ELUSIVE GHOSTLY NEUTRINOS

3/8/2010

INTRODUCTION

At every second of time, hundreds of billions of neutrinos pass through each square inch of our bodies. They come from above us during the day and from below us at night, when the sun is shining on the other side of the Earth. They rarely interact with matter. Just a single neutrino out of 10^{11} passing through the Earth interacts with it.

The sun is a large solar neutrinos factory, and the neutrinos that it produces proceed through the Earth without significant interaction. Cosmic neutrinos also reach us from a recently observed Black Hole at the center of our galaxy.

Neutrinos and their anti-matter counterpart, anti-neutrinos, are subatomic particles that interact so rarely with other matter they can pass untouched through a wall of lead stretching from the earth to the moon. Neutrinos are produced during nuclear fusion, the reaction that lights the sun and other stars. Anti-neutrinos are created in fission reactions, such as those that drive nuclear power plants, and in radioactive nuclei, such as uranium and thorium, that emit an electron and an anti-electron neutrino when they decay.

Anti-neutrinos, like neutrinos, come in three different types or "flavors," electron, muon and tau, with the anti-electron neutrino, or geoneutrino, being by far the most common. Geoneutrinos can be detected and measured via a distinctive reaction signature after the subtraction of anti-neutrinos captured from nearby reactors and in background events from alpha particles.

Particle accelerators are used to produce terrestrial neutrinos. Fission reactors also generate terrestrial antineutrinos in the radioactive decay of the fission products produced by the fission process. In fact they carry 5 percent of the fission energy produced. If the fission energy release per reaction is 200 MeV, the fission antineutrinos carry five percent of the fission energy at about 10 MeV.

From that perspective, nuclear fission reactors are a beacon radiating antineutrinos to the rest of the universe announcing humanity as an intelligent technological civilization that has mastered the control of fission energy. They emit a high source of antineutrinos: 10^{21} antineutrinos / sec.

Having been generated from nuclear reactions in stellar formations since the birth of the Universe, and interacting so little with other matter making them hard to detect, yet possessing a distinct mass, it may be plausible to infer that their accumulation over time may be at the base of the elusive dark matter in the Universe.

The imbalance of matter and antimatter in the universe suggests a theory that the Universe’s mass may have been produced from the decay of neutrinos and antineutrinos during the postulated Big Bang event. If that were the case, then they may have been the origin of everything around us and that we are descendants of the neutrinos.

NEUTRINOS IN THE STANDARD MODEL

According to the Standard Model of the constitution of matter, neutrinos are a type of lepton. Possessing no electrical or strong charge they almost never interact with any other particles. Most neutrinos pass right through the Earth without interaction.

Neutrinos are produced in a variety of interactions, especially in particle decays. In fact, it was through a careful study of radioactive decays that physicists represented by Wolfgang Pauli hypothesized the neutrino's existence along the following line of a thought experiment:

1. In a neutron rich radioactive nucleus, a neutron at rest with zero momentum decays, releasing a proton and an electron.
2. Because of the law of conservation of momentum, the resulting products of the decay must have a total momentum of zero, which the observed proton and electron clearly do not.
3. Therefore, we need to infer the presence of another particle with appropriate momentum to balance the event.
4. An antineutrino is released carrying the energy.

An example of such a reaction is the beta decay of the tritium isotope of hydrogen:

$$ {}_1T^3 \rightarrow {}_2He^3 + {}_{-1}e^0 + \nu_e^* \qquad (1) $$

Because neutrinos were produced in great abundance in the early universe and rarely interact with matter, there are a lot of them around. Their small mass, but the large energy that they carry, as well as their tremendous numbers may be contributing to the total mass of the universe and affect its expansion.

Neutrinos are leptons that ignore the electromagnetic and strong nuclear forces. Accordingly, they interact weakly with matter. They are of three families or flavors: the electron neutrino, produced with a positron, or in the form of an antineutrino with an electron, in the weak interaction force process of radioactive decay. The muon and tau families or flavors of neutrinos result from the decay events that produce muons and tau particles. These cosmic ray particles are heavier than the electron.

Matter constituents Fermions			
Quarks	First generation	Second generation	Third generation
	Up **u**	Charm **c**	Top **t**
	Down **d**	Strange **s**	Bottom **b**
Leptons	Electron $\mathbf{e^-}$	Muon $\boldsymbol{\mu^-}$	Tau $\boldsymbol{\tau^-}$
	Electron neutrino $\boldsymbol{\nu_e}$	Muon neutrino $\boldsymbol{\nu_\mu}$	Tau neutrino $\boldsymbol{\nu_\tau}$

Force carriers Bosons		
Photon **γ**	Gluon **g**	Bosons $\mathbf{W^+}$ $\mathbf{W^-}$ $\mathbf{Z^0}$

Figure 1. The Standard Model matter constituents and charge carriers showing the electron, muon and tau neutrinos.

Neutrinos from the supernova event SN 1987A reached the Earth on February 23, 1987, at 11:19 pm, GMT, 6 hours before the light from the exploding star was seen.

An article in American Scientist by M. A. Ruderman and A. H. Rosenfeld about neutrinos inspired the following scientific poem:

COSMIC GALL, By John Updike

Neutrinos, they are very small.
They have no charge and have no mass
And do not interact at all.
The Earth is just a silly ball
To them, through which they simply pass,
Like dustmaids down a drafty hall
Or photons through a sheet of glass.
They snub the most exquisite gas,
Ignore the most substantial wall,
Cold-shoulder steel and sounding brass,
Insult the stallion in his stall,
And, scorning barriers of class,
Infiltrate you and me! Like tall
And painless guillotines, they fall
Down through our heads into the grass.
At night, they enter at Nepal
And pierce the lover and his lass
From underneath the bed –you call
It wonderful; I call it crass.

DETECTION OF NEUTRINOS

The detection of neutrinos can depend on the reversal of a reaction already known to occur between a proton and a negative muon, producing a neutron and a muon neutrino:

$$ {}_1H^1 + \mu^- \rightarrow {}_0n^1 + \nu_\mu \quad (2)$$

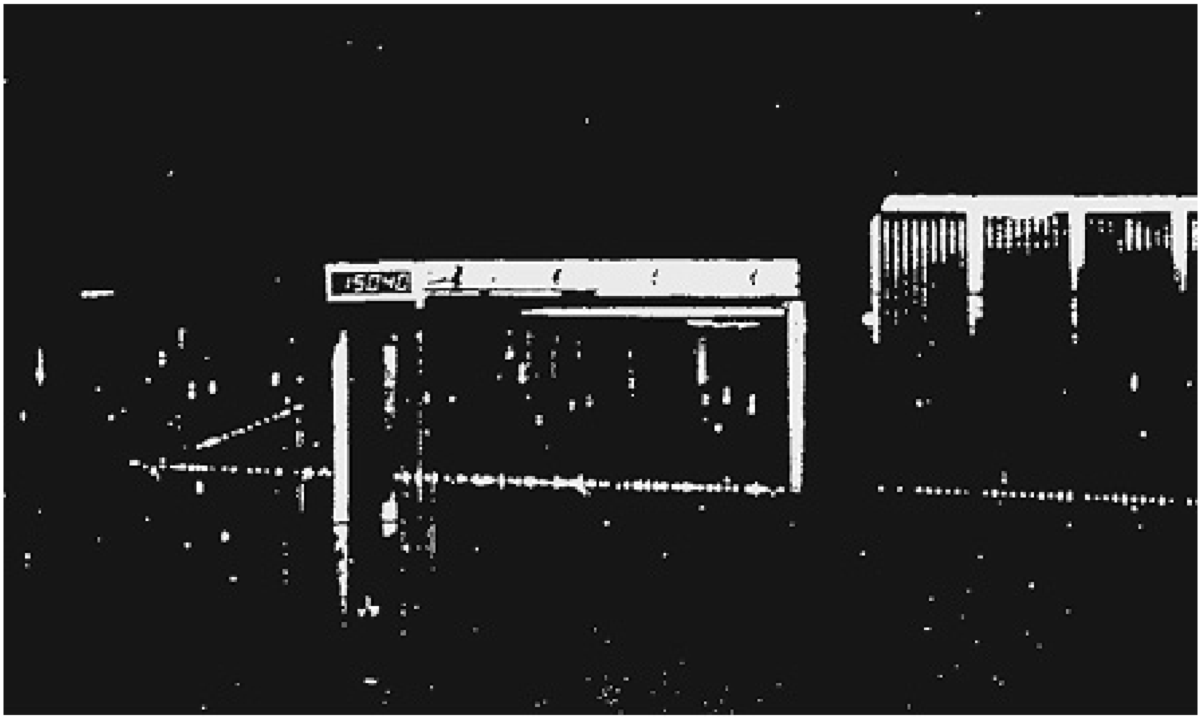

Figure 2. A high neutrino interaction in an aluminum spark chamber at Columbia University.

