Letter of Intent

For a Neutrino Beam from the Proposed Main Injector to the DUMAND Detector

The DUMAND Collaboration:
RWTH Aachen, Germany
Universität Bern, Switzerland
Boston University
University of Hawaii
Universität Kiel, Germany
Kinki University, Japan
Kobe University, Japan
Scripps Institute Of Oceanography
Tohoku University, Japan
Institute for Cosmic Ray Research, University of Tokyo, Japan
Vanderbilt University
University of Washington, Seattle
University of Wisconsin, Madison

The DUMAND collaboration is continuing work on a Fermilab proposal to study neutrino oscillations by directing a neutrino beam from the Fermilab 120 GeV injector through the 6000 km of intervening earth to the DUMAND detector at the bottom of the ocean near the coast of Hawaii. This work was begun by Learned and Peterson[1] in 1989 at the Main Injector Workshop. The importance of matter oscillations over this large distance in extending the range of parameters in which oscillations are detectable has been emphasized by Pantaleone,[2] and the relative importance of systematic errors, the detector energy threshold, and distance have been explored by Parke.[3] Copies of these three reports are appended. This note will a) affirm the continuing strong interest of the DUMAND collaboration in the possibility of such an experiment, b) describe the current status of DUMAND as a DOE approved and funded project, c) provide more recent results on the low energy thresholds of the DUMAND detector, and d) express our appreciation to the neutrino beam design group for their continuing work in exploring the problems and assembling data on the environment for the novel beam required to direct neutrinos from Fermilab to the DUMAND detector.

The small angular spread and high energy of the beam from the main injector and the long path in matter for the neutrinos make the proposed experiment uniquely sensitive (among accelerator experiments) to neutrino mass differences, δm^2, in the range down to 0.001 eV^2 and to values of the mixing angle, $\sin^2 2\theta$, down to 0.005 for ν_μ to ν_e oscillations. The matter oscillations (MSW effect) over this very long path in the earth enhance the conversion of ν_μ to ν_e and make this experiment sensitive to these very low values of $\sin^2 2\theta$.

The DUMAND detector was proposed and has been funded to study very high energy neutrinos from extraterrestrial sources. A prototype detector has been used to measure the downward flux of muons in the deep ocean (4 km) and the construction is proceeding with a goal of having one third of the detector elements in place by the end of 1992 and the remainder by the the end of 1993. The site for the proposed array is in a subsidence basin at a depth of 4.8 km, 30 km west of Keahole Point, Hawaii. The array consists of nine strings, one at the center and at each of the vertices of an octagon 40 m on a side. Each string supports 24 phototubes, 15 inches in diameter and spaced 10 m apart vertically. The spherical tubes are oriented with the photocathode pointing downward and have a sensitivity which falls linearly with the cosine of the angle between the most sensitive direction and the direction of the incident light. A cable from shore supplies electrical power to the array and has an optical fiber for data transmission from each string. Each string is controlled by an electronics module which digitizes, with a 1 ns clock, the time and charge of each signal received from a phototube on its string and transmits the digitized signal to shore. This provides adequate data for reconstruction of the trajectories of high energy muons with an rms error less than 1°. For upward muons, the signal is almost entirely due to neutrino interactions beneath the array and the effective area of the array is 20,000 m^2. The location deep in the ocean provides essential reduction in the flux of downward muons, so that our signal is dominated by muons produced by neutrino interactions over the entire hemisphere of upward muons and approximately 10° into the downward hemisphere. In this 2.3π steradian region, the isotropic background from interactions of neutrinos which are due to cosmic ray interactions is 1/3 event per year per bin of angular resolution size. The number of detected neutrino interactions from one of the more intense point sources of high energy gamma rays, such as Cygnus X-3 or Hercules X-1, is expected to be at least 10 events per year if the gamma rays are from π° decay. Thus the significance of such signals will be limited by statistics, not background. The location at 19° from the equator gives us more than 50% duty cycle for all of the sky except for a few degrees around the North Pole.

Neutrinos from a Fermilab beam would intersect the DUMAND array rising at an angle 30° below the horizontal, well within our region of best acceptance and low background. Monte Carlo calculations[4] show detection and reconstruction efficiencies which are equivalent to a target mass of approximately 10^6 metric tons (half the contained volume) for muons from interactions of 20 GeV/c neutrinos (flat y-distribution) with the array which is currently being constructed. For interactions in the contained volume, these Monte Carlo calculations give 41% trigger efficiency for interactions of ν_e and 51% for ν_μ for neutrinos with the energy distribution expected[1] for a beam from the main injector.

A modest addition of four additional strings inside this array would enhance the efficiency for low energy events. Monte Carlo studies of the optimal way in which to add detectors is in progress. The collaboration would certainly try to obtain funds to continue the scheduled production and installation to include the additional, finer-grained detector capability. The cost of such an enhancement is very roughly $2.5M, well below the cost of beam construction at Fermilab.

