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# In-Ice radio detection of air shower cores

DAVID SECKEL[1], SURUJ SEUNARINE[2], JOHN CLEM[1], AMIR JAVAID[1]
[1]*Deptartment of Physics and Astronomy, University of Delaware, Newark DE 19716*
[2]*Department of Physics, Canterbury University, Christchurch NZ.*
*seckel@bartol.udel.edu*

**Abstract:** Radio receivers (RICE, AURA) have been deployed to detect impulsive emissions from neutrino interactions in ice at South Pole. An alternative source of pulses is the cores of cosmic ray induced air showers. AIRES and CORSIKA simulations suggest that $> 10\%$ of the primary cosmic ray energy enters the ice within 20 cm of the primary axis impact point. The resulting 5-10 m cascade will make Askaryan type pulses that can be detected by in-ice receivers. Strategies are discussed for deploying a modest number of antennas which could operate in coincidence with IceCube to validate the in-situ detection of Askaryan pulses and produce a new discriminant for studying cosmic ray primary composition for energies above $10^{16}$ eV.

## Introduction

Askaryan[1] proposed that compact showers produced by high energy particles interacting in a dense medium would produce observable radio pulses. The pulses result from an excess of negatively charged electrons moving relativistically through a dielectric medium. A coherent Cerenkov pulse is created for wavelengths longer than both a) the true transverse dimensions of the shower and b) the apparent length of the shower when foreshortened by viewing from near the Cerenkov angle.

This concept has been the basis for several existing and proposed experiments looking for said pulses in the icecaps of Greenland and Antarctica, the Lunar regolith, and salt domes. Although no evidence for these signals has been seen in a natural environment, the Askaryan effect has been confirmed in a series of laboratory experiments at SLAC utilizing sand[2], salt[3], and ice[4].

It is broadly accepted that the natural effect has not been observed due to the low fluxes of particles with sufficiently high energy to make observable pulses; however, practical experiments must detect signal against a background of natural and manmade noise sources. Thus, although the technique has great potential, the possibility of systematic errors clouds the interpretation of negative results as an indicator of upper limits on flux models. In addition, when (if?) signals are detected, one may question the results until a single experiment detects events by both the radio Cerenkov method and some more conventional high energy astrophysics technique.

In this report we describe the potential to detect Askaryan pulses produced by air shower cores striking the ice surface at South Pole. A modest array of antennas could plausibly detect events in coincidence with IceTop at a rate of $\sim 1$ per hour. Such an experiment would provide a) convincing evidence for the feasiblity of triggering on radio pulses created by high energy showers and b) experience with reconstruction of events based on signals from a distributed antenna array operating in a noisy environment. Both are needed stepping stones on the path to a 1000 $\text{km}^3\cdot$sr GZK neutrino detector. In addition, the radio signals should provide an additional event by event handle on air shower development, which may be used to improve determinations of cosmic ray composition in the energy range above 10 PeV.

## Geometric and energy considerations

Askaryan pulses result from the excess charge which develops in a shower. This charge is primarily the result of low energy processes: Compton scattering, $\delta$-ray production, and in flight positron annihilation. Here, by low energy we mean processes with momentum transfers of a few electron masses. The transverse length scale of such particles in a shower is characterized by the Moliere radius, which in ice is of order 10 cm, but in air is of order 100 m. Air showers do not directly make Askaryan pulses with the same frequency content as showers developing in a dense medium.

On the other hand, air showers do have a core of high energy particles. Early in the shower the core is dominated by hadronic particles, but it eventually converts to electromagnetic energy, after which the core evolves by pair production and bremstrahlung - processes which do not create excess charge. As such, the compact core of high energy particles does not produce a significant Askaryan pulse. For modest energy air showers, the core dies out before it reaches the ground and that is the end of it. For sufficiently energetic showers, however, the core penetrates through the atmosphere and an Askaryan pulse is created when the core hits the surface of the ice and evolves into an inice shower. Qualitatively, any energy of the air shower closer to the shower axis than a Moliere radius for ice will contribute to an Askaryan pulse. More generally, the frequency content of the Askaryan pulse depends on the profile of energy contained within a radius corresponding to the wavelength of radiation.

For purpose of discussion, we consider the frequency of 500 MHz, qualitatively central to the RICE[5], ANITA[6] and AURA[7] efforts. In firn at the surface, this corresponds to a wavelength of about 40 cm. Demanding phase coherence over the core suggests a length scale of $\sim 10$ cm. Within the air shower, high energy particles have a transverse spacing $\delta x \sim \theta x_{rad}$, where $x_{rad} \sim 500$ m is the radiation length in air, and $\theta \sim \frac{1}{\gamma} \sim \frac{m_e}{E}$ is the opening angle for bremstrahlung and pair production. Folding these numbers together, radiative particles with $E > 10$ GeV, which survive to hit the ice, contribute to the creation of an in-ice Askaryan pulse.

