A radio detector for Ultra High Energy cosmic neutrinos

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Abstract: This work presents the main features of a radio neutrino detector in a salt mine. The influence of the salt medium on radiowave propagation and on antenna behavior is analyzed, together with the constraints on the minimal energy to be detected and performances of electronics. The number of detected events is calculated in the end.

Keywords: neutrino, radio detection, salt

1 Introduction

Neutrinos carry the information about the regions of the universe where the cosmic rays have been formed because they are uncharged, therefore not deflected by magnetic fields. As they only interact via the weak force, they are immune to almost all attenuation. A neutrino that reaches Earth came directly from its point of origin and so can, in principle, be used to determine the location of the source.

Neutrino telescopes may detect the three types of neutrinos via the interaction with a nucleon of the matter comprising or surrounding the detector volume [1].

Askaryan suggested that cascades generated by UHE charged leptons moving through matter, produce around 20 percent excess of negative charge moving at relativistic speed [2]. As a result nanosecond pulses of coherent Cherenkov radio emission could be observed in directions corresponding to a “spread” conical surface with the opening equal to Cherenkov angle [3]. For photons with wavelengths longer than the transverse dimensions of the cascade, like radio frequency (RF) photons, the radiation is coherent and the electric field is proportional to the negative charge in the cascade [3]. The power of radio emission grows as the square of number of charged particles in excess in the shower.

A cosmic neutrino radio detector should be set in a dielectric medium with a volume of at least 1 km³. A large volume is necessary to compensate for the small cross section and small flux at high energies. The experiment requires a large number of antenna strings that are capable of detecting the radio impulses generated by the Askaryan effect [2]. Using this method, one can determine not only the particles’ characteristics, but also identify their incoming direction. Formations of salt rock could therefore provide a viable detector for ultra high energy (UHE) neutrinos. Given that salt settlements in Romania are one of the largest in Europe, several of these will provide an ideal location in which to test UHE detectors.

2 The effects of the propagation medium

2.1 Antenna behaviour

To reconstruct the direction and energy of cosmic neutrinos, one can use a 3D network of antennas that detect the coherent broadband radio impulses created from the interaction of neutrinos in salt [4]. The detector is designed as a series of boreholed towers. Each level of the tower carries (besides antennas) all relevant electronics (e.g. filters, amplifiers etc.). This assembly is the radio detection station (RS). The whole structure is envisaged as a cube.

The behaviour of slotted cylindrical antennas has been studied previously (e.g. R.A.N.D. project [5]) so it will not be discussed here. Slotted cylindrical antennas have a few advantages: they are much more hydrodynamic than wide-band biconical antenna, the receiver no longer has to be inside the antenna, and the antenna can be transported in its completed form (no assembly required). The dipoles used in vertical polarization are inexpensive, easy to use in bore-holes and their behaviour can be modelled mathematically. Since the performance of dipoles is usually poor compared to broadband antennas, we will treat these as a conservative option.

Investigation are performed at a central frequency of 187.5MHz (a half-wave dipole working at this frequency has a physical length of 80cm). Although the Cherenkov generated field has a maximum intensity at a frequency close to a few GHz [6], we select this frequency because it is less attenuated at propagation, is less sensible at temperature variations, and allows differentiation between incidence angles [7]. The maximum field is observed at angles equal to the Cherenkov angle, as this maximizes the field’s amplitude. In order to quantify the influence of the propagation medium on the antenna’s behaviour, the transfer functions are calculated for different permittivities (figure 1). The one lobe characteristic of a dipole radiating in air is lost.

2.2 Effects on radio propagation

As already presented, if a neutrino interacts in rock salt, it creates a radio EM field by the Askaryan effect. The radio waves are measured after propagation from the neutrinos interaction point to the detecting antenna. The main characteristics of the cosmic particle are determined by an interpretation of the data. It is trivial to understand that a good theoretical description and mathematical model of propagation is impetuous. Impurities in the detection medium can theoretically affect the measured signal in two ways: by changing the number of particles produced in the shower and by distorting the wave propagation. We considered different concentrations of CaCO3 (one of the main impurity in salt) and their effect on a shower generated by a ν_e. Re-
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3 Detector limitations

In a real experiment, the voltage measured by the antenna represents the only measurement from which information about the initial neutrino can be retrieved. Unfortunately, a singly measured voltage does not always allow simultaneous determination of the distance travelled by the waves, the width of the layer, and the energy of the initial particle. This is mainly because the composition of each layer, which determines the layer’s permittivity, cannot be actuated. Moreover, the number of reflections at the interfaces of the layers (i.e. layers’ widths), which determines the slope of voltage decrease, is unknown.

