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STATUS AND AIMS OF THE DUMAND NEUTRINO PROJECT. THE OCEAN AS A NEUTRINO DETECTOR

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SUMMARY

We consider the possibility of using the ocean as a neutrino detector; neutrino-produced interactions result in charged particles that generate Cerenkov radiation in the water, which can be detected by light-gathering equipment and photomultipliers. The properties of the ocean as seen from this standpoint are critically examined, and the advantages and disadvantages pointed out. Possible uses for such a neutrino detector include 1) the detection of neutrinos emitted in gravitational collapse of stars (supernova production), not only in our own galaxy, but in other galaxies up to perhaps twenty-million light-years away, 2) the extension of high-energy neutrino physics, as currently practiced up to 200 GeV at high-energy accelerators, to energies up to 50 times higher, using neutrinos generated in the atmosphere by cosmic rays, and 3) the possible detection of neutrinos produced by cosmic-ray interactions outside the earth's atmosphere. The technology for such an undertaking seems to be within reach.

A. INTRODUCTION

Ever since Reines and Cowan first detected the neutrino emitted in beta-decay,[1] neutrino detection has proved to be a valuable and important technique in particle physics.

The detection of particles via the weak interaction is experimentally difficult. In a relatively favorable case, that of absorption of an electron antineutrino ($\bar{\nu}_e$) by a proton, with a threshold at 1.8 MeV, the cross-section is only 2.4×10^{-43} cm^2 for a 3 MeV $\bar{\nu}_e$. Thus the mean free path for such a low energy neutrino is about 100 light-years in liquid hydrogen. The detection and study of such neutrinos require a combination of high fluxes and very large detectors. Antineutrino fluxes of 2×10^{13} cm^{-2} sec^{-1} have been achieved at reactors. The nearest star, our sun, produces a ν_e flux at the earth estimated as 6×10^{10} cm^{-2} sec^{-1}, equivalent to 25 watts per m^2. R. Davis and his collaborators at the Brookhaven National Laboratory have been searching for solar neutrinos with a 100,000-gallon perchlorethylene detector at a gold-mine in Homestake, S.D. for many years, so far without success. Their absence is proving to be somewhat embarassing to theoretical astrophysicists.[2]

The detection mechanism is the reaction

$$\nu_e + {}_{17}Cl^{37} \rightarrow {}_{18}Ar^{37} + e^-$$

The radioactive Ar^{37} is collected and counted. A deep underground site is necessary to avoid the production of the same end-product by (p,n) reactions induced by cosmic-ray muons.

Cosmic rays interacting in the earth's atmosphere produce mesons (pions and kaons) which decay into muons and neutrinos. These neutrinos have been observed in a South African gold-mine by a collaborative group from the University of California (Irvine), Case-Western Reserve University and the University of the Witwatersrand.[3] The results were corroborated by an Indian-Japanese-British group working in the Kolar gold fields of India.[4]

DUMAND - Project DUMAND, which is an acronym standing for Deep Underwater Muon And Neutrino Detector, is intended as a further step in the direction of establishing experimental neutrino astronomy. Still in the formative stage, DUMAND is the outgrowth of informal conversations in the last few years among a number of cosmic-ray physicists interested in muon and neutrino detection. At first the idea of a large underwater Cerenkov detector, in which the light produced by fast charged particles in the ocean produces electrical pulses from photomultiplier tubes, arose in connection with the problem of determining the muon depth-intensity curve in a well-specified medium. Depending on the confidence with which one believed either the spectrum or the energy-loss mechanism, the measured curve relating the two could be used to deduce one or the other.

Having thus imagined an underwater detector it was natural to consider using it for neutrino detection. Three ways of using such a detector have so far been suggested: 1) the detection of neutrinos, from gravitational stellar collapse (GSC), of energy somewhere between 10 and 100 MeV (the energy is not well-known), not only from our own galaxy[5] but from other galaxies up to perhaps 2 x 10^7 light-years distant, 2) the detection and study of the high-energy tail of the neutrino spectrum (above 1 TeV) produced in the atmosphere by the interaction of cosmic rays; and 3) the detection of very high energy neutrinos produced by collisions of cosmic rays with protons and photons in interstellar and intergalactic space.

The feasibility of achieving one or more of these exciting goals has yet to be demonstrated; the DUMAND program is designed to identify, and if possible, solve the manifold problems associated with such a demonstration.

For the sake of ready reference, we have assigned acronyms to these three experiments as follows:

1) UNDINE - UNderwater Detection of Intergalactic Neutrino Emission.
2) ATHENE - ATmospheric High-Energy Neutrino Experiment.
3) UNICORN - UNderwater Interstellar COsmic-Ray Neutrinos.

B. UNDINE:

THE DETECTION OF GRAVITATIONAL STELLAR COLLAPSE

I. Neutrino Detection Mechanisms

The detection of a low-energy (10-100 MeV) neutrino flux must proceed either through the scattering or absorption of neutrinos, with the detection of a charged secondary particle. The best reaction, for which the cross-section increases as E^2 in the energy region concerned, is the conversion of $\bar{\nu}_e$ to e^+ and ν_e to e^-, (the inverse of electron capture) according to the usual charged-current weak interaction:

$$\bar{\nu}_e + p \rightarrow n + e^+ \quad . \tag{1a}$$

and

$$\nu_e + n \rightarrow p + e^- \tag{1b}$$

These reactions can occur with bound nucleons as well as free ones; but in that case they may be inhibited by the lack of available phase space for the product particles. Thus a tightly bound nucleus, such as the abundant oxygen isotope in water, O^{16}, is a particularly unfavorable target. The cross-section is extremely low until the energy is well above threshold; in the case of O^{16} it does not approach the free nucleon cross-section until above 50 MeV.[6]

The coherent scattering reaction

$$\nu_e + (Z,A) \rightarrow (Z,A) + \nu_e \tag{2}$$

whose cross-section is large for high A, and which proceeds via the neutral current interaction,[7] is important in stars because it enables neutrino momentum to be efficiently transferred to the target nucleus.[8] However, a momentum of, say, 20 MeV/c in a heavy nucleus corresponds to a kinetic energy in the keV range or less, and is worthless in a Cerenkov detector.

Thus we see that electron neutrinos, ν_e, in the energy range below, say, 30-50 MeV can be detected in water only through scattering by electrons,[9] for which the cross-section is small: $\sigma \sim 10^{-43}$ cm^2. Antineutrinos, on the other hand, are absorbed on protons, according to Eq. 1a. The hydrogen in the water is thus the effective detecting medium for $\bar{\nu}_e$ up to 50 MeV or so; above this the O^{16} begins to contribute.

For muon neutrinos and antineutrinos, the charged-current interaction cannot contribute until the neutrino energy passes the threshold for muon production, 105 MeV. Below that only the scattering due to the purely leptonic interaction is effective. Though the cross-section is much smaller than the inverse-capture reaction, this may be more than compensated by the larger number of electrons than free protons (10 rather than 2 per molecule of water) and the larger flux of ν_e, ν_μ, and $\bar{\nu}_\mu$ which may be produced in GSC.[10]

For simplicity, we will consider only the signal from $\bar{\nu}_e$ above 2 MeV, via the reaction 1a, which yields a fast positron capable of producing Cerenkov light. A 20 MeV positron will have a range of about 12 cm in water, and will produce about 6000 quanta between 250 and 600 nm.

We inquire next as to the flux and energy of the neutrinos to be expected from gravitational stellar collapse (GSC).

II. Neutrino Emission from Gravitationally Collapsing Stars (Including Supernovae)

Gravitational collapse (see Fig. 1) occurs when a massive star, of mass above the so-called Chandrasekhar limit (1.2 solar masses) runs out of nuclear fuel. The internal electron degeneracy pressure is then insufficient to restrain the gravitational force, and a collapse ensues.

Current pictures of GSC[10] envision the process as occurring in two stages, involving different neutrino production mechanisms and luminosities; in addition there are numerous variations due to differing initial composition and mass. The main features are constant however, since they refer to the innermost core.

When the collapsing star reaches a density of about 2×10^{11}g cm^{-3}, electron capture by protons from the Fermi sea of degenerate electrons, which is now filled to about 25 MeV, gives rise to a burst of about 10^{52} ergs, comprising 10^{57} electron neutrinos of mean energy about 10 MeV. This "neutronization" process, in which all the nucleons are converted to neutrons, ($e^- + p \rightarrow n + \nu_e$) lasts at most a few hundredths of a second. The mean free path of the neutrinos is comparable to the stellar radius, and the emitted neutrinos undergo elastic coherent scattering from the heavy nuclei in the stellar mantle, via the neutral current interaction. This may perhaps be the long-sought mechanism whereby momentum is transferred to the outer layers of the star, producing in at least some cases the spectacular supernova explosion, like that responsible for the expanding envelope surrounding the Crab supernova of 1054 A.D. However, it is not known whether all gravitational collapse is accompanied by visible supernova explosion; current evidence seems to be against it.

