

# Reflection of microwave from energy deposit by X-ray irradiation in rock salt

## Implication of an ultra high energy salt neutrino detector to act like a radio bubble chamber

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**Abstract.** Existence of GZK neutrinos (ultra high energy neutrinos) have been justified although the flux is very low. A new method is desired to use a huge mass of a detector medium to detect them. A fundamental study of radar method was carried out to measure microwave reflection from electromagnetic energy deposit by X-ray irradiation in a small rock salt sample. The reflection rate of  $1 \times 10^{-6}$  was found at the energy deposit of  $1 \times 10^{19}$  eV which was proportional to square of the X-ray intensity suggesting the effect to be coherent scattering. The decay time of the reflection was several seconds. This effect implies a large scale natural rock salt formation could be utilized like a bubble chamber irradiated by radio wave instead of visible light to detect GZK neutrinos.

**PACS.** 61.80.Cb X-ray effects – 95.55Vj Neutrino, pion, and other elementary particle detectors: cosmic ray detectors

## 1 Introduction

GZK (Greisen, Zatsepin and Kuzmin) neutrinos are generated by collision between ultra high energy (UHE) cosmic rays ( $\geq 4 \times 10^{19}$  eV) and cosmic microwave background Ref. [1]. Both have been observed, then GZK neutrinos ( $\geq 10^{16}$  eV) have been justified to exist although the flux is very low ( $\sim 1 \text{ km}^{-2} \text{ day}^{-1}$ ). The flux can be estimated to a certain extent since flux of UHE cosmic rays and density of cosmic microwave background are known. GZK neutrinos could become a standard candle of UHE neutrinos for finding out other conceivable UHE neutrino sources such as active galactic nuclei, topological defects and  $\gamma$ -ray bursts etc. in the universe. In order to detect GZK neutrinos, a huge mass of a detection medium as large as 50 Gt ( $3 \times 3 \times 3 \text{ km}^3$  for a rock salt case) is needed due to their low flux. Detecting radio wave from Askryan effect (coherent Cherenkov effect) Ref. [2] is a promising way to utilize a large mass of natural rock salt Ref. [3] or ice bed in Antarctica but it needs a lot of bore holes to be installed for radio wave detection antennas.