The reverse reaction occurs when a neutrino interacts with a neutron leading to the generation of a proton and a negative muon:

$$ {}_0n^1 + \nu_\mu \rightarrow {}_1H^1 + \mu^- \qquad (3) $$

The neutrino itself cannot be seen, but the negative muon can be seen in a spark chamber. In this case a collection of parallel charged plates shows the path of the particle as a set of continuous discharges as the muon moves between them. Figure 2 shows a high neutrino interaction in an aluminum spark chamber at Columbia University.

NEUTRINOS OCCURRENCE

British astrophysicist Sir Arthur Eddington in 1920 proposed that the sun generates heat and light by fusing H into He. Every time four H nuclei fuse to become a single nucleus of He in the sun's core, an amount of mass is converted into energy.

In 1930, the Austrian physicist Wolfgang Pauli conjured up the notion of a novel subatomic particle to solve a puzzle about the apparent non conservation of energy in radioactive beta decays.

A few years later, Italian physicist Enrico Fermi named the particle, which has no electrical charge, the neutrino, or “little neutral one.” At this time there was no conclusive evidence that the particle existed, and most scientists initially thought it may be impossible to ever detect it.

Hans Bethe in 1939 in a paper: "Energy Production in Stars," laid out details of how H is fused into He in stars like the sun. His work lead to the understanding that the fusion process releases not only energy but also the particles that Wolfgang Pauli conjectured their presence. Each time four H nuclei fuse into a He nucleus, two neutrinos are emitted.

In "Project Poltergeist" conducted at the Savannah River nuclear reactors site, Frederick Reines and Clyde Cowan built a neutrino detector and proved that the neutrino actually exists.

THE SOLAR NEUTRINO PROBLEM

Scientists believed they understand the thermonuclear reactions occurring at the center of the sun, they know the temperature of its core, which dictates the reaction rate, and consequently know the rate at which the solar neutrinos should be emitted. The problem was that the existing theories predicted two times the number of solar neutrinos detected on Earth.

The proton-proton fusion reaction:

$$ {}_{1}H^{1} + {}_{1}H^{1} \rightarrow {}_{1}D^{2} + {}_{+1}e^{0} + \nu_{e} \tag{4} $$

is presumed to dominate the sun's energy production process. The released "pp neutrinos" are thought to account for more than 90 percent of the neutrino flux from the sun. Several experiments had been set up for their detection.

These experiments aimed at resolving the "solar neutrino problem." The standard solar neutrino model predicted that gallium detectors should see solar neutrinos at the rate of:

$$ 132 \pm 7 \text{ SNU} $$

where: 1 SNU = 1 Solar Neutrino Unit
= one neutrino capture per second for every 10^{36} atoms of relevant target isotopic species of the detector from the reaction:

$$ \nu_{e} + {}_{31}Ga^{71} \rightarrow {}_{32}Ge^{71} + {}_{-1}e^{0} \tag{5} $$

After 295 days of exposure, the Gallex experiment collaboration reported a neutrino capture rate of:

$$ 63 \pm 16 \text{ percent} $$

of that predicted by the standard solar model.

Efforts have been made to explain the discrepancy, by lowering the temperature estimates of the sun's core: the cool sun theories, but that would not explain the luminosity of the sun.

If the Gallex and Sage experiments were discovering a severe dearth of solar neutrinos, that was be suggesting the presence of:

1. Something quite new about the sun.
2. Something new about neutrinos.

An explanation based on quantum mechanics is that neutrinos oscillate, where one kind of neutrinos turns into another kind. For instance, one can think about electron neutrinos turning into muon neutrinos. The detectors would be detecting the electron neutrinos, but not the muon neutrinos.

Results from the Sudbury Neutrino Observatory (SNO) eventually suggested the detection of neutrinos of different flavors: electron neutrinos from the sun, muon-neutrinos, and tau-neutrinos. The results suggested that the electron neutrinos actually change into other families or flavors on their long trip from the sun’s interior. This explained the mystery of the missing solar neutrinos.

HOMESTAKE MINE BROOKHAVEN NATIONAL LABORATORY, BNL EXPERIMENT, USA

Ray Davis as an experimentalist and John Bahcall as a theoretician proposed in 1964 at the Brookhaven National Laboratory, BNL that a study of neutrinos emitted from the sun could check a theoretical model of nuclear fusion in its core.

John Bahcall had created a detailed mathematical model of fusion reactions in the sun's interior. He took into account a variety of nuclear reactions at energies where measurements were difficult. He drew upon Hans Bethe's earlier work, including his estimate of the sun's core temperature. According to the model, the flux of solar neutrinos on Earth would be 10^{13} solar neutrinos / (cm^2.second).

At the bottom of the Homestake gold mine in Lead, South Dakota, sheltered from the confusing background cosmic radiation, Ray Davis oversaw the construction of a giant neutrino detector: a tank of cleaning fluid roughly as big as an Olympic size swimming pool. The cleaning fluid contained mostly Cl, which occasionally turns into a radioactive isotope of Ar gas when struck by solar neutrinos. John Bahcall has calculated that roughly 10 atoms of radioactive Ar will be produced each week, and Ray Davis was confident he can extract and measure them.

As of 1968, the Homestake experiment had detected only about 1/3 as many radioactive Ar nuclei as predicted by the theoretical model. Other scientists called the discrepancy “The Solar Neutrino Problem,” and a “Social embarrassment.” The popular press called it “The Mystery of the Missing Neutrinos.”

In the two following decades after their disappointing results, Ray Davis fine-tuned his solar neutrino detector, and John Bahcall refined and checked his calculations. Hundreds of other physicists, chemists, and astronomers also examined the work, but no one could find significant fault with either the apparatus or the calculations.

NEUTRINO OSCILLATIONS

Russian physicists Vladimir Gribov and Bruno Pontecorvo, suggested that Ray Davis and John Bahcall's missing solar neutrinos can be explained by a phenomenon of "neutrino oscillations": as they travel to Earth, some of the neutrinos made inside the sun oscillate, or change, into types of neutrinos that Davis's apparatus could not detect.

It was known since mid century that different types of neutrinos exist: electron neutrinos ν_e, muon neutrinos ν_μ , and tau neutrinos ν_τ.

Initially, few physicists took stock in Vladimir Gribov and Bruno Pontecorvo's idea. According to the Standard Model, the cornerstone of modern particle physics, neutrino types are distinct and can never change one into another, since they were thought to be massless and traveling at the speed of light, hence time was frozen for them.

Based on Gribov and Pontecorvo's suggestion, Lincoln Wolfenstein in 1978 and Stanislav Mikheyev and Alexei Smirnov in 1985 showed how electron neutrinos created at the sun's core might switch their quantum states from electron neutrinos ν_e, to muon neutrinos ν_μ, and tau neutrinos ν_τ. as they interacted with other matter in the sun and traveled outward to its surface.

If neutrinos change flavor, according to quantum theory, then they must possess a mass. If they possess a mass, then there is something that needs to be modified in the Standard Model of particle physics. This is a vast field for theoreticians to describe a universe that is getting more and more interesting to describe and study.

