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Dr. Taiji Yamanouchi
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Dear Dr. Yamanouchi:

Enclosed is a letter of intent for: "A long baseline oscillation experiment using the high intensity neutrino beam from the Fermilab main injector and the IMB water cerenkov detector."

The contact person for this experiment is:

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Sincerely,

F. Reines

Frederick Reines
Spokesman for IMB Collaboration

FR:deo

Enclosure

THE LETTER OF INTENT FOR A LONG BASELINE OSCILLATION EXPERIMENT USING THE HIGH INTENSITY NEUTRINO BEAM FROM THE FERMILAB MAIN INJECTOR AND THE IMB WATER CERENKOV DETECTOR.

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ABSTRACT

We propose to study muon neutrino oscillations by detecting neutrinos produced by the Fermilab Main Injector in the IMB detector, some 581 km distant. Interactions span the energy range 1-50 GeV. We are able to detect muon neutrino disappearance of more than a few percent down to a mass range of $\delta m^2 \sim 10^{-3}$ (eV)^2, a two orders of magnitude improvement over existing limits from the CHARM experiment. The experiment would probe a region which has been well motivated by both experimental hints (Kamiokande) and theory (flipped SU(5)).

By taking advantage of the well studied characteristics of the IMB detector for searching for nucleon decay we have the ability to unambiguously discriminate between oscillation to electron or tau neutrinos. We can positively identify electron neutrino interactions. We are still studying the question of identifying tau neutrino interactions.

1. PHYSICS MOTIVATION OF THE EXPERIMENT.

The high intensity neutrino beam from the Main Injector at FNAL presents an opportunity to conduct a long baseline ν_μ oscillation experiment. Some indications of such oscillation have been reported by the underground proton decay detectors (1). An apparent depletion of low energy muon neutrinos in the atmospheric neutrino beam, of the order of 50%, has been reported by the Kamiokande group. The analyses of this result, in conjunction with other limits on neutrino oscillation and with the solar neutrino problem, were conducted by several authors (2). These analyses lead to the conclusion, that while the electron neutrino, of a very small mass ($m(\nu_e) \sim (10^{-9}-10^{-6})$ eV) is very weakly mixed with the other neutrinos, the tau neutrino can acquire a substantial mass (0.17 eV < $m(\nu_\tau)$ < 0.63 eV) and be strongly mixed with the muon neutrino of intermediate mass ($m(\nu_\mu) \sim (0.3-2) \times 10^{-3}$ eV). The elements of the neutrino mixing matrix have been deduced by Learned et al. as follow:

$$\begin{matrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{matrix} = \begin{matrix} 1. & 0.087 & \varepsilon \\ 0.066 & 0.755 & 0.656 \\ \varepsilon' & 0.656 & 0.755 \end{matrix} \begin{matrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{matrix}$$

with $\epsilon, \epsilon' \ll 1$. Here ν_e , ν_μ , ν_τ are the gauge eigenstates, and ν_1 , ν_2 , ν_3 - the mass eigenstates. A resonable see-saw mechanism for the mass hierarchy of lepton families has been assumed in this analysis. The authors point out that with such a mixing matrix, one should observe a dramatic effect of muon neutrino depletion in a detector at a distance of L/1km > 25 × E/1 GeV !

However, the observation of such strong depletion of low energy muon neutrinos, as reported by the Kamiokande group, has not been confirmed by the other underground detectors (IMB and Frejus). Nonetheless, both these groups do observe some, of the order of 10-20%, deficit of muon signal with a statistical error of the size of the signal. Such a result, according to a Barger and Whisnant calculation, substantially widens the allowed region of neutrino square-mass differences and mixings with respect to that derived from the Kamiokande result. This region however is still testable by experiments fulfilling the condition L > 25 x E (km/GeV).

It is interesting to point out that the new GUT, "flipped" SU(5) x U(1) (3), derived from string theory, with a resonable parameterization, leads to similar conclusions. From the superpotential, invariant under the symmetry of this model, one can extract mass matrices of the fermion families. They acquire, in a natural way, a see-saw mechanism. For neutrinos, the model predicts the masses $m(\nu_e) \sim 10^{-7}$ eV and $m(\nu_\mu, \nu_\tau) < 1$ eV, and no mixing of electron neutrinos with the other neutrino species. Reasonable assumptions for the GUT scale and Yukawa couplings provide the final neutrino mixing matrix surprisingly close to the one derived by Learned et al.:

$$\begin{matrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{matrix} = \begin{matrix} 1. & \sim 0. & \sim 0. \\ \sim 0. & 0.78 & 0.62 \\ \sim 0. & -0.62 & 0.78 \end{matrix} \begin{matrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{matrix}$$

The results of the "flipped" GUT indicate that the measurement of the neutrino oscillation parameters provide a direct test of the

Grand Unification Theories. It might turn out that the fermion mass structure and their mixing would be the only window available to the grand unification energy scale.

If the analysis of the existing oscillation data and the prediction of the theory are true, there is an opportunity to observe ν_μ disappearance and ν_τ appearance at the optimal distances L>25 x E. This condition, by fortuitous accident, is realized by the neutrino beam produced at Fermilab by the Main Injector and the distance of the IMB detector.

A major goal of the experiment proposed in this Letter is to resolve the ambiguities implied by the deficit of muon neutrinos coming from the atmosphere. It can provide either a proof of the neutrino oscillation or set the new limits on the neutrino square-mass difference by two orders of magnitude below the limits currently explored, and the mixing $\sin^2(2\theta)$ above a few x 10^{-2}. If the oscillation were observed, it could also indicate which neutrino species were involved in such an oscillation. These goals can be achieved by replacing the atmospheric neutrino beam with a well understood and controlled accelerator beam, traversing a well known path between the accelerator and the detector.

