SOME USES OF NEUTRINO TELESCOPES

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ABSTRACT

We imagine that large neutrino telescopes will be built and that distant neutrino sources of high energies and fluxes exist. Some possible, if difficult, uses to which they might be put are described; including (i) detecting neutrino mass-mixing possibly upto δm^2 of $10^{-16} eV^2$; (ii) measuring neutrino cross-sections at PeV energies; (iii) detecting relic neutrinos; (iv) doing cosmology with neutrinos and (v) SETI with neutrinos.

1. Introduction

I make two optimistic assumptions. The first one is that distant neutrino sources (e.g. AGN's and GRB's) exist; and furthermore with detectable fluxes at high energies (upto and beyond PeV). The second one is that in the not too far future, very large volume, well instrumented detectors of sizes of order of KM3 and beyond will exist and be operating; and furthermore will have (a) reasonably good energy resolution, (b) good angular resolution ($\sim 1^0$?) and (c) low energy threshold ($\sim 50\ GeV$?). The ICECUBE discussed by Francis Halzen here is one example[1)].

If these assumptions are valid, then there are a number of uses these detectors can be put to. By measuring the flavor mix of the neutrinos from a known source, mixing parameters can be determined for δm^2 as small as $10^{-16} eV^2$. By measuring the attenuation of neutrinos in the earth, neutrino cross-sections at energies of PeV can be determined. By confirming that the highest energy cosmic rays come from neutrinos producing on-shell Z's, indirect evidence for relic neutrinos and their mass can be found. Measurements of flavor conversion probability (as a function of L/E) and of pulse spreading and separation can be start of neutrino cosmology (e.g. measuring red-shift in neutrinos as well q_0 and H). Finally, a detection of a few neutrino events at energy of $M_Z/2$ could be the first sighting of an advanced extra-terrestrial civilization.

2. Neutrinos from Active Galactic Nuclei

For AGN's the expectations are that they emit high energy $\nu's$; the total flux probably overtakes atmospheric ν-flux by $E_\nu \sim O(TeV)$ and the most likely flavor

mix is $\nu_\mu : \nu_e : \nu_\tau \approx 2 : 1 : 0$.

2.1. ν_τ Signature

For a ν_τ of energy above 2 PeV there is a characteristic "double bang" signature[2]. When ν_τ interacts via charged current there is a hadronic shower (of energy E_1) with about 10^{11} photons emitted; then the τ travels about 90m (for $E_\tau \sim 1.8 PeV$) and when it decays (either to e's or hadrons with 80 % probability) there is again a cascade (of energy E_2) with 2.10^{11} photons emitted in Cerenkov light. The τ track is minimum ionising and may emit $10^6 - 10^7$ photons; even if it is not resolvable, one can connect the two showers by speed of light and reconstruct the event.

The backgrounds (after appropriate cuts) are very small. Hence such "double bang" events represent either $\nu_\mu \to \nu_e$ (or $\nu_e \to \nu_\tau$) oscillations or ν_τ-emission at the source and in any case are extremely interesting. For signal events due to ν_τ, one expects $E_2/E_1 > 2$ on the average, and hence a cut of $E_2/E_1 > 1$ removes many backgrounds; another cut on the distance D between the two bangs of $D > 50m$ eliminates most of the punch-thru backgrounds[3].

2.2. Expected Flavor Mixes

Most models of ν-emission in AGN's correspond to tenuous beam dumps with little absorption and $\nu's$ come from π (and K) decay. Frequently $\gamma p \to \Delta$ is a dominant process. In these scenarios we expect at production

$$\nu_\mu : \ \nu_e : \ \nu_\tau \approx 2 : 1 : 0 \tag{1}$$

For example, in the Protheroe-Szabo model[4], they find $\nu_\mu : \nu_e \approx 1.75 : 1$ and 10% of $\nu's$ come from pp interactions. Some fraction of pp collisions will contribute to prompt $\nu's$ (including $\nu'_\tau s$) via production of c and b. In the prompt $\nu's$ the flavor mix is

$$\nu_\mu : \nu_e : \nu_\tau = 1 : 1 : p \tag{2}$$

where p can be crudely estimated to be about 0.07 to 0.1. Since the prompt $\nu's$ themselves are expected to be only 10% of total the modified flavor mix is

$$\nu_\mu : \nu_e : \nu_\tau \approx 1 : 0.6 : 0.01 \tag{3}$$

and contains less than 1% of $\nu'_\tau s$.