Regardless, it has inspired another neutrino poem written for those interested in the mystery of the solar neutrinos and the measurement of the Solar Neutrinos Units (SNUs):

STALKING SOLAR NEUTRINOS, By Barbara Goss Levi

In caverns deep under the ground
They hunt SNUs like hungry bloodhounds.
But maybe the prey
Can change 'long the way
And sneak by without being found.

Who would have thought that they could change their flavors while travelling from the sun to the Earth?

ATMOSPHERIC NEUTRINO ANOMALY, THE KAMIOKANDE EXPERIMENT, JAPAN

In 1985, using an experiment called Kamiokande, sited in the Kamioka Mozumi mine in Japan, Masatoshi Koshiba and his colleagues detected far fewer atmospheric neutrinos or neutrinos produced by the collision of cosmic rays with the Earth's atmosphere than they expected to see. While atmospheric neutrinos are a different type from the electron neutrinos produced by the sun, the so-called "Atmospheric neutrino anomaly" was similar to the solar electron neutrino problem.

SUPER KAMIOKANDE EXPERIMENT, JAPAN

A scaled-up version of Kamiokande called Super Kamiokande reported in 1998 on more than 500 days of data collecting. The detector was so large that it could tell what direction atmospheric cosmic ray neutrinos were coming from, and it picked up far fewer neutrinos traveling from the other side of the Earth than from the sky directly above. There was evidence that many of the atmospheric neutrinos from the other side of the Earth have changed into a different type of neutrino during their journey. This confirmation of neutrino oscillations carried a profound implication: the Standard Model of particle physics had to be modified, suggesting that neutrinos did not travel at the speed of light, that they had a time frame, could change their flavor, and consequently possessed a mass.

SUDBURY NEUTRON OBSERVATORY, SNO EXPERIMENT, CANADA

This experiment was located in Ontario, Canada and consisted of a 40-foot diameter sphere filled with heavy water, D_2O, buried 2,000 meters underground in a Nickel mine, and surrounded by photo multiplier tubes to detect the Cerenkov radiation emitted by neutrinos interacting with the deuterium in heavy water, D_2O.

In 2001-2002, the Sudbury Neutrino Observatory (SNO), the first neutrino detector that can pick up all three known types of neutrinos, resolved conclusively that, in the case of the missing solar neutrinos, the neutrinos are not, in fact, missing.

SNO found that the total number of neutrinos from the sun is remarkably close to what John Bahcall predicted three decades earlier. Ray Davis's experimental work was vindicated as well, because SNO found that only about 1/3 of the solar neutrinos that reached the Earth were still in the same state of electron neutrinos that Ray Davis could measure in the Homestake mine experiment, while 2/3 of them changed their type, flavor or oscillated during their journey.

NOBEL PRIZE AWARD

The Nobel Prize in Physics in 2002 was awarded to Ray Davis in the USA and Masatoshi Koshiba, the leader of the Kamiokande group in Japan. The Nobel Committee citation praised them “For pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos.” The award was a tribute to their colleagues and the many dedicated scientists whose work led to a fundamental shift in particle physics.

NEUTRINO DETECTION EXPERIMENTS

COWAN AND REINES EXPERIMENT

The ingenious experiment by Cowan and Reines at Hanford, Washington, depended on the reaction between an antineutrino from the beta decay of the fission products in a fission reactor and a proton creating a neutron and a positron:

$$^{*}\nu_e + {}_1H^1 \rightarrow {}_0n^1 + {}_{+1}e^0 \tag{6}$$

The positron meets its antiparticle the electron in the body of a detector containing H_2O and cadmium to absorb the emitted neutrons. The positron meets an electron, which is its antiparticle. The result is a matter-antimatter annihilation process in which the mass of the positron and the mass of the positron are totally convert into electromagnetic radiation in the form of two gamma ray photons:

$$_{+1}e^0 + {}_{-1}e^0 \rightarrow \gamma + \gamma \tag{7}$$

These gamma photons are detected by surrounding scintillation detectors after a 10^{-9} second time delay.

The cadmium in the water next absorbs the emitted neutron, in turn emitting gamma photons, but after 10^{-5} second.

$$_0\mathrm{n}^1 + {}_{48}\mathrm{Cd}^{114} \rightarrow {}_{48}\mathrm{Cd}^{115} + \gamma \tag{8}$$

The coincidence detection of these two events by the scintillation detector implies neutrino detection.

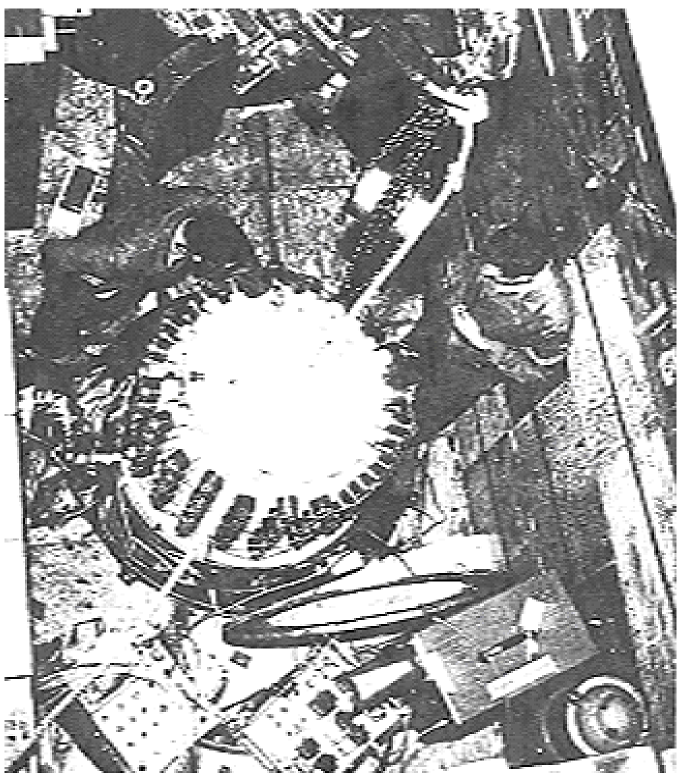

Figure 3. The scintillation counter in the Reines and Cowan experiment for neutrinos detection. The scintillation counter is the cylindrical object at the bottom of the figure.

THE GALLEX SOLAR NEUTRINO EXPERIMENT

The GALLEX (GALLium EXperiment) detector contained 30 tons of Gallium, and sat in a tunnel in a laboratory underneath the Gran Sasso d'Italia, a 2,900 meter high peak in the Appennine Mountains, where movie actor Sylvester Stallone's "Cliff Hanger" movie was filmed, northeast of Rome.

THE SAGE EXPERIMENT

The SAGE (Soviet American Gallium Experiment) was a Gallium experiment, located at the Baksan Neutrino Observatory under Mt. Andyrchi in the Caucasus, and operated with 57 tons of gallium.

THE LAKE BAIKAL EXPERIMENT

This experiment was conducted at the bottom of Russia's frigid Lake Baikal. The thickness of the lake's water absorbed cosmic particles, but neutrinos were able to penetrate it.

HOMESTAKE GOLD MINE EXPERIMENT

This experiment, now ended, was the first to detect solar neutrinos in the early 1970s. The Homestake detector, pioneered by Nobel laureate in physics Raymond Davis Jr., consisted of a tank of 615 tons of perchloro-ethylene, a dry cleaning fluid, surrounded by another ordinary water tank. The tank was situated in the Homestake gold mine in Lead, South Dakota. About twice every three days, a neutrino would interact with a nucleus of chlorine in the liquid and produce a nucleus of radioactive argon.

Raymond Davis developed techniques to extract the few atoms of radioactive argon created each month by flushing them with He gas, and count their radioactivity. He observed about 1/3 of the expected solar neutrinos. This led to the famous "solar neutrino problem," which was resolved in 2001-2002 by the Sudbury Neutrino Observatory (SNO) experiment in Canada.