There are several disadvantages of atmospheric neutrino studies. The systematic uncertainties of the low energy flux calculations are of the order of 20-30%. The atmospheric flux in the range around 1 GeV contains comparable numbers of electron and muon neurtinos so the background for some oscillation channels is very high. The event rates for atmospheric neutrino interactions, even for a detector the size of IMB, is very low. It would take about 12 years of livetime with the natural atmospheric source to achieve the contained event statistics of the proposed run. It would take 60 years of livetime to get a comparable sample of neutrino induced entering muons.

2. LAYOUT OF THE EXPERIMENT.

To perform the experiment we propose to employ the muon neutrino beam produced by a proton beam from the Main Injector at Fermilab and, as a target, the existing and well understood IMB water Cerenkov detector. The FNAL injector has a geographical latitude of 41.50 N and a longitude of 88.15 W. The IMB detector is situated in a salt mine (600 m underground) at Grand River (Ohio), at a latitude of 41.44 N and a longitude of 81.17 W. The great circle angle between the beam source and the detector is 5.23° (91.3 mrad), and the linear distance is ~581 km. The beam has to go underground with an angle of ~ 45.7 mrad with respect to the horizon, and be aimed at the detector with the accuracy of about 1 mrad.

2.1. PRELIMINARY BEAM DESIGN

The preliminary design of the required neutrino beam has been provided by L. Stutte from FNAL. It consists of a two horn focusing system and 400 m long decay tunnel. The calculations performed using FNAL version of the NUADA program show that with such an arrangement, at the distance of the IMB detector, one can expect an integrated neutrino flux of 6200 $\nu/m^{-2}/10^{13}$ppp with a mean energy of 16 GeV. The energy spectrum and the beam profile obtained from this calculation are shown in Fig 1.

Such a beam design by no means should be considered as a final one. At the moment, the horns do not exist, and it is not clear if their application is the optimal choice. We believe that we can learn from the design of the high intensity neutrino beam at CERN, and can soon come up with a better solution more suitable for a detector at a large distance. However, a beam of the described layout has been already used at FNAL, and its characteristics obtained from the NUADA program can be safely used for estimation of event rates expected in our detector.

2.2. FEATURES OF THE IMB DETECTOR

The detector consists of a rectangular volume of size 23m x 17.5m x 17m filled with highly purified water (see Fig 2). That volume is viewed from its surface by 2048 8" Hamamatsu photomultiplier tubes, each of which is instrumented with a 2'x2' waveshifter plate. Such an arrangement provides a sensitivity of 1.2 photoelectrons collected per 1 MeV energy deposited by charged particles in the detector volume. The trigger threshold of 20 MeV is far below the requirements of the discussed experiment.

The 2.7 Hz background rate of cosmic ray muons passing through the detector with a dead time of 3.5 ms per trigger provides a comfortable live time of 99%.

The absolute time of every trigger is measured by a GEOS clock with an accuracy of 0.5 ms. A local crystal provides a relative timing with the accuracy of 3 μs. These clocks provide sufficient precision to make gating of the accelerator spill unnecessary. However, we shall need an additional set of similar clocks and a tape station for recording times of accelerator spills at Fermilab for the off-line analysis of the data. With such an arrangement, we shall be able to perform the oscillation experiment with no interference with the other goals of our physics program.

The detector is triggered by interactions taking place in its volume and by entering tracks. The position of the light producing track can be reconstructed from the measured times when phototubes sense the light and from the pattern of the illuminated tubes. Reconstruction of events with a spherical light output is accurate to within 0.5 m, the beginning of single track is accurate to within 1.5 m. Tracks entering the detector produce a pattern of early tubes with large pulse height (so called "entry spot") which makes them easily distinguishable from contained interactions.

The detector provides some identification of leptons produced in neutrino interactions. Sixty percent of the negative muons stopping in the detector produce a decay electron signal. Muons with energy above about 4 GeV produce patterns of lit tubes visually distinguishable from the patterns produced by electrons.

Muons of such an energy traverse the whole detector, giving the pattern of an exiting track, while the electron shower deposits its whole energy in the detector, illuminating many tubes, but leaving a ring of tubes with a very high pulse height of the size of a few radiation lengths in water. For demonstration, in Fig 3 patterns of lit tubes produced by a muon track and an electron track, both of energy of 10 GeV are shown.

Below such energies, more elaborate methods of pattern analysis provide distinction between showering tracks (like electrons or π^{o}'s) and nonshowering tracks (like muons or charged pions) with a reliability of about 95%. These techniques have been developed over several years for use in proton decay studies. π^{o} tracks are clearly resolved from electron tracks up to energies of 500 MeV, when tracks of individual gammas are separated by more than 30°. Above this energy, some identification is possible, with the confidence diminishing with increased energy.

The layout of the detector and of the adjacent laboratory is shown in Fig 4. The neutrino beam will strike the detector from the West, almost perpendicularly to one of the walls (the West wall). It will also come from below, with an incident angle of 2.6° below the horizon. For the purpose of the proposed experiment, as discussed later, it is important to know the structure of the rock surrounding the detector, about 200m to the west, 25m below and above. This structure is known from the geological profile in the vicinity of our detector provided to us by the Morton-Thiokol Co.

