Detecting ν_T Oscillations at PeV Energies

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Abstract

It is suggested that a large deep underocean (or ice) neutrino detector, given the presence of significant numbers of neutrinos in the PeV energy range as predicted by various models of Active Galactic Nuclei, can make unique measurements of the properties of neutrinos. It will be possible to observe the existence of the ν_τ, measure its mixing with other flavors, in fact test the mixing pattern for all three flavors based upon the mixing parameters suggested by the atmospheric and solar neutrino data, and measure the ν_τ cross section. The key signature is the charged current ν_τ interaction, which produces a double cascade, one at either end of a lightly radiating track. At a few PeV these cascades would be separated by roughly 100 m, and thus be easily resolvable in next generation DUMAND-like detectors. First examples might be found in detectors presently under construction. Future applications are precise neutrino astronomy and earth tomography.

1 The Double Bang Signal

The interaction of high energy tau neutrinos (ν_τ's) in DUMAND-like detectors [1] will present a spectacular "double bang" signature. The existence of such events depends upon the presence of 10^{15} eV neutrinos in adequate numbers, as are in fact predicted from active galactic nuclei (AGN)[2] for example. The interesting signals are from the charged current (cc) quark interactions of ν_τ's. Since the τ mass is about 1.8 GeV, a τ of 1.8 PeV and with $c\tau$ of 91 μm[3] would fly roughly 90 m before decay. The signature, as illustrated in Figure 1, is:

1. a big hadronic shower from the initial ν_τ interaction,
2. a muon like τ track, and then
3. a second and even larger particle cascade.

To give some scale to this, the ratios of detectable photons from these three segments are roughly $10^{11} : 2 \cdot 10^{6} : 2 \cdot 10^{11}$. Such large bursts of light would be visible from distances of hundreds of meters by present technology photomultipliers. The charged τ will be hard to resolve from the bright Cherenkov light of the cascades, and the photon arrival times will not be very different. However, simply connecting the two cascades by the speed of light will suffice to make an unambiguous association (including direction of the cascades) of the two bursts. In fact, as we discuss later, it appears that the double bang signature alone is nearly background free, sufficiently so as not to have to invoke lack of either incoming or outgoing charged particles (muons) to produce a clean sample. The double bang event topology appears to be a unique signal for real τ production by ν_τ's, thus permitting "discovery" of the ν_τ, and inferring mixing of neutrino flavors. Finding even one of these events would have significant implications.

The rate for such events is of course unknown experimentally now. If we employ optimistic fluxes from the Szabo and Protheroe model[4] for the sum of neutrinos from all AGN, we estimate 1000 events of this type per year in a volume of 1 km^3 of water or ice, in a 2 PeV energy band. While the experiments now being constructed (AMANDA, Baikal, DUMAND, and NESTOR) would expect to see about one such event per year; they should easily determine if the AGN flux is present and if lucky may find exemplary double bang events.

We show below that ν_τ's are unlikely to originate in commonly considered astrophysical sources, but are likely to appear due to neutrino mass and mixing, over a large range of allowable (and even favored, if the solar neutrino puzzle and the atmospheric neutrino anomaly have anything to do with oscillations) neutrino mixing parameter space. The point is that in the general energy range of a few PeV there exists a powerful tool for searching for τ mixing, over an unequalled parameter space, with unambiguous identification of the τ. We know of no other way to make a ν_τ **appearance** experiment with cosmic rays, no way has been proposed for an accelerator experiment except for the use of emulsions making observations of relatively large $\delta m^2 > 1\ eV^2$, and no way of detecting ν_τ's except statistically at proposed long baseline accelerator experiments.

In the following we explore the physics implications of the observations of the double bang events in a little more detail, discussing the kinematics, sources of ν_τ's, the sensitivity to two and three neutrino mixing, and potential (and we conclude small) backgrounds.

