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Short Title

A Study of Neutrino Interactions in a Large Water Target at Great Distances from the Neutrino Source

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Summary

A Study of Neutrino Interactions in a Large Water Target at Great Distances from the Neutrino Source

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An experiment is proposed which will (a) search for electron-muon neutrino oscillations, (b) measure the neutrino nucleon differential cross section at the highest energy available, (c) measure the velocity of neutrinos to a precision of one part in 10^6, (d) search for neutrino decays.

We propose a new neutrino beam at FNAL, using a thin underground decay tunnel two km long, to illuminate a 4×10^6 ton water target-detector located about 2750 km downstream. While several sites for the detector have been considered, the most likely present candidates are Dabob Bay in Puget Sound, and off the continental shelf in the Pacific Ocean.

At a primary accelerator proton energy of 400 GeV, the calculated event rate is 0.7 neutrino interactions per 5×10^{13} protons on target. This is to be compared with 0.061 neutrino water target interactions per FNAL pulse assuming the current neutrino beam intensity, a 0.4 km decay tunnel, about 2×10^{13}ppp, and 1 interaction per 17 tons of target 1.4 km from the Al block pion and kaon generator.

Hence we anticipate 0.27 million interactions in one month's running time in the new beam line. This will allow us to measure the difference between the squares of the mu and electron neutrino masses to about 5×10^{-4} eV^2. The sensitivity parameter x/P_ν of the proposed experiment for detecting neutrino oscillations is on the order of 10^3 meters/MeV.

We estimate that we will need about one month's beam time dispersed over a year in order to test the water target detector. We could be ready for the tests early in 1978.

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I. INTRODUCTION

We propose to study the properties of neutrinos by observing neutrino interactions at very large distances from the point where they are created. The main topics of interest are neutrino mixing and decays, the neutrino masses, lepton number violation, the number of different types of neutrinos and the velocity of neutrinos. The novel feature of the experiment is the use of a massive water target with Cerenkov light detectors.

A. Neutrino Mixing

The possibility of neutrino oscillations was first proposed by Pontecorvo[1]. He later pointed out[2] that such oscillations can in part be responsible for the greatly reduced electron neutrino flux from the sun in the experiment of Davis et al[3]. Since then a number of different theories of the weak interactions have been formulated which require lepton number non-conservation and hence imply neutrino oscillations if neutrinos have a small but finite mass.

Several authors[4] propose gauge theories with V+A currents in addition to the usual V-A, new leptons and finite, unequal masses for neutrinos. In these theories the separate conservation of μ and e lepton numbers is violated and $\nu_e \leftrightarrow \nu_\mu$ oscillations take place; the oscillation length is given by $L_c = 4\pi p_\nu/\Delta$ where p_ν is the neutrino momentum and Δ is the difference of the squares of the ν_e and ν_μ neutrino masses. In this theory the lepton -number-violating decays (such as $\mu \to e\gamma$) are many orders of magnitude larger than in a pure V-A theory; nevertheless the predicted rates are well below the current experimental upper limits[5].

Bilensky and Pontecorvo[6] propose a theory in which ν_e and ν_μ (which participate in the weak interactions) are orthogonal combinations of two massive fields (with masses m and m').

In their scheme neutrino beams are no longer described by stationary states, rather they oscillate with an oscillation length $\mathcal{L}_o$. The lepton number-violating decays are suppressed to first order by a cancellation (technically similar to the suppression of strangeness changing neutral currents in the GIM scheme) yielding an estimate of the decay $\mu \to e\gamma$ many orders of magnitude below the current experimental upper limit.

Finally we mention that Bjorken and Weinberg[7] propose a simple SU(2)XU(1) gauge theory with several scalar boson doublets in which muon number is conserved by the intermediate vector boson interactions but not by effects of virtual scalar bosons. In this theory reactions such as $\nu_\mu + N \to e + N$ and $\mu \to e\gamma$ would occur at a rate that is superweak. Their estimate for the rate $\mu \to e\gamma$ is very close to the present experimental upper limit.

Quite apart from the theoretical uncertainties, there are a number of considerations which make an experimental study of neutrino oscillations desireable:

(i) due to the rather large upper limits on the neutrino masses, it is not possible to rule out neutrino oscillations.

(ii) the result of the solar neutrino experiment indicates that either our understanding of the nature of neutrinos is incomplete or that the theory describing ν_e generation by the sun is incorrect.

In this experiment we measure the ν_μ charged current event rate at FNAL (I_{FNAL}) and at a point 2750 Km away. The rates in the absence of oscillations should be related by

$$\frac{I_{FNAL}}{I_{WASH}} = \frac{mR^2}{Mr^2}$$

where m,r (M,R) are the mass and distance to the detectors at FNAL and Washington.

Since the beam consists mostly of ν_μ ($\sim$2% ν_e), $\nu_e \leftrightarrow \nu_\mu$ oscillations should cause a decrease in the rate of ν_μ charged current events detected at the remote target.

In particular the ratio I_{WASH}/I_{FNAL} may be energy dependent (if for example the oscillation length is as given above) and therefore will give an indication of the mechanism by which ν_μ depletion takes place.

B. Neutrino Velocity

If the neutrino is massless, then the special theory of relativity requires that it travel with the speed of light. We propose a direct measurement of the neutrino velocity with a precision of 1 part in 10^6. This degree of precision might be attained because the 53.1 MHz radio frequency accelerating system at FNAL delivers protons to the production target in bunches about 1 nsec in duration and 18.83 nsec apart. For sufficiently high K, π momenta the difference in velocity of the parent mesons and the decay neutrino can be neglected. Thus the uncertainty in the neutrino velocity $\delta\beta/\beta = \delta t/t$ where $\delta t < 10$ nsec and t=2750 Km/c giving $\delta t/t \sim 10^{-6}$. If the ν velocity were significantly different from the velocity of light, the times at which ν interactions occur in the detector would be delayed with respect to a clock pulse from the accelerator. Techniques exist for making such precise correlations. While a very accurate determination of the velocity is possible, no significant improvement is possible for the neutrino mass.

II. DISCUSSION OF THE APPARATUS

We propose to build a new neutrino beam at FNAL that will illuminate a water target of about one million tons at a distance of 2750 Km. The large detector is necessary in order to compensate for the small solid angle intercepted at FNAL. The proposed technique allows us to detect interactions in an underwater derector of this size at a reasonable cost. In addition a smaller detector is needed close to FNAL in order to measure the interaction rate at the laboratory.

In subsequent sections we describe a preliminary design of the beam, the expected event rate and the effect of $\nu_\mu \leftrightarrow \nu_e$ oscillations for $\Delta = (m^2_{\nu_\mu} - m^2_{\nu_e}) = 0.01\ eV^2$, the characteristics of the detector and backgrounds.

A. Neutrino Beam

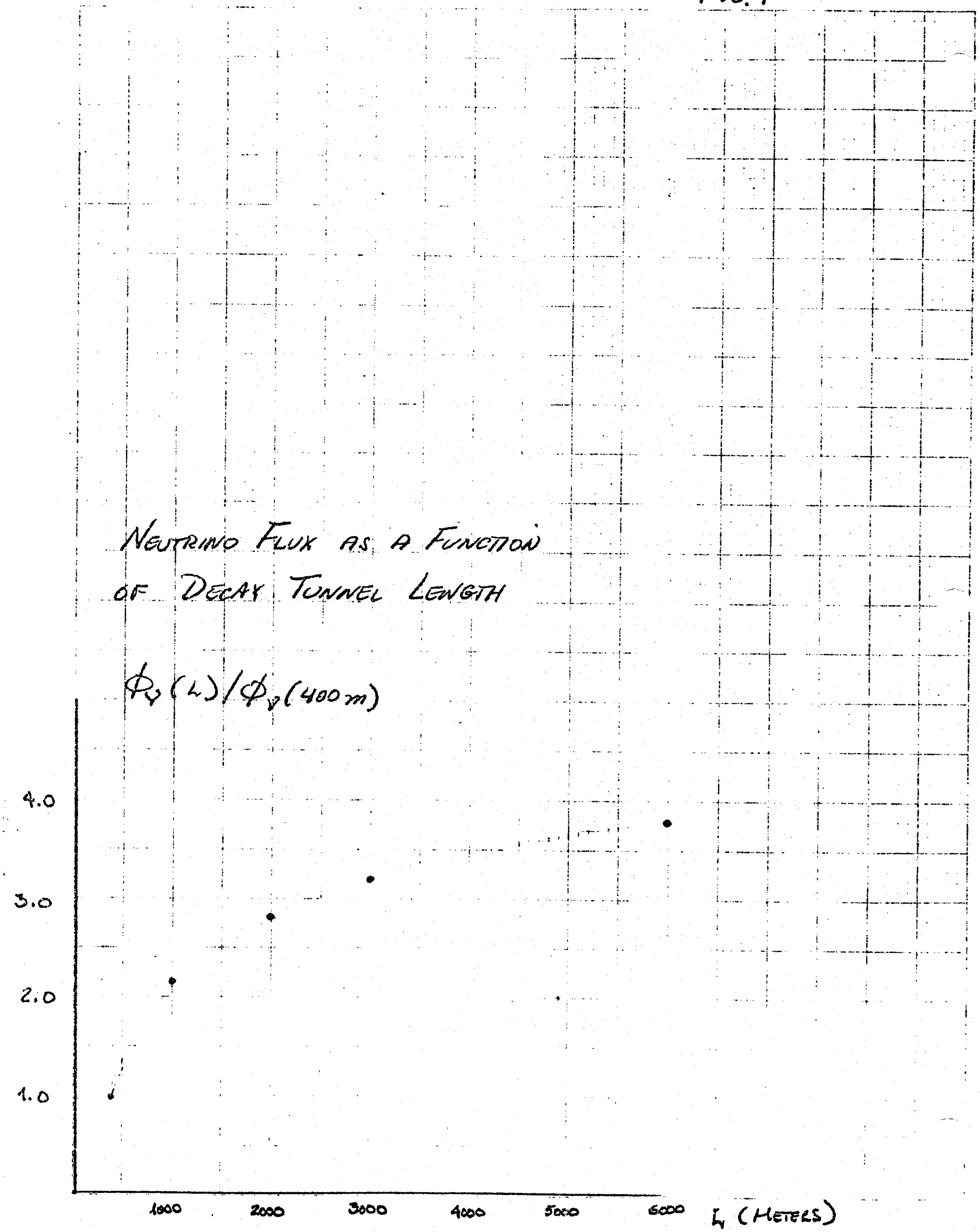
We have made Monte Carlo calculations of the neutrino flux and event rates at the water target for several lengths of decay tunnel and the 2 horn focusing train. For a 2 Km decay tunnel with 5×10^{13} protons on a 4. 10^6 ton water target at 400 GeV we expect 1.8 events/pulse.

A plot of the flux as a function of the length of the decay tunnel is shown in Fig. 1. We assume a 2 Km decay tunnel for subsequent calculations. In Fig. 2 and Fig. 3 we display the calculated ν_μ flux and event rate as a function of energy. For the event rate in Fig. 3 we have assumed a 10 sec duty cycle and about a month of running time, giving a total of 6.4×10^4 events.

The effect of $\nu_\mu \leftrightarrow \nu_e$ oscillations is to reduce the event rate by the factor $0.5(1+\cos 2\pi x/L_0)$ where x is the distance from the accelerator to the detector (2750 Km) and $L_0 = 2.5\ Km\ P_\nu(GeV)/\Delta(eV^2)$.

For a $\Delta = (m^2_{\nu_\mu} - m^2_{\nu_e})$ of $0.01\ eV^2$, the number of events with energy greater than 10 GeV is reduced by 53%. The effect on the energy distribution of the observed events is given by the dashed line in Fig. 3. We note that even in the bin from 90-100 GeV, the event rate is reduced by 10% and corresponds to a 7 standard deviation effect.

FIG. 1


NEUTRINO FLUX AS A FUNCTION
OF DECAY TUNNEL LENGTH
$\Phi_\nu(L)/\Phi_\nu(400\,m)$
4.0
3.0
2.0
1.0
1000
2000
3000
4000
5000
6000
L (METERS)

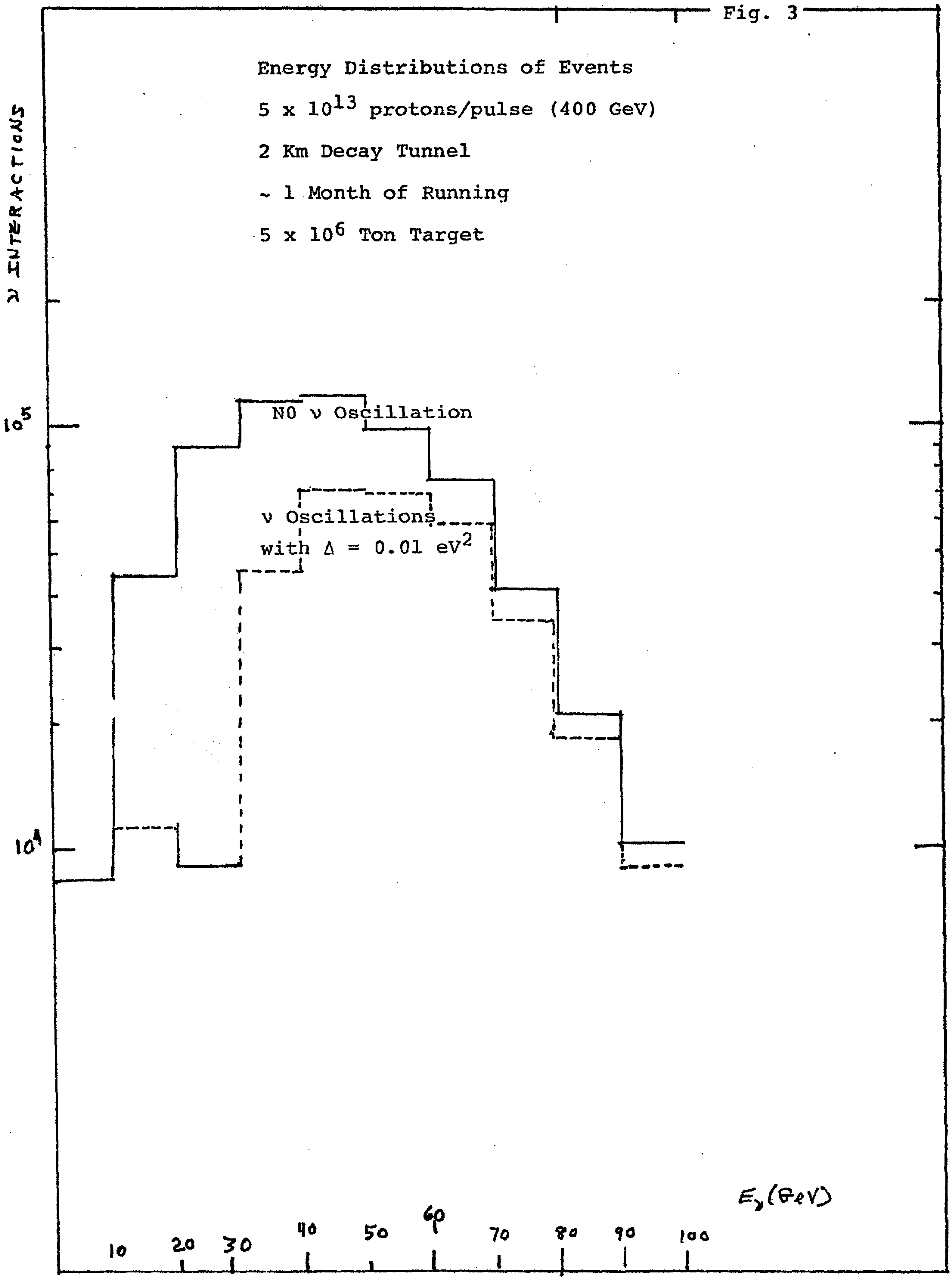


Fig. 3
Energy Distributions of Events
5 x 10^13 protons/pulse (400 GeV)
2 Km Decay Tunnel
~ 1 Month of Running
5 x 10^6 Ton Target
ν INTERACTIONS
10^5
10^4
NO ν Oscillation
ν Oscillations
with Δ = 0.01 eV^2
10
20
30
40
50
60
70
80
90
100
E_ν (GeV)

B. Characteristics of the Detector

In this section we present arguments in support of the feasibility of detecting and studying accelerator-produced neutrino reactions at sites in the ocean thousands of Km distant fron the accelerator. We will show how the proposed detector (employing 18" diameter spheres strung over 1 Km) may be able to detect 1.8 accelerator neutrino-produced muons per pulse.

The crux of the argument is the use of the charged current component of the weak interaction, the directivity of the ν_μ beam and the use of a string of widely spaced, compact underwater modules aligned in the direction of the accelerator-produced neutrino beam. The energy of the muon is inferred from its range, and the energy of the hadrons is deduced by means of a stacked hexagonal array of counters. Fig. 4 is a schematic of the system.

In the following sections we propose a three phase program leading to the detection and study of accelerator neutrinos in the open ocean at one of several possible sites. Particular attention is given to the Puget Sound site, where existing facilities and closeness to the University may reduce costs considerably.

1. Neutrino-Nucleon Cross Sections

The neutrino-nucleon interaction cross section over the energy range of a few to a few hundred GeV is linear in the energy of the incident neutrinos[7] and has the form

$$\sigma_{\nu N} = 0.75 \times 10^{-38}\ \mathrm{cm}^2\ E_\nu \qquad 10\ \mathrm{GeV} \leq E_\nu \leq 200\ \mathrm{GeV} \quad (1)$$

Where E_ν is the neutrino energy measured in GeV. In over 75% of the interactions a muon carrying about 50% of the incident neutrino energy[8,9] emerges from the debris of the interaction products*.

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*See footnote on next page .17

Figure 4

NEUTRINO SOURCE AND OCEAN NEUTRINO DETECTOR

A neutrino beam produced at the Fermilab near Chicago is detected at the Puget Sound test site by the Cerenkov light produced by the muon from the charge current component of the weak interaction

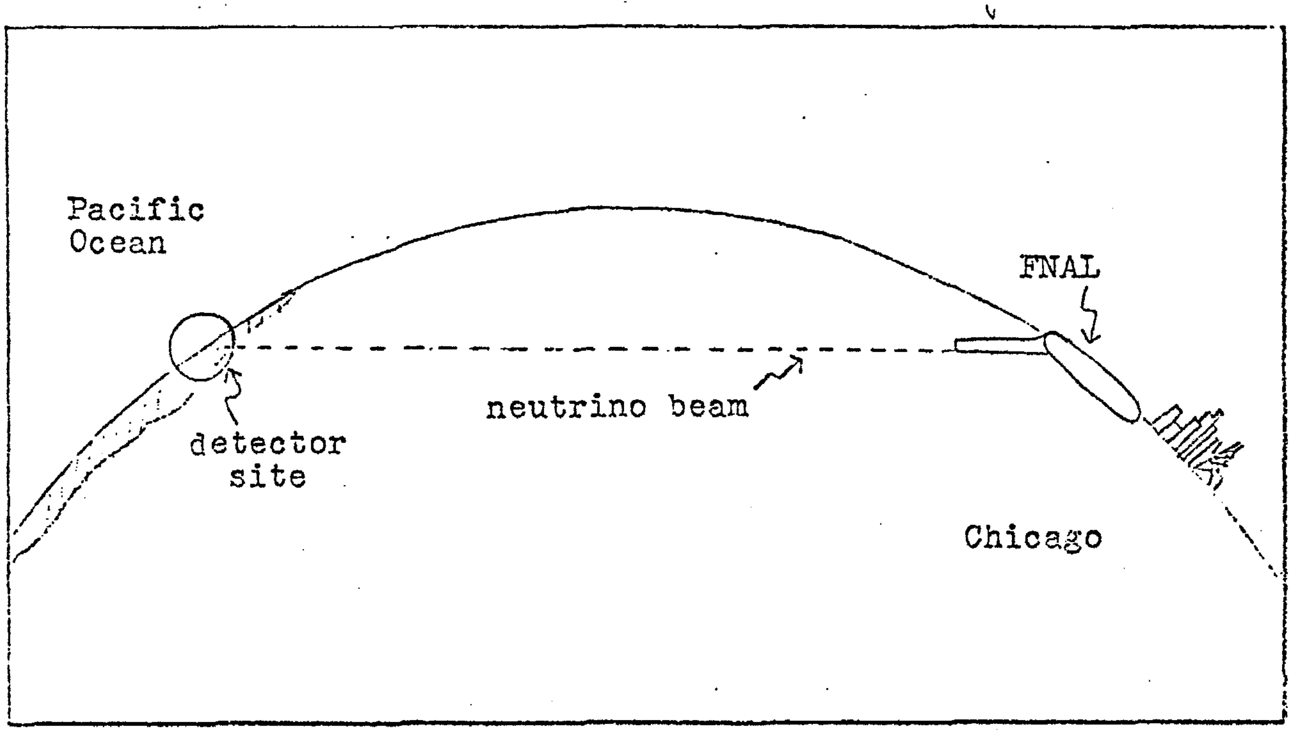


Figure 5

NEUTRINO BEAM DETECTOR ARRAY

The linear neutrino beam detection array consists of several modules aligned along the direction of the neutrino beam. The signature of an event consists of the sequential detection of the Cerenkov light intersecting several of the modules as indicated.

