by JOHN LEARNED & MICHAEL RIORDAN

In Water or Ice?

Physicists are building four huge particle-detector arrays to do high energy neutrino astronomy.

THE GHOSTLIEST of elementary particles, neutrinos have fascinated particle physicists for half a century and become the objects of intense research these past few decades. Because they interact very weakly with matter, these “little neutral ones” also provide scientists a unique way to peer inside stars and supernovae. Thermonuclear processes occurring within the cores of these celestial objects generate profuse streams of energetic neutrinos that easily penetrate the outer layers and travel enormous distances, to be recorded here on Earth by huge underground detectors.

Now, after twenty years of development, neutrino astronomy is about to forge on to its next great challenge: the study of high energy neutrinos from cosmological sources *outside* the Milky Way. In four corners of the globe, four teams of physicists are racing to build the first full-fledged high energy neutrino telescopes. And in a remarkable example of international scientific cooperation, these teams are collaborating with one another and with other interested groups on the design of a truly gargantuan neutrino telescope—encompassing a cubic kilometer in total volume—that they hope to complete by early in the following millennium.

THE ASTROPHYSICAL neutrinos observed thus far by underground detectors arrived at the Earth with energies of roughly a million electron volts (1 MeV) or more. Much lower than this and they become essentially impossible to detect—although they are perhaps the most plentiful particles in Nature, even more common than photons. Physicists have good reason to believe that every single cubic centimeter of the Universe contains over six hundred neutrinos. With an exceedingly tiny mass equivalent to just a few electron volts, these ubiquitous spooks would constitute the dominant portion of all the matter in the Universe, its much sought-after "dark matter" or "missing mass."

The observation of MeV neutrinos has allowed astrophysicists to examine the physical processes responsible for stellar burning and supernovae explosions. By determining the intensities and energies of the neutrinos spewing forth from these objects, we have in essence been able to measure their internal temperatures. And discrepancies between the predicted and observed fluxes of solar neutrinos arriving at the Earth's surface strongly suggest that we may be witnessing the results of new and fundamentally different physics. (See "What Have We Learned About Solar Neutrinos?" by John Bahcall, in the Fall/Winter 1994 *Beam Line*, Vol. 24, No. 3.)

For at least 20 years, however, many physicists have recognized that the best place to do neutrino astronomy is at extremely high energies over a trillion electron volts (1 TeV)—the realm of Fermilab energies and beyond (see box on next page). Because the probability of a neutrino's interacting grows in proportion to its energy, so does the ease with which we can detect it and determine where it came from. Thus, for neutrino astronomers TeV energies are truly the experimenters' dream.

They are also the astrophysicists' and cosmologists' dream, too, for TeV neutrinos give us the only practical way to observe physical processes occurring at the very center of galaxies—particularly the active galactic nuclei (AGN's) that have lately become a hot research topic. Nowadays many scientists suspect that the variety of highly energetic cosmic beasts distinguished by their various peculiar radiations are all in fact just different manifestations of a galaxy with an AGN, viewed in various perspectives and at various times in its evolution. Most believe that these AGN's are the sites of galaxy-class black holes a million to a billion times as massive as the Sun; they swallow up stars, gas and dust while belching back perhaps 10 percent of their feast in wildly transformed ways. Such a tiny, massive object was recently shown to exist at the core of the elliptical galaxy M87, which is practically in our own cosmological backyard.

According to one recent scenario, there is a standing shock wave outside the event horizon of the black hole, a bit like the standing waves in a river that delight white water enthusiasts. Infalling matter carries magnetic fields, which are drastically compressed and intensified by the tremendous force of gravity when the matter slams into this shock wave. Charged particles are accelerated to high energies as they ricochet back and forth between magnetized regions, like a ping pong ball between a pair of converging paddles. Energetic pions created in this process rapidly decay into pairs of gamma rays or into muons and neutrinos. The gamma rays initiate particle showers and generate a hellish photon cloud from which only the neutrinos can easily escape, streaming away with perhaps half the total energy emitted by this bizarre object.

