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EXPERIMENTAL STUDIES OF THE ACOUSTIC DETECTION OF PARTICLE SHOWERS AND NEUTRINO PHYSICS BEYOND 10 TeV*

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Abstract: The physics of deep inelastic scattering induced by atmospheric neutrinos of ~10 TeV energy is discussed. A 10^9 ton water detector at great depth in the ocean, utilizing acoustic signals from the secondary showers and muon, is investigated. Recent results from Brookhaven and Harvard on the sonic signature produced by particles in water are presented. This work suggests that the 10^9 ton detector is feasible, and that energy depositions in the laboratory as small as 10 GeV may eventually be obervable by this technique.

Resume: Nous présentons une étude de la diffusion profondément inélastique induite par des neutrinos atmosphériques d'énergie $\gtrsim$ 10 TeV. Nous étudions un détecteur de 10^9 tonnes d'eau á grande profondeur dans l'océan. Le detécteur emploie les signaux accoustiques du muon et les hadrons secondaires. Nous présentons des résultats récents de Brookhaven et Harvard sur la signature accoustique produite par des particules dans l'eau. Cette recherche indique que le détecteur de 10^9 tonnes est viable et que des dépositions d'énergie aussi petites que 10 GeV peuvent être mesurés par cette technique.

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This paper explores the feasibility of an experiment that is novel in at least three respects: It would (1) investigate cosmic ray neutrino and muon interactions at energies of $\gtrsim$ 10 TeV, far beyond those accessible at present or proposed accelerators, (2) employ a detector of massive proportions, $\sim 10^9$ tons of sea water, and (3) use a detection technology - observing particles via their sonic signatures - that has not been previously applicable. We wish to study high energy cosmic ray neutrino interactions with a level of information characteristic of that achievable in counter/calorimeter experiements at accelerators. Although this paper concentrates on neutrino reactions, muon interactions may be equally interesting, and, at the very least, muons passing through the detector provide an essential calibration tool in monitoring the performance of the detector.

We first discuss the scale and characteristics required of a detector[1] that will measure ultra high energy neutrino interactions. We then consider why one might listen rather than look at deep inelastic neutrino interactions. We discuss the acoustic parameters of a hadronic shower and the possibility of measuring a muon signature. In the last half of this paper we concentrate on the results[2] obtained to date in observing acoustic signals from hadronic showers both at Brookhaven National Laboratory (BNL) and Harvard University. This work suggests that ultrasonic particle detection is indeed feasible, currently down to the level of 10^{14} eV. Those aspects of acoustic particle observation which we presently plan to verify in accelerator tests are then outlined.

Currently planned accelerators--the Fermilab Energy Doubler, PEP, the world 60 + 60 GeV e^+e^- machine or Isabelle--will at most probe the weak interactions at a few hundred GeV in the center of mass. Thus we have taken a laboratory neutrino energy of 10 TeV (150 GeV in the center of mass) as a competitive lower bound at which to open a unique window on the weak interactions. The dramatic results achieved by increasing neutrino energy a mere factor of 10 from Gargamelle to Fermilab--neutral currents, dimuons, trimuons, the high y anomaly--stimulate a search at even higher energies. Further, high energy cosmic ray experiements suggest a threshold for new phenomena at 200 GeV. Thus obtaining neutrino energies two orders of magnitude higher than current experiements is both attractive and compelling.

Understanding new phenomena at these energies demands a detector capable of fully reconstructing the observable variables. We mention several examples: The characteristic signature of a W boson is expected to be a spike at high y or low ν=xy, where x and y are the traditional scaling variables of deep inelastic lepton scattering. The linear rise of the total neutrino cross-section observed at accelerators implies that the earth becomes opaque to neutrinos at 10 TeV. Therefore, determing the direction of the incident cosmic neutrinos and their energy is very important. A detector that reconstructs the incident direction can measure atmospheric neutrinos produced at all distances up to the diameter of the earth and obtain sensitivity to oscillations of neutrinos with masses as low as $\sim 10^{-3}$eV. Further, the origin of extraterrestrial neutrino sources could be pinpointed. Many new neutrinos would cause the neutral-to charged-current ratio to increase substantially above its low energy value of 20%. More basically, how many high energy neutrinos are produced in the atmosphere? The flux above a few GeV is unmeasured...Clearly, measurement of all four observables, the energies and angles of the muon and the hadronic shower, is necessary to unfold new physics.

What is the minimum number of neutrino events required; i.e. what is the smallest acceptable target mass? The level at which neutral current and di-muon events were first observed, $\sim$ 1 event/day, is an absolute minimum rate. Figure 1 shows the number of events per year as a function of the neutrino energy[3] if one assumes the cross section of the Weinberg model with $\sin^2\theta_W$=0.3 and a calculated atmospheric neutrino flux. A rate of one event per day at energies greater than 10 TeV requires 10^9 tons of target, e.g. $\sim$ one cubic kilometer of material. Clearly such a massive target must be constructed from a material free in nature--e.g., fresh or salt water, salt domes, or some other material that can simultaneously be target and detector. The anticipated integral neutrino flux is shown in