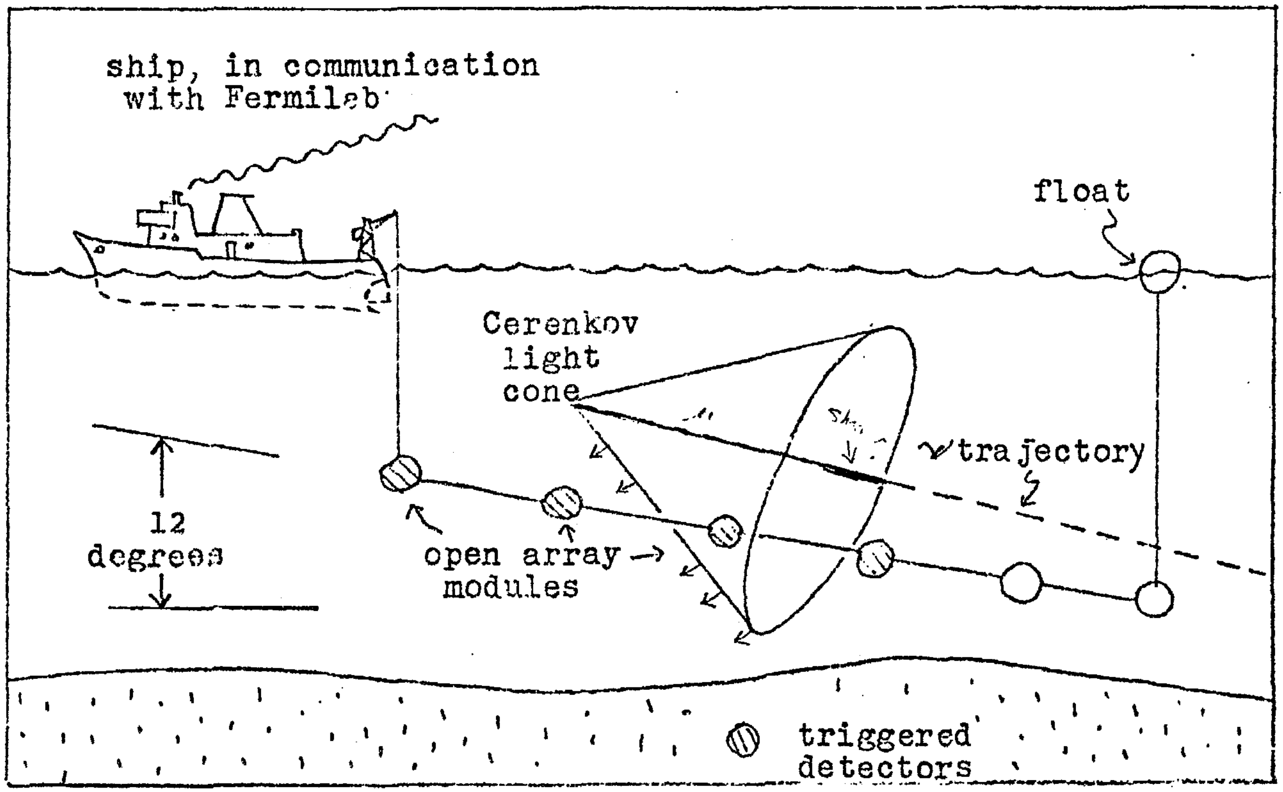
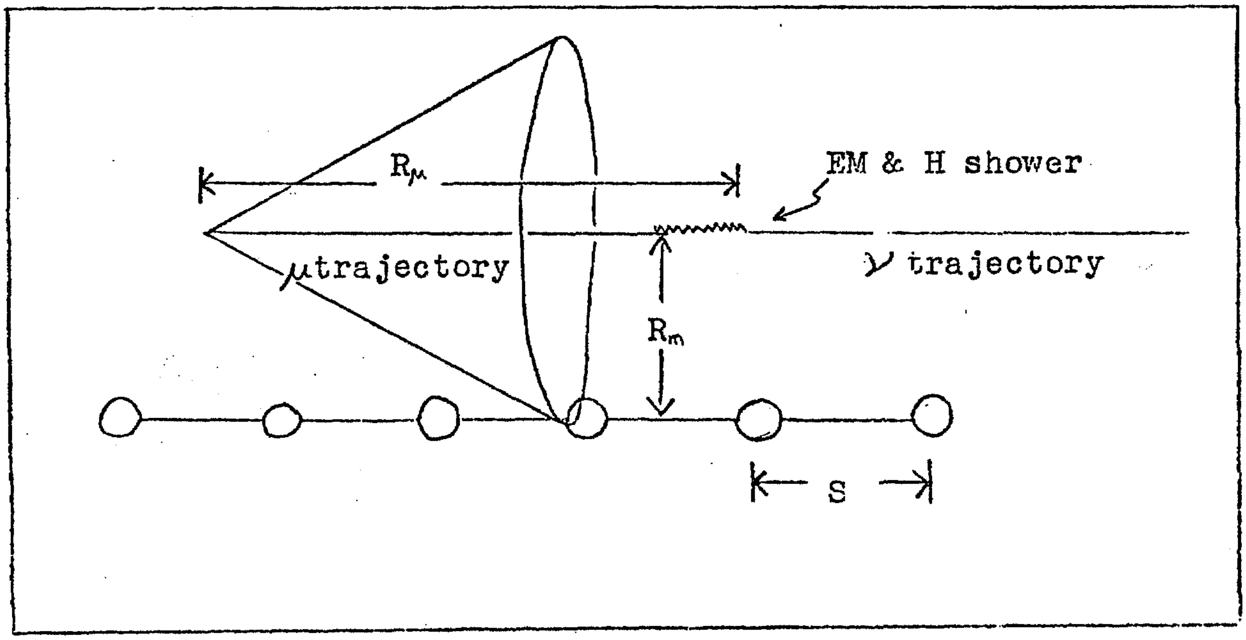


Figure 6

THE CERENKOV LIGHT CONE

The figure shows four modules which will intersect the expanding conical ring of Cerenkov light produced by the mu meson. The maximum detection range R_m, of the muon is determined by the minimum trigger level (#p.e. per module) and the order of coincidences required for determination of the event. The spacing between the modules is given by R_μ/n, where R_μ is the range of the muon and n the order of coincidence of the event. Six other parallel strings (not shown) can serve to define the hadronic shower energy as well as the muon trajectory.



The produced muons, which generate Cerenkov light, retain nearly the direction of the incident neutrino and have a long range in sea water (see Fig. 5). By detecting the amplitude and arrival time of the Cerenkov pulse from both the hadronic cascades and muons, we gain the enormous sensitive volume needed to detect neutrino beams deep undersea and remote from their production site (see Fig. 6).

2. Target and Detector

We propose to detect the interaction with a linear array of spherical modules (each of which contains several conventional photomultipliers arranged in a spherical configuration) lined up along the direction of the neutrino beam as shown in Fig. 5. The muon trajectory can be reconstructed from the amplitude and arrival time of the Cerenkov pulse at each of the modules.** By arranging for a spacing between modules to be about equal to the hadronic shower length,*** a master trigger in one module responding to the bright light from the hadronic shower can be used such that low level pulses (about one photoelectron) from distant muons can be used to reconstruct the trajectory and thereby gain enormous target volumes.

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* In antineutrino interactions the emerging muon carries away 75% of the energy of the incident neutrino; this would require 50% fewer modules in the detector. However, this must be weighed against the loss in interactions--the total cross section would be down by 1/3 over the neutrino-nucleon cross section. The ratio of the neutral to the charge cross section has been measured by Mann et al. to be 0.28.

** Two are needed in coincidence to infer arrival from FNAL (if modules are gated) and four are required to obtain the muon trajectory. See appendix III.

*** The full length (in units of grams/cm^2) of an electromagnetic-hadronic cascade as a function of energy E_0 (in units of GeV) is given by:

$$L = 554 + 634 (\log E_0 - 1)$$ (but with large fluctuations).

Thus for E_0 = 100 GeV, L = 12 meters in sea water.

The fact that the neutrino-produced muons will be coming along the horizontal (actually 13^o up from the horizontal if we use neutrino beams from the FNAL) and that the modules can be gated to the beam (with appropriate synchronization between the array and accelerator clocks) means that the background due to multiple muon cosmic ray showers and accidentals can be eliminated*. Techniques for eliminating the background due to tube noise are discussed in the Proceedings of the First Summer Workshop on Project DUMAND[10].

In the single string model, the number of target nucleons is contained within a cylindrical volume of length L (the length of the string array) and radius R_m given by the maximum perpendicular distance from the detector string at which the muon can be detected. The number of target nucleons is then given by $N = \pi R_m^2 LA$, where A is Avogadro's number and R_m and L are given in centimeters.

To estimate R_m we assume as a working number that the muon generates 500 photons per centimeter pathlength in seawater,** that the overall spectral attenuation length is 20 meters and that the spherical detector modules each contain three 5" diameter photomultipliers.

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* A small contribution to the background from atmospherically produced neutrinos is expected but can be eliminated by gating if necessary. The neutrino energy is expected to be much lower than the accelerator energy.

** The number of photons radiated per unit wavelength $dN/d\lambda$ by a particle moving with velocity $v=\beta c$ in a medium with index of refraction n is given by[12]: $dN/d\lambda = 2\pi\alpha \ell(1-(\beta n)^{-2})/\lambda^2$ where α is the fine structure constant and ℓ is the path length over which the radiation is emitted. The equation predicts muons will emit about 360 photons per centimeter over the s11 photocathode response region (300nm - 650nm) and 670 over a typical bialkali region (200nm - 600nm). Though the wavelength shifting properties of seawater due to dissolved organics such as chlorophyll, are expected to compensate in part for losses in transmission in the ultraviolet, losses due to reflections at the glass-water interface, and absorption by the glass housing should bring the number down to about 500 per centimeter for impact parameters as high as 20 meters.

If the photoconversion efficiency is 10%, then we find a signal level 1.1 photoelectrons per module generated by a muon 12 meters distant from the string detector. A string array 1 Km long would thus be associated with $N = 2.7 \times 10^{35}$ target nucleons or 4.5×10^{5} tons of water target. The optical transmission data given below are taken from Jerlove and Nielson "OPTICAL ASPECTS OF OCEANOGRAPHY", 1974.

FIG 7

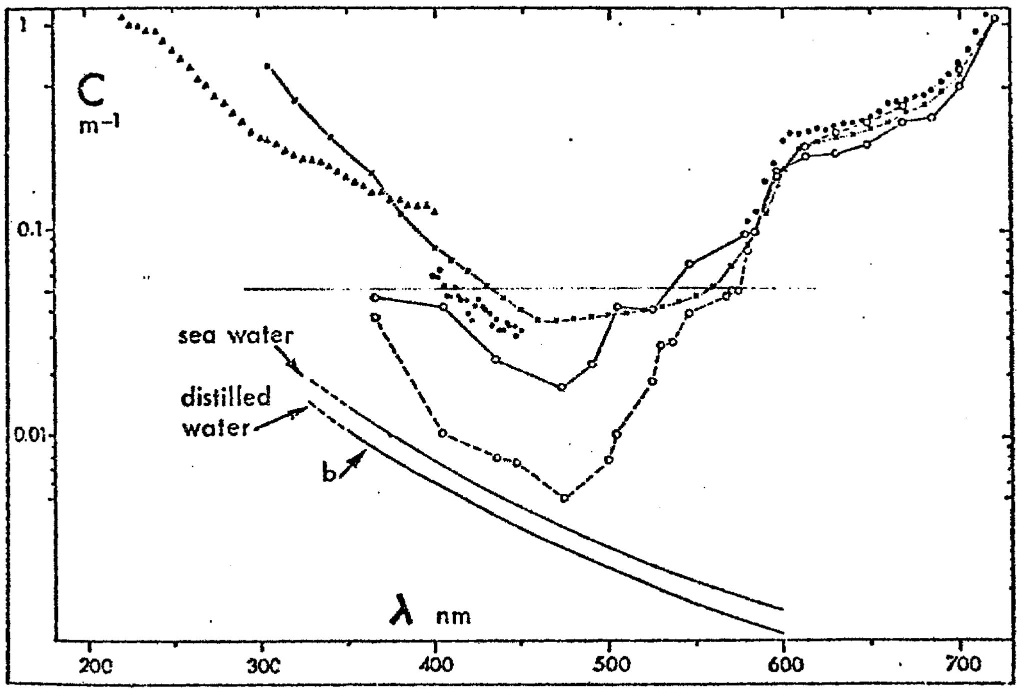

Fig. 3. Attenuation curves in the near ultraviolet and in the visible part of the spectrum.

△ Lenoble-Saint Guily (1955), path length: 400 cm;
× • • Hulburt (1934) (1945), path length: 364 cm;
● Sullivan (1963), path length: 132 cm;
○— Clarke-James (1939), path length: 97 cm (Ceresin lined tube);
○ - - - James-Birge (1938), path length: 97 cm (Silver lined tube).

Total scattering coefficient for pure water and pure sea water as a function of wavelength, according to Table 4.

III. BACKGROUND CONSIDERATIONS

The successful operation of a linear neutrino detector array depends on a thorough understanding of background in the Cerenkov mode of detection of neutrino interactions. There are five principle sources of background involved in this experiment: 1. sunlight, 2. trace radioactivity in sea water, 3. cosmic ray muons and neutrinos,* 4. bioluminescence and 5. tube noise. The problem of sunlight may be eliminated by running at night and/or by lowering the array below the penetration level of sunlight. The problem of handling tube noise and trace radioactivity may be solved by demanding coincidences among several segments of the photocathode of the module as indicated in the Proceedings of the first DUMAND Workshop, and later expanded upon in the Proceedings of the second Workshop.

The cosmic ray background can best be handled by using widely spaced modules and requiring coincidences among several of them. By choosing the appropriate number of coincidences, and gating the array information processing system to the 20μs FNAL beam spill, accidentals due to cosmic ray showers with high mu meson multiplicity will be insignificant.

Much effort during the first phase study will be devoted to the problem of the bioluminescence background. That this may be a problem was demonstrated recently when we carried out a plankton tow of 25 m^3 of seawater off the coast of Washington during the week of September 23-27. At least one flash per second was observed from the organisms taken up in the entire tow. If such light does not bunch up within the resolution time of the electronics it can be treated as additional background. Altogether the background problems do not appear to be serious.

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* Events due to the atmospheric cosmic ray neutrinos will be reduced by requiring muon trajectories from the small solid angle from the accelerator beam and gating the information processing system.

IV. NEUTRINO BEAM LINE DESIGN CONSIDERATIONS

The proposed design of the neutrino beam line is based on the use of neutrinos from π and K decays.

a. Fast Extractor

We propose a new extraction system that will require a minimal amount of bending in the plane of the accelerator. A site service area, OE3, would allow the beam to be extracted tangentially in the general direction of Puget Sound or the Solar Neutrino Laboratory.

b. Primary Beam Transport-Survey

It is necessary to bend the neutrino beam to a declination angle of about 12.1^{o} below the horizontal to deliver the beam to Puget Sound (see figure 8) About 34 standard primary beam bending magnets would be needed to bend the beam along 211 meters of pathlength. The beam would be 22 meters below the surface at the planned target-beam dump area.

c. Beam Dump and π and K Generator

We propose to use improved beam dump and π and K aluminum targets. At the dump it will be necessary to take the usual precautions to keep radio-active contamination out of the water table.

d. Focusing

A two horn wide beam focusing system is recommended for this experiment in order to gain maximum beam intensity.

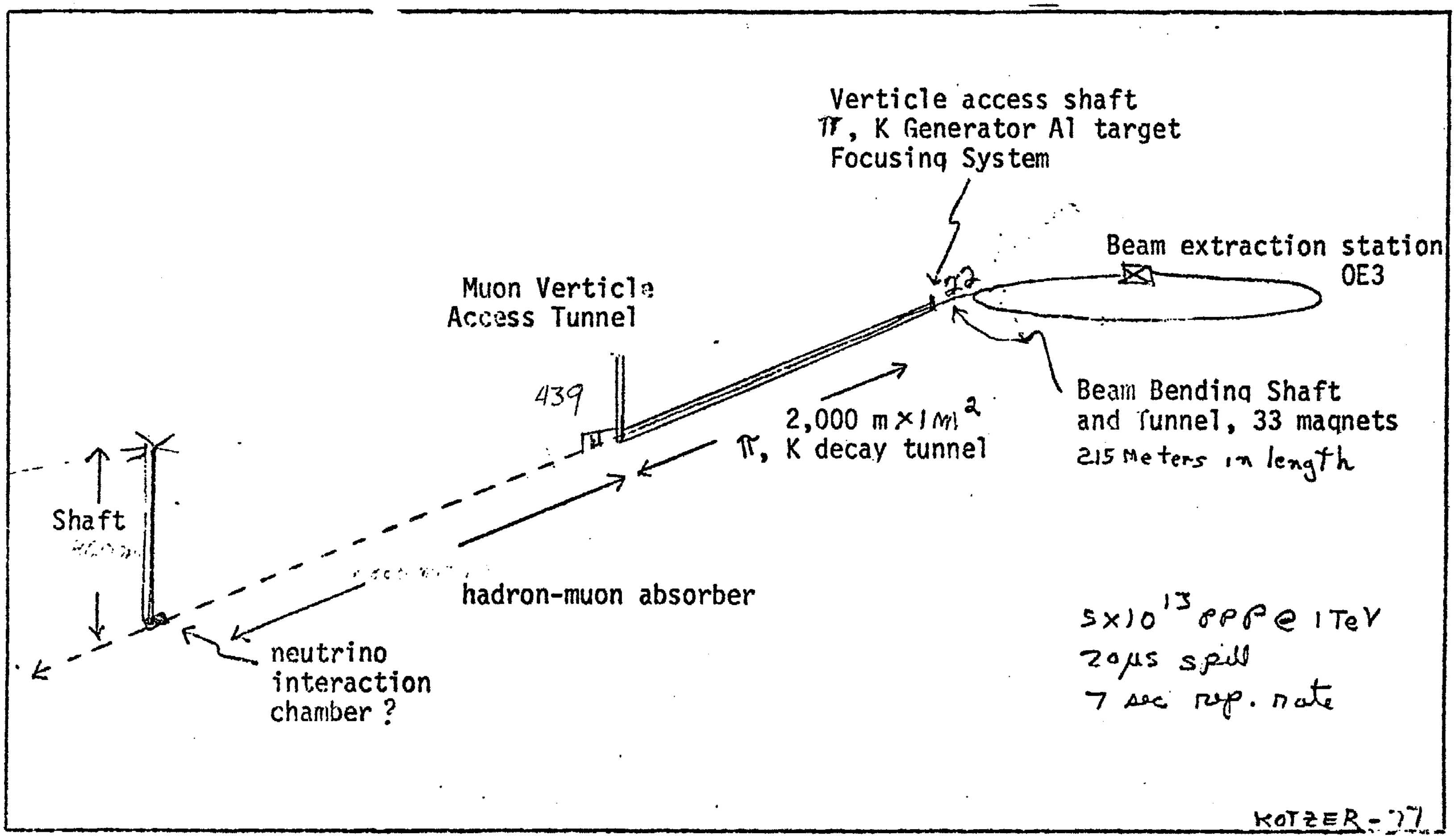
e. Decay Tunnel

The Smith Tool Company has proposed a method of boring the 2000 meter decay tunnel using vertical access shafts at either end so that the two tunnel segments meet in the middle. The first shaft, at the beginning of the straight decay tunnel, would be 22 meters deep and the one at the far end would be 508 meters.

FIG 8

NEUTRINO BEAM FACILITY FOR THE UNDERWATER 4×10^6 TON PACIFIC NORTHWEST TARGET-DETECTOR.

Figure 7



A one meter diameter tunnel 2 Km long would require the excavation of 1.6×10^3 m^3 of earth. At an estimated cost of $\$100/m^3$ this would entail a total cost of $160,000. Should the ground consist of sandstone, it may be possible to eliminate the tunnel casing.

The long decay tunnel would substantially increase the neutrino flux at the higher energy end of the spectrum by about a factor of five over the present 400 m tunnel. This has to be weighed against the cost of increasing the primary beam intensity by a factor of five or increasing the neutrino interaction target mass by the same factor.

f. Muon Monitoring Station

Here it would be desireable to construct a parallel offset extension of the decay tunnel to provide access to two caverns at 10 m and 30 m for housing a muon monitor. A muon flux station at 10 m downstream from the π, K decay tunnel should see a surviving hadronic component reduced by about 12 orders of magnitude, and a muon energy reduced by only about 5.6 GeV. Subsequent stations should yield measurements with only slightly contaminated muon fluxes.

g. Neutrino Interaction Station

It may be desireable, although it is not definitely proposed, to study neutrino interactions at an underground facility one kilometer or more from the end of the tunnel. This would require an additional vertical access shaft about 860 meters deep leading to a neutrino interaction station $10 \times 10 \times 20$ m^3.

Excavation	m^3	$
1. $2 \times 2 \times 860$ m^3 access shaft	3,440	585,000
2. $10 \times 10 \times 20$ m^3 chamber	2,000	350,000
3. Experiment facilities 10^2 tons		( )

h. Synchronization

Neutrino time of flight measurements can be carried out with the aid of cesium clocks, which are stable to one part in 10^{14}. One clock and a comparator will be located at the FNAL ν-beam line and will record the times at which the 20μs spillout pulse is initiated. A second, previously synchronized cesium clock at the ocean detector site will record the times at which the interactions are detected. Ten nanosecond synchronization would require weekly flights of the comparator clock between FNAL and the Ocean Detector. Systematic shifts due to relativistic effects will also have to be taken into account.

The following costs are estimated for the time synchronization capability of the experiment:

1. 4 Cesium clocks	32,000
2. 10 roundtrips for clock transport	1,000
3. Air travel for 1 scientist (3 trips)	1,200
4. One man-month technician time	2,500
	36,700

V Water Target Detector

The purpose of the phase II water target detector is to determine the energy of the interaction and whether it is produced by a muon or electron neutrino. The array depicted in Fig. 6 accomplishes this purpose to a large extent.

The basic structure consists of seven parallel strings of detectors. The neutrino sees essentially a stack of plane hexagonal arrays of modules (as shown in the "front view" in Fig. 9 perpendicular to the neutrino beam.

The spacings of the modules in the plane are adjusted to a distance slightly less than twice the maximum detectable distance of the closest approach of the muon (R_m) to a single module. In this way the array has an effective cross section area of a circle with radius 3 R_m.