Following the initial neutronization, the gravitational collapse accelerates. Within a few milliseconds the star collapses to essentially nuclear density, near 10^{14}g cm^{-3}, ending either as a neutron star or a black hole. At the end of the collapse, the temperature becomes very high (10^{10} K or higher), and about 10^{53} ergs, ten times as much as in the first stage, is liberated as neutrinos, formed by thermal processes. Thus the emitted neutrinos are produced in pairs, of antineutrino and neutrino, of electron and muon type; and the mean energy is initially probably higher than in the first stage (though depending critically on the temperature at formation.) The initiation of neutrino production may be accompanied by core "bounce" in which the sudden hardening of the core at nuclear densities results in the incoming material bouncing back, perhaps several times, until finally damped. Figure 2, kindly provided to us by Dr. James E. Wilson,[10] shows a recent calculation of the progress of the collapse.

There is unfortunately no agreement among theoretical astrophysicists as yet, concerning the spectrum and luminosity of the second neutrino burst. For one thing, in the collapsed state the neutrino mean free path is now much shorter than the stellar radius, and the neutrinos may lose much energy before leaking out; the walls are always thin at low energies because of the behavior of the cross-section with energy.

Figure 3 shows a set of neutrino spectra in the later stages of collapse. Figure 4 shows the $\bar{\nu}_e$ spectrum, and also the same spectrum weighted by E^2 to give a plot of the number of events seen vs. energy.

III. DUMAND and GSC

If one calculates the efficiency for detecting 10 MeV antineutrinos, one sees immediately that very large targets are necessary. The detection efficiency is proportional to the flux F (neutrinos cm^{-2}) in the GSC pulse, the proton detector mass M_p and the antineutrino cross-section σ, which for free nucleons and energies above 6 MeV or so is[11]

$$\sigma = 7. \times 10^{-44} E^2 \text{ cm}^2 \qquad (3)$$

with E in MeV. The resulting average number of antineutrino interactions, $\bar{N}$, is given by

$$\begin{aligned}\bar{N} &= 6. \times 10^{29} F \sigma M_p \\ &= 4.2 \times 10^{-14} M_p F E^2\end{aligned}$$

where M_p is the proton detector mass in metric tons. If we take $\bar{N} = 14$, then the Poisson distribution statistics tell us that the probability of seeing an event with 10 or more interactions is 0.89. Assuming that 10 interactions provide adequate identification, the required detector size for $\bar{N} = 14$ will be given by

$$MFE^2 = 3.3 \times 10^{14} \tag{4}$$

Expected Neutrino Fluxes - For a representative GSC, let us take the total energy radiated as electron antineutrinos to be 0.4×10^{53} ergs. The root mean square energy of the spectrum, from Fig. 4, is about 20 MeV; from this we calculate that the flux of $\bar{\nu}_e$ at a distance of 2×10^7 light-years is 2.5×10^5 cm^{-2}. Thus $FE^2 = 1.0 \times 10^8$, corresponding to a required proton detector of 3.3×10^6 tons. Since only the hydrogen is effective below about 50 MeV, the required mass of water is nine times greater or 3.0×10^7 tons (see Table I).

The flux of the other kinds of neutrinos may be much greater; up to nearly 100 times higher, according to Fig. 2. The scattering cross-section of these neutrinos on electrons is in the region of 10^{-43} cm^2, while the antineutrino cross-section on protons, from Eq. 3, is 2.8×10^{-41} cm^2 for 20-MeV antineutrinos. Since there are ten electrons per water molecule and only two protons, the target is effectively five times denser. Thus there seems to be a possibility that there may be appreciable contributions to the detection probability from electron scattering of the abundant neutrinos: ν_μ, $\bar{\nu}_\mu$ and ν_e.

TABLE I.

Mass of Water Required to See 10 Interactions, Per GSC Event, with 89% Efficiency, with Flux FE^2

FE^2 (cm^{-2} MeV^2)	M (metric tons)
10^4	3.0×10^{11}
10^6	3.0×10^9
10^8	3.0×10^7

Detection of Antimatter Galaxies or Stars - As we have noted, the two stages of neutrino emission are distinguished both by the type of neutrinos emitted and by their time, and perhaps energy, distribution. In stellar collapse in ordinary matter, the second stage electron antineutrinos are the primary signal source. However, should any GSC or supernova within the 20-million light-year range of the detector consist of antimatter, then the first stage emission, due to antineutronization - i.e., positron capture by antiprotons - would consist of antineutrinos rather than neutrinos, and both stages of the collapse would be detectable. Provided the two stages can be distinguished by different time and/or energy distributions, our detector thus provides a method in principle of searching for antimatter in neighboring galaxies (as well as our own). The method is unique in that it relies on the detection of distinguishable neutral particles.

If we take Fig. 2 as a guide in examining the possibility of distinguishing antistellar collapse from stellar collapse, we note that the initial neutronization burst is quite intense compared to the later thermal antineutrino emission. Possibly the energy spectra of the two detection mechanisms will allow a distinction. In the case of the antineutrino, all the energy appears in the positron and the cross-section is weighted by the square of the neutrino energy. In the neutrino-electron scattering, only half the neutrino energy is imparted to the electron on the average, and the cross-section increases only as the neutrino energy. Thus a stellar collapse shows an initial phase of neutrino-electron scattering on which later $\bar{\nu}_e$, ν_μ and $\bar{\nu}_\mu$ are superposed; an anti-stellar collapse would show a very strong initial antineutrino burst, with a later contribution from ν_μ-electron scattering.

The existing (negative) evidence concerning the existence of antimatter in the universe is derived from a) charged-particle searches in the cosmic-ray primaries, which are impractical at high energies; or b) annihilation products like gamma-rays; but these have so many possible sources that their origin is difficult to determine.

IV. Extragalactic GSC Event Rate

In order to estimate the number of GSC events that would be seen in a detector of the size envisaged, we need an estimate of the rate of events within range of our detector. This estimate is at best a very uncertain one; it contains three factors, none of which is accurately known. They are 1) The number of galaxies within range; 2) the rate at which supernovae are observed in neighboring galaxies; and 3) the ratio of the number of neutrino-emitting GSC events to visible supernovae.

Galactic Density - On examining the available estimates of galactic densities in space, we find a distressing lack of agreement. Allen[12] quotes the mean value 0.02 galaxy/Mpc^3, which translates to 5.8×10^{-4} galaxy/MLY^3. Sandage[13] estimated the total number of galaxies in the universe, obtaining a mean density 0.14/MLY^3. Estimates of the local density place it 2.5 times higher than the average - we inhabit a croweed urban area, apparently - giving 0.35/MLY^3. Finally, Shapley estimates an average of 1.0/MLY^3.[14] These estimates differ by a factor as high as 1700.

However, lists of local galaxies have been made.[15] Local galaxies are the easiest to see; if they are nearby and faint, they are probably too small to be significant. Galactic surveys are subject to considerable errors in estimating distance, since in most cases the estimates are statistical and based only on type and apparent magnitude. Shapley, striking an average,[16] estimates 1250 visible galaxies within 20 million light-years. The term "visible" excludes about half the sky, which is obscured by the Milky Way and its associated dust clouds.

Applying this correction, we arrive at 2500, giving a density of 0.075 galaxy/MLY^3.

Frequency of Occurrence of Extragalactic Supernovae - In other galaxies, rates of supernova occurence ranging from 3 in 20 years to 1 in 400 years have been observed for type II supernovae, and 1 per 1000 years to 1 per 4000 years for the much rarer type I supernovae. There is good evidence that different galactic types have significantly different supernova frequencies; spiral galaxies have more than elliptical galaxies, for example; and also that observed frequencies are observationally biased.[17]

Faced with widely diverging data, we adopt a median value of one supernova per galaxy per 30 years, as suggested, e.g., by Weekes.[18]

Ratio of GSC to Supernovae - Zeldovich and Novikov[19] point out that there should be many gravitational collapses in which no mantle blowoff, and thus no optical supernova display occurs. Lacking any quantitative estimate of the ratio GSC/supernovae, we adopt the conservative (and minimum possible) value of unity.

To recapitulate, then, assuming the figure of 2500 galaxies within 2×10^7 light years, and one GSC per galaxy per 30 years, we obtain 83/year as the expected rate of observation of collapse, or one every 4.4 days, in a detector of $3. \times 10^7$ tons.

V. Gravitational Collapse in the Local Galaxy

A supernova, or a gravitational collapse in our own galaxy would produce a far stronger signal than the ones we have been discussing at a distance of twenty-million light-years. Our galactic center is only 30,000 light-years away, and reducing the required size of the detector to as little as sixty tons would allow one to see GSC events from the galactic center. Such "small" detectors are being planned or built by several groups,[20] and at least one very interesting event has been observed.[21] The one worm in this apple is the anticipated rate of GSC in our galaxy: one in 30 years if it is similar to its neighbors. Only 7 visual supernovae have been observed in the last 1500 years;[22] all but one of these were in the immediate galactic vicinity of the sun, most of the galaxy being obscured by dust. There are consequently grounds for hoping for a higher GSC rate.

