At the AMANDA South Pole site, four new holes were drilled to depths 2050 m to 2180 m and instrumented with 86 photomultipliers (PMTs) at depths 1520-2000 m. Of these PMTs 79 are working, with 4-ns timing resolution and noise rates 300 to 600 Hz. Various diagnostic devices were deployed and are working. An observed factor 60 increase in scattering length and a sharpening of the distribution of arrival times of laser pulses relative to measurements at 800-1000 m showed that bubbles are absent below 1500 m. Absorption lengths are 100 to 150 m at wavelengths in the blue and UV to 337 nm. Muon coincidences are seen between the SPASE air shower array and the AMANDA PMTs at 800-1000 m and 1500-1900 m. The muon track rate is 30 Hz for 8-fold triggers and 10 Hz for 10-fold triggers. The present array is the nucleus for a future expanded array.

---

\(^a\)E-mail: Hulth@physto.se

\(^b\)At Bartol Research Institute, University of Delaware, Newark, Delaware

\(^c\)At Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
1 Introduction

The deep Antarctic ice is the purest, most transparent of all natural solids. As a site for a high-energy neutrino observatory it has a number of advantages compared to deep sea water. It consists of compressed pure-H$_2$O snow with the lowest contamination by aerosols and volcanic dust of any place on Earth, and it contains neither bioluminescent organisms nor radioactive $^{40}$K. Before the AMANDA collaboration began to measure the optical properties of ice at the South Pole, one could have listed a number of potential drawbacks: No one had ever drilled a hole deeper than 349 m at South Pole; the depth at which air bubbles completely transform into solid crystals of air hydrate clathrate was not known; the absorption length of light in ice was thought to be shorter than in sea water and the effects of dust, traces of marine salt, traces of natural acids, and birefringence of polycrystalline ice on scattering of light in ice at South Pole had not been studied. These issues have now been addressed.

2 Results from the AMANDA-A Array at 800 m to 1000 m

The successful deployment of the four-string AMANDA-A array with photomultipliers (PMTs) was the first step toward demonstrating that the South Pole ice is a suitable site for a high-energy neutrino observatory. With a hot-water drill, four holes 60 cm in diameter were created during the 1993-94 season and instrumented with 80 PMTs spaced at 10-m intervals from 810-1000 m. To measure optical properties, a laser in a laboratory at the surface above the holes was used to send nanosecond pulses down any of 80 optical fibers to emitting balls located near each PMT. From the distributions of arrival times at neighboring PMTs, it was possible to determine separately the absorption length $\lambda_a$ and effective scattering length, $\lambda_s = \lambda_a/(1 - <\cos \theta>)$, at wavelengths from 410 to 610 nm. Here $<\cos \theta>$ is the mean cosine of the scattering angle. Because $\lambda_s \ll \lambda_a$ the data fitted an expression for three-dimensional diffusion with absorption. In contrast to laboratory ice, for which $\lambda_a$ was reported to be $<25$ m at all wavelengths and $\lambda_a = 8$ m at the wavelength for maximum quantum efficiency of a PMT, we found values of $\lambda_a$ exceeding 100 m at wavelengths less than 480 nm and values exceeding 200 m at wavelengths less than about 420 m. We found that, independent of wavelength, $\lambda_s$ increased monotonically from 40 cm at 820 m to 80 cm at 1000 m. We interpreted this result as evidence for scattering by air bubbles with size much larger than the wavelength of light, with the size and number density of bubbles decreasing with depth.
3 Technical Aspects of the AMANDA-B 1995-96 Drilling Season

New drilling equipment, operating at a power of 1.9 MW, used water emerging at 75°C to drill at a rate up to 1 cm/s. It required a time of no more than 4 days to melt a 60-cm-diameter cylinder of ice to a depth of 2000 m. Due to a late start and several problems associated with commissioning the new equipment, only four holes were drilled, of which one reached a depth of 2180 m. It took typically 8 hours to remove the drill and water-recycling pump from a completed hole. The rate of refreeze was 6 cm decrease in diameter per day, which easily allowed time to mount PMTs and other devices on cables, to lower the cables, and to route the upper ends of the cables into the AMANDA building in time to monitor the entire refreezing process. The diagnostic devices included four inclinometers to measure shear vs time, ther-
misters to measure temperature vs depth, and pressure gauges to follow the refreezing. The measurements of temperature at three depths, together with previous measurements, confirmed the validity of a model of temperature vs depth. At the greatest depth, the temperature of the ice was -31 C, about 20 degrees warmer than at the surface. Of the 80 PMTs on the coaxial cables 73 survived the deployment and refreezing, and all of the 6 PMTs in the bottom 100 m of a prototype twisted-pair cable are working. With a total of 152 operating PMTs, the overall success rate is greater than 90% for phototube deployment on AMANDA-A and B. No PMTs have failed since refreezing of the ice. The mean time to failure is inferred to be >200 years per PMT. With no local amplification, the analog signals are preserved, though broadened, in transmission along a 2-km coaxial cable, with a standard deviation of better than 4 ns in timing resolution. Of this, 2.5 ns is due to the resolution of the optical fiber itself. The noise rates of the 8-inch Hamamatsu PMTs are in the remarkably low range of 350 Hz to 600 Hz. The twisted-pair cable has a significantly shorter rise time than the coaxial cable and requires front-end amplifier gains of only 30 instead of 100. A great advantage of the twisted-pair cable is that a single cable can supply 36 PMTs instead of only 20. At the surface, the new ADCs and new amplifiers are working as well as hoped. A newly installed trigger logic to search for gamma-ray bursts and supernovas at timescales of milliseconds and seconds is operating with 64 optical modules at 0.8 km to 1 km depth and with 79 optical modules at 1.5 km to 2.0 km. Data are being taken by our Bartol colleagues with two radio receivers at depths of 150 m and 280 m, their aim being an initial evaluation of a method of detecting Cherenkov radiation at radio frequencies by ultrahigh energy cascades in the ice. The YAG laser in the surface laboratory provides tunable pulses at 410 to 610 nm with only 10 dB loss down the optical fibers. A pulsed nitrogen laser (337 nm) at a depth of 1820 m, held at a temperature of plus 24 C, is operating flawlessly. Pulsed blue LED beacons with filters for 450 and 380 nm emission are operating at various depths. DC lamps at 350 nm, 380 nm, and broadband are also operating.