2.3. Rates

To estimate event rates we make the following assumptions: (i) assume the fluxes of Protheroe-Szabo model; (ii) integrate over all AGN's; (iii) assume an initial flavor

mix of $\nu_\mu : \nu_e : \nu_\tau \approx 2 : 1 : 0$; and (iv) a KM3 water or ice ĉ detector with 100 % detection efficiency[5]. Then we expect 1000 ν_τ "double bang" events assuming maximal $\nu_\mu - \nu_\tau$ mixing, 1000 ν_μ events and about 1800 showering events ($\nu_e CC$ and ν_α NC) per year. With the new upper limit from AMANDA presented here[1], this becomes the upper bound.

2.4. Flavor Mix on Arrival

The neutrino flavor mix can be "easily" determined from the event classification of the data. The double bang events determine $\nu_\tau + \bar{\nu}_\tau$ flux; the upcoming muons determine $\nu_\mu + \bar{\nu}_\mu$ flux; the cascade events (single bang) determine a combination of $(\nu_e + \bar{\nu}_e), (\nu_\mu + \bar{\nu}_\mu)$ and $(\nu_\tau + \bar{\nu}_\tau)$ fluxes; and Glashow Resonance (W) events determine $\bar{\nu}_e$ flux (at $E_\nu = 6.4 PeV$).

2.5. Backgrounds

We have considered several possible sources of backgrounds which fake double bang signatures. The most serious appears to be a $\nu_\mu \to \mu$ charged current event where the μ travels about 100 m without much radiation and then deposits the bulk of its energy in a catastrophic bremstrahlung. This would have all the characteristics of a genuine ν_τ event. We estimate the fraction of such events to be about $(m_e/m_\mu)^2 (100m/R_\mu)(\Delta E/E) \sim 3.10^{-3}$ and seems reassuringly small.

At the hadronic vertex, the sources of background are: (i) $\nu_e + N \to e + D_s$ produced diffractively with $D_s \to \tau\nu$; and E_2/E_1 can be of 0(1) to fake the ν_τ signal provided D_s decays quickly. The rate is expected to be of order 3.10^{-4} of cc events; (ii) $\nu_\alpha + N \to \nu_\alpha + D_s/B$ again with D_s or B decaying into τ within 10m and τ traveling 100 m. In these events we expect $E_2/E_1 < 1$ and again the rate is small of order $\sim 10^{-3}$. Other backgrounds such as coincident downgoing $\mu's$ showering is expected to be small. Hence, that after the cuts such as $E_2/E_1 > 1$ and $D > 50m$, the backgrounds are rather small.

We conclude that given AGN ν-sources, it is possible to see $\nu_\tau \to \tau$ events in a KM3 array unambigously.

2.6. Sensitivity to Oscillations

The sensitivity to oscillation parameters depends on several factors. If individual AGN's can be identified in $\nu'_\tau s$ (say upto 100 Mpc or more) then δm^2 upto $\geq 10^{-16} eV^2$ and mixing angles upto $sin^2 2\theta \stackrel{\sim}{>} 0.05$ can be probed[7]. On the other hand, if the current indications from atmospheric neutrino results are established as due to flavor

oscillations, then the oscillating term in the conversion formula:

$$P_{\alpha\beta} = sin^2 2\theta sin^2 \left(\frac{\delta m^2 L}{4E}\right) \tag{4}$$

averages to 1/2 and one can only confirm the expected value of mixing

To proceed further let us assume: (i) initial fluxes are $\nu_\mu : \nu_e : \nu_\tau \approx 2 : 1 : 0$; (ii) $\#\ \nu = \#\ \bar{\nu}$ (although this is not essential); (iii) all $\delta m^2 >> 10^{-16} eV^2$, i.e. $< sin^2\ (\delta m^2 L/4E) > \approx 1/2$; (iv) matter effects negligible at production (e.g. $N_{e^-} = N_{e^+}$) and no significant matter effects en-route (this is valid for δm^2 of current interest $\sim 10^{-2} - 10^{-6} eV^2$)[6];(v) atmospheric ν-anomaly caused by $\nu_\mu - \nu_\tau$ oscillations with $\delta m^2 \sim 5.10^{-3} eV^2$ and $\sin^2 2\theta \geq 0.6$. In this case we expect $\nu_\mu : \nu_e : \nu_\tau \approx 1 : 1 : 1$ at earth.