We estimated the minimum energy that can be reconstructed without ambiguity, and that also allows for the simultaneous determination of the propagation distance and layer width, for given SNR=6. We met the uniqueness determination criteria, which indicates that for the same propagation distance, the difference between the values of the measured voltages for two consecutive layers’ lengths should be larger than the SNR. Figure 4 [14] shows the interdependence between the propagation distance and minimum energy that can be detected, if a threshold of SNR=6 is considered. The lines represent the isocontours of the measured voltages.

Another simulation of interest is the one where we calculate the relation between the necessary number of radio stations (RS) on each axis and the minimal initial energy that can be detected. If the layers are small (2cm), the minimum energy that can be detected and reconstructed is of about $10^{21.51}$ eV, only if the distance between RS is of about 100 m. If the distance between RSs is 250m (five on each side), no event under $10^{23.71}$ eV will be detected.

For wider layers ($d_2=10$ cm), the minimum energy that can be detected and reconstructed is $10^{21.85}$ eV (ten times smaller) even if the distance between RS is up to 500 m (figure5).

Based on results we decided to select the distance between RS to be 250m (and this value will be considered throughout the rest of the paper). The minimal number of RS necessary to reconstruct an event -coincidence criteria- was imposed to be 5 (with a SNR at antenna level of 6). The minimum energy that can be measured is presented in Figure 5 [14], for different layer width. The SNR does not influence much the results, if layers are of large width. However, compared to the case when no restrictions are imposed concerning the number of RSs necessary for detection, the minimal energy decreases by 1.2 times.

Fig. 1: The antenna characteristic in salt

Fig. 2: Number of generated electrons and positrons in an electron induced shower in salt

Fig. 3: Amplitude of the electric filed at 126m from neutrino’s interaction point
Fig. 4: The isocontours for measured voltage (corresponding to a signal with a SNR greater than 6) obtained for different energies and propagation distances, for different layer widths: \(d_L=2\,\text{cm}\) (upper plot, left side), \(d_L=4\,\text{cm}\) (upper plot, right side), \(d_L=6\,\text{cm}\) (lower plot, left side) and \(d_L=10\,\text{cm}\) (lower plot, right side).

4 Conclusions

In an underground detector a particle shower can only be initiated by a neutrino interaction because all other cosmic particles have already interacted by ground level \[15\]. Potential sources of cosmic neutrinos include: stellar flares, stellar winds, black holes, supernovae (SN) and Active Galactic Nuclei (AGNs).

Extra galactic AGNs are the only sources sufficiently large and with sufficiently strong magnetic fields to accelerate particles to energies higher than \(10^{20}\,\text{eV}\). We parameterized the neutrino flux generated in AGNs according to \[16\] and simulated the total number of detected events in the \((10^{19}\,\text{eV}, 10^{24}\,\text{eV})\) energy range.

To obtain a prediction of the number of events detected in a salt detector, the interaction probability should be combined with the effective volume (the collection of potential shower positions that satisfies a signal to noise ratio greater than a given value; for each energy of the primary, the total volume 'sensed' by one detector is obtained by rotating the antenna’s characteristic (figure 1) around antenna’s main axis). Extra galactic neutrino production rate, shadowing factor (that reflects the number of neutrinos removed from the flux by interactions when crossing Earth), the probability that from the interaction to result an observable lepton in the detector (the probability is determined according to \[18\]), neutrino’s trajectory (upward or downward) etc. should also be taken into account. Further details are given in \[14\].

In all simulations was required that a number of neighbour radio stations (separated by 250m) to detect simultaneously the radio signal. If the number of necessary radio stations is set to 5 and the SNR to 6, in five years the detector will observe about one event generated by ascending \(\nu_e\) and 60 events by descending \(\nu_e\), if \(d_L=5\,\text{cm}\). For \(\nu_\mu\), it will be observed about 2 events in the ascending case and about 65 events for the descending case (for both energies \(E_{\min}\)). Using a more optimistic flux of neutrinos created in AGNs \[17\] the total number of events detected in one year is about 200 (if \(d_L=5\,\text{cm}\)) and decreases to 80, for small layers (2cm).

Neutrinos’ reactions with electrons were also taken into consideration. Neutrino scattering with atomic electrons has a cross section about three orders of magnitude lower than the neutrino-nucleon cross section \[18\]. This type of reaction is important only around 6.3 PeV (the Glashow resonance), when the cross section is large enough to produce a detectable event. In the interval \((10^{15}\,\text{eV}, 10^{16}\,\text{eV})\) were considered the anti electron neutrino reactions with free electrons (the only ones with a large enough cross section \[19\]). It was concluded that there will be no
Fig. 5: Isoconturs of number of radio stations that will detect a neutrino with energy $E_0$ if the layers have a width of $d_L=2$ cm (upper plot), $d_L=5$ cm (middle plot) and $d_L=10$ cm (lower plot). The detector has an equal number of RSs on each axis (varying from 3 to 10).

detectable event in this energy range.

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