2 Essentially Full Kinematics from Double Bang Events

One may in principle measure the total energy of the incident neutrino and nearly the full kinematics of the double bang events by adequate sampling of the Cherenkov radiation. The observation of light from the first cascade yields the energy transferred to the quark, E_1. (The fraction of energy transfered to the quark is traditionally designated as y). The magnitude of the light from the tau track plus the flash of light from the second cascade gives the energy (E_2) kept by the τ except for that carried away by the decay neutrino(s). The sum ($E_T = E_1 + E_2$) gives the rough incoming neutrino energy, and the ratio of the first cascade energy to the total energy (E_1/E_T) provides the $\sim y$ value. The cross sections and $< y >$ are almost equal for ν_τ and $\bar{\nu}_\tau$ at this energy[5]. Observing the y distribution is a check on the observations, and departures from expectations could signal new physics. In calculating the ν_τ flux, the measured y distribution will permit correction for the potentially unobserved events near $y = 0$ (no initial cascade) and near $y = 1$ (initial cascade with most of the energy and the tau decays too close to the first cascade for resolution). The near equality of the cross sections for particle and antiparticle permits the total flux to be calculated independently of the mix in the cosmic beam.

In a ν_τ cc interaction, $< y >$ is about 0.25 at these energies [4] and the energy deposited is $< E_1 >\sim 1/4\ E_\nu$. The τ carries about 0.75 times the ν_τ energy. In the subsequent decay of τ, the energy deposited will be about $2/3\ E_\tau \approx 1/2\ E_\nu$ when the decay is hadronic (which is about 64% of the time). Hence the ratio of the average energy of the second "bang" to the first one is given by $E_2/E_1 \sim\ 2$. This is characteristic of these ν_τ events and making a cut of $E_2/E_1\ > 1$ eliminates several kinds of background events as we discuss later (see Figure 2). Detailed calculations for signal as well as background E_1 versus E_2 distribution will be presented elsewhere.

The threshold energy for discriminating two cascades will be determined by requiring a τ that flies far enough so that the two cascades can be distinguished, and so that there are no "punch through" events. This distance will be of the order of some few times the cascade length (order 10 m), and thus our threshold for τ detection via this means would be, as suggested above, about a PeV. Aside from the physics limitation of several tens of meters, there will also be a detector dependent limitation depending upon detector density and response, but probably of similar magnitude.

We note that the observation of the double bang events presents the opportunity to measure the PeV ν_τ cross section via the angular distribution in the lower hemisphere which decreases towards the nadir due to attenuation through the earth ($\sim$ 90% for straight upwards travelling neutrinos in this energy range). For future studies of earth tomography, the potential of this process is great, since it does not depend upon convolution over the y distribution and muon range, as is necessary to extract information from the upcoming muon flux alone.

Also, given the enormous light output of the cascades one would expect that timing from the detectors (at intermediate distances, since nearby detectors of present design will surely be saturated) would give excellent vertex resolution, and thus the initial neutrino direction to a precision of the order of 1°. In principle, of course, having both cascades and almost all energy "visible" one can deduce the initial neutrino direction with arbitrary precision, perhaps making optical precision ultimately possible in some future neutrino telescope.

3 Deducing the Neutrino Flavor Mix

From the ensemble of measurements with a DUMAND-like array we will have:

1. The τ rate from double bang events gives the $\nu_\tau + \bar{\nu}_\tau$ flux.
2. Measurents of the UHE muon flux permits calculation the $\nu_\mu + \bar{\nu}_\mu$ flux.
3. The W^- resonant event rate yields the $\bar{\nu}_e$ flux at 6.4 PeV.
4. Observation of the cascade rate (as a function of energy) produces the sum of neutral current interactions of all flavors of neutrinos, and charged currents without visible μ's and τ's (mostly ν_e's).

If we write $r \equiv \sigma_{CC}/\sigma_{NC}$, the ratio of charged to neutral current cross sections, and we note that the cross sections are nearly flavor and charge independent at this energy, we can summarize the four observations above as:

$$N_1 = N_\tau + N_{\bar{\tau}} \tag{1}$$

$$N_2 = N_\mu + N_{\bar{\mu}} \tag{2}$$

$$N_3 = N_{\bar{e}} \tag{3}$$

$$N_4 = (N_e + N_{\bar{e}}) \cdot (1 + r) + (N_\mu + N_{\bar{\mu}}) + (N_\tau + N_{\bar{\tau}}) \tag{4}$$

Combining these four equations we can then extract 3 flavor fractions ($f_e = (N_e + N_{\bar{e}})/N_{total}$, $f_\mu = (N_\mu + N_{\bar{\mu}})/N_{total}$, and $f_\tau = (N_\tau + N_{\bar{\tau}})/N_{total}$), and the antiparticle to particle ratio, $N_{\bar{e}}/N_e$.

