We discuss the recent developments in the study of alternative detection possibilities offered by the radio technique and air shower arrays.

Neutrinos are one of the least explored fundamental sectors of the Standard Model because they have a challenging low cross section. Besides man made nuclear reactions and beam dump experiments in accelerators, neutrinos have only been detected from two astrophysical sources: the Sun and supernova SN 1987A and from the interactions of cosmic rays with the atmosphere. Their potential for fundamental research is however large as illustrated by the few events from SN 1987A and the recent evidence for flavor oscillations, completing the Standard Model and providing clues for physics beyond. Moreover, they have an unique Astronomy potential as they can travel unattenuated through matter shields that are opaque to other types of radiation.

The neutrino nucleon cross section rises with energy, first linearly and then more slowly because of the low $x$ behavior of the parton distributions, so that the Earth becomes opaque for neutrinos of $E_{\nu} \sim 100$ TeV, with relevant implications for detection techniques. In this article we will concentrate on neutrinos above the EeV energy scale with an expected cross section in the 10-100 nb range.

Existing neutrino detectors as well as those in construction or planning have motivated estimates of neutrino fluxes from many possible sources such as Active Galactic Nuclei (AGN) cores and jets, Gamma Ray Bursts (GRB) and decays of Topological Defects (TD). These calculations extend to energies in the EeV range with fluxes that are however quite uncertain because AGN and GRB are not well understood and the TD densities and annihilation rates are quite unknown. There are however better established neutrino fluxes from beam dumps in which cosmic rays interact with matter in the Universe, either the galactic disk, molecular clouds or the Earth atmosphere. Below 100 TeV atmospheric neutrinos are subject to uncertainties in the 20% range but above these uncertainties become larger because prompt decays from charm production dominates. The establishment of cosmic rays above the Greisen-Zatsepin-Kuz’min (GZK) cutoff ($\sim 6 \times 10^{19}$ eV) and the absorption of protons and nuclei in the Cosmic Microwave Background (CMB), guarantees
neutrinos of very high energies, provided these cosmic rays are of extragalactic origin, as most commonly believed. In some models neutrinos of energies above $10^{-19}$ eV act as "messengers" interacting with the cosmic neutrino background to produce cosmic rays.

Fig. 1 compares the atmospheric flux, to calculations of: prompt neutrinos, those from cosmic ray interactions with galactic matter, and with the CMB, a messenger neutrino model, production in AGN jets and cores, in GRB's, and in TD scenarios using highest injection rates allowed in ref. illustrating uncertainties. Recent bounds for mechanisms that produce neutrinos trough proton interactions with photon fields (such as AGN jet models or GRB's), obtained by demanding that cosmic rays are not overproduced, are also shown in the extremes of an optically thin target and a target which is optically thick to neutrons.

![Figure 1: Neutrino flux predictions as labelled and bounds for optically thin (lower) and thick (upper) photon targets, see text.](image)

Expected neutrino fluxes above the PeV are low and for detection large natural target volumes need to be instrumented. Conventional detectors use photomultipliers in water or ice to detect the Cherenkov light emitted by the
long range muons produced in charged current muon neutrino interactions, which retain the neutrino direction to about a degree. Upcoming events are exclusively due to interactions of neutrinos that have travelled through the Earth. For neutrinos well above $\sim$ PeV when the Earth is opaque, only down-going to horizontal neutrino events are expected which must be separated from the atmospheric muons $^3$. The Cherenkov light from high energy showers may allow such separation provided the detector has reconstruction capabilities. Detection of neutrino induced showers is moreover sensitive to all flavor neutrino interactions. These detectors are in good development and are likely to bring information on neutrino fluxes in very short time $^21$.

Alternatively the atmosphere can be instrumented to detect horizontal (or upcoming) showers. At sea level the atmosphere is roughly 36 times deeper in the horizontal than in the vertical direction. As a result horizontal showers induced by cosmic rays get absorbed and only the shower muons can be detected at sea level. Showers induced by cosmic rays in the horizontal direction differ from typical ones (vertical) in that they hardly have any electron or photon density, the arrival time of particles on the ground has less spread and agrees better with that of an ideal plane of simultaneous muons and lastly they have a characteristic double ellipse density profile due to the magnetic field of the Earth. It is known since the 60’s that penetrating particles such as muons and neutrinos can induce showers in the horizontal direction $^22$ that look like typical vertical showers. At very high energies the atmospheric muon flux becomes negligible and only neutrinos can produce deep showers which can be identified provided the detector has an adequate rejection power for those unusual ”muon showers” induced by cosmic rays.

