

Observations of the Askaryan Effect in Ice

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We report on the first observations of the Askaryan effect in ice: coherent impulsive radio Cherenkov radiation from the charge asymmetry in an electromagnetic (EM) shower. Such radiation has been observed in silica sand and rock salt, but this is the first direct observation from an EM shower in ice. These measurements are important since the majority of experiments to date that rely on the effect for ultra-high energy neutrino detection are being performed using ice as the target medium. As part of the complete validation process for the Antarctic Impulsive Transient Antenna (ANITA) experiment, we performed an experiment at the Stanford Linear Accelerator Center (SLAC) in June 2006 using a 7.5 metric ton ice target, yielding results fully consistent with theoretical expectations.

Very large scale optical Cherenkov detectors such as the Antarctic Muon and Neutrino Detector Array (AMANDA) and its successor IceCube have demonstrated the excellent utility of Cherenkov radiation in detection of neutrino interactions at $> \text{TeV}$ energies [1, 2] with ice as a target medium. However, at neutrino energies above 100 PeV, the cubic-km scale of such detectors is inadequate to detect more than a handful of events from the predicted cosmogenic neutrino fluxes [3] which represent the most compelling models at these energies. The relevant detector volume for convincing detection and characterization of these neutrinos is in the range of hundreds to thousands of cubic km of water equivalent mass, and the economic constraints of scaling up the optical Cherenkov technique almost certainly preclude extending it much beyond the size of the current IceCube detector, which will be completed early in the next decade.

Given the need for an alternative technique with a more tractable economy of scale to reach into the EeV ($=1000$ PeV) energy regime, a new method which we denote the radio Cherenkov technique, has emerged within the last decade. This method relies on properties of electromagnetic cascades in a dielectric medium. It was first hypothesized by Askaryan [4] and confirmed in 2001 at SLAC [5]. High energy processes such as Compton, Bhabha, and Moller scattering, along with positron annihilation rapidly lead to a $\sim 20\%$ negative charge asymmetry in the electron-photon part of a cascade. In dense media the shower charge bunch is compact, largely contained within a several cm radius. At wavelengths of 10 cm or more, much larger than the characteristic shower bunch size, the relativistic shower bunch appears as

a single charge moving through the dielectric over a distance of several meters or more. As an example, a typical shower with mean Bjorken inelasticity $\langle y \rangle = 0.2$, initiated by a $E_V = 100$ PeV neutrino will create a total number of charged particles at shower maximum of order $n_{e^+} + n_{e^-} = \langle y \rangle E_V / 1 \text{ GeV} \sim 2 \times 10^7$. The net charge is thus $n_{e^+} - n_{e^-} \sim 4 \times 10^6 e$. Since the radiated power for Cherenkov emission grows quadratically with the charge of the emitter, the coherent power in the cm-to-m wavelength regime is $\sim 10^{13}$ times greater than that emitted incoherently, far exceeding any other secondary emission in optical or longer-wave bands.

Prior to the first laboratory tests of the Askaryan effect in 1999-2000 [5, 6], and subsequent measurements in 2002 [12], it had been largely ignored since initial putative measurements of the effect in air showers were found instead to be due to a process related to synchrotron emission [13, 14]. In the mid-to-late 1980's, proposals to observe Askaryan impulses from neutrino interactions in Antarctic ice [15, 16, 17] and the Lunar regolith [18] created a renewed interest in Askaryan's work. In the early 1990's, the first comprehensive effort to combine EM shower simulations in ice with electrodynamics resulted in strong support for the validity of the methods [10], and in the later 1990's the Radio Ice Cherenkov Experiment (RICE) [19], and Goldstone Lunar Ultra-high energy neutrino Experiment (GLUE) [20] began operation of experiments designed to exploit the effect. More recently, the Fast On-orbit Recorder of Transient Events (FORTE) [21] satellite and the ANITA [8] experiment have extended the method to synoptic spacecraft or balloon-payload observations of ultra-large volumes of the Greenland or Antarctic ice sheet.