3. EVENT RATE AT IMB DETECTOR

If we assume, that the results of the NUADA program give a good estimate of the neutrino flux at the IMB detector, and that we can aim the beam toward the detector with an accuracy of 0.5 mrad, we can expect 1.8 charged current and neutral current neutrino interactions per hour in the volume of the detector. Thus, we can collect in a half year (25 weeks, 100 hours per week) 4400 interactions. A sample of this size assures 1.5% statistical accuracy, which is probably better than the systematic uncertainties of the experiment.

In addition to the contained events, the detector collects muons produced by neutrino interactions in the surrounding salt. The effective target mass for interactions producing muons, which would enter the detector through the west wall, can be roughly estimated from the formula:

$$V \rho = S \langle E_\nu \rangle \langle y \rangle \rho \,/\, (dE/dx \, \rho)$$

where ρ is a density of salt rock, S=300 m^2 is the surface area of the West wall. $\langle E_\nu \rangle$=23 is the mean neutrino energy weighted by the interaction cross section, $\langle y \rangle$=0.5 is the average energy transfer to muon, and dE/dx =1.6 MeV/g/cm^2.

It is important to notice, that this mass depends on the type of matter only through the dE/dx, which does not vary much from one type of rock to another. Nonetheless, as we mentioned before, the structure of the matter surrounding the detector, in the volume of interest, is well known, and all the voids well measured.

Substituting the above values one gets the target mass of 21.6 kton from the above formula. A more realistic Monte Carlo integration gives an effective mass of 23.7 kton for all neutrino induced muons entering the detector. This target mass provides 4.8 muon tracks per hour recorded by the detector (12 000 per half year).

The background from cosmic ray induced events will be negligible for a number of reasons. The rate of 1.8 contained events per hour from the accelerator is large compared to the ambient event rate at IMB of about 1 contained event per day. The accelerator neutrino interactions could have a minimum duty factor of about 10^{-5}, compared to 100% for the ambient rate. The accelerator events come from a specific direction whereas the ambient rate is isotropic. These factors imply an ambient background of about $2x10^{-9}$ per event. Atmospheric events are also usually of lower energy than the accelerator induced ones. For these lower energies the background could rise to $4x10^{-8}$.

The external event sample will also have a much higher rate than that from external ambient neutrino interactions. Because the accelerator beam is near the horizon some surface muons may be mistaken for accelerator induced neutrino interactions. A rough estimate, using a duty factor of 10^{-5} indicates a background from this source to be about 10^{-8} per external neutrino event.

These factors indicate that the experiment will not even be close to being background limited and can in fact be operated with a much longer spill if that is required for other experiments.

4. SEARCH FOR NEUTRINO OSCILLATION

4.1 MUON NEUTRINO DISAPPEARANCE

The first indication of muon neutrino oscillation would be their disappearance from the beam. One can look for such disappearance in two different ways, each of them with different systematic limitations:

1. One can measure the ratio of the number of muons entering the detector from the surrounding rock to the number of contained interactions. The contained events serve as a measure of the total neutrino flux, while entering muons serve as a measure of the muon neutrino abundance in the beam. The number of entering muons can be predicted from the known structure of the rock surrounding the detector and from the characteristics of the beam.

2. The muon neutrino content in the beam can be measured from the fraction of contained events classified as having a muon track. This parameter suffers from a poorer statistical accuracy and strongly depends on muon identification capabilities. However, since it is automaticly measured with the first one, it may be

considered complementary.

4.1.1 SYSTEMATIC UNCERTAINTIES

The main source of systematic uncertainty of the first method is the misassignment of contained and entering events. While, the signature of the "entry spot" seems to be sufficient for identification of entering tracks, the efficiency of this signature has to be carefully tested. We shall be able to provide adequate data on this subject after finishing the current maintenance of the detector. If this efficiency turns out to be insufficient, we can build an active veto on the West wall of the detector.

The other source of the systematic uncertainties of the first method is due to the hadronic component of neutrino interactions. Most of the pions interact in the rock and do not enter the detector; however some may not be absorbed and simulate a muon track, and a few will decay in flight leading to a muon. The extent of such possible admixture requires detailed Monte Carlo studies of the hadronic sector of neutrino interactions, and will be provided in the forthcoming proposal of the experiment but we only expect a contribution at the level of 1%. Our capability of recording the muon decay electron should be very helpful in eliminating a substantial portion of negative pions. The distribution of energies of muons, when they enter the detector is shown in Fig 5. 7.6% of them have energies below 1 GeV, where the major contribution of entering pions is expected. This is a good estimate of the upper limit of the systematic error of this method.

The second method may suffer from higher systematic uncertainties. For the contained events all the hadronic particles produced in the interactions are recorded in the detector and lepton tracks have to be extracted from their background. The spectrum of muons from the contained charged current interactions is shown in Fig 6. 32% of the muons have energies below 5 GeV, where one has to worry about mixing of muon and pion tracks, and 2.0% have energies below 500 MeV, where track identification is less certain. Here again, the percentage of the troublesome tracks indicates the upper level of the systematic uncertainties. Its detailed evaluation requires a Monte Carlo simulation of the hadronic sector, and will be available in the formal proposal.

In summary, we are convinced that the search for muon neutrino disappearance using the ratio of the number of entering muons to the number of contained events alone provides a sufficient sensitivity to motivate the experiment. The other method, for which the data are automatically provided, can lead to useful, complementary information after in depth analysis.

