The Prediction and Detection of UHE Neutrino Bursts.

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In this paper we look at $\sim 10^{14}$ eV neutrino bursts which are predicted to be observed in correlation with gamma ray bursts (GRBs). We describe an efficient way of constructing a km^2 effective area detector for these neutrino bursts. The proposed detector will cost $<$ \$3M and will operate in the 4-km deep water off St. Croix for at least one year, sufficient time to collect the expected ~ 20 events in coincidence with satellite measured GRBs provided the fireball model is correct. Coincident gamma ray and neutrino bursts can be used to test the limits of the relativity principles.

I. INTRODUCTION

Gamma ray bursts are presently the most enigmatic astrophysical phenomenon. Recent observations indicate that they originate from cosmological sources [1]. They are observed in satellites near the Earth at a rate of ~ 1 per day. The relativistic fireball model is consistent with all observed features of GRBs and has been used by Waxman and Bahcall [2] to predict a measurable flux of $\sim 10^{14}$ eV neutrinos. According to this model, a detector of ~ 1 km^2 effective area will observe ~ 20 neutrino induced muons per year in coincidence with GRBs. Other models of astrophysical processes also demand production of high-energy neutrinos, including other burst models, AGN models, and topological string models. The Neutrino Burster Experiment (NuBE) will measure the flux of UHE ($>$ 1 TeV) neutrinos over a $\sim$ km^2 effective area and will test the fireball model stringently and uniquely, with an inexpensive, quick and robust experiment.

II. UHE NEUTRINOS COINCIDENT WITH GRBS, DIFFERENT MODELS

A. Ultra-relativistic Fireball Model

General phenomenological considerations indicate that GRBs could be produced by the dissipation of the kinetic energy of a relativistic expanding fireball. According to Waxman and Bahcall [2], a natural consequence of the dissipative cosmological fireball model of gamma ray bursters is the conversion of a significant fraction of fireball energy into an accompanying burst of $\sim 10^{14}$ eV neutrinos, created by photomeson production of pions in interactions between the fireball γ rays and accelerated protons. The basic picture is that of a compact source producing a relativistic wind. The variability of the source output results in fluctuations of the wind bulk Lorentz factor which leads to internal shocks in the ejecta. Both protons and electrons are accelerated at the shock and γ rays are radiated by synchrotron and inverse Compton radiation of shock accelerated electrons. The accelerated protons undergo photomeson interactions and produce a burst of neutrinos to accompany the GRB.

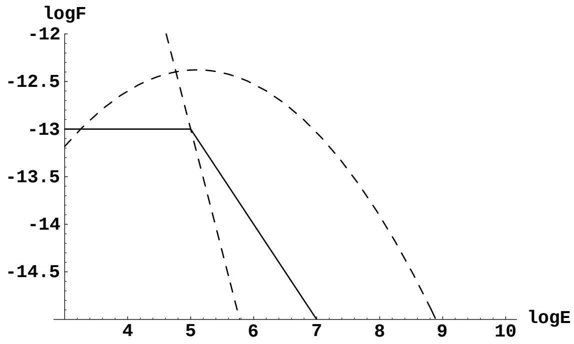

FIG. 1. Plot of the expected $\nu_\mu + \bar{\nu}_\mu$ flux considering atmospheric background, an Active Galactic Nuclei (AGN) model and the relativistic fireball GRB model (solid line). Here F is in cm^{-2} s^{-1} sr^{-1} and neutrino energy E has units of GeV.

Figure 1 illustrates the expected neutrino flux from the GRB model described above in comparison to a typical AGN model and the expected atmospheric neutrino background. These neutrino bursts should be easily detected above the background, since they would be correlated both in time and angle to the GRB γ rays.

B. Cosmic String Model of Neutrino Production

UHE neutrinos may also originate in cosmic strings. Cosmic strings are topological relics from the early universe which could be superconducting and carry electric current under certain circumstances. A free string (a nonconducting string uncoupled from electromagnetic and gravitational fields) generically attains the velocity of light at isolated points in time and space, which are known as cusps. Superconducting cosmic strings (SCS) emit energy in the form of classical electromagnetic radiation and ultra-heavy fermions or bosons which decay or cascade at or near the cusp. Using recent progress on the nature of electromagnetic symmetry restoration in strong magnetic fields, the study of the decay products of ultraheavy fermions near SCS cusps consistent with an SCS explanation of γ ray bursts shows that the energy emitted from the cusps is found to be mostly in the form of high energy neutrinos [3]. The neutrino flux is roughly nine orders of magnitude higher than that of the γ rays. Therefore this is another model that predicts high energy neutrinos to be observed in coincidence with γ ray bursts.

