# Neutrino Astronomy

The Sun generates energy deep in its core by nuclear fusion processes. A SUPERNOVA (of type II) explodes and blows off the entire star by gravitational energy liberated when the central core collapses. These interesting phenomena of energy generation can never be observed with visible light or any other electromagnetic waves. The places where these phenomena take place are buried deep in dense material and the created heat is quickly thermalized before it comes out of the stellar surface. Relevant information is lost during thermal equilibration.

Nevertheless, one may want to observationally probe the deep interior of the Sun or the gravitational collapse in the supernova core. One then has to find electrically neutral particles that have guaranteed straight travel paths in space. They obviously have to be produced in the regions and should not participate in thermal equilibration in order to bring the desired information. NEUTRINOS are exactly the particles that possess these features. Neutrinos are produced in nuclear processes, but interact with matter so weakly that as soon as they are created they leave the region with very nearly the speed of light as their mass is very small.

The universe about 1 s after the big bang had a temperature as high as the core of a supernova, and light particles such as electrons and positrons were in thermal equilibrium. Cosmic expansion in the meantime cooled down the universe and lowered the energy density. Electrons and positrons then annihilated, disappeared and created photons and neutrinos. These relic neutrinos should exist in the present universe and have important information on the early universe.

COSMIC RAYS are accelerated somewhere in our Galaxy or, if they are very energetic, perhaps in distant active galaxies, too. The extremely energetic cosmic rays (above $10^{20}$ eV) might even be produced by the decay of exotic objects created in the early universe and floating around even at the present, whose existence is conjectured in grand unified theories of elementary particles. Cosmic rays bend in galactic or intergalactic magnetic fields and cannot be traced back to their birthplaces. Even to this day, we do not know for sure where cosmic rays are actually born. Cosmic rays may interact with the medium surrounding the acceleration region and produce mesons, which decay in a short time and produce neutrinos. Neutrinos then escape freely to open space and may reach Earth with fruitful information.

Neutrino astronomy is used to study the central engines of the Sun and supernova, to identify the origin of cosmic rays and to study the very early universe. Astronomical neutrinos can also be used as beams useful for investigating neutrino properties, such as mass and mixing. Indeed, only after having completed the study of neutrino properties can one begin real neutrino astronomy.

Neutrinos from the Sun were first observed by R Davis Jr in the Homestake gold mine in the late 1960s. The experiment is still going on 30 yr after the initial operation. Since then four other experiments have joined this field and two more are coming into operation in the near future. All five experiments did observe solar neutrinos, thus confirming that the Sun is actually generating energy by nuclear fusion processes (see SOLAR INTERIOR: NEUTRINOS). The reason why this field is still so active even now is that there are serious discrepancies between observations and expectations. What the experiments observed is only 30–60% of what the standard solar model predicts. It would be shocking if the Sun were not working as theory tells us, because all life on Earth depends on stable solar heat generation. The so-called solar neutrino problem has not been completely solved. The most popular idea is not that the solar engine works with an efficiency of only 30–60% but that the 'deficit' of solar neutrinos is caused by neutrino oscillations, namely electron neutrinos that are produced in the Sun are converted to a different kind of neutrino, probably muon neutrinos, either in the solar interior or on the way to Earth. Muon neutrinos are impossible or difficult to observe, hence leading to an apparent deficit of solar neutrinos. This idea will be tested by new-generation experiments in the near future.

23 February 1987 will be remembered as the day when a real instance of the gravitational collapse and the subsequent birth of a NEUTRON STAR were first observed with neutrinos. Two large water Cherenkov detectors, Kamiokande and IMB, observed 11 and eight neutrino events, respectively. Although the observed neutrinos were few, these observations beautifully demonstrated that the underlying theory of the explosion of a type II supernova is correct, namely that the explosion was initiated by the gravitational collapse and the total energy released was about $3\times10^{53}$ erg, which roughly corresponds to $500\times$solar luminosity$\times$4.6 billion years.

