THE HIGHEST ENERGY COSMIC RAYS, GAMMA-RAYS AND NEUTRINOS: FACTS, FANCY AND RESOLUTION

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Although cosmic rays were discovered 90 years ago, we do not know how and where they are accelerated. There is compelling evidence that the highest energy cosmic rays are extra-galactic — they cannot be contained by our galaxy’s magnetic field anyway because their gyroradius exceeds its dimensions. Elementary elementary-particle physics dictates a universal upper limit on their energy of $5 \times 10^{19}$ eV, the so-called Greisen-Kuzmin-Zatsepin cutoff; however, particles in excess of this energy have been observed, adding one more puzzle to the cosmic ray mystery. Mystery is nonetheless fertile ground for progress: we will review the facts and mention some very speculative interpretations. There is indeed a realistic hope that the oldest problem in astronomy will be resolved soon by ambitious experimentation: air shower arrays of $10^4$ km$^2$ area, arrays of air Cerenkov detectors and kilometer-scale neutrino observatories.

1 The New Astronomy

Conventional astronomy spans 60 octaves in photon frequency, from $10^4$ cm radio-waves to $10^{-14}$ cm photons of GeV energy; see Fig. 1. This is an amazing expansion of the power of our eyes which scan the sky over less than a single octave just above $10^{-5}$ cm wavelength. The new astronomy, discussed in this talk, probes the Universe with new wavelengths, smaller than $10^{-14}$ cm, or photon energies larger than 10 GeV. Besides gamma rays, gravitational waves and neutrinos as well as very high energy protons that are only weakly deflected by the magnetic field of our galaxy, become astronomical messengers from the Universe. As exemplified time and again, the development of novel ways of looking into space invariably results in the discovery of unanticipated phenomena. As is the case with new accelerators, observing the predicted will be slightly disappointing.

Why do high energy astronomy with neutrinos or protons despite the considerable instrumental challenges which we will discuss further on? A mundane reason is that the Universe is not transparent to photons of TeV energy and above (units are: GeV/TeV/PeV/EeV/ZeV in ascending factors of $10^3$). For instance, a PeV energy photon $\gamma$ cannot reach us from a source at the edge of our own galaxy because it will annihilate into an electron pair in an encounter with a 2.7 degree Kelvin microwave photon $\gamma_{CMB}$ before reaching our telescope. Energetic photons are absorbed on background light by pair production $\gamma + \gamma_{bkgd} \to e^+ + e^-$ of electrons above a threshold $E$ given by

$$4E\epsilon \sim (2m_e)^2,$$

where $E$ and $\epsilon$ are the energy of the high-energy and background photon, respectively. Eq. (1) implies that TeV photons are absorbed on infrared light, PeV photons on the cosmic microwave background and EeV photons on radio-waves. Only neutrinos can reach us without attenuation from the edge of the Universe.

At EeV energies proton astronomy may be possible. Near 50 EeV and above, the arrival directions of electrically charged cosmic rays are no longer scrambled by the ambient magnetic field of our own galaxy. They point back to their sources with an accuracy determined by their gyroradius in the intergalactic magnetic field $B$:

$$\theta \approx \frac{d}{R_{gyro}} = \frac{dB}{E},$$

where $d$ is the distance to the source. Scaled
to units relevant to the problem,

$$\frac{\theta}{0.1^\circ} \approx \left( \frac{d}{1 \text{ Mpc}} \right) \left( \frac{B}{10^{-9} \text{ G}} \right) \left( \frac{E}{3 \times 10^{20} \text{ eV}} \right).$$  (3)

Speculations on the strength of the intergalactic magnetic field range from $10^{-7}$ to $10^{-12}$ Gauss. For a distance of 100 Mpc, the resolution may therefore be anywhere from sub-degree to nonexistent. It is still reasonable to expect that the arrival directions of the highest energy cosmic rays provide information on the location of their sources. Proton astronomy should be possible; it may also provide indirect information on intergalactic magnetic fields. Determining their strength by conventional astronomical means has turned out to be challenging.