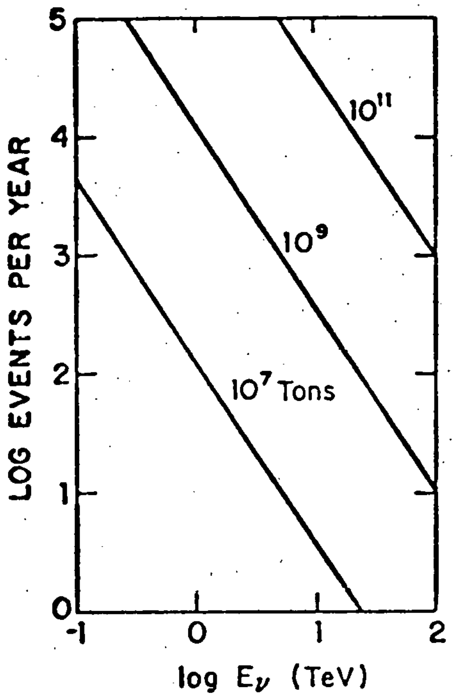


Fig. 1

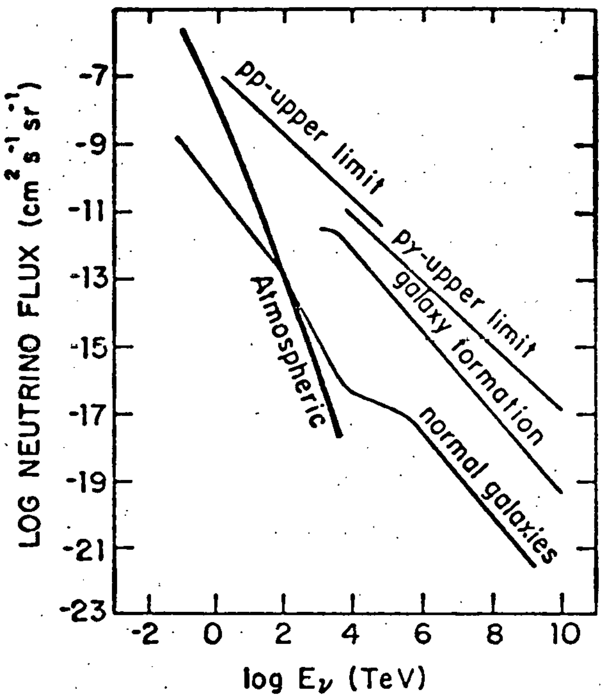


Fig. 2

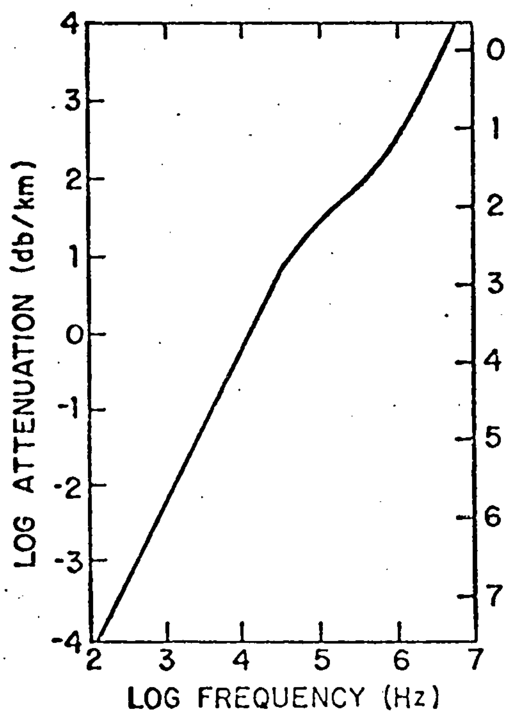


Fig. 3

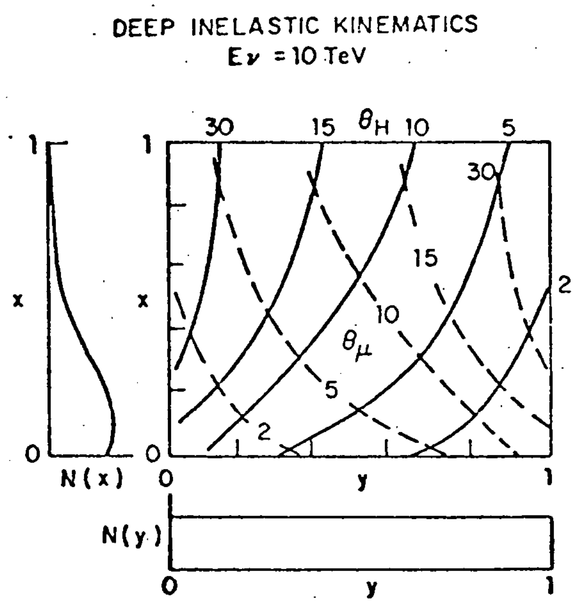


Fig. 4

Figure 2. This flux is calculated from an extrapolation of the muon spectrum, which is only measured to 1 TeV. Note that a muon flux at 1 TeV only fixes the neutrino spectrum to $\sim$ 300 GeV. Thus the extrapolation to 10 TeV neutrino energy must be carefully considered. In addition to the prosaic atmospheric sources of neutrinos, Berezinsky and Zatsepin[4] have suggested many more extraterrestrial neutrino sources which could be significant even at 10 TeV. In particular, cosmic ray protons can produce pions by interacting either with the gas in inter-galactic space (pp in Figure 2) or with the 3° black body radiation ($p\gamma$).

The background to high energy cosmic neutrino interactions is dominated by cosmic muons which undergo inelastic interactions producing a hadronic shower that takes a significant portion of the initial muon energy. Requiring the number of these events to be of the same order as the neutrino reactions limits the cosmic muon rate[3] to less than 10 muons/sec/km^2. A depth of 500 kg is necessary to achieve this shielding. The sea offers both a massive target and sufficient shielding if these depths (5 km) are accessible to detection apparatus.