These are the only successful observations of astronomical neutrinos. Large under-ice and under-water detectors are being built and tested for high-energy cosmic ray neutrinos with energies above $10^{12}$ eV. It will still take several more years before these neutrinos are first observed.

There is absolutely no idea how to detect relic neutrinos born in the early universe. They are expected to have an average energy of only 0.000 17 eV which is too low to have a meaningful interaction probability (cross section) with matter.

## What neutrinos are

Particle physics tells us that the ELEMENTARY PARTICLES (or simply called particles) are classified in four types: up-quark (u), down-quark (d), electron (e) and electron neutrino ($\nu_e$). These particles are said to form a family. Three families have in fact been found in nature and hence there are 12 elementary particles altogether. They are listed in table 1. Three neutrino species are called the electron neutrino ($\nu_e$), muon neutrino ($\nu_\mu$), and tau neutrino ($\nu_\tau$), corresponding to charged counterparts, electron (e), muon ($\mu$) and tau lepton ($\tau$), respectively.

The unique characteristics of neutrinos are as follows.

**Table 1.** Table of elementary particles. Rows in the second column correspond to u-quark, d-quark, electron and electron neutrino. They are classified by electric charge. The columns correspond to families. Families are distinguished only by the masses of the particles.

| Charge | | | |
|---|---|---|---|
| 2/3 | u | c | t |
| −1/3 | d | s | b |
| −1 | e | $\mu$ | $\tau$ |
| 0 | $\nu_e$ | $\nu_\mu$ | $\nu_\tau$ |

- They are electrically neutral and fly straight even in the presence of magnetic fields.
- Only weak forces act on neutrinos and hence they have a great ability to penetrate matter.
- Neutrinos are produced in high-temperature and high-density environments such as the center of stars and easily escape out of the star and reach Earth, bringing information on nuclear processes, energy generation etc at the production site.
- Great penetrability in turn makes neutrino detection quite difficult and the target size of a detector should be as large as possible.

## Solar neutrinos

According to the standard solar model the central temperature and density of the Sun are about 15 million kelvins ($kT \simeq 14$ keV) and 150 g cm$^{-3}$, respectively. These conditions allow protons to overcome the repelling force from their positive charges (Coulomb barrier) and to initiate nuclear reactions.

The following nuclear fusion processes are taking place in the Sun:

$$p + p \longrightarrow d + e^+ + \nu_e \quad (1)$$

$$d + p \longrightarrow {}^3\mathrm{He} + \gamma \quad (2)$$

$${}^3\mathrm{He} + {}^3\mathrm{He} \longrightarrow {}^4\mathrm{He} + 2p \quad (3)$$

or

$${}^3\mathrm{He} + {}^4\mathrm{He} \longrightarrow {}^7\mathrm{Be} + \gamma \quad (4)$$

$${}^7\mathrm{Be} + e^- \longrightarrow {}^7\mathrm{Li} + \nu_e \quad (5)$$

$${}^7\mathrm{Be} + p \longrightarrow {}^8\mathrm{B} + \gamma \quad (6)$$

$${}^8\mathrm{B} \longrightarrow {}^8\mathrm{Be}^* + e^+ + \nu_e. \quad (7)$$

The product $^7$Li further reacts with a proton and produces two $^4$He. The product $^8$Be$^*$ immediately decays into two $^4$He also. The reaction chain is now complete. One can see that electron neutrinos are produced by weak interactions (equation (1) and equation (5)) and a weak decay (equation (7)). These neutrinos are called pp neutrinos, $^7$Be neutrinos and $^8$B neutrinos, respectively. pp and $^8$B neutrinos have continuous energy spectra approximately given as $E_\nu^2 E_e p_e$, where $E_\nu$, $E_e$ and $p_e$ are neutrino energy, positron energy and positron momentum, respectively. $E_\nu$ is given by $Q - E_e$, where $Q$ is the available energy for the neutrino+positron pair ($Q$ value); the maximum $E_\nu$ are 0.42 MeV and 15 MeV for pp and $^8$B neutrinos, respectively. $^7$Be neutrinos have a line spectrum as equation (5) is a two-body reaction. Their energy is either 0.86 MeV (90%) or 0.38 MeV (10%).