This process can explain the intensities of X rays and ultraviolet radiation emitted by some AGN's, from which the flux of high energy neutrinos can then be inferred. A number of theorists have now estimated this flux; they agree that a significant (meaning measurable) flux exists up to about 1–10 PeV (1,000–10,000 TeV). Quite apart from the great interest in using such high energy neutrinos to observe AGN dynamics, the prospect of detecting them has naturally spurred particle physicists to build big neutrino telescopes. For the foreseeable future, we have no chance of producing such particles in earthbound accelerators.

Of course, this is only one particular model that may in fact be wrong. Over the decades we have dreamed of doing high energy neutrino astronomy, many promising models have come and gone. But the established existence of extremely high energy cosmic rays, with energies up to a hundred million TeV, means that TeV neutrinos must also be plentiful in the Universe. Given what we know about particle physics, it is inconceivable that such tremendous energy could be concentrated into photons and protons without a substantial amount of it spilling over into the neutrino sector.

There are a number of more "prosaic" sources of high energy neutrinos coming from within the Milky Way galaxy itself. One source is the shock waves generated by a supernova, in a mechanism analogous to that described above for AGN's. Another is the lighthouse-like particle beam thought to be emanating from its pulsar remnant. X-ray binaries—in which neutron stars blaze away, fueled by feeding off their companion stars—have also been suggested to be a potent neutrino source. Whatever the case, TeV neutrinos from our own galaxy are absolutely guaranteed. The existing flux of high energy cosmic rays, mostly protons wandering about the galaxy, trapped by its magnetic fields, will lead to collisions with dust and gas, generating neutrinos that come from the galactic plane. Observing these neutrinos may help us solve the still

Optimum Energies for Neutrino Astronomy

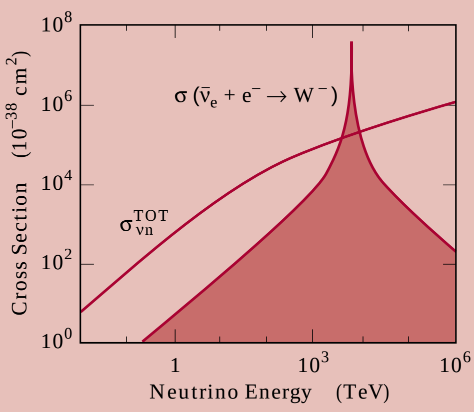
BECAUSE THEIR DETECTABILITY improves steeply with energy, neutrinos of TeV energies and above have long been viewed as the natural starting point for neutrino astronomy. But since the flux of neutrinos falls off with energy, an optimum must exist.

Factors favoring higher energies include the increasing neutrino cross section (their probability of interacting with matter); the increasing range of the muons produced in these interactions (which means the sensitive volume of a detector grows with energy); the decreasing angle between such a muon and its parent neutrino (and thus the point source direction, yielding better resolution); and the increasing signal-to-noise background ratio between astrophysical neutrinos and those produced in Earth's atmosphere.

The last factor is a bit speculative but has pretty good justification. These background neutrinos are produced by ordinary charged cosmic rays interacting with air molecules. As the energy increases, a smaller and smaller fraction of the secondary particles produced in these collisions can decay into neutrinos before hitting the Earth. Such local, atmospheric neutrinos constitute the background against which point sources of astrophysical neutrinos must be resolved. Because the atmospheric neutrino spectrum is expected to fall off more steeply than those of many astrophysical neutrino sources, higher energies are clearly preferred.

While all of the above factors favor higher energies as something like E^4, they begin to saturate at a point that is typically in the energy region 1–10 TeV. This turns out to be the optimum range to begin doing neutrino astronomy.