2 The Highest Energy Cosmic Rays: Facts

In October 1991, the Fly’s Eye cosmic ray detector recorded an event of energy $3.0 \pm 0.36 \times 10^{20} \text{ eV}$\(^\text{[2]}\). This event, together with an event recorded by the Yakutsk air shower array in May 1989\(^\text{[2]}\) of estimated energy $\sim 2 \times 10^{20} \text{ eV}$, constituted at the time the two highest energy cosmic rays ever seen. Their energy corresponds to a center of mass energy of the order of 700 TeV or $\sim 50$ Joules, almost 50 times LHC energy. In fact, all experiments\(^\text{[3]}\) have detected cosmic rays in the vicinity of 100 EeV since their discovery by the Haverah Park air shower array.\(^\text{[4]}\) The AGASA air shower array in Japan\(^\text{[5]}\) has by now accumulated an impressive 10 events with energy in excess of $10^{20} \text{ eV}$\(^\text{[6]}\).

How well experiments can determine the energy of these events is a critical issue. With a particle flux of order 1 event per km\(^2\) per century, these events can only be studied by using the earth’s atmosphere as a particle detector. The experimental signatures of a shower initiated by a cosmic particle are illustrated in the cartoon shown in Fig. 2. The primary particle creates an electromagnetic and hadronic cascade. The electromagnetic shower grows to a shower maximum, and is
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Figure 2. Particles interacting near the top of the atmosphere initiate an electromagnetic and hadronic particle cascade. Its profile is shown on the right. The different detection methods are illustrated. Mirrors collect the Cerenkov and nitrogen fluorescent light, arrays of detectors sample the shower reaching the ground, and underground detectors identify the muon component of the shower.

subsequently absorbed by the atmosphere. This leads to the characteristic shower profile shown on the right hand side of the figure. The shower can be observed by: i) sampling the electromagnetic and hadronic components when they reach the ground with an array of particle detectors such as scintillators, ii) detecting the fluorescent light emitted by atmospheric nitrogen excited by the passage of the shower particles, iii) detecting the Cerenkov light emitted by the large number of particles at shower maximum, and iv) detecting muons and neutrinos underground. Fluorescent and Cerenkov light is collected by large mirrors and recorded by arrays of photomultipliers in their focus. The bottom line on energy measurement is that, at this time, several experiments using the first two techniques agree on the energy of EeV-showers within a typical resolution of 25%. Additionally, there is a systematic error of order 10% associated with the modeling of the showers. All techniques are indeed subject to the ambiguity of particle simulations that involve physics beyond LHC. If the final outcome turns out to be erroneous inference
of the energy of the shower because of new physics associated with particle interactions, we will be happy to contemplate this discovery instead.

Whether the error in the energy measurement could be significantly larger is a key question to which the answer is almost certainly negative. A variety of techniques have been developed to overcome the fact that conventional air shower arrays do calorimetry by sampling at a single depth. They give results within the range already mentioned. So do the fluorescence experiments that embody continuous sampling calorimetry. The latter are subject to understanding the transmission of fluorescent light in the dark night atmosphere — a challenging problem given its variation with weather. Stereo fluorescence detectors will eliminate this last hurdle by doing two redundant measurements of the same shower from different locations. The HiRes collaborators have one year of data on tape which should allow them to settle any doubts as to energy calibration once and for all.

The premier experiments, HiRes and AGASA, agree that cosmic rays with energy in excess of $10^{18}$ EeV are not a feature of our galaxy and that their spectrum extends beyond $10^{19}$ EeV. They disagree on almost everything else. The AGASA experiment claims evidence that they come from point sources, and that they are mostly heavy nuclei. The HiRes data do not support this. Because of statistics, interpreting the measured fluxes as a function of energy is like reading tea leaves; one cannot help however reading different messages in the spectra (see Fig. 3). More about that later.

3 The Highest Energy Cosmic Rays: Fancy

3.1 Acceleration to $> 100$ EeV?

It is sensible to assume that, in order to accelerate a proton to energy $E$ in a magnetic field $B$, the size $R$ of the accelerator must be larger than the gyroradius of the particle:

$$ R > R_{\text{gyro}} = \frac{E}{B}. \quad (4) $$

I.e. the accelerating magnetic field must contain the particle orbit. This condition yields a maximum energy

$$ E = \Gamma BR \quad (5) $$

by dimensional analysis and nothing more. The $\Gamma$-factor has been included to allow for the possibility that we may not be at rest in the frame of the cosmic accelerator resulting in the observation of boosted particle en-
energies. Theorists’ imagination regarding the accelerators is limited to dense regions where exceptional gravitational forces create relativistic particle flows: the dense cores of exploding stars, inflows on supermassive black holes at the centers of active galaxies, annihilating black holes or neutron stars? All speculations involve collapsed objects and we can therefore replace $R$ by the Schwartzschild radius

$$R \sim \frac{GM}{c^2}$$

(6)

to obtain

$$E \sim \Gamma BM.$$  

(7)