4.1.2 ESTIMATED OSCILLATION LIMITS

In the estimation of the oscillation limits we assume that the systematic errors of the method used are smaller than the statistical ones, after a half year of data collection. It is not obvious yet if this assumption is correct. Then, if the observed signal is in agreement with the expectation, one can set the limits on the square-mass difference and the mixing angle shown in Fig 7. These limits apply to the oscillation of muon neutrinos to anything. They have been derived from the formula:

$$P(\nu_\mu \rightarrow \nu_x) < \sin^2(2\theta) \int \rho(E)\sin^2(1.27\ \delta m^2\ L/E)\ dE$$

where $\rho(E)$ is the neutrino energy spectrum, and L is the oscillation distance (L=581 km). If the systematic errors were larger than the statistical ones, the limit on $\sin^2(2\theta)$ would increase proportionally to the ratio of these errors, and the limit on δm^2 - proportionally to square root of this ratio.

4.2 SEARCH FOR APPEARANCE OF OTHER NEUTRINOS

4.2.1 ELECTRON NEUTRINO APPEARANCE

If muon neutrinos oscillate to electron neutrinos, one should observe more charged current contained interactions with electron tracks than expected from the beam composition. The energy spectrum of these electrons should be the same as that of muons from similar contained interactions. One does not expect such high energy (few GeV) electrons from any other source, except for about 2% contamination of the neutrino beam at the source by electron neutrinos. If after a half year of data collection we do not observe any excess of electron tracks with energies higher than say 5 GeV above 2% expected from the beam contamination, we can set the limits on the vacuum oscillation $\nu_\mu \rightarrow \nu_e$ shown in Fig 8. These assumptions are valid if there is no significant contribution of π^0 tracks of energies above 5 GeV. The validity of this assumption requires further Monte Carlo studies.

4.2.2 TAU NEUTRINO APPEARANCE

It is extremely important to be able to search for a signal of tau neutrino appearance. A possible signature of such process can be an excess of electron tracks from τ meson decay in the contained sample. However, such a signal is probably deeply hidden by π^0 tracks, and its demonstration may be very difficult. Here again, detailed Monte Carlo studies of tau neutrino charged current interaction, of τ meson decay, and of π^0 production in neutral current muon neutrino interactions are required for deriving any conclusion.

Nonetheless, if the muon neutrino disappearance is demonstrated, and no excess of high energy electron tracks is observed, tau neutrinos (if they really exist) would be the most natural channel to which the oscillation could take place. Their positive identification as taus would perhaps require modifications to the detector.

Because of the importance of the positive detection we shall pursue studies attempting to find a mode which will positively identify τ decay.

5. TIME SCHEDULE

We have outlined in this document only the basic ideas of the proposed long baseline oscillation experiment. Many questions, as indicated, require more detailed studies. We expect to generate the answers to these questions, and any addressed by the readers of this document, in the next, more complete letter by the end of 1989. The studies and design of the beam line could take an additional year.

6. FERMILAB INVOLVEMENT

We expect that the FNAL participation in the experiment will involve at least:

a. active help in designing the beam line and its construction,

b. during the data taking FNAL will provide space and equipment necessary for monitoring and recording the beam timing, intensity and other characteristics needed for control of the neutrino beam flux at the detector.

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2. J.G. Learned et al. Phys. Lett. B207, 79, (1988). V. Barger and K. Whisnaut, Phys. Lett. B209, 365, (1988).
3. G.K. Leontaris and D.V. Nanopoulos, Phys. Lett. B212, 327, (1988).