The neutrino cross section is given as a function of energy in the graph. It spans a range from 0.01 TeV (10^{10} eV) to 10^6 TeV (10^{18} eV, or 1 EeV); the lower end of this range corresponds to the energies of neutrinos produced at earthbound particle accelerators, while the upper end approaches the highest energies so far encountered in cosmic rays. The shaded curve peaking at 6.4 PeV represents the cross section for the interaction of electron antineutrinos with atomic electrons, leading to the production of the W^- boson in what is known as the "Glashow resonance." Over the energy range from 4 to10 PeV, this striking process dominates all the other neutrino interactions. Because of this large cross section, such electron antineutrinos will not penetrate through the Earth; instead, they must be absorbed in such relatively short distances (depending on energy) as a few kilometers.



mysterious puzzle of the origin of cosmic rays.

A much more exotic potential source is the gamma-ray bursts recently found to populate the sky uniformly in all directions. If these weird objects are indeed occurring outside our galaxy, as most astronomers now believe, then a large fraction of a solar mass is being converted into energy in each event. The neutrino flux that some think must accompany these tremendous bursts of energy might well be seen by underground detectors now being built. Such an observation would of course help with understanding the nature of these enigmatic cosmic explosions.

Finally, big neutrino telescopes will be important aids in searching for a key component of dark matter—the vast halo of weakly interacting massive particles, or WIMPs, thought to cluster about the Milky Way and most other galaxies. Often thought to be supersymmetric particles left over from the Big Bang, these WIMPs should become concentrated inside the Earth's core and that of the Sun due to glancing collisions with atomic nuclei there. Occasionally a WIMP would encounter its antiparticle and annihilate it, however, producing a spasm of other particles. But only neutrinos can escape these core regions and reach our detectors, which would then record fluxes of high energy neutrinos coming from the centers of the Earth and Sun. The big neutrino telescopes now being built or contemplated will be sensitive to WIMP masses from 10 GeV to 1 TeV, covering essentially the entire range of masses expected for the lightest particles predicted by supersymmetric theories.

High energy neutrino astronomy can open a surprising new window on the Universe, with implications for distance scales from the largest to the smallest.

And with a large enough neutrino telescope, we can study inner space as well as outer space. By counting the flux of neutrinos and antineutrinos hitting the detector from different directions, one could measure their attenuation in the Earth and do "Earth tomography"—much like computer-aided tomography, or CAT scans, are done on people using X rays. With sufficient statistics, neutrino telescopes will be able to measure the density of the Earth's core, for example, a feat that is not possible by any other means.

The possibility of completely unanticipated discoveries is also a potent reason for building big neutrino telescopes. The history of astronomy has shown us time and again that the most important observations by a new kind of device were not even predicted when the first such instrument was being built. High energy neutrino astronomy can and almost surely will open a surprising new window on the Universe, with implications for distance scales from the largest to the smallest. It will bring us a grand sense of witnessing a new projection of the life that exists outside the murky cave in which we find ourselves.

SCIENTISTS WORKING on neutrino detection have realized for decades that the Cherenkov radiation generated by neutrino interaction products in water (and ice) provides an inexpensive way to build large-volume detectors. Charged particles speeding through transparent media at velocities near the speed of light throw a cone of blue light in the forward direction. Sensitive detectors can "see" these particles at distances on the order of 100 meters in deep, clear ocean water (which has a characteristic attenuation length of 50 m). Large photomultiplier tubes sensitive to this blue light are available for a few thousand dollars apiece. The typical cost of such a photosensor module (including electronics, cabling and housing) comes to about $10,000 each. As each module covers an effective area of 100 m2, the cost per square meter for such detectors is roughly $100—far cheaper than typical accelerator-based detectors (but at the cost of poorer resolution).