Given the microgauss magnetic field of our galaxy, no structures are large or massive enough to reach the energies of the highest energy cosmic rays. Dimensional analysis therefore limits their sources to extragalactic objects; a few common speculations are listed in Table 1. Nearby active galactic nuclei distant by $\sim 100$ Mpc and powered by a billion solar mass black holes are candidates. With kilo-Gauss fields we reach 100 EeV. The jets (blazars) emitted by the central black hole could reach similar energies in accelerating substructures boosted in our direction by a $\Gamma$-factor of 10, possibly higher. The neutron star or black hole remnant of a collapsing supermassive star could support magnetic fields of $10^{12}$ Gauss, possibly larger. Shocks with $\Gamma > 10^2$ emanating from the collapsed black hole could be the origin of gamma ray bursts and, possibly, the source of the highest energy cosmic rays.

The above speculations are reinforced by the fact that the sources listed happen to also be the sources of the highest energy gamma rays observed. At this point however a reality check is in order. Let me first point out that the above dimensional analysis applies to the Fermilab accelerator: 10 kGauss fields over several kilometers yield 1 TeV. The argument holds because, with optimized design and perfect alignment of magnets, the accelerator reaches efficiencies matching the dimensional limit. It is highly questionable that Nature can achieve this feat. Theorists can imagine acceleration in shocks with efficiency of perhaps 10%.

The astrophysics problem is so daunting that many believe that cosmic rays are not the beam of cosmic accelerators but the decay products of remnants from the early Universe, for instance topological defects associated with a grand unified GUT phase transition. A topological defect will suffer a chain decay into GUT particles X,Y, that subsequently decay to familiar weak bosons, leptons and quark- or gluon jets. Cosmic rays are the fragmentation products of these jets. We know from accelerator studies that, among the fragmentation products of jets, neutral pions (decaying into photons) dominate protons by two orders of magnitude. Therefore, if the decay of topological defects is the source of the highest energy cosmic rays, they must be photons. This is a problem because the highest energy event observed by the Fly’s Eye is not likely to be a photon. A photon of 300 EeV will interact with the magnetic field of the earth far above the atmosphere and disintegrate into lower energy cascades — roughly ten at this par-
ticular energy. The measured shower profile of the event does not support this assumption; see Fig. 4. One can live and die by a single event!

![Figure 4](image_url)

Figure 4. The composite atmospheric shower profile of a $3 \times 10^{20}$ eV $\gamma$-ray shower calculated with Landau-Pomeranchuk-Migdal (solid) and Bethe-Heitler (dashed) electromagnetic cross sections. The central line shows the average shower profile and the upper and lower lines show 1 $\sigma$ deviations — not visible for the BH case, where lines overlap. The experimental shower profile is shown along with the data points. It does not fit the profile of a photon shower.

### 3.2 Are Cosmic Rays Really Protons: the GZK Cutoff?

All experimental signatures agree on the particle nature of the cosmic rays — they look like protons, or, possibly, nuclei. We mentioned at the beginning of this article that the Universe is opaque to photons with energy in excess of tens of TeV because they annihilate into electron pairs in interactions with background light. Also protons interact with background light, predominantly by photoproduction of the $\Delta$-resonance, i.e. $p + \gamma_{\text{CMB}} \rightarrow \Delta \rightarrow \pi + p$ above a threshold energy $E_p$ of about 50 TeV given by:

$$2E_p \epsilon > (m_{\Delta}^2 - m_p^2) .$$

The major source of proton energy loss is photoproduction of pions on a target of cosmic microwave photons of energy $\epsilon$. The Universe is therefore also opaque to the highest energy cosmic rays, with an absorption length:

$$\lambda_{\gamma p} = (n_{\text{CMB}} \sigma p+\gamma_{\text{CMB}})^{-1} \equiv 10 \text{Mpc},$$

or only tens of megaparsecs when their energy exceeds 50 EeV. This so-called GZK cutoff establishes a universal upper limit on the energy of the cosmic rays. The cutoff is robust, depending only on two known numbers: $n_{\text{CMB}} = 400 \text{cm}^{-3}$ and $\sigma p+\gamma_{\text{CMB}} = 10^{-28} \text{cm}^2$.