If should be stressed that this result viz. $\nu_\mu : \nu_e : \nu_\tau \cong$ 1:1:1 depends crucially on the large $\nu_\mu - \nu_\tau$ mixing and is relatively insensitive to the mixing of ν_e[8]. For example, the wide variety of neutrino mixing matrices currently under consideration: (i) Bi-maximal mixing, (ii)Tri-maximal mixing, (iii) SMA (small angle MSW), (iv) Fritzsch-Xing mixing; all lead to the same result as long as the initial flavor mix is $\nu_\mu : \nu_e : \nu_\tau = 2 : 1 : \epsilon$. Of course, if a source emits a universal flavor mix i.e $\nu_\mu : \nu_e : \nu_\tau = 1 : 1 : 1$, it remains unchanged by oscillations.

Extra bonuses from observing the double-bang events are (i) the use of the zenith angle distribution to measure ν_τ cross section via attenuation and (ii) use of enormous light collection and good timing to get good vertex resolution and determine ν_τ direction to within a degree or so. Proposals to account for the highest energy cosmic rays include some[9] in which the neutrino cross-sections are enhanced at very high energies. Because of unitarity constraints, in the 2-20 PeV range they can increase by almost an order of magnitude. Such scenarios can be possibly probed.

3. Detecting Relic Neutrinos

In the standard hot Big Bang Model[10], the effective temperature today of relic neutrinos is $1.9^0 K$; the number density per flavor is 110/cc (adding $\nu's$ and $\bar{\nu's}$); the average momentum is $5.2.10^{-4}$ eV/c. The current density is $\sim 3.10^{12} cm^{-2} s^{-1}$ for massless neutrinos and $5.10^9 cm^{-2} s^{-1}$for a neutrino mass of $5.10^9 cm^{-2} s^{-1}$. The ν_α-scattering cross section (at very low energies) for Dirac neutrinos for allowed transitions goes as

$$\sigma_\alpha \sim \frac{a_\alpha^2\ G_F^2\ m_\nu^2}{\pi} \tag{5}$$

where $a_\alpha\ = (3Z - A)$ for $\alpha = e$ and $a_\alpha\ = (A - Z)$ for $\alpha = \mu$ or τ. Many early proposals to detect relic neutrinos by reflection or coherent effects turned out to be incorrect. There are three methods which some day may prove to be practical.

The first is a 1975 proposal due to Stodolsky[11]. The idea needs neutrino asymmetry i.e. excess of ν (or $\bar{\nu}$) over $\bar{\nu}$ (or ν) in order to work. Then a polarized electron

moving in a background of CMB neutrinos can change its polarization due to the axial vector parity violating interaction. The effective interaction goes as

$$H_{eff} \sim \frac{2G_F}{\sqrt{2}} \underline{\sigma_e}.\underline{v}\ n_\nu \tag{6}$$

With $v \sim 300\ kms^{-1}$ and $n_\nu \sim 10^7/cc$ this correspond to an energy of about $10^{-33}eV$ and leads to a rotation of the polarization of about 0.02" in a year. Can such small spin rotations can be detected? Certainly not at present, but technology may someday allow this.

The second method is one suggested by Zeldovich and collaborators [12]. The idea is to take advantage of momentum transfer in neutrino-nucleus scattering. Consider an object made up of small spheres of radius $a \approx \lambda$ (neutrino wavelength) packed loosely with pore sizes also of the same size. (to avoid destructive interference). If the number of atoms in the target is N_A, then the effective coherent cross-section is

$$\sigma = \sigma_\alpha\ N_A^2 \tag{7}$$

where σ_α is as given in Eq. (10). Assuming total reflection, momentum transfer is

$$\Delta p \cong 2m_\nu\ v_\nu \tag{8}$$

and the force $f = j_\nu \sigma \Delta p$ is given by

$$f = 2n_\nu \sigma_\alpha\ N_A^2 m_\nu\ v_\nu^2 \tag{9}$$

The most optimistic estimates are obtained by assuming some clustering ($n_\nu \sim 10^7/cc), m_\nu \sim 0(eV), v_\nu \sim 10^7 cms^{-1}, \rho \sim 20gm/cc$; leading to

$$a = \frac{f}{m} = \frac{f}{N_A m_N} \sim 10^{-23}(a_\alpha/A)^2\ cm.s^{-2} \tag{10}$$

