TECHVIEW: PARTICLE PHYSICS

Neutrinos Underground

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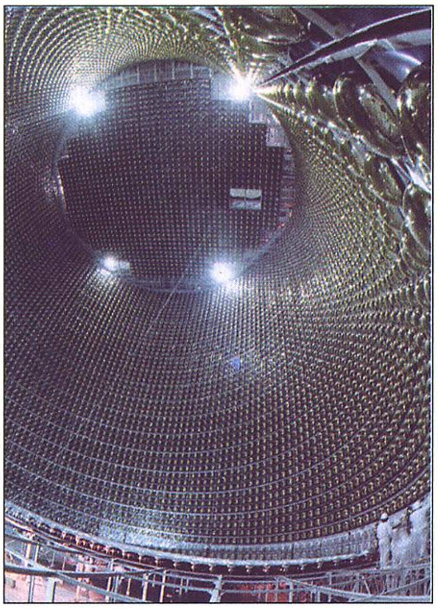
Large mass underground detectors have ushered in a new era in neutrino physics. These detectors enable the detection of neutrinos produced in the atmosphere, the sun, and other stellar objects, and permit the investigation of their properties with unprecedented accuracy. Recent results from the Super-Kamiokande (SK) detector in Japan show clear evidence that neutrinos have mass (*1*) and provide fruitful information for elementary particle physics and astrophysics.

Neutrinos were theoretically predicted by Pauli in 1930 to explain the missing energy in beta decay. They are the stable elementary particles, but detection and characterization have proved difficult because neutrinos do not have charge and interact only very weakly with matter. Hence, large detectors are necessary to get sufficient signal for measuring their mass and other properties.

There are three types of neutrinos: ν_μ, ν_e, and ν_τ. Many attempts have been made to measure their masses directly, but none succeeded in obtaining a finite mass for the particles. The observation of neutrino oscillations at SK has provided the first, albeit indirect, evidence for neutrino mass; neutrino oscillations occur when neutrinos change from one type to another, and require the particles to have mass.

Large underground neutrino detectors are located in various places around the world (see the table). They are constructed 500 to 2000 meters underground to reduce the flux of cosmic ray muons (particles that are similar to the electron but have much greater mass and a lifetime of only 2×10^{-6} s) and other secondary particles. SK is the largest existing underground detector, with a 50-kiloton water tank 42 m in height and 40 m in diameter. The detector consists of inner and outer parts. The inner part (see the image, this page) contains 32 kilotons of water that are viewed by 11,146 photomultipliers, each with a diameter of 50 cm. Forty percent of the inner surface of the inner detector is covered by their photosensitive area.

The detector is based on the following principle. When charged particles travel through water with a speed faster than the velocity of light in water, bluish light (called Cherenkov light) is emitted at an angle of about 42°. This emission is observed as a ring on the surface of the photomultiplier plane (see the figure, top of the next page). Any charged particle arriving from outside the detector gives a Cherenkov signal in the outer detector. Neutrinos generated inside the detector can therefore easily be distinguished from those arriving from the outside. Neutrinos themselves are not charged, but neutrino interactions produce muons and electrons that can be detected. The image of the Cherenkov ring also shows whether the neutrino originates from ν_μs (which produce muons) or ν_es (which produce electrons).



Inside view of the SK detector, the largest of its kind in the world. Detectors of this type are often called "imaging Cherenkov counters."

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SK has been taking data since April 1996, and evidence for neutrino oscillations from atmospheric neutrinos was found in 1998. Atmospheric neutrinos are produced by interactions of cosmic rays in the atmosphere. The primary cosmic rays (protons, helium nuclei, etc.) produce mostly pions, a type of particle that takes part in strong interactions. Pions decay further, producing two ν_μs and one ν_e per pion decay. The ratio of ν_μ and ν_e can therefore be predicted very precisely, even though the absolute flux of each neutrino cannot be predicted very accurately. However, the ν_μ/ν_e ratio observed by SK was about 35% lower than the expected value. Similar observations were reported about 10 years ago from smaller detectors (*2*, *3*).

