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On the feasibility of RADAR detection of high-energy neutrino-induced showers in ice

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ABSTRACT

In this article we try to answer the question whether the radar detection technique can be used for the detection of high-energy-neutrino induced particle cascades in ice. A high-energy neutrino interacting in ice will induce a particle cascade, also referred to as a particle shower, moving at approximately the speed of light. Passing through, the cascade will ionize the medium, leaving behind a plasma tube. The different properties of the plasma-tube, such as its lifetime, size and the charge-density will be used to obtain an estimate if it is possible to detect this tube by means of the radar detection technique. Next to the ionization electrons a second plasma due to mobile protons induced by the particle cascade is discussed. An energy threshold for the cascade inducing particle of 4 PeV for the electron plasma, and 20 PeV for the proton plasma is obtained. This allows the radar detection technique, if successful, to cover the energy-gap between several PeV and a few EeV in the currently operating neutrino detectors, where on the low side IceCube runs out of events, and on the high side the Askaryan radio detectors begin to have large effective volumes.

1. Introduction

Recently the IceCube neutrino observatory [1] for the first time showed the existence of high-energy cosmic neutrinos. Since neutrinos are not deflected by magnetic fields in our universe, they should point back to their original source. This opens a new field in physics, the field of neutrino astronomy. At the highest energies, these cosmic neutrinos are extremely rare. At energies above several PeV, IceCube runs out of events and an even larger detector volume than the 1 km^3 covered by IceCube is needed for their detection. Due to the long attenuation length of the radio signal, the radio detection technique is an excellent candidate to detect these rare events.

Several radio detectors have been developed to detect the radio emission from neutrino-induced particle cascades in ice and moon rock [2–10]. These are based on the emission from a net electron excess which develops when the particle cascade evolves, the Askaryan effect [11–13]. The Askaryan radio-emission mechanism has been confirmed experimentally at SLAC [14] and in the radio emission from air showers [15,16]. The Askaryan radio detection experiments have been developed to detect the GZK neutrino flux [17,18], which should arise from the interaction of high-energy protons ($E > 10^{19.5}$ eV) interacting with the Cosmic Microwave Background. Therefore, these detectors start to have large effective volumes for cascade inducing particles having energies in the EeV region and above, where the GZK flux is expected. It follows that there is an energy gap between IceCube, which is sensitive below several PeV, and the Askaryan radio detectors which start to have large effective volumes at EeV energies. In this article, we discuss the radar detection technique as a possible method to bridge this important energy region between several PeV and a few EeV.

The concept of radar detection of cosmic-ray-induced particle cascades in air dates back to the 1940s of the previous century. Blacket and Lovel [19] proposed to use the radar detection technique to measure these cosmic-ray-induced air showers. Initial experimental attempts using the radar technique were done, but no conclusive evidence for the detection of air showers was found. It would take another 50 years before the interest in this subject was renewed [20,21]. This triggered several new modeling attempts [22–24] and experiments [25–30]. Even-though a first possible detection of a cosmic-ray-induced air shower might have been observed [28], no conclusive evidence for such a detection has been obtained so-far. Next to the efforts done for the radar detection of cosmic-ray air showers, recently suggestions were

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made to measure the reflection of radio waves from particle cascades induced in rock salt and ice [31].

With the existing infrastructure already available at the different Askaryan radio detection sites such as ARA [32] and ARIANNA [33], in this article, we discuss the radar detection technique for the detection of high-energy cosmic neutrinos. An energy threshold for the primary cascade inducing particle is derived for coherent scattering of the over-dense plasma region. The over-dense plasma region is defined by the condition that the detection frequency is below the plasma frequency, where the plasma frequency scales with the electron density. In this regime, the incoming radio signal does not penetrate the plasma and scatters of the surface of the plasma tube. This brings a great advantage of ice as a medium over air. The volume in which the particle cascade is confined decreases dramatically in ice, resulting in higher plasma frequencies. It should be noted however, that it is also possible to scatter of the individual electrons in the under-dense plasma. Currently, most of the existing radar facilities for the detection of air showers are based on the detection of the under-dense plasma.

In the first section, we discuss the particle cascade and the induced ionization plasma. We discuss results obtained experimentally by irradiating ice with 3 MeV electrons and X-rays, where it is found that next to the ionization electrons, a long-lived plasma exists which is attributed to free protons [34–37]. In the following we use the experimentally obtained lifetime of these plasmas to determine an energy threshold for the radar detection of the over-dense plasma region. Finally, we conclude by calculating the radar return power for the different components of the plasma. This allows us to determine the maximum detection range for different values of the radar power considering two different cascade geometries.