Such accelerations are at least ten orders of magnitude removed from current sensibility and possible detection remains far in future [13]. Incidentally, this is based on having Dirac neutrinos; for Majorana neutrinos, one would need spin alignment in a macroscopic sample.

The third possibility is the one proposed by Weiler in 1984 [14]. The basic idea is as follows. If neutrinos have masses in the eV range and there are sources of very high energy neutrinos at large distances, then the H.E. ν can annihilate on the C.B.R. $\bar{\nu}$ and make a Z^0 on-shell at resonance creating an absorption dip in the neutrino spectrum. The threshold for Z production would be at $E \sim m_Z^2/2m_\nu$ which is about 4.10^{21} eV for an eV neutrino mass. This seemed like an unlikely possibility, since it required large neutrino fluxes at very high energies to see the neutrino spectrum and then the absorption dip. But all this changed dramatically recently with the clear signal of cosmic rays beyond the GZK cut-off [15]. The GZK cut-off is the energy at which

cosmic ray protons pass the threshold for pion production off the CMB photons. This is at an energy $E \sim m_\pi mp/E_\gamma \sim 6.10^{19}$ eV. Above this energy, the mean free path of protons is less than 10 Mpc and hence these protons have to be "local". The flux should then decrease dramatically since we believe the cosmic rays are not produced locally. Recently, what used to be hints of the cosmic ray signal extending beyond this cut-off, has become a clear signal [16]. The events are most likely due to primary protons. Then an explanation is called for. One intriguing proposal [17] is that these events are nothing but a signal for the Z's produced by the $\nu\bar{\nu} \to Z$ process with the protons coming from the subsequent Z decay! Of course, the original problem of needing sources of high energy neutrinos remains. If this explanation is valid, we have already seen (indirect) evidence for the existence of relic neutrinos. In principle, this proposal can be tested: (i) the events should point back at the neutrino sources; (ii) there is an eventual cut-off when the energy reaches the threshold energy for Z production, $E \sim 4.10^{21} \left(\frac{eV}{m_\nu}\right)$ eV; (iii) γ/p ratio should be large near threshold and (iv) the large ν-flux should be eventually seen directly in large ν-telescopes. There is the bonus that the cut-off energy also measures the mass of the relic neutrinos! Thus neutrino telescopes can give existence proof of relic neutrinos as well as measure their mass.

4. Cosmology with neutrinos

We know from supernova studies that there are several effects of neutrino masses and mixings on the observation of neutrino bursts. A pulse spreads in time due to dispersion of velocities (from non-zero mass); a pulse separates into several pulses due to a neutrino of a given flavor being a mixture of different mass eigenstates and the original flavor composition can change due to mixing and oscillations. One can apply these considerations to neutrino pulses from sources which are at cosmological distances. Then the effects come to depend on cosmological parameters.

For example, the time difference [18] between two mass eigen-states which left at the same time is given by

$$\Delta t \approx z/H \left[1 - \frac{(3+q_0)}{2} z .... \right] \frac{1}{2} \left[\frac{m_1^2}{E_1^2} - \frac{m_2^2}{E_2^2}\right] \tag{11}$$

where E_i are the energies observed at earth and z, H and q have the usual meanings. The spreading of a pulse of a given mass neutrino is given by [18]

$$\Delta t \approx z/H \left[1 - \frac{(3+q_0)}{2} z ..... \right] \frac{1}{2} m^2 \left\{\frac{1}{E_1^2} - \frac{1}{E_2^2}\right\} \tag{12}$$

