Abstract

A high-energy neutrino telescope, such as the operating AMANDA detector, may detect neutrinos produced in sources, possibly active galactic nuclei or gamma-ray bursts, distant by a thousand megaparsecs. These sources produce mostly $\nu_e$ or $\nu_\mu$ neutrinos. Above 1 PeV, $\nu_e$ and $\nu_\mu$ are absorbed by charged-current interactions in the Earth before reaching the opposite surface. However, the Earth never becomes opaque to $\nu_\tau$ since the $\tau^-$ produced in a charged-current $\nu_\tau$ interaction decays back into $\nu_\tau$ before losing significant energy. This preferential penetration of tau neutrinos through the Earth above $10^{14}$ eV provides an experimental signature for neutrino oscillations. The appearance of a $\nu_\tau$ component would be evident as a flat zenith angle dependence of a source intensity at the highest neutrino energies. Such an angular dependence would indicate $\nu_\tau$ mixing with a sensitivity to $\Delta m^2$ as low as $10^{-17}$ eV$^2$, for the farthest sources. In addition, the presence of tau neutrino mixing would provide the opportunity for neutrino astronomy well beyond the PeV cutoff, possibly out to the energies matching those of the highest energy protons observed above $10^{20}$ eV.
I. INTRODUCTION

High-energy neutrino detectors roughly two orders of magnitude larger in effective telescope area than the Super-Kamiokande experiment are being constructed to detect astronomical neutrino sources beyond the Sun [1]. The most powerful sources may be far beyond the boundaries of our galaxy, with active galactic nuclei (AGN) and gamma-ray bursts (GRB) being the leading candidates simply because they are the sources of the highest energy photons. They may also be the accelerators of the highest energy cosmic rays.

If AGN and GRBs are the source of the high-energy cosmic-ray spectrum, which is known to extend beyond \(10^{20}\) eV, they will likely produce neutrinos from the decay of charged pions. These are the secondary particles in the interactions of accelerated protons with the very high density of photons in the source. Production occurs near the \(\Delta\) resonance in the p-\(\gamma\) interaction and the beam is exclusively composed of \(\nu_e\) and \(\nu_\mu\). The flux of neutrinos is calculable because the properties of the beam and target can be deduced from the observations of high-energy protons and gamma rays at Earth. The prediction is of the order of 50 detected neutrinos per year in a high energy neutrino telescope with an effective area of 1 km\(^2\) [1,2]. Their energies cluster in the vicinity of 100 TeV for GRBs and 100 PeV for neutrinos originating in AGN jets. For the latter, even larger fluxes of lower energy energy neutrinos may emanate from their associated accretion disks [3].

Whereas AGN exist within 100 Mpc, the most powerful are at cosmological distances. So are GRBs and therefore, from a particle physics point of view, we have the extraordinary opportunity to observe neutrinos which have traveled more than 1000 Mpc. With this baseline, the presence of tau neutrinos from such sources would indicate the presence of neutrino oscillations with \(\Delta m^2\) as low as \(10^{-17}\) eV\(^2\), where the mass difference squared is relative to the original \(\nu_e,\mu\). For example, such a search for \(\nu_\tau\) appearance would extend the current searches for \(\nu_\mu\rightarrow\nu_\tau\) oscillations using atmospheric neutrinos by 14 orders of magnitude.

This particle physics experiment is made possible by the fact that the \(\nu_\tau\) can be identified by two of signatures: by “double-bang” events from the production and decay of the \(\tau\) lepton, and by the absence of absorption by the Earth. The “double-bang” signature has been described elsewhere [4]. Observation of double-bang events is difficult in a first generation telescope such as AMANDA.

We present in this letter a second signature for \(\nu_\tau\) appearance in a cosmic beam. For energies above 10–100 TeV, \(\nu_e,\mu\) neutrinos no longer efficiently penetrate the Earth and are preferentially observed near the horizon where they traverse a reduced chord of the Earth. Our critical observation is that above these energies the Earth remains effectively transparent to \(\nu_\tau\). A high-energy \(\nu_\tau\) will interact with the Earth and produce another \(\nu_\tau\) of lower energy. In a neutral-current interaction its energy is, on average, about half. In a charged-current interaction a \(\tau\) is produced which decays in a number of ways, yet there is always another \(\nu_\tau\) in the final state. Its energy is reduced, on average, to about one fifth. So, high-energy
ντ’s will initiate a cascade in the Earth which will contain a ντ of reduced energy in each interaction. Once its energy falls below threshold for absorption, i.e., its interaction length becomes comparable to the diameter of the Earth, the neutrino will propagate to the detector with an energy in the vicinity of 10–100 TeV. Figure 1 shows the characteristic relationship between the incoming ντ energy and the energy of the final ντ from a simple Monte Carlo. The simulation includes the \( Q^2 \) dependence of the \( W \) propagator and proton structure [1]. The ντ will be detected by the appearance of a \( \tau^- \) which decays to \( \mu^- \) just below the detector.

