Measurement of a Phase of a Radio Wave Reflected from Rock Salt and Ice Irradiated by an Electron Beam for Detection of Ultra-High-Energy Neutrinos

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Abstract. We had found radio-wave-reflection effect in rock salt for detection of an ultra-high energy neutrino (UHEν) which was expected to be generated in Greisen, Zatsepin, and Kuzmin (GZK) processes in the universe. When an UHEν interacts with rock salt or ice as a detection medium, a shower is generated. That is composed of hadronic and electromagnetic avalanche processes. The energy of the UHEν shower converts to a thermal energy through the ionization processes. Consequently, a temperature gives rise along an UHEν shower at the interaction location. The refractive indices of the media arise with respect to the temperature. The irregularity of the refractive index in the medium leads to a reflection of radio wave. The reflection effect with a long attenuation length of radio wave in rock salt and ice would yield a new method to detect UHEν. We measured phase of the reflected radio wave under irradiation of an electron beam on ice and rock-salt powder. The measured phase showed excellent consistence with the power reflection rate which was measured directly. A model taking into account the temperature change explained the phase and the amplitude of the reflected wave. Therefore the reflection mechanism was confirmed. Power reflection rate was compared with that of Fresnel equations, a ratio between the measured and the Fresnel equations in ice was larger than that of rock salt.

Keywords: Neutrino detectors; ultra-high-energy cosmic rays; Rock salt; Antarctic ice sheet; Radar
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INTRODUCTION

Ultra-high-energy neutrinos (UHEν) are predicted to be produced at a collision of UHE-cosmic ray with the cosmic-microwave-radiation background by Greisen, Zatsepin, and Kuzmin (GZK) [1, 2]. In order to detect them we had studied and found radio-wave-reflection effect in rock salt [3 – 5]. A gigantic detector is needed for the detection due to the ultra-low flux of 1 $km^{-2} \cdot d^{-1}$. When an UHEν interacts with rock salt or ice as a detection medium, a shower is generated. That is composed of hadronic and electromagnetic avalanche processes. The energy of the UHEν shower converts finally to a thermal energy through the ionization processes. Consequently, a temperature gives rise along an UHEν shower at the interaction location. The refractive index arises with respect to the temperature. The irregularity of the refractive index in the medium for radio wave gives rise to a reflection. The reflection effect with a long attenuation length of radio wave in rock salt and ice would yield a new method to detect UHEν. We could find a huge amount of rock salt or ice over 50 Gt in natural rock salt formation or Antarctic ice sheet. The volume of the rock salt is $3 \times 3 \times 3$ km^3. Radio wave transmitted into the medium generated by a radar system with a phased array antenna could be reflected by the shower. Receiving the reflected radio wave would yield the detection of the UHEν.

We had carried out an experiment to observe microwave reflection effect from a small rock-salt sample of $2 \times 2 \times 10$ mm^3 irradiated by a synchrotron radiation X-ray with a pulse width of 1.7 s. It was set in a 9.4 GHz waveguide [3] while continuous microwave was injected to the waveguide. A null-detection method was employed to detect the feeble reflected signal in the waveguide circuit. Reflected microwave was observed with a power reflection rate of 1×10^{-6} and a decay time of 8 s. The shape of the power reflection rate with respect to the time was similar to the temperature. The reflection rate was proportional to the square of the X-ray intensity.

A larger rock salt sample of 10 cm cube was irradiated by a 2 MeV electron beam with a duration of 60 s which was set in a free space without using a waveguide [4]. A continuous 435 MHz radio wave struck at the cube from a 6 elements Uda-Yagi antenna. The reflected power rate increased with a temperature rise of an irradiated surface of the cube. The observation of the reflection rejected a possibility that the effect was due to a distortion of the waveguide heated by X-ray irradiation at the experiment [3].

A 435 MHz waveguide filled with rock salt powder was used to measure the radio wave reflection effect [5]. The 2 MeV electron beam was injected to rock salt powder through an aluminum-beam window of 20 × 20 cm^2 with a thickness of 0.5 mm. A continuous 435 MHz radio wave of 10^{-4} W was emitted by an antenna of quarter-wavelength installed in the salt powder and the reflected-radio wave was detected by the same. The reflection rate increased with the square of a temperature rise at an irradiated surface of the rock salt powder. The reflection rate could be explained by the Fresnel equations.