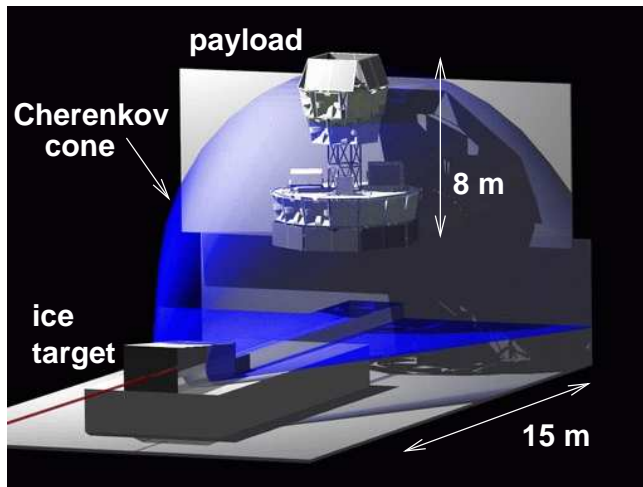
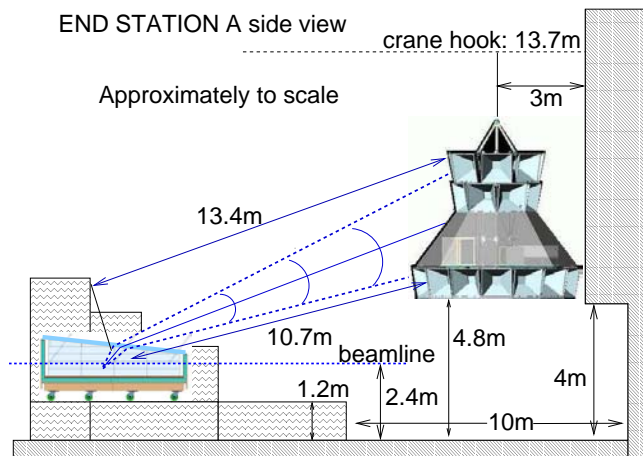


FIG. 1: Top: Side view schematic of the target and receiver arrangement in ESA. Bottom: Perspective view of the setup, showing the key elements.

Despite confirmation of Askaryan’s theory for sand and salt, there are important reasons to test it in ice as well, since so much study and experimental effort have been directed at ice as the target medium. First, although the effect is primarily determined by shower physics, the radio production and transmission occurs under conditions where the properties of the medium could play a role in modifying the behavior of the emission; the possibility of unknown media-dependent effects which might suppress the emission must be explored. Second, the radio Cherenkov method is most effective at shower energies above 10-100 PeV, where muon or other cosmic-ray backgrounds are negligible, and the method thus “suffers” from the virtue of having no natural backgrounds with which to calibrate the Cherenkov intensity and corresponding detection efficiency. In this context, laboratory calibrations of the radiation behavior are critical to the accuracy of results. And finally, the increased richness of these radio observations, which directly measure electric field strength and vector polarization, require more comprehensive experimental treatment

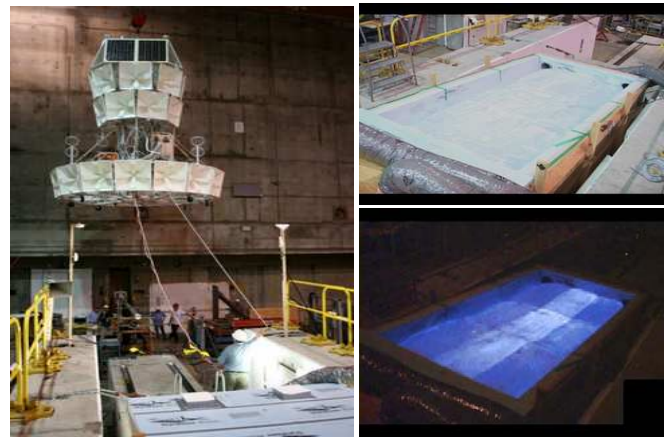


FIG. 2: (color online) Left: The ANITA payload (center) above and downstream of the ice target (here covered). Right top, target with cover removed, in ambient light. Right bottom: ice target illuminated from interior scattered optical Cherenkov radiation.

and validation than observations of scalar intensity.