Finally, the conversion probability for an emitted flavor α to become β at detection is given by

$$P_{\alpha\beta} = sin^2 2\theta \; sin^2 \phi/2 \tag{13}$$

where the phase ϕ is [19]

$$\phi \cong z/H \left[1 - \frac{(3+q_0)}{2} z .... \right] \frac{\delta m^2}{2E} \tag{14}$$

The basic flight time factors are rather small, for eV neutrino masses and GeV energies, $\Delta t \sim 50$ milliseconds at 1000 MPc. These time spreads and separation may be shorter than the times involved in the production process thus making them difficult to observe. On the other hand if the current suggestions for O(KeV) masses[20] for ν_μ and ν_τ to act as warm dark matter[21] turn out to be valid, then time delays are much larger (e.g. O(sec) at distances of Mpc).

As for flavor conversion, emitted $\nu'_\mu s$ can get converted into $\nu'_\tau s$ and thus produce a significant incoming flux of $\nu'_\tau s$ (which is essentially absent initially in most neutrino production scenarios). With the flavor mix of the incoming beam determined as discussed above, $P_{\alpha\beta}$ and hence the phase ϕ can be deduced by comparing to expected initial relative fluxes. Provided the phase $\phi/2$ is not too large (and $\sin^2 \phi/2$ does not average to 1/2) one has sensitivity to the parameters z, q_0, and H.

With such measurements of Δt and ϕ, one can potentially measure these cosmological parameters. This would be the first time that the red-shift or other cosmological parameters are measured for anything other than light. There is another advantage of using neutrinos. This is the fact that the initial flavor mixing only depends on microphysics and so the comparison is free from problems such as evolution or worries about standard candles etc.

5. SETI with Neutrino

Yes, I do mean[22] search for extra-terrestrial intelligence. There is a school of thought that holds that this search in futile, pointless, and bound to yield null results. However, as has been pointed out, absence of evidence is not necessarily evidence of absence.

Imagine that an advanced civilization exists in the galaxy, with many outposts. It will need to maintain time standards over a long base line. In turn, this will require (i) stable clocks of high precision, (ii) fast processes for transmitting and receiving time markers and (iii) a form of radiation which will faithfully carry timing data over long distances.

The need for clock synchronization stems from the fact that standard clocks have to exchange timing data to remain synchronized. This is in order to correct for general relativistic effects which depend on positions and motions of nearby massive objects. Furthermore, the presence of chaos in many body systems means that such corrections

cannot be calculated indefinitely from initial data alone, so that the synchronization has to be done repeatedly.

The requirements of a mobile, spread out civilization would suggest the use of isotropic synchronization signals. Other arguments suggest the same thing. Hence, even though it raises the required energy budget, this is the most likely scenario.

The fastest known process is the Z^0 decay with a lifetime of $2.5 \times 10^{-25} s$. It also produces neutrinos of 45.6 GeV, satisfying the requirements of radiation which can carry information intact thru many obstacles.

If an advanced civilization is using this process to send timing signals, a neutrino telescope can detect some neutrino events at the energy of 45.6 GeV. If the source is a few kpc from us, then a KM3 water/ice $\hat{c}$ detector will detect a few events per year (all flavors in equal numbers).

The ETI would have to overcome many technical problems to implement such a scheme. We have addressed some of them elsewhere[22]. The power requirements to give a few events per year in a KM3 detector at a distance of few kpc are huge; approximately the solar luminosity $\sim 10^{45} eV/sec$. This, of course, is *their* problem and we have to imagine that they have solved it. Is it possible that a technology radiating such huge amounts of power within a few kpc has escaped our detection? We speculate that this would correspond to a "Dyson shell." Dyson had suggested that if an advanced civilization surrounds a star with a shell of material and uses heat engines to extract power, then the system would appear as an infra-red source. Since the IRAS data include over 50,000 IR sources, some of these indeed could well be "Dyson shells".

These synchronization neutrino signals at E = $M_Z/2$ are extremely distinctive in that they are not expected to occur naturally and are therefore unlikely to be mistaken for anything else. In view of the spectacular nature of the timing signal and the enormous implications of its detection, we believe it is surely worth keeping watch for it.

6. Conclusion

Neutrino telescopes are "Field of Dreams"! If we build them; the neutrinos, they will come!