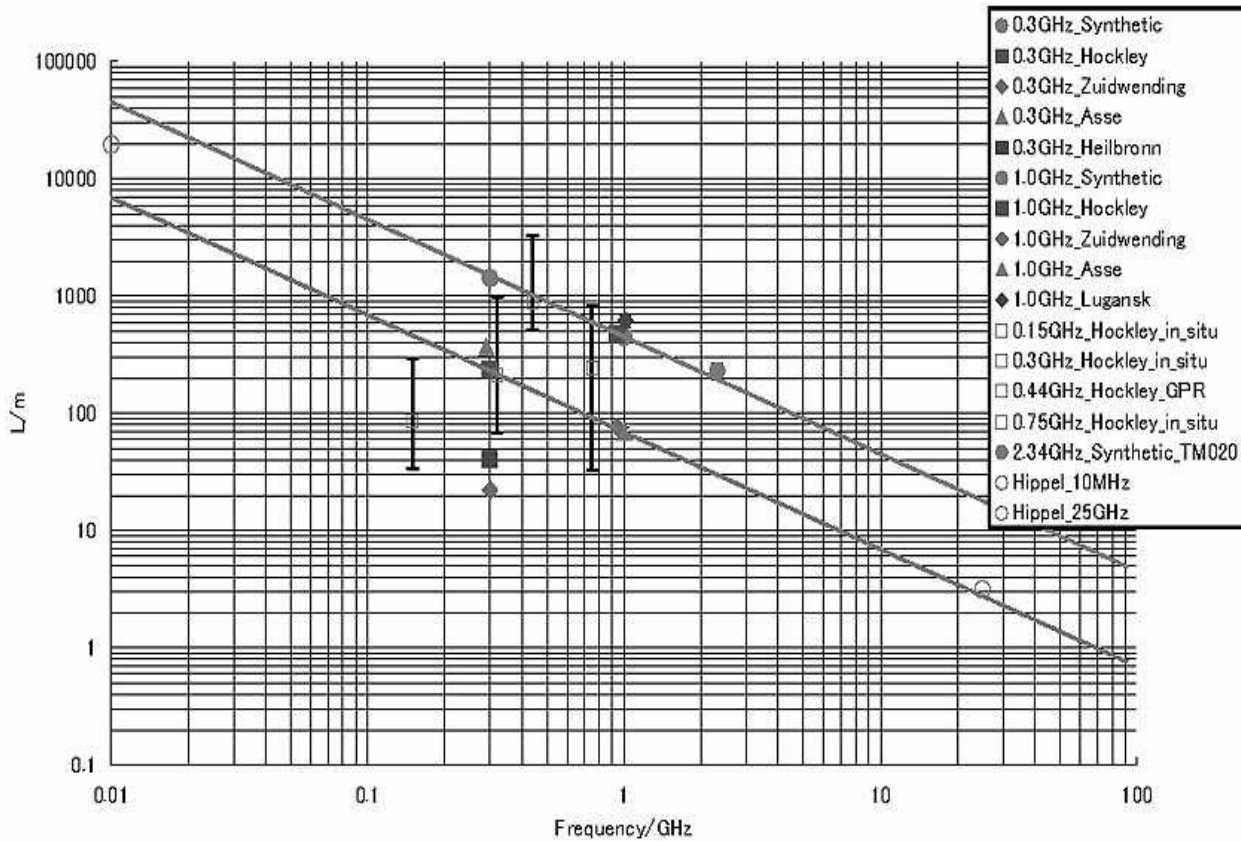
We had measured attenuation length of natural rock salt samples as well as synthetic rock salt samples of single crystal by a perturbed cavity resonator method. We found long attenuation lengths for electric field more than 200 m at 0.3 - 1 GHz in the samples of natural rock salt Ref. [4] as shown in fig. 1. Data noted as "Hockley\_in\_situ" in the legend are in-situ measurements at Hockley salt mine Ref. [6]. The long attenuation length allows us to utilize a rock salt formation as a UHE neutrino detector Ref. [5].

A basic study of a new detection method has been carried out to measure radio wave reflection from electromagnetic energy deposit by X-ray irradiation in a small rock salt sample. If we could detect the radio wave reflection by an enough reflection rate, a large scale natural rock salt formation would work as a radio bubble chamber using radio wave instead of visible light to get 3 dimensional information of the energy deposit of the shower generated by the UHE neutrino.

## 2 Experiment

We studied microwave reflection rate from a small rock salt sample irradiated by X rays, set in a metal wave

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**Fig. 1.** Attenuation lengths for electric field are plotted with respect to frequency for synthetic and natural rock salt. The upper and the lower straight lines are fitted to synthetic and natural rock salt samples of Asse salt mine, respectively, assuming loss tangent is constant with respect to the frequency.

guide. Decay time of the reflection rate after the irradiation and the coherency of the microwave scattering were measured.