Protons with energy in excess of 100 EeV, emitted in distant quasars and gamma ray bursts, will have lost their energy to pions before reaching our detectors. They have, nevertheless, been observed, as we have previously discussed. They do not point to any sources within the GZK-horizon however, i.e. to sources in our local cluster of galaxies. There are three possible resolutions: i) the protons are accelerated in nearby sources, ii) they do reach us from distant sources which accelerate them to much higher energies than we observe, thus exacerbating the acceleration problem, or iii) the highest energy cosmic rays are not protons.

The first possibility raises the challenge of finding an appropriate accelerator by confining these already unimaginable sources to our local galaxy cluster. It is not impossible that all cosmic rays are produced by the active galaxy M87, or by a nearby gamma ray burst which exploded a few hundred years ago. The sources identified by the AGASA array do not correlate however with any such candidates.

Stecker\[8\] has speculated that the highest energy cosmic rays are Fe nuclei with a delayed GZK cutoff. The details are complicated but the relevant quantity in the problem is $\gamma = E/AM$, where A is the atomic
number and $M$ the nucleon mass. For a fixed observed energy, the smallest boost above GZK threshold is associated with the largest atomic mass, i.e. Fe.

### 3.3 Could Cosmic Rays be Photons or Neutrinos?

When discussing topological defects, I already challenged the possibility that the original Fly’s Eye event is a photon. The detector collects light produced by the fluorescence of atmospheric nitrogen along the path of the high-energy shower traversing the atmosphere. The anticipated shower profile of a $300\text{EeV}$ photon is shown in Fig. 4. It disagrees with the data.

The observed shower profile roughly fits that of a primary proton, or, possibly, that of a nucleus. The shower profile information is however sufficient to conclude that the event is unlikely to be of photon origin. The same conclusion is reached for the Yakutsk event that is characterized by a huge number of secondary muons, inconsistent with an electromagnetic cascade initiated by a gamma-ray. Finally, the AGASA collaboration claims evidence for “point” sources above $10\text{EeV}$. The arrival directions are however smeared out in a way consistent with primaries deflected by the galactic magnetic field. Again, this indicates charged primaries and excludes photons.

Neutrino primaries are definitely ruled out. Standard model neutrino physics is understood, even for EeV energy. The average $x$ of the parton mediating the neutrino interaction is of order $x \sim \sqrt{M_W^2/s} \sim 10^{-6}$ so that the perturbative result for the neutrino-nucleus cross section is calculable from measured HERA structure functions. Even at $100\text{EeV}$ a reliable value of the cross section can be obtained based on QCD-inspired extrapolations of the structure function. The neutrino cross section is known to better than an order of magnitude. It falls 5 orders of magnitude short of the strong cross sections required to make a neutrino interact in the upper atmosphere to create an air shower.

Could EeV neutrinos be strongly interacting because of new physics? In theories with TeV-scale gravity one can imagine that graviton exchange dominates all interactions and thus erases the difference between quarks and neutrinos at the energies under consideration. Notice however that the actual models performing this feat require a fast turn-on of the cross section with energy that violates $S$-wave unitarity.

We thus exhausted the possibilities: neutrons, muons and other candidate primaries one may think of are unstable. EeV neutrinos barely live long enough to reach us from sources at the edge of our galaxy.

### 4 A Three Prong Assault on the Cosmic Ray Puzzle

We conclude that, where the highest energy cosmic rays are concerned, both the accelerator mechanism and the particle physics are totally enigmatic. The mystery has inspired a worldwide effort to tackle the problem with novel experimentation in three complementary areas of research: air shower detection, atmospheric Cerenkov astronomy and underground neutrino physics. While some of the future instruments have other missions, all are likely to have a major impact on cosmic ray physics.

#### 4.1 Giant Cosmic Ray Detectors

With super-GZK fluxes of the order of a single event per kilometer-squared per century, the outstanding problem is the lack of statistics; see Fig. 3. In the next five years, a qualitative improvement can be expected from the operation of the HiRes fluorescence detector in Utah. With improved instrumentation yielding high quality data from 2 detectors operated in coincidence, the interplay between sky transparency and energy measure-
ment can be studied in detail. We can safely anticipate that the existence of super-Greisen energies will be conclusively demonstrated by using the instrument’s calorimetric measurements. A mostly Japanese collaboration has proposed a next-generation fluorescence detector, the Telescope Array.