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8. References

1) F. Halzen, *these proceedings.*
2) J.G. Learned and S. Pakvasa, *Astropart. Phys.* **3** (1995) 267 .
3) These qualitative conclusions in J. Learned and S. Pakvasa, Ref. 2, have been confirmed in more detailed considerations: H. Athar, G. Parente and E. Zas, *Phys. Rev.* **D62,**(2000) 093010.
4) R. Protheroe and A.P. Szabo, *Astropart. Phys.* **2** (1994) 375.
5) We used charged current neutrino cross-sections corresponding to about $\sigma_{\nu N} \sim 10^{33} cm^2$ at $E \sim PeV$; this is consistent with recent estimates: G. Frichter, D.W. McKay and J. P. Ralston, *Phys. Rev. Lett.* **74** (1995) 1508; R. Gandhi, C. Quigg, M. H. Reno and I Sarcevic, *Phys. Rev.* **D58** (1998) 093009; J. Kwiecinski, A.D. Martin and A.M. Stasto, *hep-ph/0004109.*
6) See for example, C. Lunardini and A. Smirnov, *hep-ph/0012056.*
7) J. G. Learned and S. Pakvasa, Ref.2; S. Iyer, M. H. Reno, and I. Sarcevic, *Phys. Rev.* **D61**(2000)053003.
8) This was first observed in J.G. Learned and S. Pakvasa, Ref. 1; S. Pakvasa, *Beyond the Desert 1999, Proc. of the Second International Conference on Particle Physics Beyond the Standard Model*, Castle Ringberg, Germany, 6-12 June 1999, Ed. H.V. Klapdor-Kleingrothaus and I.V. Krivosheina, IOP Publishing, Bristol (2000) p. 247; *hep-ph/9910246.* It has since been rediscovered by a number of authors: L. Bento, P. Keranen and J. Maalampi, *Phys. Lett.* **B476** (2000) 205; H. Athar, M. Jezabek, and O. Yasuda, *Phys. Rev.* **D62** (2000) 103007; D. Ahluwalia, *hep-ph/00104316.*
9) G. Domokos and S. Kovesi-Domokos, *Phys. Rev. Lett.* **82** (1999) 1366; J. Bordes *et al*; *Astropart. Phys.* **8** (1998) 135; P. Jain *et al*; *Phys. Lett.* **B484** (2000) 267, *hep-ph/0001031.*
10) See for example, E. Kolb and M. Turner, *The Early Universe*, Addison - Wesley (1988).
11) L. Stodolsky, *Phys. Rev. Lett.* **34** (1975) 110; B.A. Campbell and P.J. O'Donnell, *Phys. Rev.* **D26** (1982) 1487 generalized the result to include neutral currents and massive neutrinos.
12) B.F. Shvartsman *et al*, *JETP Lett.* **36** (1982) 277.
13) Several ideas have been proposed to render this effect detectable; P.F. Smith and J.D. Lewin, *Phys. Rep.* **187** (1990) 203; C. Hagmann, *hep-ph/9905258.*
14) T.J. Weiler, *Ap.J.* **285** (1984) 495.
15) K. Greisen, *Phys. Rev. Lett.* **16** (1966) 748; G. Zatsepin and V. Kuzmin, *JETP Lett.* **4** (1966) 78.
16) M. Takeda *et al*, *Phys. Rev. Lett.* **81** (1998) 1163; M. Are *et al*, *Phys. Rev.*

Lett. **85** (2000) 2244.
17) T.J. Weiler, *Astropart. Phys.* **11** (1999) 303; D. Fargion, S. Mele and J. Salis, *Astrophys. J.* **517** (1999) 725; T. J. Weiler, *these proceedings.*
18) L. Stodolsky, *Phys. Lett.* **B473** (2000) 61.
19) T.J. Weiler, W. Simmons, J.G. Learned, and S. Pakvasa, *hep-ph/9411432.*
20) G.F. Giudice *et al*, *hep-ph/0012317.*
21) P. Bode, J. P. Ostriker and N. Turok, *astro-ph/0010389.*
22) J.G. Learned, S. Pakvasa, W.A. Simmons and X. Tata, *Q.J.R. Astro. Soc.* **35** (1994) 321.