections for these processes reach their maximum values for $E_\nu < 1$ GeV/c there is little advantage to using higher energy neutrinos.

3. Low energy secondary particles are relatively easy to detect and to separate from each other. The sizes of detectors required to make these measurements are manageable.

4. The proposed detector is a totally active one; there are no passive elements. The detector utilizes a number of desirable features including Cerenkov detection, tracking, timing, and segmentation. The detector is

inexpensive to build, reliable, and easy to run and maintain. Finally, the detector is excellently matched to the capabilities of the Booster.

5. The experiment has real potential to address the possibility of observing mass differences and couplings in the regions reported by LSND and in the atmospheric neutrino experiments with few of the normalization problems associated with those experiments. The experiment measures the neutrino flux through the measurement of the ν_μ quasi elastic charge current channel and uses that data to normalize the ν_e–e, elastic scattering events. The experiment has the capability of extending and improving upon the best current limits and reported results.

6. The experiment can be set up in a relatively short time period of two years and at a cost which is modest. It is entirely possible that physics results could emerge early enough to affect designs of much more expensive endeavors. If successful, the experiment could be upgraded to a size an order of magnitude larger at reasonable cost.

7. The potential reward to risk factor is high.

We ask that the laboratory initiate efforts to examine the necessary modifications to the Booster that would provide for an extracted proton beam which could produce a narrow band π beam and a subsequent and appropriate neutrino beam. A design of such a beam together with estimations of fluxes, backgrounds, momentum spread, etc., will enable us to develop a more detailed full scale proposal. Discussions on the requirements of an adequate experimental area together with its infrastructure would also clearly be desirable.

If Fermilab demonstrates interest in developing this program, we shall immediately initiate efforts to recruit additional personnel to the proposal. We are confident that with the state of interest in the question of neutrino mass that a large and eager community of scientists exists to embark upon the endeavor.