Measurement of Attenuation Length for Radio Wave in Natural Rock Salt and Performance of Detecting Ultra High-Energy Neutrinos

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Abstract. Ultra high-energy (UHE) neutrinos (E>10^{15} eV) is expected to exist due to presence of the cosmic microwave background and UHE cosmic rays implied by Greisen, Zatsepin and Kuz’min (GZK). The low rate of GZK neutrinos requires us to utilize a large mass (50 Gton) of detection medium. Collision between the UHE neutrino and the rock salt produces electromagnetic shower, which includes a huge number of unpaired electrons in rock salt. They would emit sensible radio wave by coherent Cherenkov effect. Attenuation lengths of natural rock salt at 0.3 and 1.0 GHz were measured to know possibility of a salt neutrino detector. The result indicates a feasible plan with economical antenna spacing. Detection possibility of GZK neutrinos in natural huge rock salt formation has been simulated including attenuation length, background noise and bandwidth of antennae so that GZK neutrinos of 8-62 per year would be detected.

1. Introduction
Neutrinos can travel cosmological long distance from the early universe due to their weak interaction with matter, compared with electromagnetic wave of its wavelength longer than visible light. During the journey to the earth they are deflected by distortion of the space and time predicted by general theory of relativity originated in dark mass and dark energy as well as visible astronomical objects. In addition to the deflection, neutrinos with minute mass are bent at an infinitesimal amount by a gravitational force. The path could bring us information about gravitational structure of the space including the stellar objects through the cosmological distances. It is indispensable to explore the unknown mass and energy, which occupies 95% of the universe. Ultra-high energy (UHE) cosmic neutrinos (E>10^{15} eV) come from the cosmological distance is expected to be larger flux than those generated in the earth atmosphere, the solar and the galactic system at UHE.

Active galactic nuclei, γ ray bursts, topological defects etc. are forecasted to emit UHE neutrinos. In addition those generation is suggested in Greisen, Zatsepin and Kuz’m (GZK) cut-off process [1]. UHE protons (E>10^{20} eV) would lose the energy to produce Δ(1232) resonances while traveling 50Mpc (163Mly) due to interaction with 2.7K cosmic microwave backgrounds. The energy of GZK neutrinos ranges 10^{15} eV-10^{20} eV while generated in a decay chain from Δ(1232) resonance, and the flux is estimated to be few around 1 km^2 day^{-1}. An gigantic detector made of rock salt with a mass of...
50Gton or the volume of \((3\text{km})^3\) is needed being sensitive to the energy, the direction, the time and the flavor of the GZK neutrinos [2].

Such a huge detection medium requires long-range transmission wave, which carries information of neutrino interaction in the medium. Radio wave would have a long range through natural rock salt. G A Askar’yan [3] had proposed detection of radio wave emission with coherent Cherenkov effect produced by excess electrons in an electro-magnetic shower in dense materials. The effect was confirmed using a bunched \(\gamma\) beam at SLAC [4]. While for low-density medium, radio emission was calculated in an atmospheric shower by M Fujii and J Nishimura and recently confirmed experimentally [5]. In figure 1, we show Cherenkov radiation energy detected at 300m from an EM shower with respect to the EM shower energy including the attenuation length. Radio wave radiation energy is stronger than that of optical region over \(10^{16}\) eV. This shows that detection of Askar’yan radiation is suitable way in the UHE region.

We are contemplating Salt Neutrino Detector (SND), which aims to detect the UHE neutrinos. Rock salt domes are distributed widely and there would be a suitable site [6]. We have been studied rock salt samples having good radio wave transparency [7]. Interaction between an UHE neutrino and rock salt produces hadron showers composed of mainly charged and neutral pions. One third of pions are \(\pi^0\)s and each annihilates into 2\(\gamma\). Thus, a huge electromagnetic (EM) shower is generated. F Halzen, E Zas, and T Stanev [8] calculated the electric field strength of radio wave radiated from high-energy \((\leq 10^{15}\text{eV})\) EM shower in ice. We have made SND simulator, which is able to calculate electric field strength of radio wave radiated from EM shower with energy more than \(10^{15}\) eV in rock salt using a structure function [9], which is a space distribution of the excess electrons for longitudinal direction (1 dimensional structure function model). Neutrino detection sensitivity and performance are presented using SND simulator.

2. Attenuation length of radio wave in rock salt
We have measured complex permittivity in rock salt samples by perturbation method [10] using cylindrical cavity resonators of 0.3 GHz (749 mm\(\phi\) \times 100 mm) and 1.0 GHz (225 mm\(\phi\) \times 30 mm). Both have the Q values about 10,000 at TM\(_{010}\) mode.

We obtained real part (square of refractive index) and imaginary part (absorption in a medium) of complex permittivity, by measuring decease of the resonance frequency and widening of the resonance width after insertion of the samples, respectively. The attenuation length \(L\) is calculated by (1):

\[
L = \frac{\lambda}{\pi \sqrt{\varepsilon'} \tan \delta}
\]

\[
\tan \delta = \frac{\varepsilon''}{\varepsilon'}
\]

Where \(\varepsilon', \varepsilon'', \tan \delta\) and \(\lambda\) are real permittivity, imaginary permittivity, loss tangent defined in (2) and wavelength of the radio wave, respectively. At the traveling distance of \(L\), the electric field strength is diminished to \(1/e\).