VI. The Ocean as a Neutrino Detector

As soon as one is several hundred meters below the surface the light intensity has decreased to the background value: the light attenuation length near the surface is less than the 20 meters we hope for at great depths; so that at 1 km, the light attenuation will exceed 10^{22}.

Counting backgrounds in the ocean will include cosmic rays, the radioactivity of the seawater, and bioluminescent light due to the ocean flora and fauna. To decrease the first, we need a depth of at least 5 km; Figure 3 shows the attenuation of the muon rate with depth for detectors with areas in the range $10^3 - 10^6$ m^2. At 6 km, a 3×10^7 ton detector would have a cosmic-ray muon background of about 0.4 sec^{-1}, a comfortable calibration rate.

Bioluminescence exists at all depths at which it has been studied; and though it diminishes with depth it undoubtedly will be present at 5 - 6 km as well. We propose to make studies of it as part of the site selection procedure; but since the time distribution of the light from bioluminescent sources is entirely different from that from cosmic rays, we do not anticipate difficulties in distinguishing the two sources.

Ocean Radioactivity - Finally, the radioactivity of seawater provides an irreducible minimum to the counting rate of a photomultiplier.[24] There are two independent sources of background counts: the first is the beta-radioactivity of the water, which is primarily due to K^{40}, which has an intensity of 13 disintegrations sec^{-1} per liter. The other is the gamma-ray background (manifesting itself as Compton electrons) due to neutron capture in seawater, primarily the fraction captured by Cl^{35}. The neutrons (and also some prompt, or nearly so, gamma-rays) arise from the minute amount of uranium found in seawater, namely 3 micrograms per liter. Most of these neutrons arise from spontaneous fission; some come from the (α,n) reactions induced in a few nuclides present in seawater, by a small high-energy fraction of the alpha-emitters of the uranium decay chain.

The effect of the rather high counting rate due to K^{40} is to make mandatory the use of coincidence techniques. The potassium beta-rays produce only a few photons; so the efficiency of detecting them is low, and only very rarely would two coincident detectors detect the same decay. Even without the K^{40} decay, the very low rates needed in individual modules, as we will show, would demand coincidence techniques.

The effect of the neutron-induced gamma-ray activity (and also gamma-rays from spontaneous fission) is to impose an energy threshold on detected electron pulses. The energies of the Cl^{35}

capture gamma-rays range up to about 8 MeV, and a threshold in that neighborhood will be required to keep the background rate in each module to a low enough value. Thus we see that ocean radio-activity prevents us from detecting neutrinos below 10 MeV or so.

Detector Logic - We envision the 3 x 10^7 tons of ocean subdivided into a large number J of similar modules, each of dimensions limited by the light attenuation to be of the order of the attenuation length, 20 m. A single module might then be a 20 m cube, or ca 10^4 tons, and the number of modules J about 3000. In order to obtain an unequivocal signal from a GSC, we should require a minimum number of neutrino interactions - say 10, for each event. As noted above, the mean number required to yield a detection efficiency of .9 for 10 or more events is 14. The estimated duration of neutrino escape from the thermal stage of the GSC is 0.1 sec (a value which, as one might surmise, is also open to question.) If we now require that any 10 of J modules fire within a time t, the random background rate of 10-fold coincidences will be $(JNt)^{10}$; in which we have already fixed J as 3000 and t as 0.1 sec. If we set the background rate at 10^{-8} sec^{-1}, we find that JNt must be 0.16 sec^{-1}, giving N = 5. x 10^{-4} sec^{-1}. This rate is remarkably independent of the order of coincidence and of the required background rate. Thus individual module counting rates near 10^{-3} sec^{-1} are needed, and these can only be obtained by coincidence methods; at least 3-fold coincidences are required.

Optical Collection Efficiency - The total number of Cerenkov quanta produced between 250 and 600 nm by a 20 MeV positron (created by antineutrino absorption) is only about 5500. Of these two-thirds are below 400 nm, in the ultraviolet; and without them the prospects of detecting the positron simultaneously by at least three photomultipliers, each of which should receive at least 20-30 quanta, would be even more dismal. The probability of seeing zero photoelectrons if the average number produced is $\bar{n}$ is given by $\exp(-\bar{n})$ for a Poisson distribution. If $\bar{n} = 3$ (which happens with about 20 quanta only if the photocathode efficiency is as high as 15%) the probability of detecting at least one photoelectron in each tube is only .95, yielding .85 as the threefold coincidence efficiency. We dare not go much below this.

The achievement of a quantum collection efficiency of several percent, using only a few phototubes, in a volume of 8000 m^3 - a 20 m cube - will be no small feat. At the moment the most promising idea is to multiply the effective collecting area of the photocathode several hundredfold, by using wavelength shifters dissolved in plastic light guides for trapping the incident light.[25] To give the Cerenkov light the maximum range, all the UV should be converted to the blue-green. We thus envision a two-stage process: first, a wavelength-shifter transforming to the blue-green (475 nm), uniformly dispersed through the water, either in solution if the module is enclosed, or on a plastic backing, if not. Second, a trapping system of light-guides that accepts the 475 nm and re-radiates it at a somewhat longer wavelength efficiently transmitted by the light-guide, to which the photocathode efficiency is still high - perhaps 550 nm. The feasibility of this process has yet to be demonstrated. Figure 5 is a schematic representation of such an array of wavelength-shifters and light-traps.

The use of wavelength shifters does not preclude the need for large-area phototubes; it makes it a little more tractable. A 10^4 ton module will distribute Cerenkov light over an area of about 2500 m^2. Without wavelength shifting we would need a minimum photocathode area of 50 m^2. Let us suppose we need to subtend 20% of the area with light-traps to end up with 2% of the light; we then need 500 m^2 of light-traps. If the use of light-trapping gives an area gain of 10^3, we need 0.5 m^2 of photocathode; of the gain is only 100, we need 5. m^2. Even in the latter case, this corresponds to the area of 3 spheres of 51 cm radius (see Fig. 7).

C. ATHENE: HIGH ENERGY NEUTRINO PHYSICS

From our knowledge of the cosmic ray muon spectrum, we can predict with fair accuracy the neutrino flux due to interactions of cosmic rays with the atmosphere. The energy spectrum extends to very high values; but the flux falls off very rapidly with increasing energy.[23]

The advent of the Fermilab 500-GeV accelerator has given us accelerator based neutrino data to over 200 GeV. The accuracy and detail of accelerator measurements, whenever they are possible, far exceed that obtainable with any conceivable cosmic ray experiment. In planning a cosmic-ray measurement on neutrinos, one would do well to consider only energies which appear to be inaccessible to accelerators.

In the immediate future the Fermilab accelerator can be raised to about 1000 GeV, or 1 TeV, by the use of superconducting magnets. The following stage at Fermilab is undoubtedly some application of the accelerator to the production and use of colliding beams; but colliding beams, though they raise the center-of-mass energy of a collision, do not produce neutrinos of higher energy in the laboratory than the colliding particles. To get neutrinos above 1 TeV, a still larger accelerator will have to be built. Fermilab Director, R. R. Wilson, has proposed an internationally sponsored 10 TeV accelerator; "it will cost a billion dollars, ten trillion volts 'twill give." If past history is a guide, the gestation period of such a suggestion after the physics community lines up behind it, will be at least 5 to 10 years - even more if economic conditions remain unfavorable.

Thus, a high-energy neutrino experiment in cosmic rays would have to offer valuable information in the range well above 1 TeV, and preferably above 3 TeV in order not to be overtaken in the next 20 years. There is important knowledge to be obtained in this energy range. If, for example, the total cross-section for neutrinos in the 1-10 TeV range could be measured, one could tell whether the proposed 37-GeV charged intermediate boson exists; if it does, the cross section would stop increasing linearly with energy at about 2 TeV. Another parameter well worth measuring would be the relative abundance of neutrino absorptions in which zero, one, and more than one muon are emitted. This would give the ratio of neutral to charged currents and give data at higher energies on the recently observed events in which two muons are produced, and currently tentatively ascribed to charmed hadrons.[26]

I. Neutrino Flux

The detection of high energy neutrinos is very easy compared to supernova neutrinos, but unfortunately, the flux is low. Figure 8 shows the number of interactions to be expected per year[27] from cosmic ray neutrinos in detectors of 2×10^7 and 10^9 tons. The cross-section is assumed to be

$$\sigma = 0.8 \times 10^{-38} E_\nu \text{ cm}^2/\text{nucleon} \qquad (5)$$

with E_ν in GeV[28].

Each event produces a hadronic shower of perhaps 10^9 quanta or more, so that there is no problem of detecting individual events; only the question how to extract sufficient information from an event. There is no serious background for such events; bioluminescent light sources give comparable amounts of light, but extended over periods approaching one second. Good time resolution among many detectors is the key to selecting high energy neutrino events. An experimental arrangement to give the desired information still remains to be designed.