Since all ντ with energy greater than 100 TeV will have their energy reduced by this process to about 100 TeV by the time they reach the detector, a pile-up of events near 100 TeV would be one clear signature of a ντ component in the cosmic beam. However, this would require the energy spectrum to fall more slowly than \( E^{-2} \). For diffuse or point sources, the νe,µ will also show a characteristic absorption as a function of the zenith angle of the source, but ντ will show none. It is straightforward to calculate absorption quantitatively because the neutrino cross sections are determined from parton distribution functions that are constrained by accelerator data. Deviation from the calculated zenith angle distribution towards flatness is a signature for ντ appearance. Figure 2 compares the zenith angle distributions of observed source intensities for νµ and ντ.

Despite the loss of energy in the cascade, the energies involved are high enough so that the final ντ still points back to its source. So if there is any large-angle neutrino oscillations involving ντ with sufficient \( \Delta m^2 \) (such as that consistent with the Super-Kamiokande data [3]) even a pure νµ source can be seen above \( 10^{15} \) eV, even out to \( 10^{21} \) eV where the highest energy cosmic-ray protons have been observed. These neutrinos will point back to their sources.

II. ντ FROM GAMMA-RAY BURSTS: AN EXAMPLE

Recently, GRBs may have become the best motivated source for high energy neutrinos [2]. Their neutrino flux can be calculated in a relatively model-independent way. Although their neutrinos may be less copious and less energetic than those anticipated from AGN, the predicted fluxes can be bracketed with more confidence. In GRBs a fraction of a solar mass of energy (\( \sim 10^{53} \) ergs) is released over a time scale of order 1 second as photons with a very hard spectrum. It has been suggested [6] that, though unknown, the same cataclysmic events also produce the highest energy cosmic-ray protons. This association is reinforced by more than the phenomenal energy and luminosity:

- Both GRBs and the highest energy cosmic rays are produced in cosmological sources, i.e., distributed throughout the Universe.
- The average rate \( \dot{E} \approx 4 \times 10^{44} \) Mpc\(^{-3}\) yr\(^{-1} \) at which energy is injected into the Universe as gamma rays from GRBs is similar to the rate at which energy must be injected in
the highest energy cosmic rays in order to produce the observed cosmic ray flux beyond the “ankle” in the spectrum at $10^{19}$ eV.

There is increasing observational support for a model where an initial event involving neutron stars or black holes deposits a solar mass of energy into a radius of order 100 km [7]. Such a state is opaque to light. The observed gamma ray display is the result of a relativistic shock which expands the original fireball by a factor $10^6$ over 1 second. Gamma rays are produced by synchrotron radiation by relativistic electrons accelerated in the shock, possibly followed by inverse-Compton scattering. The association of cosmic rays with GRBs obviously requires that kinetic energy in the shock is converted into the acceleration of protons as well as electrons. It is assumed that the efficiency with which kinetic energy is converted to accelerated protons is comparable to that for electrons. The production of high-energy neutrinos is a feature of the fireball model because the protons will photoproduce pions and, therefore, neutrinos on the gamma rays in the burst. We have a beam dump configuration where both the beam and target are constrained by observation: the cosmic ray beam and the observed GRB photon fluxes at Earth, respectively.

The predicted neutrino flux is [2]

\[
\frac{dN}{dE} = \frac{A}{E^2} \quad \text{for } E > E_b
\]

\[
= \frac{A}{(E_b E)} \quad \text{for } E < E_b
\]

with $A = 4 \times 10^{-11}$ TeV (cm$^2$ s sr)$^{-1}$ and $E_b \simeq 100$ TeV.