The standard solar model calculates the neutrino flux on Earth from each source. The fluxes obviously depend on the temperature, density of each chemical element, thermal conduction of the surrounding medium, etc. The calculated fluxes are enormous: $5.9 \pm 0.06 \times 10^{10}$ cm$^{-2}$ s$^{-1}$, $0.48 \pm 0.04 \times 10^{10}$ cm$^{-2}$ s$^{-1}$ and $5.2^{+1.0}_{-0.7} \times 10^6$ cm$^{-2}$ s$^{-1}$ for pp, $^7$Be and $^8$B neutrinos, respectively.

Neutrinos have to be detected on Earth. In general particle detectors utilize particles' electric charge to produce observable signals. Neutral particles such as neutrinos must first interact with target particles and produce charged particles that produce signals. For solar neutrinos the following reactions have been used:

$$\nu_e + e^- \longrightarrow e^- + \nu_e \quad (8)$$

$$\nu_e + {}^{37}\mathrm{Cl} \longrightarrow e^- + {}^{37}\mathrm{Ar} \quad (9)$$

$$\nu_e + {}^{71}\mathrm{Ga} \longrightarrow e^- + {}^{71}\mathrm{Ge}. \quad (10)$$

In water Cherenkov experiments, Kamiokande and Super-Kamiokande (figure 1), water is the target material and electrons emitted from reaction (8) are detected. Only electrons with $E_e \geq 5.5$ MeV are detected owing to severe background problems. Thus the experiment is sensitive only to $^8$B neutrinos. For the latter two reactions, the end products $^{37}$Ar and $^{71}$Ge are extracted by the radiochemical technique and their numbers counted. The pioneering experiment Homestake used reaction (9) with a threshold energy of 0.81 MeV, and was thus sensitive to $^7$Be and $^8$B neutrinos, and subsequent SAGE and GALLEX experiments adopted reaction (10) with a threshold energy of 0.23 MeV, sensitive to pp, $^7$Be and $^8$B neutrinos.

The observational results are surprising. All five experiments observed much fewer neutrinos than what the standard solar model predicts. If one takes the ratio of observed to predicted numbers, the results were $0.27 \pm 0.02$, $0.42 \pm 0.06$, $0.47 \pm 0.015$, $0.56 \pm 0.06$, $0.50 \pm 0.09$ for Homestake, Kamiokande, Super-Kamiokande, GALLEX and SAGE, respectively.

These serious discrepancies are called the solar neutrino problem and its solution has not been found yet, although neutrino oscillation is the most likely clue. Super-Kamiokande and coming experiments, SNO and BOREXINO, will challenge the problem further.

## Supernova neutrinos

The theory of the type II supernova explosion can be summarized as follows.

A star with mass larger than $8M_\odot$ (solar mass) rapidly burns out its nuclear fuels. Nuclear ashes form an onionskin-like structure: the iron core at the center, then successively silicon, oxygen, neon, carbon, helium layers