II. Measurements Required for Athene

If we examine the detectors used by the two high-energy neutrino counter groups that have been working at Fermilab on detecting and measuring neutrinos in the 10-200 GeV range for the last few years, it becomes clear that the requirements for getting good data include the following:

1) Knowledge of the neutrino momentum and direction.
2) Measurement of the energy and direction of the hadronic cascade produced by the neutrino.
3) Identification of the outgoing muon (or muons), and experimental certainty of the absence of an outgoing muon when it does not appear. Only when this is attained can neutral current events be identified correctly.

4) Observation of the sign, direction, and momenta of the outgoing muon(s).

It is possible to do experiments without all these data; but the greater the fraction obtaine., the muore useful the informaion becomes.

In the ocean, which of these must we abandon, and which can we hope to achieve? We consider them in turn.

1) We cannot have for cosmic rays the a priori information on neutrino direction or energy given by the accelerator beam. However, a downward-directed neutrino originating in pion or kaon decay above 1 TeV or so, will frequently be accompanied by the muon with which it was born. At these high energies that sister muon will scatter so little that even at 5 km depth it will be only a few meters away. In that case, the neutrino direction will be that of the muon within a milliradian or so.

2) The direction of the hadronic shower core is most important. We must collect sufficient data on the Cerenkov light cone to obtain its axis. Multiple sampling of the cone is therefore necessary: See Fig. 9.

3) The outgoing muon (or muons) can be identified as such by its great range. Its sign is inaccessible to measurement; its energy may not be. Transition radiation detectors have shown themselves useful in the appropriate range of gamma, for electrons. A set of foam radiators (filled with He at ambient pressure), and very thin scintillation crystal x-ray detectors (NaI or CsI) deposited on transparent plastic sheets provide a conceptual detector potentially capable of 10 or 20% accuracy.

From this we see that for ATHENE it is important to leave the direction of the primary Cerenkov cone undisturbed; UV wavelength shifters are out. On the other hand, wavelength shifting in a light-trapping plastic light-guide collector is still both permissible and desirable.

It thus appears that the requirements of UNDINE and ATHENE may be difficult if not impossible to reconcile. It may be necessary to use different arrays.

D. UNICORN: HIGH ENERGY EXTRATERRESTRIAL NEUTRINO EVENTS

As pointed out by Berezinskii and Smirnov,[29] high energy neutrinos (> 10^{12} ev) are produced by p-p collisions in interstellar or intergalactic space. Even higher energies (> 10^{17} eV) neutrinos are produced by the decay of pions from the collision of protons with the 3° K relict radiation from the big bang. Events of such prodigious energy are relatively easy to detect, but they are very rare, and would require a detector mass in the vicinity of 10^{9} tons or more to yield a rate of several events per year.[30] We are still at the very beginning of consideration of this problem; we do not know whether these events are distinguishable from ATHENE events.

E. OCEANOGRAPHIC CONSIDERATIONS

The 1975 DUMAND Summer Workshop[31] considered at length the problem of installing, supplying, and collecting data from a detector array at a depth of 20,000 ft; it also considered possible sites. Among the sites selected as most promising (subject to verification by measurements and soundings) is one in the vicinity of the Hawaiian islands, where an abyssal plain at 20,000 ft. is close offshore. Apparatus has been operated at such depths, but never so much of it for so long a time (a duration of 5 years was postulated.) It was the consensus of the oceanographic experts that, though it entailed a considerable challenge, there is no reason one cannot design and build an array to work unattended at these depths for several years, with power supplied by a cable to a land base, which would also carry back the data.

F. STATUS AND PLANS OF DUMAND

Interest in the DUMAND idea was evidenced by discussions at the XIV International Conference on Cosmic Rays at Munich, in the summer of 1975 and at the present Conference. Such interest may result in the establishment of a collaborative international effort.

1976 Summer Workshop - At present the DUMAND project is an informal voluntary association of scientists and engineers interested in the aims and methodology of the project. Only the U.S. part of the project has been formally organized, to the extent of adopting a constitution, electing a steering committee,[32] holding regular meetings, and planning and executing experimental work. The project has at present no explicit funding; its members are supported by other means. However, a second Summer Workshop is planned, to be held at the University of Hawaii, in Honolulu, September 6-19 1976. It is expected that this Workshop will advance the aims considerably, since it will be larger than the first, and will be international in scope. It is expected that it will be supported in part by several government agencies.

The major purpose of the Workshop will be to establish the feasibility of at least one of the three projects identified to date. By this we mean the following:

1) For UNDINE: we hope to make sufficient progress to decide whether a supernova detector is technically feasible; failing that, to identify the additional information needed to make that decision. In this case there is no question concerning

the desirability of the scientific objective, but only about the techniques.

2) For ATHENE: Here there is no problem in principle in observing the events. Instead, can we design an experiment that will yield data sufficiently interesting and unique to make the effort worthwhile?

3) For UNICORN: The problems combine those of UNDINE and ATHENE: we know neither the source nor the techniques.

In any event, it is evident that these projects share many common features and problems, and that progress in any one area will benefit all three.

In addition, there will of course be further considerations of the oceanological and marine engineering aspects of the project. It is hoped that underwater measurements near Hawaii of water transparency and bioluminescence will be in progress sometime this year.

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REFERENCES

[1] F. Reines and C. L. Cowan, Phys. Rev. 92, 830 (1953); C. L. Cowan, F. Reines, F. B. Harrison, H. W. Kruse, A. D. McGuire, Science 124, 103 (1956).

[2] J. N. Bahcall and R. Davis Jr., Science 191, 264 (1976).

[3] F. Reines, M. F. Crouch, T. L. Jenkins, W. R. Kropp, H. S. Gurr, G. R. Smith, J. P. F. Fellschop and B. S. Meyer, Phys. Rev. Lett. 15, 551 (1965); F. Reines, W. R. Kropp, H. W. Sobel, H. S. Gurr, J. Lathrop, M. F. Crouch, J. P. F. Fellschop and B. S. Meyer, Phys. Rev. B4, 3 (1971).

[4] C. V. Achar, M. G. K. Menon, V. S. Narasimham, P. V. Ramana Murthy, B. V. Sreekantan, K. Hinotani, S. Miyake, D. R. Creed, J. L. Osborne, J. B. M. Pattison, and A. W. Wolfendale, Phys. Lett. 18, 196 (1965); M. R. Krishnaswamy, M. G. K. Menon, V. S. Narasimham, K. Hinotani, N. Ito, S. Miyake, J. L. Osborne, A. J. Parsons and A. W. Wolfendale, Proc. Roy. Soc. London A323, 489 (1971).

[5] J. B. Langworthy, B. A. Lamers and H. Uberall (in press).

[6] G. V. Domogatsky and G. T. Zatsepin first suggested this possibility, Proc. IX. Intl. Cosmic Ray Conf., V. 2, p. 1031, London (1966); a giant underwater detector to study high-energy cosmic ray neutrinos was considered by F. Reines, Proc. Roy. Soc. London A301, 107 (1967).

[7] Neutral currents were discovered at CERN in 1973: A. Rousset, Neutrinos-1974, p. 141, Amer. Inst. of Phys., New York, 1974, presents a detailed discussion of the early evidence for neutral currents.

[8] D. Z. Freedman, Phys. Rev. D9, 1389 (1974).

[9] F. Reines, H. S. Gurr, H. W. Sobel, Univ. of Calif., Irvine Preprint, May 1976; (submitted for publication to Phys. Rev. Letters).

[10] See e.g., D. N. Schramm and W. D. Arnett, Mercury, May-June 1975, p. 16 (a popular summary); ibid., Ap. J. 198, 629 (1975); or S. Bludman, Neutrino Dynamics in Stellar Collapse, Int. Conf. on Neutrino Science, Balatonfured, 1975, p. 329; J. Wilson, private communication (to be published).

[11] For a derivation of the cross-section for reaction 1a, see C. S. Wu and S. A. Moszkowski, "Beta-Decay", p. 207 ff, Interscience, New York (1966).

[12] C. W. Allen, "Astrophysical Quantities", Univ. of London, Athlone Press, Third Ed. p. 289 (1973).

[13] A. Sandage, "Hubble Atlas of Galaxies", Carnegie Inst. of Washington, Washington (1961).

[14] H. Shapley, "Galaxies", Third Ed., Harvard Press, Cambridge (1972).

[15] Shapley-Ames Catalogue of Galaxies; de Vancouleurs; "Atlas of Brightest Galaxies".

[16] H. Shapley, loc. cit.

[17] J. Maza and S. Van den Bergh, Ap. J. 204, 519 (1976).

[18] T. C. Weekes, "High Energy Astrophysics" Chapter 3, Chapman and Hall, London, 1969.

[19] Ya. B. Zeldovich and I. D. Novikov, "Relativistic Astrophysics", vol. 1, Univ. of Chicago Press, Chicago, 1971.

[20] A. E. Chudakov, O. G. Ryajskaya and G. T. Zatsepin, Proc. XIII Intl. Conf. on Cosmic Rays, Denver, p. 2007 (1973); E. Fenyves,

K. Lande, G. Bozoki, W. Frati, and C. K. Lee, Ann. N. Y. Acad. Sci. 224, 333 (1973); W. Frati, K. Lande, J. Supplee, E. Fenyves, and C. K. Lee , Int. Conf. Neutrino Sci., Balatonfured, p. 396 (1975).

