Simulations of radio signals produced by ultra-high and extremely high energy neutrino induced cascades in Antarctic ice and lunar regolith

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Abstract: Radio signals produced in ice by electromagnetic cascades with energies up to 10^{12} eV have been calculated. Simulations of cascades were performed using the SIMEX Code System. The simulation results in the matrix form, which described the charge excess evolution, were used to calculate coherent Cherenkov radiowave emission from electromagnetic cascades. Comparison with results at energies 10^{11} - 10^{12} eV received in the frameworks of the GEANT-4 Code System was made. A new algorithm PHUT6 was also developed to simulate radio signals produced by extremely high energy (up to 10^{21} eV) electron-photon and electron-hadron cascades in dense media. The base of the algorithm is a multilevel numerical scheme. The Migdal cross-sections are used to take into account the Landau-Pomeranchuk-Migdal (LPM) effect. Initially a Monte Carlo approach is used at the single particle level. When number of particles in a cascade increases up to 100-1000 transport equations are used. At the last step the lateral and angular distributions of negative and positive charges in the EHE cascade can be estimated as a sum of known charge distributions in low energy cascades. To test this approach some simulations with the help of the GEANT-4 code and EGS-4 code have been carried out at energies 10^{14} and 10^{15} eV.

Introduction

Last years the radiowave method of elementary particle cascade detection in dielectric media, suggested by G. Askaryan [1], was successfully applied to search for ultra-high energy (UHE, $>10^{15}$ eV) and extremely high energy (EHE, 10^{18} – 10^{21} eV) cosmic neutrinos in Antarctica. Experiments based on this technique would provide development of a new branch of Astronomy – "High-Energy Neutrino Astronomy" - to receive unique information on the most energetic processes in the Universe (e.g., active galactic nuclei, topological defects, GZK processes, etc.). The basic idea was to utilize a novel method for UHE and EHE neutrino detection by means of coherent Cherenkov radiowave emission from neutrino-induced electromagnetic and hadronic showers in the cold Antarctic ice [2].

The first studies of this method for the neutrino astronomy were made by the Institute for Nuclear Research (INR, Moscow) and the Arctic and Antarctic Research Institute (AARI, St. Petersburg) in 1984-1990 at the Soviet Antarctic station Vostok, where 1, 3 and 7-antenna prototypes of the Radio Antarctic Muon And Neutrino Detector (RAMAND) placed on the ice surface was constructed and tested. The background processes for RAMAND were studied by these prototype modules and the feasibility of the RAMAND project of 400 antennas for detection of UHE neutrinos (with an effective detection volume of the cubic kilometer-size) had been confirmed [3,4]. Unfortunately, such works at Vostok were abruptly discontinued in 1991.

In 1995-2005, the first experiment to search for cosmic EHE neutrino, with 18 antennas buried in ice (RICE project [5]) was performed by KU at Amundsen-Scott base (South Pole).

To obtain information on fluxes of EHE cosmic neutrinos (E > 10^{20}eV) and to improve the existing upper limit of the fluxes, monitoring of nanosecond radio pulses from the Moon regolith – the giant natural target for radio detection of EHE cosmic rays [6] - is on-going and is planned in the near future by several teams over the world. Some observations of the Moon had been already done with the Goldstone 70-meter dish [7] and with Kalyasin 64-meter dish [8]. New teams are planning to make similar observations with additional ground-based as well as with on-board-around-the Moon satellite radio telescopes (see, for example, [9] and [10]).

Since 2003, the University of Hawaii and a number of US Universities have been developing the radiowave neutrino telescope ANITA [11]. ANITA consists of 30 antennas placed in the gondola of a balloon which had passed over Antarctica at 40 km elevation in December 2006 – January 2007 to search for radio pulses produced by EHE neutrinos in glacial ice.

The radiowave neutrino experiments with salt targets are planning too.

