Tau Neutrino Appearance with a 1000 Megaparsec Baseline

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A high-energy neutrino telescope, such as the AMANDA detector, may detect neutrinos produced in sources, distant by a 1000 megaparsecs, which produce mostly ν_e or ν_μ neutrinos. Above 1 PeV, ν_e and ν_μ are absorbed by charged-current interactions in the Earth, but the Earth never becomes opaque to ν_τ since the τ^- produced in a charged-current ν_τ interaction decays back into ν_τ. This provides an experimental signature for neutrino oscillations. The appearance of a ν_τ component would be evident as a flat zenith angle dependence of a source intensity at the highest neutrino energies, which would indicate ν_τ mixing with a sensitivity to Δm^2 as low as 10^{-17} eV^2, for the farthest sources. In addition, the presence of tau neutrino mixing would allow neutrino astronomy well beyond the PeV cutoff, possibly out to the energies of protons observed above 10^{20} eV. [S0031-9007(98)07717-5]

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High-energy neutrino detectors roughly 2 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's) 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 GRB's 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 pions are secondary particles produced in the interactions of accelerated protons with photons in the source. Production occurs near the Δ resonance in the p-γ interaction and the beam is exclusively composed of ν_e and ν_μ. 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 the 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 GRB's and 100 PeV (1 PeV $= 1 \times 10^{15}$ eV) for neutrinos originating in AGN jets. For the latter, even larger fluxes of lower energy neutrinos may emanate from their associated accretion disks [3].

Whereas AGN exist within 100 Mpc, the most powerful are at cosmological distances. GRB's are also located at cosmological distances; 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 Δm^2 as low as 10^{-17} eV^2, where the mass difference squared is relative to the original $\nu_{e,\mu}$. This technique probes large mixing angles, so that the neutrino beam at the Earth may have a ν_τ component as large as 50%. For example, such a search for ν_τ appearance would extend the current searches for ν_μ-ν_τ oscillations using atmospheric neutrinos by 14 orders of magnitude.

This particle physics experiment is made possible by the fact that the ν_τ can be identified by two signatures: by "double-bang" events from the production and decay of the τ 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 ν_τ 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 ν_τ. A high-energy ν_τ will interact with the Earth and produce another ν_τ of lower energy. In a neutral-current interaction its energy is, on average, about one-half. In a charged-current interaction a τ is produced which decays in a number of ways, yet there is always another ν_τ in the final state. Its energy is reduced, on average, to about one-fifth. So, high-energy ν_τ's will initiate a cascade in the Earth which will contain a ν_τ 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 ν_τ energy and the energy of the final ν_τ from a simple Monte Carlo. The simulation includes the Q^2 dependence of the W propagator and proton structure [1]. The ν_τ will be detected by

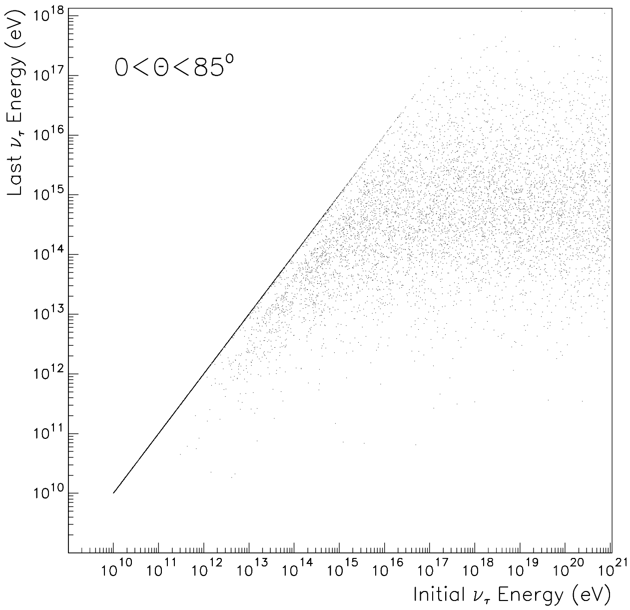

FIG. 1. Plot of the energy of the final ν_τ in the cascade through the Earth versus the energy of the initial ν_τ. The straight line corresponds to neutrinos that do not interact. Angles larger than 85° with respect to the nadir are excluded because the ν_τ have not yet been moderated to 10^{15} eV. Note that an especially hard ν_τ input spectrum was chosen for this figure to illustrate the effect.

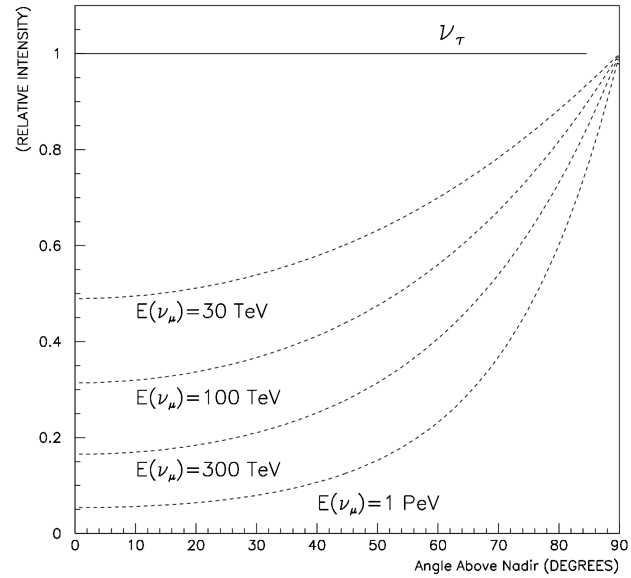

FIG. 2. Plot of the transmission of ν_μ and ν_τ through the Earth. The transmission of ν_τ is essentially independent of their energy, as described in the text. The event rates are normalized to the maximum.

the appearance of a τ^- which decays to μ^- just below the detector.