III. DETECTION OF UHE NEUTRINO BURSTS

A. Description of the Detector

The neutrino burst experiment (NuBE) is designed to search for UHE neutrinos in coincidence with GRBs. NuBE is a water Cherenkov detector whose simple design derives from the very high energy of the GRB neutrinos. The expected energy of the neutrinos in the fireball model is $\sim$ 100 TeV, which leads to Cherenkov signals detectable with high efficiency at large distances from the core track. We can detect a muon core when the muon neutrino interacts in material within $\sim$ 10 km of the array, leading to a highly radiative muon observable with high efficiency at perpendicular distances $>$ 150 m from the core all along its multi-km length. An electron neutrino has a core track which is itself only a few meters in length, but the light from this short core is intense and can be seen by the proposed array at distances in excess of 500 m. Coincidence is required with measurements of the photon arrival time and the GRB location provided by detection in satellites.

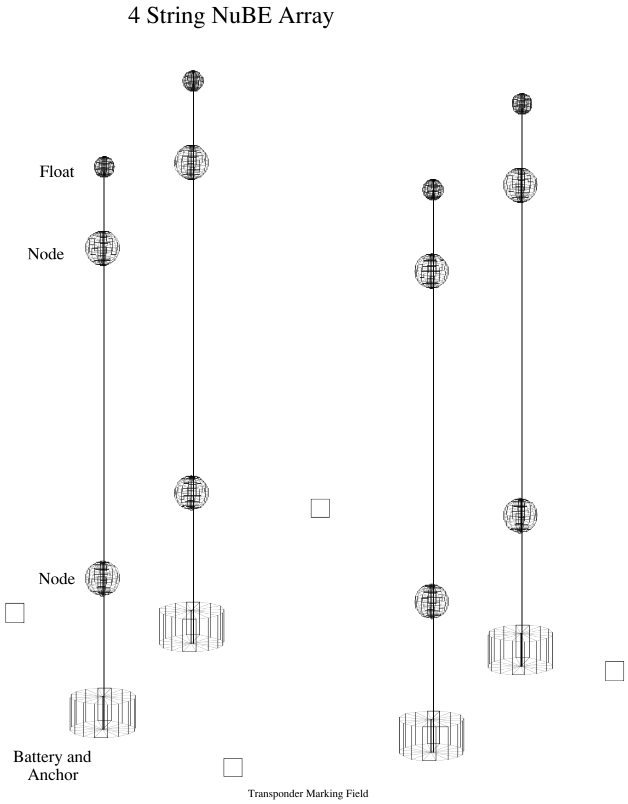

FIG. 2. Schematic Diagram of the 4 String NuBE Detector.

The 4π NuBE detector approximates a sphere of diameter $>$ 700m, creating an effective area of $>$1.5 km^2. The detector consists of four strings placed in the clear water of the deep ocean with their anchors at the corners of a square having $>$ 400m sides, as shown in Figure 2. Each string has two photon-detector nodes separated by $>$ 400m along the string. Each node acts independently of the other 7 nodes in the array, having its own local trigger and data acquisition and storage, thus providing robustness and redundancy. Local node clocks are periodically synchronized using bright flashes of blue light from calibration spheres at each node. Absolute time is kept via these clocks to accuracy of $<$ 1 second per year. A signal of a high energy event in NuBE consists of a locally triggered event in any node occurring within 5 μs of a locally triggered event in any other node. The 5 μs accounts for the muon or photon transit time across the array. The coincidence that indicates high energy events is determined off-line. In a 2-node event the time difference between the arrival times at each node gives the incident track direction on a cone, while events having more nodes hit provide the incident direction to within as little as ~ 10 degrees. This angular resolution capability provides robust verification of correlation with the GRB for any signal that arrives in the GRB time window. The electronics connecting the photon detector to the data acquisition system is straightforward, requiring no further R&D. It includes a 5ns resolution TDC for relative arrival time which allows up/down discrimination on local events and provides a measurement of the number of photoelectrons produced by the time over threshold for the signal.