If photomultipliers are used to see, for instance, the Cerenkov light produced by charged particles, the 500 atmospheres of pressure at 5 km depth presents a serious constraint on their construction. However, a severe limitation is caused by the attenuation length of light in the sea, which is at best 30m but typically is 15m. A cubic kilometer of detector would require on the order of 10^5 to 10^6 photomultipliers--the entire volume of the detector must be filled. In contrast, sound, as is shown in Figure 3, has an attenuation length at 10 KHz of 3 km! At lower frequencies f it is much longer, being proportional to $1/f^2$. A 3 km attenuation length means that the detector array need only cover the surface (and not the volume) of the target.

The range of scaling variables expected for the hadronic showers and muons from 10 TeV neutrino interactions determines the requirements placed on the angular and energy resolution of the detector. Assuming scaling continues to 10 TeV, Figure 4 shows the x,y plot.[5] Typical opening angles between the hadronic shower θ_H and the muon θ_μ ($\langle y \rangle \sim 1/2$) are on the order of 20 mr. The uniform y-distribution means that a typical 20 TeV neutrino deposits 10 TeV in the hadronic shower and emits a 10 TeV muon.

The development of a 10 TeV shower in seawater has been calculated by W. V. Jones.[6] It possesses a hot core ∿ 10 cm in diameter and 5m long. The total shower extends over 25 meters, and typically has 10^4 particles at the shower maximum.

The 10 TeV secondary muon is well above the 1 TeV critical energy (where radiative losses equal ionization losses), as is demonstrated in Figure 5. Above 1 TeV the dE/dx losses, including those from bremsstrahlung and pair production, rise linearly with the energy of the muon.[7] At 10 TeV, a muon deposits 40 MeV/gm instead of the customary 2 MeV/gm at low energies; the radiation length is 1 km. Thus, a 10 TeV muon loses 3 TeV in traversing 1 km, and this massive energy loss may also be observable by acoustic detection.

What sonic signature do we expect from the hot rod core of a hadronic shower? If one idealizes the energy deposition as a uniform cylinder as shown in Figure 6, then naive wave considerations suggest the following: (1) The wavelength λ would be on the order of the diameter d of the energy deposition (10 cm for a 10 TeV shower). (2) The fundamental frequency f of the sound emitted would be on the order of $c/2\lambda$ where c is the speed of sound ($f \sim 8$ KHz, since $c \sim 1.5$ km/sec=1.5m/ms=1.5mm/μs). (3) The sonic wave from this cylindrical acoustic antenna would be coherent (a very tight sonic disc) within an angle $\theta = \lambda/L$, where L is the length of the energy deposition ($\theta \sim$ 0.1m/25m=4mr). This inherent angular resolution is well matched to the neutrino kinematics mentioned above. It also implies coherency over a distance of 4m at 1 km, thus determining the maximum grid size. (4) The coherency and its $1/\sqrt{R}$ falloff characteristic of the cylindrical antenna extend to a near field limit $A = L^2/\lambda \sim (25m)^2/0.1m = 6km$. Any detector considered here would be operating in the near field.)

The actual pattern of energy deposition of a hadronic shower may reveal its direction and distinguish it from an electromagnetic shower. Initially the hot