A decay tunnel 300 to 400 m long, approximately due west and 30° below the horizontal is needed to point the neutrino beam at the DUMAND detector, and a 30° arc of main injector magnets is required to point the proton beam down the tunnel. Figure 1 shows a vertical cut through a suitable tunnel. The arc, which transports the extracted proton beam, extends through the glacial drift and well into the upper Dolomite layers. Thus the proton target and the decay path would lie in the Dolomite and perhaps (depending on the decay length) in the St. Peter sandstone beneath it. Experience with protection of water and soil from the radiation produced by such beams at Fermilab has been in the upper glacial drift layer. The soil and rock structure at these depths has been extensively studied for the SSC proposal by the Illinois State Geological Survey, and this group is preparing a summary of the rock and water conditions to be expected in a tunnel such as we propose. It is already clear that water fills the fissures between chunks of dolomite rock, but the diffusion time scale, and hence the decay of the isotopes of concern (^{22}Na and ^{3}H), is clearly very different for production in large chunks of rock than in the fine-grained glacial drift on the surface. The laboratory procedures for adequate protection of water from radioactive isotopes produced by particle beams were developed for the glacial drift of the surface aquifer, and modifications for application to the dolomite layer may well be desirable. Since rather modest changes in the permitted production of ^{22}Na and ^{3}H in the material outside the "protected" shielding can lead to rather dramatic changes in the cost of the tunnel, it is premature to attempt very detailed beam designs or flux estimates. For example, the water in the St. Peter sandstone is much more mobile than in the dolomite and must be very carefully shielded. We could, with relatively modest changes in the neutrino flux, shorten the decay tunnel so that the absorber is above the St. Peter or extend the decay tunnel so that the stopper is beneath it. Such decisions should be made after we have the report of the Illinois State Geological Survey. We appreciate the cooperation and support which we have had from the radiation protection and beam facilities groups and we expect to continue to work with them to evaluate the various designs and construction methods for this unusual beam.

Anticipated Physics Results

The question of neutrino masses and mixing is a central one in current particle and astrophysics, and almost certainly requires going beyond the standard model. Recent interpretations of measurements of solar neutrino interactions argue for a rather small difference in the ν_μ and ν_e masses but it is clear that additional information from an accelerator experiment would help to constrain the hypothesises available to explain the solar neutrino data.

The deficit in the ν_μ/ν_e ratio claimed by the Kamioka Group[5] may be interpreted as $\nu_\mu \rightarrow \nu_\tau$ oscillations[6] . This is made more plausible by the suggestion of see-saw mass relationships (Ref. 6) which could encompass a small δm^2 for $\nu_e \leftrightarrow \nu_\mu$ solving the solar neutrino problem and a $\delta m^2 \approx 0.01\text{eV}^2$ for $\nu_\mu \leftrightarrow \nu_\tau$, which would be detectable by DUMAND. The advantage DUMAND, at 6000 km, has over IMB, at 600 km, remains to be examined in detail in the proposal. The identification of ν_τ interactions is difficult for

all the detectors and we are investigating the discriminating power of the DUMAND array for identification of ν_τ interactions.

The search for mixing or oscillation in a ν beam from the main injector requires knowledge of the beam composition at production and measurement of flux and composition at the distant point. The central portion of the beam is ν_μ with a few percent of ν_e, and this small fraction of ν_e can be calculated accurately enough for our purposes. Since the beam is considerably wider than the DUMAND detector (Ref. 1), and the determination of the absolute intensities of neutrino beams has often been difficult, it is important to be able to measure the flux incident on the detector. The Monte Carlo work which has been done since the first estimates[1] shows that the detection efficiency for interactions within the contained volume of the detector for ν_e with the energy spectrum of the ν_μ beam is approximately 40% and the detection efficiency for ν_μ interactions in the same volume is approximately 50%. Approximately 10,000 contained events are expected[1] in a six month run, so the number of detected events would be approximately 5000 and would provide a beam normalization of about two percent statistical error and a few percent systematic error, which is nearly independent of both beam flavor composition at the detector and of our ability to distinguish muon from electron events.

The presence of electromagnetic showers from π°'s in the contained ν_μ interactions complicates the identification of the electron events at low electron energies for all detectors, and requires a cut on the shower energy or muon range, so that the full statistics of the contained events are not useful for the determination of flavor content at the detector. The effects of such a cut for data from the DUMAND detector are under investigation, but we note that the comparison of the non-contained μ-events with the contained μ-events provides a cross check and that the the sensitivity estimates, Pantaleone's[2] Figure 3, were based on muons above 10 GeV.

In summary, the new threshold Monte Carlo calculations show that the sensitivity of the DUMAND array to electron events and to relatively low energy events of both flavors provides adequate beam normalization so that the additional sensitivity provided by matter oscillations in this very long baseline experiment can be utilized. Consequently this experiment offers the best prospects for exploring the range of small values of the $\sin^2 2\theta$.