The experiment, SLAC T486, was performed in the End Station A (ESA) facility during the period from June 19-24, 2006. A target of very pure carving-grade ice was constructed from close-packing rectangular 136 kg blocks (about 55 were used) to form a stack approximately 2 m wide by 1.5m tall (at the beam entrance) by 5 m long. The upper surface of the ice was carved to a slope of $\sim 8^\circ$ in the forward direction giving the block a trapezoidal longitudinal cross section along the beam axis. This was done to avoid total-internal reflection (TIR), of the emerging Cherenkov radiation at the surface. The surface after carving was measured to have a root-mean-square (rms) roughness of 2.3 cm. The beam entered this target about 40 cm above the target floor, which was lined with 10 cm ferrite tiles to suppress reflections off the bottom.

The showers were produced by 28.5 GeV electrons in 10 picosecond bunches of typically 10^9 particles. Monte-Carlo simulations of the showers indicate that about 90% of the shower was contained in the target; the remainder was dumped into a pair of downstream concrete blocks. In contrast to previous experiments [5, 12], we did not convert the electrons to photons via a bremsstrahlung radiator. Such methods were used in earlier Askaryan discovery experiments to avoid any initial excess charge in the shower development. In our case, the typical shower had a total composite energy of 3×10^{19} eV, with a total of $\sim 2 \times 10^{10}$ e^+e^- pairs at shower maximum. EGS simulations of the charge excess development indicate a net charge asymmetry of about 20%. Thus the initial electrons contribute at most $\sim 15\%$ of the total negative charge excess in the shower, and we have corrected for this bias in the results we show here. In addition, radio absorbing foam was in place on the front face of the ice, and very effectively suppressed RF signals from the upstream metal beam vacuum windows and air gaps.

A schematic of the experiment layout is shown in Fig. 1.

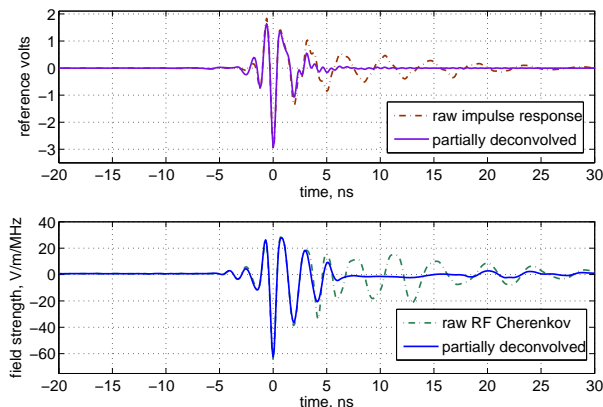


FIG. 3: Top: Raw, and partially-deconvolved impulse response of the ANITA receiver system. Bottom: Pulse received during the T486 experiment in an upper-ring antenna near the peak of the Cherenkov cone, also showing the raw pulse, and partially partially-deconvolved response. The apparent “ringing” artifact of the raw impulses is due to group delay variation of the passband edges of the bandpass filters employed.

The ice was contained in a 10 cm thick insulating foam-lined box, and a 10 cm foam lid was used during operation, along with a freezer unit, to maintain temperatures of between -5 to -20 C. Such temperatures are adequate to avoid significant RF absorption over the several m pathlengths of the radiation through the ice [9].