Modules consisting of three 5" diameter photomultipliers facing the beam direction yielded an R_m of 12 meters. Hence, an effective cross sectional area of 4,100 meter^2 is possible for the detector. A one kilometer long array then can have an effective target mass of about 4.1 x 10^6 tons.

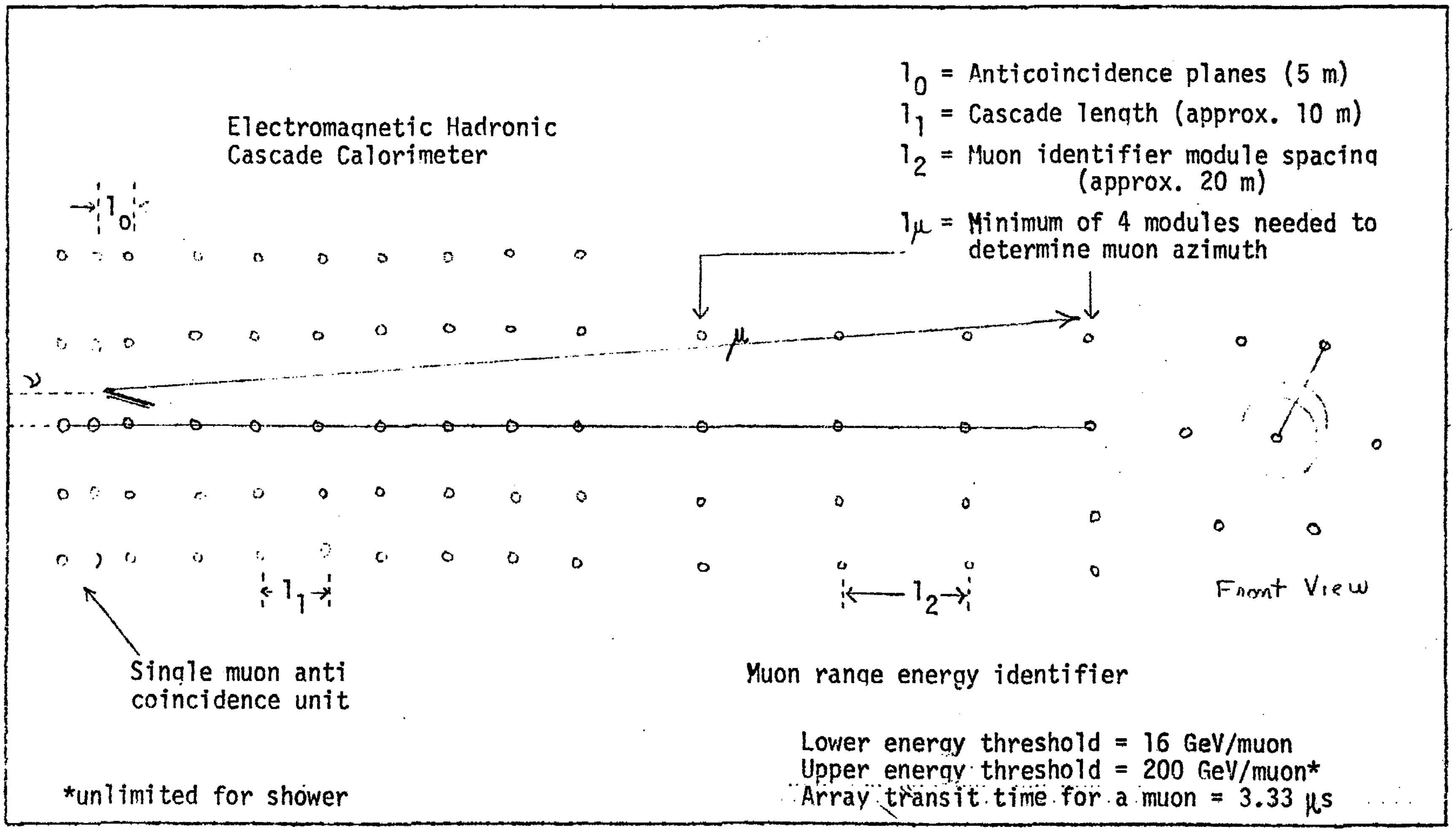
The development of a 38 cm diameter spherical photomultiplier as described in the first DUMAND Proceedings should allow spacings of 40 meters or more.

The spacing between the planes is adjusted to break the detector into several functional parts. The first two planes can be used to anti-out any cosmic ray muons coming up from the direction of the beam. Though no such cosmic ray muons have been detected by other experiments, the large array should see these muons produced by atmospheric neutrinos. The next section is used as a Cascade Calorimeter in which the spacings between the planes are just short of the shower length (5 to 10 meters) in order to obtain several sample points in the hadronic shower.

The remaining section of the array (third functional part) determines

Figure 9

UNDERSEAS NEUTRINO CALORIMETER



the energy of the muon from its range. By extending the array to 1 Km, the energy of muons up to a 200 GeV limit can be determined. It may be possible to determine muons of higher energy from the fluctuations in the Cerenkov light produced by pair production and muon bremsstrahlung processes. This portion allows us to also determine multiple muon events (di and tri muon events) since the intensity of the Cerenkov light detected by the modules is directly proportional to the number of muons traversing the target.

In Puget Sound it may be possible to string modules to 5 Km, thereby determining the energy of muons up to 1 TeV from a range measurement.

VI Intercomparison With Other Proposed Detectors

Although several proposals for large scale detectors of neutrino oscillations exist, we turn our attention toward the most recent description by Mann and Primakoff given in the Physical Review article appended to this proposal. We also include event rates expected if the beam were directed to the 610 ton Solar Neutrino detector of Raymond Davis Jr. although other descriptions and proposals exist, we have no further information concerning their characteristics. Table II gives the relative event rates of some neutrino oscillation detectors.

Table II

Relative Event Rates of Proposed Neutrino Oscillation Detectors

Group	U. of Penn. Quebec	R. Davis Jr. Homestake	U of W & WWSC Puget Sound
Target Detector Mass in Metric Tons	2.1×10^2	6.10×10^2	4.1×10^6
Separation between FNAL neutrino source and detector	1,000 Km	1,280 Km	2,750 Km
Event Rate Relative to that proposed by Mann and Primakoff	1	1.77	2.6×10^3

Hence in a comparable running time (500 hours) and by scaling up from the Mann-Primakoff detector, we anticipate 258,000 neutrino interactions. Taking into consideration the use of a 2 Km long decay tunnel and a higher intensity beam, a substantial increase in the interaction rate is possible.

VII Comments Regarding the Feasibility of Construction, Deployment and Operation of the Underseas Neutrino Detector.

Here in the Northwest we have a repository of underseas radiation measurements, dating back to the work of Sanderman Utterback in the 1930's. Since that time there has been a gradual expansion in underwater radiation experiments which includes a vigorous measurements program using both manned submersibles, habitats (permanent underseas manned laboratories) and SCUBA divers.

Some of our recent results on underseas radiation are found in the references of our published papers. In addition, we include a description of the Oceanographic Research Vessel, The Thomas G. Thompson (Appendix II) which is being used in supporting studies and appears adequate for the purposes of deploying the final array. In addition, our experience with manned submersibles with manipulator capability gives us reason to believe they can inspect and make accurate adjustments to align the individual modules. One such submersible may be the Johnson SeaLink we now use, which is described in the Appendix III. The Applied Physics Laboratory of the University of Washington, in addition to being a valuable resource in the Marine Engineering aspects of our underseas research programs, is expert in underwater accoustics and can build and deploy systems which will monitor the position of the modules to less than 0.1 meter accuracy.

While there are several possible sites in the Pacific Northwest, such as Lake Chelan and the Pacific Ocean, we have tentatively chosen Puget Sound as the site of the detector. Should the experiment and theory indicate search for longer oscillation lengths, the array is mobile and could be transported to some point near the side of the earth oppositeto Fermi Lab (There is an island in that vicinity which could serve as a stagging area). We now indicate why Puget Sound appears as a suitable site for the detector.

SITE SELECTION CONSIDERATIONS

It will be necessary to conduct module and systems tests in the marine environment. Here we suggest that Puget Sound is the ideal site for this testing program. Additionally, Puget Sound would be an excellent location for the final experiment itself. Puget Sound is the home of several organizations dealing with marine sciences and technology, such as NOAA and the University of Washington; in particular, there are facilities in Puget Sound which can accurately locate the modules to a few feet of relative error. Furthermore, the Highline Diving School can regularly send divers to 200 feet underwater for deployment, inspection and repair of the shallower portions of the array (the difference in the vertical depths of either end of a one km long array is 210 meters). A submersible can be used to service portions of the array.

VIII
EXPERIMENT SUPPORT STATUS

The current underseas activities directly related to this proposed experiment are supported by the ONR. They include the construction and test (with Cosmic Ray Muons) of a small number of modules. In addition, we are continuing studies of the underseas cosmic radiation to 305 meters under NOAA sponsorship. This program utilizes manned submersibles with manipulator (soft touch and working) and lock-out and lock-in capability to designated depths. Interest in providing logistical and other marine facility support has been expressed by this agency to the ONR.

It is our understanding that the ONR is willing to support the entire underseas detector construction operation and deployment portion of this experiment. In addition, they appear willing to cost share the neutrino beam line facilities development.

ACKNOWLEDGEMENTS

We are particularly indebted to Dr. S. Csnora for the calculations of the neutrino spectrum ,the lucid discussion of the current theoretical ststus of neutrino oscillations to both Richard Davisson and Steven Csnora for their aid in the discussion of the effects of the oscillation on the predicted energy spectrum in puget sound.

P. Kotzer

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Budget for FNAL

Neutrino Beam Facility for

The Pacific Northwest

Underwater Target

12.1^{o} Declination Angle

I. Phase I, Facilities Development		
1. Beam extraction for service station OE3	250,000	
2. Beam Bending Tunnel 215 x 2 x 2 m^3 *	146,000	
3. 33 Bending Magnets		
a. Standard for 400 GeV Beam @$10,000	330,000	
b. Superconducting for the 1,000 GeV beam @ $20,000	( )	
c. Beam control and surveying	10,000	
4. π, K Generator room		
a. Vertical access tunnel 22 x 2 x 2 m^3 = 88 m^3	14,960	
b. Target, Beam dump, water retainer, two horn focusing magnetic-narrow beam	250,000	
c. Generator room 3 x 3 x 15 m^3	23,950	
5. π, K decay tunnel 1 m diameter x 2 Km	340,000	
		1,364,910**
6. Mu Neutrino Flux Detector		
a. Vertical access shaft 2 x 2 x 439 m^3	299,000	
b. Muon monotoring chamber room 3 x 3 x 20 m^3	30,600	
c. Muon spectrum detectors	40,000	
		369,600**
II. Phase II FNAL Underground ν Interaction Station		
a. Vertical access shaft 2 x 2 x 860 m^3 = 3,440 m^3	585,000	
b. Neutrino interaction chamber 10 x 10 x 20 m^3	350,000	
c. Neutrino interaction detector	( )	
		935,000
Grand Total 2,669,510		

* All excavation costs are estimated at $170/$m^3$ including decay tunnel costs.

**Cost sharing with the sponsoring agency is possible.

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APPENDIX I

"Neutrino Oscillations and the Number of Neutrino Types"

A.K. Mann and H. Primakoff

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Neutrino oscillations and the number of neutrino types*

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A brief treatment of neutrino oscillations, generalized to an arbitrary number of neutrino types, is given as the basis for design of a feasible experiment to search for neutrino oscillations using the neutrino beam produced at a high-energy proton accelerator.

INTRODUCTION

It is generally assumed that the known neutrinos ν_e and ν_μ (and $\bar{\nu}_e$, $\bar{\nu}_\mu$) have zero mass, although the present experimental limits[1] are only $m(\nu_e)<60$ eV and $m(\nu_\mu)<650$ keV. This physical assumption corresponds to the mathematical assumption that all terms involving neutrino fields ψ_ν in the world Hamiltonian are invariant under the transformation $\psi_\nu \to \gamma_5\psi_\nu$.

There are a number of reasons to question the validity of rigorous γ_5 invariance in addition to the loose experimental limits on $m(\nu_e)$ and $m(\nu_\mu)$. Even in the purely leptonic reaction $\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$, the γ_5 invariance of the leptonic weak currents is experimentally verified (e.g., by helicity measurements) to no better than 1%, i.e.,

$$l_\alpha = \psi_\mu^\dagger \gamma_4\gamma_\alpha[(1+\gamma_5)+\epsilon(1-\gamma_5)]\psi_{\nu_\mu}$$

with $|\epsilon|^2<0.01$. In addition, there is a hint in the analysis of inelastic neutrino-nucleon scattering[2] that the hadronic weak current may have a right-handed part, i.e., $\psi_{q_2}^\dagger\gamma_4\gamma_\alpha(1-\gamma_5)\psi_{q_1}$, where ψ_{q_1} and ψ_{q_2} are quark fields; if this is true, the introduction of the $\epsilon\psi_\mu^\dagger\gamma_4\gamma_\alpha(1-\gamma_5)\psi_{\nu_\mu}$ term into l_α is perhaps more plausible. More generally, the principle of γ_5 invariance is at best significantly more restricted than the analogous principle of electromagnetic gauge invariance. Thus, electromagnetic gauge invariance, which ensures both zero mass of the photon and conservation of electric charge, applies to all parts of the world Hamiltonian. But, as we have noted, γ_5 invariance is thought to apply only to those parts involving neutrinos, and is in fact further implemented by the assumption that no terms exist in the world Hamiltonian which fail to preserve *separately* the conservation of muon lepton number and electron lepton number. In the same vein, since there are at least two nominally independent types of neutrinos, ν_e and ν_μ, with associated charged leptons of very different mass, a situation in which both types of neutrinos have zero mass (and are therefore distinguished from each other only by their leptonic quantum numbers) suggests either a remarkable coincidence or some much higher symmetry in nature than we have heretofore encountered.[3] In this conjectured "supersymmetry," zero-mass particles might form a unique family, independent of their boson or fermion properties, distinct from the conventional separate families of bosons and fermions all with nonzero mass.

Apart from the implications of nonzero neutrino mass for particle physics and field theory, there would also be significant repercussions in astrophysics and cosmology, if only because the total number of neutrinos in the universe is expected to be large.[4] There is no reliable theoretical guide to the region in which to look for nonzero neutrino mass, but the importance of the question leads us to speculate on how to measure very small neutrino masses, say, $\lesssim 10^{-3}$ times the present limit on $m(\nu_e)$. Even a mass as small as 10^{-1} to 10^{-2} eV would be significant because it would point to an interaction responsible for that mass value and would possibly also signal a violation of the separate conservation of muon lepton number and electron lepton number.

One possibility with regard to such a measurement lies in the suggestion of Pontecorvo[5] that neutrinos of different types may exhibit oscillations of type as a function of time, similar to the oscillations between K^0 (strangeness = +1) and $\bar{K}^0$ (strangeness = −1). Neutrino oscillations were discussed initially by Pontecorvo,[5] and by Gribov and Pontecorvo,[6] and more recently by Pakvasa and Tennakone,[7] by Eliezer and Swift,[8] and by Fritzsch and Minkowski[9]; in addition, a general review of the subject has just been given by Bilenky and Pontecorvo.[10] Here we wish to consider a realistic experiment to search for neutrino oscillations using a neutrino beam produced by the protons from a high-energy proton accelerator. This experiment, if it were to observe neutrino oscillations, would lead immediately to three important results: (i) The mass of at least one of the neutrino types would be nonzero, (ii) the separate conservation of muon lepton number and electron lepton number would not hold, and (iii) the total number of neutrino types would be determined.

It is perhaps worth mentioning again[5] that any actual neutrino-oscillation phenomenon, e.g., $\nu_\mu \to \nu_e$, while undoubtedly associated with an oscillation length much longer than that between K^0 and $\bar{K}^0$, might conceivably provide another means of observing a CP violation and thus allow a new attack on that fundamental problem. Furthermore, the question of a neutrino with relatively large mass, capable of decaying to another (lighter) neutrino[11] and (for example) a photon, will be addressed by the experiment considered here.

THEORY

In this section we give a brief account of the theory of neutrino oscillations. Our treatment, while generally similar to that previously developed in Refs. 5–10, does introduce several modifications and also discusses the case of three neutrino types explicitly. In addition, we present some speculations on the lower limit for the oscillation length based on the experimental upper limit on the branching ratio for the decay $\mu^+ \to e^+ + \gamma$.

Let $|\nu_\xi\rangle$ denote a state with definite momentum $\vec{p}_\nu$ occupied by a single neutrino of type ξ; here $\nu_\xi = \nu_e$ or ν_μ or ν_L or $\cdots$, so that the states $|\nu_\xi\rangle$ are produced in the various known weak-interaction processes, e.g., $\pi^+ \to \mu^+ + \nu_\mu$. Further, let the states $|\nu_j\rangle$ $(j = 1, 2, 3, \ldots)$ be such linear combinations of the states $|\nu_\xi\rangle$ that

$$H|\nu_j\rangle = (H^{(0)} + H^{(1)})|\nu_j\rangle = E_j|\nu_j\rangle\,, \tag{1}$$

where H is the Hamiltonian of the world and $H^{(1)}$ is the part of H which is responsible for the neutrino oscillations. Since $H^{(0)} = H - H^{(1)}$ is invariant under $\psi_{\nu_\xi} \to \gamma_5\psi_{\nu_\xi}$ and conserves muon lepton number and electron lepton number *separately*, we have $\langle\nu_\xi|H^{(0)}|\nu_\xi\rangle = p_\nu$ and $\langle\nu_\xi|H^{(0)}|\nu_\eta\rangle = 0$. On the other hand, we shall assume that $\langle\nu_\xi|H^{(1)}|\nu_\xi\rangle$ is greater than zero and $\langle\nu_\xi|H^{(1)}|\nu_\eta\rangle$ is different from zero so that we shall consider situations where $\nu_e, \nu_\mu, \nu_L, \ldots$ are endowed with mass and where *separate* conservation of muon and electron lepton number does not hold. As we shall see, both of these conditions must be satisfied if neutrino oscillations are to occur.

To proceed, we write

$$\begin{aligned} |\nu_j\rangle &= \sum_\xi |\nu_\xi\rangle\langle\nu_\xi|\nu_j\rangle\,, \\ |\nu_\eta\rangle &= \sum_k |\nu_k\rangle\langle\nu_k|\nu_\eta\rangle \\ &= \sum_k |\nu_k\rangle\langle\nu_\eta|\nu_k\rangle^*\,, \end{aligned} \tag{2}$$

whence

$$\begin{aligned} \langle E\rangle_\xi &= \langle\nu_\xi|(H^{(0)} + H^{(1)})|\nu_\xi\rangle \\ &= \sum_j |\langle\nu_j|\nu_\xi\rangle|^2 E_j\,, \\ \langle E\rangle_\xi &= p_\nu + \langle\nu_\xi|H^{(1)}|\nu_\xi\rangle\,, \\ m(\nu_\xi) &\equiv \{\langle E\rangle_\xi\}_{p_\nu=0} \\ &= \langle\nu_\xi|H^{(1)}|\nu_\xi\rangle_{p_\nu=0}\,, \\ E_j &= \langle\nu_j|(H^{(0)} + H^{(1)})|\nu_j\rangle \\ &= \sum_\xi |\langle\nu_\xi|\nu_j\rangle|^2\langle E\rangle_\xi \\ &\quad + \sum_{\xi,\eta}{}' \langle\nu_\xi|\nu_j\rangle^*\langle\nu_\eta|\nu_j\rangle\langle\nu_\xi|H^{(1)}|\nu_\eta\rangle\,, \end{aligned} \tag{3a}$$

$$\begin{aligned} E_j &= \{p_\nu^2 + [m(\nu_j)]^2\}^{1/2} \\ &= p_\nu + \langle\nu_j|H^{(1)}|\nu_j\rangle\,, \end{aligned} \tag{3b}$$

$$\sum_\xi \langle E\rangle_\xi = \sum_j E_j\,, \tag{3c}$$

and

$$\begin{aligned} P(\nu_\eta; t|\nu_\xi; 0) &= |\langle\nu_\eta|e^{-itH}\nu_\xi\rangle|^2 \\ &= \sum_j |\langle\nu_\eta|\nu_j\rangle|^2\,|\langle\nu_j|\nu_\xi\rangle|^2 \\ &\quad + \sum_{j,k}{}' \langle\nu_\eta|\nu_j\rangle\langle\nu_\eta|\nu_k\rangle^*\langle\nu_j|\nu_\xi\rangle \\ &\qquad \times\langle\nu_k|\nu_\xi\rangle^* e^{i(E_k - E_j)t}\,, \end{aligned}$$

$$\langle P(\nu_\eta; t|\nu_\xi; 0)\rangle_{\text{time average}} = \sum_j |\langle\nu_\eta|\nu_j\rangle|^2|\langle\nu_j|\nu_\xi\rangle|^2\,, \tag{4}$$

where $P(\nu_\eta; t|\nu_\xi; 0)$ is the probability of finding a neutrino of type η at time t in a physical situation where a neutrino of type ξ is present initially. We see from Eq. (3c) that if each of the $m(\nu_\xi)$ vanishes, each of the $m(\nu_j)$ will vanish as well; under these circumstances each of the $E_k - E_j$ must also vanish and, as seen from Eq. (4), neutrino oscillations will not occur. Conversely, if neutrino oscillations do occur, at least one of the oscillation frequencies

$$(E_k - E_j) \cong (1/2p_\nu)[m(\nu_k) + m(\nu_j)]\,[m(\nu_k) - m(\nu_j)]$$

must be nonzero, and this implies [again according to Eq. (3c)] that one or more of the $m(\nu_\xi)$ are nonzero. Similarly, if each of the $\langle\nu_\xi|H^{(1)}|\nu_\eta\rangle$ in Eq. (3b) vanishes, $|\nu_\xi\rangle, |\nu_\eta\rangle, \ldots$ can be identified with $|\nu_j\rangle, |\nu_k\rangle, \ldots$, and again [as seen from Eq. (4)] neutrino oscillations will not occur. Thus, the other necessary condition for the existence of neutrino oscillations is the nonvanishing of at least one of the $\langle \nu_\xi | H^{(1)} | \nu_\eta \rangle$.

