UHE Neutrinos with Auger

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We explore the neutrino capabilities of the Pierre Auger Observatory at Ultra-High Energy (UHE), beyond 10^{18} eV. Neutrino events are revealed as nearly horizontal air showers originating deep within the atmosphere. We show that detection of ν_μ or ν_e neutrinos is unlikely unless there are unexpectedly strong sources of such particles. However, the detection of ν_τ events from oscillation of ν_μ neutrinos produced in the course of intergalactic propagation of UHE cosmic rays is possible.

UHE cosmic rays interact with the cosmic microwave background, ultimately limiting the range of propagation of such particles. A cutoff in the energy spectrum is expected due to this effect, the so-called GZK cutoff. By the same token, pions produced in such interactions will decay, producing muons and associated neutrinos, and the subsequent muon decays yield further neutrinos. Therefore, one expects that the UHE flux should include ν_μ and ν_e; indeed, such GZK neutrinos could be present in comparable numbers to charged particles. Moreover, if neutrinos oscillate as indicated by SuperKamiokande and other experiments, there could be an admixture of ν_μ, ν_τ and ν_e.

Possibilities for the origin of the highest energy cosmic rays include exotic sources such as topological defects formed during phase transitions as the early Universe cooled, a product of spontaneous symmetry breaking implicit in some Grand Unified Theories (GUTs) [1, 2, 3, 4, 5, 6]. Relic topological defects, such as ordinary and superconducting cosmic strings, domain walls, or magnetic monopoles, are relatively stable topologically, but can release part of their energy in the form of X particles, if they collapse or annihilate. These X particles, with typical GUT scale masses on the order of 10^{24} eV, subsequently decay into leptons and quarks, including neutrinos. The spectrum of cosmic rays generated by this mechanism could extend to extraordinarily high energies, perhaps as much as 10^{24} eV. In at least one topological defect decay model [7], the highest energy cosmic rays are dominated by neutrinos, so that there is an interesting prediction of significant numbers of neutrinos being present at the upper end of the spectrum.

A summary [8] of theoretical predictions for neutrino fluxes (in this case ν_μ) at energies beyond 10^{12} eV from various models is shown in Figure 1. On it, the closed hatched region indicates atmospheric neutrinos over a range of zenith angles, the open hatched region neutrinos resulting from cosmic-ray interactions within the intergalactic medium in galactic clusters, and thick solid lines represent neutrinos from cosmic-ray interactions with the interstellar medium in our own Galaxy (the upper and lower curves are for extrema of galactic latitude). These predictions are deemed well founded, and neutrinos from these sources are certain. The thick dashed curves and the dotted curves below about 10^{20} eV represent diffuse neutrinos produced in association with gamma ray bursts, in proton blazar models. These sources are thought to be somewhat more speculative, but still fairly certain. Finally, the dotted curves beyond about 10^{20} eV are for neutrinos from topological defect decay models, quite speculative.

Neutrino-induced air showers are identifiable as such only for nearly horizontal showers. Indeed, the Earth's atmosphere presents a target of thickness only about 1000 g/cm^2 to cosmic ray particles arriving vertically, but a target of thickness 36,000 g/cm^2 to nearly horizontal particles. With a charged current interaction cross section of order 10^{-32} cm^2 at 10^{18} eV, a neutrino arriving at a large zenith angle has a signifiant probability of interacting in the atmosphere within a few kilometers of an Auger array covering 3,000 km^2. The hadrons produced in the neutrino interaction initiate an air shower which is in all respects similar to cosmic ray induced showers, except that the neutrino-induced shower can begin deep in the atmosphere. In the charged current interaction of a ν_e, a UHE electron is produced which also initiates a large electromagnetic cascade.

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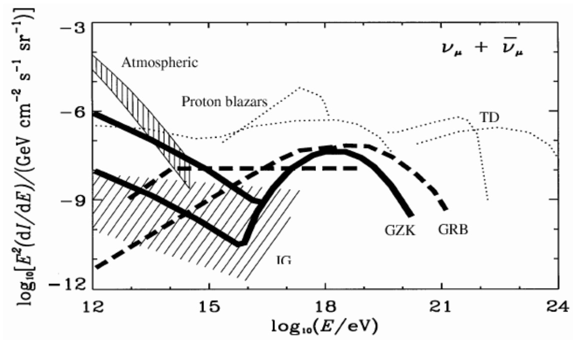

Figure 1: Summary of predicted ν_μ fluxes from different models. The various curves are explained in the text.

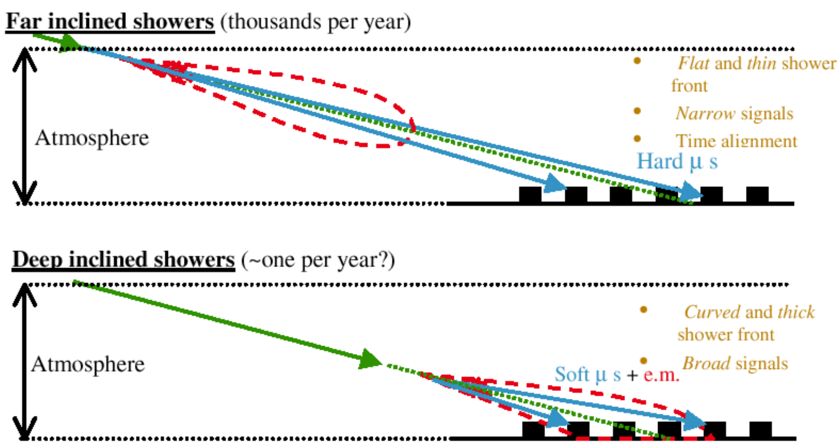

Figure 2: Schematic representation of a UHE air shower, and of its placement with respect to the ground and the Auger array. A "far inclined" shower is likely to be due to a hadronic cosmic ray, whereas a "deep inclined" shower can only be caused by a neutrino.

