Center for Astrophysical Research in Antarctica

First data and future prospects for AMANDA, the antarctic muon and neutrino detector

THE AMANDA COLLABORATION: P. ASKEBJER, S. BARWICK, L. BERGSTRÖM, A. BOUCHTA, S. CARIUS, K. ENGEL, B. ERLANDSSON, A. GOOBAR, L. GRAY, A. HALLGREN, F. HALZEN, P.O. HULTH, J. JACOBSEN, S. JOHANSSON, V. KANDHADAI, I. LIUBARSKY, D. LOWDER, T. MILLER, P. MOCK, R. MORSE, R. PORRATA, P.B. PRICE, A. RICHARDS, H. RUBINSTEIN, Q. SUN, S. TILAV, C. WALCK, *and* G. YODH

Correspondence to: P.B. PRICE, *Department of Physics, University of California, Berkeley, California 94720*

The AMANDA high-energy neutrino observatory will address fundamental questions in astronomy and particle physics. AMANDA can search for the sources of the highest energy cosmic rays and for dark matter; it can address the question of whether neutrinos have mass; and it can look for entirely unanticipated phenomena. In contrast to high-energy photons, which are absorbed by matter, high-energy neutrinos can help scientists do a tomographic study of such objects as active galactic nuclei and even our Earth's core.

To accomplish these goals, one needs an observatory that can be scaled up to about 1 cubic kilometer (km^3). All designs share the same idea: a three-dimensional array of large phototubes embedded in a transparent medium to look down—through the Earth—at the Cherenkov light emitted by an upward-moving muon. (High-energy neutrinos are transformed into muons as they pass upward through the Earth.) By measuring arrival times of Cherenkov photons at various phototubes, researchers can reconstruct the direction of the neutrino. In contrast to other concepts, which would locate the observatory in a deep lake or the deep ocean, AMANDA's design puts all electronics on the surface above short cables that simply carry signals up from the phototubes, and the medium (ice) is truly dark and free of radioactivity.

Technology

Using hot-water drilling, we succeeded in producing four holes 1 km deep and 60 centimeters (cm) in diameter. It took about four days and 11,000 liters of fuel per hole. We lost 3 out of 80 modules during deployment, and 4 modules are operating less than perfectly. As we gained experience, we succeeded in deploying the last two strings with the loss of only a single module. The 73 perfect modules have been operating at the single-photoelectron level since January 1994. We set up a calibration system consisting of a laser at the surface that can send pulses along fiber-optic cables into nylon diffuser balls, one positioned 30 cm below each module. Before filtering, 40 megabytes of data are collected every hour at a trigger rate of 22 hertz (Hz). The data sent back in real time via satellite consist of 10 megabytes per day now and 50 megabytes per day in the future.

Measuring properties of deep ice

Using the laser calibration system, we made detailed measurements of *in situ* ice (AMANDA collaboration in press). Pulses of 500-nanometer (nm) light are sent down the optic fibers to the nylon spheres, which radiate light isotropically. By measuring the relative timing of signals received by the various phototubes, which have a time resolution of 2 nanoseconds, we were able to determine the optical properties of the ice and to derive accurately the positions of the tubes. As figure 1 shows, the timing data are well described by a random walk model that includes absorption of the light in the ice and scattering on residual bubbles. From data such as that in figure 1, we obtain a value of 59±3 for the absorption length of 500-nm light in the ice itself. Figure 2 shows how the reciprocal of the scattering length ($\lambda^{-1} = n\sigma$ = concentration × cross section) decreases with depth. As figure 2*A* shows, our data are consistent with values of scattering length inferred from deep cores from Vostok and Byrd. Extrapolation of our data using a kinetic model (Price in press) indicates that bubbles should disappear at a depth of approximately 1,400 meters (m).

Status of muon reconstruction

In the presence of bubbles, the AMANDA detector operates like a drift chamber instead of like a Cherenkov detector. The light pattern of a muon is that of an isotropic light source traveling through the ice with speed *c*/*n* (where *c* is the speed of light and *n* is the refractive index of light in ice). With modifications of the analysis procedure, we find that approximately 90 percent of the muon trajectories can be reconstructed well enough to obtain their zenith angle distribution. Early