[21] K. Lande, G. Bozoki, W. Frati, C. K. Lee, and O. Saavedra, Nature 251, 485 (1974).

[22] F. R. Stephenson and D. H. Clark, "Historical Supernovas", Scientific American 234 No. 6, p. 100, June, 1976.

[23] J. C. Barton and C. T. Stockel, Can. J. Phys. 46, S318 (1968).

[24] S. N. Anderson and J. R. Lord, Paper No. XIV, Proc. 1975 Dumand Summer Workshop, Western Wash. State College, Bellingham (1975).

[25] This technique has been used in water Cerenkov detectors by J. W. Keuffel, et al.; see, e.g., G. L. Cassaday, D. E. Groom, and M. O. Larson, Nucl. Inst. and Meth. 107, 509 (1973). It was proposed for muon and neutrino detection in the ocean by H. Uberall, C. Cowen, Proc. Conf. on Exptl. Neutrino Physics, CERN, Jan. 1965: CERN Report 65-32, p. 231; also C. L. Cowan, H. Uberall and C. P. Wang, N. Cim. 44, 526 (1966). Preliminary experimental data were reported by G. K. Riel, et al., Bull. APS 12, 1075 (1967).

[26] See, e.g., C. Rubbia, Proc. Intl. Symposium on Lepton and Photon Inter. at High Energy, p. 1049, SLAC, Stanford (1975).

[27] These data were derived from Eq. (5), using a neutrino spectrum identical with the muon spectrum of Ref. 23.

[28] F. Sciulli, Neutrino-74, p. 166, Amer. Institute of Phys., New York, 1974; this paper summarizes accelerator data to date.

[29] V. S. Berezinskii and A. Yu. Smirnov, Astrophys, & Space Sci. 32, 461 (1975).

[30] V. S. Berezinskii and G. T. Zatsepin (to be published).

[31] Proceedings of 1975 Summer Workshop (DUMAND), P. Kotzer, ed., Western Washington State College, Bellingham, Wash. (1976).

[32] Members of the DUMAND Steering Committee are currently F. Reines, chairman; H. Blood, U. Camerini, D. Cline, P. Kotzer, J. Learned, C. Lister, S. Neddermeyer, A. Roberts, and D. Schramm.

FIGURE CAPTIONS

Figure 1: Schematic representation of the successive stages of nuclear burning leading eventually to gravitational collapse in a star of mass about 7 solar masses. The values of t, which differ by a factor of 10^3 from one stage to the next, indicate the order of magnitude of the duration of each stage of the burning. The gravitational collapse follows on the exhaustion of the nuclear fuel, and involves only the inner core portion of the star; the outer mantle does not participate in the collapse, being too far away.

Figure 2: Neutrino luminosity curves for GSC, plotted separately for different neutrino types. Curves marked L_{max} refer to the stellar interior, L_{out} to the luminosity on the stellar surface; the delay is due to the time required for the neutrons to diffuse outward. Neutronization corresponds to the sharp rise at 0.665 seconds; the subsequent collapse is 10-20 milliseconds later. The apparent decay period of the neutrino luminosity is of order 0.1 sec. Note that $\bar{\nu}_e$ is the last to appear. (Curves by courtesy of Dr. James R. Wilson, from unpublished calculations, Ref. 10).

Figure 3: The neutrino spectra predicted by the same calculations, for the later stages of collapse.

Figure 4: The $\bar{\nu}_e$ spectrum replotted on a linear scale, and also weighted by the square of the neutrino energy; the latter curve gives the probability of interaction in

the detector. Note that little of the spectrum will be lost by a 10-MeV cutoff in detection.

Figure 5: Depth-intensity curves for muons in the ocean, for several different areas of detector. Data for muon intensities from Ref. 23.

Figure 6: General principles of efficient light collection from a weak pulse of Cerenkov light emitted by a low-energy positron produced by antineutrino reaction with a proton. A detector module, about 20 m on a side, consists of an array of streamers of very thin plastic (mylar, cellulose acetate, etc.), coated with a layer of wave-length shifter (WLS) which absorbs UV and fluoresces near 470 nm, where the water transmission is best. The WLS is sealed to prevent dissolving it. The resultant isotropic blue light is picked up by the light-trapping plastic (LT) which once again reradiates the light at a longer wavelength, perhaps 500 to 550 nm, thus trapping a good fraction of it within the light-pipe which is adiabatically connected to the phototube cathode. Thus a multiplication of effective photocathode area by a factor from 100 to 1000 can hopefully be attained.

Figure 7: Schematic representation of a large dual spherical photomultiplier in a high-pressure glass envelope. Electrons from the spherical inner surface are focussed onto a small channel electron multiplier plate; the

electronics are sealed into the pressure vessel. After E. Sternglass, Ref. 31.

Figure 8: Expected cosmic-ray neutrino counting rates; these are integral spectra, showing the total rate for all particles of given energy and above. Curves A and B show the rates in detectors of 2. x 10^7 and 10^9 tons, respectively. Data from Ref. 21, with cross-sections from Eq. 5.

Figure 9: Schematic representation of a cosmic-ray neutrino event. The incoming neutrino is often accompanied by its muon twin; at the energies in question the two have the same spectrum and practically the same direction, and the muon scattering in 5-6 km of ocean is only of the order 10 meters at 3 TeV. The cascade produced by the neutrino contains perhaps 10^9 quanta, whose directions are determined by a Cerenkov cone around the shower axis, most particles being closely axial until they are quite slow. The ellipse which represents the intersection of this cone with a detector plane of arbitrary orientation with respect to it can be detected for 40-50 meters; enough data are required to define the cascade adequately. In addition muons produced in the neutrino interaction (μ_2, etc.) must be counted, identified, and if possible, measured in energy. A sign determination does not seem possible.

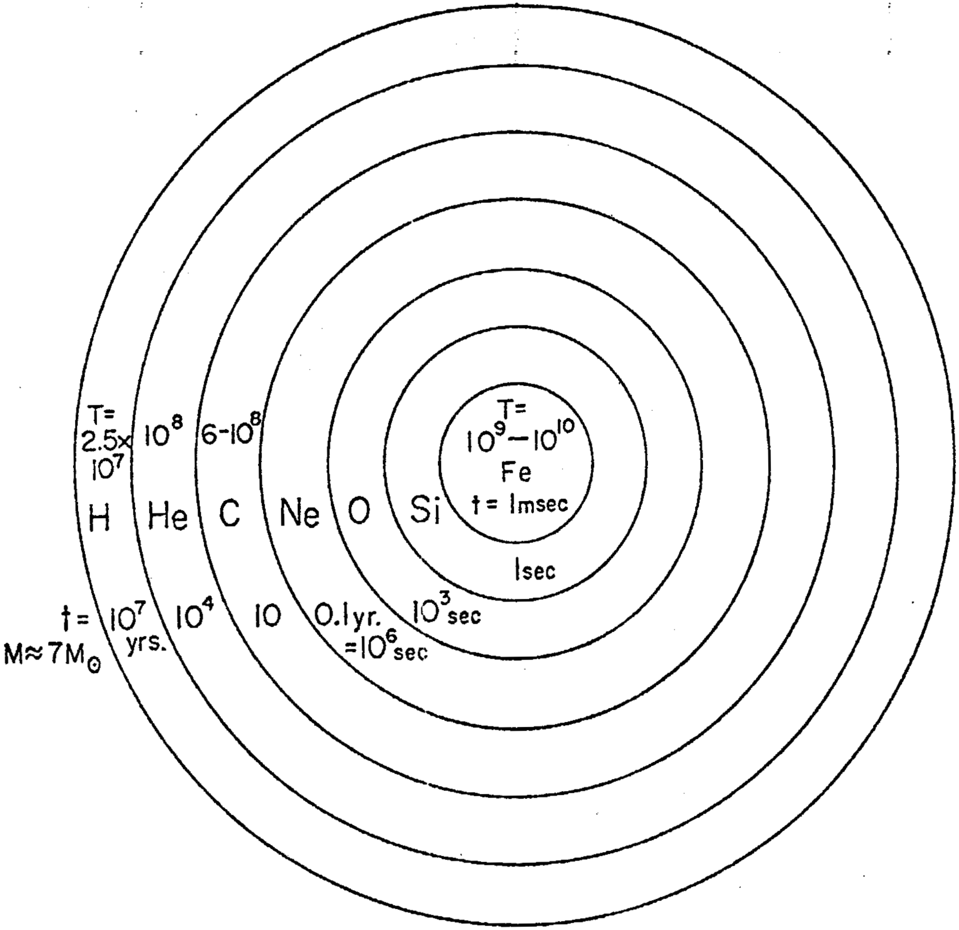

T=
2.5×
10^7
10^8
6-10^8
T=
10^9—10^10
Fe
t = 1msec
H
He
C
Ne
O
Si
1sec
t =
10^7
yrs.
10^4
10
0.1yr.
=10^6sec
10^3sec
M≈7M⊙