## 2.1 X ray irradiation and apparatus

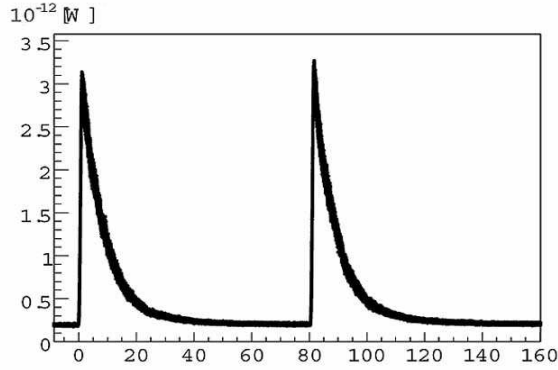
A X-ray beam of synchrotron radiation from a bending magnet was supplied to NE5A station by 6.5 GeV Accumulation Ring (AR) of KEK photon factory with the electron beam current of 40 - 60 mA. The X ray was a white spectrum ranging 8 - 100 keV with the number of photons of  $N_\gamma = 10^{15} \text{ s}^{-1}$  at the beam current of 60 mA. In order to get a strong X-ray irradiation, we did not use a spectroscopy in the beam line. The X ray was chopped by 4 mm thick lead circular disk with a  $4 \times 4 \text{ mm}^2$  orifice at the radius of 50 mm. The disk was rotated by a stepping motor. Duty of the irradiation was 1.27% in time. The irradiation time was controlled by revolving speed of the disk. A synthetic single crystal of rock salt with a size of  $2 \times 2 \times 10 \text{ mm}^3$  was set  $45^\circ$  rotated to the square orifice sides to reduce the microwave reflection from the sample. It was inserted in a X band rectangular metal wave guide of  $TE_{10}$  mode. The X ray was irradiated to the longitudinal direction of the sample and the energy deposit was  $1 \times 10^{19} \text{ eV s}^{-1}$  which was calculated by geant4 simulation. The microwave was irradiated to the sample in the lateral

direction with the electric field being parallel to the X-ray direction of travel.

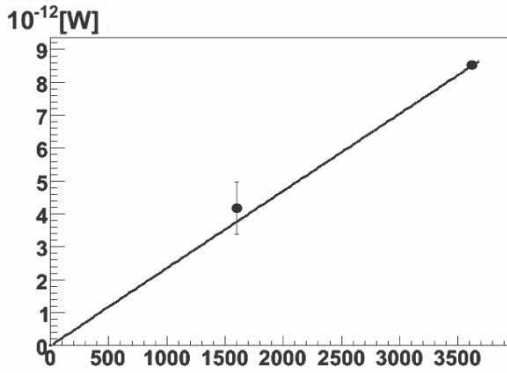
Both X ray and a continuous coherent microwave of 9.4 GHz with  $10^{-4} \text{ W}$  from an oscillator were irradiated simultaneously to the rock salt to measure the reflection of microwave from the electromagnetic energy deposit. The microwave was fed to the waveguide through a coaxial-to-waveguide converter. The wavelength of the microwave was 31.9 mm in vacuum and 13.3 mm in rock salt. Refractive index of rock salt is 2.4. Null method was employed to measure a very small reflection signal. Before the X-ray irradiation, the microwave reflection signal and a split signal from the oscillator were tuned so that the phase difference was  $\pi$  radian and the amplitudes were equal. Consequently the sum of the reflection and the split signals became zero. The sum was fed to a receiver equipped with a logarithmic amplifier which was sensitive as low as  $10^{-14} \text{ W}$ . The output of the receiver was recorded by a digital oscilloscope as shown in fig. 2.

## 2.2 Data analysis

The reflected power of the microwave with respect to the elapsed time from the X ray irradiation of 1.7 s was measured as shown in fig.2. The irradiation time of 1.7 s was a duration from a time of the forward side



**Fig. 2.** Reflected power of the microwave against the elapse of time in a unit of s. X ray was irradiated 1.7 s for each.



**Fig. 3.** Reflection of the microwave in power with respect to square of the AR beam current in a unit of  $(\text{mA})^2$ .

of the orifice touching the first corner of the rock salt sample and the backward side of the orifice crossing the last corner of the rock salt sample. Full open time of the orifice to the salt sample was 0.29 s during the irradiation time of 1.7 s. Averaging the irradiation time of 1.7, 4.8, 9.6 and 16.0 s, the decay time was  $8.3 \pm 1.5$  s at the AR beam current of 60 mA. The reflection rate ( $\Gamma = 1 \times 10^{-6}$ ) with regard to power is evaluated for the energy deposit of  $1 \times 10^{19}$  eV taking account of loss in the waveguide circuit and the geometrical cross section ratio between the rock salt sample and the waveguide.