We now specialize our results to the cases of two and three neutrino types: $\nu_\xi = \nu_e$ or ν_μ and $\nu_\xi = \nu_e$ or ν_μ or ν_L. Considering first the case of two neutrino types and parametrizing the $\langle \nu_\xi | \nu_j \rangle$ as

$$\begin{pmatrix} \langle \nu_e|\nu_1\rangle & \langle \nu_e|\nu_2\rangle \\ \langle \nu_\mu|\nu_1\rangle & \langle \nu_\mu|\nu_2\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}, \quad (5)$$

we have, substituting Eq. (5) into Eqs. (2), (3a), and (3b),

$$\begin{aligned} |\nu_1\rangle &= |\nu_e\rangle\cos\theta + |\nu_\mu\rangle(-\sin\theta), \\ |\nu_2\rangle &= |\nu_e\rangle\sin\theta + |\nu_\mu\rangle\cos\theta, \\ |\nu_e\rangle &= |\nu_1\rangle\cos\theta + |\nu_2\rangle\sin\theta, \\ |\nu_\mu\rangle &= |\nu_1\rangle(-\sin\theta) + |\nu_2\rangle\cos\theta, \end{aligned} \quad (6)$$

$$\begin{aligned} m(\nu_e) &= \tfrac{1}{2}[m(\nu_1)+m(\nu_2)] + \tfrac{1}{2}\cos2\theta[m(\nu_1)-m(\nu_2)], \\ m(\nu_\mu) &= \tfrac{1}{2}[m(\nu_1)+m(\nu_2)] - \tfrac{1}{2}\cos2\theta[m(\nu_1)-m(\nu_2)], \\ m(\nu_1) &= \tfrac{1}{2}[m(\nu_e)+m(\nu_\mu)] + \tfrac{1}{2}\cos2\theta[m(\nu_e)-m(\nu_\mu)] \\ &\quad - \tfrac{1}{2}\sin2\theta m_{e\mu}, \quad (7a) \\ m(\nu_2) &= \tfrac{1}{2}[m(\nu_e)+m(\nu_\mu)] - \tfrac{1}{2}\cos2\theta[m(\nu_e)-m(\nu_\mu)] \\ &\quad + \tfrac{1}{2}\sin2\theta m_{e\mu}, \\ m_{e\mu} &\equiv 2\,\mathrm{Re}\langle \nu_e|H^{(1)}|\nu_\mu\rangle_{p_\nu=0}, \quad (7b) \end{aligned}$$

while substitution of Eq. (7b) into Eq. (7a) [corresponding in the general case to substitution of Eq. (3b) into Eq. (3a)] yields

$$\tan2\theta = \frac{m_{e\mu}}{m(\nu_\mu)-m(\nu_e)}. \quad (8)$$

Further, substituting Eq. (5) into Eq. (4), and using Eq. (8), we obtain

$$\begin{aligned} P(\nu_e;t|\nu_\mu;0) &= \frac{1}{2}\left(\frac{m_{e\mu}^2}{[m(\nu_\mu)-m(\nu_e)]^2+m_{e\mu}^2}\right) \\ &\quad \times[1-\cos(E_2-E_1)t], \\ P(\nu_\mu;t|\nu_\mu;0) &= 1-\frac{1}{2}\left(\frac{m_{e\mu}^2}{[m(\nu_\mu)-m(\nu_e)]^2+m_{e\mu}^2}\right) \\ &\quad \times[1-\cos(E_2-E_1)t], \quad (9) \\ \langle P(\nu_e;t|\nu_\mu;0)\rangle_{\text{time average}} &= \frac{1}{2}\left(\frac{m_{e\mu}^2}{[m(\nu_\mu)-m(\nu_e)]^2+m_{e\mu}^2}\right), \\ \langle P(\nu_\mu;t|\nu_\mu;0)\rangle_{\text{time average}} &= 1-\frac{1}{2}\left(\frac{m_{e\mu}^2}{[m(\nu_\mu)-m(\nu_e)]^2+m_{e\mu}^2}\right), \end{aligned}$$

with the oscillation frequency given by Eqs. (7b) and (8), as

$$\begin{aligned} E_2-E_1 &\cong \frac{1}{2p_\nu}[m(\nu_2)+m(\nu_1)][m(\nu_2)-m(\nu_1)] \\ &= \frac{1}{2p_\nu}[m(\nu_\mu)+m(\nu_e)] \\ &\quad \times\{[m(\nu_\mu)-m(\nu_e)]^2+m_{e\mu}^2\}^{1/2}. \end{aligned} \quad (10)$$

Equations (9) and (10) show explicitly that $P(\nu_e;t|\nu_\mu;0)=0$ and no oscillations occur if $m(\nu_\mu)=m(\nu_e)=0$, or if $m_{e\mu}=0$ [with $m(\nu_\mu)\neq0$ and $m(\nu_e)\neq0$].

Again, consider the particular values: $\cos\theta = \sin\theta = 1\sqrt{2}$. In this case Eqs. (7a), (7b), (9), and (10) become

$$\begin{aligned} m(\nu_e) &= \tfrac{1}{2}[m(\nu_1)+m(\nu_2)] = m(\nu_\mu), \\ m(\nu_1) &= m(\nu_\mu) - \tfrac{1}{2}m_{e\mu}, \\ m(\nu_2) &= m(\nu_\mu) + \tfrac{1}{2}m_{e\mu}, \\ P(\nu_e;t|\nu_\mu;0) &= \tfrac{1}{2}[1-\cos(E_2-E_1)t], \\ P(\nu_\mu;t|\nu_\mu;0) &= \tfrac{1}{2}[1+\cos(E_2-E_1)t], \quad (11) \\ \langle P(\nu_e;t|\nu_\mu;0)\rangle_{\text{time average}} &= \langle P(\nu_\mu;t|\nu_\mu;0)\rangle_{\text{time average}} \\ &= \tfrac{1}{2}, \\ E_2-E_1 &\simeq \frac{1}{2p_\nu}[m(\nu_2)+m(\nu_1)][m(\nu_2)-m(\nu_1)] \\ &= \frac{1}{2p_\nu}[2m(\nu_\mu)](m_{e\mu}). \end{aligned}$$

Equations (11) describe what might be called the "maximal" oscillation situation in the case of two neutrino types, i.e., the situation in which $\langle P(\nu_e;t|\nu_\mu;0)\rangle_{\text{time average}}$ has its maximum possible value of $\frac{1}{2}$, i.e., 1/(number of neutrino types).

We consider next the case of three neutrino type types. As an example, we assign numerical values to the $\langle \nu_\xi|\nu_j\rangle$ as follows:

$$\begin{bmatrix} \langle \nu_e|\nu_1\rangle & \langle \nu_e|\nu_2\rangle & \langle \nu_e|\nu_3\rangle \\ \langle \nu_\mu|\nu_1\rangle & \langle \nu_\mu|\nu_2\rangle & \langle \nu_\mu|\nu_3\rangle \\ \langle \nu_L|\nu_1\rangle & \langle \nu_L|\nu_2\rangle & \langle \nu_L|\nu_3\rangle \end{bmatrix} = \begin{bmatrix} -\frac{1}{\sqrt{2}} & 0 & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \\ \frac{1}{\sqrt{6}} & -\frac{2}{\sqrt{6}} & \frac{1}{\sqrt{6}} \end{bmatrix}. \quad (12)$$

Then, substituting Eq. (12) into Eqs. (2), (3a), (3b), and (4) we have

$$|\nu_1\rangle = |\nu_e\rangle\left(-\frac{1}{\sqrt{2}}\right) + |\nu_\mu\rangle\frac{1}{\sqrt{3}} + |\nu_L\rangle\frac{1}{\sqrt{6}},$$

$$|\nu_2\rangle = |\nu_\mu\rangle\frac{1}{\sqrt{3}} + |\nu_L\rangle\left(-\frac{2}{\sqrt{6}}\right),$$

$$|\nu_3\rangle = |\nu_e\rangle\frac{1}{\sqrt{2}} + |\nu_\mu\rangle\frac{1}{\sqrt{3}} + |\nu_L\rangle\frac{1}{\sqrt{6}}, \qquad (13)$$

$$|\nu_e\rangle = |\nu_1\rangle\left(-\frac{1}{\sqrt{2}}\right) + |\nu_3\rangle\frac{1}{\sqrt{2}},$$

$$|\nu_\mu\rangle = |\nu_1\rangle\frac{1}{\sqrt{3}} + |\nu_2\rangle\frac{1}{\sqrt{3}} + |\nu_3\rangle\frac{1}{\sqrt{3}},$$

$$|\nu_L\rangle = |\nu_1\rangle\frac{1}{\sqrt{6}} + |\nu_2\rangle\left(-\frac{2}{\sqrt{6}}\right) + |\nu_3\rangle\frac{1}{\sqrt{6}},$$

$$m(\nu_e) = \tfrac{1}{2}[m(\nu_1) + m(\nu_3)],$$

$$m(\nu_\mu) = \tfrac{1}{3}[m(\nu_1) + m(\nu_2) + m(\nu_3)],$$

$$m(\nu_L) = \tfrac{1}{6}[m(\nu_1) + 4m(\nu_2) + m(\nu_3)], \qquad (14a)$$

$$m(\nu_1) = \tfrac{1}{2}m(\nu_e) + \tfrac{1}{3}m(\nu_\mu) + \tfrac{1}{6}m(\nu_L) - \frac{1}{\sqrt{6}}m_{e\mu} + \frac{1}{\sqrt{18}}m_{\mu L} - \frac{1}{\sqrt{12}}m_{Le},$$

$$m(\nu_2) = \tfrac{1}{3}m(\nu_\mu) + \tfrac{2}{3}m(\nu_L) - \frac{2}{\sqrt{18}}m_{\mu L}, \qquad (14b)$$

$$m(\nu_3) = \tfrac{1}{2}m(\nu_e) + \tfrac{1}{3}m(\nu_\mu) + \tfrac{1}{6}m(\nu_L) + \frac{1}{\sqrt{6}}m_{e\mu} + \frac{1}{\sqrt{18}}m_{\mu L} + \frac{1}{\sqrt{12}}m_{Le},$$

while substitution of Eq. (14b) into Eq. (14a) yields

$$m(\nu_e) = m(\nu_\mu) = m(\nu_L), \quad m_{\mu L} = 0, \qquad (15)$$

so that

$$m(\nu_1) = m(\nu_\mu) - \tfrac{1}{2}M,$$

$$m(\nu_2) = m(\nu_\mu), \qquad (16)$$

$$m(\nu_3) = m(\nu_\mu) + \tfrac{1}{2}M$$

where

$$M \equiv 2\left(\frac{m_{e\mu}}{\sqrt{6}} + \frac{m_{Le}}{\sqrt{12}}\right).$$

Further, substituting Eq. (12) into Eq. (4) yields

$$P(\nu_e;t\,|\,\nu_\mu;0) = \tfrac{1}{3}[1 - \cos(E_3 - E_1)t],$$

$$P(\nu_L;t\,|\,\nu_\mu;0) = \tfrac{1}{3}[1 - \tfrac{2}{3}\cos(E_2 - E_1)t - \tfrac{2}{3}\cos(E_3 - E_2)t + \tfrac{1}{3}\cos(E_3 - E_1)t],$$

$$P(\nu_\mu;t\,|\,\nu_\mu;0) = \tfrac{1}{3}[1 + \tfrac{2}{3}\cos(E_2 - E_1)t + \tfrac{2}{3}\cos(E_3 - E_2)t + \tfrac{2}{3}\cos(E_3 - E_1)t],$$

$$\langle P(\nu_e;t\,|\,\nu_\mu;0)\rangle_{\text{time average}} = \langle P(\nu_L;t\,|\,\nu_\mu;0)\rangle_{\text{time average}} = \langle P(\nu_\mu;t\,|\,\nu_\mu;0)\rangle_{\text{time average}} = \tfrac{1}{3}, \qquad (17)$$

$$E_2 - E_1 \cong \frac{1}{2p_\nu}[m(\nu_2) + m(\nu_1)][m(\nu_2) - m(\nu_1)] = \frac{1}{2p_\nu}[2m(\nu_\mu) - \tfrac{1}{2}M](\tfrac{1}{2}M),$$

$$E_3 - E_2 \cong \frac{1}{2p_\nu}[m(\nu_3) + m(\nu_2)][m(\nu_3) - m(\nu_2)] = \frac{1}{2p_\nu}[2m(\nu_\mu) + \tfrac{1}{2}M](\tfrac{1}{2}M),$$

$$E_3 - E_1 \cong \frac{1}{2p_\nu}[m(\nu_3) + m(\nu_1)][m(\nu_3) - m(\nu_1)] = \frac{1}{2p_\nu}[2m(\nu_\mu)](M).$$

Equations (12)–(17) describe a "maximal" oscillation situation in the case of three neutrino types since

$$\langle P(\nu_e;t\,|\,\nu_\mu;0)\rangle_{\text{time average}} = \langle P(\nu_L;t\,|\,\nu_\mu;0)\rangle_{\text{time average}} = \langle P(\nu_\mu;t\,|\,\nu_\mu;0)\rangle_{\text{time average}} = 1/(\text{number of neutrino types}).$$

Also, Eqs. (15)–(17) show explicitly that $P(\nu_e;t\,|\,\nu_\mu;0) = P(\nu_L;t\,|\,\nu_\mu;0) = 0$, and no oscillations occur if $m(\nu_e) = m(\nu_\mu) = m(\nu_L) = 0$ [remember that $m(\nu_1), m(\nu_2), m(\nu_3)$ are each ≥ 0] or if $M = 0$ [with $m(\nu_e) = m(\nu_\mu) = m(\nu_L) \neq 0$].

Finally, we present some conjectures on the lower limit for oscillation length. Confining ourselves for the sake of simplicity to the "maximal" oscillation situation in the case of two neutrino types, we attempt to estimate an upper limit on the quantity $\{[m(\nu_2)]^2 - [m(\nu_1)]^2\}$ which enters into the expression for the oscillation frequency $E_2 - E_1$ [Eq. (11)]. We do this by consideration of the radiative weak decay $\mu^+ \to e^+ + \gamma$. Thus, if ν_μ and ν_e were identical ($\nu_\mu \equiv \nu_e \equiv \nu$), this decay might be expected to proceed at a rate

$$\Gamma(\mu^+ \to e^+ + \gamma;\ \nu_\mu \equiv \nu_e) \approx \frac{\alpha}{\pi}(\tau_\mu)^{-1},$$

where $\tau_\mu = 2.2 \times 10^{-6}$ sec is the muon lifetime.[12] On the other hand, if muon lepton number and electron lepton number are separately conserved, $\Gamma(\mu^+ \to e^+ + \gamma)$ must vanish. However, if $\nu_\mu \leftrightarrow \nu_e$ oscillations take place, $\mu^+ \to e^+ + \gamma$ might also be expected to proceed at a nonvanishing rate, $\Gamma(\mu^+ \to e^+ + \gamma;\ \nu_\mu \leftrightarrow \nu_e)$, with the relation between $\Gamma(\mu^+ \to e^+ + \gamma;\ \nu_\mu \leftrightarrow \nu_e)$ and $\Gamma(\mu^+ \to e^+ + \gamma;\ \nu_\mu \equiv \nu_e)$ given by

$$\Gamma(\mu^+\to e^+ +\gamma;\ \nu_\mu \to \nu_e) \approx \Gamma(\mu^+\to e^+ +\gamma;\ \nu_\mu \equiv \nu_e) \int_0^\infty P(\nu_e;t\,|\,\nu_\mu;0)e^{-t/\tau^*}\frac{dt}{\tau^*}\,. \tag{18}$$

Here τ^* is the average time that the neutrinos, which we assume mediate the $\mu\to e$ transition, are present, and the form of $P(\nu_e;t|\nu_\mu;0)$ is supposed to be specified by Eq. (11). Evaluation of the integral yields approximately

$$\tfrac{1}{2}[(E_2-E_1)\tau^*]^2 \approx \frac{\Gamma(\mu^+\to e^+ +\gamma;\ \nu_\mu\to\nu_e)}{\Gamma(\mu^+\to e^+ +\gamma;\ \nu_\mu\equiv\nu_e)} \lesssim \frac{\Gamma(\mu^+\to e^+ +\gamma;\ \text{exper. limit})}{(\alpha/\pi)(\tau_\mu)^{-1}} = \frac{1.5\times 10^{-8}(\tau_\mu)^{-1}}{(\alpha/\pi)(\tau_\mu)^{-1}} = 6.5\times 10^{-6}\,, \tag{19}$$

where

$$E_2-E_1 \cong \frac{1}{2p^*}\{[m(\nu_2)]^2-[m(\nu_1)]^2\} \cong \frac{l^*}{2}\{m(\nu_2)]^2-[m(\nu_1)]^2\}\,, \tag{20}$$

with p^* the average momentum of the mediating neutrinos and l^* the average linear dimension of the region within which these neutrinos are confined. Equations (19) and (20) give (restoring the appropriate powers of $\hbar$ and c)

$$[m(\nu_2)]^2-[m(\nu_1)]^2 \lesssim 7\times 10^{-3}\left(\frac{\hbar}{cl^*}\right)\left(\frac{\hbar}{c^2\tau^*}\right), \tag{21}$$

and if $\mathrm{Re}\langle \nu_e|H^{(1)}|\nu_\mu\rangle_{p_\nu=0} \equiv \frac{1}{2}m_{e\mu} \cong m(\nu_\mu) = \langle\nu_\mu|H^{(1)}|\nu_\mu\rangle_{p_\nu=0}$ [which corresponds to $m(\nu_1)\cong 0$], Eqs. (21) and (11) yield in addition

$$m(\nu_\mu)=m(\nu_e)\cong\tfrac{1}{2}\{[m(\nu_2)]^2-[m(\nu_1)]^2\}^{1/2} \lesssim 4\times 10^{-2}\left(\frac{\hbar^2/c^3}{l^*\tau^*}\right)^{1/2}. \tag{22}$$

From Eq. (21) we obtain at once the upper limits on the $\nu_\mu\to\nu_e$ oscillation period and oscillation length. We have from Eqs. (11) and (21)

$$c\tau_{osc}(p_\nu) = l_{osc}(p_\nu) = \frac{2\pi\hbar c}{E_2-E_1} \cong \frac{4\pi p_\nu\hbar/c^2}{[m(\nu_2)]^2-[m(\nu_1)]^2} \gtrsim 1.8\times 10^3\left(\frac{p_\nu l^*}{\hbar}\right)(c\tau^*)\,, \tag{23}$$

and we implement this last equation by considering various possible values of τ^* and l^*. One possibility is suggested by a lowest-order perturbation treatment of a model where the neutrinos (and the vector boson W^+) which mediate $\mu^+\to e^+ +\gamma$ undergo the sequence

$$\mu^+\to\bar\nu_\mu + W^+ \to \bar\nu_\mu + W^+ +\gamma \xrightarrow[\text{via } \nu_\mu\to\nu_e \text{ oscillations}]{} \bar\nu_e + W^+ +\gamma \to e^+ +\gamma\,.$$

This yields

$$\tau^* \approx \hbar/\{[(m_W c^2)^2 + (c\hbar/l^*)^2]^{1/2} + (c\hbar/l^*)\}$$

and $(\hbar/l^*)\approx m_W c$, i.e., $\tau^*\approx(l^*/c)\approx(\hbar/m_W c^2) = 1.3\times 10^{-26}$ sec for $m_W = 50$ GeV/c^2,[13] whence, using Eqs. (21) and (23), we have $\{[m(\nu_2)]^2-[m(\nu_1)]^2\}^{1/2} \lesssim 4$ GeV/c^2 and $l_{osc}(p_\nu)\gtrsim 3\times 10^{-13}$ cm for $p_\nu = 20$ GeV/c. Obviously, these limits are not very helpful since we already know from experiment that $l_{osc}(p_\nu\approx 20$ GeV/$c)\gtrsim 2$ km (Ref. 14) and thus $\{[m(\nu_2)]^2-[m(\nu_1)]^2\}^{1/2}\lesssim 5$ eV/c^2. A possibility of a very different kind is suggested by the idea that dynamical constraints may exist which permit the neutrinos that mediate $\mu^+\to e^+ +\gamma$ to remain confined in the region of linear dimension l^* for a time $\tau^*\gg l^*/c$. This inequality holds, for example, in the case that τ^* and l^* are assumed to have their maximum "reasonable" values, i.e., $\tau^*\approx\tau_\mu = 2\times 10^{-6}$ sec and $l^*\approx l_\mu \equiv$ upper limit on the radius of the muon $\approx 10^{-2}(\hbar/m_\mu c) = 2\times 10^{-15}$ cm.[15] (Here l_μ is the length which determines the deviation of muonic QED behavior from that of a point.) These values for τ^* and l^* lead to a very small upper limit, $\{[m(\nu_2)]^2-[m(\nu_1)]^2\}^{1/2}\lesssim 0.15$ eV/c^2, and a very large lower limit, $l_{osc}(p_\nu)\gtrsim 2000$ km for $p_\nu = 20$ GeV/c. We also mention that a lower limit some 30 times smaller than this, i.e., $l_{osc}(p_\nu)\gtrsim 70$ km for $p_\nu = 20$ GeV/c, is obtained if one assumes $\tau^*\approx\tau_\mu$ and $l^*\approx$ length characteristic of the weak interactions $= (G/\hbar c)^{1/2}$. Thus, none of our speculations on the lower limit of the oscillation length (at $p_\nu \lesssim 20$ GeV/c) appears to be significantly larger than the distance between the accelerator and the (distant) detector (≅1000 km) contemplated in the next section.