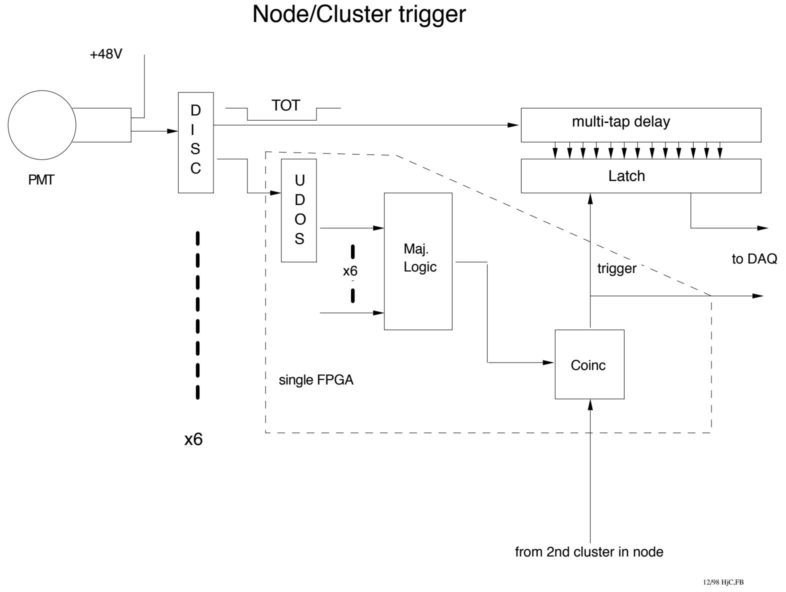

FIG. 3. Systematic Diagram of the NuBE Node/Cluster Trigger

Much of the detector can be assembled from "off-the-shelf" items; anchors, strings and housing spheres are items of commerce familiar to many of our collaborators. Deep-sea rated battery packs on each node can provide > 1 year of untended operation. The detector is easy to deploy and to recover in any of a variety of locations, since it doesn't require accurate positioning. Placing the strings in the location at a site off the coast of St. Croix in the US Virgin islands can be done easily by vessels of opportunity or with minimum schedule lead time. This site has the additional advantage of providing 4km deep water within 15km of the shore, a clear virtue for site visits and data retrieval. The 4km depth attenuates the cosmic ray muon background to a few per minute per node, an ideal calibration rate. Up/down discrimination allows us to calibrate with the Superkamiokande experiment for their highest energy upward signals, giving verification of an energy threshold for each node. NuBE provides > 1 km^2 collecting area in its 4-string implementation and can tell us quickly whether the fireball model is correct in its predictions of high-energy neutrino bursts. The total project, from initial approval to completion of data analysis, will take < 3 years and cost $<$ \$ 3M.

B. Underlying Physics in the Detection of Neutrino Bursts

It is important to maximize the physical inferences that can be drawn from coincident photon and neutrino detection [4]. The possible simultaneous or near simultaneous observation of neutrinos and γ rays will provide many important new insights into the properties of neutrinos and GRB sources. It will also yield a novel test of the weak equivalence principle (WEP). This has been previously noted for the SN1987A explosion where neutrinos were observed within a known (but large) time interval of γ ray emission. The same tests can be done for a much higher accuracy and with better statistics since we will be dealing with multiple sources at cosmological distances. The fact that the mystery of the distance scale for GRBs has been solved in some sources makes this statement stronger.