The scattering mechanism is not known yet. But electrons, color centers, phonons, polarons and polaritons etc. could be candidates of particles as targets of the microwave scattering. The lifetime of the particles should be as long as several seconds. Energy deposit during X ray irradiation would be accumulated in the lifetime. We study whether the scattering is coherent or not. Reflected power ( $P_r$ ) is a square of electric field vector sum at a receiving antenna in a waveguide-to-coaxial converter as in eq. (1).

$$P_r = |\mathbf{E}_1 + \mathbf{E}_2 + \cdots + \mathbf{E}_i + \cdots + \mathbf{E}_n|^2 \quad (1)$$

$$= |\mathbf{E}_1|^2 + |\mathbf{E}_2|^2 + \cdots + |\mathbf{E}_n|^2 + \cdots + 2\mathbf{E}_i \cdot \mathbf{E}_j + \cdots \quad (2)$$

$$= n^x |\mathbf{E}_i|^2 \quad (3)$$

Where  $n$  is number of the particles. Each vector of  $\mathbf{E}_i$  is electric field come from each particle. We expand

eq. (1) and get eq. (2) which includes the cross terms. If the wavelength of the microwave in the rock salt is well longer than distances between the particles, phase of the scattered wave is almost the same and the cross terms are added constructively. We define coherence parameter  $x$  which spans from 2 to 1 for full coherence to null coherence, respectively. The null coherence means the scattered waves are in random phase. The scattered power is proportional to square of  $n$  as written in eq. (3) in case of the longer wavelength.

Amount of increase in the reflected power during the full open time of 0.8 s were deduced in different irradiation time (beam current) for 16.0 s (60 mA) and, 4.8 and 9.6 s (40 mA). Increases of the reflected power were  $(8.5 \pm 0.05) \times 10^{-12}$  and  $(4.2 \pm 0.8) \times 10^{-12}$  W for the beam current of 60 and 40 mA, respectively, as shown in fig. 3. The coherence parameter was  $x = 1.8 \pm 0.4$ .

A sharp rise at the beginning of the irradiation in fig. 2, we fitted the curve with eq. (3) where  $n$  is substituted to the elapse of time from the beginning of the irradiation. The number  $n$  increases proportionally with the elapse of irradiation time. The coherence parameter became  $x = 1.7 \pm 0.6$  which is consistent with the beam current case described above. Both analyses show that the scattering is coherent. It means that each particle interacts with incident microwave independently and the distances among them should be considerably shorter than the wavelength of microwave in the rock salt sample.

Number of particles is estimated assuming Thomson scattering cross section of  $\sigma_T = 6.653 \times 10^{-25}$  cm<sup>2</sup> between the microwave and the particles. We get the number of particles assuming full coherence of  $x = 2$  in eq. (4):

$$n = \sqrt{\frac{\Gamma}{\sigma_T}} = 1.2 \times 10^9 \quad (4)$$

We estimate production cross section of the particles ( $\sigma_t$ ) in the interaction between the X ray and electrons ( $N_e = 3 \times 10^{22}$ ) in the rock salt sample. We get the cross section in eq. (5):

$$\sigma_t = \frac{n}{N_\gamma N_e} = 3 \times 10^{-29} \text{ cm}^2 \quad (5)$$

The cross section is  $10^{-4}$  smaller compared with Compton scattering cross section of the order of  $10^{-25}$  cm<sup>2</sup>. It might mean that the particles were not free electrons produced by Compton effect and stopped by ionization loss inside the rock salt sample.