REFERENCES

1. J. G. Learned and V. Z. Peterson, Neutrino Oscillation Experiment in DUMAND II employing a beam from the 150 GeV injector, in *Proceedings of the Workshop on Physics at the Main Injector*, Fermilab, 18 May 1989.
2. J. Pantaleone, Matter Enhanced Oscillations of Accelerator Neutrinos, Hawaii DUMAND Center-6-90.
3. Stephen J. Parke, Terrestrial long-baseline neutrino oscillation experiments, Fermilab report, July 24, 1990.
4. V. Stenger, Response of Octagon to Fermilab Neutrinos, DUMAND Internal Report-8-90 MC Results on low energy neutrinos in DUMAND, DIR-10-90 present Monte Carlo calculations of detection and reconstruction efficiencies for through-going muons and for low energy electron and muon events respectively.
5. Kamioka, 25th International Conference on High Energy Physics, Singapore 2-8-1990, T. Kajita et. al.
6. Learned, Pakvasa and Weiler, Phys.Lett. B, **207** (90), 79

FIGURE CAPTIONS

1. Vertical section of tunnel for neutrino beam to DUMAND. The type of soil or rock is shown at the left axis. Extraction on the north side of the injector is assumed, and the beam stopper at the end would be well within the lab boundary, somewhat south of the main gate on Kirk road.

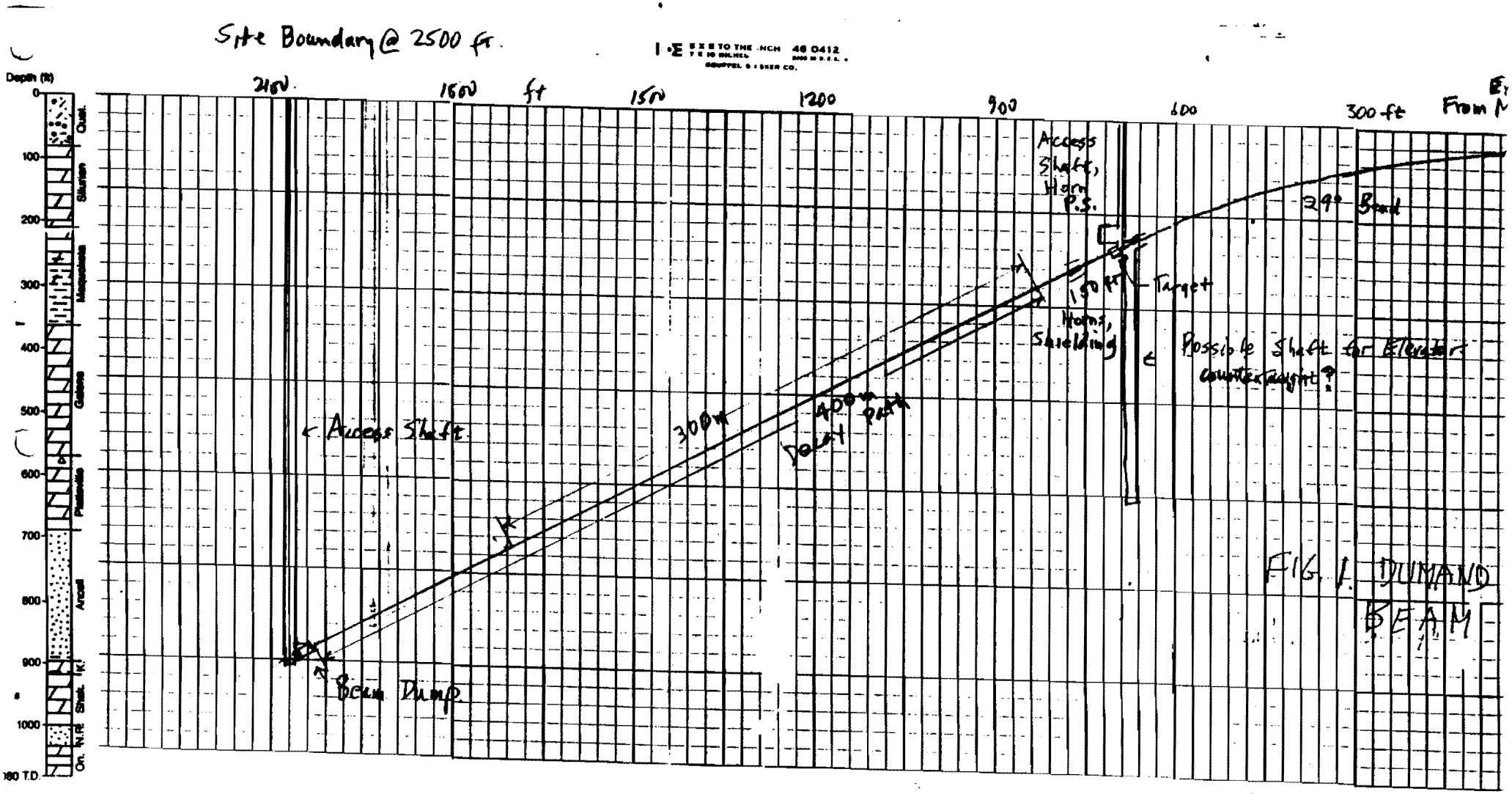

FIG. 1. DUMAND BEAM