For simplicity we have ignored energy dependence and experimental factors of acceptance, exposure, and efficiency. A full error analysis is experimentally dependent, and beyond the scope of this note. However, we point out that by employing ratios, particularly involving N_1, N_3, and N_4, much of the systematic error will cancel. In fact if we assume that we know $N_{\bar{e}}/N_e$, then we can calculate the flavor ratios without employing the muon measurements (which will have different systematic errors). For the more optimistic AGN fluxes cited[4] the numbers of events collected in a km^3 detector in one year would permit calculation of the flavor content to a few percent.

4 Atrophysical Neutrino Flavor Content

In the absence of neutrino oscillations (discussed in the following section) we expect almost no ν_τ content in astrophysical sources, as we discuss in the following.

From the most discussed and seemingly most likely astrophysical high energy neutrino sources we expect nearly equal numbers of particles and antiparticles, half as many ν_e's as ν_μ's and virtually no ν_τ's. This comes about simply because the neutrinos are thought to originate in decays of pions (and kaons) and subsequent decays of muons. Most astrophysical targets are tenuous even compared to the earth's atmosphere, and would allow for full muon decay in flight.

The extreme case of an astrophyscial beam dump target of sufficient density to suppress π and k decay (as would happen with a nucleon beam striking a neutron star), but not so thick as to absorb the directly produced fluxes (a neutron star would absorb almost any but a tangential netrino beam), seems to be unlikely. Beyond the geometric difficulty, producing a detectable flux of high energy neutrinos from such an inefficient source makes it even more improbable. There are some predictions for flavor independent fluxes from cosmic defects and exotic objects such as evaportaing black holes. Observation of tau neutrinos from these would have great importance. Indeed as we show below, for such exotic sources along with the presence of oscillations, we would have a unique flavor signature permitting unravelling the source content.

The flux ratio of $\nu_\mu : \nu_e : \nu_\tau = 2 : 1 : 0$ is certainly valid for AGN models such as the ones due Stecker et al [6] in which the neutrinos come from $\pi's$ produced via the process $\gamma + p \rightarrow N + \pi$. In the calculations of Protheroe and Szabo [2] there are two additional features: the additional ν_e flux due to escaping neutrons modifies the $\nu_\mu : \nu_e$ flux ratio to 1.75 : 1 and about 10% of the ν-flux is due to proton-proton (pp) interactions. Some fraction of the pp

neutrinos will then give rise to neutrinos from rapidly decaying secondaries containing heavy quarks ("prompt" production).

Depending on the amount of prompt ν-flux due to D_S and $B\bar{B}$ production (and decay) there could be a non-zero ν_τ component present. We now turn to a numerical estimate of such an initial ν_τ flux fraction. The relative fluxes of prompt neutrino flavors can be written as [7]:

$$\nu_\mu : \nu_e : \nu_\tau = 1 : 1 : t,$$

where

$$t = \left\{ \frac{f}{B_\mu^D / B_\tau^s \ + f(1+2f) B_\mu^s / (2+f) B_\tau^s} + \epsilon \left(\frac{B_\tau^b}{B_\mu^b} \right) \left(\frac{B_\mu^b}{B_\mu^D} \right) \right\} / \left[1 + \epsilon \frac{B_\mu^b}{B_\mu^D} \right] \tag{5}$$

and where $f = \sigma_{D_s}/\sigma_{D\bar{D}}$, $\epsilon = \sigma_{b\bar{b}}/\sigma_D$, $B_\mu^D = \frac{1}{2}(B_\mu^{D^0} + B_\mu^{D^+}) = 0.125$, $B_\tau^S = Br(D_s \to \tau\nu_\tau) \sim 0.04$, $B_\mu^s = Br(D_s \to \mu x) = 0.08$, $B_\tau^b = 0.025$ and $B_\mu^b = 0.10$ [3]. Using a value for $f \sim 0.15$ [8] and $\epsilon \sim 0.1$, we find the right hand side to be $1 : 1 : (0.07 \sim 0.1)$. Hence, in the Protheroe-Szabo AGN model, the fluxes go as

$$\nu_\mu : \nu_e : \nu_\tau \ = 1.0 : 0.6 : < 0.01.$$

Actually this is a conservative upper bound on the ν_τ content because most of the secondary pions will have ample opportunity to decay and in that case the τ fraction will be nearer 10^{-4}.