EXPERIMENT

We report a new experiment using a coaxial tube (WX-20D) with the diameter of 20 mm and the length of 100 mm. An electron beam was injected into an open end of the coaxial tube set in a dry-ice-cooling box. The coaxial tube was filled with rock salt power or ice and was set in the cooling box as in Fig. 1. The temperature was measured by a chromel-alumel thermocouple set 2 mm from the surface of the open end. Refractive indices of rock salt powder and ice were measured by reflection method from 0.4 MHz to 1 GHz in a coaxial tube yielding 1.79 ± 0.01 at 22 ℃ and 1.76 ± 0.01 at -60 ℃, respectively. Then the diameter of the inner conductor was made to 4.5 mm so as to become the impedance of 50 Ω when the media were filled. We utilized a 2 MeV electron beam produced by a Cockcroft-Walton accelerator located Takasaki Advanced Radiation Research Institute (TARRI), Japan Atomic Energy Agency (JAEA). The electron beam of 2 MeV was irradiated on the open end of the coaxial tube with 4 J/s at the current of 1 mA. The electron beam was swept 1 m width (200 Hz) over a target for the irradiation of a large area. Only a small part of the beam hit the open end of the coaxial tube. Increase of refractive index with respect to the temperature gave rise a radio-wave reflection. We observed the reflection effect from ice as well as rock salt.

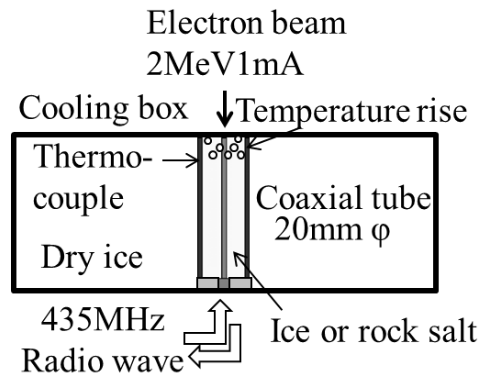

FIGURE 1. A coaxial tube with a diameter of 20 mm and a length of 100 mm was filled with rock salt power or ice. It was set in the cooling box of 300 × 300 ×100 mm^3. The temperature in the medium was measured 2 mm under the open surface. An electron beam was injected into the open end.

As shown in Fig. 2, a 435 MHz continuous wave of 10^{-4} W from an Oscillator (Rohde & Schwarz SMB100A) was split (Mini-Circuits ZMSC-2) into a signal $\vec{a}$ (expressed in a vector) sent to the coaxial tube through a circulator (MTC B115FFF) and another as a reference signal $\vec{d}$ that could be phase shifted by a variable phase shifter (Mini-Circuits JSPHS-446). The reflected signal $\vec{b}$ from the coaxial tube was sent to a combiner (Mini-Circuits ZMSC-2) through the circulator. The combined signal of $\vec{c} = \vec{b} + \vec{d}$ was split into a real-time spectrum analyzer (Tektronix RSA3303B) and a detector (Power Detector, Mini-Circuits ZX47-60-S+) for the power measurement. In order to reject noises due to the power source of 50 Hz, from the real-time spectrum analyzer (RSA), 1024 data within 128 ms in the time domain was fast-Fourier transformed to the frequency domain. The peak at 435 MHz was selected apart from $\pm$ 8 Hz to reject the noise. In order to tune the frequency precisely between the oscillator and RSA, they were locked by 10 MHz signal generated by a Rubidium-frequency standard (Stanford Research Systems FS725).

The output signal of the detector was put in an Educational-Laboratory-Virtual-Instruments Suite (National Instruments NI ELVIS) based on NI LabVIEW system where the signal was digitized by an ADC. The data was changed to a proper value by a control program of LabVIEW and converted to an analog voltage by a DAC in the NI ELVIS. It was fed to the variable phase shifter as a control voltage where the phase of the reference signal $\vec{d}$ was shifted according to the voltage. It was fed to the combiner again. The feedback loop was repeated ~ 13 Hz.