One of the important tasks related to neutrino radio detection is simulation of the radio emission produced in ice by electron-photon (hadron) cascades at energies 10^{11} – 10^{20} eV and higher. Independent calculations of cascade curves, the negative charge excess in cascades and radio signals should be performed using different code systems.

In this paper results of new calculations of coherent Cherenkov radio emission from electromagnetic cascades with energies up to 10^{12} eV are presented. The new hybrid multilevel scheme for simulation of cascades at UHE and EHE energies (up to 10^{21} eV) is described.

Monte Carlo simulations for UHE and EHE neutrino radiowave detection in Antarctic ice using the SIMEX software

Electron-photon cascades up to energy 10^{12} eV were simulated using the SIMEX software, developed at INR [12].

Comparisons with results obtained using the GEANT-4 code were made at an energy of 10^{11} eV. Lateral and longitudinal charge excess profiles, tracklengths of charged particles and other characteristics agree with an accuracy of about 10%. Profiles for the total number of particles (electrons + positrons) as well as the excess charge (electrons - positrons) in showers initiated in ice (d = 0.92 g/cm^3) by electrons with energy 100 GeV have been calculated using a kinetic energy threshold of 0.3 MeV. A comparison between shower profiles obtained from SIMEX vs. GEANT-4 is shown in Fig. 1.

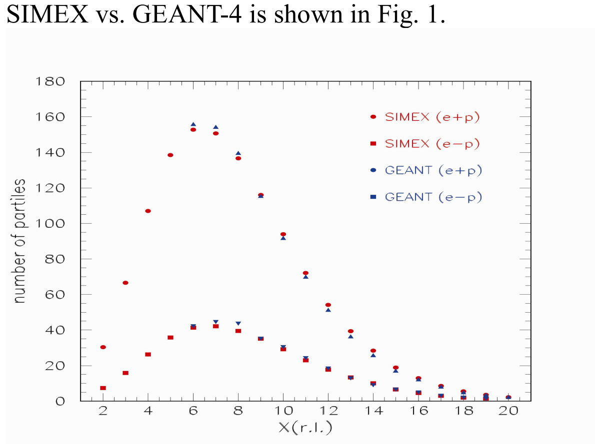

Figure 1: Comparison between shower profiles of a 100 GeV shower from SIMEX and GEANT-4.

As an example the frequency spectra of cascade radio emission are shown in the accompanying Figure 2, in comparison with the result of ZHS code [13] at a cascade energy 1 TeV and also with the GEANT-4 result [14] at energy 100 GeV. In the frequency range below 1 GHz the field strength is 10% lower than the GEANT-4 result,

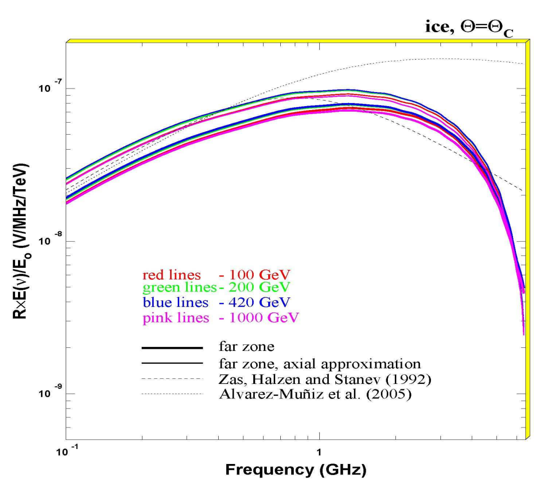

Figure 2: Comparison of results of ZHS, GEANT-4 and SIMEX simulations of radio emission from cascade in ice.

which may be explained by the accuracy of simulation of the main cascade characteristics and also by different methods of the Cherenkov radiofrequency field calculation. The obtained results allow more accurate estimates of the energy threshold of neutrino detection radio methods in ice.