Even in the extreme case that the matter density is so high that only the prompt neutrinos survive (for which as stated earlier we know of no proposed astrophysical situation), the flux ratios are:

$$\nu_\mu : \nu_e : \nu_\tau \ = 1.0 : 1.0 : < 0.1.$$

The conclusion is that the most likely expected astrophysical neutrino sources will have very little ν_τ flux, and that observation of such particles is a signal for either or both of dramatic new sources and neutrino mass and oscillations.

5 Sensitivity to Neutrino Oscillations

The δm^2 sensitivity (from L/E) for this observation is then fantastic, going down to the order of 10^{-16} eV^2 (the distance is out to the AGN, ~ 100 Mpc). To determine the two neutrino mixing angle sensitivity limit requires detector specific simulations. The limitation has to do with the AGN neutrino flux magnitude and effective volume for these events, and will probably be limited by statistics, at least in the near future. We guess it will be no better than 0.01 in the best of situations (as with most oscillation experiments).

To discuss the (to be observed) fluxes in terms of neutrino oscillations we make a number of simplifying (but reasonable) assumptions. Explicitly, we assume that:

1. the initial fluxes are in the proportion $\nu_\mu : \nu_e : \nu_\tau :: 2 : 1 : 0$ (as generally expected),
2. there are equal numbers of neutrinos and anti-neutrinos (although this is not crucial and can easily be dropped in actual analysis),
3. all the δm^2 are above 10^{-16} eV^2, and that $sin^2(\delta m^2 L/4E)$ all average to 1/2,
4. matter effects at the production site are negligible (this is reasonable since $N_{e^-} \simeq N_{e^+}$ and baryon densities are low for AGN), and
5. that there are no large matter effects in the path to earth. The latter is reasonable in the δm^2 range of interest (10^{-2} to 10^{-6} eV^2).

With these assumptions, let us first consider the case where the low energy atmospheric neutrino anomaly is accounted for by simple two flavor neutrino oscillations [9]. The oscillations could be either $\nu_\mu \leftrightarrow \nu_e$ or $\nu_\mu \leftrightarrow \nu_\tau$ with δm^2 of $10^{-2} - 10^{-3}$ eV^2 and $sin^2 2\theta$ ranging from 0.5 to 1.0.

In both cases the ν_μ/ν_e ratio should be modified **exactly** as in the atmospheric case[9]: given that the ν_μ/ν_e is found to be 0.6 of the expected value of 2, we expect exactly the same thing from the distant cosmic sources of much higher energy, $\nu_\mu : \nu_e = 1.2 : 1$. In the $\nu_\mu \leftrightarrow \nu_e$ mixing case this translates into $\nu_\mu : \nu_e : \nu_\tau :: 1.64 : 1.36 : 0.0$ (using the earlier normalization to 3 total). In the other case, of $\nu_\mu \leftrightarrow \nu_\tau$ mixing, we predict $\nu_\mu : \nu_e : \nu_\tau ::$

1.2 : 1.0 : 0.8. It is easy to see that in the two flavor mixing case, ν_e/ν_μ can never be greater than one. Even when the mixing is maximal on finds $\nu_\mu : \nu_e : \nu_\tau :: 1.5 : 1.5 : 0.0$ in the $\nu_\mu \leftrightarrow \nu_e$ mixing case, and $\nu_\mu : \nu_e : \nu_\tau :: 1 : 1 : 1$ in the $\nu_\mu \leftrightarrow \nu_\tau$ case.

We can now ask how expectations will change if we include neutrino oscillation solutions to the solar neutrino deficit. We can consider two distinct possibilities:

1. The ν_e mixing is with either other species with a small angle, as in the small angle MSW regime, then the above results remain unaffected.
2. All three flavors mix substantially and the δm^2's are in the range of 10^{-5} to 10^{-6} eV^2 (corresponding to the MSW "large angle" solution) or 10^{-10} eV^2 (corresponding to the "long wavelength" case).

The parameter space for a combined fit to the atmospheric and solar neutrino data allowing for three flavor mixing has been given for each of the above cases by Fogli, *et al.*[10], and by Acker, *et al.*[11], respectively. We have evaluated the survival and transition probabilities for the whole range of allowed values of the three mixing angles, and the results are shown in Figure 3. This figure plots the fraction of muon neutrinos versus the fraction of electron neutrinos, and thus where each point specifies a fraction of tau neutrinos (it is analogous to the color triangle). The initial expected flux ($\nu_\mu : \nu_e : \nu_\tau :: 2 : 1 : 0$) is at $f_\mu = 0.66$ and $f_e = 0.33$.