The ANITA payload, consisting of an array of 32 dual-polarization quad-ridged horn antennas was used to receive the emission at a location about 15 m away from the center of the target, as shown in Fig. 2. The antenna frequency range is from 200-1200 MHz, which covers the majority of the frequency range over which the RF transmissivity of ice is at its highest [9]. Eight additional vertically polarized broadband monitor antennas (four bicones and four discones) are used to complement the suite of horn antennas. The ANITA horn antennas are arranged so that adjacent antennas in both the lower and upper payload sections respond well even to a signal directed along their nearest neighbors’ boresights. This allows multiple antennas (typically 4 to 6 horns and 3 to 4 of the bicone/discones) to sample the arriving wavefront. The signals are digitized by custom compact-PCI-based 8-channel digitizer modules [22], 9 of which are used to record all 72 antenna signals simultaneously at 2.6 Gsamples/sec.

Figure 3 shows an example of the impulse response of the system (top), and one of the measured waveforms near the peak of the Cherenkov cone. The apparent “ringing” of the receiving system is due to the group delay of the edge response of the bandpass filters, but most of the energy arrives within a fraction of a nanosecond, as determined in previous measurements of the Askaryan effect [7]. In the measured T486 waveform of Fig. 3 (bottom), later-time reflections from shielding and railing near the target, as well as the payload structure, introduce some additional power into the pulse tail.

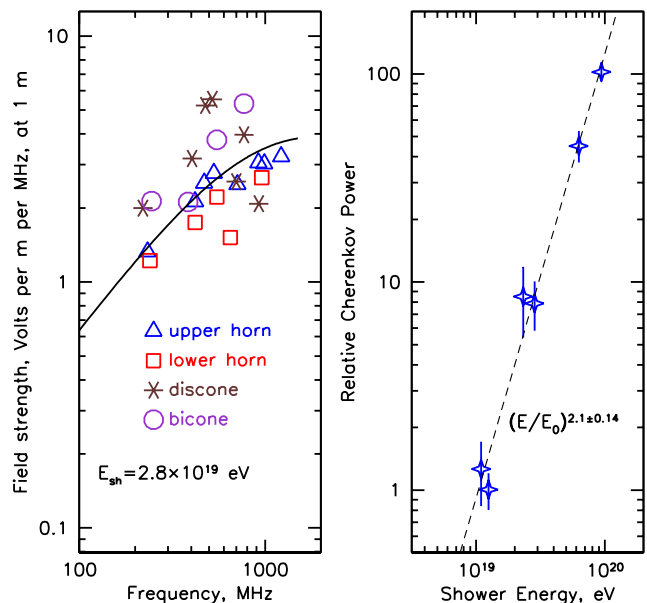


FIG. 4: Left: Field strength vs. frequency of radio Cherenkov radiation in the T486 experiment. The curve is the theoretical expectation for a shower in ice at this energy. Right: Quadratic dependence of the pulse power of the radiation detected in T486, indicating the coherence of the Cherenkov emission.

In Figure 4 (left) we display measurements of the absolute field strength in several different antennas, both upper and lower quad-ridged horns, bicone, and discone antennas. The discone and bicone antennas have a nearly omnidirectional response and complement the highly directive horns by providing pulse-phase interferometry. The uncertainty in these data are dominated by systematic, rather than statistical errors, and are about $\pm 40\%$ in field strength (± 3 dB). These are dominated by a combination of the 1-2dB uncertainty in the gain calibration of the antennas, and by comparable uncertainties in removing secondary reflections from the measured impulse power. The field strengths are compared to a parameterization based on shower+electrodynamics simulations for ice [10, 11], and the agreement is well within our experimental errors. Figure 4(right) shows results of the scaling of the pulse power with shower energy. The dependence is completely consistent with quadratic scaling over the energy range we probed, indicating that the radiation is coherent over the 200-1200 MHz frequency window.