4 Physics Results

4.1 Ice properties at 1500 - 2000 m

The burning issue – whether the bubbles are still present at depths 1500 m to 2000 m – is now settled. Preliminary analysis show $\lambda_e$ in the range 25-30 m which is two orders of magnitude greater than at 800-1000 m. The value of $\lambda_e$ shows no strong dependence on wavelength nor on depth. Because $\lambda_e$ is comparable to the spacing between neighboring optical modules, many
of the photons from one emitter have undergone zero or few scatters before reaching a PMT. Thus, the analytic expression for diffusion with absorption is inapplicable (because the photons are not in the diffusion regime). Our present approach is to use Monte Carlo modeling and statistical techniques to find the best values of $\lambda_a$ and $\lambda_e$ for each combination of emitter, receiver, and wavelength. The large absorption length of ice in the blue and UV wavelength regimes is confirmed by the AMANDA-B data. At 337 nm, $\lambda_a$ is of order 100 m, which is astonishing in view of the fact that $\lambda_a$ is only a few meters for lake water and ocean water, and was reported to be only 5 m for laboratory ice. At wavelengths in the blue, values of $\lambda_a$ significantly longer than 100 m are being inferred from the data. Comparison of the data on $\lambda_a$ at 1500 m to 2000 m with data at wavelengths 410 nm to 610 nm and at depths 810 m to 1000 m suggests that the concentration of absorbing dust is greater at the greater depths. This is consistent with our observation that, at short wavelengths where $\lambda_a$ is most sensitive to dust, $\lambda_a$ is constant at depths 800-900 m and decreases at depths 900-1000 m. Our interpretation is that the ice at 800-900 m was formed in the post-glacial Holocene period ($<13,000$ years BP) where the dust concentration has been remarkably low, and that the ice at 900-1000 m was formed near the end of the most recent ice age, with a peak in the dust concentration 17,000 years BP. Despite the larger concentration of dust at 1500-2000 m, the absorption lengths and scattering lengths are acceptably long, allowing us to move forward with plans for an extension of the AMANDA array.

4.2 Data taking

We are now continuously taking data with AMANDA-A and AMANDA-B. The rate in AMANDA-B is 30 Hz for 8 triggers (at least 8 PMTs) within 2 microseconds, and is 10 Hz for 10 triggers. Coincidences of tracks of energetic muons between the surface SPASE array, AMANDA-A, and AMANDA-B is also registered. We are presently studying pattern recognition and muon track reconstruction, with the goal of finding upward-going neutrino candidates. The long tails of the timing distributions for muon tracks can be greatly narrowed by cutting on two photoelectrons (p.e.), leading to much longer effective scattering lengths than the 25-30 m values measured for single p.e. signals.

In addition to the muon triggers both AMANDA-A and AMANDA-B are sampling the total PMT noise rate. The low counting rate of all PMTs could e.g. be increased by Cerenkov light from interactions of low energy (few MeV) neutrinos from stellar collapses. A stellar collapse, similar to SN1987A and at 8kpc distance, would yield about 100 counts per PMT in AMANDA-B. This
is large enough to already regard AMANDA-B with its only 86 PMTs as a
detector for neutrinos from supernovae up to the center of our galaxy.

5 Conclusions and future

By any measure the 1995-96 AMANDA expedition has been a great success.
The large values of $\lambda_a$ mean that experiments that require large transparent
volumes without the need for tracking are already very effective. These include
searches for neutrinos accompanying gamma-ray bursts and accompanying super-
nova explosions. The values of $\lambda_e$ of 25 m to 30 m are acceptably long,
provided the spacing of PMTs is optimized. We are now preparing 6 new
strings to be deployed during 96/97 in the AMANDA-B detector. By chang-
ing to twisted pair cables for transmitting the PMT signals to surface we are
able to have 36 optical modules per string. We are also going to test an analog
optical transmission of the PMT signals over optical fibers allowing the "true"
PMT signal at surface.

Acknowledgments

We are indebted to the Polar Ice Coring Office and to Bruce Koci for the
successful drilling operations, and to the National Science Foundation (USA),
the Swedish National Research Council, the K. A. Wallenberg Foundation and
the Swedish Polar Research Secretariat.

References

1. T. C. Grenfell and D. K. Perovich, J. Geophys. Res. 86 (1981) 7447
2. D. K. Perovich and J. W. Govoni, Geophys. Res. Lett. 18 (1991) 1233.
3. See papers by P. C. Mock et al. and by L. Gray et al. in Proc. 24th
   Intern. Cosmic Ray Conf., Rome, (1995).
4. P. Askebjer et al. Science 267 (1995) 1147.
5. P. Askebjer et al., Wavelength Dependence of Light Scattering and Ab-
sorption in Deep Ice at the South Pole, submitted to J. Geophys. Res.
6. AMANDA Collaboration, Optical Properties of Deep Ice at the South
   Pole: Absorption, to be submitted to Applied Optics.
7. P. B. Price, Science 267 (1995) 1802.
8. AMANDA Collaboration, J. Glaciology 41 (1995) 445.