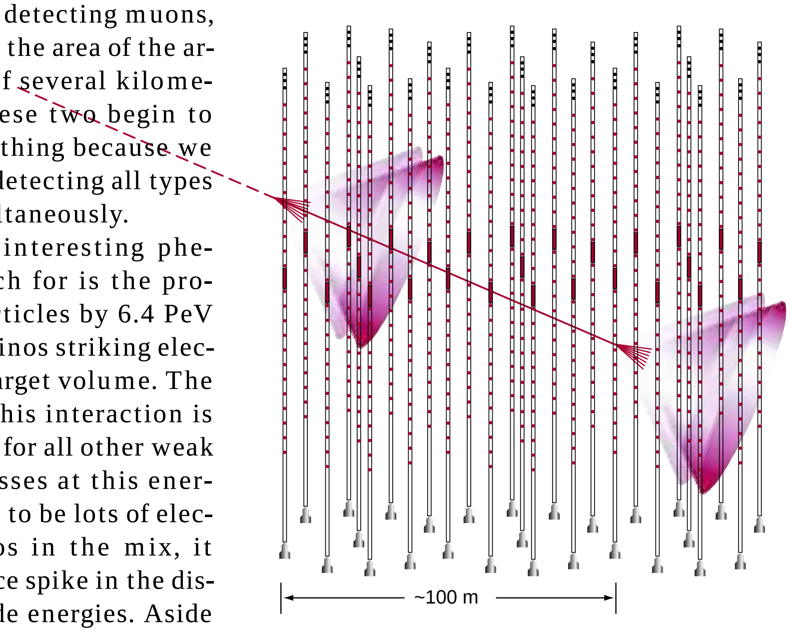
Whenever a muon neutrino (or antineutrino) interacts with an atomic nucleus by the exchange of a W particle, it produces a muon that carries off the bulk of the neutrino's energy. Because muons have a long lifetime and do not interact very strongly with matter, they can carry the news of neutrino collisions a very long way—*kilometers* in the case of very high energy neutrinos. A muon produced at PeV energies, for example, can travel 20 kilometers. It is no wonder that neutrino detectors currently under construction have focused upon muon detection in order to attain the large target volumes needed.

The precision with which we can measure the direction of the muon—and that of the neutrino producing it—will depend largely on how well we can determine the exact times at which its Cherenkov light strikes the individual modules. Fortunately, the latest generation of large-area photomultipliers has such good time resolution (a few nanoseconds) that we can expect to attain an angular resolution of about a degree for TeV muons that traverse the entire array. Neutrino telescopes will not be able to challenge optical or radio telescopes in this department, but their angular resolution improves gradually with energy. And statistical techniques can be used to refine our measurements still further, so that we may eventually be able to pinpoint a neutrino source to perhaps a hundredth of a degree.

Electron neutrinos and tau neutrinos do not produce prompt, high energy muons—and neither do muon neutrinos when they exchange a Z particle with the struck nucleus. In these cases we have to observe the cascades of secondary particles (mostly hadrons, few of which travel very far) produced by the recoiling quarks in the struck nuclei. For Cherenkov detection of these large cascades, we must position the modules with typical spacings determined by the mean transparency of our medium to blue light. Therefore the sensitive target volume of our array for detecting cascades grows only as the total volume surrounded by it—unlike that for detecting muons, which increases as the area of the array. At the scale of several kilometers, however, these two begin to converge—a good thing because we can learn a lot by detecting all types of neutrinos simultaneously.

A unique and interesting phenomenon to watch for is the production of W^- particles by 6.4 PeV electron antineutrinos striking electrons within the target volume. The cross section for this interaction is much greater than for all other weak interaction processes at this energy; if there happen to be lots of electron antineutrinos in the mix, it should lead to a nice spike in the distribution of cascade energies. Aside from the aesthetic pleasure of finding this so-far unobserved fundamental process, it will give us a good energy calibration and a handle on the fraction of electron neutrinos at this energy.

With a large enough detector array we may be able to observe what we call "double-bang" events produced by tau neutrinos of a few PeV. Upon striking a nucleus in our target volume, such a neutrino will often produce a tau lepton that travels about a hundred meters before decaying. There will be one cascade at the point of collision and another at the point of tau decay, connected by a softly ionizing particle between the two. The first cascade will contain about half the energy of the second, on average; both should be easily visible, generating about 100 billion photons apiece. With a sufficient sample of these double-bang events, we would be able to measure the percentage of tau neutrinos at energies of a few PeV; by



A typical "double-bang" event that might be observed in a very large neutrino telescope, produced by interaction of a multi-PeV tau neutrino. It generates a huge shower, together with a tau lepton that travels around 100 meters before decaying in a second shower with about twice the energy of the first.