It involved the Brookhaven National laboratory (BNL) solar neutrino detector. It was composed of a tank 20 feet in diameter and 48 feet in length containing 10,000 gallons of perchloro-ethylene, a dry-cleaning fluid containing substantial amounts of chlorine. It was located 4,850 feet underground at Lead, South Dakota's Homestake gold mine for a duration of 20 years. The underground location was meant to minimize the noise caused by cosmic rays, which are stopped by the overlaying rock. This detector was designed to observe the solar neutrino flux by the capture of neutrinos to form radioactive argon by the reaction with the chlorine in perchloro-ethylene:

$$\nu_e + {}_{17}\mathrm{Cl}^{37} \rightarrow {}_{18}\mathrm{Ar}^{37} + {}_{-1}\mathrm{e}^{0} \tag{9}$$

Every 2 months, the quantity of argon indicated the number of neutrinos collisions, which was extrapolated to the total number of neutrinos passing through the tank.

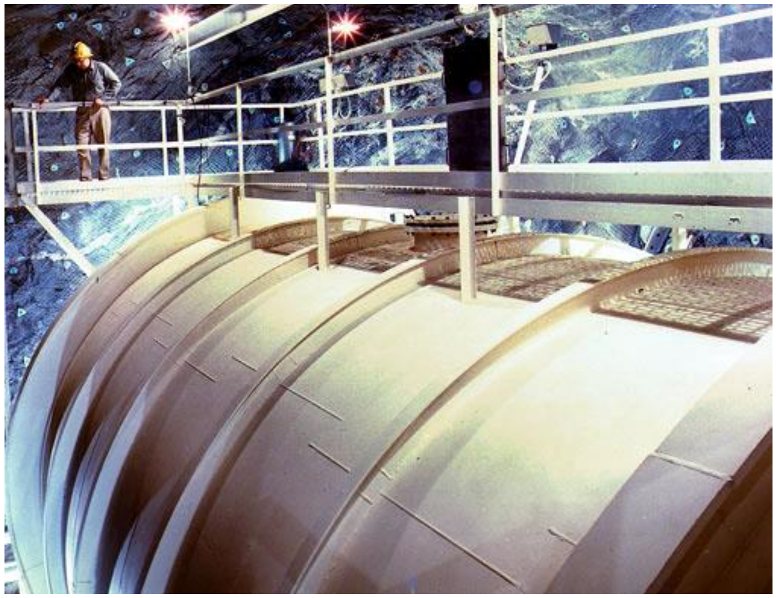

Figure 4. The Homestake gold mine solar neutrino experiment in South Dakota, USA. Source: BNL.

KAMIOKA LIQUID SCINTILLATOR ANTINEUTRINO DETECTOR, KAMLAND DETECTOR

An international team of physicists completed construction on the Kamland detector in 1997 on the Japanese island of Honshu. This experiment targeted antineutrinos, the antimatter opposites of neutrinos, which signal the latter's presence.

KamLAND consists of a weather balloon, 13 meters or 43 feet in diameter, filled with about one thousand ton of liquid scintillator, a chemical soup that emits flashes of light when an incoming anti-neutrino collides with a proton. These light flashes are detected by a surrounding array of 1,879 photomultiplier light sensors which convert the flashes into electronic signals that computers can analyze. The photomultipliers are attached to the inner surface of an 18 meters in diameter stainless steel sphere and separated from the weather balloon by a buffering bath of inert oil and water which helps suppress interference from background radiation.

The detector used a telescope made of 1,000 tons of mineral oil and benzene in a stainless steel tank two thirds of a mile below the Earth's surface to measure antineutrinos issuing from nuclear power reactors and natural nuclear reactions such as the decay of the radioactive isotopes in the Earth’s core and mantle.

In July 2005, Kamland scientists measured the Earth's total radioactivity for the first time. Their findings will allow them to better understand what keeps the planet warm, the volcanic activity, the continental drift, and the Earth’s magnetic field churning and the core dynamo: phenomena that enable life on Earth. Until this discovery, geologists relied on earthquakes’ seismic data to estimate the planet's radioactivity.

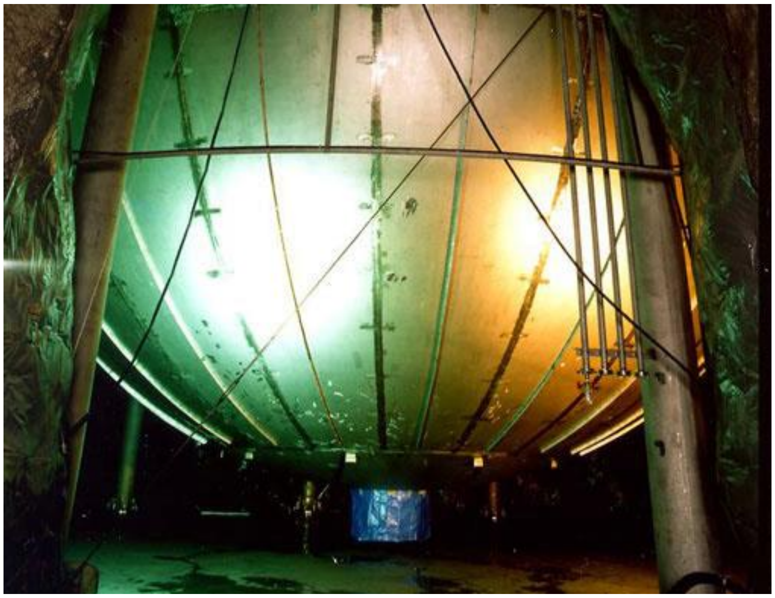

Figure 5. The Kamland antineutrino detector, on the Honshu Island, Japan.

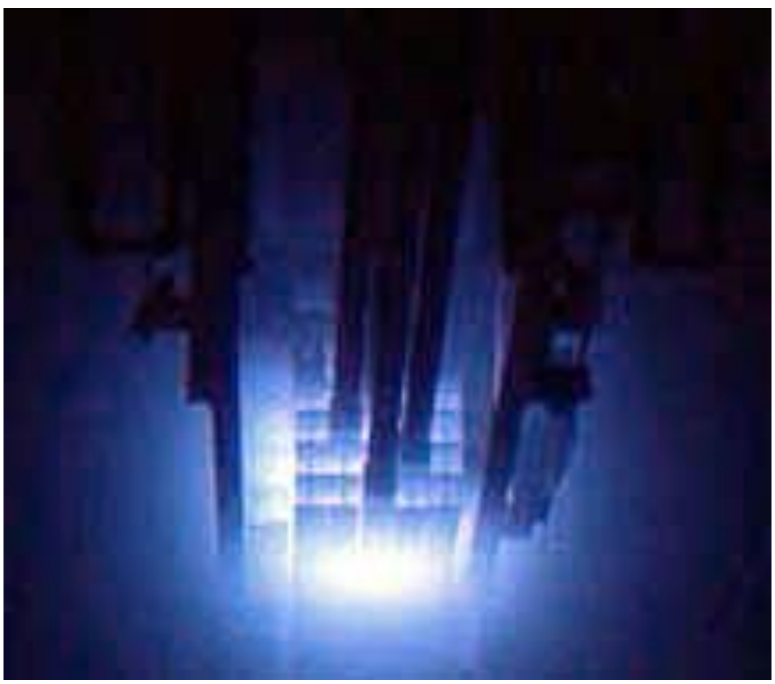

Figure 6. Cerenkov radiation emitted by electrons moving in water of a pool type research fission reactor.

THE MiniBooNE EXPERIMENT AT FERMILAB

This experiment at the Fermi National Accelerator Laboratory, Fermilab, in Batavia, Illinois, investigates the oscillation of neutrinos from one type to another. Since 2003, it has observed neutrinos created from protons in Fermilab's particle booster, part of the system that the laboratory normally employs to accelerate protons to higher energies for other experiments.

MiniBooNE is a 40 feet diameter spherical steel tank filled with 800 tons of mineral oil and lined with 1,280 phototubes that produce a flash of Cerenkov light when charged particles travel through them. Analysis of these Cerenkov radiation flashes provide information about the nonzero status of the neutrino mass.

Figure 7. Phototubes being adjusted in the MiniBooNE experiment at Fermi Lab, Batavia, Illinois.