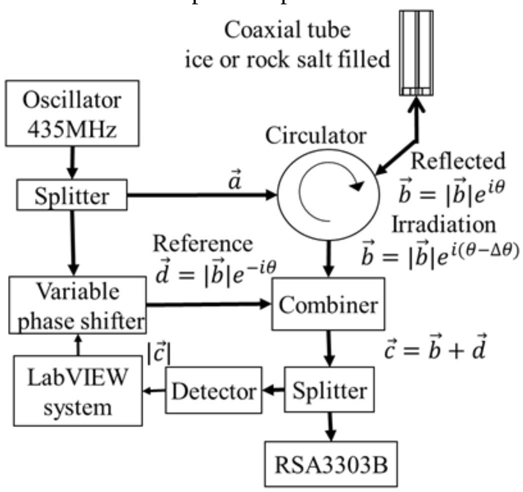

FIGURE 2. A 435MHz continuous wave of 10^{-4} W from an Oscillator (Rohde & Schwarz SMB100A) was split (Mini-Circuits ZMSC-2) into a signal $\vec{a}$ sent to the coaxial tube through a circulator (MTC B115FFF) and another as a reference signal $\vec{d}$ that was phase shifted by a variable phase shifter (Mini-Circuits JSPHS-446). The reflected signal $\vec{b}$ from the coaxial tube was sent to a combiner (Mini-Circuits ZMSC-2) through the circulator. The combined energy was measured by a real-time spectrum analyzer (Tektronix RSA3303B) and an ADC in NI ELVIS based on NI LabVIEW system through a detector, respectively. An output of the DAC in the NI ELVIS was fed to a variable phase shifter (Mini-Circuits JSPHS-446) to minimize $|\vec{c}|$, repeating a feedback in a loop.

A measurement of the power reflection rate was done as follows. Before the electron beam irradiation, the vector of reflection signal was $\vec{b} = |\vec{b}|e^{i\theta}$ where a phase of θ was a constant without the irradiation. Phase of the reference signal was tuned to $-\theta$ so as to an output of the combiner $\vec{c} = \vec{b} + \vec{d}$ become close to zero. The amplitude $|\vec{b}|$ of the reference signal was tuned slightly by a variable attenuator (Mini-Circuits ZX73-2500-s) which was set just after the variable phase shifter so as to be realized $\vec{d} = |\vec{b}|e^{-i\theta}$. Such a feedback was repeated tuning the variable phase shifter and the variable attenuator simultaneously by the control program. The control voltages of the variable phase shifter and the attenuator were recorded in each loop to know the phase shift and the attenuation. When the irradiation began, we stopped the feedback loop through the control program i.e. $\vec{d} = |\vec{b}|e^{-i\theta}$ being fixed. At the same time, the phase Δθ of the reflection signal had begun to change in $\vec{b} = |\vec{b}|e^{i(\theta-\Delta\theta)}$. Consequently, the reflection amplitude of $|\vec{c}| = |\vec{b} + \vec{d}|$ begun to increase and was measured by the RSA and the ADC of NI ELVIS.

In case of a measurement of the phase, we did not stop the feedback loop when the irradiation started. The phase was tuned automatically in the loop to get $|\vec{c}|$ close to zero by the same way as the amplitude measurement. The reference signal was kept as $\vec{d} = |\vec{b}|e^{i(-\theta+\Delta\theta)}$. From the recorded phase of $-\theta + \Delta\theta$, we got $\Delta\theta$ of the reflected signal.

FIGURE 3 shows a result of the measurements for an ice target. The electron beam of 2 MeV with 2 mA was irradiated in 60 s. As the beam irradiated, the temperature increased from -60 ℃ to -35 ℃ with respect to time. The temperature was measured by the thermocouple which was recorded by a NI CompactDAQ. Power reflection rate measured by RSA is plotted in a small closed circle which is a reflection power rate between the reflected wave and the injected wave to the coaxial tube. Five data points with an interval of 128 ms are in 1 s. They increased from 0 to 8 $\times 10^{-7}$ with the temperature rise and traced a curve without large fluctuations. The phase $\Delta\theta$ got by the variable phase shifter decreased from 0° to -0.2°. The relative refraction indices of n in ice [6] and the rock salt powder [7] increased with the temperature rise as in equations (1) and (2), respectively, where T is expressed in ℃. The refractive index of rock salt powder is corrected from the refractive index of rock salt in a lump using our measured value. The decrease of the phase is explained by the decrease of the velocity of the wave in the ice due to the increase of n.