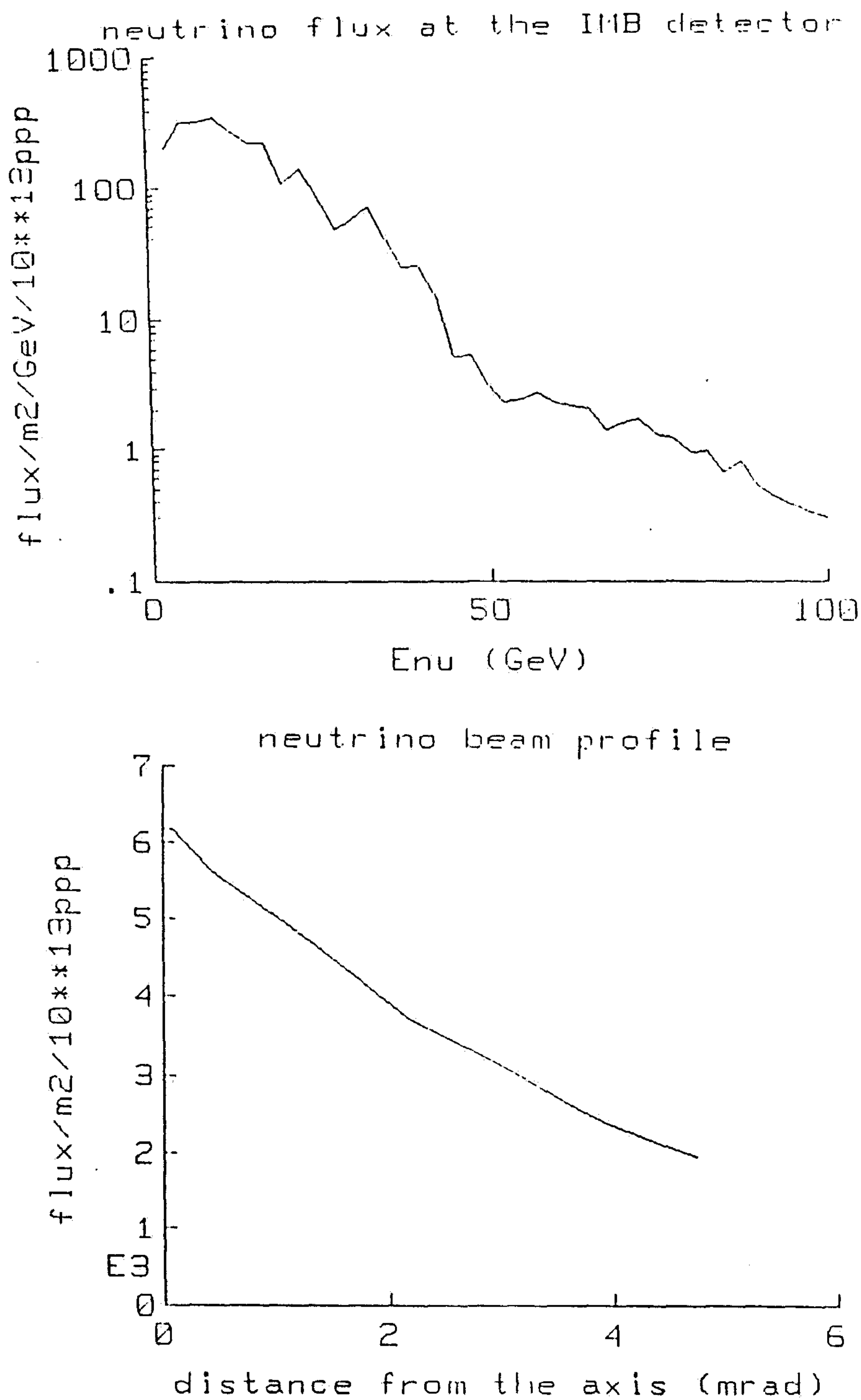

Fig. 1. Energy spectrum and an angular profile of the neutrino beam produced by the FNAL Main Injector as predicted by NUADA program for two horn focusing.

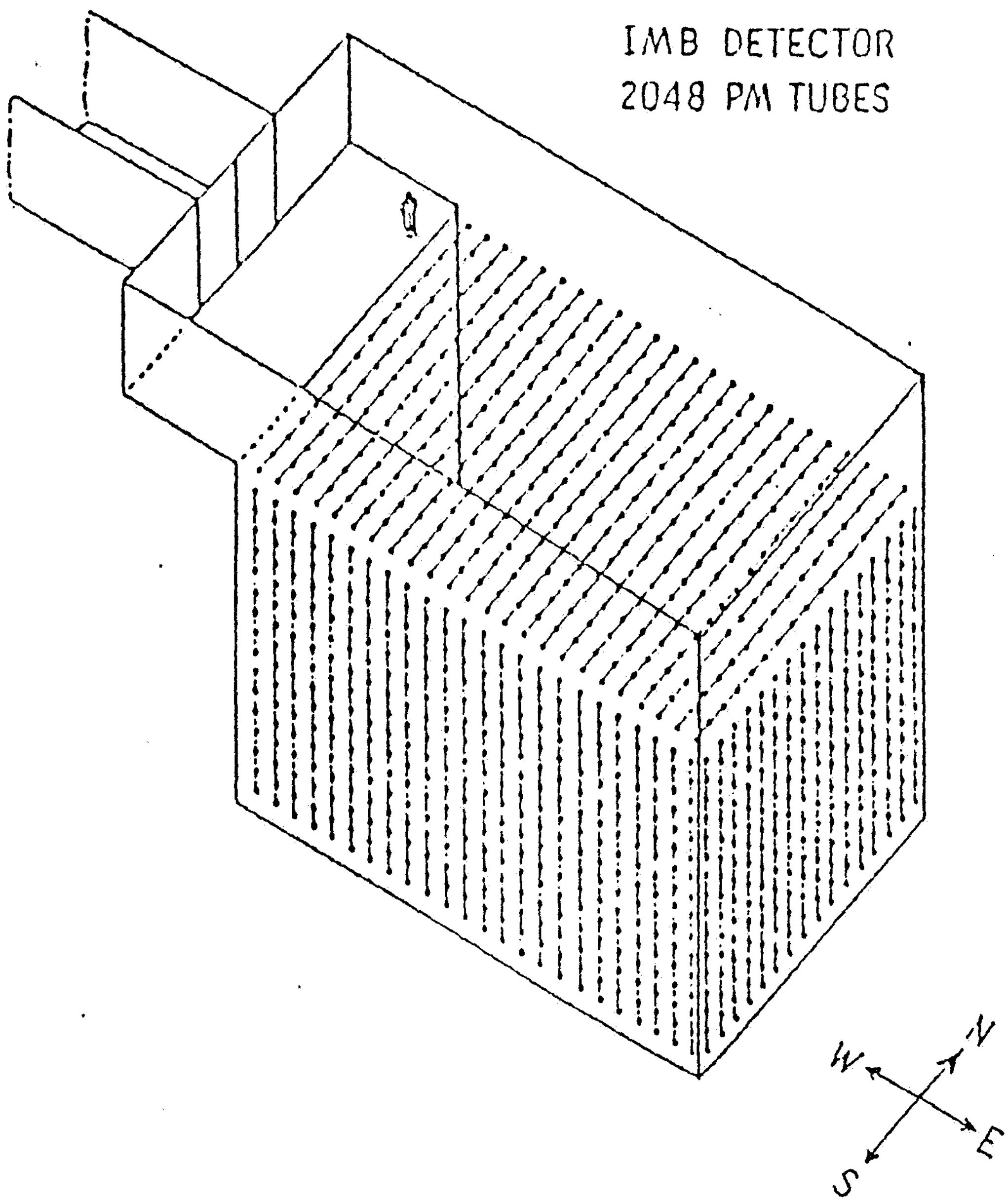

Fig. 2. Picture of the IMB water Cerenkov detector.