The Auger air shower array is tackling the low rate problem with a huge collection area covering 3000 square kilometers on an elevated plain in Western Argentina. The instrumentation consists of 1600 water Cerenkov detectors spaced by 1.5 km. For calibration, about 15 percent of the showers occurring at night will be viewed by 3 HiRes-style fluorescence detectors. The detector will observe several thousand events per year above 10 EeV and tens above 100 EeV, with the exact numbers depending on the detailed shape of the observed spectrum which is at present a matter of speculation; see Fig. 3.

4.2 Gamma-Rays from Cosmic Accelerators

An alternative way to identify the sources of the cosmic rays is illustrated in Fig. 5. The cartoon draws our attention to the fact that cosmic accelerators are also cosmic beam dumps producing secondary photon and neutrino beams. Accelerating particles to TeV energy and above requires high-speed, massive bulk flows. These are likely to have their origin in exceptional gravitational forces associated with dense cores of exploding stars, inflows onto supermassive black holes at the centers of active galaxies, annihilating black holes or neutron stars. In such situations, accelerated particles are likely to pass through intense radiation fields or dense clouds of gas leading to production of secondary photons and neutrinos that accompany the primary cosmic-ray beam. An example of an electromagnetic beam dump is the X-ray radiation fields surrounding the central black holes of active galaxies. The target material, whether a gas or particles or of photons, is likely to be sufficiently tenuous so that the primary beam and the photon beam are only partially attenuated. However, it is also a real possibility that one could have a shrouded source from which only the neutrinos can emerge, as in terrestrial beam dumps at CERN and Fermilab.

The astronomy event of the 21st century could be the simultaneous observation of TeV-gamma rays, neutrinos and gravitational waves from cataclysmic events associated with the source of the cosmic rays.

We first concentrate on the possibility of detecting high-energy photon beams. After two decades, ground-based gamma ray astronomy has become a mature science. A large mirror, viewed by an array of photomultipliers, collects the Cerenkov light emitted by air showers and images the showers in order to determine the arrival direction as well as the nature of the primary particle; see Fig. 2. These experiments have opened a new window in astronomy by extending the photon spectrum to 20 TeV, possibly beyond. Observations have revealed spectacular TeV-emission from galactic supernova remnants and nearby quasars, some of which emit most of their energy in very short burst of TeV-photons.

But there is the dog that didn’t bark. No evidence has emerged for π⁰ origin of the TeV radiation and, therefore, no cosmic ray sources have yet been identified. Dedicated searches for photon beams from suspected cosmic ray sources, such as the supernova remnants IC433 and γ-Cygni, came up empty handed. While not relevant to the topic covered by this talk, supernova remnants are theorized to be the sources of the bulk of the cosmic rays that are of galactic origin. The evidence is still circumstantial.

The field of gamma ray astronomy is buzzing with activity to construct second-generation instruments. Space-based detectors are extending their reach from GeV
to TeV energy with AMS and, especially, GLAST, while the ground-based Cerenkov collaborations are designing instruments with lower thresholds. In the not so far future both techniques should generate overlapping measurements in the $10^{17}$ to $10^{19}$ GeV energy range.

All ground-based air Cerenkov experiments aim at lower threshold, better angular- and energy-resolution, and a longer duty cycle. One can however identify three pathways to reach these goals:

1. larger mirror area, exploiting the parasitic use of solar collectors during nighttime (CELESTE, STACEY and SOLAR II),

2. better, or rather, ultimate imaging with the 17 m MAGIC mirror,

3. larger field of view using multiple telescopes (VERITAS, HEGRA and HESS).

The Whipple telescope pioneered the atmospheric Cerenkov technique. VERITAS is an array of 9 upgraded Whipple telescopes, each with a field of view of 6 degrees. These can be operated in coincidence for improved angular resolution, or be pointed at 9 different 6 degree bins in the night sky, thus achieving a large field of view. The HEGRA collaboration is already operating four telescopes in coincidence and is building an upgraded facility with excellent viewing and optimal location near the equator in Namibia.

There is a dark horse in this race: Milagro. The Milagro idea is to lower the threshold of conventional air shower arrays to 100 GeV by instrumenting a pond of five million gallons of ultra-pure water with photomultipliers. For time-varying signals, such as bursts, the threshold may be lower.