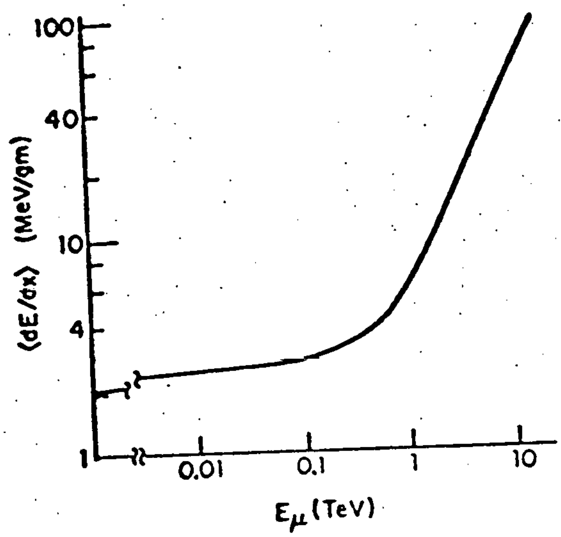


Fig. 5

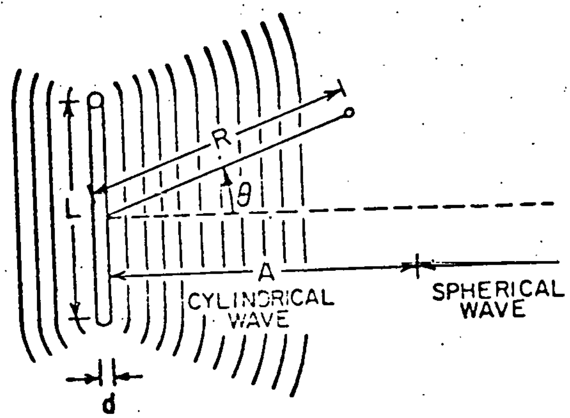


Fig. 6

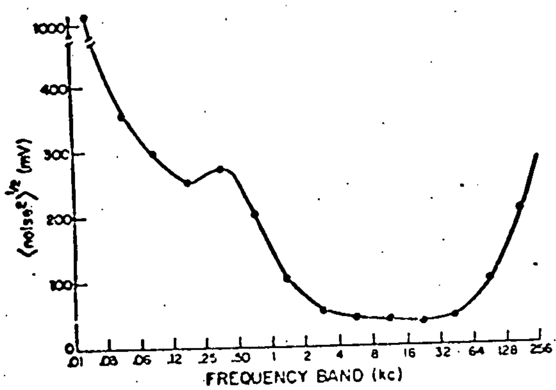


Fig. 7

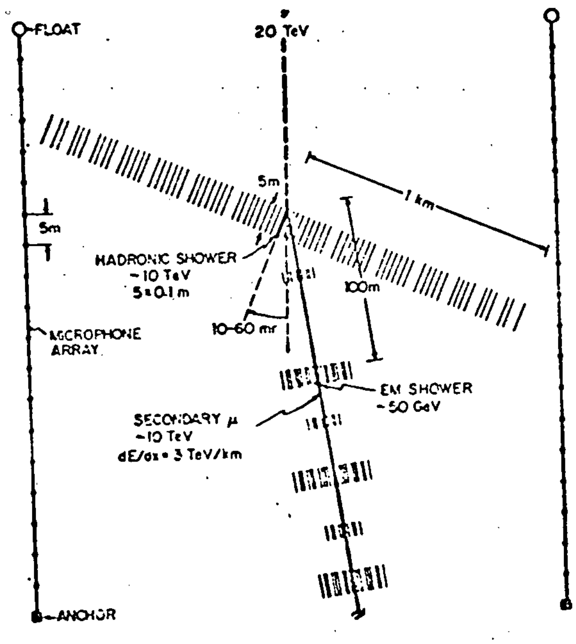


Fig. 8

core of the shower is ∼ 2 cm in diameter; ∼ 5 m later (larger than the grid size of the detector) it is ∼ 20 cm in diameter.[7] The fundamental frequency will change from ∼ 100 KHz near the vertex of the shower to ∼ 10 KHz after full development. Thus transducers must be sensitive to at least 2 bandpasses if they are to determine the direction of the hadronic shower. Indeed the ultrasonic image of the hadronic shower should reveal details of its structure via Fourier decomposition of the signal as a function of position in the shower. E.g. very tight showers characteristic of electromagnetic origin should be distinguishable from hadronic showers with their broad structure characteristic of the 300 MeV transverse momentum inherent in their secondary interactions.

From purely dimensional analysis, we expect the pressure p of the signal to be proportional to the volume coefficient of expansion K (10^{-4}/°C for H_2O) divided by the specific heat C_p (1 cal/g/°C). It should be linearly related to the energy deposited D, and in the near field of an acoustic antenna should be proportional to $1/\sqrt{LR}$,

$$P\ (\text{dynes/cm}^2) \propto [(K/C_p)\ (E/\sqrt{LR})]M.$$

Dimensional analysis does not determine the model dependent term M (units of sec^{-2}). Two models have been proposed. A pessimistic model[8] by Dolgoshein and Askarian, assuming uniform heating in the hot rod, yields an important f^2 dependence (which could compensate for the f^2 increase of the attenuation length) multiplied by a (sin x)/x term characteristic of a cylindrical antenna: $M=(f^2/2)(\sin x)/x$, where $x=(L/2\lambda)\sin\theta$. A calculation[9] of Bowen makes an optimistic assumption that the hot rod is composed of many hot needles (the delta rays along the particle tracks) whose locally high energy density produces a sound which propagates out faster than the local heat diffuses out. The resulting large enhancement factor is inversely proportional to the thermal coefficient D (1.4×10^{-3} am^2/sec in H_2O): $M=c^2 4\pi D\tau$. If detection threshold is 6×10^{-5} dynes/cm^2, the Dolgoshein-Askarian calculation requires that 10^{14} eV be deposited 150 m from the transducer while the Bowen calculation requires only 10^6 eV! However, neither calculation considers other sound generating mechanisms: e.g. microbubble implosions, ion formation in the high electric fields of the shower, slow neutron contributions, etc.

The determination of the sound intensity is a vital experimental question. Previous measurements[10] of sound production in materials have been done by Hofstadter and others in aluminum and piezoelectric material. However, the quantitative interpretation of the results is difficult due to the small size of the targets and the complicated acoustic behavior of solids. Recent tests[2] in water to determine the actual mechanism of the sound are the subject of the last half of this talk.

We first consider the level of noise we expect in the sea. The absolute minimum is the thermal noise which rises as $\sqrt{f}$ and has a value of 6×10^{-5} dynes/cm^2/Hz$^{1/2}$ at 30 KHz. The noise pressure spectrum as a function of frequency has not been measured for f>300Hz at depths>3 km. However, the known spectrum near the surface(including shipping noise, wind, and rain which dominate the noise), when propagated to 5 km depth using Figure 3, is less than the thermal noise for $f \gtrsim 10$ KHz. Thus a window exists between 10 and 30 KHz with a noise level noted above. (A reference point for this sound level is the sensitivity of the ear,which is only 10 db above this expected noise level.) Let us compare the expected noise in the sea with that measured in a barrel of water in the tunnel of the fast-extracted beam line at the BNL AGS (see Figure 7),with water pumps, magnet hum, fans, etc., producing noise. Again an acoustic window appears between 10 and 30 KHz. The rise above 30 KHz is due to thermal noise; the noise level in the window is 3×10^{-3} dynes/cm^2/10 KHz. The noise in the ocean at 5 km depth should be much less than this, particularly since there are several temperature inversion layers (which cause speed of sound inversion layers) in the first two kilometers. These total internal reflection layers are expected to suppress the noise level at depth far below that expected from an exponential attenuation of the surface noise.