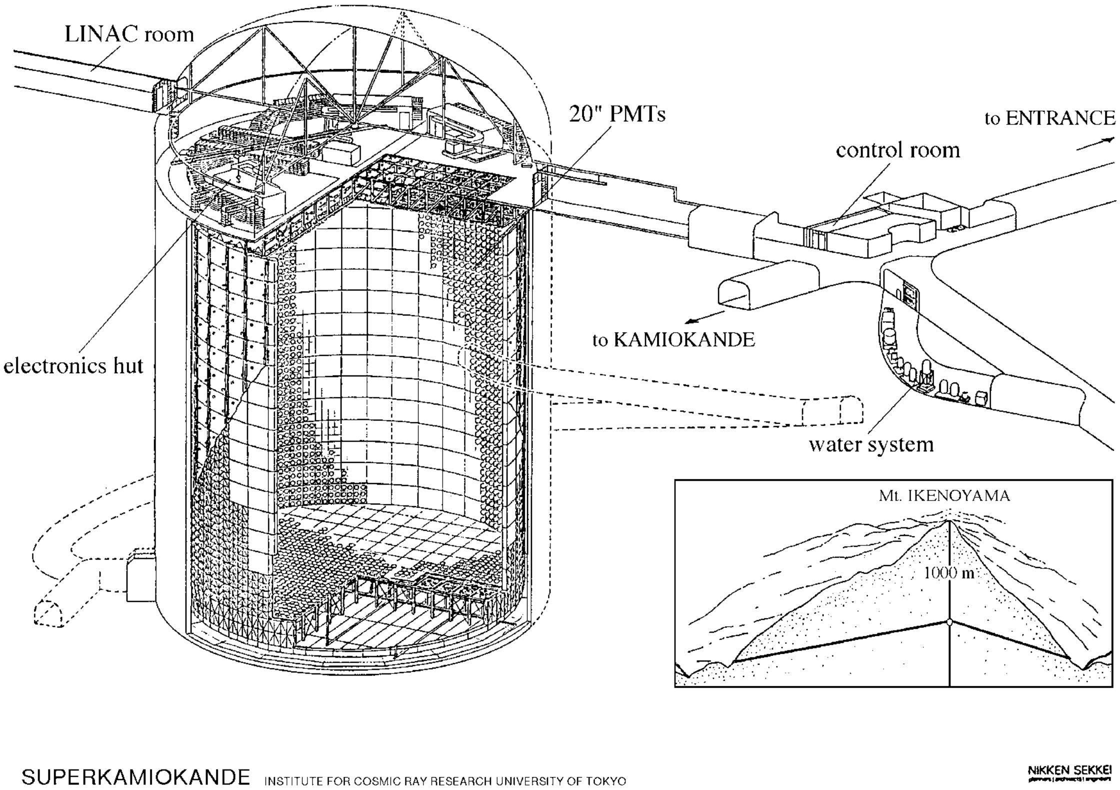


**Figure 1.** The Super-Kamiokande detector. It consists of inner and outer parts, each of which contains 32 000 tons and 18 000 tons of pure water, surrounded by 11 200 50 cm diameter photomultiplier tubes (PMTs) and 1800 20 cm diameter PMTs, respectively. A charged particle moving faster than the speed of light in water emits blue light named after the discoverer P Cherenkov with an opening angle of about 42°. The energy, direction and type of the particle are determined by measuring the arrival time, intensity and ring pattern of the Cherenkov light. The Super-Kamiokande experiment discovered the finite mass of neutrinos from detailed observation of atmospheric neutrinos.

and the hydrogen layer at the outermost layer. The central iron core becomes unstable when its mass exceeds the Chandrasekhar mass ($\sim 1.4 M_\odot$) and eventually collapses gravitationally. The central core is pressurized by falling matter, stiffened and bounces back. How large the bounce is depends on the elasticity or equation of state of the matter. The temperature rises above 100 billion kelvins ($kT \sim 10$ MeV) and the inverse beta decay process sets in:

$$\mathrm{p} + \mathrm{e}^- \longrightarrow \mathrm{n} + \nu_\mathrm{e}. \tag{11}$$

An electron neutrino burst of about 10 ms duration thus follows. It is called a neutronization burst and signals the real onset of the supernova explosion. A neutron-rich high-density ball forms which is called a proto-neutron star as it will later become a neutron star. The matter density is now above $10^{11}$ g cm$^{-3}$, which is high enough that even neutrinos frequently interact with matter and are trapped inside. Neutrinos are in approximate thermal equilibrium with electrons, protons and neutrons. Neutrinos of all kinds now evaporate from the surface of the neutron-rich, high-density sphere called a neutrinosphere, the radius of which was initially several tens of km. The underlying process for neutrino emission is the thermal one:

$$\mathrm{e}^+ + \mathrm{e}^- \longrightarrow \nu_i + \bar{\nu}_i \tag{12}$$

where $\nu_i$ denotes any of the three neutrino species and $\bar{\nu}_i$ its antineutrino. The hot proto-neutron star quickly cools down with a time scale of about 5 s, where neutrino and antineutrino pairs carry off thermal energy. Note that the proto-neutron star is still surrounded by thick falling matter. Hence heat cannot be transported by electromagnetic waves. The proto-neutron star shrinks to a radius of about 10 km and the density reaches $\sim 10^{14}$ g cm$^{-3}$, at which neutrons are packed in contact with each other. It has become a neutron star. The reverse shock produced at the core bounce, and probably the reheat caused by the outgoing neutrinos, later blow off the whole star and the explosion becomes optically visible, thus the birth of a supernova.

The total energy carried off by neutrinos, the luminosity, is equal to the gravitational potential of a neutron star with radius $R \sim 10$ km and mass $M \sim 1.4 M_\odot$:

$$L_\nu = \frac{3}{5}\frac{GM^2}{R} \simeq 3 \times 10^{53}\ \text{erg}. \tag{13}$$

The neutrino energy distribution approximately follows the Fermi–Dirac distribution,

$$\frac{dN_\nu}{dE} = 4\pi R^2 \frac{g\pi c}{(2\pi\hbar c)^3} \frac{E^2}{\exp[(E-\mu)/kT]+1} \frac{1}{4\pi D^2} \tag{14}$$

where $E$, $T$ and $R$ are the neutrino energy, temperature and radius of the neutrinosphere, respectively. $g(=1)$ is the helicity weight of the neutrino, $\mu$ the chemical potential and $D$ the distance to the supernova. The average neutrino energy is, for zero chemical potential, $\langle E \rangle \simeq 3.15kT$.

The cross sections satisfy the following inequalities: $\sigma_{\nu_e} > \sigma_{\bar{\nu}_e} > \sigma_{\nu_\mu} = \sigma_{\nu_\tau} > \sigma_{\bar{\nu}_\mu} = \sigma_{\bar{\nu}_\tau}$. Neutrinos with a smaller cross section can leave the proto-neutron star at the denser and deeper region where the temperature is higher. The average energy of those neutrinos is thus higher. According to calculations, $\langle E_{\nu_e} \rangle \sim 10$ MeV, $\langle E_{\bar{\nu}_e} \rangle \sim 15$ MeV and $\langle E_{\nu_\mu} \rangle \sim 20$ MeV. It was also found that the luminosity is equipartitioned among neutrino species, $L_{\nu_e} \simeq L_{\bar{\nu}_e} \simeq L_{\nu_\mu} \simeq L_{\bar{\nu}_\mu} \simeq L_{\nu_\tau} \simeq L_{\bar{\nu}_\tau}$.

Neutrinos from SUPERNOVA 1987A (SN1987A) were observed using the following reactions which took place in the detector water:

$$\bar{\nu}_e + p \longrightarrow e^+ + n \tag{15}$$

$$\nu_i + e^- \longrightarrow \nu_i + e^- \tag{16}$$

where $\nu_i$ is any of the neutrino species, and emitted $e^+$ and $e^-$ were detected. However, the cross section of equation (15) is almost 100 times larger than that of the elastic scattering (equation (16)), and hence almost all of the observed events were due to $\bar{\nu}_e$. There was no clear evidence that elastic-scattering events (equation (16)) had been detected.

Assume that the radius of the neutrinosphere $R$ is constant in time while its temperature $T$ behaves like $T = T_0 \exp(-t/4\tau)$. The factor 4 was introduced in order for the luminosity $L_\nu$ to take the form $\exp(-t/\tau)$, since the luminosity is proportional to $T^4$.