MAIN INJECTOR NEUTRINO OSCILLATION SEARCH, MINOS DETECTORS

MINOS is a two detector experiment at Fermilab that began studying neutrino oscillations in 2003. It uses a beam of neutrinos that first pass through a detector at Fermilab and then through another detector hundreds of miles away deep within the Soudan Iron Mine in northern Minnesota. The distance between the two detectors maximizes the probability that the neutrinos will have revealing interactions over the course of their journey.

An international collaboration of particle physicists at Fermilab uses MINOS to investigate the puzzle of neutrino mass. The 98 feet long detector consists of 486 massive octagonal planes, lined up like the slices of a loaf of bread. Each plane is made of a sheet of steel covered on one side with a layer of plastic that emits light when struck by a charged particle. MINOS is meant to help researchers answer some of the fundamental questions of particle physics, such as how particles acquire mass.

Figure 8. Inside of MINOS detector setup at Fermilab.

THE SUPER KAMIOKANDE EXPERIMENT

This detector began operating in 1996, half a mile underground in a zinc mine in Kamioka, Japan. Japanese and American scientists erected a huge tank of water 138 feet tall to hunt for neutrinos. The walls, ceiling, and floor of the 12.5 million gallons tank were lined with 11,242 light sensitive phototubes. These picked up and measured bluish streaks of light in the form of Cerenkov radiation, which is left behind as neutrinos travel through the water.

Super Kamiokande detected neutrinos that nuclear interactions in the sun and the cosmic rays interactions in the Earth's atmosphere produce. In 2001, after several promising discoveries related to potential neutrino mass, the Super Kamiokande was crippled when several thousand of its light detectors exploded. Repairs on the detectors were completed in 2007.

The experiment started operation in 1996 and contained 50,000 tons of ultra pure water. By 1998 the experiment had gathered sufficient evidence of neutrino oscillations, which is the metamorphosis of one neutrinos subspecies or flavor into another. Starting 1999, man-made neutrinos pulses created 250 kilometers away at the KEK particle accelerator in Tsukuba, were directed towards it. The 11,000 photo multiplier tubes meant to detect solar neutrinos could more easily detect those from the KEK to Kamioka or K2K experiment.

Over two and a half years, Super-K detected 56 K2K neutrinos, compared with 81 expected in the absence of neutrinos oscillations. This suggested new physics; implying that on the way to Kamioka one third of the neutrinos oscillate to a flavor that Super-K could not detect.

A new experiment was planned designated as JHF-Kamioka. It would sent a 10 times more intense neutrino beam from a new accelerator being built at Tokaimura, 300 kilometers away. Long range plans call for the construction of Hyper-Kamiokande which would contain 20 times the water content of Super-K at 1 megaton of pure water.

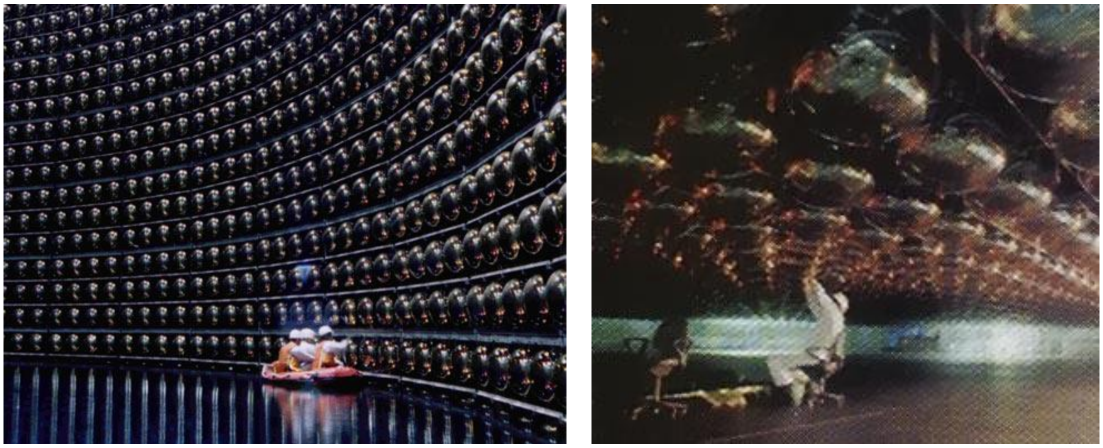

Figure 9. The Super Kamiokande array of detectors, Japan.

THE SUDBURY NEUTRINO OBSERVATORY, SNO

The Sudbury Neutrino Observatory (SNO) is a collaborative effort among physicists from Canada, the UK, and the USA, using 1,000 tons of heavy water, D_2O and almost 10,000 photo detectors. These measure the flux, energy, and direction of solar neutrinos, which originate in the sun. SNO, located 6,800 feet underground in an active Ontario nickel mine, can also detect the other two types of neutrinos, muon neutrinos and tau neutrinos.

In 2001, just two years after the observatory opened, physicists at SNO solved the mystery of the "missing solar neutrinos." They found that the answer does not originate with the sun, where many physicists had suspected that solar neutrinos undergo changes, but with the journey they take from the core of the sun to the Earth where they undergo oscillations changing their flavors from one type of neutrino to another.

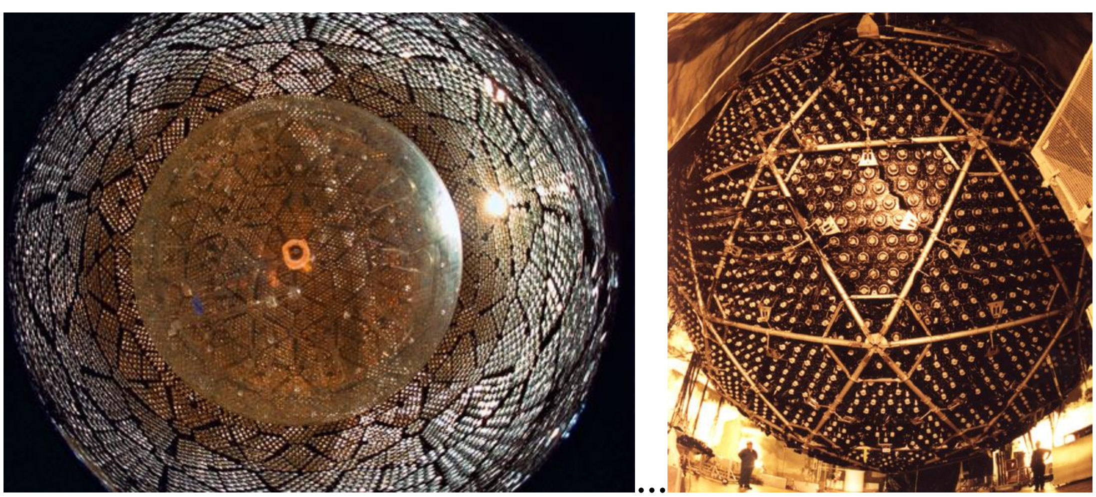

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Figure 10. Overall view of the Sudbury Neutrino Observatory, SNO, Canada.

COSMIC NEUTRINOS: THE ANTARCTIC MUON AND NEUTRINO DETECTOR ARRAY, AMANDA

Researchers from the USA, Belgium, Germany, and Sweden have been trying to observe the most energetic astronomical phenomena and objects that cannot be seen with ordinary telescopes by observing neutrinos and muons.

The instrument used is The Antarctic Muon and Neutrino Detector Array (Amanda). Three stages of the experiment are shown in the figure: Amanda-A with 4 strings of instruments, Amanda-B with 10 strings, and Amanda II with 3 strings measuring the characteristics of ice above it and 6 strings forming a cylinder around Amanda-B.