A typical neutrino detector might consist of a series of vertical strings, each with ~ 200 microphones spaced at 5 meter intervals between an anchor at the bottom and a float at the top. See Figure 8 for a cross-sectional schematic of such an array. From above, the array might consist of 40 such strings placed at 100-meter intervals along the border of 1 km^2. The required number of phones is $\sim$ 10,000. (An array of microphones of this size had already been deployed by the Navy as early as 1955.) Each station would include one transducer, an FET preamp, a discriminator, 1 TDC, $\geq$ 2ADC's (each in a different band pass), and MOS local storage. Similar electronics in comparable quantities is currently being used in several high energy counter experiments.[11] Communication from a central terminal to each station could be done along a single line (with each station having its own code). Typical total power consumption might be 20 kw.

Although this simple scheme has not been optimized, the tight sonic disc signature of a hadronic shower produced inside the volume is generally detected by $\sim$ 80 hydrophones. Even if the sound from the muon is below the single microphone threshold level, the vertex of the hadronic shower determines a point along the muon track. Further, the muon track must lie in a narrow cone relative to the direction of the hadronic shower. Using phased antenna array techniques (familiar in radar and astronomy) and knowing the autocorrelation length, a muon track with a signal several orders of magnitude into the noise should be detectable.

Further, the energy E_μ of the muon may even be measurable via the radiative dE/dx losses. The contributions[7] from ionization, pair production, bremsstrahlung, and nuclear interactions are, respectively,

$$dE/dx(\text{MeV gm}^{-1}\ \text{cm}^{-2}) = 2 + (1.7 + 1.3 + 0.4)E_\mu\ (\text{TeV}).$$

The 1.7 MeV gm^{-1} cm^{-2}/TeV contribution from pair production is particularly useful because the muon energy loss to each pair is peaked at small fractions, typically $m_e/m_\mu \sim 1/200$ of the muon energy. A muon of 10 TeV induces $\sim$ 10 showers of $\sim$ 50 GeV as it passes through 1 km of water. Thus pair production deposition is similar to ionization losses and allows a determination of the muon energy from several dE/dx measurements. The distribution of fractional energy depositions due to bremsstrahlung is uniform from 0 to 1. Therefore, one would add these rare but large losses to the muon energy determined from the regular small dE/dx losses, if such large losses occur before sufficient dE/dx measurements have been made to determine the muon energy.

regular small losses. The technique is similar to that used to handle large Landau fluctuations in multiple dE/dx measurements at low energies. Monte Carlo calculations[12] by Miyake's group in Japan suggest that multiple dE/dx measurements and a fit to the pair production distribution yield acceptable resolutions. For energies $\gtrsim$ 10 TeV and 100 measurements with a 10 m grid size, an energy resolution of 20% is obtained.

But the crucial experimental question remains: Do showers produce detectable sonic signals at these energy depositions? Three experimental tests have been done. One at the 200 MeV linac at BNL with heavily ionizing protons stopping in water (range = 30 cm) with total energy depositions between 10^{19} and 10^{21} eV and deposition times ranging from 3 μs to 200 μs. The diameter of the beam was fixed at 6 cm (a characteristic time of 30 μs). A similar test has been done at the 160 MeV cyclotron at Harvard where the energy deposition could be decreased to 10^{15} eV. A third test has been done with minimum ionizing protons from the 32 GeV fast extracted beam at BNL. As in the BNL linac test, the beam could not be tuned below energy depositions of 10^{19} eV. Typically 3×10^{11} protons traversed 30 cm of water during a deposition time of 2 μs with a beam diameter variable between 5 and 20 cm. The detector arrangement for the linac test is schematically drawn in Figure 9. In both tests at BNL, the sound was extremely loud to the naked ear without any amplification. At the linac, the sound was heard through 10m of water. The transducers used in these test were of two varieties. One type is a standard Navy hydrophone with gain variable between 0 and 110 db and a sensitivity of -80 db re 1 volt/dyne cm^2, uniform between 1 KHz and 200 KHz. The high frequency cutoff is determined solely by the diameter (2 cm) of the cylindrical piezoelectric (PZT4) transducer. A second, smaller type hydrophone is sensitive to about 1 MHz. However, its smaller size limits its gain to -115 db re 1 volt/dyne cm^2. Figure 10 shows the signals from the two large-style hydrophones situated as shown in Figure 9. The two scope traces show a remarkably simple bi-polar pulses followed by reflections from the bottom of the tank after an