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The large number of atmospheric neutrino events in SK allowed the event rates of ν_μ and ν_e to be accurately studied as a function of the distance between the point where the neutrino was produced and the detector. This distance correlates with the zenith angle of the observed events. The zenith angle distributions of electron-like and muon-like events were measured for 1144 days of detector exposure. The zenith angle distribution must be up/down symmetric, that is the flux of upward- and downward-going neutrinos must be the same because the cosmic rays arrive essentially isotropically from the universe. The distribution for electron-like events matches expectations (left panel in the bottom figure, next page), but the number of observed μ-like events with large zenith angle is only about half of the expected value (right panel). Large zenith angle events are caused by neutrinos that have traveled a large distance (up to 13,000 km) through the earth. The probability of neutrino oscillation generally increases with distance, and this is what

UNDERGROUND NEUTRINO DETECTORS

Detector	Type	Mass or size	Location
Super-Kamiokande	Water Cherenkov	32,000 tons	Japan
MACRO	Tracking + scintillator	77 m × 12 m × 9 m	Italy
Soudan-2	Fe target with drift-chamber	963 tons	USA
SNO	D_2O Cherenkov	1000 tons	Canada
Homestake	C_2Cl_4 radio-chemical solar ν	680 tons	USA
GNO(GALLEX)	Gallium radio-chemical solar ν	30 tons	Italy
SAGE	Gallium radio-chemical solar ν	57 tons	Russia
Baksan	Liquid scintillator	330 tons	Russia
LVD	Liquid scintillator	700 tons	Italy
AMANDA	Ice Cherenkov	200 m* × 500 mL	Antarctic
BAIKAL	Lake Cherenkov	43 m* × 73 mL	Russia
BOREXINO†	Liquid scintillator	300 tons	Italy
KamLAND†	Liquid scintillator	1000 tons	Japan

*Indicates diameter †Under construction

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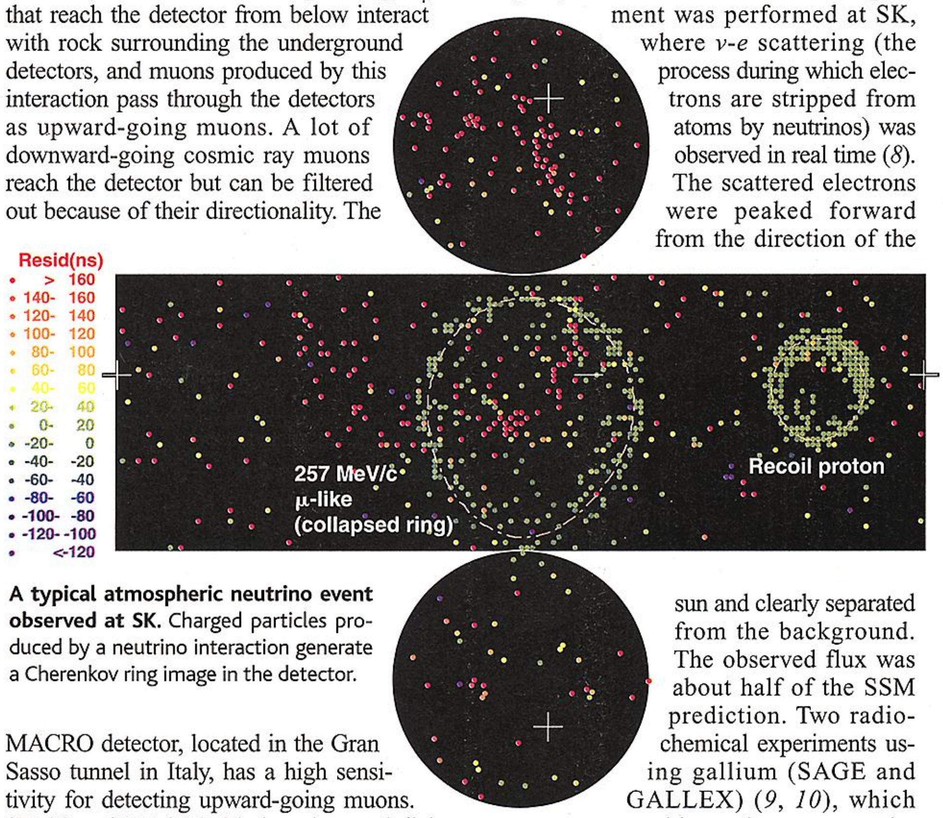
causes the asymmetric distribution of the μ-like events, which provides indirect evidence that neutrinos have mass.

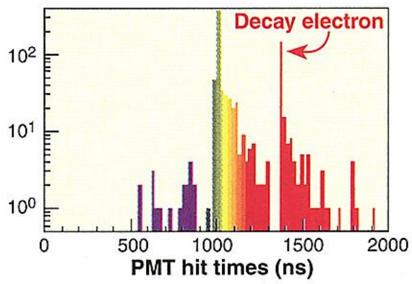


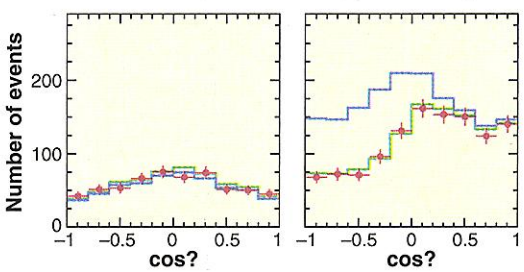
A typical atmospheric neutrino event observed at SK. Charged particles produced by a neutrino interaction generate a Cherenkov ring image in the detector.