Expt	Location	Depth (km)	Medium	Size of Array Height (m)	Width (m)	No. Strings	No. Modules	Estimated Year of Operation
AMANDA	Antarctica	1–2	ice	390	110	16	478	2000
Baikal	Siberia	1.1	lake	70	43	8	96[a]	1997
DUMAND	Hawaii	4.8	ocean	230	106	9	216	1997
NESTOR	Greece	3.7	sea	220	32	7[b]	168	1997

[a]1 module contains 2 photomultiplier tubes
[b]1 tower is equivalent to 7 strings.

comparing this ratio with those of electron and muon neutrinos, we will be able to study neutrino mixing with unmatched sensitivity to mass differences. The observation of such events would also be strong evidence for neutrino mass.

In addition to sampling the Cherenkov light produced by interacting high energy neutrinos, physicists have considered the possibility of detecting the radio and sound waves generated by their violent collisions with matter. Small radio pulses occur because oppositely charged particles in a cascade generate opposing microwave signals that do not completely cancel (owing to the fact that its electrons migrate further than its positrons). The best available medium for detecting such pulses appears to be polar ice, which will transmit microwaves for kilometers at temperatures below –60°C. Acoustic pulses occur because cascades deposit heat energy instantaneously in narrow cylinders up to about 10 meters long. Detecting the sound waves generated (with typical frequencies of 20 kHz) will be difficult, but it may be possible in the very quiet deep ocean for neutrinos with energies above a few PeV. Both techniques show good promise for extending neutrino astronomy to ultrahigh energies and to truly gargantuan volumes, but both will probably have to ride piggyback first on a Cherenkov-light detector in order to demonstrate their feasibility.

FOUR LARGE detectors of high energy neutrinos are now in various stages of design and construction. They sport the names DUMAND (in the Pacific Ocean off Hawaii), AMANDA (in ice at the South Pole), Baikal (in Lake Baikal, Siberia) and NESTOR (in the Mediterranean Sea near Greece). All are at least ten times larger than their low-energy brethren—such as Japan's SuperKamiokande detector—in their enclosed volumes and muon-catching area, and their threshold energy sensitivity is typically a thousand times higher.

Having begun life in a series of late-1970s workshops, DUMAND is the elderly sibling of the other projects. As currently envisioned, it will consist of nine strings of photosensor modules in an octagonal array (with one string at the center) submerged over 4 km deep off the Big Island of Hawaii. This array will enclose about 2 megatons of water and have an effective area of 20,000 m^2 for the detection of energetic muons, with an angular resolution of about a degree. Since the early 1980s, a group of physicists from Europe, Japan, and the United States has been working from the University of Hawaii, doing R&D on this project—acquiring valuable experience in how to apply the techniques of high energy physics to the deep-ocean environment.

Each DUMAND string contains 24 photosensor modules spaced 10 m apart along its instrumented section—plus floats to provide the necessary tension, hydrophones, environmental sensors and an electronics package. It is tethered to the ocean bottom with a remotely commandable release to facilitate recovery and allow reconfiguration of the array if desired. The electronics unit communicates with all the sensors and sends a data stream to shore (including optical, acoustic, environmental and housekeeping data) via fiber-optic cable through a common junction box.