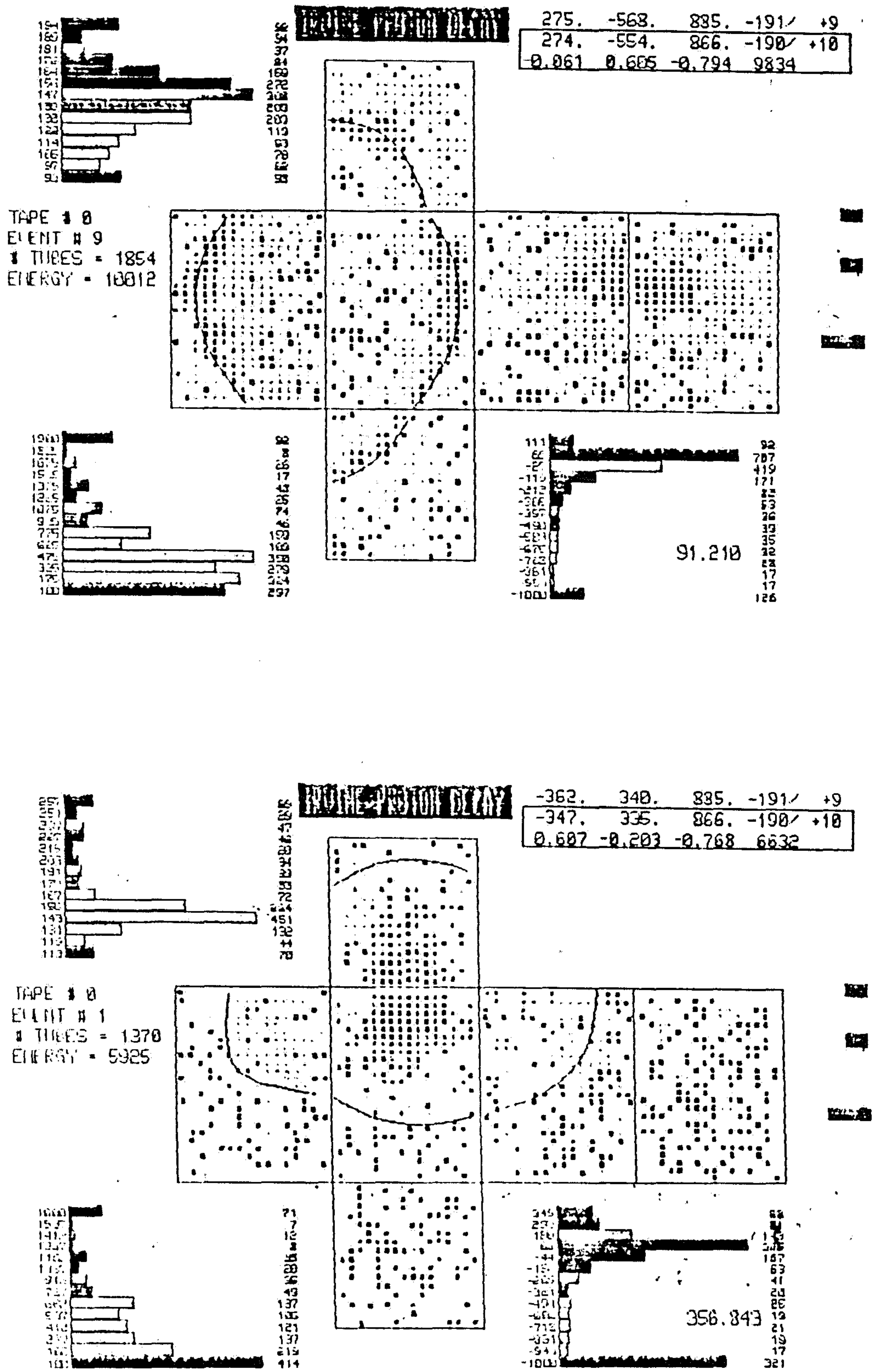

Fig. 3. Pattern of lit tubes by an electron track (above) and a muon track (belove). Both particles had energy of 10 GeV and entered the top wall of the detector (the right-most rectangle).