$$n = 0.000260T + 1.786 \tag{1}$$

$$n = 0.000498T + 1.781 \tag{2}$$

The reflected wave in power was calculated by eq. (3) as a balance $\vec{c}$ of vector subtraction between two vectors with the length of $|\vec{b}|$ and the rotation angle of $\Delta\theta$.

$$|\vec{c}|^2 = 2|\vec{b}|^2\{1 - cos(\Delta\theta)\} \tag{3}$$

The power reflection rate was got by a calculation using the phase difference $\Delta\theta$ and plotted as a short hyphen in the Fig. 3. They are somewhat scattered but coincide very well with the RSA data.

A model calculation was done to confirm the cause of the radio wave reflection effect. We assumed that ice temperature from the open end to 10 mm of the coaxial tube was the same as the measured temperature at 2 mm from the open end. We calculated the power reflection rate based on Telegrapher's equation. The result was accord with the RSA value within 50 % during the irradiation and the shape was similar to the temperature with time.

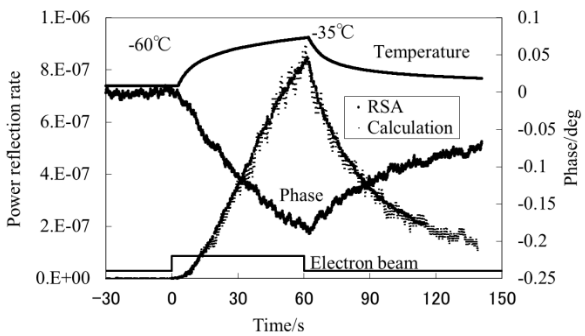

FIGURE 3. As the electron beam irradiated, the temperature increased from -60 ℃ to -35 ℃ with time. Power reflection rate measured by RSA is plotted in a small closed circle which increased from 0 to 8 × 10^{-7} with the temperature. Phase $\Delta\theta$ got by the variable phase shifter decreased from 0° to -0.2°. The power reflection rate was got by a calculation using the phase $\Delta\theta$ and plotted as a short hyphen**.**

Power reflection rate with respective to the square of the temperature rise is shown in Fig. 4. We compared the power reflection rates at the irradiation time of 60 s for the beam current of 1, 2 and 3 mA with the power reflection rate Γ of Fresnel equations as shown in equation (4). The refractive indices n_1 and n_2 are calculated from the measured temperatures before and during the irradiation, respectively.

$$\Gamma = \frac{(n_2 - n_1)^2}{(n_2 + n_1)^2} \tag{4}$$

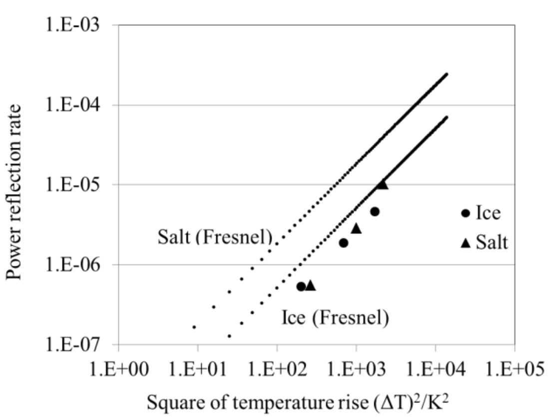

FIGURE 4. Power reflection rate with respective to the square of the temperature rise are shown. Calculated values and measured values of the salt powder or the ice are depicted as "Salt (Fresnel)" "Ice(Fresnel)" by a line connected by dots and "Salt" by closed triangles or "Ice" by closed circles, respectively.