Since all ν_τ 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 pileup of events near 100 TeV would be one clear signature of a ν_τ 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 $\nu_{e,\mu}$ will also show a characteristic absorption as a function of the zenith angle of the source, but ν_τ 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 ν_τ appearance. Figure 2 compares the zenith angle distributions of observed source intensities for ν_μ and ν_τ.

The energies involved are high enough so that the final ν_τ still points back to its source. So if there exist large-angle vacuum neutrino oscillations involving ν_τ with sufficient Δm^2 (such as that consistent with the Super-Kamiokande data [5]) even a pure ν_μ 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.

Before working through a simple example, we emphasize that the oscillation experiment can be performed with any high-energy neutrino source, whether point or diffuse. The possibility that AGN are beams of very high-energy neutrinos has been extensively studied [1]. In this context AGN are ideal sources because their directions and distances are usually well known. With first-generation detectors it is likely that GRB's are easier to identify using the temporal coincidence with gamma-ray detectors. Note that, while the time coincidence facilitates the observation, it is not essential.

An example: ν_τ appearance in gamma-ray burst neutrino beams through vacuum oscillation.—Recently, GRB's 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 GRB's a fraction of a solar mass of energy ($\sim 10^{53}$ ergs) is released over a time scale of order 1 sec 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 rays. This association is reinforced by more than the phenomenal energy and luminosity.

(i) Both GRB's and the highest energy cosmic rays are produced in cosmological sources, i.e., distributed throughout the Universe.

(ii) The average rate $\dot{E} \simeq 4 \times 10^{44}$ Mpc^{-3} yr^{-1} at which energy is injected into the Universe as gamma rays from GRB's 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 of 10^6 over 1 sec. 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 GRB's 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 upward neutrino flux is [2]

$$dN/dE = A/E^2 \quad \text{for} \quad E > E_b\,, \tag{1}$$

$$= A/(E_b E) \quad \text{for} \quad E < E_b\,, \tag{2}$$

with $A = 4 \times 10^{-11}$ TeV $(\text{cm}^2\,\text{s}\,\text{sr})^{-1}$ 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:

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

i.e., we expect 50 events in a km^2 detector in one year. Here f_π, estimated 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 GRB's 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 ν_τ would be indicated by a pileup of events at 100 TeV.

Note that GRB's, like AGN, produce a "burst" spectrum in neutrinos; after folding the falling GRB energy spectrum with the increasing detection efficiency, burst events are detected with an average energy of several hundred TeV. Even with the relatively poor energy resolution of neutrino telescopes of 30% or worse, it should not be a challenge to separate these high-energy events from the steeply falling background of atmospheric neutrinos. The possibility of seeing a multi-TeV atmospheric neutrino that penetrated the Earth is extremely unlikely, especially for such short time scales.

Interestingly, this flux may be observable in the currently operating AMANDA detector. Its effective area for the detection of 100 TeV neutrinos is already of the order of 0.1 km^2. The effective area for a ν_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 ν_μ 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. In the model we are considering [2], these spectacular events arrive with the GRB time stamp of the order of 1 sec precision and with an unmistakable high-energy signature (they are a factor of 10^{3-4} above AMANDA's nominal threshold); no background rejection is required. After correcting for the fact that Burst and Transient Source Experiment (BATSE) photon detectors report only about one-third of the bursts and that AMANDA has 4π acceptance for these events, we predict tens of events per year. Such events should be observed in coincidence with a BATSE burst within a 1 sec 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, respectively, with an efficiency for 100 TeV neutrinos of 0.4 and 0.1, respectively [8]. They do not form an irreducible background because reconstruction can confirm their GRB origin. Although, on average, we expect much less than one event per burst, a relatively near burst would 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 ν_τ appearance as described above. For some GRB's the distance is measured by redshift.

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 [9]. The fluxes are produced over minutes, possibly longer. Identification of the signal now would require reconstruction matching the photon and neutrino directions. This should not be too challenging given the clear experimental signature of such high-energy events. A rejection of 10^{-4} is required when 10–100 Hz background rate accumulates over several minutes. This is well within the capability of neutrino telescopes which are designed to achieve better than 10^{-6}.

It is important to point out that AGN neutrinos are expected to reach energies a factor of 1000 or more higher than those from GRB's [1]. The predicted rates in the present AMANDA detector range from copious to nonobservable, 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 GRB's [10]. 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.

In conclusion, we have described a property of tau neutrinos which allows their efficient detection by neutrino detectors above 1 PeV. The differential attenuation of ν_μ versus ν_τ 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 ν_τ appearance over a 1000 megaparsec baseline at 10^{15} eV, corresponding to a sensitivity in Δm^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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