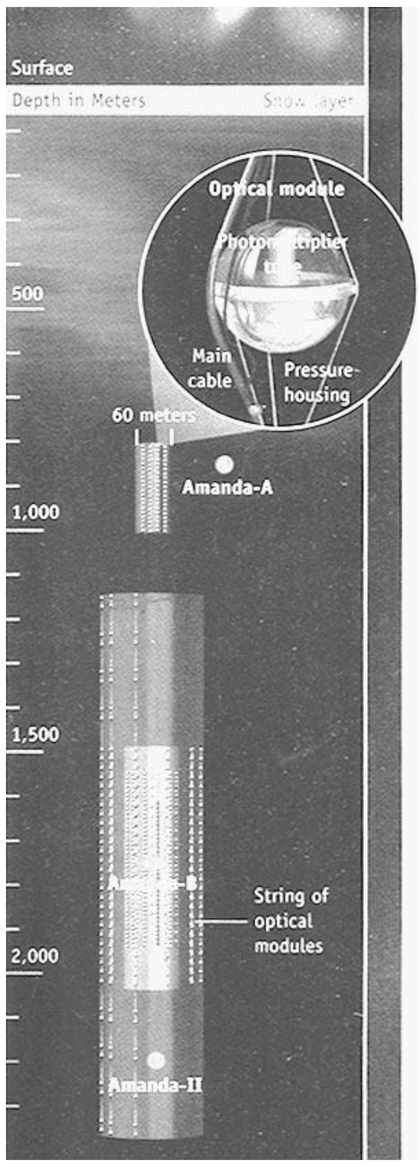

Figure 11. The Antarctic Muon and Neutrino Detector Array (AMANDA) under ice.

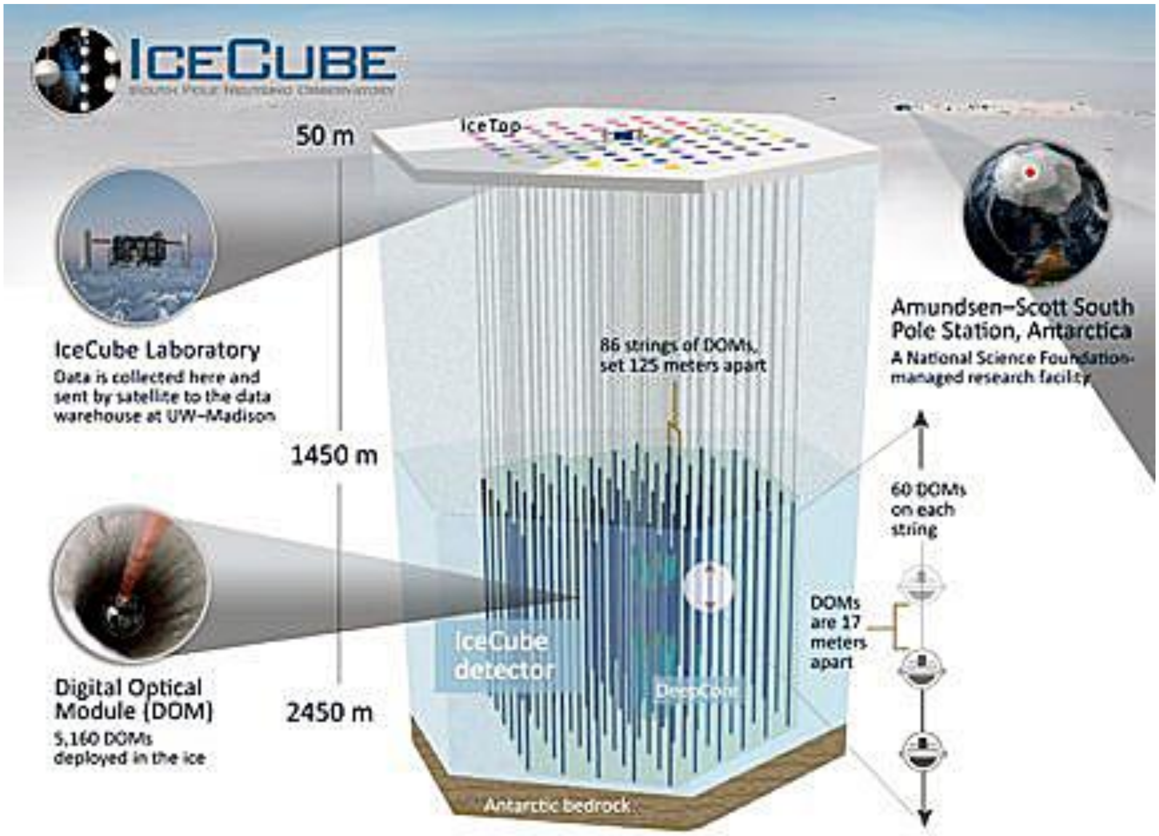

Figure 12. IceCube neutrinos detector, Antartica.

The experiment is housed in holes in Antarctic ice drilled by injecting hot water into the ice. It consists of arrays of optical modules containing photo multiplier tubes strung on vertical cables within an imaginary cylinder 200 m in diameter and 500 m high buried beneath 2 km of ice.

The objective is not the solar neutrinos, but the cosmic neutrinos emitted by colliding black holes, exploding stars or supernovae, gamma ray bursts, and other energetic cosmic phenomena.

These cosmic neutrinos are 10^5 times more energetic than solar neutrinos, and also 10^{-12} times rarer in occurrence. This requires a large size detector to detect them. One needs weakly interacting particles like neutrinos to see the rest of the universe, since photons of comparable energy cannot reach Earth from beyond the Milky Way Galaxy, being mostly absorbed by interactions with photons left over from the postulated Big Bang event. The flux of these high-energy neutrinos is smaller at higher energies necessitating large detectors.

The detection depends on the inverse reaction where a neutrino interacts with a neutron producing a proton and negative muon described earlier. In this case the detection process attempts at detecting the blue Cerenkov radiation emitted by the muon as it moves through the ice at faster than the speed of light in ice. The photo-multiplier tubes are meant to detect and amplify the Cerenkov radiation by a factor of 10^8 times. The light is turned into electrical pulses to be recorded by electronic counters. By studying the track of the muon, the energy of the original particle can be inferred, as well as the direction that it came from. One hopes to identify consequently its source. From this perspective, it becomes a new kind of telescopic instrument.

Antarctica is an inhospitable place to build and operate a telescope. But crystal-clear ice is an excellent medium for observing neutrinos as they pass through the Earth. Since 1999, AMANDA, has used the Antarctic ice to seek out neutrinos. When the particles interact in the ice they can produce muons, charged particles that are like electrons but heavier. The muons create faint flashes of light as they pass through the ice some 1.2 miles below the surface, where they are sensed by AMANDA's hundreds of light sensitive phototubes supported on 19 tethers frozen in the ice. AMANDA's goal is to conduct neutrino astronomy, identifying and characterizing extra solar sources of neutrinos, which could provide important clues in the search for dark matter.

Figure 13. Holes drilling for the AMANDA Experiment, Antarctica.

ICE CUBE INTERNATIONAL NEUTRINO EXPERIMENT

An event occurred in 1998, where Amanda tracked a neutrino 400 meters through the ice. This was the highest energy neutrino ever recorded, but was not tied to any extra galactic source. To do the intended job, its size would have to be extended 10 times to a 1 cubic kilometer. This detector is named: IceCube, and will have 5,000 optical modules.

The hope is to learn about new phenomena that photon telescopes cannot deal with. For instance the enigmatic Gamma Ray Bursts are believed to emit neutrinos after the electromagnetic radiation has occurred. This could also shed light on another mystery concerned with the origin of high-energy cosmic rays, which may prove to be two aspects of a single phenomenon.

Completed in 2009, IceCube, an international neutrino experiment involving more than 20 research institutions, became the largest particle detector ever built. Setting

IceCube's 4,200 optical modules deep within the Antarctic ice, where the detector joins its predecessor, AMANDA, required drilling 70 holes a mile and a half deep each using a novel hot water drill.

The detector's goal is to investigate the still mysterious sources of cosmic rays. IceCube's telescope will use the Antarctic ice to look for the signatures of cosmic neutrinos, elusive particles produced in violent cosmic events such as colliding galaxies, black holes, quasars, and other phenomena occurring at the margins of the universe.

Figure 14. IceCube hot water drilling in Antarctica’s ice.