Calculated values Γ by eq. (4) using eq. (1) and measured values of the salt powder are depicted as "Salt (Fresnel)" by a line connected by dots and the measured value "Salt" by closed triangles, respectively. A line connected by dots of "Ice (Fresnel)" is also calculated by eq. (4). "Salt (Fresnel)" is 3.6 times larger than "Ice (Fresnel)", but the experimental data of "Ice" of closed circles and "Salt" of closed triangles are roughly the same with respect to the square of the temperature rise. The data of "Salt" and "Ice" are 16 and 54 % compared with "Salt (Fresnel)" and "Ice (Fresnel)", respectively. The loss of the reflection rate was partly due to imperfect signal transmission of the coaxial tube and the partial measurement of the temperature. The higher power reflection rate in "Ice" compared to "Salt" suggests that the ice was partly melted along an electron track locally. Refractive index of water at 0 ℃ is 5.3 times larger than that of ice. It might enhance the power reflection rate.

SUMMARY

We found radio wave reflection effect from ice as well as rock salt with an electron beam irradiation. Adding to the amplitude measurement, we measured the phase of the reflected radio wave from ice and rock salt constructing the automatic feedback loop of null detection method in which the variable phase shifter was tuned to get the null output. The reflection in power was calculated as a balance of vector subtraction between two vectors with the length and the rotation angle. Moreover we explained the reflection by a model in which the phase delay of the reflected wave was caused by the increase of the refractive index due to the temperature rise. The radio wave reflection effect is applicable to a radar method to detect GZKν in a huge amount of rock salt formation, Antarctic ice sheet and the moon crust.

Five types of radiation detectors using thermal effect are compared in TABLE 1. "Radar Chamber" as well as "Bolometer" detects a temperature rise due to an energy deposit of incident radiation. It receives reflected radio wave (10 MHz – 1 GHz) from a heated portion emitted by a transmitter. It is appropriate to detect weak interacting particle like neutrinos since the media has large density of solid. The change of refractive index of a medium is rather small due to the smaller temperature rise in the large volume of the shower. However the coherent reflection effect between the reflected waves from the many heated points distributed in the large volume of the shower might enhance the reflection rate for the longer wave length than the shower diameter. Even the coherent effect the reflected radio wave is weak and "Radar

Chamber" is suitable for a large energy deposit. The detector size depends on the reflection rate and the attenuation length of radio wave in the media. The attenuation along the path could be compensated by a strong and narrow beam of radio wave generated artificially. We could detect GZKν by a peak power of 1 GW (Equivalent Isotropic Radiation Power) radio wave supplied by a phased array antenna set on a surface of the media. We do not need expensive boreholes where many antennas should be installed. "Radar Chamber" has a long memory time and we could scan the effective volume by a radio wave beam within the memory time. So it could be operated as a stand-alone detector without a trigger detector system.

According to the elucidation of the radio wave reflection mechanism, a new radiation detector "Radar Chamber" is applicable for all dielectric media where the refractive indices change with temperature. It is not only for radiation detection but also for other purposes using materials with inhomogeneous refractive index in space and time. An application for human-body imaging inside could be investigated at 10 MHz where the attenuation length is ∼ 5 cm.

TABLE 1. Radiation detectors using heat effects.

	Bolometer	**Cloud Chamber**	**Bubble Chamber**	**Acoustic Detector**	**Radar Chamber**
Inventor	S.P. Langley	C.T.R. Wilson	D.A. Glaser	G.A. Askaryan	M. Chiba, et al.
Year	1878	1911	1952	1957	2007
Medium	Solid	Gas	Liquid	Solid, Liquid	Solid
Wave length	-	∼ 500 nm	∼ 500 nm	∼ 1m	0.3 ∼ 30m
Body	Absorber	Liquid particle,	Bubble,	Heated portion,	Heated portion,
Body size	-	∼ 0.5 mm	∼ 0.1 mm	0.1 φ × 5 m	0.1 φ × 5 m
Reflection or Emission	-	Reflection	Reflection	Emission	Reflection
Operation	-	Decompression	Decompression	-	-
Process	Heating	Super cooling	Super heating	Heating	Heating
Amplification	Small heat capacity	Growth of liquid particle	Growth of bubble	-	Coherent reflection
Sensitivity	> 1 eV	∼ 100 eV	∼ 100 eV	> 10^{12} eV	> 10^{12} eV
Position resolution	-	∼ 0.5 mm	∼ 0.1 mm	∼ 30 m	∼ 30 m
Detector size	∼ 1 cm	∼ 1 m	∼ 3 m	∼ 3 km	∼ 3 km
Memory time	∼ 1s	∼10 ms	∼ 1 μs	-	∼ 10 s

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