FIGURE 1

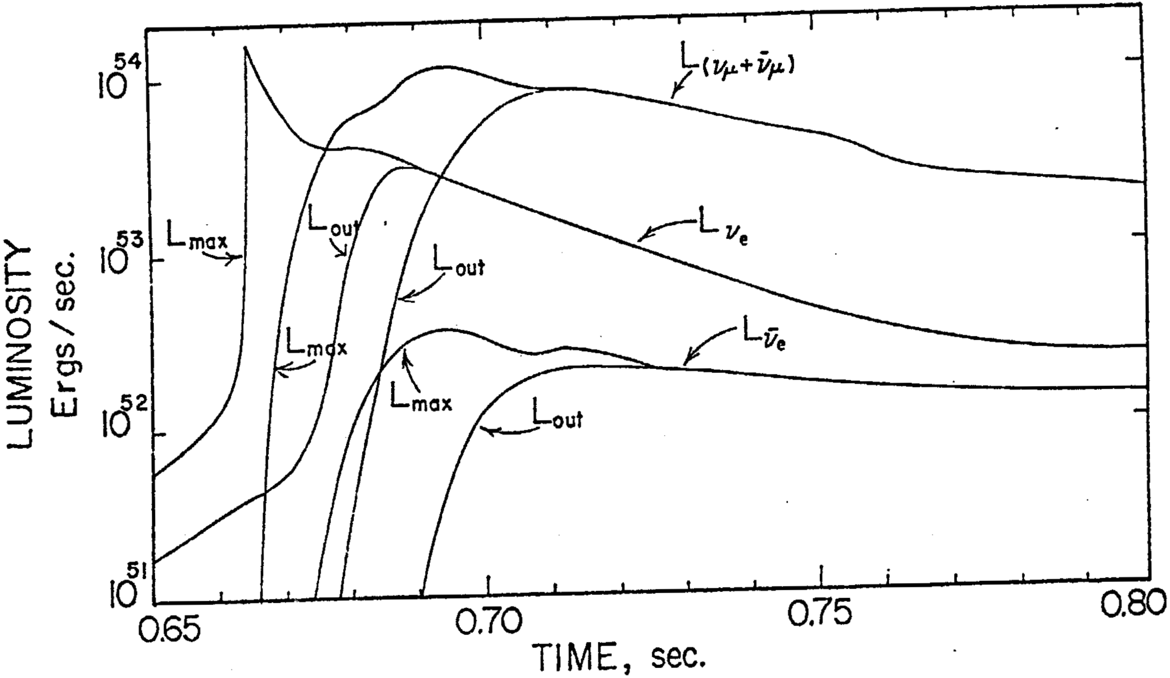

LUMINOSITY
Ergs / sec.
10^{54}
10^{53}
10^{52}
10^{51}
0.65
0.70
0.75
0.80
TIME, sec.
$L_{(\nu_\mu+\bar{\nu}_\mu)}$
L_{ν_e}
$L_{\bar{\nu}_e}$
L_{max}
L_{out}
L_{max}
L_{out}
L_{max}
L_{out}

FIGURE 2

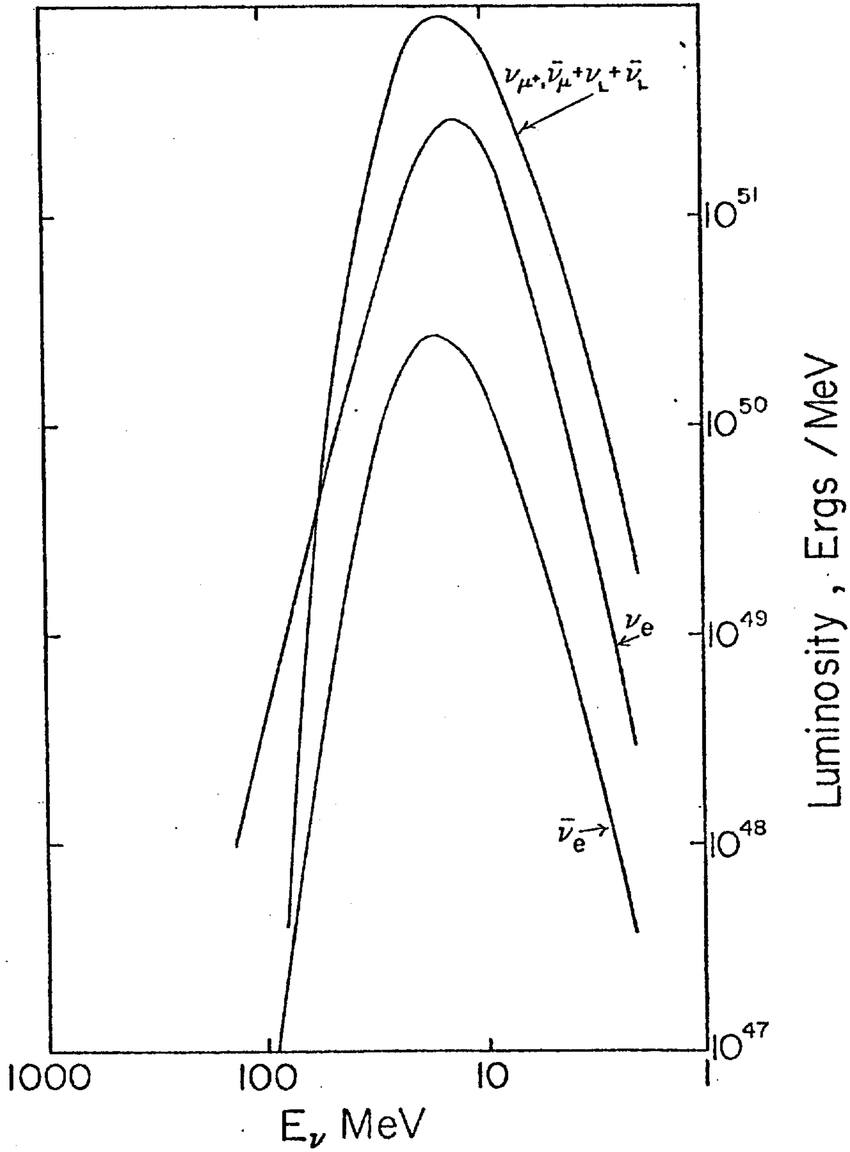

$\nu_\mu + \bar{\nu}_\mu + \nu_L + \bar{\nu}_L$
ν_e
$\bar{\nu}_e$
10^{51}
10^{50}
10^{49}
10^{48}
10^{47}
Luminosity , Ergs / MeV
1000
100
10
1
E_ν MeV

FIGURE 3

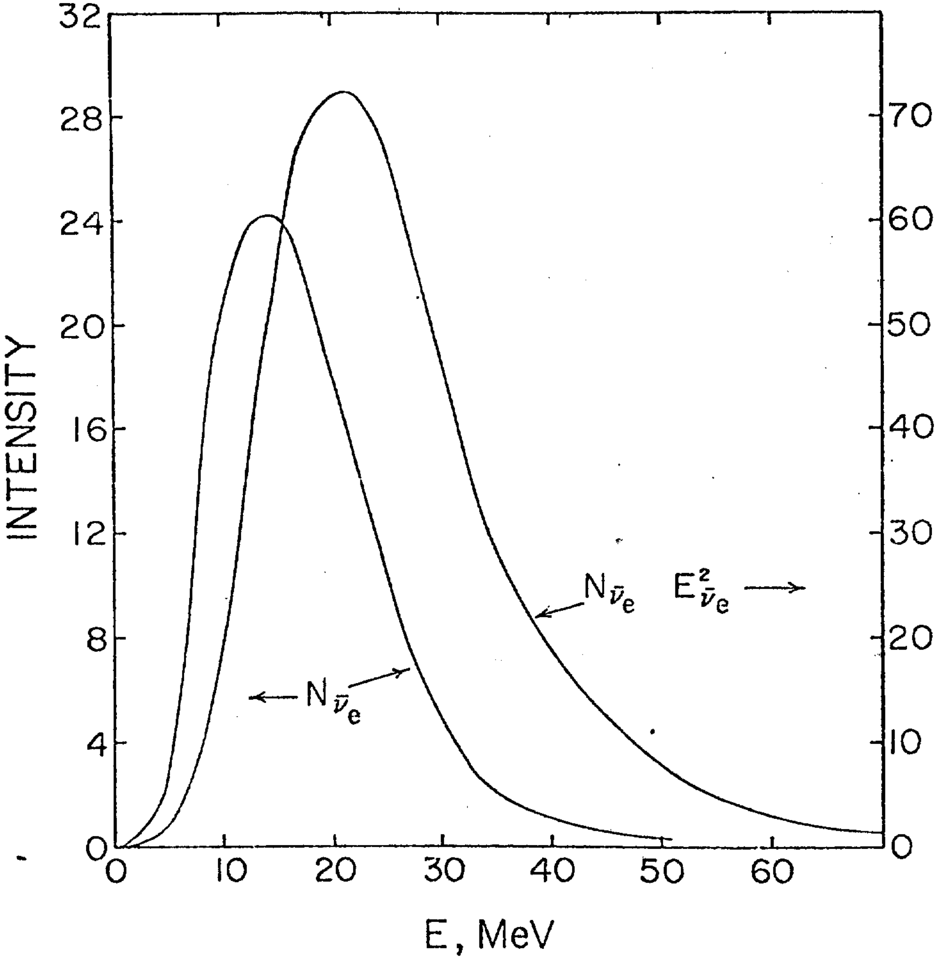

INTENSITY
0
4
8
12
16
20
24
28
32
0
10
20
30
40
50
60
70
0
10
20
30
40
50
60
E, MeV
$N_{\bar{\nu}_e}$ $E^2_{\bar{\nu}_e}$ →
← $N_{\bar{\nu}_e}$

