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Radar for detection of ultra-high-energy neutrinos reacting in a rock salt dome

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ABSTRACT

Detection of GZK (Greisen, Zatsepin and Kuzmin) neutrinos that have an energy larger than 1×10^{16} eV are expected to explore ultra-high-energy (UHE) interactions between UHE protons ($>4\times10^{19}$ eV) and cosmic-microwave background in the cosmological distances. A study of the radar method was carried out using a 2 MeV electron beam to irradiate rock salt powder filled in a 435 MHz waveguide. Reflection of radio wave from the irradiated rock-salt powder was observed inside the waveguide. The reflection mechanism was elucidated and the reflection power ratio was compared with a Fresnel equation.

1. Introduction

Detection of GZK (Greisen, Zatsepin and Kuzmin) neutrinos that have an energy larger than 1×10^{16} eV are expected to explore ultra-high-energy (UHE) interactions between UHE protons ($>4\times10^{19}$ eV) and cosmic-microwave background in the cosmological distances [1]. In the collision, a Δ^+ resonance is produced, which gives rise to a charged pion and it decays into GZK neutrinos. Adding to the information of UHE states at cosmological distances, the UHE-neutrino interactions with matter would give us novel knowledge about the cross-section including gluon-fusion processes in the unexplored-energy region [2]. The GZK neutrino flux of 1 km^{-2} day^{-1} is so low that a huge mass of detection medium of 50 Gt ($3\times3\times3$ km^3 in case of rock salt) is necessary to detect UHE neutrinos with meaningful number of events in statistics, i.e. around 10/year.

In order to detect UHE neutrinos in the enormous medium, a coherent-Cherenkov effect in radio wave was suggested by Askaryan [3]. Excess number of electrons over positrons is generated in electromagnetic showers in an UHE-neutrino interaction with matter. They emit coherent-Cherenkov radiation in the radio-wave region. The radiated energy is proportional to the square of the shower energy due to the coherence effect among the radiated-radio wave in case of longer wavelength compared to the transverse size of the shower. Rock-salt domes [4] and ice sheets in Antarctica are suitable sites for the detector due to its long attenuation length for the radio wave. For example, attenuation length of samples at the Asse salt mine in Germany was as long as around 300 m at 200 MHz measured by the perturbed-cavity-resonator method with a closable-sample-insertion hole [5]. Recently an in situ measurement in the Cote Blanche salt mine showed the attenuation length of around 90 m at 200 MHz [6]. In order to use the Askaryan effect we need many antennas installed in around 100 bore holes spaced in the order of the attenuation length [5–7].

For purpose of reducing the number of expensive boreholes, we had investigated a radar method. At first, we had studied a reflection of 9.4 GHz microwave [8] from a rock salt sample of $2\times2\times10$ mm^3 in an X-band-metal waveguide. The sample was irradiated by X-rays from 6.5 GeV electron-synchrotron-radiation facilities at KEK for 1.7 s on the axis through a hole of the waveguide. We found a reflection of microwave power with a sharp rise and slow decay time of 8 s. The energy reflection rate was around 10^{-6} at the absorbed energy of 10^{19} eV. The sharp rise has almost the same slope of temperature. It meant that the reflection had some relation with the temperature. The reflected power was proportional to the square of the irradiated X-ray energy.

The next experiment was carried out to confirm the radio-wave-reflection effect from a larger rock-salt sample of 10 cm^3 set in free space, which was irradiated by a 2 MeV electron beam produced by a Cockcroft–Walton accelerator located at Takasaki Advanced Radiation Research Institute (TARRI), Japan Atomic Energy Agency (JAEA). In this experiment any waveguide was not employed; therefore this was a good check to know whether the reflection effect originated in change of the reflection probability in the rock salt or in a thermal expansion of the waveguide. The electron beam went downward vertically and irradiated the upper surface of the

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rock salt target. The beam was swept to 1.2 m width so that 6% of the beam intensity was irradiated on the sample of 10 cm^3. A six elements Uda–Yagi antenna of 435 MHz was set horizontally 10 cm from the target with horizontal polarization. We confirmed to observe the radio-wave-reflection effect [2].

We would apply the radio-wave-reflection effect to detect UHE neutrinos as a radar method. The advantage of the radar method is that we do not need a large number of antennas spaced closely because a huge peak power of pulsed radio wave is feasible by a transmitter. The huge peak power could cope with the low-reflection rate, the attenuation in a long distance through the propagation and a small solid angle from an antenna to a shower originating in an UHE neutrino and vice versa.

In this paper we present a study of the radio-wave-reflection effect from irradiated-rock-salt powder by the 2 MeV electron beam in a 435 MHz metal waveguide of TE_{10} mode filled with rock-salt powder.

2. Experiment

The 2 MeV electron beam was produced by a Cockcroft–Walton accelerator founded at TARRI, JAEA. The electron beam irradiated downward vertically the upper surface of the 435 MHz aluminum waveguide. The shape of the beam was a Gaussian with a FWHM of 8 cm. The beam scanned horizontally a 1.2 m width perpendicular to the longest axis of the waveguide, with the frequency of 200 Hz by an electromagnet. The beam of 16.7% hit the aluminum beam window of $20 \times 20\ cm^2$ with a thickness of 0.5 mm on the waveguide, which was filled with the salt powder. The density of the rock-salt powder was low compared to a lump of rock salt whose density and permittivity ε' were 2.2 g/cm^3 and 5.9, respectively. The permittivity ε' of the salt powder was measured by a resonance method in the waveguide to be $\varepsilon' = 3.339$ and consequently, the refractive index was $n = \sqrt{\varepsilon'} = 1.827$. The wavelength of 435 MHz radio wave in the salt powder was 37.7 cm. The transmission loss in the wave guide was a negligible amount.