ASTRONOMY WITH A NEUTRINO TELESCOPE AND ABYSS ENVIRONMENTAL RESEARCH, THE ANTARES EXPERIMENT

The Amanda ice experiment is supplemented by an experiment attempting to detect Cerenkov radiation in water under-sea in the Mediterranean. The Astronomy Neutrino Telescope Abyss Research (ANTARES) is secured 2,330 meters under water off the coast of Toulon, France, and a separate string near Marseilles. It is initially planned on consisting of 13 strings of optical modules within an area 300 meters in diameter. Later, it will be expanded into a kilometer-cube array. The Amanda and Antares experiments will complement each other. But to have a full coverage of the sky, some initiative is needed to build a similar experiment in the southern hemisphere.

The aim of this experiment is to answer questions about the composition of deep space by detecting neutrinos on the sea floor. ANTARES started operation in 2006 and used water 8,200 feet below the surface of the Mediterranean Sea off the south coast of France to detect muons which are produced when neutrinos from space interact in the Earth's core.

Muons create Cerenkov radiation as they pass through water, and an array of approximately 1,000 photomultiplier tubes on 10 vertical strings spread over a mile and a half of seafloor would sense and measure them.

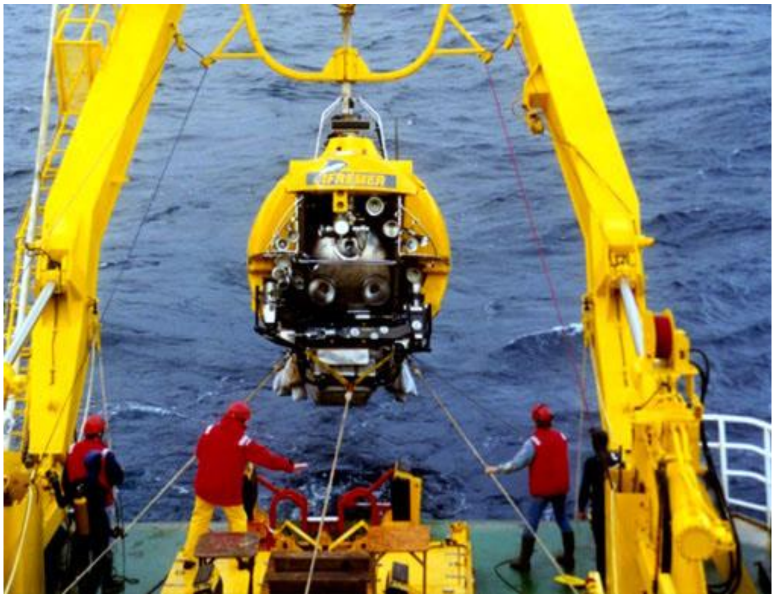

Figure 15. Installation of the ANTARES experiment in the Mediterranean Sea.

ANITA NEUTRINO DETECTOR, ANTARCTICA

If successful, the ambitious and innovative ANITA neutrino detector will be the first device to identify high energy neutrinos created by collisions between cosmic rays and cosmic microwave photons in space. Studying neutrinos from these sources offers an opportunity to learn about exotic objects at the edge of the universe, such as the black holes.

In 2006, ANITA was a balloon borne radio detector experiment circling the Antarctic continent at 115,000 feet during approximately 18 day missions. It scanned the vast expanses of ice for telltale pulses of radio emission generated by neutrino interactions.

Figure 16. Balloon carrying the ANITA neutrino detector.

ANNIHILATION OF MUON NEUTRINOS AND ANTINEUTRINOS INTO ELECTRON-POSITRON PAIRS

According to V. A. Gusseinov, various processes of inelastic scattering of cosmic neutrinos and antineutrinos of ultra high energy on low energy relic antineutrinos and neutrinos in the Milky Way Galaxy can be considered as a possible source of cosmic ray electrons and positrons of high energy through the process:

$$\nu_{\mu} + \nu_{\mu}^{*} \rightarrow e^{+} + e^{-} \tag{10}$$

The channel of the reaction is thought to arise at the expense of quantum effects. For the strong magnetic field case the cross section of the process does not depend on the masses of the charged leptons. The contribution of the weak external field to the cross section of the process is very small.

ANTINEUTRINOS MONITORING OF FISSION REACTORS

Antineutrinos result from the beta decay of the fission products and carry about five percent of the energy of the fission process. They can be used to monitor the fission process in fission reactors in real time. The International Atomic Energy Agency IAEA) considers 8 kgs of Pu^{239} to be a proliferation concern, and needs to monitor about 400 civilian reactors worldwide.

The process of fission of the isotopes U^{235} and Pu^{239} results in the creation of antineutrinos possessing different properties allowing the measurement of the ratios of the two isotopes in a fission reactor. Over a broad range of antineutrino energies, the number emitted by Pu^{239} is substantially less from the number emitted by U^{235} over a particular energy range. As Pu^{239} is bred from U^{238} and builds up in the fuel, the antineutrino count rate is observed to drop by 5-10 percent over the fuel cycle lifetime. Fission reactors emit a high flux rate of antineutrinos of 10^{21} antineutrinos / sec, which compensated for their low interaction probability, and allowing their detection.

A method to detect antineutrinos can depend on coherent scattering from the nuclei. In this case, an antineutrino passing close to a nucleus causes it to shake and shed a few electrons in the process.

Another possible detection mechanism is the inverse beta decay process, where an antineutrino interacts with a free proton in the detector creating a neutron and a positron. The positron provides a measurable signature through the coincidence counting of the two gamma photons emitted by the annihilation process with an electron from Eqns. 6 and 7; essentially the same process used for their detection by Reines and Cowan:

$$
\begin{gathered}
{}^{*}\nu_{e} + {}_{1}H^{1} \rightarrow {}_{0}n^{1} + {}_{+1}e^{0} \\
{}_{+1}e^{0} + {}_{-1}e^{0} \rightarrow \gamma + \gamma
\end{gathered}
$$

A detector would consist of three subsystems:

1. Central detector: is where the antineutrino are detected consisting of stainless steel cells filled of a liquid scintillator. The scintillator contains quasi-free electrons and is doped with gadolinium atoms. The antineutron interaction with the proton creates a positron which soaks its energy converting it into a flash of electromagnetic radiation and induces a scintillation in the scintillator liquid. Another flash of light is emitted a nanosecond later by the positron annihilation with an electron producing 2 gamma photons. A third flash is emitted 30 microseconds later by the neutron absorption by a gadolinium nucleus, reaching an excited state and then being de-excited by the emission of a high energy gamma photon. The three consecutive flashes of light are detected by photomultiplier tubes situated above the scintillation fluid and constitute a signature of an antineutrino interaction.
2. Passive water shield: surrounds on all sides the central detector. It attenuates the gamma and neutron backgrounds.
3. Active water shield: is placed outside the passive shield and detects the penetrating cosmic rays signals which can mimic the antineutrinos and vetoes them out.

Two methods can be used to track the Pu^{239} and U^{235} ratio in a fission reactor:

1. The first method depends on a correlation designated as the burnup effect, and measures the changes in the total rate of detected antineutrinos over time. Since the Pu^{239} produces less antineutrinos than U^{235}, the change in the antineutrinos rate tracks the production of Pu^{239} over time. If the antineutrinos count rate is 1,000 per day and decreases to 900 per day, and if the Pu is removed along the way or its production is increased, the changes will appear in the antineutrino count rate. This requires the simultaneous measurement of the reactor power level; otherwise a reduction in the antineutrino count can be masked by an increase in the reactor's power.
2. The second method considers changes in the antineutrinos energy spectrum, and does not need a measurement of the reactor power level, even though it needs a longer counting time to achieve an acceptable statistical error. It depends on the different energy spectra of the antineutrinos emitted by Pu^{239} and U^{235} and measures the ratios between the low and high ends parts of the spectrum.

Such detectors can be placed outside the reactor's containment and would be independent of the power production process. Since 2003, a 2x3 m prototype placed 17 m below ground and 25 m away from the reactor core, has been operational at the San Onofre plant in San Clemente, California.

FASTER THAN THE SPEED OF LIGHT MYSTERY

An international team of scientists reported neutrinos travelling at faster than the speed of light. Measurements taken over three years showed neutrinos pumped from the CERN Laboratory near Geneva, Switzerland to Gran Sasso in Italy had arrived 60 nanoseconds quicker than light would have done.