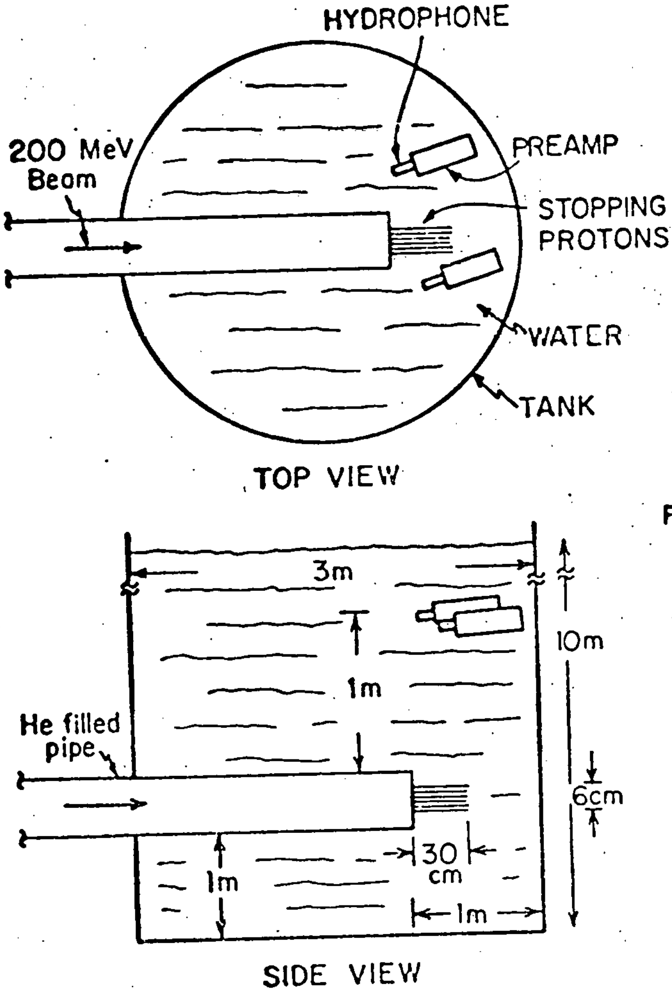

HYDROPHONE
200 MeV Beam
PREAMP
STOPPING PROTONS
WATER
TANK
TOP VIEW
3m
10m
1m
He filled pipe
6cm
30 cm
1m
1m
SIDE VIEW

Fig. 9

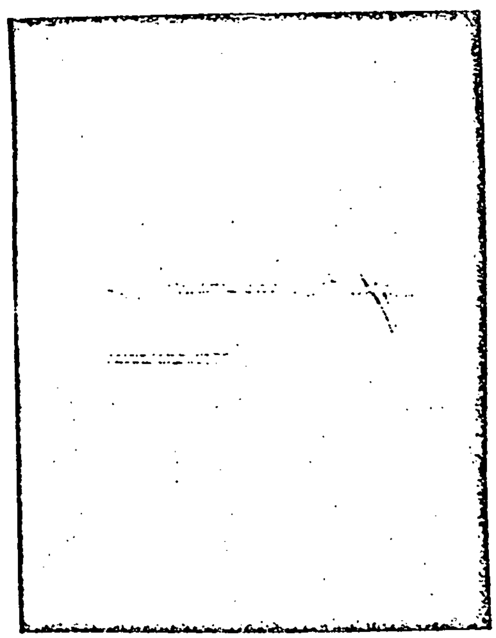


Fig. 10

appropriate time delay. (The two hydrophones are operated out of phase.) The half period of the bi-polar signal (30 μs) is just what one expects from the sound transit time across the beam radius (3 cm). The time delay between the signals (150 μsec) is due to the difference in path length to the two microphones from the source(∿ 20 cm). For beam durations longer than the transit time characteristic of the diameter, destructive interference occurs after the initial compressional wave and before the final rarefaction wave. The peak pressure saturates at these long durations (see Figure 11), and therefore, we discuss only data taken with spill times short compared to the transit time characteristic of the diameter.

Figure 12 shows the pressure amplitude as a function of energy deposition. It is linear over > 2 orders of magnitude, with a slope ∿ 10 times the value predicted by the Dolgoshein calculation.

Moving the hydrophones away from the source, as shown in Figure 13, demonstrates that the pressure decreases as 1/R. This was anticipated in the test, since the source distances involved are in the far field of the 6 cm diameter by 30 cm long energy deposition.

At the AGS, we varied the beam diameter and measured the period of the pressure wave. The relationship, shown in Figure 14, is consistent with a linear dependence of the period on the diameter.

A Fourier decomposition of the signal seen in that test is shown in Figures 15. The frequency spectrum of the rarefaction wave (Figure 15b) is peaked around 50 KHz, which is characteristic of the 1 cm diameter of the AGS beam. This is what one expects from the collapse of a uniform hot rod. However, the compressional wave (Figure 15a) shows strong Fourier components all the way up to 300 KHz, where the sensitivity of the microphone starts to drop. The spectrum of the compressional wave implies that the initial energy deposition consists of many hot needles of diameters small compared to the overall size of the energy deposition.

The tests with minimum ionizing protons obtained an absolute pressure amplitude a factor of∿100 times that of the Dolgoshein calculation.