The combined Kamiokande and IMB data have been analyzed with an assumption that $\mu = 0$ in equation (14). The results are

$$kT_0 = 4.5^{+1.1}_{-0.9}\ \text{MeV}$$

$$\tau = 4.2^{+2.5}_{-1.5}\ \text{s}$$

$$R = 23^{+22}_{-10}\ \text{km}$$

$$L_{\bar{\nu}_e} = 5^{+8}_{-3} \times 10^{52}\ \text{erg}.$$

$L_{\bar{\nu}_e}$ was calculated from

$$L_{\bar{\nu}_e} = \int E \frac{dN_\nu}{dE\,dt} 4\pi D^2\, dE_\nu\, dt$$

where $D = 50$ kpc was assumed and $dN_\nu/dE\,dt$ is given by equation (14).

Note that the total neutrino luminosity $L_{\text{tot}}$ is given as $L_{\text{tot}} = 6L_{\bar{\nu}_e}$, which leads to

$$L_{\text{tot}} = 3^{+5}_{-2} \times 10^{53}\ \text{erg}.$$

This is in excellent agreement with the naive expectation of equation (13). The cooling time $\tau$ and the temperature $T_0$ are also quite reasonable. Thus the observations of SN1987A beautifully confirmed the basic part of the supernova theory.

More data are obviously needed for further studies of the gravitational collapse. The new detector, SUPER-KAMIOKANDE, which is 15 times larger than Kamiokande, has been in operation since 1996. If the next supernova occurs at a distance of 10 kpc, i.e. close to the Galactic center, Super-Kamiokande will observe 4000 $\bar{\nu}_e$ events (by equation (15)) and about 250 elastic events (by equation (16)). Super-Kamiokande may be able to see about 10 neutronization-burst events, too. The only question is now when the next supernova will happen.

## High-energy cosmic ray neutrinos

The CRAB NEBULA is known to emit gamma rays with energies larger than $10^{12}$ eV (TeV gamma rays). The energy spectrum was measured and found to obey a power law with a spectral index close to 2. Detailed studies together with other wavelength data revealed that TeV gamma rays are most likely produced by the inverse Compton process, namely collision of high-energy electrons ($\leq 10^{14}$ eV) with synchrotron photons or microwave background photons. Several other PULSARS have also been found as TeV gamma ray sources. Their production mechanism is considered to be the same as that for Crab Nebula. Nonthermal x-ray emission was found at the expanding shell of a supernova remnant SN1006. These x-rays are presumably synchrotron photons radiated by high-energy electrons ($\leq 10^{13}$ eV). TeV gamma rays were indeed found coming exactly from the same shell, indicating again that the inverse Compton process is responsible. TeV gamma rays are also coming from extragalactic objects, BL Lac sources Mkn421 (redshift 0.031) and Mkn501 (redshift 0.032). Their production mechanism is not clear but is presumably the inverse Compton process, too.

Hence acceleration sites of high-energy electrons have been identified. However, where are protons and other nuclei then accelerated? We know that they are dominant components of cosmic rays and moreover we know that their energies extend beyond $10^{20}$ eV. The acceleration site may be surrounded by intense photons or to a lesser extent a thick gas, i.e. optically thick, so that TeV gamma rays may have been absorbed before escaping the acceleration region. If this is the case, one expects the site to be a strong source of neutrinos, whose energies may extend as high as $10^{17}$ eV. Production processes of neutrinos are

$$p + \gamma \longrightarrow \pi^+ + n \tag{17}$$

$$\pi^+ \longrightarrow \mu^+ + \nu_\mu \tag{18}$$

$$\mu^+ \longrightarrow \bar{\nu}_\mu + e^+ + \nu_e \tag{19}$$

where $\gamma$ is an ambient photon. Muon neutrinos and electron neutrinos are produced with a ratio of 2 to 1.