If confirmed, the discovery would have undermined Albert Einstein's 1905 theory of special relativity, which says that the speed of light is a "cosmic constant" and that nothing in the universe can travel faster. That assertion, which has withstood over a century of testing, is one of the key elements of the so-called Standard Model of physics, which attempts to describe the way the universe and everything in it works.

The unexpected finding emerged from research by physicists working on an experiment dubbed OPERA run jointly by the CERN particle research center near Geneva, Switzerland and the Gran Sasso Laboratory in central Italy. A total of 15,000 beams of neutrinos were fired over a period of 3 years from CERN towards Gran Sasso 730 km or 500 miles away, where they were picked up by giant detectors.

Light would have covered the distance in around 2.4 thousandths of a second, but the neutrinos took 60 nanoseconds, or 60 billionths of a second less than light beams would have taken. To reach Gran Sasso, the neutrinos originated from a special installation at CERN, also home to the Large Hadron Collider probing the origins of the universe, have to pass through water, air and rock. The underground Italian laboratory, some 120 km or 75 miles to the south of Rome, is the largest of its type in the world for particle physics and cosmic rays research. Around 750 scientists from 22 different countries work there, attracted by the possibility of staging experiments in its three massive halls, protected from cosmic rays by some 1,400 meters or 4,200 feet of rock overhead.

Much science-fiction literature is based on the idea that, if the light-speed barrier can be overcome, time travel might theoretically become possible. Scientists, intrigued by the anomalous result generated more than 80 explanations. Some suggest the possibility of new physics, such as neutrinos that are travelling through extra or neutrinos at particular energies travelling at faster than the speed of light.

An objection to the faster-than-light interpretation came from an astrophysical observation. In 1987, a powerful supernova event showered the Earth with light and neutrinos. While neutrino detectors observed neutrinos arriving about three hours before the light, this was due to the light weight particles getting a head start. Neutrinos, which hardly interact with matter, escaped the exploding stellar core with relative ease while photons, absorbed and re-emitted by the various elements, took longer to flee. If the effect from OPERA were as large as observed, scientists calculated that the neutrinos should have arrived more than four years in advance of the light.

Others have taken the faster-than-light results to task using the Standard Model of physics, which describes all known subatomic particles and their interactions. According to the Standard Model, neutrinos at sufficiently high energies should produce a virtual electron-positron pair through a process known at the Cohen-Glashow emission. These emanations would have sapped energy from the faster-than-light neutrinos, causing them to slow down.

The Standard Model's properties suggest that making neutrinos go faster than light requires electrons to do the same. But if an electron neutrino moved at the speed suggested by the OPERA experiment, then electrons should also travel faster than the speed of light by at least one part in one billion. Experiments have established theoretical limits that electrons remain subluminal at a precision down to more than 5 parts in a thousand trillion, effectively ruling this scenario out.

An argument invoking Einstein's supposedly challenged theory of relativity suggests that the OPERA team used Global Positioning System (GPS) satellites to accurately measure the 730 km distance between their detector and the CERN beam where the neutrinos were produced. According to special relativity, calculations will be slightly different when two observers are moving relative to one another. Since the satellites were zipping around the Earth, the positions of the neutrino source and the detector changed. Accordingly the movement would account for a 64 nanoseconds discrepancy, nearly exactly what the OPERA team observes.

It will take more time and scholarship before the physics community settles on the true explanation for the OPERA results.

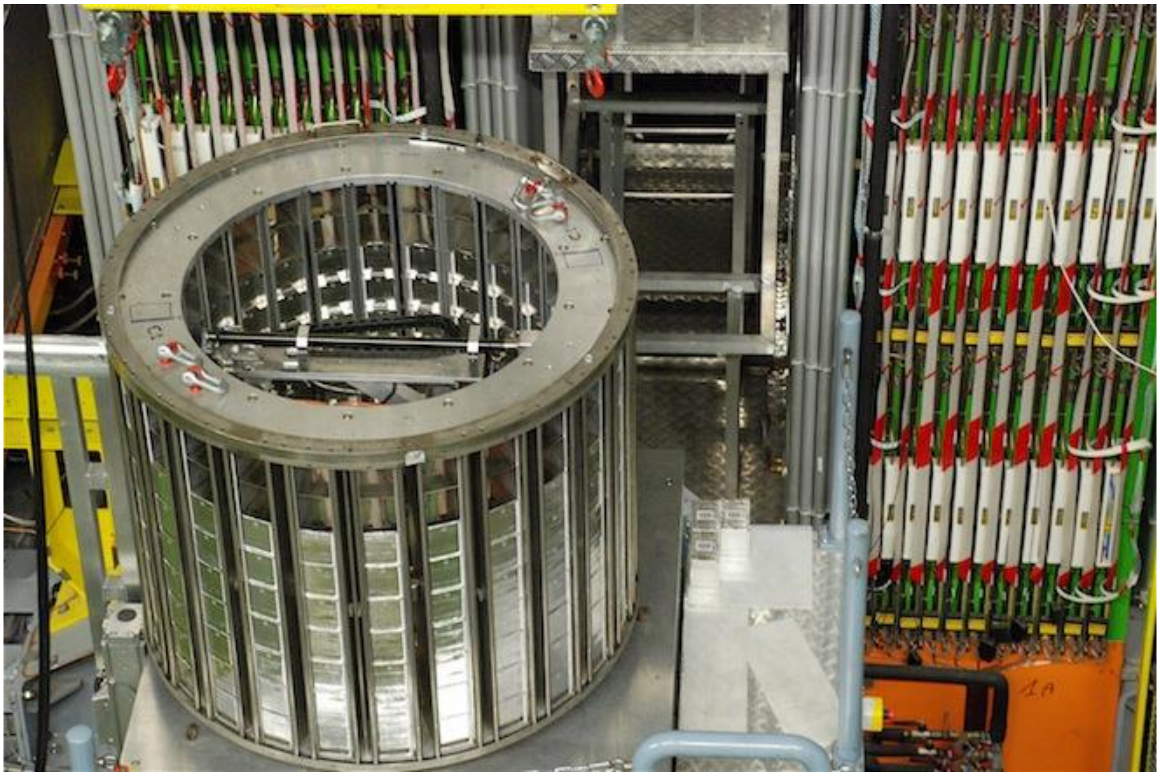

Figure 17. The OPERA neutrino experiment. Source: CERN.

ANTINEUTRINO SETI BEACON PROPOSAL

Nuclear fission reactors are a beacon radiating antineutrinos to the rest of the universe announcing the existence of humanity as an intelligent technological civilization that has mastered the control of fission energy.

By dedicating a nuclear reactor to ramping and operation at specific power levels, humanity can construct a beacon communicating with any possible existing other technological civilizations.

With a programmed ramping of the fission reactor, these technological civilizations would quickly realize the non random nature of the emissions. By teaching them how to interpret subsequent messages, a language can be taught to them. Once a language is taught, the text of an Encyclopedia, or maybe Wikipedia could be transmitted.

A key aspect is the development of a methodology that would teach the required communication language from scratch.

This would constitute a mirror image of the Search for Extra Terrestrial Intelligence (SETI) project. In fact by announcing its presence, humanity may well receive a programmed response instead of looking for the signature of a message that may not have ever been sent.

A sobering thought is that the same reasoning may have occurred to some other intelligent civilization. With the recent discovery of planetary systems, one can suggest narrowing out the SETI search to antineutrinos emissions from these needles in the cosmic haystack.

DISCUSSION

In 2002, the Sudbury Neutrino Observatory (SNO) confirmed that the flux of all neutrinos coming from the sun matches the prediction of the solar standard model for electron neutrinos alone. However, only half of them are electron neutrinos. This solved the solar neutrino problem as fusion processes in the sun only produce electron neutrinos. Physicists were puzzled when it turned out in 1967 that only 1/3-1/2 of the predicted number reaches the Earth. As they can change into other types during their journey, the puzzle is now solved.

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