2. The plasma

When a high-energy cosmic neutrino interacts in the medium a cascade of secondary particles is induced. To model the electromagnetic cascade we use a Heitler model [38], stating that every interaction length λ, the total number of particles doubles and their average energy is split. This goes on up to the critical energy where the brems-strahlung, and creation–annihilation cross-sections become small compared to the ionization cross-sections. The critical energy of electrons in ice and their radiation length is given by,

$$E_c = 0.0786\ \text{GeV}, \tag{1}$$

$$X_0 = 36.08\ \text{g/cm}^2, \tag{2}$$

$$L_0 = \frac{36.08\ \text{g/cm}^2}{0.92\ \text{g/cm}^3} = 39.22\ \text{cm}. \tag{3}$$

Where the ice density is assumed to be constant and equal to $\rho_{ice} = 0.92\ \text{g/cm}^3$. Using the radiation length X_0, the interaction length is given by, $\lambda = X_0 \ln(2) = 25.01\ \text{g/cm}^2 = 27.19$ cm. Now following the Heitler model stating that every radiation length the total number of particles is doubled and their energy is split, we can make an estimate for the maximum number of particles in the shower and the shower length. The maximum number of particles in the cascade can be estimated by,

$$N_{max} = \frac{E_p[\text{GeV}]}{E_c[\text{GeV}]} = 12.72\ E_p[\text{GeV}]. \tag{4}$$

A more realistic shower development is given by the NKG parameterization, developed by Kamata and Nishimura [39], and Greisen [40]. It follows (see Appendix A) that the maximum number of particles in the Heitler model is overestimated by a factor of 10 independent of energy in the TeV to EeV energy range. Therefore, in the following we will consider,

$$N_{max}^{NKG} = 1.27\ E_p[\text{GeV}]. \tag{5}$$

The shower maximum is reached after $n = \ln(E_p/E_c)/\ln(2)$ divisions, leading to an estimate for the shower length of,

$$l_c = n\lambda = L_0\ \ln(E_p/E_c) \approx 0.4\ \ln(12.72\ E_p[\text{GeV}])\ \text{m}. \tag{6}$$

This is the length it takes for the cascade to reach its maximum, the total length will therefore in general be at least a factor of two longer. In Fig. 1, the shower length is plotted as a function of primary energy from 1 TeV to 1 EeV and is found to be of the order of 5–10 meters. This corresponds well to the values obtained using the NKG parameterization (see Appendix A). It should be noted that we ignore the LPM effect [41,42] which becomes significant above PeV-EeV energies [43,44], giving rise to an increased shower length.

So-far, we discussed the high-energy electron–positron pairs in the shower front. Nevertheless, we will not focus on this high energetic shower front for the radar detection of the cascade. This is mainly due to two reasons, one is that the particle density is too low, the second is that the shower front is very narrow such that we would need to measure at very high frequencies. More interesting are the low-energy ionization electrons left behind when the shower front has passed. The ionization energy of ice can be estimated as $E_{H_2O}^{ionization} \approx 20$ eV. Assuming that most of the energy loss of the electrons or positrons goes into ionization, the energy lost in one radiation length at the shower maximum equals $E^{lost} = E_c - (1/e)E_c \approx 50$ MeV per high energy electron in the shower front. Hence the number of ionization electrons created by a single high energy electron equals $N^{ion} = E^{lost}/E_{H_2O}^{ionization}/L_0 = 6.93 \cdot 10^4\ \text{cm}^{-1}$. The total number of ionization electrons created is thus given by,

$$N_e^{tot} = N_{max} \cdot N^{ion} = 8.80 \cdot 10^4\ E_p[\text{GeV}]\ \text{cm}^{-1}. \tag{7}$$

To convert the line density to a volume density, we need to consider the radial particle distribution in the cascade. This is modeled by modifying the parameterization used in [45], which was originally developed for air showers,

$$w(r) = \frac{\Gamma(4.5 - s)}{\Gamma(s)\Gamma(4.5 - 2s)} \left(\frac{r}{r_0}\right)^{s-1} \left(\frac{r}{r_0} + 1\right)^{s-4.5}, \tag{8}$$

The shower age parameter is taken to be its value at the shower maximum, $s = 1$, and the distance parameter $r_0^{ice} = 7$ cm is converted using its value in air. More details can be found in Appendix B. In Fig. 2, we plot the radial particle distribution. It follows that the radial particle distribution is a fast decreasing function and hence

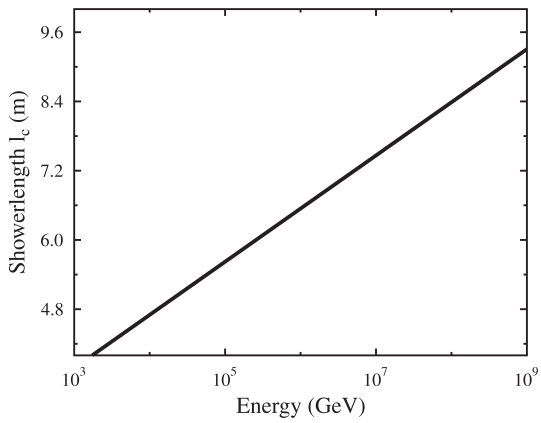

Fig. 1. The shower length l_c given in Eq. (6), as a function of the energy of the primary shower inducing particle.