Simulation of the radio signal from ultrahigh energy neutrino-initiated showers

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PeV neutrinos produce particle showers when they interact with the atomic nuclei in ice. We briefly describe characteristics of these showers and the radio Cherenkov signal produced by the showers. We study pulses from electromagnetic (em), hadronic, and combined em-hadronic showers and propose extrapolations to EeV energies.

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I. INTRODUCTION

Ultrahigh energy (UHE) neutrinos have energies of a PeV and higher. Although these neutrinos have not been observed, a number of models predict their existence. Another reason to believe in UHE neutrinos is the existence of UHE cosmic rays which have been observed by a number of detectors. Any models that account for these cosmic rays also predict existence of UHE neutrinos. Ultrahigh energy neutrino detection will have a great impact on fundamental physics and astrophysics. Because of their ultrahigh energies, they will help us explore fundamental interactions at energies well beyond the reach of man-made accelerators. Also, being neutral and presumably weekly interacting, these neutrinos, unlike charged particles, will bring us directional information about the source. Being weakly interacting they can help us explore regions of astrophysical objects which otherwise are opaque.

The electrons and hadrons from the neutrino-nucleon interactions will initiate particle showers as, unlike muons and taus, they dump their energy very quickly in matter through electromagnetic and strong interactions. These showers produce radio and optical radiation which can be detected in detectors like RICE and ICECUBE. Radio ice Cherenkov experiment (RICE), located at the south pole, can detect these showers from the radio signal they produce.

Here we give a brief introduction to the theory of radio emission from the showers. Particle showers in matter, unlike air showers, travel only a few 10's of meters and dump all their energy in the target material. The number of particles and the spacial size of the shower depends on the energy of the primary particle. For ultrahigh energy primaries, the shower, at a given time at shower maximum (which occurs at a few meters from the primary vertex), has millions of particles located in a few cubic centimeters. As these particles are moving faster than the speed of light in the given material, the charged particles will emit Cherenkov radiation at all wavelengths. Whether this radiation will be coherent depends on its wavelength, the net charge in the shower, and the shower size (the volume in which most of the shower particles are contained at a given time). For a typical shower size (a few cubic centimeters) one expects to get a coherent signal at Cherenkov angle due to constructive interference of the radio radiation from different parts of the shower. Hence one gets a strong radio signal from the shower which makes the radio detection of the showers (RICE) a very attractive technique as compared to the optical detection (ICECUBE).

For radio detection of the showers, one needs a radio transparent material, with a huge volume (to have detector effective volume large enough, of the order of a cubic kilometer, to detect tiny fluxes of UHE neutrinos), in a region with as low as possible background radio signal. The last requirement makes a cold (to reduce background radio emission from atoms due to their vibrations at finite temperature) and isolated area an ideal environment for radio detection. Cold ice is remarkably transparent to radio transmission, with attenuation length of more than a kilometer.

RICE, founded in 1995, is located 100m below surface, above AMANDA, at the South pole. The instrumented volume is (200m)³ which consists of 20 radio dipole antennas optimized to detect 0.5GHz radio signal. The effective volume depends on signal strength which in turn depends on the energy of the primary. For UHE showers, RICE effective volume is of the order of a km³. RICE expects to upgrade its volume by an order of magnitude in the coming years.

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II. SHOWER SIMULATIONS

As mentioned above one expects to get a coherent radio signal from the particle showers produced by UHE neutrinos. The dependence of this signal on the distance between the shower and the observer is trivial: the signal goes like 1/R, where R is the distance, with a weak exponential attenuation. We want to know, at a given neutrino energy: How will this signal vary with angle (of the cone around shower axis) and frequency (of the emitted radiation)? How will this signal vary for different primary particles (from UHE neutrino interaction with nuclei)? At ultrahigh energies, far above the reach of accelerators, one has to rely on numerical simulations of the radio signal from the showers which contain millions of particles.

To simulate the shower signal in ice, one propagates the shower particles in ice and calculates the radio signal from them at every step in space and time\[^6\]. Here we extend the simulation to ultrahigh energies. In this case the shower contains millions of particles at the shower maximum. We have used PYTHIA\[^8\] as an event generator software to produce an event vertex due to a neutrino-nucleon interaction. Then we feed these particles to GEANT4\[^9\] assuming they are located at the same point (event vertex) in space and time\[^10\].

III. SIMULATION RESULTS

For CC interaction of the neutrinos, $\nu_\mu$ and $\nu_\tau$ are not as efficient as $\nu_e$ in producing the signal. This is because the muons and taus produced in a CC interaction take away some energy and do not contribute to the shower (at these energies, typically they can go a long way without decaying; also their electromagnetic (em) energy losses are very small as compared to the electrons) while electrons will dump all their energy into em energy which contributes to the signal. In Fig. 1 we see the signal at a fixed frequency peaks at the Cherenkov angle in ice as expected.

Next we look at the energy dependence of the signal from em and hadronic showers. Figure 2 shows the signal as a function of energy for different primaries. We see although hadrons, as compared to electrons, are less efficient in producing the signal at lower energies, at higher energies they are equally efficient. We extrapolate the signal for hadrons above a 100TeV and for electrons and neutrinos above a PeV. We see the fit for electrons is almost linear.

IV. SUMMARY

Ultrahigh energy neutrinos are a window to explore fundamental physics and astrophysics. They have not been observed/identified yet. However, a number of experiments have observed UHE cosmic rays and almost all the models that account for these cosmic rays also predict the existence of UHE neutrinos. These neutrinos can produce particle showers when they interact with matter. These showers produce coherent radio signal while their optical signal is
The strength of the radio signal depends on the net charge in the shower which in turn depends on the number of particles in the shower which increases with neutrino energy. This makes radio detection technique very powerful at UHE energies (as the coherent radio signal is much larger than the optical signal at these energies). RICE expects to detect the radio signal from these UHE initiated neutrino showers. So far RICE has produced strict upper bounds on some of the UHE neutrino flux models.

Simulation results show that hadronic showers, as compared to EM showers for energies below a PeV, are not as efficient in producing radio signal. However, as one goes to ultrahigh energies, hadronic and EM showers become equally efficient in producing radio signals. The signal rises linearly with energy at ultrahigh energies. UHE neutrino detection situation is promising. AMANDA and RICE are taking data. RICE expects upgrade in the coming years which will increase its volume by an order of magnitude. ICECUBE and ANITA are funded and in development stages. A number of other projects are underway.

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For an expert reader, GEANT4.5.2 includes LPM effect in bremsstrahlung only. LPM effect in pair production has not been implemented yet in GEANT.