We further observe that:

1. Almost all combinations of acceptable mixing angles result in saturation values to be observed with AGN neutrinos which lie between the lines $f_e + f_\mu = 0.88$ and $f_e + f_\mu = 0.66$. Hence a substantial number of ν_τ events are expected ($0.34 > f_\tau > 0.12$) for all situations which solve the solar and atmospheric problems with neutrino oscillations.
2. Since in the case of two flavor mixing it is impossible to obtain $f_e/f_\mu > 1$, observation of the data falling above the diagonal $f_e = f_\mu$ line is clear evidence for three flavor mixing.

We would like to stress that a small "impurity" of ν_τ's in the initial neutrino fluxes, as discussed in the previous section, has a negligible effect on the ν_τ signal due to $\nu_\mu - \nu_\tau$ oscillations with moderately large mixing angles. For example, in the Protheroe-Szabo case, (for $P_{\mu\mu} \sim 0.6$ and $P_{\mu\tau} \sim 0.4$) the fluxes at the earth become:

$$\nu_\mu : \nu_e : \ \nu_\tau = 1.0 : 1.0 : 0.7,$$

which is quite similar to the pattern in the case above.

Interestingly, the purely prompt flux case, for which we are not aware of any model, gives rise to a very distinct flux pattern on arrival,

$$\nu_\mu : \nu_e : \nu_\tau \ = 1.0 : 1.56 : 0.72 = 0.3 : 0.47 : 0.23.$$

This represents a very singular point in Figure 3, distinguished by the dominance of the ν_e flux. We also note in passing that in the unexpected case of initial flavor independent flux, the equal fluxes remain so in any combination of neutrino mass and mixing. We thus conclude that almost any astrophysical source of neutrinos will result in significant numbers of ν_τ's, if neutrinos have mass and they oscillate.

6 Backgrounds: Almost None

By background we mean events which can fake the double bang signature of two huge cascades spaced roughly 100 m apart, with the second larger than the first (by typically a factor of two), and the sum of the visible energy being in the range of a few PeV. There are two general types of possible backgrounds due to neutrinos: those into which the neutrino transforms (e, μ and τ), and particles generated in the cascade resulting from the energy transferred to the struck quark. Neutral current events with an outgoing neutrino have interaction lengths so great as to be negligibly likely to interact again at close range ($< 10^{-6}$ at this PeV energy). Electrons will immediately radiate, and be added to the initial a cascade, and be indistinguishable from neutral current events.

The most serious background is due to ν_μ cc events in which the muon travels about 100 m and then loses most of its energy in a single catastrophic Bremsstrahlung radiation. Such events will have energy characteristics similar to signal events. The rate for such events as a fraction of cc events can be estimated as

$$\left(\frac{m_e}{m_\mu}\right)^2 \left(\frac{100m}{R}\right) \left(\frac{\Delta E}{E}\right) \tag{6}$$

where R is the radiation length in water and $\Delta E/E \sim 0(1/3)$ for the fraction of energy deposited. This number is of the order $3 \cdot 10^{-3}$ and is reassuringly small although a more accurate calculation is called for.

Once again, detector dependent simulations are required to numerically evaluate the confusion probability. Whatever that probability is, and we expect it to be low at 2 PeV, it decreases rapidly with increasing energy (short range muon radiation goes up while the tau decay length increases). In a large array, one may also demand that there be no continuing track, since the probablility of a 2 PeV muon stopping after 100 m is negligible. However, we estimate that this constraint will not be needed.

The other potential source of background from neutrino interactions is from the hadronic side of the neutrino interaction vertex. First of all, we do not know of any particle with the ability to penetrate $\sim 10^4\ gm/cm^2$ of matter before decaying or interacting (100 m is about 100 strong interaction lengths in water), except for leptons. Thus the only situation with which we must be concerned is when a τ results from the decays of particles in the cascade, and moreover when this τ has most of the energy, which we show below to be quite unlikely.