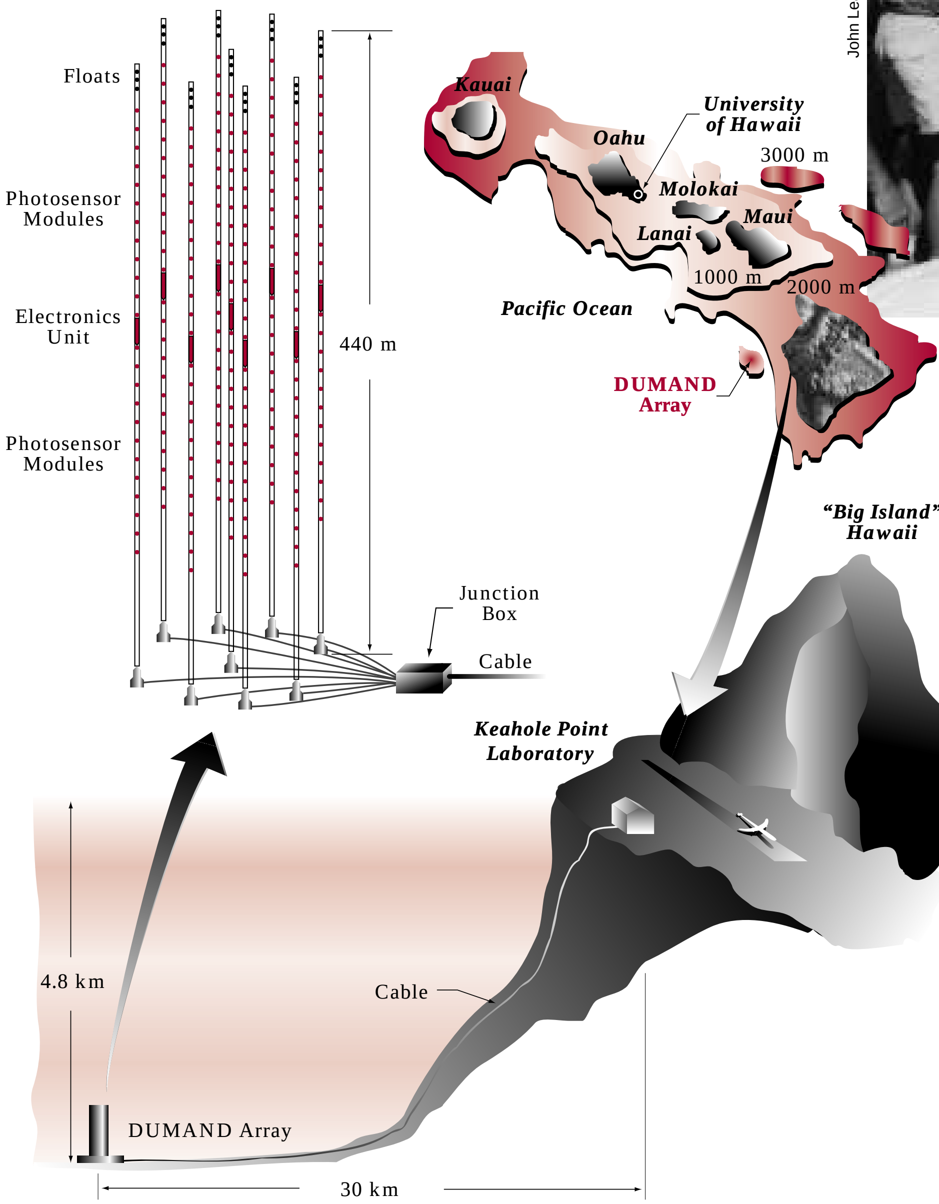
In December 1993 the collaboration successfully laid the shore cable along the ocean bottom from the experimental site 30 km west of the Big Island to the laboratory at Keahole Point. Attached to this junction box before deployment, the first detector string worked well for a short time but its electronics package failed due to a leak. Data acquired before this failure confirmed expectations about the overall system performance and background counting rates. After further ship-suspended tests in the winter of 1995–96, placement of three complete strings will occur in the summer of 1996.

Having begun South Pole operations in 1991, AMANDA is the

Right: Physicists deploying the first DUMAND string from the deck of the research vessel T. G. Thompson in December of 1993. One of the optical photosensors hangs in midair as the central electronics package is readied for submersion.

Bottom: Artist's conception of the planned DUMAND array and its deep-sea location off the Big Island of Hawaii. The cable and junction box are now in position; another attempt to install the first of nine strings of photosensors and other detectors will occur in 1996.