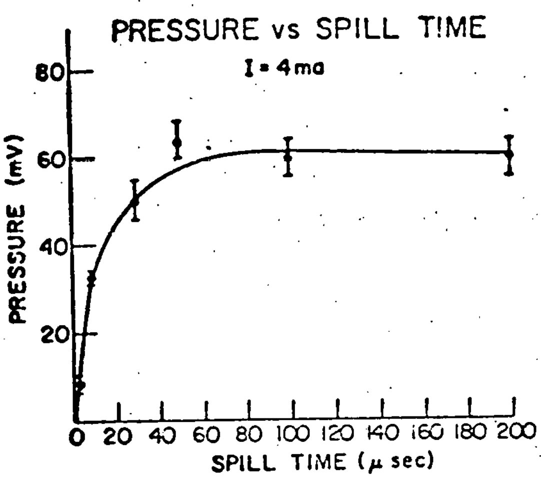


Fig. 11

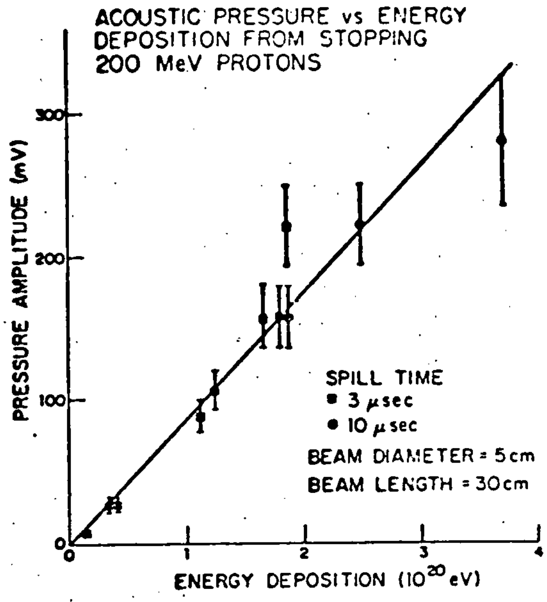


Fig. 12

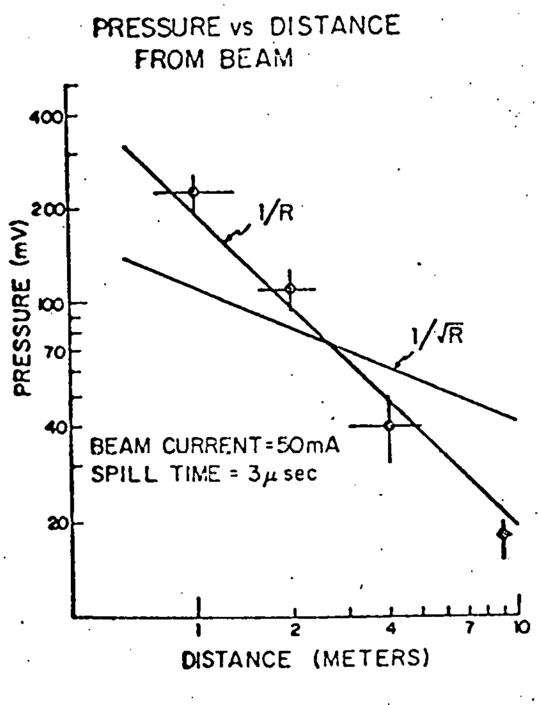


Fig. 13

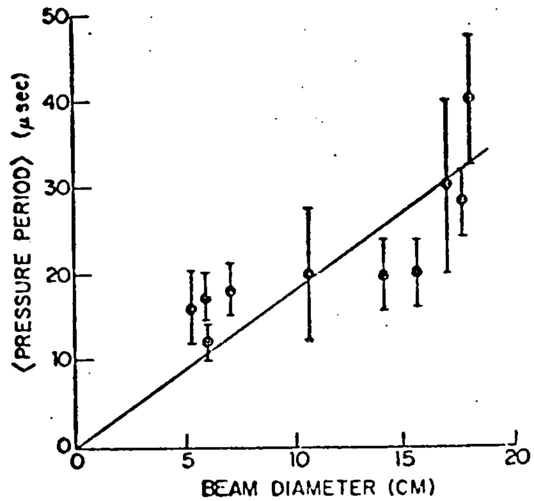


Fig. 14

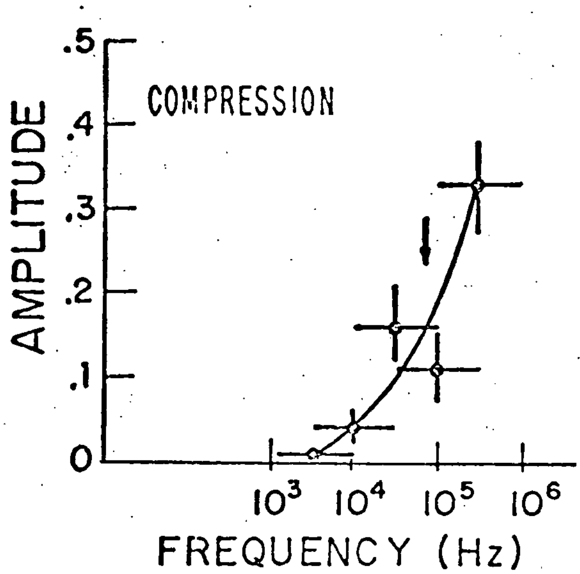


Fig. 15a

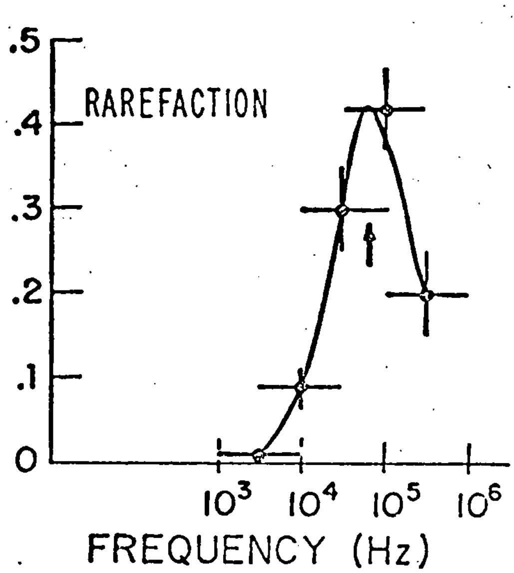


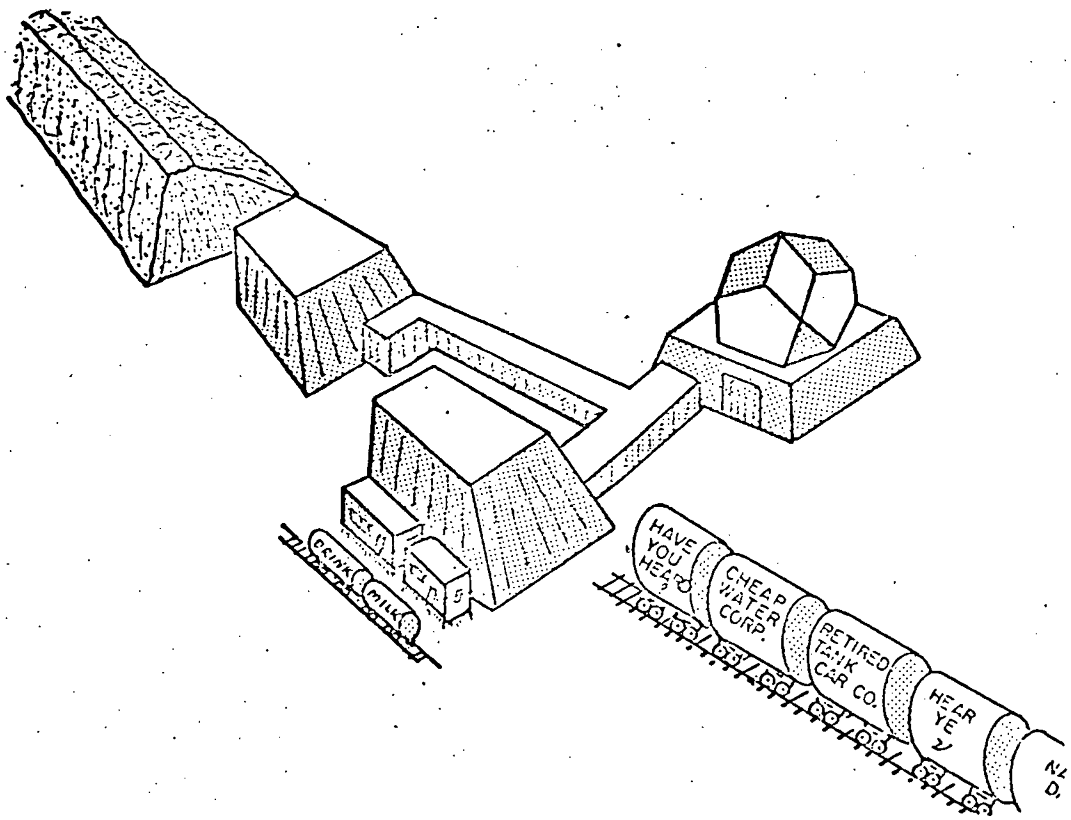
Fig. 15b

Tests at the Harvard cyclotron allowed us to decrease the energy deposition down to 10^{15} eV. The signal seen there, 2×10^{-2} dynes/cm^2/10 KHz, is consistent with a linear extrapolation down 5 orders of magnitude from the tests at the linac. For a sea noise of 6×10^{-5} dynes/cm^2/Hz$^{1/2}$, heavily ionizing particles depositing 100 TeV and minimum ionizing particles depositing 10 TeV should be measurable with a signal to noise ratio of 1:1. Note that these thresholds are obtained with no tricks; i.e. we have not used coincidence, phase information, or summing of many microphone signals. For instance, an event in the detector of Figure 10 would include information from typically 80 microphones. If the data from the microphones were added incoherently, one would gain a factor of 9 in signal to noise; added coherently, a factor of 80.

We have investigated the effect of the ambient pressure on the sonic signal, which would be important if microbubbles were a dominant mechanism of sound production. At the Harvard cyclotron we find that the sound is unchanged for either fresh or sea water between 1 and 15 atmospheres. The signal from sea water is within a factor of two of that from fresh water.

Future tests are planned to further understand the sonic technique of particle detection. At the cyclotron, we hope to push the threshold down $\sim$ three orders of magnitude (rf noise is our current problem). We wish to understand the factor of 10 to 100 enhancement above the simple Dolgoshein model, and to measure several