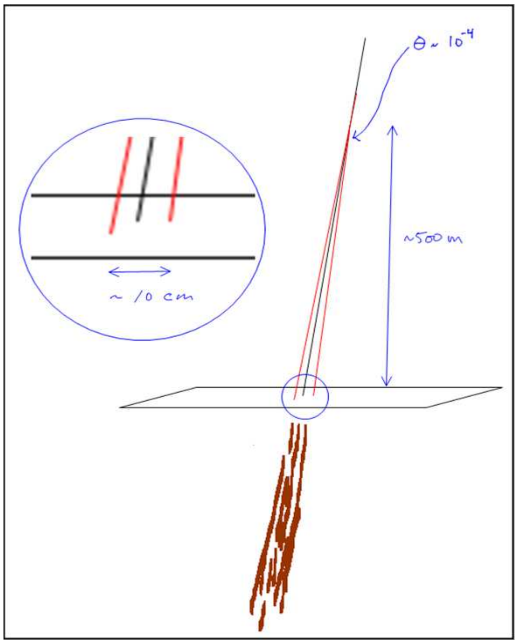

Figure 1: Geometry of air shower core.

## Monte Carlo results

We employed AIRES and CORSIKA to study the fraction of shower energy which strikes the ground as 10 GeV or higher particles. We ran the simulations for protons and iron for a South Pole atmosphere. Since we are not interested in the low energy particles at all, we set the particle threshold to 10 GeV, enabling us to complete simulations of showers with primary energies up to 1 EeV with modest computing resources.

The ground level particles include radiative particles, muons, mesons and baryons. As expected, the $E > 10$ GeV radiative particles are tightly clustered in the shower core. Mesons and baryons also shower in ice, but have larger production angles $\theta \sim \frac{\Lambda_{\mathrm{QCD}}}{E}$, are more distributed at the surface, and are less abundant than electrons and photons. There is a significant amount of energy in muons above 10 GeV of energy, but since muons do not shower and are widely distributed, they do not contribute to Askaryan pulses. We find that the fraction of shower energy in $> 10$ GeV radiative particles increase with primary energy, from typically a few percent at 1 PeV to greater than 10% at 1

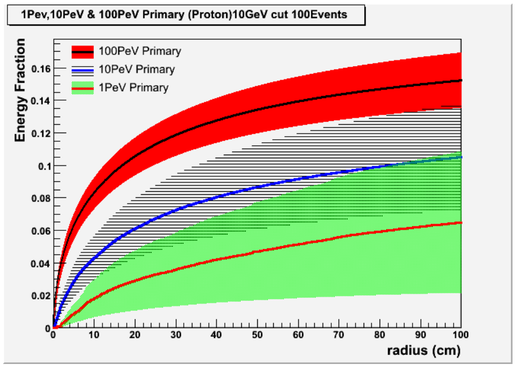

Figure 2: Contained energy vs radius. Energy within ~10 cm contributes to coherent radio emission at frequencies ~300 MHz.

EeV. Further, the concentration of this energy into a tight core also improves with primary energy.

## Askaryan pulses

The next step is to determine the $E$-field produced by the multitude of subshowers in the core. Coherence is critical. Accordingly, we perform a synthetic waveform calculation keeping track of the relative arrival phase of the field from each subshower, assuming the radiation is emitted from shower max. For an observer near the Cerenkov cone, the scatter in arrival time for radiation from subshowers is dominated by the transverse position of the subshower. Figure 3 shows the field from a $10^{7.33}$ GeV (21 PeV) proton induced air shower. Subshowers from all particles with energies greater than 10 GeV at the surface were included. The light radiative particles are more concentrated near the core, and dominate the high frequency signal. Mesons and baryons are less concentrated and fewer in number, and the resulting contributions to $E$ are suppressed.

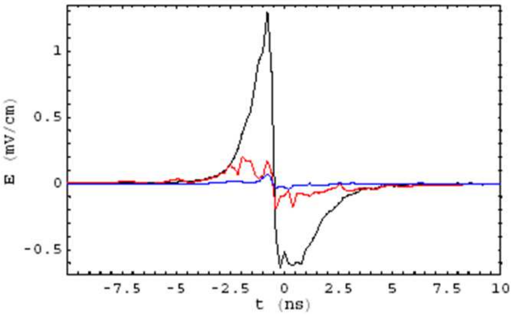

Figure 3: RF pulse at 20 m from the radiative(black), baryonic(red), and mesonic(blue) particles with $E > 10$ GeV from an air shower core induced by a 21 PeV proton.