The flux of these neutrinos is estimated by assuming that observed TeV gamma rays are produced not by the inverse Compton process but by the nuclear processes, namely, corresponding to equation (17),

$$p + \gamma \longrightarrow \pi^0 + p \tag{20}$$

$$\pi^0 \longrightarrow \gamma + \gamma. \tag{21}$$

By estimating somehow the optical thickness, one can relate the gamma ray flux to that of neutrinos. These estimates are, however, quite uncertain owing to the poorly known optical thickness. The energy spectrum is expected to obey a power law with a spectral index of about 2, the same as for gamma rays. The estimated fluxes of $\nu_\mu + \bar{\nu}_\mu$, $F_\nu$, are, for $E_\nu \geq 1$ TeV, $F_\nu \sim 10^{-12}$ cm$^{-2}$ s$^{-1}$ TeV$^{-1}$ for AGN 3C279 and $F_\nu \sim 10^{-11}$ cm$^{-2}$ s$^{-1}$ TeV$^{-1}$ for Mkn421 and 3C273. These numbers may be quite optimistic and could be smaller by several orders of magnitude.

Muon neutrinos from astronomical objects interact with rock in Earth and produce muons:

$$\nu_\mu + N \longrightarrow \mu^- + \cdots. \tag{22}$$

Detection of astronomical muon neutrinos adopts this reaction. A large-area muon detector is deployed deep underground in order to reduce the atmospheric muon background. Rock beneath the detector is the target. A high-energy muon produced in the rock travels a long distance upward, approximately $E_\mu/(2$ MeV$)$ g cm$^{-2}$, reaches the detector and is detected. Downward-going muons are completely swamped by atmospheric muons and cannot be detected. In order to overcome the huge background of atmospheric neutrinos, which are produced by cosmic rays in the atmosphere associated with atmospheric muons, a high-energy threshold must be set, say 1 TeV–100 TeV, depending on what objects are to be observed. A rough estimate of the observed rate is

$$N_\mu \sim \frac{0.5\ \text{events}(E_\mu \geq 1\ \text{TeV})}{10^5\ \text{m}^2\ \text{yr}} \frac{F_\nu(\geq 1\ \text{TeV})}{10^{-12}\ \text{cm}^{-2}\ \text{s}^{-1}}. \tag{23}$$

The largest detector under test is the AMANDA-B (figure 2) detector which is located 1500 m under Antarctic ice. The detector has cylindrical shape with 120 m radius and 400 m height. Cherenkov light emitted in the ice is detected with a number of photomultipliers. AMANDA-B may still be too small. There is a plan to enlarge it to a size of 1 km$^3$, and underwater projects of similar size are being seriously considered.

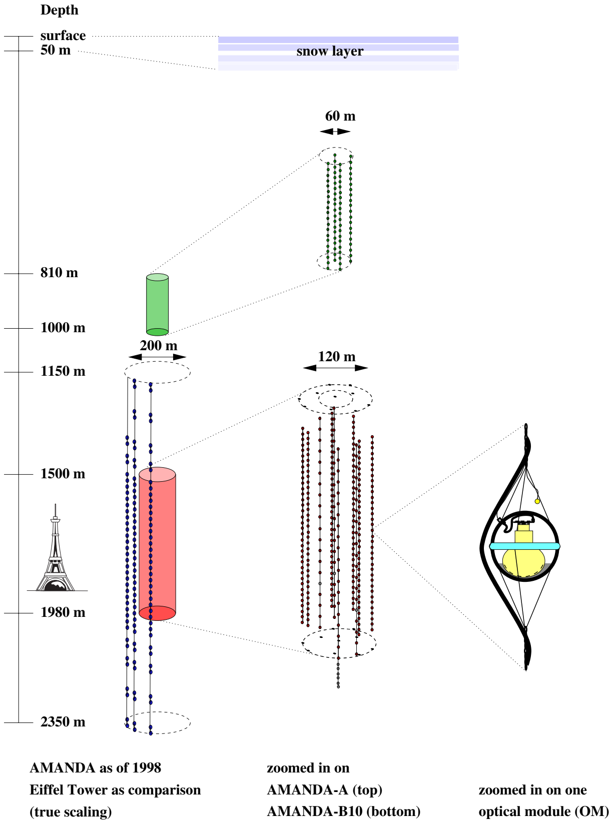


**Figure 2.** The AMANDA-B detector. A number of optical modules (20 cm diameter photomultipliers) are deployed within a volume 120 m in diameter and 400 m high. A high-energy upward-going muon produced by a cosmic ray muon neutrino in the rock passes through the region and emits Cherenkov light which is detected by optical modules. The direction and energy are obtained by measuring arrival time and intensity of the Cherenkov light. It could be extended to a km$^3$ detector.