From an observational point of view, the predicted flux is better summarized in terms of the main ingredients of the model:

\[
N_\nu = 50 \left[ \frac{f_\pi}{20\%} \right] \left[ \frac{\dot{E}}{4 \times 10^{44} \text{ Mpc}^{-3} \text{ yr}^{-1}} \right] \left[ \frac{E_\nu}{100 \text{ TeV}} \right]^{-1},
\]

\( i.e., \) we expect 50 events in a km$^2$ detector in one year. Here $f_\pi$, assumed to be 20%, is the efficiency by which proton energy is converted into the production of pions and $\dot{E}$ is the total injection rate into GRBs averaged over volume and time. The energy of the neutrinos is fixed by the threshold for photoproduction of pions by the protons on the GRB photons in the shock. The neutrino rate depends weakly on their energy: increased energy per neutrino reduces the flux as $E^{-1}$. As long as the detected neutrino flux does not fall off too quickly with energy, the presence of $\nu_\tau$ would be indicated by a pile-up of events at 100 TeV.

Interestingly, this flux may be observable in the currently operating AMANDA detector. Its effective area for the detection of 100 TeV neutrinos is 0.24 and 0.06 km$^2$ for $\nu_\mu$ and $\nu_e$, respectively [8]. Although these results were obtained by Monte Carlo simulation, the
effective area for a $\nu_e$ can be estimated from the fact that an electromagnetic shower of 100 TeV energy produces single photoelectron signals in ice over a radius of 250 m. The effective area for a $\nu_\mu$ is larger because the muon has a range of 10 km (water-equivalent) and produces single photoelectrons to 100 m from the track by catastrophic energy losses. Because these spectacular events arrive with the GRB time-stamp of 1 second precision and with an unmistakable high-energy signature (they are a factor $10^{3-4}$ above AMANDA’s nominal threshold), no background rejection is required. After correcting for the fact that BATSE photon detectors only report one quarter of the bursts and that AMANDA has $4\pi$ acceptance for these events, we predict 30 events per year. Such events should be observed in coincidence with a BATSE burst within a 1 second interval about twice per month. To sharpen the evidence one could select high-energy events only, for instance, events where more than 80 and 150 optical modules report in the trigger. Such events occur at a rate of 1 and 0.05 Hz, with an efficiency for 100 TeV neutrinos of 0.4 and 0.1, respectively. They do not form an irreducible background because reconstruction can confirm their GRB origin. About once per year a relatively near burst could produce multiple events in a single second.

Once a GRB beam has been established, the zenith angle distribution of the sources can be used to search for $\nu_\tau$ appearance as described above. The technique may also be applied to a uniform diffuse source.

There is also the possibility that high-energy gamma rays and neutrinos are produced when the shock expands into the interstellar medium. This mechanism has been invoked as the origin of the delayed high energy gamma rays. The fluxes are expected to be lower, and are produced over minutes, not seconds, making their identification more challenging because because matching of the photon and neutrino directions is now required.

It is important to point out that AGN neutrinos are expected to reach energies a factor one thousand or more higher than those from GRBs. The predicted rates in the present AMANDA detector range from copious to non-observable, depending on the theoretical model. If one associates AGN with the source of the highest energy cosmic rays, the predicted flux is, not surprisingly, similar to the one obtained for GRBs. Neutrinos are mostly produced near the maximum energy of 100 PeV, rather than 100 TeV. Such a beam would be ideal for searching for tau neutrinos.

III. CONCLUSION

We have described a property of tau neutrinos which allows their efficient detection by neutrino detectors above 1 PeV. The differential attenuation of $\nu_\mu$ versus $\nu_\tau$ can be used in existing and future large-area neutrino detectors such as AMANDA to search for neutrino oscillations. A flat azimuthal dependence of point or diffuse sources could demonstrate $\nu_\tau$ appearance over a 1000 megaparsec baseline at $10^{15}$ eV, corresponding to a sensitivity in
$\Delta m^2$ of $10^{-17}$ eV$^2$. In the presence of neutrino oscillations, these high energy neutrinos may be useful for finding sources of extremely high-energy neutrinos such as gamma-ray bursts and active galactic nuclei.
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FIG. 1. Plot of the energy of the final $\nu_\tau$ in the cascade through the Earth versus the energy of the initial $\nu_\tau$. The straight line corresponds to neutrinos that do not interact. Angles larger than $85^\circ$ with respect to the nadir are excluded because the $\nu_\tau$ have not yet been moderated to $10^{15}$ eV. Note that an especially hard $\nu_\tau$ input spectrum was chosen for this figure to illustrate the effect.
FIG. 2. Plot of the transmission of $\nu_\mu$ and $\nu_\tau$ through the Earth’s. The transmission of $\nu_\tau$ is essentially independent of their energy, as described in the text. The event rates are normalized to the maximum.