A R Hipple [11] gave the attenuation length or \(\tan \delta\) at 10 MHz and 25 GHz, which were only lower limits of the attenuation length for rock salt. The attenuation lengths larger than 250 m were given in 150, 300 and 750 MHz by in situ measurements at United Salt’s Hockley mine located near Houston, Texas [12]. We show recent measurements at 0.3 and 1.0 GHz in figure 2 using rock salt samples of Hockley (USA), Zuidwending (Netherlands), Asse (Germany), Heilbronn (Germany) and Lugansk (Ukraine).
The attenuation lengths at 0.3 GHz of synthetic (1430 ± 216m) and Asse (367 ± 51m) rock salts are longer than those at 1.0GHz (451 ± 34m) and (67 ± 7m), respectively. The tendency is consistent with a hypothesis as $\tan \delta$ being constant with the frequency. On the contrary, the attenuation length at 1GHz of Hockley (471 ± 56m) and Zuidwending (77 ± 7m) are longer than those at 0.3GHz (237 ± 33m) and (22 ± 1m), respectively. The frequency dependence is the same as the in situ measurement at Hockley [12]. The errors are estimated by deviation of the measured values. The cause is estimated as setting errors in position and inclination of the samples at the center of the cavity, and finite gaps between the flat surfaces of a cylindrical sample and closing caps of sample insertion holes. They are mainly comes from imperfect carving of the samples. Lugansk sample was carved out from an almost single crystal block showing the long attenuation length. Attenuation lengths of rock salt samples with respect to frequency are shown in figure 3. The upper and lower straight lines pass synthetic rock salt values and Asse rock salt values, respectively.
3. Simulation

Simulation of UHE-EM shower of an event at E=10^{16} eV needs 5 days using program code Geant4.5.2 [13] by our computer with 3.4 GHz clock frequency in linux operating system. In order to calculate electric field strength in higher energies, we employed 1 dimensional structure function model. This model treats an EM shower as a 1 dimensional charge distribution \( Q(r) \). The charge runs in light velocity. Thus, Geant4 simulation of EM shower could be replaced by using the structure function. Electric field strength was calculated by the following equation described in [14].

\[
E(R, \omega, \theta) = \frac{i e \omega}{\sqrt{2 \pi R^2}} \left( \frac{n^2}{c} \right) e^{i \omega R} \sin \theta \int Q(r) e^{i \omega r} dr.
\]

\[
p = (1 - n \cdot \cos \theta) \omega / c.
\]

Where \( e \) is elementary electric charge, \( \omega \) is angular frequency of radiation, \( R \) is the distance from the origin of EM shower to the observation point, \( r \) is the position of charge, \( n (=2.4) \) is refractive index of rock salt, \( k \) is wave number, and \( \theta \) is observation angle against the EM shower axis shown in figure 4.

![Figure 4](image_url)  
**Figure 4.** Charge position \( r \) is distance from the starting position on the shower axis. Observation point of electric field strength is located \( R \) from the start with angel \( \theta \) against to the shower axis.

![Figure 5](image_url)  
**Figure 5.** Longitudinal distribution of excess charge for incident electron energy from 10^{15} to 10^{18} eV. Solid line is 1D model compared with histogram of Geant4 at 10^{15} and 10^{16} eV.

We introduce the structure function \( Q(r) \) for excess charge extending Greisen formula.

\[
Q(r) = \frac{0.31 \times 0.26}{\sqrt{\alpha}} \exp \left\{ \beta t (1 - \gamma \times \ln \left( \frac{3 \times \beta t}{\beta t + 2 \alpha} \right) \right\}.
\]

Where \( t \) is a distance from the origin of EM shower in radiation length and \( \alpha, \beta, \) and \( \gamma \) which are determined at 10^{15} and 10^{16} eV fitting one event generated by Geant4 simulation. \( r \) is in cm. Excess charge is mainly come from recoil Compton effect. Geant4 includes LPM effect in bremsstrahlung at and larger than 10^{15} eV. Threshold energy of the simulation was 1MeV. Excess electrons of about 68% are due to recoil electrons of Compton effect. The coefficient of 0.26 is a ratio of the total track length of the excess electrons to that of the total electrons and positrons. The coefficient of 0.31 is given by Greisen formula. The parameters are defined in (6), (7), (8) and (9).

\[
\alpha = \ln \left[ \frac{\text{Energy}}{44.686 \times (E + 1)^{9} - 34.9092} \times 10^{4} \times \varepsilon \right]
\]

\[
\beta = 0.15 - 0.021 \times \ln(\text{Energy})
\]
\[
\gamma = 5.1 - 0.11 \times \ln(\text{Energy})
\]

(8)

\[
E = \log_{10} \left( \frac{\text{Energy}}{10^{15} \text{ eV}} \right)
\]

(9)

Where \( \varepsilon \) is the critical energy of 43MeV in rock salt. The excess electrons emit radio wave by Askar’yan effect. Figure 5 shows that the 1D model is consistent with the Geant 4 at \( 10^{15} \) and \( 10^{16} \) eV, and the capability to simulate the higher energies in a short computation time.