materials with different K and c_p values to test the hypothesis that simple thermal expansion is the sound generating mechanism. In a Fermilab test (Proposal 528), we plan to measure the intensity of sound as a function of angle and to verify the $1/\sqrt{R}$ dependence for the near field. We want to observe the signal from a shower initiated by a single 100 GeV particle and to measure the radiation from various regions of the shower to verify the feasibility of a 10^5 ton water detector for accelerator neutrino physics.

In summary, we have at the very least invented a new beam monitor; a 10^9 ton neutrino detector, with capabilities at 10 TeV comparable to those of counter detectors at low energy accelerator experiments, seems feasible; and perhaps a 10^5 ton train of retired, water-filled tank cars, equipped with electronic stethoscopes, may be the future generation of neutrino detector at the Fermilab Doubler or the SPS.



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1) The capabilities and design of a deep underwater muon and neutrino detector (DUMAND) have been explored in depth during two summer studies. The work of the most recent study has been published at Fermilab as the Proceedings of the 1976 DUMAND Summer Workshop, A. Roberts, ed., Honolulu, September 6-19, 1976. We refer to it below as "DUMAND 76".

2) A detailed account of these results is in preparation for publication in Nuclear Instruments and Methods. Previous descriptions of the work have appeared in"A Proposal to Test the Feasibility of Acoustic Detection of Particle Showers,"T. Bowen, H. Bradner, W. V. Jones, J. Learned, I. Linscott, A. Parvulescu, B. Pifer, P. Polakos, J. Strait, and L. Sulak, "DUMAND 76", p. 547 and in"Studies of the Experimental Feasibility of Acoustic Detection of Particle Showers: A Progress Report,"ibid., p. 559.

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