John Learned



youngest of the four projects but has made impressive progress. Its approach is simple: use hot water to drill holes in the Antarctic ice pack, freeze photomultiplier tubes in place, and use standard electronics techniques to get a large neutrino detector built rapidly with a minimum of new technology development. The ice is very cloudy near the surface but was expected to be spectacularly clear at some depth beyond about 500 m.

Led by the University of Wisconsin, the collaboration installed four of the planned six strings, each containing 20 modules, at depths of 800–1000 m during the summer of 1993–94. Upon activating these strings, however, physicists found bubble densities in the ice substantially higher than anticipated; scattering of light from these bubbles made accurate signal timing impossible. In effect, AMANDA has blurry

Bob Morse

A well-clad physicist stands beside the hot-water drill used to bore the first four AMANDA holes 1000 meters into the Antarctic ice cap at the South Pole. This equipment will be used to bore additional holes to depths of about 1500 meters during the austral summer of 1995–96.

vision—as if it were looking for muons through translucent glasses.

The big question is whether the ice clarity improves enough with depth to permit a full-scale experiment this austral summer (1995–96). Drilling costs grow with depth, and expensive fiber-optic techniques may be needed to obtain good timing. AMANDA will run out of ice at about 2500 m, although the team may give up if the clarity is still poor at1500 m. With the observed low light absorption in ice, however, the array might still make an excellent calorimeter—and microwave detection techniques hold great promise in this medium, too.

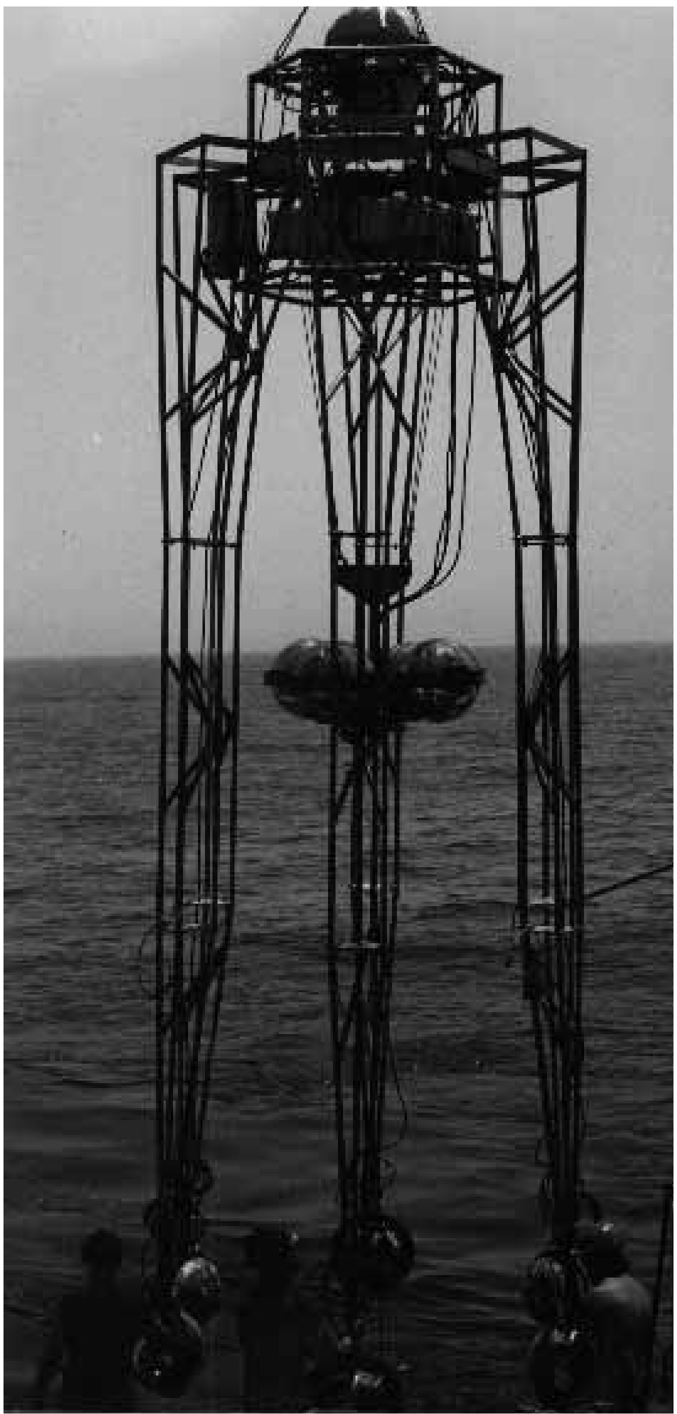
A group of Russian and German physicists building the Baikal detector includes some of the elders in this field, who began work about the same time as DUMAND. The deepest (1.4 km) clear lake in the world, Lake Baikal was chosen in the hopes of avoiding the major background flux of light due to radioactivity, but there appears to be an obscure, unanticipated source that varies with time—making it about as noisy as the deep ocean. One advantage is Baikal's ability to place and retrieve instruments in winter, without use of ships. Its unique cable-laying method uses a sled with a huge saw to cut a slot in the ice, through which a following sled unreels the cable as both drive shoreward; the slot rapidly freezes behind. So far 36 modules (each with two photomultipliers acting in coincidence) have been placed, with data being recorded and analyzed at a shore station. This group has suffered from the lack of funding and high-technology materials, but the recent addition of the DESY laboratory in Hamburg, Germany, to the collaboration brings great hope of solving these problems.