In contrast, the charged current interaction of a ν_μ produces a muon, which is not detectable by Auger.

For ordinary air showers occurring at large zenith angles, the electromagnetic component is attenuated long before the shower front reaches the ground, whereas the hard muon component (in the energy range 10 to 1000 GeV) can reach a ground-based detector array, accompanied by a small amount of radiative products which arrive at the ground at the same time (within a few tens of nanoseconds). Therefore the shower front for such an event is rather flat and thin, with all particles arriving within about 100 ns of a planar front. This represents a "far inclined" shower. In contrast, a neutrino-induced event deep in the atmosphere (a "deep inclined" shower) yields a much larger electromagnetic contribution at the ground. This is illustrated in Figure 2, which shows the geometry of an inclined air shower in relation to a ground array. The shower front in the case of a deep shower departs measurably from a plane, and particle arrival times can be spread out over several microseconds. In principle then, given the ability of Auger to distinguish between muons and electromagnetic activity, it is straightforward to distinguish between neutrino-induced events at large zeniths (from 70° to the horizon) from other types of cosmic rays.

With one Auger ground array alone, a ν_μ or ν_e acceptance of 18,000 km^{3}sr at 10^{18} eV is achieved (for ν_τ, the acceptance is even greater, as it includes the rock underneath the array, as described below). This can be estimated roughly by multiplying the surface area of 3,000 km^2 by an effective solid angle of 2 sr beyond 70° and by an effective production height above ground varying between 0 and 5 km, depending on zenith angle (the useful shower length being about 15 km at 10^{18} eV). At energies below 10^{18} eV, the acceptance is reduced because of the diminished lateral extent of the electromagnetic component, which then requires the shower front to strike the ground in a position with respect to the array that is favorable for triggering. At energies greater than 10^{18} eV,

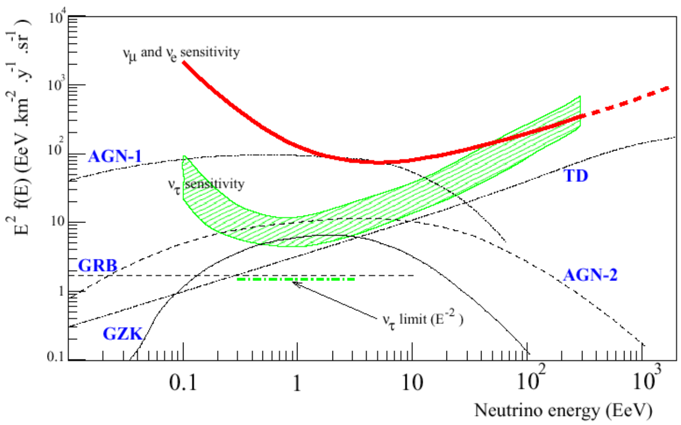

Figure 3: Auger neutrino sensitivity for ν_μ, ν_e or ν_τ, corresponding to one event per year per energy decade. A number of model predictions are shown. Also shown is a 90% C.L. upper limit after five years, if no events are seen.

the acceptance increases smoothly with energy owing to an increased effective shower length. It is worth noting that 18,000 km^{3}sr of air corresponds to roughly 18 km^{3}sr of water, i.e., a size comparable to the acceptance of proposed ice Cherenkov projects such as the ICECUBE detector. An important distinction however is due to the fact that the Earth is opaque to the 10^{18} eV neutrinos that will be detectable by Auger, for which the target is the atmosphere. Hence the ice Cherenkov projects will aim at a much lower energy regime, and Auger is truly complementary to these other efforts.

The considerations and simple estimates above are borne out by Monte Carlo calculations of the response of a simulated array to hadron-induced showers injected at various altitudes and zenith angles [9, 10, 11, 12]. Expected event rates due to horizontal UHE neutrinos depend on a number of factors, such as the source of the neutrinos, the behavior of the neutrino interaction cross-section with energy, the details of the array triggering efficiency, etc. Approximate neutrino rates have been calculated for different neutrino interaction cross-sections. Figure 3 depicts the expected Auger sensitivity to ν_μ or ν_e, compared to a number of model predictions [13]. The curve is obtained for one event per year per energy decade. It appears that detection of ν_μ or ν_e would be quite difficult given the hypothesized sources, and that new physics would be required for a significant signal.

In addition to ν_μ or ν_e neutrinos, ν_τ could be present in significant numbers, in view of the $\nu_\mu \leftrightarrow \nu_\tau$ mixing observed in the study of atmospheric and solar neutrinos. A 2×10^{17} eV τ lepton produced in the ν_τ interaction would travel a distance of $\gamma c\tau \sim 10$ km before decaying, yielding a large air shower detectable by Auger. Thus, ν_τ interactions in the few km of rock underneath the array, or within the Andes mountains 50 km to the West of the array, could result in a measurable signal. Preliminary simulations indicate that this effect results in an increase in effective acceptance by a factor of about 10. This is illustrated in Figure 3, where the ν_τ Auger sensitivity curve is shown. Note that τ energy losses in the rock have been explicitly taken into account in this calculation. It appears that GZK ν_τ events might be seen at a level just sufficient to claim detection. A larger rate would point to new and fundamental physics.

Acknowledgments

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