Figure 5 shows the measured and predicted angular dependence of the radiation. The Cherenkov cone refracts into the forward direction out of the ice, and is clearly delineated by the data. Here we show statistical+systematic errors within a measurement run; the overall normalization (with separate systematic error) is taken from Fig. 4. We scale these data within the overall systematic errors to match the peak of the field strength. The radiation frequency limit where full coherence obtains is given approximately by the requirement that $kL \gg 1$, where the wavenumber $k = 2\pi\nu/c$ for frequency

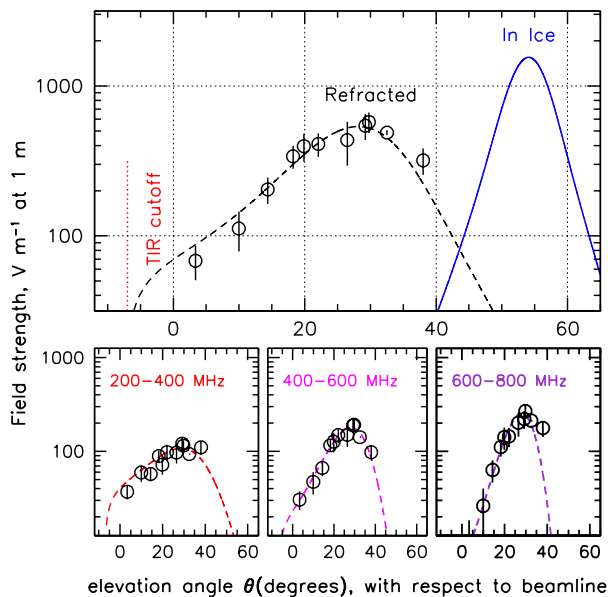


FIG. 5: Top: Angular dependence of the radiation for both the in-ice and refracted case, for a frequency range from 200-800MHz, compared to data. The data errors are combined statistical and systematic, but with an overall normalization that arbitrary here (but see Fig. 4 for the normalization factor). The in-ice and refracted curves are the theoretical expectation for a shower in ice at a beam current of 10^9 e^- per bunch and 28.5 GeV electrons, and the refraction includes only geometric optics. Bottom: Same as top for three different sub-frequency bands.

v and index of refraction n . In this regime, the Cherenkov

field strength ($V m^{-1} Hz^{-1}$) can be approximated as [21]: $|RE(v)| = \sqrt{2\pi} \mu\mu_0 QLv \sin\theta \exp[-(kL)^2(\cos\theta - 1/n)^2/2]$ where for typical dielectrics $\mu = 1$, $\mu_0 = 4\pi \times 10^{-7}$ is the permeability of free space, L is the parameter determined from the Gaussian fit of $q(z) = Q \exp(-(z - z_{max})^2/2L^2)$ to the shower profile with maximum at z_{max} , θ is the polar angle around the shower axis, and R is the distance to the shower. For T486, $L \sim 1.2$ m. The measured angular dependence thus follows closely the expectations for Cherenkov radiation, including the narrowing of the Cherenkov cone with higher frequencies. These results further strengthen the identification of its origin. We also measured the vector E-field polarization of the impulses and found it to be entirely consistent with 100% linear polarization in the plane containing the Poynting vector and shower momentum vectors, again completely consistent with radio Cherenkov theory.

In summary, Askaryan's hypothesis has now been confirmed in detail by laboratory experiments for virtually all of the dielectrics (ice, salt, sand—the latter approximating the Lunar regolith) that Askaryan envisioned as the best media in which to exploit the coherent radio Cherenkov emission from high energy particle showers. Askaryan's intent was to illuminate a methodology by which low fluxes of ultra-high energy particles could be made observable through exploitation of huge volumes of natural materials. With the recent sharpening of predictions for the fluxes of ultra-high energy neutrinos, and the growth in the number of experiments that make use of it, we expect that Askaryan's hope will be soon fulfilled.

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