Neutrino oscillations can also be observed by another method. High-energy ν_μs that reach the detector from below interact with rock surrounding the underground detectors, and muons produced by this interaction pass through the detectors as upward-going muons. A lot of downward-going cosmic ray muons reach the detector but can be filtered out because of their directionality. The MACRO detector, located in the Gran Sasso tunnel in Italy, has a high sensitivity for detecting upward-going muons. SK (*4*) and MACRO (*5*) data show a deficit in upward-going muons near the vertical direction, whereas in the horizontal direction observations are consistent with expectation. The upward-going muons detected by SK and MACRO confirm the ν_μ oscillations observed in the SK experiments described above. Further evidence comes from Soudan-2, an iron-calorimeter detector with excellent particle identification and tracking capabilities. Although the amount of detector exposure is less than 10% of SK, Soudan-2 observed up/down asymmetry in ν_μ events, whereas the ν_e events were consistent with the expectation (*6*).

The ν_μ oscillations were thus shown to originate from atmospheric neutrinos. What about ν_e? The best source of neutrinos for investigating ν_e oscillations are solar neutrinos produced in nuclear fusion reactions in the sun's core. Solar neutrinos have been detected by several underground detectors. The pioneering solar neutrino detector was constructed by R. Davis *et al.* in the 1960s at Homestake Goldmine in South Dakota, U.S.A. (*7*). The argon atoms produced by the reaction of solar neutrinos in a 615-ton tank filled with perchloroethylene were extracted by purging helium gas and counted with a low-background counter. The observed number of argon atoms was about 0.5 atoms/day, about a third of that expected from the standard solar model (SSM). The second solar neutrino experiment was performed at SK, where ν-e scattering (the process during which electrons are stripped from atoms by neutrinos) was observed in real time (*8*). The scattered electrons were peaked forward from the direction of the sun and clearly separated from the background. The observed flux was about half of the SSM prediction. Two radiochemical experiments using gallium (SAGE and GALLEX) (*9*, *10*), which were sensitive to low-energy solar neutrinos, confirmed the deficit of solar neutrinos, with an observed flux of about 60% of the expectation.

The flux deficit, called "solar neutrino problem," most likely results from ν_e oscillations, but there is no convincing evidence for the oscillations yet. If the solar neutrino problem is due to neutrino oscillations, we may observe (i) distortion of the energy spectrum of solar neutrinos, (ii) flux changes on a short time scale, like day/night, and (iii) a total neutrino flux ($\nu_e + \nu_\mu + \nu_\tau$) that is different from the pure ν_e flux. Recently, solar neutrino detectors have been designed to study these possibilities. SK detects solar neutrinos by ν-e scattering with an unprecedented event rate. It has observed about 15,000 solar neutrino events over 3 years, and their energy spectrum and time variations have been studied (*11*). At SNO (Sudbury Neutrino Observatory), a 1000-ton heavy water (D_2O)–imaging Cherenkov detector located 2040 m underground in Sudbury mine in Canada (*12*), data have been taken since last year as a first phase of the experiment. SNO is now measuring the ν_e flux using $\nu_e + D \rightarrow e^- + p + p$ reactions. After the first phase, MgCl salt or ^3He counters will be put in the heavy water, and the total neutrino flux will be measured using $\nu + D \rightarrow \nu + n + p$ reactions. A 300-ton liquid scintillator detector dedicated to the detection of mono-energetic ^7Be solar neutrinos (BOREXINO) is under construction at Gran Sasso and will start taking data in 2001. Given these efforts, the solar neutrino problem may be solved in the not-too-distant future.





Neutrino oscillations. Zenith angle distributions for electron-like events (left) and muon-like events (right) compared with predictions (blue lines). The poor fit for muon-like events can only be explained by neutrino oscillations (green).

Underground detectors have led to important advances in neutrino physics, but this was not their initial goal. The original motivation for constructing large mass detectors in the 1980s was the search for proton decay, which is predicted by Grand Unified Theories (GUTs). Even though underground detectors have been increased in mass for nearly 20 years, none of them has ever observed proton decays. We may need much larger detectors for entering the next era in elementary particle physics and astrophysics.

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