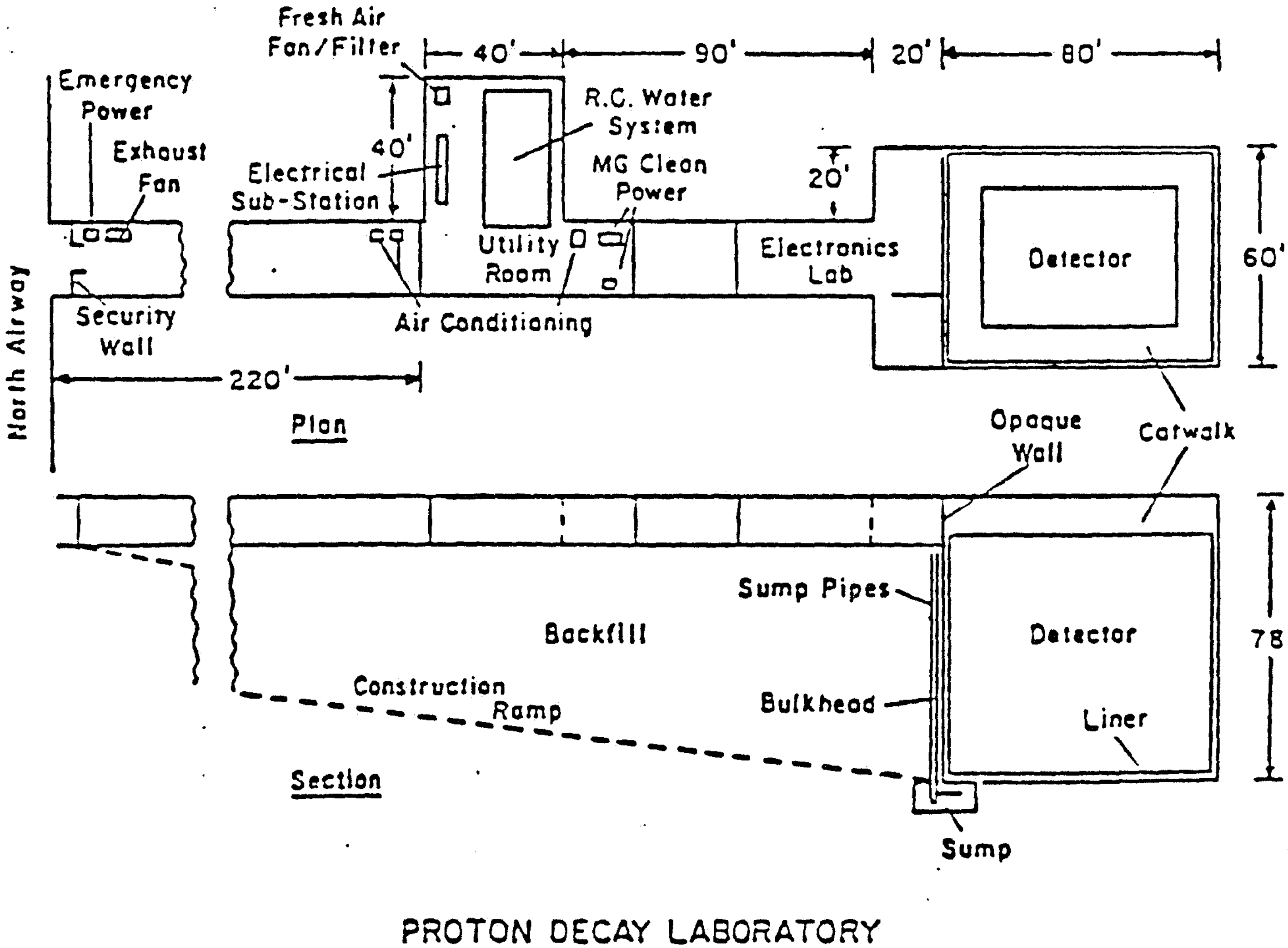

Fig. 4. Layout of the IMB detector and of the adjacent laboratory.

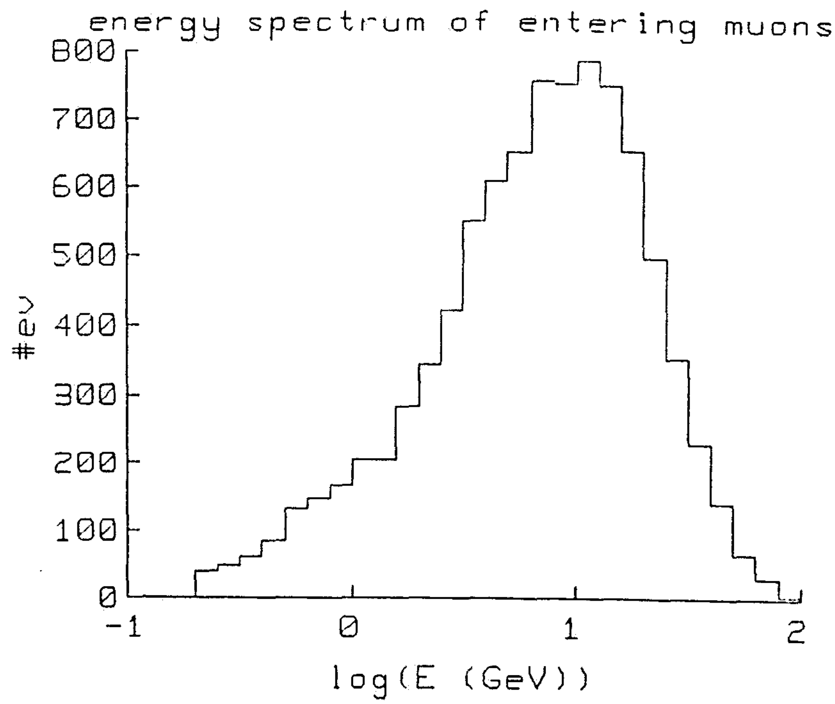

Fig. 5. Distribution of muon energies entering the detector from the surrounding rock.