### 4.3 High Energy Neutrino Telescopes

Although neutrino telescopes have multiple interdisciplinary science missions, the search for the sources of the highest-energy cosmic rays stands out because it clearly iden-
tifies the size of the detector required to do the science. For guidance in estimating expected signals, one makes use of data covering the highest-energy cosmic rays in Fig. 3 as well as known sources of non-thermal, high-energy gamma rays. Accelerating particles to TeV energy and above involves neutron stars or black holes. As already explained in the context of Fig. 5, some fraction of them will interact in the radiation fields surrounding the source, whatever it may be, to produce pions. These interactions may also be hadronic collisions with ambient gas. In either case, the neutral pions decay to photons while charged pions include neutrinos among their decay products with spectra related to the observed gamma-ray spectra. Estimates based on this relationship show that a kilometer-scale detector is needed to see neutrino signals.

The same conclusion is reached in specific models. Assuming, for instance, that gamma ray bursts are the cosmic accelerators of the highest-energy cosmic rays, one can calculate from textbook particle physics how many neutrinos are produced when the particle beam coexists with the observed MeV energy photons in the original fireball. We thus predict the observation of 10–100 neutrinos of PeV energy per year in a detector with a kilometer-square effective area. In general, the potential scientific payoff of doing neutrino astronomy arises from the great penetrating power of neutrinos, which allows them to emerge from dense inner regions of energetic sources.

Whereas the science is compelling, the real challenge has been to develop a reliable, expandable and affordable detector technology. Suggestions to use a large volume of deep ocean water for high-energy neutrino astronomy were made as early as the 1960s. In the case of the muon neutrino, for instance, the neutrino ($\nu_\mu$) interacts with a hydrogen or oxygen nucleus in the water and produces a muon travelling in nearly the same direction as the neutrino. The blue Cerenkov light emitted along the muon’s ~kilometer-long trajectory is detected by strings of photomultiplier tubes deployed deep below the surface. With the first observation of neutrinos in the Lake Baikal and the (under-ice) South Pole neutrino telescopes, there is optimism that the technological challenges to build neutrino telescopes have been met.

The first generation of neutrino telescopes, launched by the bold decision of the DUMAND collaboration to construct such an instrument, are designed to reach a large telescope area and detection volume for a neutrino threshold of order 10 GeV. The optical requirements of the detector medium are severe. A large absorption length is required because it determines the spacings of the optical sensors and, to a significant extent, the cost of the detector. A long scattering length is needed to preserve the geometry of the Cerenkov pattern. Nature has been kind and offered ice and water as adequate natural Cerenkov media. Their optical properties are, in fact, complementary. Water and ice have similar attenuation length, with the role of scattering and absorption reversed. Optics seems, at present, to drive the evolution of ice and water detectors in predictable directions: towards very large telescope area in ice exploiting the long absorption length, and towards lower threshold and good muon track reconstruction in water exploiting the long scattering length.

DUMAND, the pioneering project located off the coast of Hawaii, demonstrated that muons could be detected by this technique, but the planned detector was never realized. A detector composed of 96 photomultiplier tubes located deep in Lake Baikal was the first to demonstrate the detection of neutrino-induced muons in natural water. In the following years, NT-200 will be operated as a neutrino telescope with an effective area between $10^3 \sim 5 \times 10^3 \text{m}^2$, depending on energy. Presumably too small to detect neutrinos from extraterrestrial sources, NT-
200 will serve as the prototype for a larger telescope. For instance, with 2000 OMs, a threshold of 10~20 GeV and an effective area of $5 \times 10^4$~$10^5$ m$^2$, an expanded Baikal telescope would fill the gap between present detectors and planned high-threshold detectors of cubic kilometer size. Its key advantage would be low threshold.

The Baikal experiment represents a proof of concept for deep ocean projects. These do however have the advantage of larger depth and optically superior water. Their challenge is to find reliable and affordable solutions to a variety of technological challenges for deploying a deep underwater detector. The European collaborations ANTARES and NESTOR plan to deploy large-area detectors in the Mediterranean Sea within the next year. The NEMO Collaboration is conducting a site study for a future kilometer-scale detector in the Mediterranean.