We conclude this account of the theory of neutrino oscillations by emphasizing that the time-averaged oscillation probability for a fixed neutrino momentum p_ν [Eqs. (4), (9), (11), (17)] is equal to the average of the oscillation probability over a broad neutrino momentum spectrum $N(p_\nu)$ at a fixed time t, i.e., at a fixed distance x between the neutrino detector and the accelerator.[16] More precisely, this equality holds if

$$\left[\frac{\langle(p_\nu-\langle p_\nu\rangle)^2\rangle}{(\langle p_\nu\rangle)^2}\right]^{1/2}\equiv\frac{\Delta p_\nu}{\langle p_\nu\rangle}\gtrsim\frac{l_{osc}(\langle p_\nu\rangle)}{x},$$

so that, under these circumstances,

$$\langle P(\nu_\eta;t\,|\,\nu_\xi;0)\rangle_{\substack{\text{time average}\\ \text{fixed } p_\nu}}=\sum_j|\langle\nu_\eta|\nu_j\rangle|^2|\langle\nu_j|\nu_\xi\rangle|^2$$

$$=\langle P(\nu_\eta;t\,|\,\nu_\xi;0\,|\rangle_{\substack{p_\nu \text{ average}\\ \text{fixed } t \text{ or } x}}$$

i.e. $(T\gg 2\pi[E_k(p_\nu)-E_j(p_\nu)]^{-1})$, (24)

$$\frac{1}{T}\int_0^T\sum_{j,k}{}'\,\langle\nu_\eta|\nu_j\rangle\langle\nu_\eta|\nu_k\rangle^*\langle\nu_j|\nu_\xi\rangle\langle\nu_k|\nu_\xi\rangle^* e^{i[E_k(p_\nu)-E_j(p_\nu)]t}dt$$

$$=0$$

$$=\int_0^\infty\sum_{j,k}{}'\,\langle\nu_\eta|\nu_j\rangle\langle\nu_\eta|\nu_k\rangle^*\langle\nu_j|\nu_\xi\rangle\langle\nu_k|\nu_\xi\rangle^* e^{i[E_k(p_\nu)-E_j(p_\nu)]t}N(p_\nu)dp_\nu\,. \quad (25)$$

Accordingly, for a broad-band neutrino spectrum, the neutrino-momentum-averaged oscillation probability will not vanish at any detector-accelerator distance $>l_{osc}(\langle p_\nu\rangle)$ as long as the neutrino oscillations actually occur.

EXPERIMENT

Arrangement of neutrino beam and detectors

To be concrete, consider an experimental arrangement as in Fig. 1 with detectors I and II separated by $x=10^3$ km, approximately $\frac{1}{6}$ of the earth's radius. To reach detector II the neutrino beam must initially be directed about 78 mrad below the horizontal. It will emerge at detector II directed 78 mrad above the horizontal. As shown in Fig. 1, the sagitta between the earth's surface and the beam path is 19 km. To form the neutrino beam from the decays of secondary mesons produced by a high-energy proton beam requires a free region about 1 m in diameter and roughly 200 m long, which would therefore have its downstream end 15 m below the horizontal. A typical neutrino beam produced by, say, 300-GeV protons has an angular divergence of about 1 mrad. Hence, at a distance of 10^3 km from its source, the beam has a radius of 1 km.

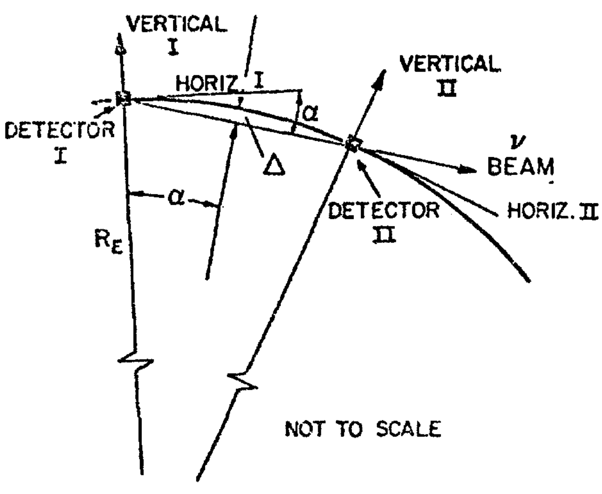

FIG. 1. Geometry of a feasible experiment. If the distance between detectors I and II is 1000 km, then $\alpha=0.078$ rad and $\Delta=19$ km. R_E is the radius of the earth $=6.4\times10^3$ km.

There is no special requirement on the neutrino-beam energy, although lower energy is somewhat favored. The total cross section for ν-nucleon interactions rises linearly with laboratory energy E_ν, which accordingly increases the observed interaction rate at detector II as higher-energy neutrinos are employed. On the other hand, the oscillation length [Eq. (23)] also increases linearly with E_ν, which leads to the possibility of violating the condition $\Delta E_\nu/\langle E_\nu\rangle\gtrsim l_{osc}(\langle E_\nu\rangle)/x$ if too-high-energy neutrinos are employed. In addition, the "on" time of the beam should be as short as possible to minimize the background at detector II. This will be discussed in more detail later.

Interaction rates at detector II

Each of the detectors I and II must be capable of detecting electrons from ν_e-induced reactions, $\nu_e+N\to e^-+$ hadrons, and muons from ν_μ-induced reactions, $\nu_\mu+N\to\mu^-+$ hadrons, where N is a nucleon. Weak neutral-current reactions, that may

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in some detectors appear as ν_e interactions, will be discussed in the section on backgrounds. A realistic area for detector II is 10 m × 10 m, with about 220 metric tons of ν_e-detecting capacity and 220 metric tons of ν_μ-detecting capacity. Hence detector II subtends 0.32×10^{-4} of the neutrino beam area at detector I.

(*a*) *If only* ν_e *and* ν_μ *exist and "maximally" oscillate one into another* [*Eq.* (*11*)]. At a detector (the equivalent of detector I) in the Fermilab ν beam, at present, one observes about 30 muons from ν_μ-induced events per metric ton of detector per hour. Thus at detector II one might expect 30 muons/(metric ton × hour) × 220 metric tons $\times 0.32 \times 10^{-4} \approx 0.2$ muon/hr, and $\lesssim 0.005$ electron/hr, if $\tau_{osc} \gg t_{II}$, because the number of ν_e's initially in the beam[17] is $\lesssim 2 \times 10^{-2}$ times the number of ν_μ's. For $\tau_{osc} \ll t_{II}$, we should observe 0.10 muon/hr and 0.10 electron/hr. In a 500-hour run, we obtain 51 muon events and 51 electron events, if oscillations are present, to be contrasted with 100 muon events and less than 3 electron events if no oscillations take place.

(*b*) *If neutrinos other than* ν_e *and* ν_μ *also exist and* ν_μ *maximally oscillates into all the others* [*Eq.* (*17*)]. As discussed earlier, if there exist a total of n different but communicating neutrino types, all of comparable mass, the expected muon and electron count rates in detector II are more complicated but still quite distinctive. We assume the additional neutrinos $\nu_L, \nu_{L'}, \ldots$ to be associated with charged heavy leptons of mass $m_L, m_{L'}, \ldots \gtrsim 1.5$ GeV, which will decay both leptonically and semileptonically with a lifetime $<10^{-11}$ sec. These leptons will be produced by the interactions of $\nu_L, \nu_{L'}, \ldots$ in detector II through $\nu_L + N \to L^- +$ hadrons, etc. The leptonic decay modes, $L^- \to \mu^- + \bar{\nu}_\mu + \nu_L$ and $L^- \to e^- + \bar{\nu}_e + \nu_L$, will occur with approximately equal probability and therefore contribute to the observed muon and electron events in detector II in the same ratio as the muons and electrons that come directly from ν_μ and ν_e interactions in detector II. The semileptonic decay modes, $L^- \to \nu_L +$ hadrons, will make negligible contribution to the observed muon and electron count rates. Thus, if the purely leptonic branching fraction is f, we again expect the observed number of muons and electrons to be equal to each other but given by $N_\mu = N_e = (N_0/n)[1 + (n-2)f/2]$, where N_0 is the total number of muons that would be observed in detector II in the absence of oscillations. We plot in Fig. 2 the ratio N_μ/N_0 against the number of different neutrino types n for different values of f. We conclude from Fig. 2 that, if oscillations are observed, and if $f \lesssim 0.5$ as expected for the leptonic decays of heavy leptons,[18] it is possible to determine n if n is large, say $\gtrsim 5$, and to

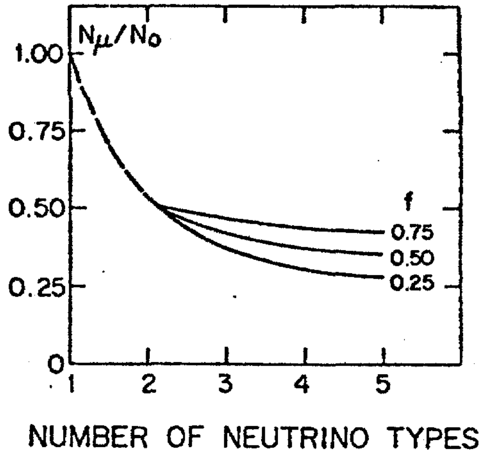

FIG. 2. Plot of N_μ, the number of observed muons if oscillations occur, divided by N_0, the number of observed muons if no oscillations take place, against number of neutrino types n for different values of the leptonic branching ratio f. The value of N_μ/N_0 at $n=1$ corresponds to no neutrino oscillations.

set an upper limit on n if n is smaller than 5. The accuracy with which this is done depends on the uncertainty in N_0, which would be directly determined by measurement in detector I.

Apparatus

There are a number of possible detector arrangements that would satisfy the relatively simple requirements of this search for a signal of neutrino oscillations. The apparatus described here has been constructed for and in part tested in previous neutrino experiments.[19] It provides a definite design of a feasible experiment that incorporates adequate reliability and redundancy in its performance.

The basic idea is to use a target-detector that serves as the target for both ν_e and ν_μ interactions. It is also the specific detector for the ν_e interactions. Immediately downstream of the target is a 1-m-thick iron wall, the rear surface of which is covered with large-area liquid scintillation counters (see Fig. 3). The iron wall absorbs all hadrons and electromagnetic radiation produced in the target but permits muons of energy greater than about 1 GeV to penetrate to the scintillation counters behind it. Thus a count in the downstream counters in time coincidence with both a count in the target-detector and a gate from the accelerator serves to identify muons from ν_μ reactions, $\nu_\mu + N \to \mu^- +$ hadrons, in the target. In contrast, a count in the target-detector representing the deposition therein of more than a few GeV of energy in time coincidence with a

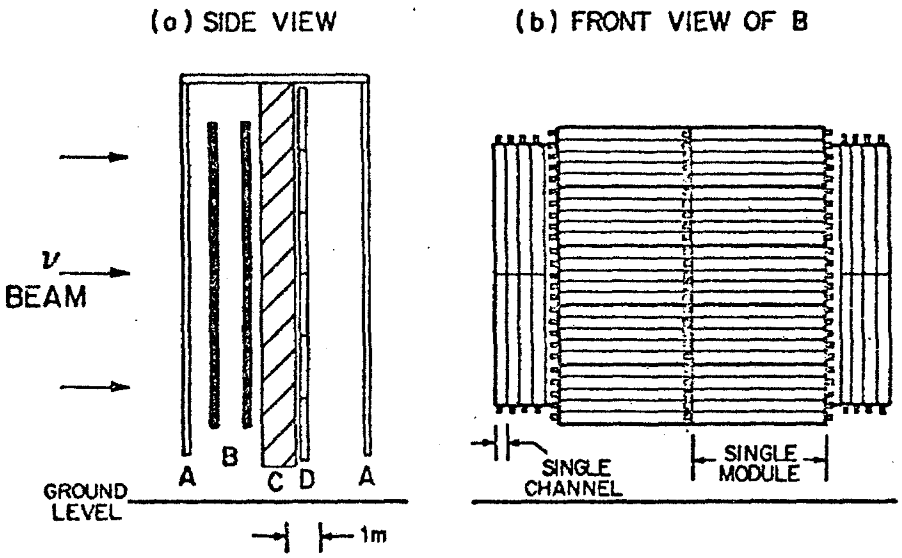

FIG. 3. Schematic diagram of the apparatus. (a) Here A is a liquid scintallator anticounter (if necessary), B is the target-detector, C is a 1-meter thickness of iron, and D is a liquid scintillator counter to record muons that pass through C. (b) Front view of the target-detector showing a possible geometric arrangement of individual modules. Many but not all photomultiplier tubes are also shown. Observe that the fiducial area can be varied horizontally and vertically by including more or fewer of the individual channels in each module.

gate from the accelerator, and the absence of a count in the muon identifying counters, is the signal of a ν_e interaction, $\nu_e+N\rightarrow e^-+$hadrons, in the target-detector.

The 220-metric-ton modular target-detector might consist of 28 modules in two arrays of 14 modules as shown in Fig. 3. Each module has an area of 4 m × 2 m and is approximately 8 metric tons in weight. A module contains alternating thicknesses of lead sheets and liquid scintillator to form a very efficient ($\cong 14\lambda_{rad}$) electromagnetic shower detector. The total thickness of the double array in Fig. 3 is, however, about one absorption length for strongly interacting particles, and will certainly be penetrated by muons with energy greater than about 0.5 GeV.

A ν_μ-induced reaction in the target-detector will give rise to an average deposition of energy in the target-detector $\langle E_D\rangle_\mu$ about equal to the energy carried by the neutral-pion component of the hadronic cascade, i.e., $\langle E_D\rangle_\mu \approx 0.25\ E_\nu$. If ν_e interactions with nucleons have the same essential nature as ν_μ interactions, then $\langle E_D\rangle_e \approx 0.75\ E_\nu$, since the energy spectrum of the ν_e induced by oscillations should be the same as that of the original ν_μ, and the energy of the outgoing electron will on average equal 0.5 E_ν. Thus an additional signature of a statistically significant sample of ν_e-induced events due to oscillations would be the ratio $\langle E_D\rangle_e/\langle E_D\rangle_\mu \approx 3$. This is a useful check on the experiment, and is particularly important in discriminating against the background of muonless (i.e., weak-neutral-current) events that will be produced by ν_μ interacting in the target-detector, as discussed in the next section.

Backgrounds

(*a*) *Cosmic rays.* It will be convenient and relatively inexpensive if detector II can be located at the earth's surface, even if it is necessary to provide active (anticounter) shielding against cosmic rays for the entire detector. This depends on the magnitude and nature of the cosmic-ray background at the surface, the time duration and structure of the ν_μ beam pulse from the accelerator, and the precision with which a timing signal from the accelerator can be brought to detector II. In the Harvard-Pennsylvania-Wisconsin-Fermilab neutrino experiment[19] at Fermilab, the observed time-averaged cosmic-ray rate in a part of the apparatus with a geometrical arrangement similar to, and an area $\frac{1}{8}$, that of the experimental arrangement shown in Fig. 3 is about 10^3 total cosmic-ray counts per second. To extract protons from over the entire circumference of the Fermilab proton synchrotron requires 20 μsec, which is therefore the shortest-duration accelerator pulse, apart from the rf structure of the beam pulse. Correcting for the ratio of the areas gives about 0.02 cosmic-ray count per shortest accelerator pulse for the apparatus in

Fig. 3, which indicates the feasibility of locating detector II at the earth's surface, if only a minimal amount of active shielding against cosmic rays is provided. The actual background rate is further reduced by discrimination against the very low energy (< 100 MeV) deposition in the target-detector of cosmic-ray muons traversing it in favor of the larger deposition ($\gtrsim$500 MeV) due to ν-induced reactions.

It is, nevertheless, worth noting that almost total active shielding against all types of cosmic-ray events (showers as well as single muons) can be accomplished with the anticounter arrangement shown in Fig. 3, which will reduce the cosmic-ray background of all kinds by more than two orders of magnitude. The upstream and overhead counters in Fig. 3 serve directly as anticounters in the usual way. The downstream counters must be used to veto cosmic rays by a time-of-flight discrimination against particles directed from downstream toward upstream. Since the shortest flight path is 4 m, or about 13 nsec as shown in Fig. 3, it is easily possible with present timing techniques to distinguish upstream-going cosmic rays. Further reduction by another factor of 100 at a small sacrifice of useful target tonnage can be obtained by using the outer sections of each target-detector module as a veto counter against charged particles incident from the outside. Thus the counts due to cosmic rays in detector II located at the earth's surface may certainly be made negligible with active shielding, compared with the expected neutrino-induced count rate of >0.2 counts/hr.

(*b*) *Neutrino-beam-induced backgrounds.* These are events produced by ν_μ coming from the accelerator for which a muon is not observed in the muon identifier. They arise primarily from weak neutral-current interactions, although some will be the result of geometric detection inefficiency. This type of event will simulate a ν_e-induced event in the target-detector of Fig. 3. Observe, however, that for these events $\langle E_D\rangle \leq 0.25\, E_\nu$, as mentioned earlier, which will aid in identifying them as spurious. Furthermore, it is known[20] that at Fermilab energies

$$R^\nu = \frac{\sigma(\nu_\mu + N \to \nu_\mu + \text{hadrons})}{\sigma(\nu_\mu + N \to \mu^- + \text{hadrons})} = 0.30 \pm 0.03\,.$$

In the 500-hr sample experiment given above, we might then expect $100 \times (0.30 \pm 0.03) = 30 \pm 4$ muonless or spurious ν_e events, even in the absence of neutrino oscillations. If oscillations and only two neutrinos are present, we would again obtain [assuming $\sigma(\nu_e + N \to \nu_e + \text{hadrons}) = \sigma(\nu_\mu + N \to \nu_\mu + \text{hadrons})$] $50 \times (0.30 \pm 0.03) \times 2 = 30 \pm 5$ spurious ν_e events. Hence, with no oscillations, $N_e/N_\mu \approx 33/100 = 0.33$, i.e., $\approx R^\nu$, while with oscillations $N_e/N_\mu \approx 84/51 = 1.6$, and the raw N_e/N_μ signal again clearly distinguishes the presence of real ν_e events even without energy discrimination.

Another source of error may arise from a difference in the angular distributions of ν_e and ν_μ produced at the accelerator, which would modify the ratio with no oscillations, but this is a small effect.

Unstable neutrinos

We conclude this discussion of the particulars of the proposed experiment by noting that if $m(\nu_\mu)$ is several times larger than $m(\nu_e)$ and *separate* conservation of muon and electron lepton number does not hold, ν_μ will be unstable and should decay into $\nu_e + \gamma$. Theoretical estimates of $[\Gamma(\nu_\mu \to \nu_e + \gamma)]^{-1}$, e.g.,

$$[\Gamma(\nu_\mu \to \nu_e + \gamma)]^{-1} \approx [\Gamma(\mu^+ \to e^+ + \gamma)]^{-1} \frac{m_\mu}{m(\nu_\mu)} > \left(\frac{2 \times 10^{-6}\ \text{sec}}{1.5 \times 10^{-8}}\right)\left(\frac{0.1\ \text{GeV}}{m(\nu_\mu)}\right) = (1.3 \times 10^{10}\ \text{sec}) \times [m(\nu_\mu)\ \text{in eV}]^{-1}\,,$$

indicate that the ν_μ lifetime in its rest frame is enormously greater than the value

$$\left(\frac{x}{c}\right)\left(\frac{m(\nu_\mu)}{E_\nu}\right) = \left(\frac{10^3\ \text{km}}{3 \times 10^{10}\ \text{cm/sec}}\right)\left(\frac{m(\nu_\mu)}{20\ \text{GeV}}\right) \approx (1.6 \times 10^{-13}\ \text{sec}) \times [m(\nu_\mu)\ \text{in eV}]$$

which is set by the scale of our experiment. However, if the theoretical estimate above is entirely wrong, the $\nu_\mu \to \nu_e + \gamma$ decay might significantly modify the ratio N_e/N_μ and provide an experimental value for the ν_μ lifetime which would be $\approx 10^3$ times longer than any existing direct limit on the instability of the ν_μ.[21]

SUMMARY AND CONCLUSIONS

The essential content of this paper is the assertion that a realistic experimental search for neutrino oscillations may at present be made over a distance of approximately 10^3 km. The experiment would utilize a high-energy ν_μ beam from a proton accelerator such as that at Fermilab, and existing neutrino-detecting apparatus. The approximate geography of an experiment with a neutrino beam originating at Fermilab is shown in Fig. 4.

If neutrino oscillations of the kind $\nu_\mu \leftrightarrow \nu_e$ do occur, they would significantly modify the ratio

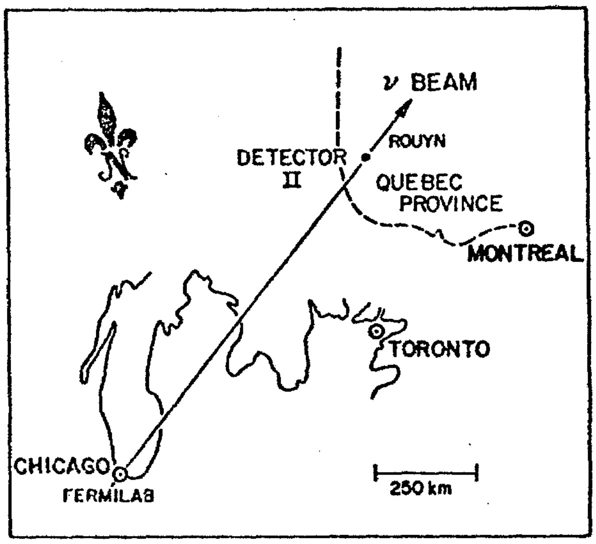

FIG. 4. Approximate geography of the proposed experiment. The present ν beam at Fermilab is directed 38°13′52″ east of north as indicated roughly.

of ν_e-induced electrons to ν_μ-induced muons observed in the distant detector relative to the same ratio observed in the detector much nearer to the origin of the neutrino beam. Thus, for example, an experiment of 500 hours' duration using a Fermilab neutrino beam of average energy ≈20 GeV with a detector separation of 10^3 km would yield a clear signal of neutrino oscillations if the oscillation length is less than 10^3 km.