One source of this type of background is the production (and decay to τ) of D_s (and $B\bar{B}$ pairs) in neutral current interactions of ν_e (and ν_μ) and charged current interactions of ν_e. These could give rise to "double bang" events like the ν_τ events if D_S (or B) should decay within 10 m to produce an energetic τ which then travels about 100 m before decaying. In such events the average energy of the second bang $E_2 \sim 2/3E_\tau \sim 1/2E_h \sim 1/8zE_\nu$ where $z = E_h/E_\nu$. Since z is expected to be rather small, we expect $E_2/E_1 << 1$. Hence the $E_2/E_1 > 1$ cut will remove most such events. The number of such events will be $N \sim \{rN_\mu + (1+r)N_e\}(f_{D_s}B^s_\tau + f^2_B B^B_\tau)$ wheref_i are the fractional production of D_s and $B\bar{B}$ respectively. For $f_i \sim 10^{-2}, r \sim 1/3, N_\mu = N_e$; we find $N \sim 1.5 \cdot 10^{-3} N_\mu$, most of which will be removed by the energy fraction cut.

A somewhat more serious background is diffractive production of D_s via charm changing cc interaction of ν_e in the reaction $\nu_e + N \rightarrow e + D_s + x$. There is no Cabibbo suppression, the rate can be as high as $6 \cdot 10^{-3}$ times the *cc* rate and furthermore D_s can have average energy of about $1/2\ E_\nu$ [13]. Thus E_2/E_1 can be of order 1 and some events may pass the E_2/E_1 cut. However, the rate is given by $6 \cdot 10^{-3} \cdot B_\tau^{D_s} \sim 2.5 \cdot 10^{-4} N_e$ and is thus also quite small.

Another class of potential background might be due to downgoing muons which originate in primary cosmic ray interactions in the atmosphere. The angular distribution of the downgoing muons peaks strongly near the zenith, while the double bang events would be uniform in direction in the upper hemisphere. A stronger constraint is that events with such high energy are not expected from downgoing muons at depths of a few km. Bremsstrahlung and pair production events of a few hundred GeV are plentiful, but the flux falls very fast with energy, and negligible numbers are expected above 100 TeV[13]. The probability of observing two cascades meeting the spacing, total energy and energy sharing requirement is vanishingly small.

There are also muons arriving from all directions, due to distant neutrino interactions. Clearly if the muon charged current interaction is not a problem, as discussed above, then the probability of two bursts of adequate energy and spacing will not be a problem, even without invoking observation of incoming or outgoing muons as a veto.

Finally, we note that as a check, studies of the decay path length distribution requiring consistency with the known tau lifetime, should confirm the detection of taus and the lack of contamination of the sample. In sum we conclude that the data selection criteria on spacing and energy of the two bangs will remove virtually all backgrounds and leave a verifiably pure sample of UHE τ events.

7 Old Idea, New Combination and Impact

The above is not entirely a new idea. Several authors have written about τ signatures in the past[14]. The new recognition is in coupling the uniqueness of the double bang signature, the encouraging recent flux predictions from AGN, plus the modern hints about neutrino oscillations, and thus being able to claim to have a good chance to observe a pure sample of ν_τ interactions in detectors within the realm of possibility in the next few years. Further we now recognize that detection of this novel class of interactions makes possible observations of the neutrino flavor mix, oscillations, distinction of some exotic class of sources, precise measurements of the neutrino cross section in the PeV energy range, and more distantly in the future, earth tomography with greater sensitivity than has been thought possible.

One impact of the consideration of this potential observation gives motivation to fill the volume, somewhat, of a hypothetical 1 km^3 array. Indeed this experiment itself could perhaps justify construction of that instrument.

Also, given that these events are near the anticipated acoustic detection threshold[15], one may contemplate hearing the double clicks from such events at few km ranges and higher energies. The unusual property of acoustic pulse amplitude which results in slow decrease with distance in water may make practical the search for higher energy neutrino interactions from volumes of many cubic kilometers. Additionally, the possibility of detecting neutrino induced cacades via radio pulses of GHz frequency range continues to be explored in deep ice[16]. As for acoustic sensing, the double microwave pulses due to τ production and decay should provide dramatic and unique signatures.

We remind the reader that all of the above requires the existence of substantial numbers of PeV neutrinos, which matter should be resolved in the next few years by the AMANDA, Baikal, DUMAND, and NESTOR experiments now under construction. If those ultra high energy neutrinos are present in expected numbers, then we believe that the observation of the double bang events, along with other previously discussed interactions, will lead to important particle physics measurements which cannot be carried out in any other way on earth.