We compare electric field strength \( E \) given by the 1D model to the Geant4 with respect to the emission angle and the radio frequency. Number of events for the figures is \( 10^4 \) and 1 for 1D model and Geant4, respectively. We show the electric field \( E \) times the distance \( R \) in figure 6 at \( 10^{15} \) eV. The 1D model shows clear interference pattern due to the high statistics. The Geant4 is consistent with the 1D model in the envelope. In figure 7, \( R \times E \) of Geant4 is normalized to that of SLAC experiment [4] at 2GHz. The electric field for 1D model is 20\% larger than Geant4 at 1GHz and becomes close to Geant4 at the lower frequency in which SND experiment would detect the radio wave. The figures show that the 1D model could be used to draw up SND project.

![Figure 6. Angular distribution of \( R \times E \). Both coincide in the envelopes.](image)

![Figure 7. Frequency dependence of \( R \times E \).](image)

We simulated performance of SND including attenuation length, radio noise arise from black body radiation (BBR) of rock salt, and bandwidth of antennae. The attenuation length has the frequency dependence followed by (1). We used the value similar to the rock salt sample of Asse (\( \varepsilon' = 5.97, \tan \delta = 5.28 \times 10^{-4} \)) [7]. The attenuation lengths calculated are 740, 247 and 74m at 0.1, 0.3GHz and 1GHz, respectively where the lower straight line passes through in figure 3. We take temperature in the rock salt dome as 300K for BBR, which is consistent with measured value of BBR [12]. The receiver-frequency band ranges from 0.1 to 0.5GHz. Antenna array with hit antennae for \( 10^{19} \) eV horizontal EM shower is shown in figure 8. We can see the Cherenkov rings in the layers. Volume of SND is a cube of 3x3x3 km\(^3\). Number of antenna installed in the rock salt is 5000 (10x10x50) as shown figure 8. Antennae are installed in 2.5x2.5x2.5 km\(^3\). Interval of antennae is 250 m in x and y direction, and 50m in depth. We could get electric field strength of antennas from EM shower for the energy of \( 10^{16} \) - \( 10^{19} \) eV. Hit antenna is counted when the electric field strength of the Askar’yan radio wave is larger than 300K-blackbody emission (E>6.9 [V/m]). The number of hit antennae should be equal or more than 5. Cherenkov angle is 65.7° for rock salt. In each energy of \( 10^{17}, 10^{18}, \) and \( 10^{19} \) eV, \( 10^5 \) neutrinos are entered in the zenith angle between 0 and 2\( \pi/3 \) radian within 3x3x3 km\(^3\) region randomly. The
interaction between UHE neutrinos and the rock salt takes place following to cross-section of the standard model taking into account the energy dependence. The interaction generates electromagnetic shower with excess electrons of the 1D charge distribution. The number of hit antennae is 6, 34, and 176 for energy of $10^{17}$, $10^{18}$, and $10^{19}$ eV, respectively. GZK neutrinos of 8-62 per year depending on the model would be detected by SND, which is shown in figure 9 together with other limits of the past and the future experiments.

![Figure 8](image1.png)  
**Figure 8.** Display of antenna array with hit ones at $10^{19}$eV. Cross point (×) is hit antenna. The horizontal straight line is a trajectory of the incident neutrino.

![Figure 9](image2.png)  
**Figure 9.** Neutrino detection sensitivity per year. The line of SND is drawn, when number of hit antennae is larger than or equals 5.

4. Summary

We have measured complex permittivity in natural rock salt samples by perturbation method using cylindrical cavity resonators of 0.3GHz and 1.0GHz. Long attenuation length is found at Asse and Hockley rock salt samples. There are two types of frequency dependences of the attenuation length. Synthetic and Asse rock salts are consistent with a hypothesis as $\tan \delta$ being constant with frequency. The attenuation lengths of Asse ($367 \pm 51$ m) at 0.3GHz and Hockley ($471 \pm 34$ m) at 1GHz indicate the realization of the salt neutrino detector. Using the attenuation length, SND simulation resulted that economical antenna spacing could detect 8-62 GZK neutrinos/year with a rock salt volume of $(3\text{km})^3$.

Simulation is done taking into realistic attenuation length of natural rock salt, blackbody radiation, and receiver bandwidth. Due to the 1D structure function, computation time of 5days using Geant4 is shortened to fewer than 1s at $10^{16}$eV. We calculated the GZK neutrino detection sensitivity of SND. It can detect radio wave radiated from EM shower higher than energy of $10^{17}$eV. The interaction cross section between UHE neutrinos and rock salt becomes rather high. The number of interaction between them is 3 events against $10^4$ of incident neutrinos at $10^{18}$eV. As a consequence, GZK neutrinos of 8-62 per year would be detected. Thus, SND is suitable to detect GZK neutrinos. We should continue the research by measuring the attenuation length at the lower frequency and by the simulation to take into account antenna performance and neutrino flavor difference.

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