If neutrino oscillations are observed, it would necessarily imply that the mass of at least one of the neutrino types, ν_μ or ν_e, is nonzero, and that the separate conservation of muon and electron lepton number does not hold. Subsequent experiments to determine the actual oscillation length (by moving the distant detector closer to the accelerator) would then explicitly measure the quantity $[m(\nu_2)]^2 - [m(\nu_1)]^2$ in Eq. (11) or the quantities $[m(\nu_2)]^2 - [m(\nu_1)]^2$ and $[m(\nu_3)]^2 - [m(\nu_2)]^2$ in Eqs. (15)–(17).

Furthermore, if neutrino oscillations do occur, it should be possible in the same experiment to determine the total number of "communicating" neutrino types by a direct comparison of the absolute number of ν_μ-induced muons in the distant detector with the absolute number predicted from measurement in the near detector of the ν_μ flux and the ν_μ-beam divergence. This is the only method known to us which holds forth at least the promise of specifying the total number of neutrino types in a single terrestrial experiment.

If neutrino oscillations are not observed, but if one still assumes that separate conservation of muon and electron number does not hold (i.e., $\mathrm{Re}\langle\nu_e|H^{(1)}|\nu_\mu\rangle_{p_\nu=0} \equiv \frac{1}{2}m_{e\mu} \neq 0$) and that, for the sake of simplicity, $m(\nu_e) = m(\nu_\mu)$, the principal result of the 10^3-km experiment with 20-GeV neutrinos would be an upper limit on the quantity $\{[m(\nu_2)]^2 - [m(\nu_1)]^2\}^{1/2} = \{2m(\nu_\mu)m_{e\mu}\}^{1/2}$, namely ≤ 0.2 eV/c^2. Thus, granting in addition the approximate equality $\frac{1}{2}m_{e\mu} \cong m(\nu_\mu)$ [as in the discussion following Eq. (21)], a negative result at 10^3 km with 20-GeV neutrinos would yield an upper limit on $m(\nu_\mu)$ or $m(\nu_e)$ of about 0.1 eV/c^2. Note that extension of the 10^3-km experiment at 20 GeV to the maximum possible terrestrial distance of about 10^4 km would reduce this upper limit on $\{[m(\nu_2)]^2 - [m(\nu_1)]^2\}^{1/2}$ by only a factor of about $\sqrt{10}$.

If no increase is observed in the ν_e signal and no decrease of the ν_μ signal is noted relative to the expected ν_μ and ν_e signals at the distant detector, a second result of interest is a limit on the instability of ν_μ. For a ν_μ with a mass equal to 1 eV, the mean life in the neutrino rest frame would be greater than about 10^{-13} sec.

Finally, there are interesting dividends, apart from those mentioned above, to be expected from any terrestrial neutrino experiment using an accelerator-produced neutrino beam over a distance of 10^3 km. The problem of correlated timing over large distances is under attack in long-baseline radio astronomy[22] and in terrestrial neutrino astronomy;[23] but certain aspects of the timing problem in an accelerator-based terrestrial neutrino experiment present a significant additional challenge, as, for example, in the attempt to correlate the time at the distant detector with the rf structure of the accelerator pulse. Furthermore, relatively high precision is required of the survey necessary to locate the distant detector close to the center of the accelerator neutrino beam, and good control of the direction of the extracted proton beam from the accelerator is necessary to maintain a constant neutrino beam direction. Partial solutions of these technical problems are available that are sufficient to permit the experiment described here to be carried out, but further development of these solutions would be advantageous to this experiment and, possibly, to other areas of physics.

ACKNOWLEDGMENTS

We have profited from discussion of various aspects of this subject with K. Lande. One of us (A.K.M.) wishes to acknowledge valuable discussions with B. Pontecorvo and S. M. Bilenky. We are also grateful for helpful communications from H. Fritzsch and S. Pakvasa.

*Work supported in part by the U.S. Energy Research and Development Administration and by the U.S. National Science Foundation.

[1]K. Bergkvist, Nucl. Phys. B39, 317 (1972); A. R. Clark *et al.*, Phys. Rev. D 9, 533 (1974); M. Daum *et al.*, Phys. Lett. 60B, 380 (1976).

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[7]S. Pakvasa and K. Tennakone, Phys. Rev. Lett. 27, 757 (1971); 28, 1415 (1972); Lett. Nuovo Cimento 6, 675 (1973).

[8]S. Eliezer and A. R. Swift, Nucl. Phys. B105, 45 (1976). See also S. Eliezer and D. A. Ross, Phys. Rev. D 10, 3088 (1974).

[9]H. Fritzsch and P. Minkowski, Phys. Lett. 62B, 72 (1976).

[10]S. M. Bilenky and B. Pontecorvo, report presented at the International Conference on High Energy Physics, Tbilisi, USSR, 1976 (unpublished).

[11]J. N. Bahcall, N. Cabibbo, and A. Yahil, Phys. Rev. Lett. 28, 316 (1972); Pakvasa and Tennakone, Ref. 7; Eliezer and Swift and Eliezer and Ross, Ref. 8; M. N. Nakagawa *et al.*, Prog, Theor. Phys. 30, 727 (1963).

[12]See, for example, S. Frankel, in *Muon Physics*, Vol. II, edited by V. W. Hughes and C. S. Wu (Academic, New York, 1975).

[13]Upon substitution into Eqs. (19) and (20), the values $\tau^* \approx \hbar/m_W c^2$ and $l^* \approx \hbar/m_W c$ yield the result

$$\frac{\Gamma(\mu^+ \to e^+ + \gamma;\ \nu_\mu \to \nu_e)}{\tau_\mu^{-1}} \approx \frac{\alpha}{8\pi}\left(\frac{[m(\nu_2)]^2 - [m(\nu_1)]^2}{m_W^2}\right)^2,$$

in essential agreement with a formula derived directly by Fritzsch (private communication).

[14]In the Harvard-Pennsylvania-Wisconsin-Fermilab experiments so far performed at Fermilab the distance between the source of roughly 20-GeV neutrinos and the detector is ≈2 km. No indication of neutrino oscillations is found in these experiments.

[15]As an illustration, admittedly in a completely different context, the lifetime of a positive pion, τ_π, could be viewed as the average time that the confined quarks, which mediate the pionic weak decay, are present within a region of linear dimension comparable with the radius of the pion, l_π. In this case, the mediation occurs via $\pi^+ \to u + \bar{d}$ and $u + \bar{d} \to \mu^+ + \nu_\mu$ with the u and $\bar{d}$ in strong mutual dynamical interaction. One has $\tau_\pi \gg l_\pi/c$ since $\tau_\pi = 2.6 \times 10^{-8}$ sec and $l_\pi \cong 8 \times 10^{-14}$ cm.

[16]Averaging the oscillation probability over the neutrino momentum spectrum has been discussed by J. Bahcall and S. Frautschi [Phys. Lett. 29B, 623 (1969)] in connection with the effect of any $\nu_e \to \nu_\mu$ oscillations on the terrestrially detected ν_e flux from the sun. As may be seen, e.g., from our Eq. (11), the averaging in question produces a decrease in the flux by a factor of 2. The appropriate decrease in the flux in the case of more than two neutrino types which can oscillate one into another, i.e., in the case of $\nu_e \to \nu_\mu, \nu_e \to \nu_L$, ... oscillations, is discussed by S. Nussinov [Phys. Lett. 63B, 201 (1976)].

[17]See, for example, G. R. Kalbfleisch, in *Proceedings of the 1969 Summer Study. National Accelerator Laboratory*, Vol. I, edited by A. Roberts (NAL, Batavia, Ill., 1969).

[18]Y.-S. Tsai, Phys. Rev. D 4, 2821 (1971).

[19]A. Benvenuti *et al.*, Nucl. Instrum. Methods 125, 447 (1975); 125, 457 (1975).

[20]A. Benvenuti *et al.*, Phys. Rev. Lett. 37, 1039 (1976).

[21]For a discussion of an indirect limit on the instability of the ν_μ see Eliezer and Swift in Ref. 8.

[22]F. Drake, colloquium at Fermilab, 1976 (unpublished).

[23]K. Lande, private communication.

APPENDIX II

"Horizontal Boring Scheme"

James H. Allen

SMITH TOOL
Division of Smith International, Inc

P. O. Box 15500
17871 Von Karman Ave.
Irvine, California 92705
Phone (714) 540-7010 Telex: 6-74575

December 8, 1976

Dr. Peter Koetzer
Physics Hall, FM15
Applied Physics Lab
University of Washington
Seattle, Washington 98195

Dear Professor Koetzer:

In accord with our recent discussion concerning horizontal hole drilling, I am enclosing copies of several articles and studies that have been provided by Myron Embry of Dyna-Drill.

After reviewing Dowding's study and other state-of-the-art case studies, I have prepared the attached concept depicting a boring and drilling scheme for a one meter hole x 4 Kilometers long x 15^o from horizontal at Batavia, Illinois. I believe the vertical access shafts are necessary for a hole of this diameter and length. I also believe you can obtain more realistic cost estimates from boring and shaft drilling contractors with this approach. Over twenty large diameter vertical holes have been drilled in Illinois to depths of 1300 feet in the last ten years.

I have talked to Mr. Jack Kelner, Manager of Research and Development, Drilco Industrial, Midland, Texas, and Mr. Myron Emery, Manager of Technical Services, Dyna-Drill, Long Beach, California, about this projects. Both of these gentlemen have had considerable experience with horizontal boring projects. Both are considered to be experts in this field. I would recommend that you contact both of them.

Attached are names of contractors that may be of assistance.

We are very interested in this project and believe it to be worthy for consideration as an unsolicited proposal for further research and development study and funding. Should such a possibility materialize we hope you will consider the interests of Smith International, Inc.

Sii SMITH TOOL
Division of Smith International, Inc.

Please contact me if we can provide additional information.

Very truly yours,

Sii SMITH TOOL

James H. Allen
Director
Technical Services

JHA:sd
cc: Myron Emery
Jack Kelner

SMITH TOOL
Division of Smith International, Inc.

Horizontal Boring Equipment

Mr. Myron Emery
Manager of Technical Services
Sii Dyna-Drill
P.O. Box 327
Long Beach, California 90801

Mr. Jack Kelner
Manager of Research & Development
Drilco-Industrial
P.O. Box 3135
Midland, Texas 79701

Horizontal Boring Contractors

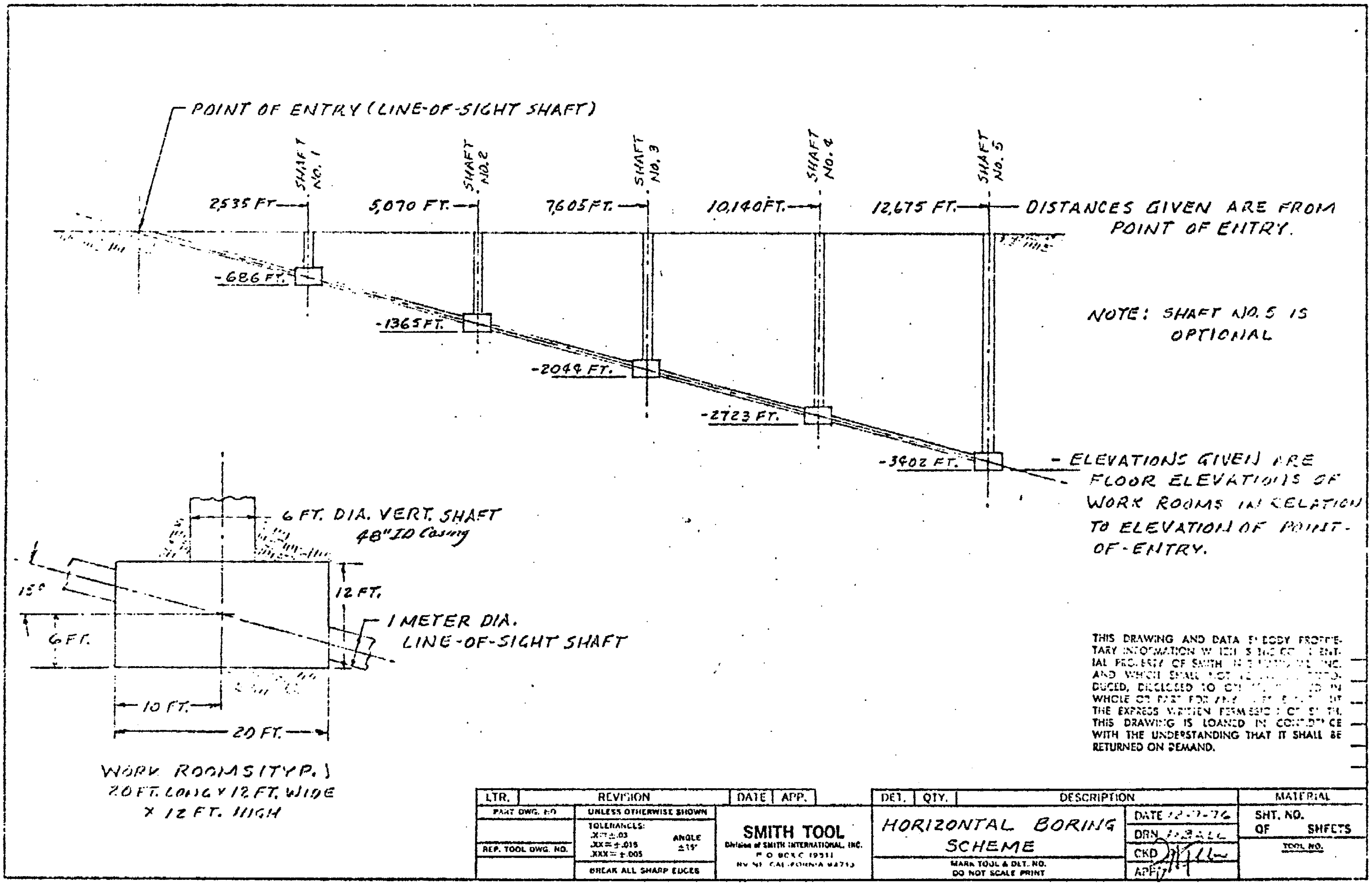
Titan Contracotrs Corporation
Sacramento, California

Vertical Shaft Contractors

Camay Drilling Company
Los Angeles, California

Mr. Bill Holbert
Rowan International
Midland, Texas

Loffland Brothers Company
Tulsa, Oklahoma



POINT OF ENTRY (LINE-OF-SIGHT SHAFT)
SHAFT NO. 1
SHAFT NO. 2
SHAFT NO. 3
SHAFT NO. 4
SHAFT NO. 5
2,535 FT.
5,070 FT.
7,605 FT.
10,140 FT.
12,675 FT.
DISTANCES GIVEN ARE FROM POINT OF ENTRY.
-686 FT.
-1365 FT.
-2044 FT.
-2723 FT.
-3402 FT.
NOTE: SHAFT NO. 5 IS OPTIONAL
ELEVATIONS GIVEN ARE FLOOR ELEVATIONS OF WORK ROOMS IN RELATION TO ELEVATION OF POINT-OF-ENTRY.
6 FT. DIA. VERT. SHAFT
48" ID Casing
12 FT.
1 METER DIA. LINE-OF-SIGHT SHAFT
15°
6 FT.
10 FT.
20 FT.
WORK ROOMS (TYP.)
20 FT. LONG X 12 FT. WIDE X 12 FT. HIGH
LTR.
REVISION
DATE
APP.
PART DWG. NO.
REF. TOOL DWG. NO.
UNLESS OTHERWISE SHOWN
TOLERANCES:
.XX = ±.015
.XXX = ±.005
ANGLE ±15'
BREAK ALL SHARP EDGES
SMITH TOOL
Division of SMITH INTERNATIONAL, INC.
DET.
QTY.
DESCRIPTION
HORIZONTAL BORING SCHEME
MARK TOOL & DET. NO.
DO NOT SCALE PRINT
DATE
DRN
CKD
APP
MATERIAL
SHT. NO.
OF SHEETS
TOOL NO.

APPENDIX III

"Trajectory Reconstruction"

Dick Davisson

Trajectory Reconstruction

Dick Davisson
March 12, 1977

We treat here the special case of a single particle moving in a straight line through water and producing Cerenkov light. That light is detected by a single line of photodetectors. The problem is to deduce the parameters of the particle's path from the signals from the photodetectors.

In general, the path of the particle is skew relative to the line of detectors. That path can be characterized by several parameters. The first is b, a vector joining the two lines and perpendicular to both, from the detector to the track. The magnitude of b, i.e. b, measures the distance of closest approach of the particle to the line of detectors. The azimuthal direction is intrinsically unmeasurable from the data. Henceforth, we only discuss measurement of the magnitude, b.

The third parameter is the time at which the particle reaches the terminal end of b. We'll call that T.

Time, by the way, is to be measured in meters or whatever unit of length is chosen. The units of time are such that the vacuum velocity of light is one (the particle is presumed to move at the vacuum velocity of light).

We should note that not only the direction of b, but also the sign of Q is unmeasurable. Accordingly, the parameters we hope to determine are: b, h, cos Q, and T.

A separate class of parameters are required to complete the reconstruction process. Let's use k for the Cerenkov angle, n to designate the index of the individual photodetector and s to represent the spacing between detectors. We'll use L for the "average" attenuation length of the light in water.

Time Signals as Information Elements

Consider the plane surface which contains and moves with the particle and which is perpendicular to the path of the particle. Let us designate by t_{on} the time at which this plane reaches the n'th detector, and t_n the time when the Cerenkov light reaches it. Let us designate by r_n the perpendicular distance from the track to the n'th detector. We have at once $t_n = t_{on} + r_n \tan k$. That is the only place where k will impinge on our considerations.

The times t_{on} are given by:

$$t_{on} = T + (ns - h) \cos Q.$$

The distances satisfy:

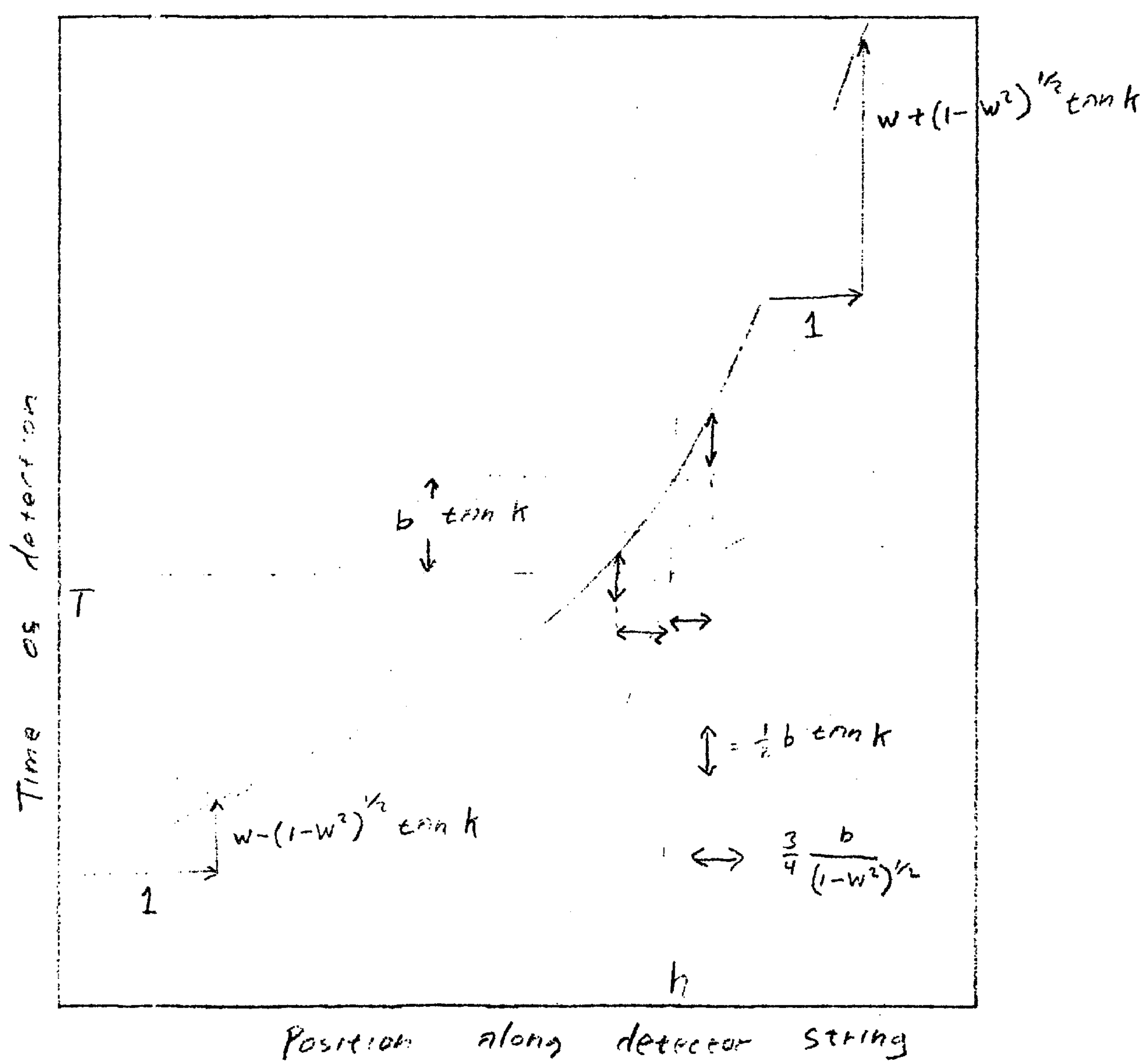
$$r_n^2 = b^2 + (ns - h)^2 \sin^2 Q.$$

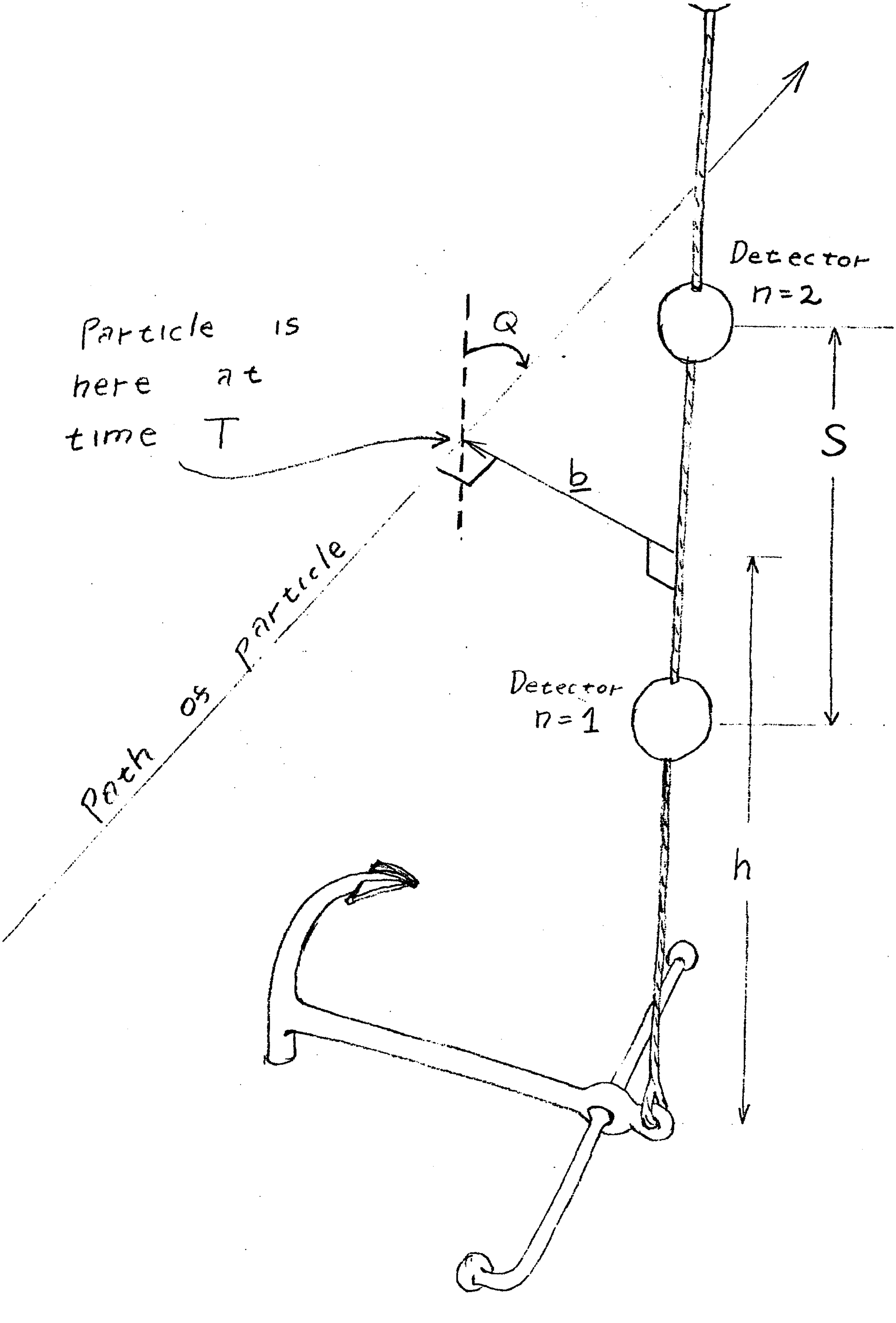
This gives us the general expression:

$$t_n = T + (ns - h)\, W + \left(\sqrt{b^2 \quad (ns - h)^2 \, (1 - W^2)}\right) \tan K.$$

Where $W = \cos Q$.

It is unrewarding to attempt to invert the equation for t_n. We can assume that the several parameters will be extracted through a least squares fit of the measured t_n to the given equation. Let us consider what t_n, considered as a function of ns, looks like. Clearly there are two assymptotic regions in which the b under the square root can be neglected. For $(1 - W^2)$ $(ns - h) - b$ we have $t_n = T + (ns - h)(W - (1 - W^2)$ $\tan k)$. For $(1 - W^2)$ $(ns - h) + b$ we have $t_n = T + (ns - h)(W + (1 - W^2)$ $\tan K)$. These two assymptotes meet at $t_n = T$; $ns = h$. The actual value of t_n at $ns - h = 0$ is $T + b \tan k$. The character of these relations is illustrated in the sketch below.




Detector
n=2
Q
Particle is
here at
time T
b
S
Path of particle
Detector
n=1
h

APPENDIX IV

"Johnson Sea Link Manned Submersible with Manipulator Capability"

Harbor Branch Foundation

JOHNSON-SEA-LINK I & II

Specifications*

DIMENSIONS

Overall

Length	22' - 10"
Beam	7' - 11"
Height	10' - 7"
Draft	7' - 6"
Gross Weight	23,000 lbs.

Pilot Sphere

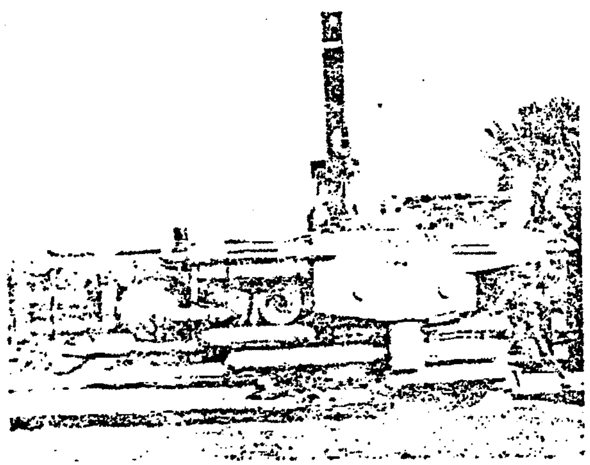
Outside Diameter	66"
Inside Diameter	58"
Thickness	4"
Internal Volume	59 cu. ft.
Hatch Clear Opening	18" diameter
Material	Acrylic Plexiglas Grade "G" Annealed

Diver Compartment

Length	8'
Outside Diameter	59½"
Internal Diameter	53"
Hatch Clear Opening	20" diameter
Material	Aluminum Alloy 5456
Internal Pressure	Test pressure 1,000 psi Operating pressure 670 psi

*Specifications apply to both submersibles, since they differ only in minor respects.

Side view of Johnson-Sea-Link



2

OPERATING CHARACTERISTICS

Depth

Operating Depth	1,000'
ABS Classification Depth	1,000'
Test Depth	2,000'
Crush Depth	6,000'

Speed

Cruise	3.4 knots
Maximum	1.2.4 knots

Life Support

Endurance	480 man-hours (20 man-days)
Carbon Dioxide Scrubbers	
Pilot Sphere	Harbor Branch Foundation
Diver Compartment	Lindbergh-Hammar
Emergency Breathing Masks	
Pilot Sphere	Two
Diver Compartment	Two
Metabolic Oxygen Bleed	
Oxygen Analyzer	
Pilot Sphere	One Analyzer, One Remote Meter from Diver Compartment
Diver Compartment	One Oxygen Monitor
Carbon Dioxide Monitors	
Pilot Sphere	One Carbon Dioxide Monitor, One Analyzer, One Remote Meter from Diver Compartment
Diver Compartment	One Monitor, One Analyzer

Emergency Life Support-Rebreathers

Pilot Sphere	Two
Diver Compartment	Two

Power

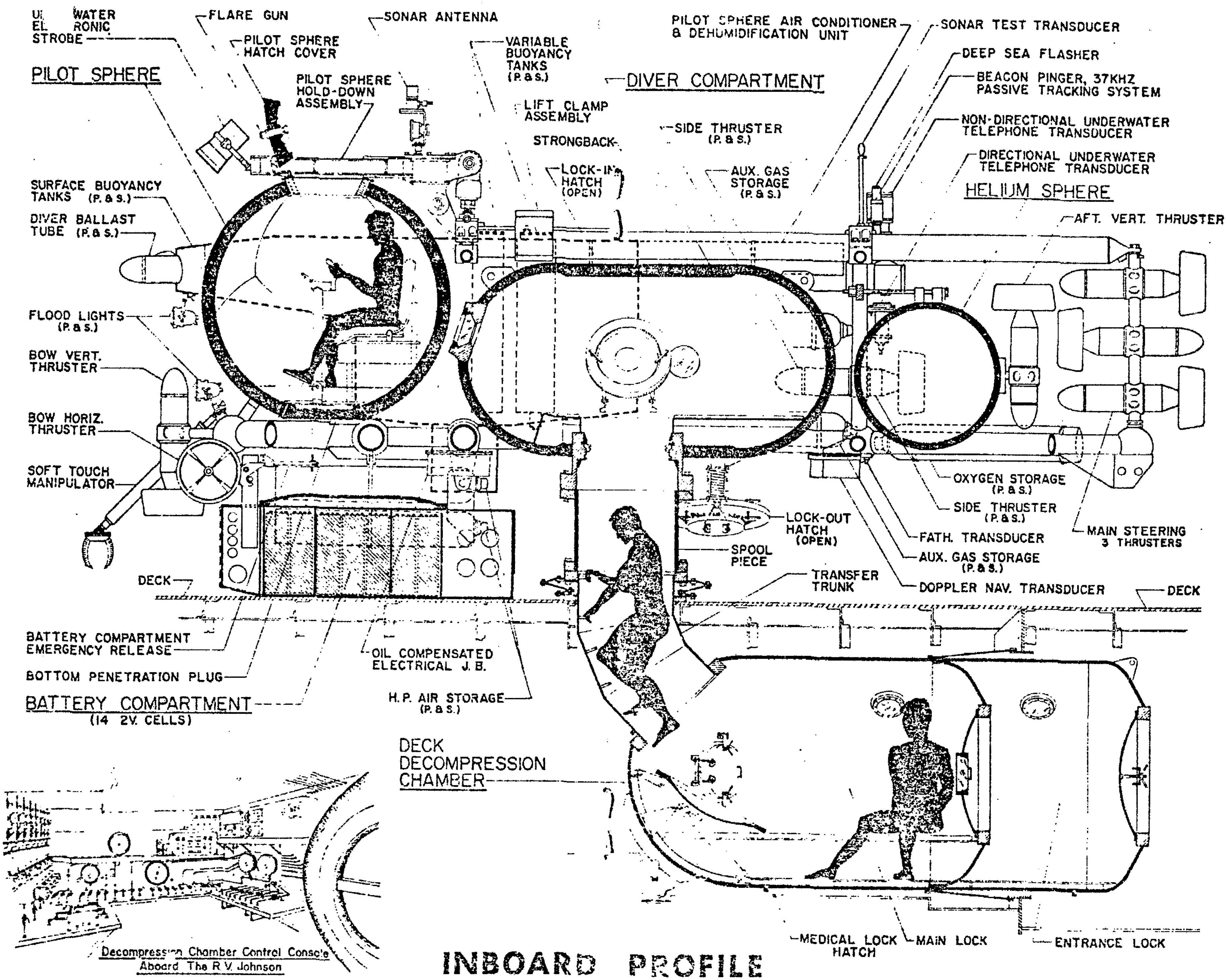
Oil Compensated Lead Acid Battery	32 KWH @ 28 VDC
Inverter	117 VAC @ 2.5 amps 60 HZ

Equipment on Board

- Six Function Manipulator
- Sonar
- Doppler Navigation
- Underwater Telephone
- VHF Transceiver
- Zenon Short Arc Light
- Flood and Spot Lights
- Emergency Location and Rescue Buoy
- Deep Sea Still, Movie and Video Camera Systems
- Video Tape Recorder
- Fail Safe Drop Lock Sub Release System
- Adjustable Equipment Arm
- Diver Self-Contained Rebreathing Apparatus

Optional Equipment

- Cable Cutter
- Line Cutter
- Rotenone Dispenser
- Sea Hook
- Corer



INBOARD PROFILE

JOHNSON - SEA - LINK I SUBMERSIBLE & DECK DECOMPRESSION CHAMBER

APPENDIX V

R/V Thomas G Thompson Information Booklet

U. of Washington

UNIVERSITY OF WASHINGTON

DEPARTMENT OF OCEANOGRAPHY

MARINE OPERATIONS

R/V THOMAS G. THOMPSON

SHIP INFORMATION BOOKLET

This booklet is issued to acquaint members of scientific parties with our research ship, THOMAS G. THOMPSON, and, for those making their 'first cruise' with us, our method of 'running the ship' and some traditional courtesies and cautions associated with living aboard ship.

The assistance of Dr. James C. Kelley in preparing this booklet is gratefully acknowledged.

We hope that you have a pleasant and rewarding cruise...............

A. C. Duxbury
Director of Operations

John B. Watkins, Jr.
Asst. Manager of Research Facilities, Services and Operations

CONTENTS

Introduction

The research vessel, THOMAS G. THOMPSON, Navy designation--AGOR 9, was built for the United States Navy by Marinette Marine Corporation, at Marinette, Wisconsin and delivered to the University of Washington at Boston, Massachusetts, September 21, 1965.

THOMAS G. THOMPSON is a single screw, diesel-electric ship, powered by two 697-horsepower diesel engines, each driving a 472 KW generator, which in turn furnish power to a double-armature 1150 shaft horsepower main motor, driving a single 5-bladed propeller. The main propulsion diesel generators may be used singly or in combination. A 175-horsepower bow propulsion unit which can be rotated through 360° is provided for maintaining position when 'on station'.

Primary ship's service electric power is supplied by two 300 KW AC diesel generators. A 150 KW AC-DC diesel generator can furnish limited ship's service power or power for the bow unit. A 150 KW AC-DC gas turbine generator can furnish limited power to the main propulsion motor or to the bow propulsion unit.

The main engines can be controlled either from the engine room or the bridge. The bow unit is controlled from the bridge. Bridge control can be exercised either from the pilot house or the starboard bridge wing.

Navigation and communication equipment include two radars, radio direction finder, loran, satellite navigation set, two fathometers, radio telegraph (CW), and voice radio, AM, FM and SSB, on all commonly used frequencies for these equipments. Radio communication is maintained by commercial methods through ITT/World Communications, Inc., supplemented when necessary through Scripps Radio Station WWD.

The ship maintains the highest hull and machinery classification of the American Bureau of Shipping, and meets United States Coast Guard requirements for inspected vessels. All persons in the crew are licensed or certificated by the United States Coast Guard.

SHIP'S OPERATING PERSONNEL

The ship's officers include the Master, three deck officers and three engineering officers.

At sea and in port the Master is in general command of the vessel. The activities of the deck crew are under the command of the Chief Mate. All engineering operations are under the command of the Chief Engineer. The deck crew normally consists of six seamen. The engine crew normally consists of three oilers, an electrician and a wiper. In addition, there is an Electronics Technician and Radio Operator who is a member of the scientific party. When required, one or two Marine Technicians are also assigned to the scientific party.

Finally, there are the members of the steward's department which normally consists of three persons--a Chief Steward, a cook and a mess attendant. These latter do much toward keeping both crew and scienfific party in good health and humor.

The head of the scientific party is the Chief Scientist who has final responsibility for the conduct of the cruise. He is responsible for the activities of the scientific party, but ultimate responsibility for the safety of the vessel and all persons on board rests with the Master. The Chief Scientist will appoint a Cruise Leader who is primarily responsible for logistics planning and coordinating the activities of the scientific party.

Requests by scientists for assistance from the ship's operating staff should be relayed through the Cruise Leader. All requests regarding the operation of the ship must be relayed to the Master through the Chief Scientist. Once cruise procedures are established by the Master and the Chief Scientist, scientists may communicate directly with the watch officer on the bridge regarding the execution of the plan, but all major modifications in the operating plan must be relayed to the Master through the Chief Scientist. Requests for assistance by the crew are made to the bridge watch officer.

SHIP'S SCIENTIFIC FACILITIES

Laboratory Facilities

THOMPSON has four laboratories: Laboratory 1, main deck, amidships, is used primarily for the computer system and date acquisition systems gear; laboratories 2 and 3 in the after section of the enclosed area of the main deck (laboratory 2 is starboard side and laboratory 3 is port side)[1,2] are devoted to wet chemical analyses, biological studies, geological studies, and hydrography. Laboratory 4 is a small laboratory aft of the navigation bridge. Space is usually available for scientific equipment on the 1st platform, Frames 72-79, but no water is available.

1. Seawater is continually pumped from a 3-meter-deep intake on the port side amidships to labs 2 and 3 through the PVC piping with outlets at each sink and on the starboard side of the fantail.

2. Sink drains, especially that in lab 2, have a tendency to clog and overflow the sink. Plumbing problems should be reported directly to the bridge watch officer.

Data Acquisition and Computing Equipment

Standard data acquisition equipment on the vessel includes sensors with readouts in lab 1 for ship's heading , ship's speed, and relative wind direction and speed. Data from these sensors can be digitized and recorded on paper tape by a Hewlett-Packard data acquisition system (DAS) in lab 1. This system can also record data from sea surface temperature and salinity sensors in a sea chest in the engine room. In addition the system can acquire and record other sensor outputs as voltage (AC or DC), frequency, or resistance, up to a total of 25 sensor outputs. A Bissett-Berman STD system is also part of the ship's equipment and data from the STD is acquired and recorded by the DAS.

The DAS output can be analyzed on-line or off-line by the shipboard computing system, also located in lab 1. The system consists of an IBM 1130 computer, with card reader/punch, printer, paper-tape reader, 30" calcomp plotter, dual transport 7-track magnetic tape and two cartridge disk drives.

Bottom Sounding and Profiling Equipment

Four 12 KHz transducers are permanently installed with cabling to CSI for depth recording. A 3.5 KHz transducer is installed in the aft transducer tube with cabling to CSI for subbottom profiling. Depth and profiling recorders can be provided in lab 2. A Ross Fine-Line 200 KHz transducer is also installed in lab 2. Portable transducers can be rigged in either of two transducer tubes.

Deck Facilities

THOMPSON carries 3 major winches: #1, starboard side on the upper deck is a hydrographic winch with 10,000 meters of either stainless steel or galvanized hydrographic wire and is normally used for bottle casts; #2, port side on the upper deck, which carries 2400 meters of Amergraph cable and is normally used for STD work; #3, an intermediate winch with interchangeable drums; one which carries 5,000 meters of 17,000-pound test Amergraph cable for special trawling work, and the other which carries 30,000 feet of 1/2" wire for coring and dredging.

Wire for winch #3 is led over a metering wheel on the A-frame at the after end of the fantail. Wire from winch #1 is led over a metering block on a short boom extending outboard on the starboard side forward of the hydro cage. #2 winch fairleads to STD boom, port side. This boom is swung out and in by hydraulic controls on the after port bulkhead of the deck house. In addition, there is an articulating crane on the after starboard corner of the boat deck which is used primarily for onloading and off-loading gear. All winches and the crane are manned by seamen and requests for winch operators should be directed to the officer on the bridge.

Other Scientific Facilities

Scientific office: A scientific office is located on the port side at the after end of the main passage.

SHIP'S LIVING FACILITIES

Staterooms. Staterooms normally berth 2 scientists in bunk berths. Berthing assignments are available from the Cruise Leader. Staterooms include lockers, a washbasin, and a desk. A few also include heads and showers. Linen (towels and sheets) are provided clean weekly according to a schedule normally posted in the galley. Scientists are responsible for maintaining their quarters in a clean and orderly condition and leaving them so upon completion of the cruise. Plans of berthing and messing spaces are attached.

Heads and Showers. Communal heads and showers are for the use of both scientists and ship's operating crew and are cleaned daily by a deck crewman, but all members of the scientific party should try to help maintain these facilities in a clean and orderly condition. It is normal etiquette to leave a head door fastened ajar when not in use. Soap is available. It is recommended that scientists bring their own washcloths and towels.

Galley. The messing facilities aboard the THOMPSON are small and all of the ship's company messes together. Meals are served cafeteria style. Observance of a few rules on the mess deck will save everyone a great deal of inconvenience and strained relations.

Meal hours are posted on the crew's mess bulletin board. They should be observed rigidly. The ending time of a meal indicates the time one should expect to finish eating - not the last time should appear in the mess line. Usually space limitations require that the crew and scientific party mess in two sittings. The ship's crew messes at the table next to the galley. Officers and scientists mess separately in the mess room port side. The forward table is reserved for the ship's officers and the after table for scientists. Scientists may sit at the forward table if there is space available but should ask permission of the officers at the table.

Scientists may mess with the crew, if all crewmen waiting to eat can be seated, but don't overload the table with scientists - 2 or 3 are the maximum under most circumstances. This part of the mess deck is the only place on the ship where the crew can gather when off watch and relax. Be considerate and don't monopolize the area.

Library. A ship's library is located on the boat deck for the use of all persons on board. Some books are available for the use of the party, but please return them when you are finished. It is a good idea to bring your own reading material.

Laundry. A ship's laundry with a washer and dryer is located on the port side of the passageway forward of the galley. A schedule for the use of the laundry will be available from the Cruise Leader. Please follow washing and drying instructions posted in the laundry.

Movies. On most cruises movies are shown, usually with the same movies on two successive nights, first night at 1800 and next night at 2000 so that all watch standers may enjoy all the movie programs. These shows are for all hands so try not to monopolize the limited seating available.

Potable Water Supply. The potable water on the ship is produced by sea water evaporators which use the waste heat from the ship's propulsion engines. Therefore, water is produced rapidly when both engines are in use, at a satisfactory rate when one engine is in use, at a very low rate when the ship is holding station with one engine idling, or if immersion heaters must be used, and not at all when the ship is in port. In any case, there is never an overabundance of potable water and all members of the party are asked to make an effort to conserve water. This can be done by using water sparingly when showering and by laundering only when necessary and only full loads. The laundry is secured when the ship is in port, and showers will be secured if necessary, so members of the party should do their final laundering at least 12 hours before the ship reaches port. Water notices are posted on the bulletin board in the crew's mess.