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[1] We use DUMAND herein to refer to a generic deep (km or more) un-

der water or under ice detector which senses Cherenkov radiation with photomultiplier tubes at distances of tens of meters from the tracks. Arrays with dimensions of order 100 *m* are now under construction in the ocean (DUMAND and NESTOR), a lake (Baikal) and the polar ice (AMANDA). See review paper by J. G. Learned, Phil. Trans. R. Soc. Lond. A **346**, 99 (1994), and references therein. A future *km* scale detector is presently under discussion in the community and could be constructed within a decade.

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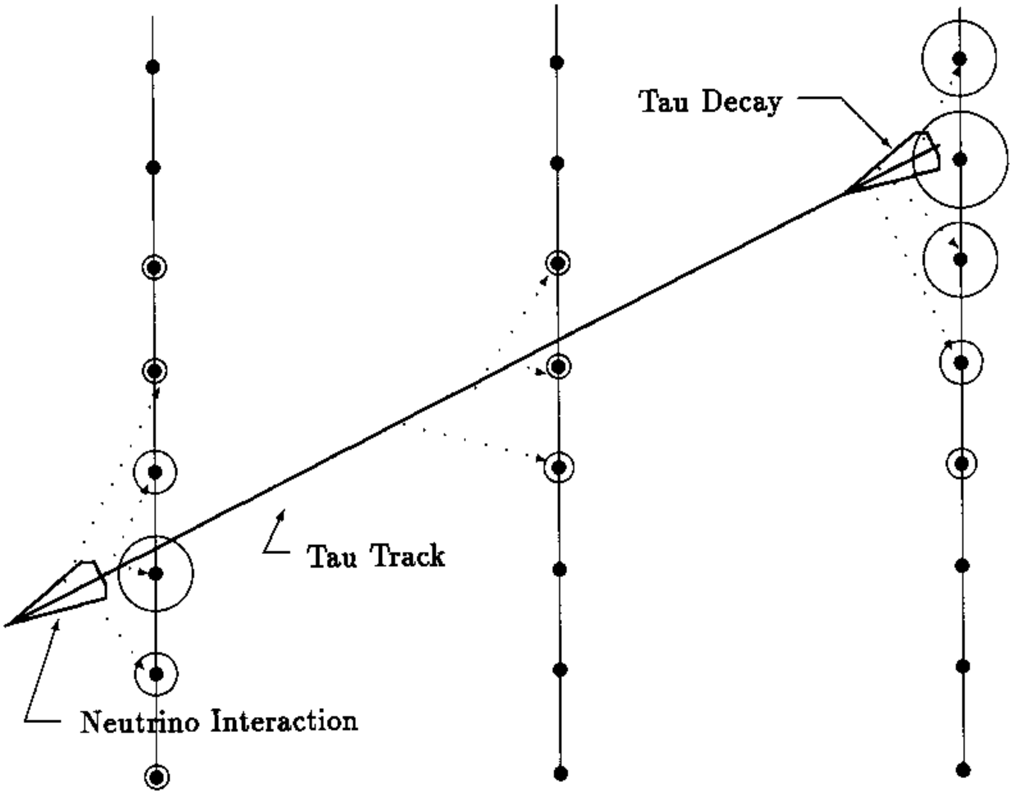

Figure 1: A schematic view of a "double bang" event near a deep ocean detector whose modules are indicated by dots. Such cascades should be visible to detectors from hundreds of meters distance.