FIGURE 4

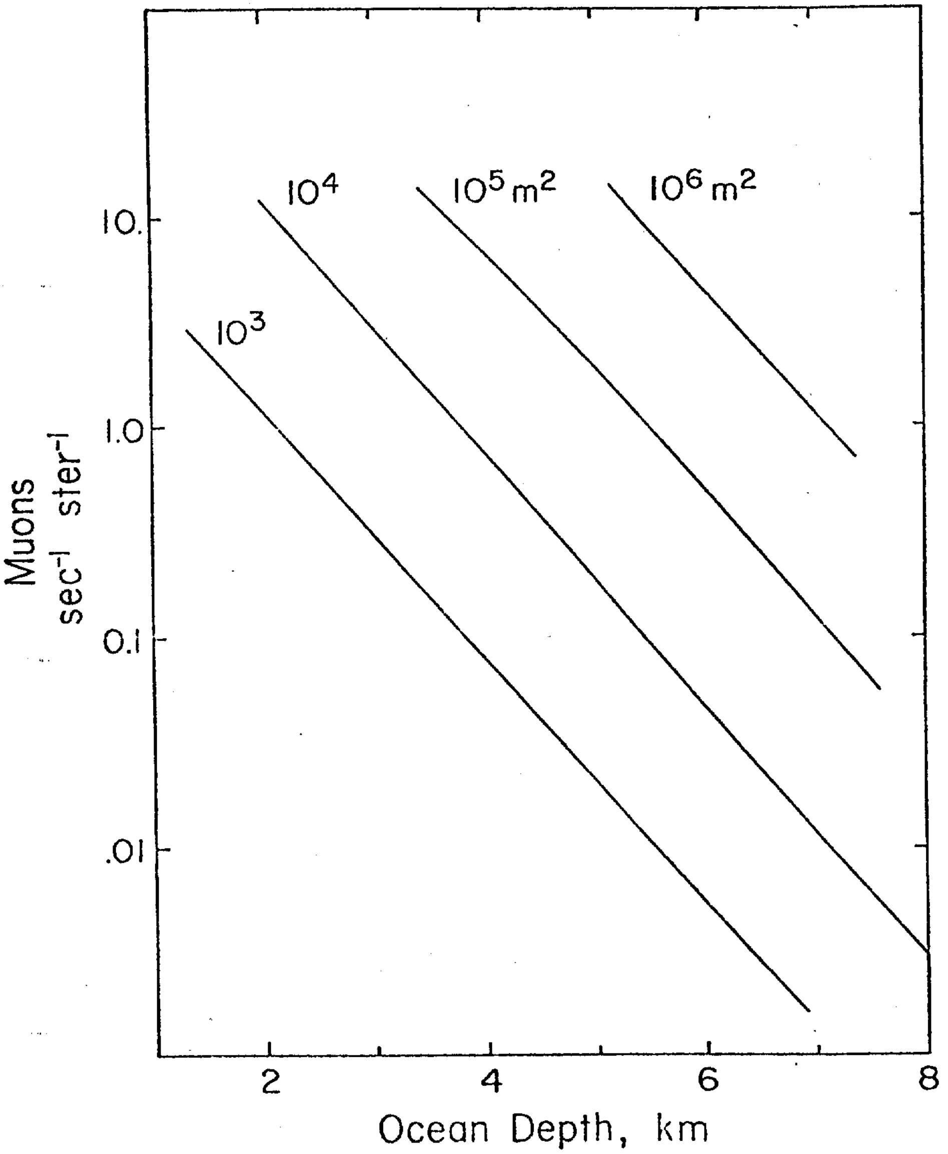

Muons
sec^{-1} ster^{-1}
10.
1.0
0.1
.01
10^3
10^4
10^5 m^2
10^6 m^2
2
4
6
8
Ocean Depth, km