## Relic neutrinos

In the hot and dense universe up to about 1 s after the big bang, electrons and neutrinos were in thermal equilibrium. They were interacting each other,

$$e^+ + e^- \longleftrightarrow \nu_i + \bar{\nu}_i \tag{24}$$

where $\nu_i$ is a neutrino of any kind.

Surprisingly, the environment at that time was much more modest than that in the core of the supernova. The temperature was 10 billion kelvins ($kT \sim 1$ MeV), which is about 5 times lower, and the energy (or mass) density was almost 9 orders of magnitude less than those of a hot neutron star.

The universe expanded rapidly and hence cooled down (see UNIVERSE: THERMAL HISTORY). The thermal equilibrium could not hold and eventually the reaction from right to left of equation (24) ceased. Neutrinos were left behind in the universe and their energies became lower and lower until the present day. Electrons and positrons rapidly annihilated into two photons whose energies were also redshifted to a wavelength of a few mm. These photons are called the COSMIC MICROWAVE BACKGROUND (CMB) and detailed studies are being carried out. Relic neutrinos and photons obey Fermi–Dirac and Planck distributions, respectively. The number densities are

$$n_\nu = 1.5\frac{\zeta(3)}{\pi^2(\hbar c)^3}(kT_\nu)^3 \tag{25}$$

$$n_\gamma = 2\frac{\zeta(3)}{\pi^2(\hbar c)^3}(kT_\gamma)^3 \tag{26}$$

where $\zeta(3)/\pi^2 = 0.121\ldots$. The neutrino number density corresponds to one species only. There is a simple relation between the two temperatures,

$$\frac{T_\nu}{T_\gamma} = \left(\frac{4}{11}\right)^{1/3} = 0.714. \tag{27}$$

The CMB temperature was measured to be 2.74 K. Hence $n_\gamma = 420$ cm$^{-3}$ which is in good agreement with measurement. The neutrino temperature and number density per species should therefore be 1.96 K (0.000 17 eV) and $n_\nu = 115$ cm$^{-3}$, respectively.

These relic neutrinos must exist in the present universe. Recently the Super-Kamiokande experiment has discovered the finite neutrino mass from a detailed study of atmospheric neutrinos. However, the experiment is sensitive only to the mass-squared difference, not to each mass value. The measured value is $\Delta m^2$ ($\equiv m^2_{\nu_\tau} - m^2_{\nu_\mu}$) = (1.5–6) $\times 10^{-3}$ eV$^2$. From this the tau neutrino mass is constrained as $m_{\nu_\tau} \geq 0.04$ eV, which is much larger than the temperature 0.000 17 eV. Thus the relic tau neutrinos should be nonrelativistic. Their velocity is about 300 km s$^{-1}$ which is determined from other astronomical factors such as the Earth's motion in the Galaxy.

The neutrino mass could be as large as a few eV. If this is the case, the relic neutrinos are the hot dark matter component and could significantly contribute to the energy density of the universe.

There is at present no idea how to detect such low-energy neutrinos.

*Bibliography*

General review:

Totsuka Y 1992 *Rep. Prog. Phys.* **55** 377

High-energy cosmic ray neutrinos:

Gaisser T K, Halzen F and Stanev T 1995 *Phys. Rep.* **258** 173

Solar neutrinos and SN1987A:

Bahcall J N 1989 *Neutrino Astrophysics* (Cambridge: Cambridge University Press)

Neutrino physics and neutrino astronomy:

Winter K (ed) 1991 *Neutrino Physics* (Cambridge: Cambridge University Press)

Recent results on neutrino physics and astrophysics:

Suzuki Y (ed) 1999 *Proc. 18th Int. Conf. on Neutrino Physics and Astrophysics* (Amsterdam: Elsevier)

*Yoji Totsuka*