The neutrinos from GRBs can be used to test the limits of the relativity principles. This was done for the neutrino emission from SN1987A [5]. Neutrinos from GRBs could be used to test the simultaneity of neutrino and photon arrival to an accuracy of 1s (1ms for short bursts), checking the assumption that photons and neutrinos should have the same limiting speed. Considering a burst at $\sim$ 100 Mpc with $\sim$ 1s accuracy, as an example, the fractional difference in limiting speed of $\sim 10^{-16}$ is revealed. This may be compared to the SN1987A value of 10^{-8}. According to the WEP, the photons and neutrinos should suffer the same time delay as they pass through a gravitational potential. If the most influential gravitational potential along the path is the local galaxy, we can compute a time difference that would result from various trajectories with respect to the galactic nucleus, the suspected site of the black hole [6]. NuBE detection of GRB neutrinos would allow a test of the WEP to an accuracy of 10^{-7}. Results from measurements on low energy neutrinos from the supernova 1987A probed this value to 10^{-2} [5]. On the other hand the most influential gravitational potential sampled may be near the source itself. If we see nearly the same delay for all GRB events regardless of distance this may point to a failure of general relativity in predicting the exit time from the source. Since there are several GRB sources the corresponding statistics would increase, and the GRB sources being much further away than the SN1987A would offer a new distance scale and improved sensitivity.

It would be interesting to investigate the possible detection of Tau neutrinos. This would imply neutrino oscillations in transit because none of our astrophysical models predict Tau neutrinos to be produced at the source. The key signature is the charged current Tau neutrino interaction, which produces a double cascade, one on either end of a minimum ionising track. Tau neutrinos could be theoretically identified by the double bang events [7] but the two individual bangs would be very difficult to resolve in our proposed detector.

This experiment could be an indirect test for pointing to the model for the highest energy cosmic ray production. There have been suggestions that GRBs could be the source of Ultra High Energy (UHE) Cosmic Rays (CR) [8]. This source model is consistent with the observed CR flux above 10^{20} eV. For a homogeneous GRB distribution this model predicts an isotropic, time dependent CR flux.

Thus the large distances, short emission time, and trajectory through varying gravitational fields, leads to the potential for tests of some fundamental neutrino properties not possible in terrestrial laboratories [4]. Limits may also be placed on neutrino mass, lifetime, electric charge and on neutrino oscillation parameters.

IV. CONCLUSIONS AND PRESENT STATUS OF FIELD

There are a number of active efforts to observe high energy astrophysical neutrinos including AMANDA, NESTOR, Baikal, ANTARES and Superkamiokande. The relatively dense instrumentation of these experiments, compared to NuBE, is intended to derive source origin by pointing back to the neutrino trajectory with a high degree of accuracy. The Superkamiokande detector in particular provides an excellent calibration point for a large area detector because of its very high efficiency for GeV neutrinos. However these are all relatively small arrays and consequently will detect at best only one or two neutrinos coincident with GRBs per year. NuBE in comparison is aimed at making a large ($> 1\mathrm{km}^2$ effective area), sparse detector to look specifically for neutrinos > 10 TeV and to determine whether they are in coincidence with the GRBs. It is the most efficient and robust way of constructing a detector for UHE neutrino bursts and will detect ~ 20 events per year (as predicted by the fireball model).

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[1] K. Hurley, e-print astro-ph/9812052, Review paper presented at the 3rd INTEGRAL Workshop, Taormina, Sicily, September 1998, to be published in Astrophysical Letters and Communications; T. Piran, Nucl.Phys.Proc.Suppl.**70**, 431 (1999).

[2] E. Waxman and J. Bahcall, Phys. Rev. Lett., **78**, 2292 (1997).

[3] R. Plaga, Astrophys. J. Lett. **424**, L9 (1994); D.N. Spergel, *et. al.*, Nucl. Phys. **B291**, 847 (1987).

[4] T.J. Weiler *et. al.*, hep-ph/9411432, Preprint VAND-TH-94-20 & UH-511-801-94.

[5] M.J. Longo, Phys. Rev. D, **36**, 3276 (1987); M.J. Longo, Phys. Rev. Letts. **60**, 173 (1988); L.M. Krauss and S. Tremaine, Phys. Rev. Lett. **60**, 176 (1988); S. Pakvasa *et.al.*, Phys. Rev. D **39**, 1761 (1989).

[6] S. Markoff *et. al.*, Astrophys. Journal **489**, L47 (1997); J. Haller *et. al.*, Astrophys. Journal **456**, 194 (1996).

[7] J.G . Learned and S.Pakvasa, Astroparticle Physics, **3**, 267 (1995).

[8] Eli Waxman, Phys.Rev.Lett. **75** 386 (1995); M. Milgrom and V.V. Usov, Astrophys. Journal, **449**, L37 (1995); M. Vietri, Astrophys. Journal **453**, 883 (1995).