The recently approved Pierre Auger Observatory in Argentina, will be the largest installation (3000 km$^2$) to measure air showers. Such a detector array (plans are to build two, one in each Hemisphere) can do this separation at least based on both timing and muon content and has an acceptance of order 10 km$^3$ sr water equivalent $^23$. The rate of cosmic ray background showers has been estimated to be a few thousand showers per year depending on trigger conditions $^24$.

As a second alternative Antarctic ice can be instrumented with radio antennas to detect the coherent radio pulses produced by high energy showers. The idea dates also from the 60’s and it is particularly attractive for high energy showers. Provided the wavelength is larger than the relevant shower dimensions the emission from all shower particles is coherent and that from electrons and positrons cancels out. But as matter electrons constitute the target for the dominant interactions below the critical energy ($E_c \sim 73$ MeV $^a$).
in ice), an excess negative charge develops in the shower averaging to about 20% of the shower size. As a result the electric field becomes proportional with the excess charge and since this scales with shower energy, the power in radio emission becomes proportional to the square of shower energy. Many experimental difficulties are however anticipated\textsuperscript{25} and presently antennas are being tested deep under ice using the AMANDA bore holes in Antarctica (RICE)\textsuperscript{26}.

The first numerical calculation of the radio pulse frequency spectrum in the Fraunhofer approximation for electromagnetic showers in ice up to 10 PeV revealed a rich diffractive pattern but established a threshold of about 10 PeV for detection at distances above 1 km. It suggested that the technique could become competitive for higher energies. The simulation becomes increasingly problematic from the computational point of view for energies roughly above 10 PeV as particles have to be tracked down to kinetic energies in the 100 keV range. Alternative calculation methods are crucial if this possibility is ever to be seriously considered. The simulation of EeV showers in ice has only been recently approached both for electromagnetic and hadronic type showers with a method combining simulation and parameterizations in the one dimensional approximation. This is also the first time that the Cherenkov light in a dense medium is studied in this energy range.

Figure 2: Longitudinal development of electromagnetic (dashed curves) and hadronic (solid curves) showers in ice. The energies shown are from bottom to top 10 TeV, 1 PeV, 100 PeV and 10 EeV.
For energies below about 20 PeV in ice showers induced by electrons or photons produce very similar pulses to those induced by hadrons. At very high energies however showers behave very differently in dense media because of the Landau-Pomeranchuk-Migdal (LPM) effect. As the incident photon or electron rises its energy the characteristic length of interactions with an electro-static potential rises to become larger than the interatomic spacing. Collective atomic effects manifest as a drastic reduction of the cross section for pair production and bremsstrahlung that govern shower development. The LPM effect also suppresses the central part of the differential cross section for pair production (where the electron and positron carry similar fractions of the incoming photon energy) and cuts the cross section off for bremsstrahlung of low energy photons. As a result the showers can become very long (hundreds of radiation lengths). Hadronic showers show much smaller elongation because most of shower electrons and photons come from decays of \( \pi^0 \) produced in hadronic interactions. Pion decay in ice above 40 PeV is suppressed because they are more likely to interact so that even for EeV showers only a small fraction of the shower is subject to LPM elongations.\(^27_{28}^{}\) In Fig. 2 the simulation results for the developments of hadronic and electromagnetic showers in ice are compared.

The LPM has implications for any detector sensitive to the showers and in principle allows the separation of showers induced by electrons in charged current electron neutrino interactions from the other showers which are produced by the nucleon fragments.\(^29^{}\) The radio emission from a shower can be viewed, as a first approximation, as the Fourier transform of the longitudinal development of the shower. The modifications introduced by the LPM effect are quite dramatic as the angular spread of the diffraction pattern narrows linearly as the shower elongates.\(^27_{28}^{}\) For hadronic showers the pattern shows two angular periodicities corresponding to the two shower scales.\(^3\) In summary the confirmation of cosmic rays of energies above \(10^{20}\) eV is very suggestive for the existence of EeV neutrino fluxes at levels which may be detectable in the foreseeable future. Conventional neutrino detectors will have the first word on high energy neutrino fluxes but alternative techniques can also contribute particularly in the EeV region. While horizontal shower measurements will play an important role as the next generation of detectors has an acceptance which is of order 10 km\(^3\)sr, the radio technique provides a most interesting possibility which may turn out to be most adequate if acceptances above km\(^3\) are required. They moreover have many added advantages due to the coherence character of the signal to be measured which will be of great use in trying to establish neutrino flavor, particularly if combined with other techniques.
Figure 3: Angular distribution of radiopulse around the Cherenkov angle for the electromagnetic (dashes) and hadronic (solid) showers shown in Fig. 2 for shower energies 1 PeV and 10 EeV.

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