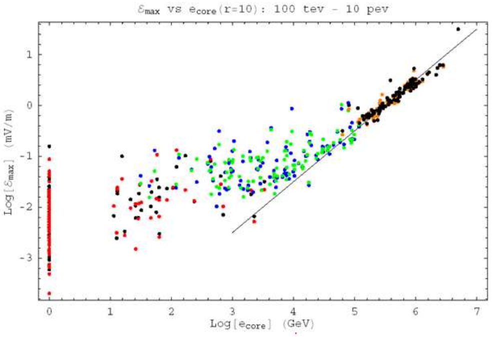

Figure 4: Demonstration that core energy correlates with peak $E$-field.

The resulting signal was calculated for an observer at about 20m from shower max, and relatively near the Cerenkov cone. The ~1 mV/m field strength is about threshold for detection against thermal background. The shape of the pulse is not particularly smooth. This is probably a marginally detectable signal. As shown in Figure 2, as the energy of the primary is increased, the fraction of primary energy which remains in the core also increases. Thus, if the core of a 20 PeV proton shower is marginally detectable at 20 m, it follows that the core from a 1 EeV primary is detectable at ~1 km.

Figure 4 shows a scatterplot of field strength vs. energy contained within a 20 cm core, for primary energies of 100 TeV, 1 PeV and 10 PeV. For each shower, the field was “measured” at two points 90 degrees apart around the Cerenkov cone. For 10 PeV these points are plotted in orange and black. The tight linear correlation of points for the 10 PeV primaries suggests that energy inside 20 cm (‘etot20’) can be used as a proxy for coherent radiation from the air shower core, without huge fluctuations. At lower energies, the fluctuations are large and the signals are marginal.

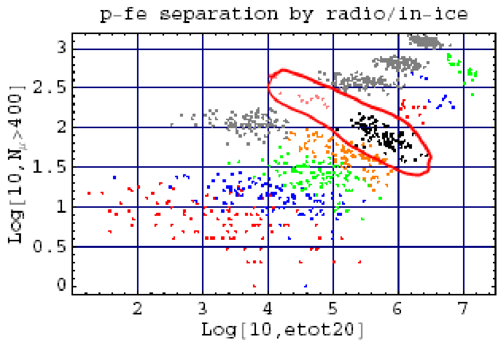

Figure 5: Correlation of $E$-field and in-ice muons can be used to separate air showers induced by proton and iron primaries. Primary energies increase from $\log_{10}(E) = 5.67$ to 8.0.

## Cosmic ray composition

The Askaryan signal relies on the air shower core surviving to reach the ground. This is a function of the energy per nucleon, and increases with $x_{max}$. Thus, for the same energy, we expect a significantly smaller radio signal from iron nuclei than from protons. At the same time, with smaller $x_{max}$, iron are more likely to produce high energy muons that penetrate through to the in-ice component of IceCube. Thus, Figure 5 shows a) an anticorrelation of core energy with the number of muons expected in IceCube and b) reasonably good separation of iron and protons.

In fact, the only true simulated iron nuclei Figure 5 are pink dots representing 10 PeV Fe. The grey dots are “pseudo-Fe” modeled by overlaying the subshowers from 56 lower energy protons. The colored dots form an energy segmented proton band. From the figure, it seems that if a modest array could detect events in coincidence with in-ice and surface components of Icecube, that determination of cosmic ray composition would be improved.

## Detection scenarios

We make a few remarks concerning rates and possible antenna arrays which may detect the Askaryan pulses discussed here. First, the intensity of signal from EeV primary protons permits detection at distances of roughly 1 km. Within the footprint of IceCube, the rate of $E >$ EeV primaries is about 50/yr. It follows that a modest deployment of radio antennas at 1 km depth on IceCube strings could expect an event rate of $\sim$ 1/week. Similarly, if the depth is decreased to 100 m to reduce threshold, and the full footprint of IceCube were instrumented, the rate would be of order one every few hours, although this number must be taken with caution pending more detailed study. One might also consider a small shallow array within one “square” of IceTop, which could operate at 10 PeV threshold and have similar coincidence rates.

Another possible application would be detection of UHE cosmic rays by the ANITA instrument. Every day more than a thousand cosmic rays of $E > 10^{19}$ eV land within the ANITA field of view. Unfortunately their Askaryan pulses propagate into the ice, and must experience attenuation and a bottom reflection to be seen by ANITA, so thin ice is preferred. At the same time the Ross and Ronne ice shelfs may not be appropriate since the deeper atmosphere may prevent air shower cores from penetrating to the surface. The detection of UHECRs by ANITA is under further review.

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