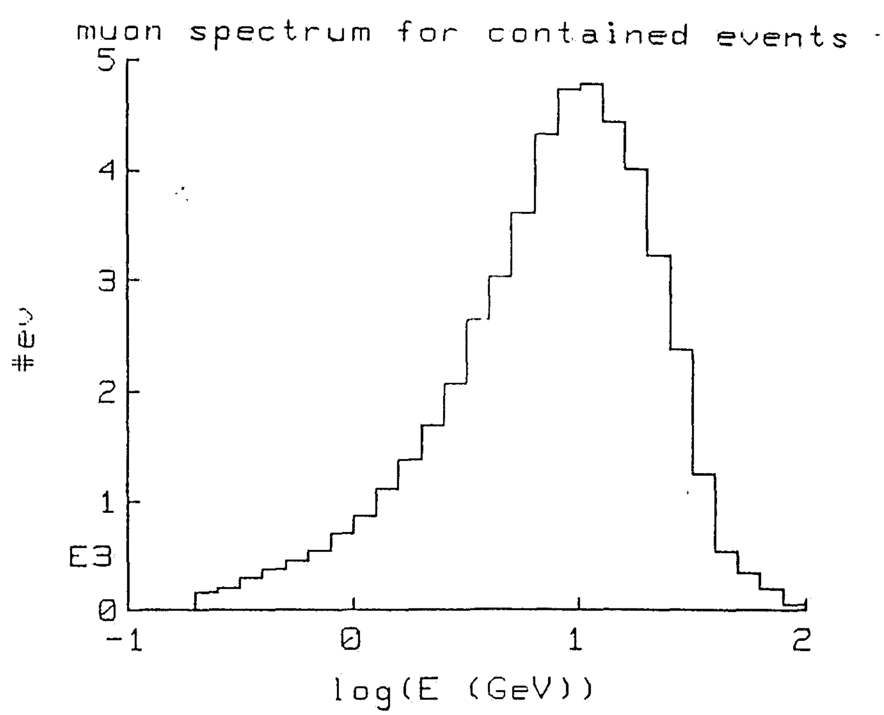

Fig. 6. Spectrum of muons produced in the contained neutrino interactions.

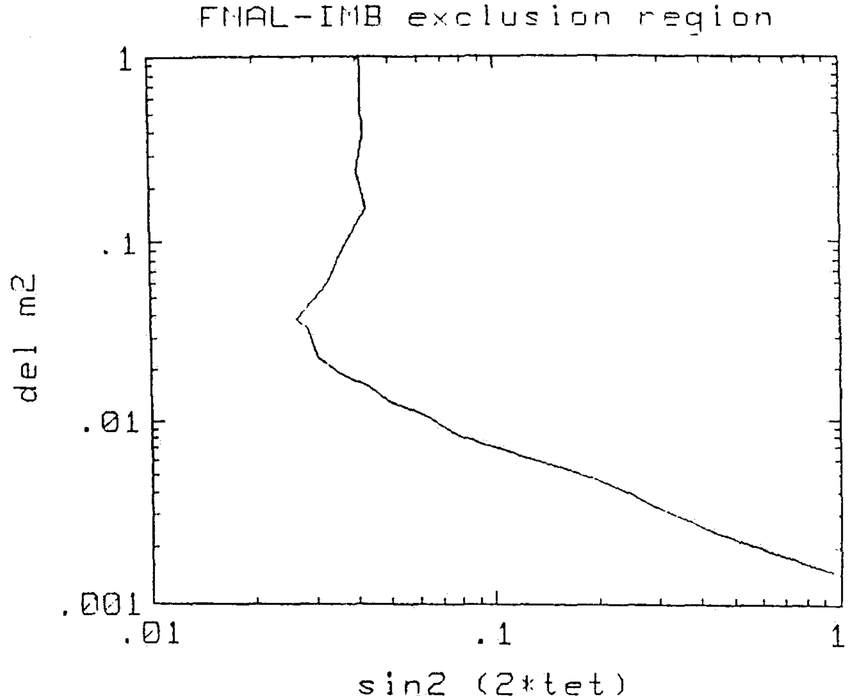

Fig. 7. Limits on square mass difference and the mixing angle for muon neutrino oscillation to anything which can be obtained by the IMB detector.

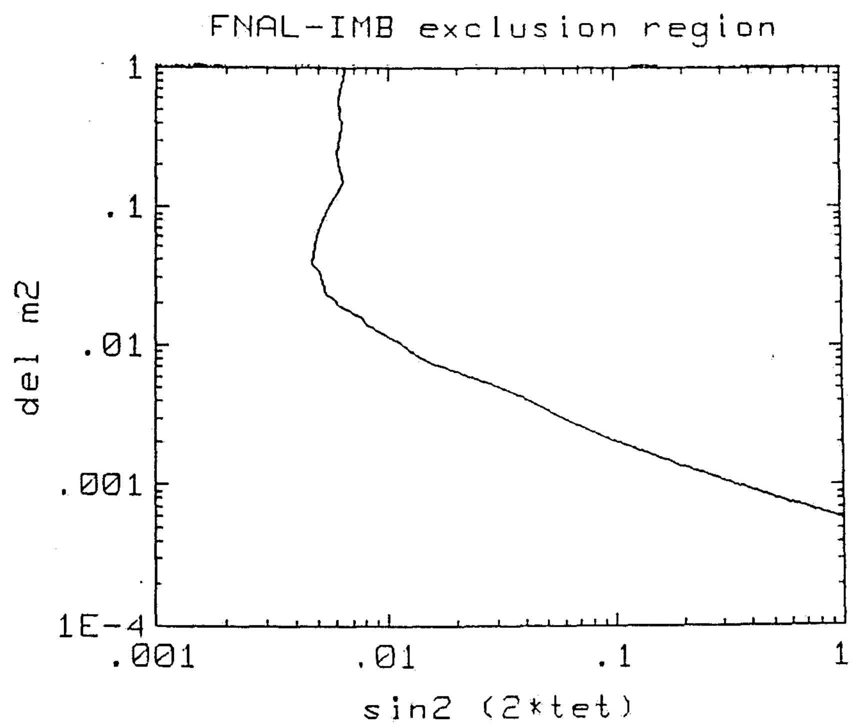

Fig. 8. Limits on square mass difference and the mixing angle for muon neutrino oscillation to electron neutrino which can be obtained by the IMB detector.