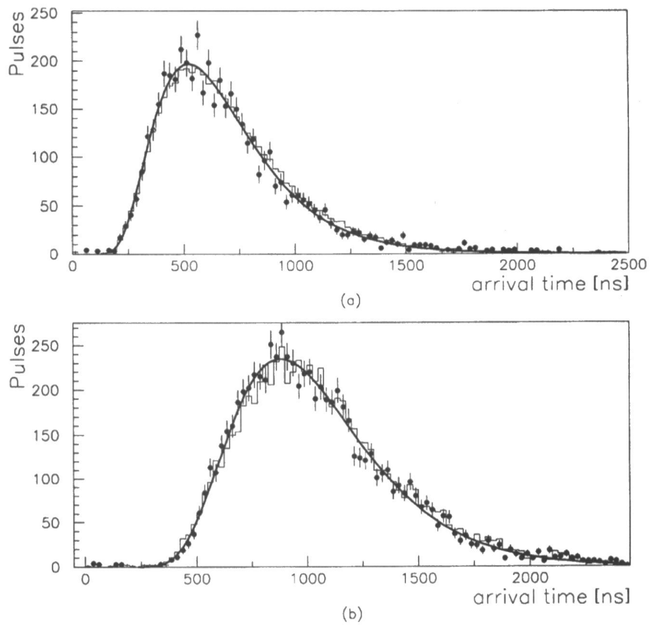

Figure 1. Time distribution of laser light as detected by an optical module after traveling (a) 21 m and (b) 32 m. The data on light propagation are reproduced by a Monte Carlo which includes absorption and scattering on residual bubbles. (ns denotes nanoseconds.)

results, shown in figure 3, encourage us to believe that most muon trajectories can be determined fairly well even in the presence of bubbles.

Triggers on SPASE–AMANDA coincidences

We observe coincidences with the South Pole air shower experiment (SPASE) array situated on the ice surface at a zenith angle of approximately 45° with respect to AMANDA. The surprisingly large rate of coincidences (more than 100 per day for a tenfold trigger) indicated that the strings detected downward muons at larger distances than expected for bubble-free ice. The four-string AMANDA is by far the largest muon detector ever built. Using such coincidence data, we and our SPASE collaborators hope to make progress in resolving the question of the cosmic-ray composition in the region of the "knee" at approximately 10^{16} electronvolts in the primary energy spectrum. The method exploits the fact that high-energy heavy nuclei produce more muons than do protons.

Will deeper ice be suitable as a muon detector?

The quality of the image of a muon's trajectory is limited both by scattering from dust and bubbles and by refraction at boundaries between ice crystals and at boundaries between crystals of air hydrate (into which bubbles convert at great depths) and normal ice crystals. At 1,500 m all bubbles should have undergone a phase transition to air hydrate crystals. Fortunately, the refractive index of the hydrate phase relative to that of pure ice is approximately 1.004, which is so close to unity that the lateral deflection of Cherenkov photons refracting at boundaries between the two phases will be negligibly small. Thus, air hydrate crystals have virtually no effect on the imaging of muon trajectories. The same conclusion applies to refraction at boundaries between randomly oriented normal ice crystals.

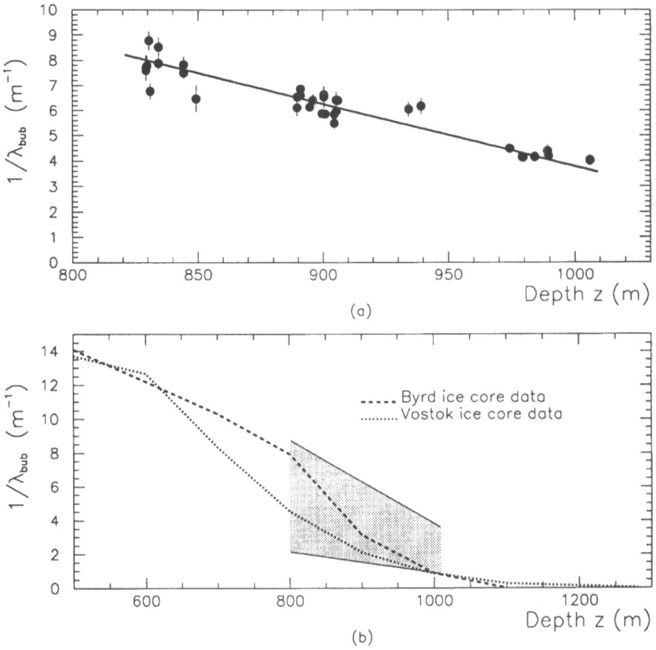

Figure 2. *A.* The inverse scattering length on residual bubbles as a function of depth. By linear extrapolation the inverse scattering length vanishes at a depth of 1,100 m. *B.* Comparison of the bubble density inferred from the laser data (AMANDA collaboration in press) with the density measured in cores at Vostok and Byrd Station.

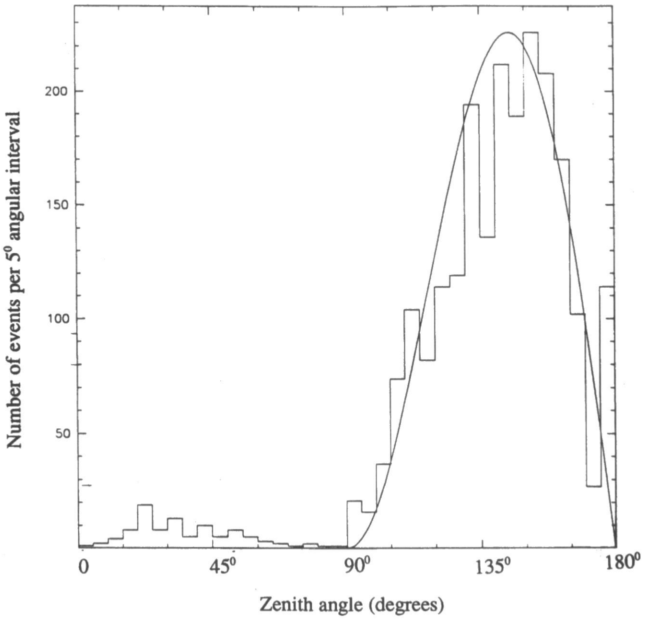

Figure 3. First-pass reconstruction of cosmic-ray muon triggers (histogram) compared with the Monte Carlo (MC) expectation (curve).