Sunbathing. On warm weather cruises, scientists are asked to bring their own mats or cots if they wish to sunbathe. Ship's blankets, towels or linen are not to be used for this purpose.

GENERAL COMMENTS

Bridge Etiquette. Many scientists enjoy visiting the bridge, but the frequency of these visits often gets out of hand. First, recognize that even though you may be off watch, the bridge officer is on watch and is responsible for the safety of the entire ship when he is on the bridge. Recognize too, that it may be uncomfortable for him to have to order you off the bridge. So use your judgment and be considerate. Stay completely off the bridge and bridge wings when the ship is maneuvering in potentially dangerous situations, such as entering and leaving port, operating in heavy traffic or even light traffic at night, operating in fog, etc. It is courteous and traditional to ask the permission of the officer on watch to visit the bridge. Again, use judgment. The officer is responsible for navigation of the vessel and is not free to engage in lengthy conversation, even if he, or the seamen, are a captive audience. Don't monopolize the binoculars or stand in the doorways, and don't change the adjustments of any equipment on the bridge or in the pilot house or chart house. Don't be a 'button pusher'.

Safety. If you are injured at sea, you may have to wait a considerable period to see a doctor. If you fall overboard during the day with a deck full of people watching, you may be recovered. If you fall overboard at night, we may find out you are missing about dinnertime the following day. Use your head and remember that you are in a very big ocean. Don't sit on the rail, don't tempt fate, and don't wander alone on the deck at night.

Weather and schedule permitting, 'swim calls' may be authorized by the Master. Only swim with the permission of the Chief Scientist and then stay near the ship.

When heavy equipment is being handled on the deck, try to stay well out of the way unless you are involved in the work, and then don't get under the load.

Tax-free Cigarettes. These are available during foreign cruises. The variety of brands is limited, however most popular types are carried.

Money. Personal checks can be cashed by the Master at announced times, usually a day or two before a port call. Checks should be made payable to the University of Washington. A $4.00 fee is charged for checks returned by your bank.

Customs, Immigration and Health. Shortly before arrival in port, you will be asked to submit your passport, International Immunization Certificate, and other documents in connection with port entry and clearance. Entry to a U.S. port will entail filling out a customs declaration which will be provided you.

The Master will also need some personal information to prepare the crew list. This is set forth in a standard form which you will be asked to fill out.

Some Personal "Do's and Don'ts". Keep clothing and personal gear in your own quarters--not scattered about the ship.

If living quarters are shared, keep gear neatly stowed in such manner as to afford the least possible annoyance and inconvenience to your room-mate.

Maintain your own quarters in a neat and clean condition. Keep the decks, bulkheads, washbasins, mirrors, etc. clean. No steward service is provided. Upon vacating your quarters at the end of the cruise, be sure that the bunks are stripped and all soiled linen taken to the laundry room.

Enter no personal quarters without first obtaining permission of the occupant.

Check bulletin board for notices.

Leave no food lying exposed in quarters which might attract rats or vermin. In the event traces of rats or vermin are found, please report same to the Master.

Shore Leave. Shore leave may be granted at all ports of call subject to the safety and general welfare of the ship and personnel, and local harbor regulations. Shore leave is under the general direction and control of the Master. Scientific party personnel desiring to go ashore should request permission from the Chief Scientist or the Cruise Leader.

Excessive Noise. Avoid excessive noise, boisterous talk or loud radios. It will be appreciated by your shipmates who may be trying to rest. This applies particularly to the messing area just outside the galley. Noise emanating from this space is quite audible in the Chief Scientist's and Master's staterooms and in the berthing spaces immediately below. In general, people trying to rest are not interested in listening to your adventures ashore during the middle of the night.

Seasickness. In the event of imminent motion-sickness, use the lee rail (the side of the ship away from the wind), or use the nearest head or bucket which is provided for that purpose. Anti-motion-sickness tablets are provided. In the event your 'estimated time of arrival' is in error, it will be appreciated if you will make a tidy disposal of your previous meal.

Head and Washrooms. Those of you not assigned a stateroom with private head should assist the crew in maintaining a clean, sanitary and pleasant condition of the heads you use. These are cleaned daily, usually during the forenoon watch. Avoid using the deck and installed utilities as general receptacles for paper towels, toilet tissues, cigarettes, matches, etc.

Fire and Boat Drill. Fire and boat drills are held weekly. Be familiar with your assignment for these drills so that you will be prepared, in case of an actual emergency, to participate properly in controlling the emergency.

Each lifeboat is capable of carrying all persons on board. In addition we have inflatable liferafts, individual life jackets, life rings, etc. You should be familiar with the location of life rings and other equipment so that they may be properly and timely used if necessary. Do not use life jackets for pillows.

Visitors. General visiting is not usually permitted except as previously authorized by the Master and Chief Scientist. Personal guests are permitted on board during normal working hours, 0800 to 1630, with the permission of the deck watch officer. Visitors may be permitted on board as late as 2300 when specifically authorized by the Master or, in his absence, senior deck officer. If you are inviting friends or guests aboard for a meal, you should let the Chief Steward know ahead of time.

Firearms, Ammunition and Explosives. These must not be brought aboard except with the permission of the Master before sailing. There is no suitable place to stow firearms on the ship. They are usually not needed during the cruise and cannot be landed in foreign ports. In the event firearms are carried on board, they are not to be fired without permission of the Chief Scientist and the Master.

Watertight Doors. You will find the ship is fitted with heavy, steel water-tight doors in certain bulkheads. The function of these doors is to provide a strong watertight boundary in certain portions of the ship, particularly below the main deck. Watertight doors below the main deck are to be closed at all times when not in use. Other doors in watertight bulkheads and weather doors, that is those leading outdoors, should be closed after you have completed your entry or egress. The purpose of this is to maintain the ship's air conditioning boundary and to keep insects out of the ship as well as rain. These doors are heavy and when the ship is rolling or pitching great care must be exercised in opening them and closing them. Be careful not to put your hand around the edge of the door because if the ship should take a sudden roll, you may have a badly injured hand. When closing these doors, do so gently but firmly, and avoid slamming them as it disturbs people who are resting or sleeping while off watch. All doors should be dogged closed or, if they are to be left open, they must be secured by the retaining or 'stand-off' hook.

Stowage of Equipment and Stores. All scientific equipment must be securely installed to avoid damage caused by ship motion. All gear and stores must be securely stored for the same reason. Just prior to or immediately after leaving port and certainly before proceeding to the open sea, securing of all equipment and the stowage of gear and stores is checked by the Chief Mate and if in his opinion it is not sufficiently secured, you will be asked to do so. This is especially true when station work is completed and when you are through working in the laboratory. The sea can make up with a dismaying rapidity--particularly during the night--and gear and equipment not properly secured will be damaged or lost.

Cleanliness of the Laboratories. This is the responsibility of the scientific party and this task will be made easier if each person will insure that he does not contribute to the untidiness of these laboratories. Of particular importance is avoiding debris accumulation on deck, particularly filter papers. The deck drains are not sized to handle such material with the result that the drain scuppers become plugged and water sloshes back and forth over the laboratory deck. In many cases, once scientific equipment has been installed in the laboratories, the deck drains are not readily available for cleaning out. The laboratories are to be thoroughly cleaned up at the end of each cruise. This task is considered part of the offloading routine.

Ship's Tools and Stores. These are available to scientific parties when needed, and may be obtained by contacting either the deck watch officer or the engineering officer on the watch. Be sure to return them as they may be needed.

Electrical Precautions. Do not use light fixtures or electric cabling for coat hangers or for securing gear. The use of portable electric leads and portable electric tools cannot be avoided, but extreme care must be exercised in their use to avoid a lethal shock. Do not forget the ship is an absolute 'zero' ground and unless you take particular care in the use of portable electric leads and portable electric tools, you run a serious risk of electric shock. The ship's electrician is available to assist you in rigging portable leads and in checking over any portable electric equipment which you may need to use.

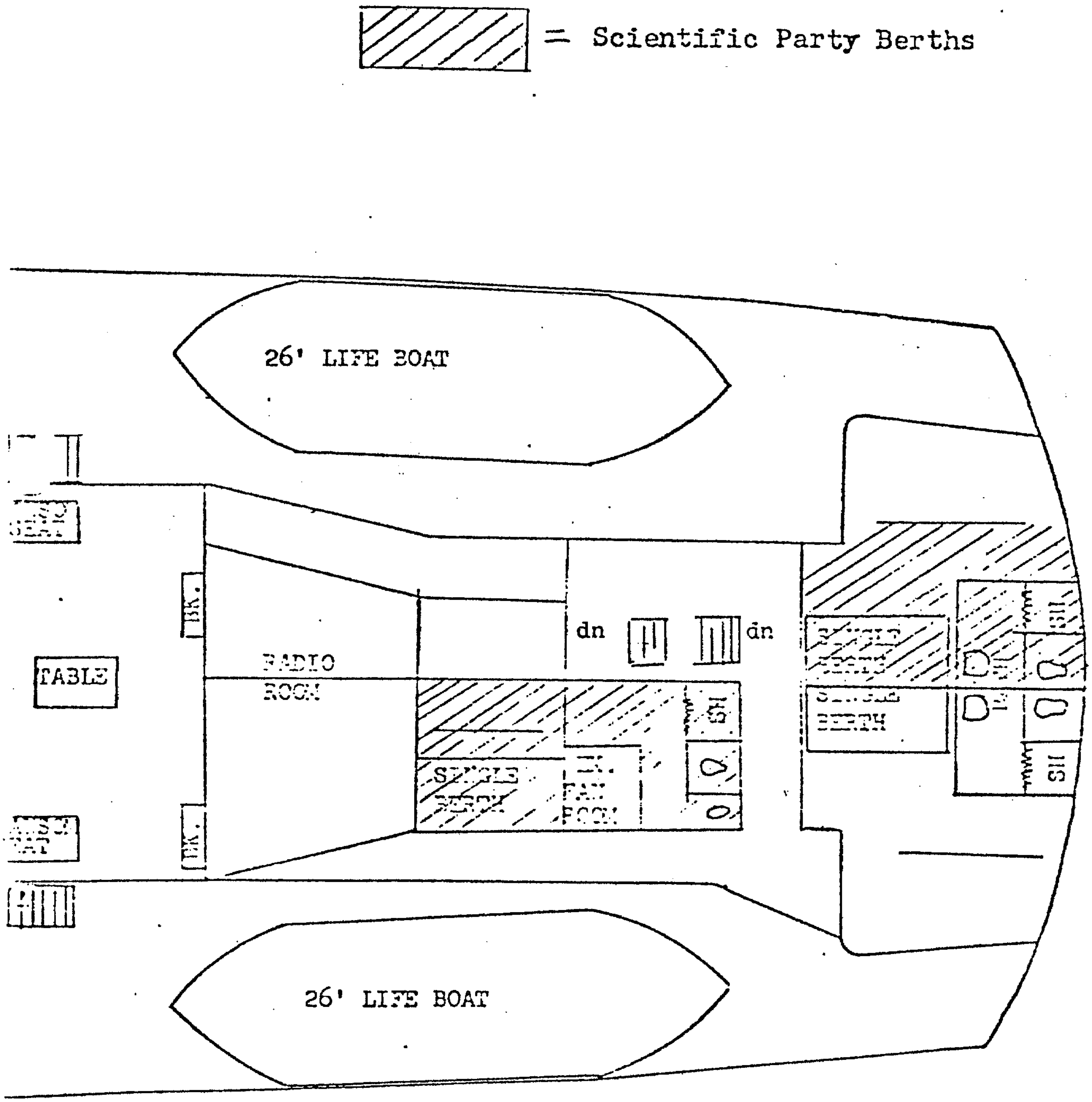
Station Work. During routine station work, such as bottle casts, STD, etc., the winch operator is directed by a member of the Scientific Party. Before starting such work, check your communications, and if you must rely on hand signals, be sure that the winch operator will understand them. Only one person should give directions to the winch operator to avoid confusion and the attendant risk of losing gear. These same precautions apply to coring and dredging operations. Heavy lifts over the side are generally under the direction of the Chief Mate--this applies particularly to instrumented buoys, drogues, etc. This is generally determined ahead of time between the Chief Scientist and the Master. During such operations only one person is to give orders to the winch operator and to direct personnel assisting. This is usually the mate. Keep in mind that the winch operator can only watch one person for hand signals.

When wires are in the water, they must be watched constantly and the bridge kept informed of the direction they lead and the wire angle. Direction is reported by the 'clock dial' method: dead ahead is 12 o'clock, dead astern, 6 o'clock, abeam to starboard, 3 o'clock, etc. Wire angle is reported in degrees from the vertical, e.g. "2 o'clock, 10°". The watch officer on the bridge cannot see any of the wires except that from the starboard hydrographic winch, and his view of this wire is limited.

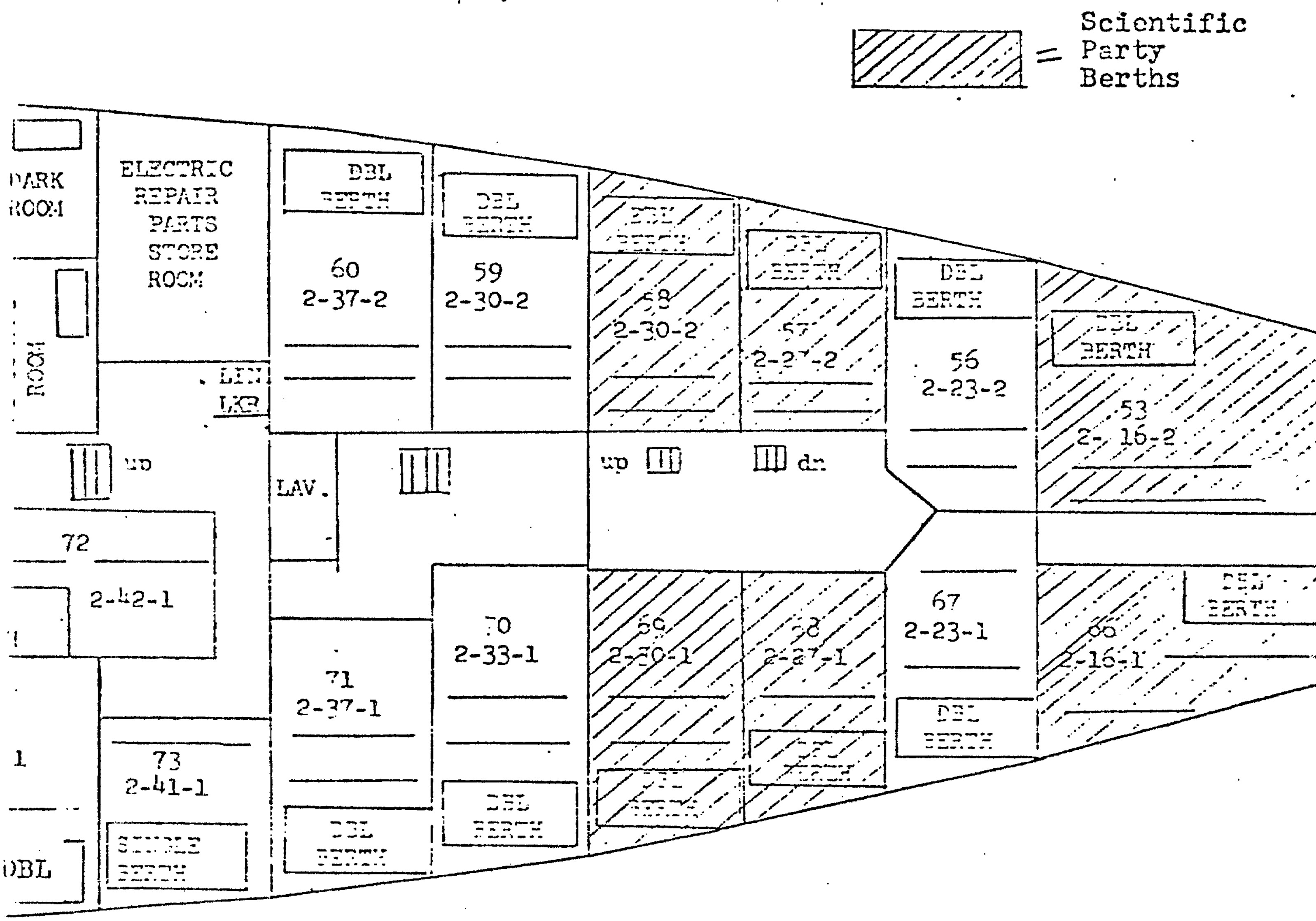
Most of the sampling devices and instruments are not only very expensive, but are critical to the research being done. Their loss is thus not only costly from a replacement standpoint, but could result in curtailment of the work or an aborted cruise.

During lowering and retrieving--that is, when the winch is in actual operation, the wire must never be left untended. The winch operator cannot see the wire and total reliance cannot be placed on dial readings. Winch operators are to stop the winch whenever the wire is left untended while lowering or retrieving. Make sure your special instructions such as lowering speed or repreiving speed, depth not to be exceeded, and line tension desired is given to and understood by the winch operator on each lowering.

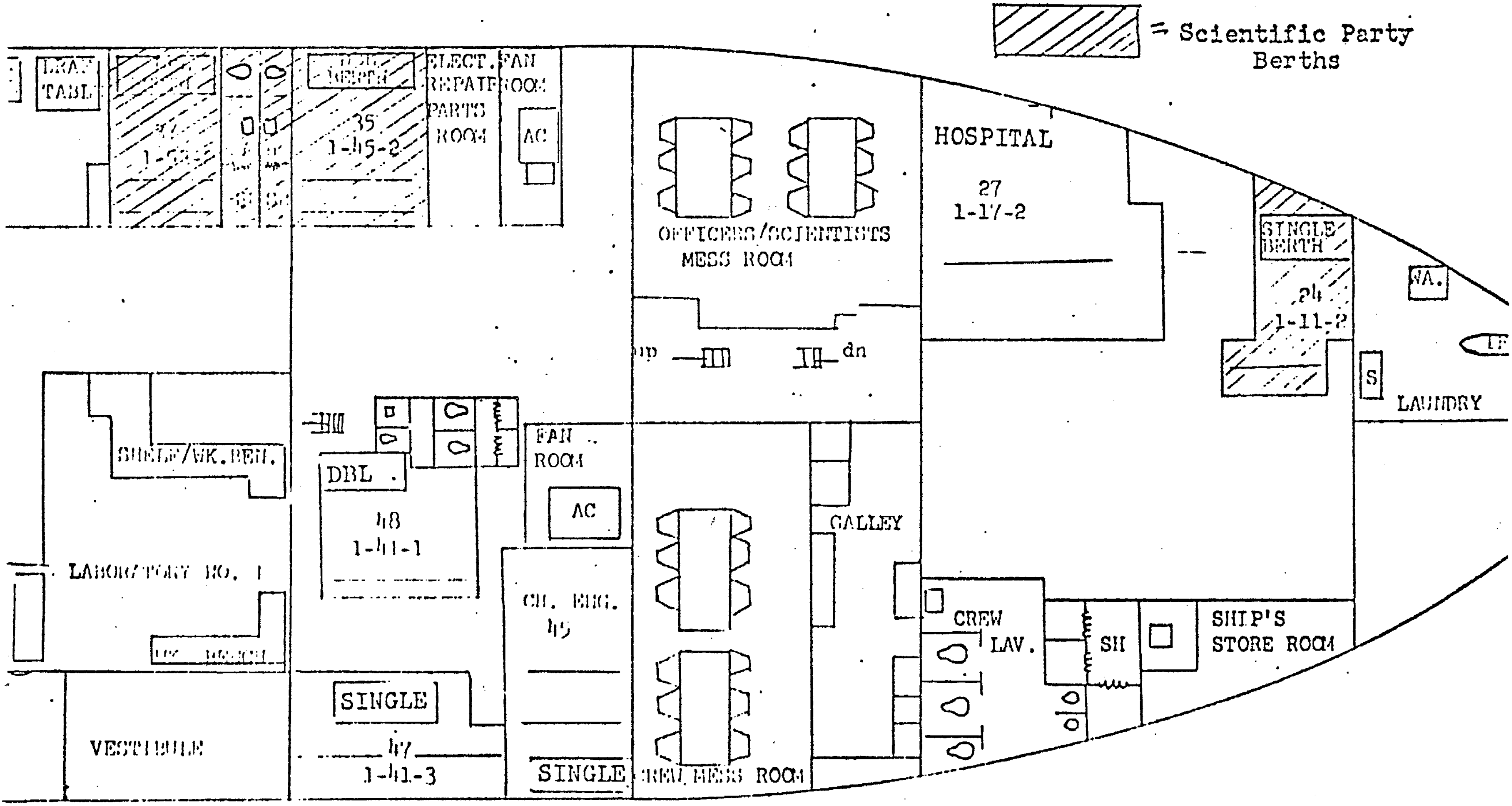
SLEEPING QUARTERS ON 01 LEVEL



SLEEPING QUARTERS ON FIRST PLATFORM



SLEEPING QUARTERS ON MAIN DECK



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Department of Oceanography
Cable Address: UNWADO

R/V THOMAS G. THOMPSON
Scientist's Personnel Data

Date ____________

Name in Full ____________

Permanent Home Address ____________

____

Next of Kin: Name ____________

Relationship ____________

Address ____________

Nationality ____________ Soc. Sec. No. ____________

Passport No. ____________ Date last physical exam ____________

Issued by ____________ Date of birth ____________

Expiration date ____________ Birthplace ____________

Visas ____________ Intl. Immun. Record Date

____________ Smallpox ____________

Tourist Cards (No.) (Country) ____________ Tetanus ____________

____________ Yellow Fever ____________

____________ Cholera ____________

____________ Blood Type ____________

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Signature in full.