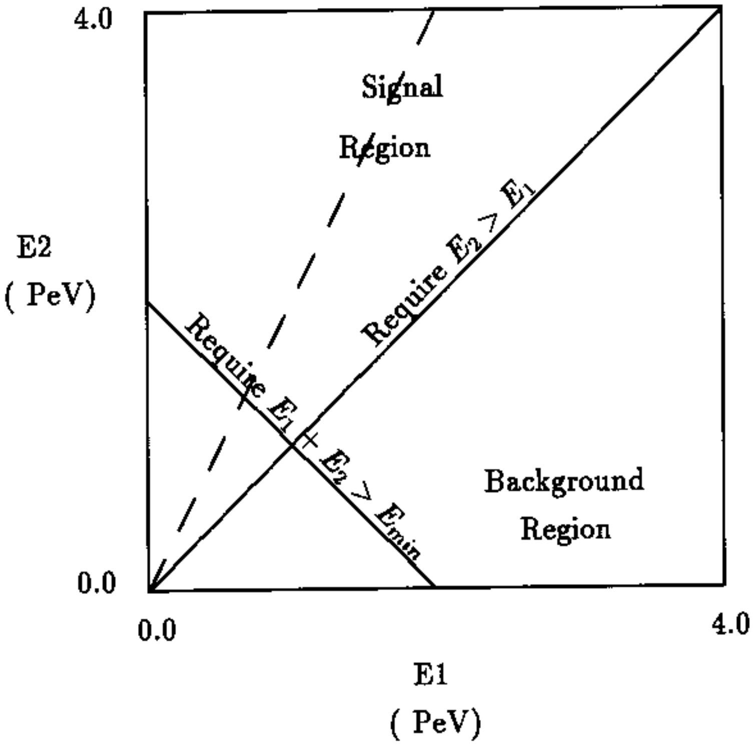

Figure 2: Diagramatic representation of the region of double bang signals and background signals, as discussed in the text. The signal is essentially background free after cuts on minimum total energy and requiring the second cascade to be the larger.

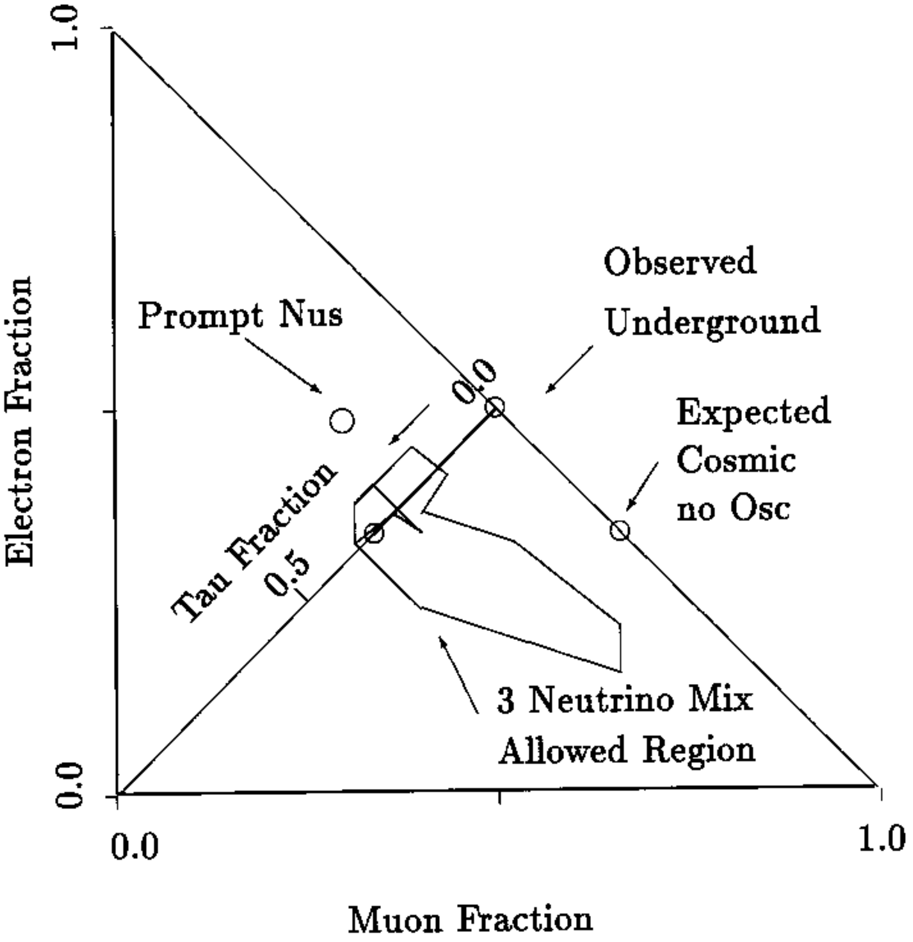

Figure 3: The fraction of muon neutrinos versus electron neutrinos, allowing for a fraction of tau neutrinos. Expected initial flux is at 2/3, 1/3. Full mixing would result in 1/3, 1/3. The points represent various solutions to the solar and atmospheric neutrino problems. The point corresponding to pure prompt ν-beam is at 0.30, 0.47 & 0.23 taus.