Measurements of size distributions and of light scattering (Royer, DeAngelis, and Petit 1983) from dust as a function of depth in ice cores have shown that the dust concentration is 1 to 2 orders of magnitude higher during an ice age than during interglacial periods. Using an iceflow model to estimate age vs. depth, we conclude that major peaks in the dust concentration in South Pole ice occur at approximately 1,000 m and approximately 2,600 m. We estimate that the scattering length for dust at 1,500 m will be about 20 m and will not significantly distort trajectories of Cherenkov photons.

Future plans

Knowing that the absorption length is approximately 60 m instead of 25 m, we will increase the dimensions of the remaining portion of AMANDA so as to measure trajectories more accurately and improve up-down discrimination. During the next drilling season, we will drill six holes to depths of approximately 1,700 m and with lateral spacings between holes of 50 to 60 m instead of 30 m. Each string will contain 13 optical modules with a vertical spacing of 20 m. The effective volume of the pentagonal cylinder plus central string will be approximately 10^7 cubic meters, nearly an order of magnitude larger than that in the original plan. With the larger spacing, the threshold for muon detection will be a factor of approximately 5 higher than for the compact design.

Achieving a volume of 1 km^3 in South Pole ice now appears feasible. The optimal vertical size and depth of this future observatory will depend on drilling economics, attenuation in cables, and depth of disappearance of bubbles. One attractive scheme for the horizontal configuration is to surround a central AMANDA six-string "supermodule" with two concentric rings of identical supermodules at radial distances of 250 and 500 m from the central supermodule. With an increase of the string length from 200 to 800 m, the total number of phototubes will be 4,590, and the effective volume will be approximately 1 km^3. A rough estimate of the total cost for the 90 holes, equipment, and deployment, is $50 million.

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South Pole air shower experiment

PAUL EVENSON, T.K. GAISSER, DANIELE MARTELLO, TIM MILLER, JOHN PETRAKIS, *and* TODOR STANEV, *Bartol Research Institute, University of Delaware, Newark, Delaware 19716*
JOHN BEAMAN, SIMON HART, JEREMY LLOYD-EVANS, PAUL OGDEN, *and* A.A. WATSON, *Department of Physics, University of Leeds, Leeds LS2 9JT, United Kingdom*

Since February 1994 the South Pole air shower experiment (SPASE) (Beaman et al. 1993) has been running in coincidence with four strings of the antarctic muon and neutrino detector array (AMANDA) experiment (Lowder et al. 1993; Miller 1993) that were deployed during the 1993–1994 austral summer. The air shower array consists of 16 scintillator detectors, each of 1-square-meter area, on a triangular grid with 30-meter (m) spacing. In addition, there are eight guard ring detectors on an approximately 80-m radius, which are similar in size and construction, except that they lack the fast-timing capability of the central detectors. When the surface array is triggered by a cosmic-ray cascade in the atmosphere, a signal is transmitted some 800 m over a cable to alert the electronics in the AMANDA central station to read out its data. The AMANDA data for each event consist of a list of tubes that fired during the 8-microsecond window opened by the SPASE trigger together with the time and duration of the signal in each of the 73 operating AMANDA phototube modules that fired. Each AMANDA string has 20 phototube modules at 10-m intervals from 800 to 1,000 m below the surface of the polar ice cap.

The coincident events are caused by atmospheric cascades generated when an ultra-high-energy cosmic-ray particle (proton or heavier ionized nucleus with energy more than several times 10^{13} electronvolts) interacts high in the atmosphere. The surface array responds primarily to the many electrons and positrons in the shower front; the shower front propagates somewhat like a 1-m thick pancake through the atmosphere nearly at the speed of light. The shower front is perpendicular to the direction of the incident cosmic ray, and that direction is reconstructed from the timing pattern of the SPASE detectors. The electrons and positrons are absorbed by a few meters of snow, but the core of the shower, which consists of energetic mu-mesons, penetrates deep into the ice. If the shower is pointing toward the under-ice AMANDA detector, those muons should be seen by the AMANDA phototubes.

The figure shows data taken by Simon Hart and Tim Miller during 2 days of testing in February at South Pole. The first panel shows essentially all events. These are mostly accidentals—random noise in one or two modules within the time window opened by the SPASE trigger. Since most showers that trigger the surface air shower array do not point toward AMANDA, we do not expect to see a true coincidence most of the time. The second and third panels show the angular distribution of events in which more than 2 and more than 5 modules in AMANDA fired during the window opened by SPASE. The peak around the aziumthal angle of 120° (the direction from