FIGURE 5

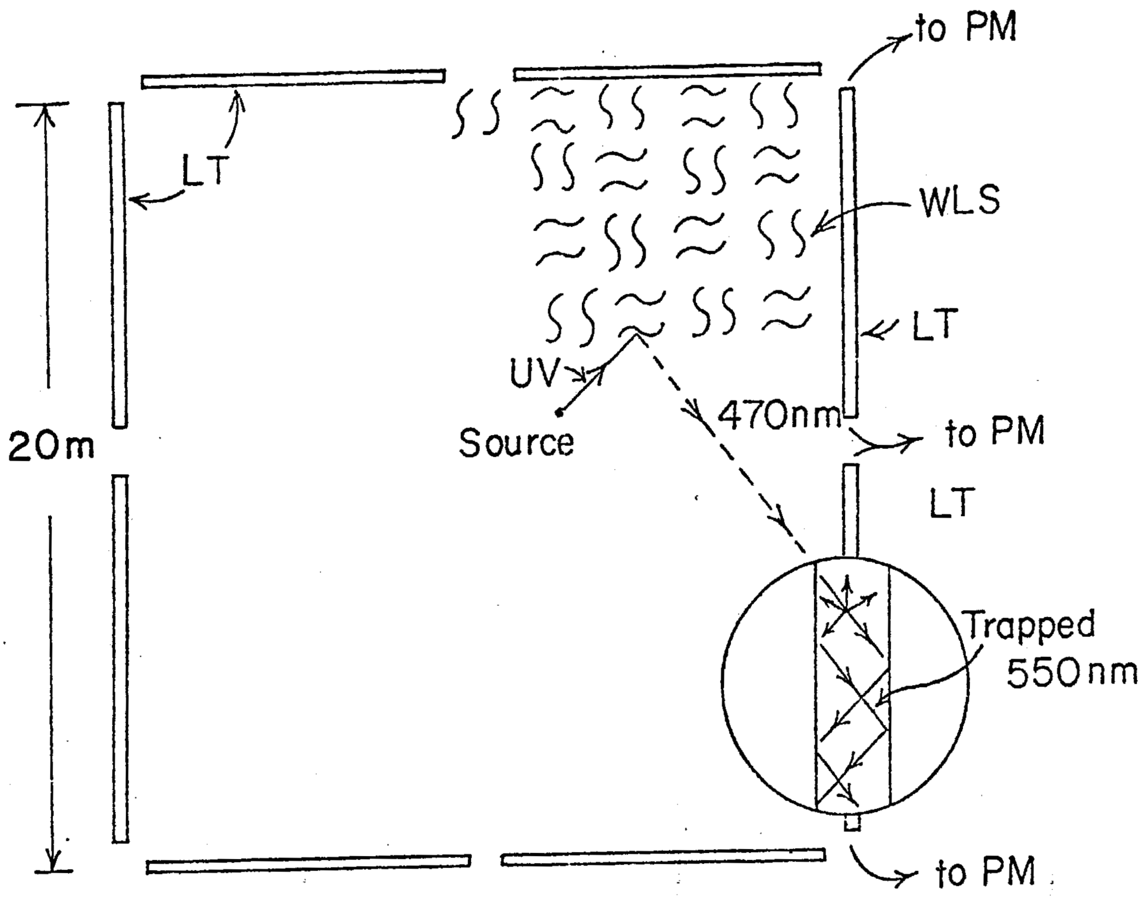


FIGURE 6

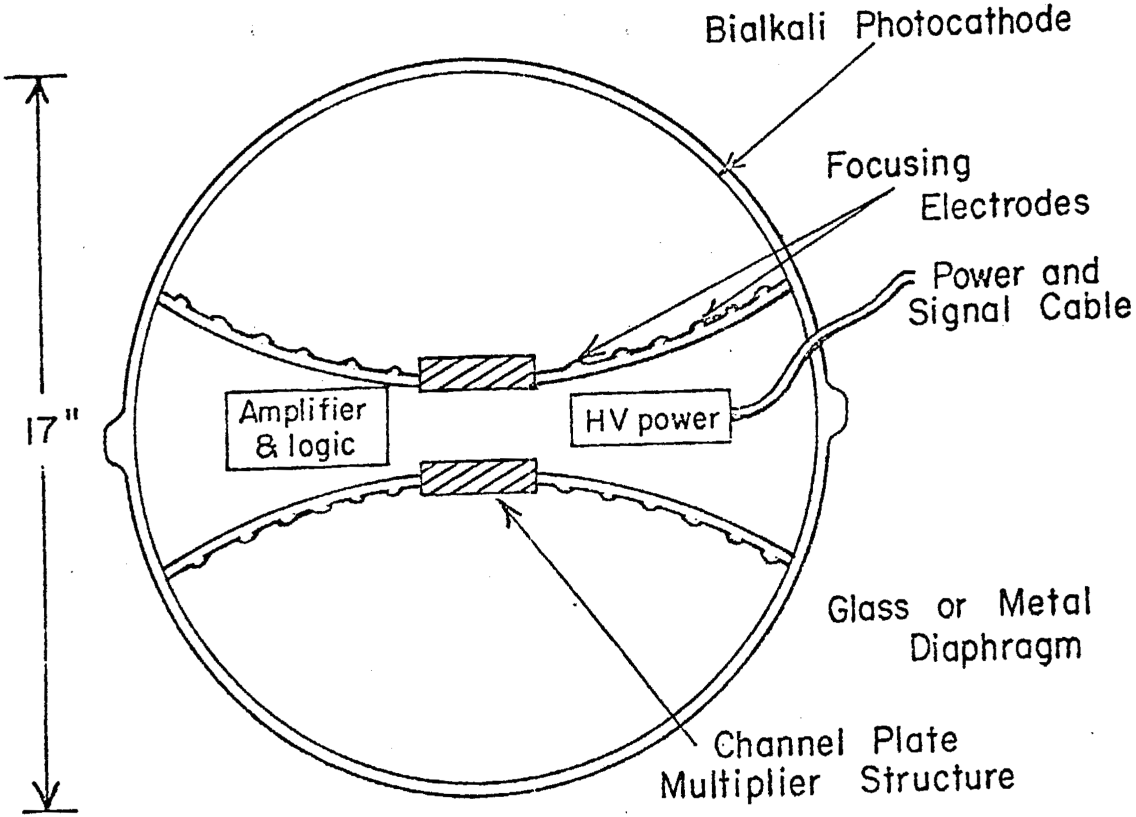
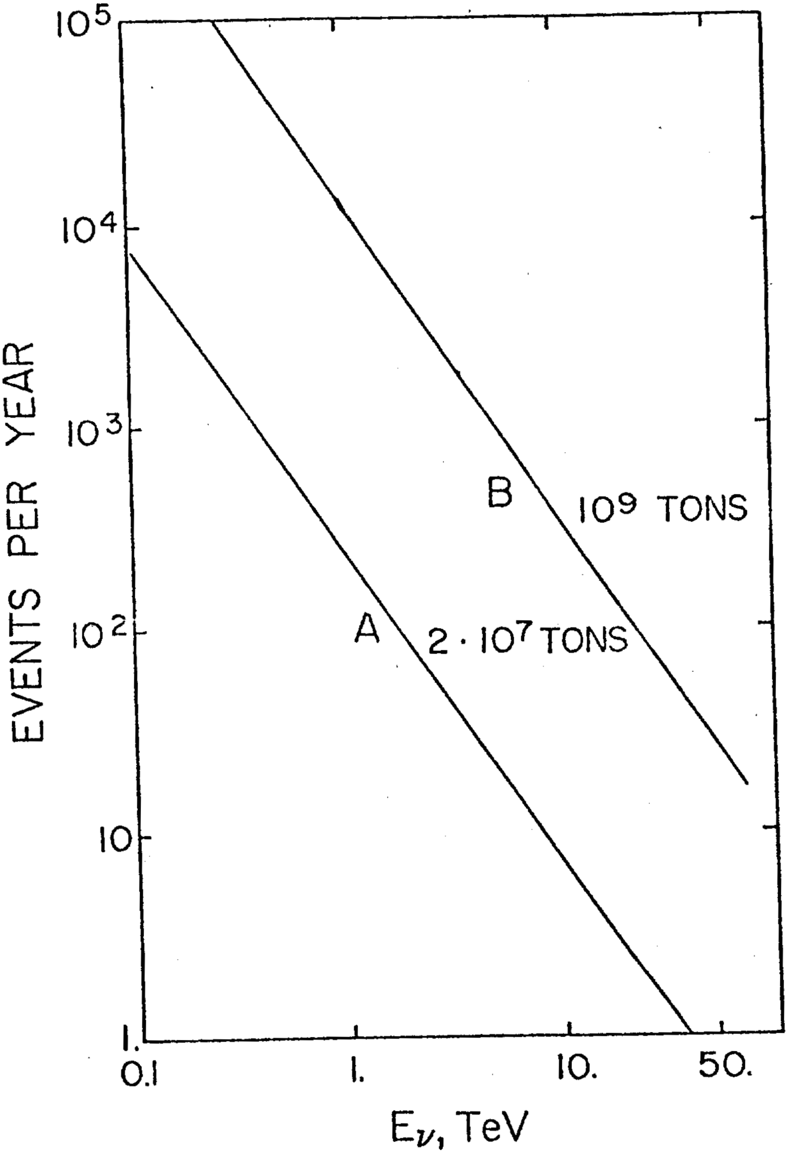

Bialkali Photocathode
Focusing Electrodes
Power and Signal Cable
17"
Amplifier & logic
HV power
Glass or Metal Diaphragm
Channel Plate Multiplier Structure

FIGURE 7



10^5
10^4
10^3
10^2
10
1.
EVENTS PER YEAR
B
10^9 TONS
A
$2 \cdot 10^7$ TONS
0.1
1.
10.
50.
E_ν, TeV

FIGURE 8

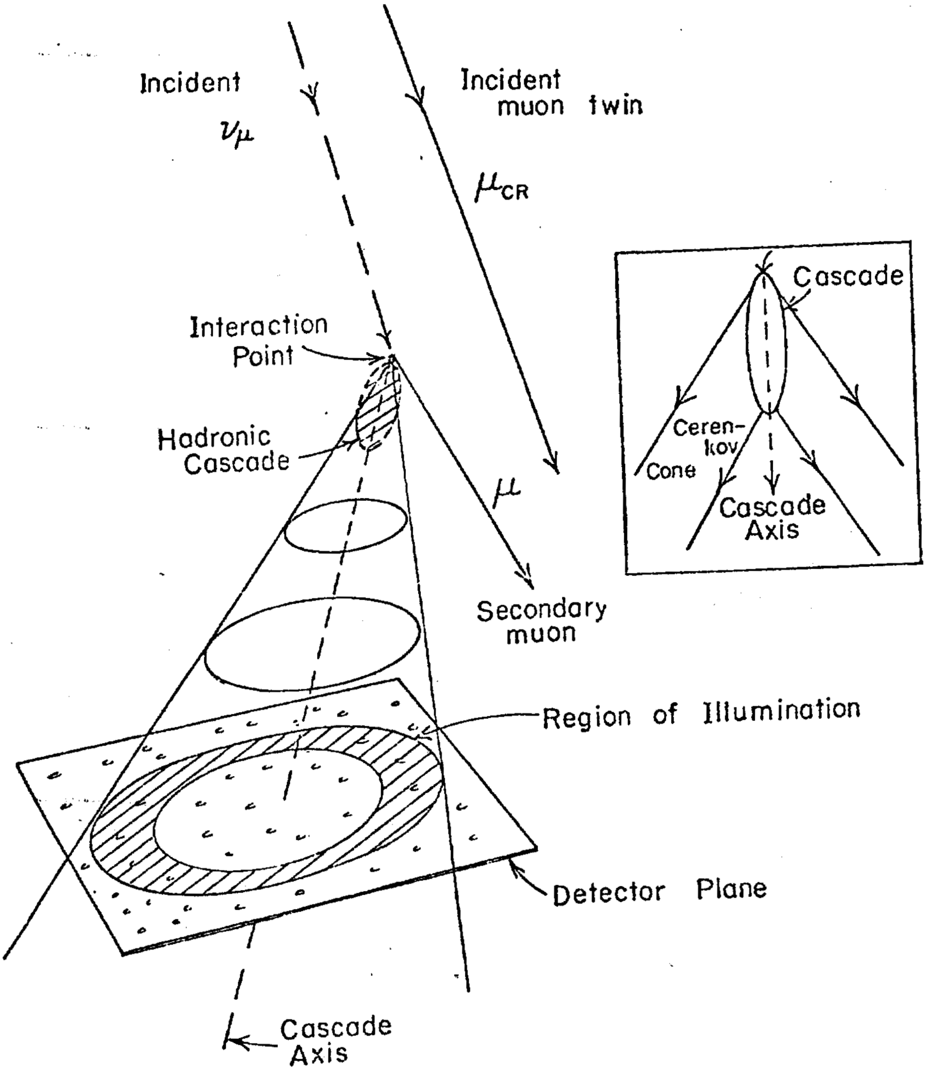

Incident
ν_μ
Incident
muon twin
μ_{CR}
Interaction
Point
Hadronic
Cascade
μ
Secondary
muon
Region of Illumination
Detector Plane
Cascade
Axis
Cascade
Ceren-
kov
Cone
Cascade
Axis

FIGURE 9