Most of the coherence of scattering are among particles in the transverse region when the wavelength are comparable to the longitudinal size of the electromagnetic energy deposit. We compare the coherence among particles in the transverse region of an actual UHE shower with the rock salt sample used in this experiment. We observed the coherent scattering with the transverse size of  $w = 2$  mm in the sample for the wavelength of  $\lambda = 13.3$  mm microwave (9.4 GHz) in the rock salt. The ratio is  $w\lambda^{-1} = 0.15$ . If we use the frequency of 10 MHz for the actual UHE electromagnetic shower keeping the same ratio of 0.15, the

**Table 1.** Range of radar (peak power of 1 MW & 1 GW) against the shower energy deposit and reflection rate  $\Gamma$ .

shower $E/\text{eV}$	$\Gamma$	$R/\text{m}(1 \text{ MW})$	$R/\text{m}(1 \text{ GW})$
$10^{17}$	$10^{-10}$	88	469
$10^{18}$	$10^{-8}$	271	1310
$10^{19}$	$10^{-6}$	796	3180

transverse size of 190 cm is allowed to a coherent scattering. The size seems to be large enough compared with the lateral size of the UHE shower.

We estimate the range of a radar in the rock salt formation assuming transmitting and receiving antennas having isotropic sensitivity. Peak power of the radar is assumed as 1 MW - 1 GW with a pulse duration of 1  $\mu\text{s}$  which means that spacial resolution is about 100 m along a direction between the antenna and a UHE shower. The reflection rate of  $\Gamma$  is proportional to square of an electromagnetic energy deposit ( $E$  [eV]) in the rock salt. We get reflection rate using  $\Gamma = 10^{-6}$  at the energy deposit of  $10^{19}$  eV as in eq. (6):

$$\Gamma = 10^{-6} \cdot (10^{19} \cdot E)^2 \quad (6)$$

Attenuation rate  $\alpha$  in power is calculated in eq. (7):

$$\alpha = (\exp(-2R/L))^2 \quad (7)$$

Where  $R$  is a range of the radar between the antenna and the UHE shower, and  $L$  is an attenuation length of radio wave for electric field. Receiving power is expressed by eq. (8):

$$P_r = P_e \cdot \alpha \cdot \Gamma \cdot (4\pi R^2)^{-2} \cdot S_1 \cdot S_2 \quad (8)$$

Where  $P_e$  is an emission power at the transmission antenna,  $S_1$  and  $S_2$  are effective cross sections of the UHE shower and the receiving antenna, respectively. From our measurements of the perturbed cavity resonator method as in fig. 1, the attenuation length is extrapolated to 10 MHz. Then we get  $L = 7000$  m. We assume that the detection limit of radio wave is  $P_r \geq 10^{-14}$  W and the effective cross sections of the UHE shower and the receiving antenna are  $S_1 = S_2 = 1 \text{ m}^2$ . We get the range of the radar as shown in table 1.

### 3 Summary

Microwave was reflected at the rate of  $10^{-6}$  from X ray irradiated rock salt in the energy deposit of  $1 \times 10^{19}$  eV. Life time of particles which was responsible to the decay time of the microwave reflection was several seconds. It is long enough to employ periodic transmission of radar pulses without triggered by reception of Askaryan radio wave. Microwave scattering from the irradiated rock salt was coherent but the particle species working as the scattering targets is not known.

Power of radio wave emitted by Askaryan effect increases proportionally to the frequency. At the higher frequency the attenuation length becomes short as shown

in fig. 1. On the contrary radar method is not imposed such a restriction on the frequency. Strong artificial radar pulses are available for the radar method. Consequently, we could get long range of detection.

Times and amplitude from several receiving antennas could give us 3 dimensional information of the UHE shower with its energy. In order to utilize a salt dome with a diameter of 3 km and a depth of 3 km (50 Gt), several bore holes are needed in which the transmitting and receiving antennas are installed. Radar method would have a potential to realize Salt Neutrino Detector to act like a Radio Bubble Chamber to detect GZK neutrinos.

If we could get the peak power of the radar considerably larger than 1 GW, the range becomes long enough to know whether GZK neutrinos exist or not without expensive bore holes. The antennas would be installed slightly under a floor in an excavated space of a rock salt dome.

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