Planned for a deep-sea site southwest of Pylos, Greece, NESTOR is closest in concept to DUMAND. At a depth of 3.5 km the Mediterranean is surprisingly clear; a good site has been located and studied a mere 20 km from shore. This site is also close to a line extended from CERN through Italy's Gran Sasso Laboratory, so that a proposed neutrino beam might be extended to the detector to permit a search for neutrino oscillations. The detector array will be a hexagonal cluster of seven towers, each standing 450 m tall and containing 12 umbrella-like floors with 14 modules per floor. Installation of the first tower is expected to occur in 1997. Led by the University of Athens, the NESTOR collaboration includes teams of physicists from France, Greece, Italy and Russia—among them a Saclay group that provides the support and infrastructure of a major French national laboratory.

EVER SINCE the late 1970s it has been clear to neutrino astronomers that an array filling an entire cubic kilometer is really needed to begin serious work in the field. Everyone recognizes that we are really building demonstration devices—perhaps big enough to find a few exciting things—as exploratory stepping stones to the huge detector we really need to finish the job. Many independent calculations have converged upon a cubic kilometer as the appropriate volume. Such a

Right: One of the Baikal detector modules being lowered through the ice together with cabling and electronics. Each module consists of two photosensors in two separate pressure-resistant glass spheres.
Bottom: A prototype NESTOR "floor," which consists of 14 photosensors in an umbrella-like array, being lowered into the Mediterranean Sea off Greece. Slated for initial deployment in 1997, each tower in this neutrino telescope will consist of 12 such floors, whose arms open radially once in the water.

Bob Morse



Leo Resvanis

device should function well in detecting neutrinos from point sources, the galactic plane, gamma-ray bursters, AGNs and WIMPs.

In 1994 there were several meetings at which physicists discussed the idea of forming a world collaboration to design and build such a gargantuan detector. The AMANDA and DUMAND teams plus a few newcomers have been working with the Jet Propulsion Laboratory, a major national laboratory in Pasadena, California, with the big-project experience needed in such an effort, which is clearly beyond the capability of a single university. The Saclay group joined NESTOR partly in order to gain experience towards building such a facility. Many of us hope to merge these two efforts into a single international project.

One thing we are all proud of in this emerging field is the tremendously supportive interaction among the physicists involved. Although there is lots of competition, as all of us naturally want to be first with any important discovery, we realize that by helping each other we also help ourselves in the long run. All four teams have meanwhile got their work cut out for them. No cubic-kilometer detector will ever begin construction until we can get at least one (and hopefully more) of the current generation up and counting neutrinos. Only then will we have the information we need to decide whether the next step for neutrino astronomy should occur in water or ice.