New hybrid multilevel scheme for fast simulation of cascades at UHE and EHE energies

To reduce the CPU time for simulation of cascades at UHE energies (above 10^{15} eV) a hybrid multilevel scheme was developed at Moscow State University. The hybrid scheme has been suggested to estimate both the radio and acoustical signals caused by neutrino-induced cascades in dense media (e.g. in ice and water) at ultra high energies (up to 10^{21} eV) [15]. The Monte Carlo approach should be initially used to take into account fluctuations in the development of the individual cascades. It should be mentioned that these fluctuations are very large at high energies because of the Landau-Pomeranchuck-Migdal (LPM) effect.

Due to this effect the mean interaction length may increase many times and become much larger than the cascade radiation length. For this reason, the cascade curve would have a stochastic form. A program which realizes this Monte Carlo approach for the Migdal cross sections for processes of pair creation and bremsstrahlung has been developed and tested. It should be mentioned that to calculate these cross sections accurately, very small energy bins (order of 10^{-4}) have been used. It was found that the cascade length increases as energy$^{0.395}$ and at the energy of 10^{20} eV can exceed the value of 1 km (to be compared with the standard Bethe-Gaitler length of several dozen meters). For the next step the transport cascade equations can be exploited to take into account the spread of the large number of secondary particles which have been produced at the first stage of the cascade development. The source terms which describe these particles have been included in these equations. The integral forms of these equations have been used to be able to find out the solutions by simple iterative procedures. Computer code has been written to solve these equations iteratively. It should be mentioned that the numerical solution can be obtained in nearly 10 min for the very large energy interval of 10^{10} – 10^{20} eV. It is therefore very attractive to use such program codes for the very intense and rather accurate calculations needed for estimates of radio signals. To test this approach some simulations with the help of the GEANT-4 code and EGS-4 code have been carried out at energies 10^{14} and 10^{15} eV. Results of calculations obtained with the help of EGS coincides within several per cent with the numerical solutions of transport equations – PHUT6 code [Fig. 3]. Both results were obtained for cascades in air. Some difference between results of PHUT6 (air) and GEANT-4 (water) can be explained by LPM-effect in water at first 300 grams (see lower solid and dotted curves if x<300 g/cm^2).

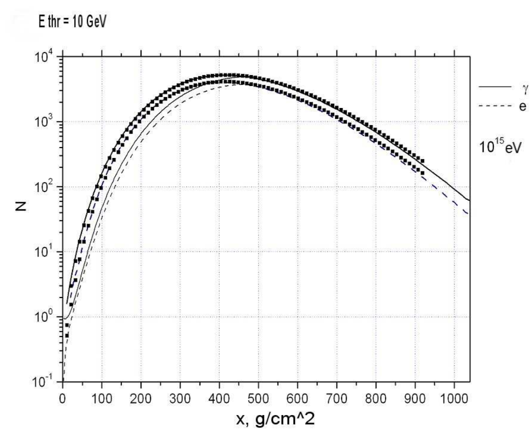

Figure 3: Comparison (preliminary) of results of calculations of N - numbers electrons + positrons and gamma quanta with energies higher than 10 GeV - using different codes: PHUT6 (hybrid one), EGS-4, GEANT-4; E = 10^{15} eV.

Thus, we conclude that the full set of programs to simulate the electron-photon cascades at energies up to 10^{21} eV are functional. Moreover the CPU time needed for such simulations is not large. For cascades initiated by low energy electrons and gammas (with energies below 10 GeV), one should take into account correctly Coulomb scattering. To this end, we suggest employing either the GEANT4 or SIMEX particle-level codes to create a library of radio signals from cascades. For hadronic cascades, both the Monte Carlo approach and the method based on the numerical solutions of the transport equations for hadrons have been developed and tested. The photons produced via decays of neutral pions may be regarded as source terms for the transport equations for electrons and gammas. Thus, a complete set of programs to estimate radio signals produced by neutrino–induced cascades in ice (lunar regolit etc) at ultra-high and extremely high energies has been developed.

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