The AMANDA collaboration, situated at the U.S. Amundsen-Scott South Pole Station, has demonstrated the merits of natural ice as a Cerenkov detector medium. In 1996, AMANDA was able to observe atmospheric neutrino candidates using only 80 eight-inch photomultiplier tubes.

With 302 optical modules instrumenting approximately 6000 tons of ice, AMANDA extracted several hundred atmospheric neutrino events from its first 130 days of data. AMANDA was thus the first first-generation neutrino telescope with an effective area in excess of 10,000 square meters for TeV muons. In rate and all characteristics the events are consistent with atmospheric neutrino origin. Their energies are in the 0.1–1 TeV range. The shape of the zenith angle distribution is compared to a simulation of the atmospheric neutrino signal in Fig. 6. The variation of the measured rate with zenith angle is reproduced by the simulation to within the statistical uncertainty. Note that the tall geometry of the detector strongly influences the dependence on zenith angle in favor of more vertical muons.

The arrival directions of the neutrinos are shown in Fig. 7. A statistical analysis indicates no evidence for point sources in this sample. An estimate of the energies of the up-going muons (based on simulations of the number of reporting optical modules) indicates that all events have energies consistent with an atmospheric neutrino origin. This enables AMANDA to reach a level of sensitivity to a diffuse flux of high energy extraterrestrial neutrinos of order $dN/dE_\nu = 10^{-6} E_\nu^{-2} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{GeV}^{-1}$, assuming an $E^{-2}$ spectrum. At this level they exclude a variety of theoretical models which assume...
the hadronic origin of TeV photons from active galaxies and blazars. Searches for neutrinos from gamma-ray bursts, for magnetic monopoles, and for a cold dark matter signal from the center of the Earth are also in progress and, with only 138 days of data, yield limits comparable to or better than those from smaller underground neutrino detectors that have operated for a much longer period.

In January 2000, AMANDA-II was completed. It consists of 19 strings with a total of 677 OMs arranged in concentric circles, with the ten strings from AMANDA forming the central core of the new detector. First data with the expanded detector indicate an atmospheric neutrino rate increased by a factor of three, to 4–5 events per day. AMANDA-II has met the key challenge of neutrino astronomy: it has developed a reliable, expandable, and affordable technology for deploying a kilometer-scale neutrino detector named IceCube.

Figure 8. Although IceCube detects neutrinos of any flavor above a threshold of \( \sim 0.1 \text{ TeV} \), it can identify their flavor and measure their energy in the ranges shown. Filled areas: particle identification, energy, and angle. Shaded areas: energy and angle.

IceCube is an instrument optimised to detect and characterize sub-TeV to multi-PeV neutrinos of all flavors (see Fig. 8) from extraterrestrial sources. It will consist of 80 strings, each with 60 10-inch photomultipliers spaced 17 m apart. The deepest module is 2.4 km below the surface. The strings are arranged at the apexes of equilateral triangles 125 m on a side. The effective detector volume is about a cubic kilometer, its precise value depending on the characteristics of the signal. IceCube will offer great advantages over AMANDA II beyond its larger size: it will have a much higher efficiency to reconstruct tracks, map showers from electron- and tau-neutrinos (events where both the production and decay of a \( \tau \) produced by a \( \nu_\tau \) can be identified; see Fig. 9) and, most importantly, measure neutrino energy. Simulations indicate that the direction of muons can be determined with sub-degree accuracy and their energy measured to better than 30% in the logarithm of the energy. Even the di-
rection of showers can be reconstructed to better than 10° in both $\theta$, $\phi$ above 10 TeV. Simulations predict a linear response in energy of better than 20%. This has to be contrasted with the logarithmic energy resolution of first-generation detectors. Energy resolution is critical because, once one establishes that the energy exceeds 100 TeV, there is no atmospheric neutrino background in a kilometer-square detector.

At this point in time, several of the new instruments, such as the partially deployed Auger array and HiRes to Magic to Milagro and AMANDA II, are less than one year from delivering results. With rapidly growing observational capabilities, one can express the realistic hope that the cosmic ray puzzle will be solved soon. The solution will almost certainly reveal unexpected astrophysics, if not particle physics.

Acknowledgements

I thank Concha Gonzalez-Garcia and Vernon Barger for comments on the manuscript. This research was supported in part by the U.S. Department of Energy under Grant No. DE-FG02-95ER40896 and in part by the University of Wisconsin Research Committee with funds granted by the Wisconsin Alumni Research Foundation.

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