The electron beam was injected to the salt powder through the beam window. A continuous radio wave of 435 MHz with 10^{-4} W was emitted by an antenna of quarter-wave length $\lambda/4$ installed in the salt powder and the reflected-radio wave was detected by the same as shown in Fig. 1. At the end of the waveguide, there was another $\lambda/4$ antenna to reduce the reflection at the end. The reflection in power decreased to a hundredth.

The transmitted and received signals from the same antenna were separated by a circulator. In order to make a weak-reflected signal conspicuous, we employed a null detection method. The received signal and a small portion parted from the emitted signal were added, and tuned to the same amplitude by attenuators with a phase difference of π rad by phase shifters so as to get minimum output when the electron beam was off. When the beam was on, the excess of the received signal remained. The signal was fed into a spectrum analyzer of specat2 made by NEC Corporation. The data were recorded by a computer once a second. As shown in Fig.1, refractive indices at the room temperature of 15 °C and the heated portion were $n_1 = 1.827$ and n_2, respectively.

The electron beam of 1 mA with 2 MeV was irradiated on the beam window with duration of 60 s. The beam being on or off was controlled by a beam shutter. An alumel–chromel thermocouple was set at the center of the beam window buried 2 mm under the surface of the salt powder. The range of the electron beam in the salt powder was around 5 mm. Reflection-power ratio Γ vs. time is compared with the temperature squared every second. They are shown as a function of the beam current in Fig. 2. Γ was deduced that the received power of radio wave was divided by the emitted power of 10^{-4} W.

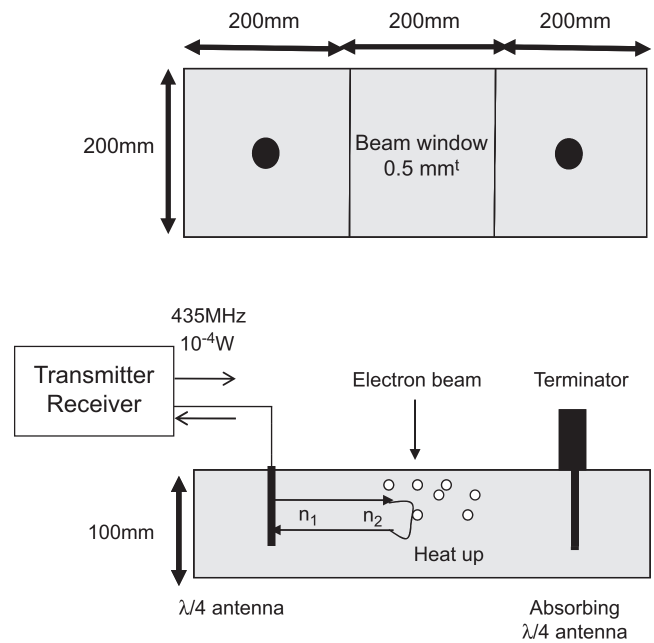

Fig. 1. Waveguide of 435 MHz filled with rock salt powder. Two antennas of quarter-wave length $\lambda/4$ are installed in salt powder. One is for transmission and receiving, and other for absorbing to reduce reflection. Beam window of $200 \times 200 \times 0.5\ mm^3$ aluminum for the electron beam irradiation is at the center.

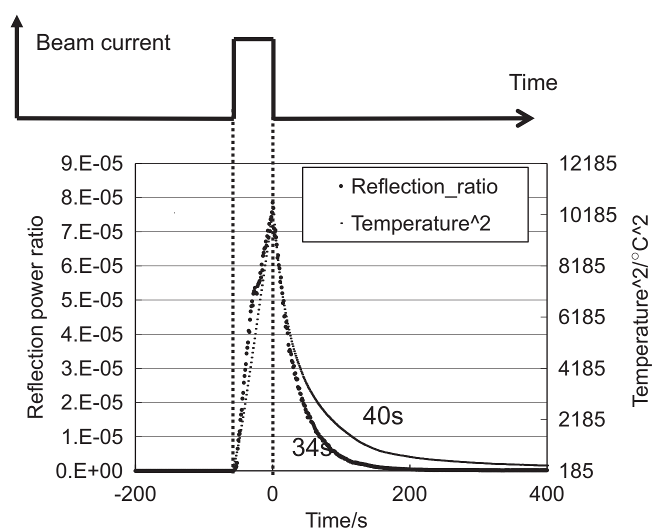

Fig. 2. Reflection-power ratio Γ vs. time is compared with temperature squared vs. time. 2 MeV electron beam of 1 mA was irradiated from −60 to 0 s as depicted at top.

The electron beam was irradiated from −60 to 0 s as in Fig. 2. The temperature increased from 15 to 102 °C and normalized to Γ at −60 and 0 s. The stability in Γ measurement was kept 10^{-9} by the null system. The precession of Γ measured by specat2 and the temperature were 1% and 1 °C, respectively. Γ and temperature was read out by computers at the accuracy of 0.1 s. Γ is compared with the temperature squared, which is explained later. Γ increased and decreased faster than the temperature squared. The thermocouple yielded slower response than the radio wave reflection. The decay times of Γ and the temperature squared were 34 and 40 s, respectively. This is due to the fact that an average temperature of the heated area was lower than the measured temperature since the beam profile had Gaussian-like shape and the thermocouple was placed at the peak position of the Gaussian