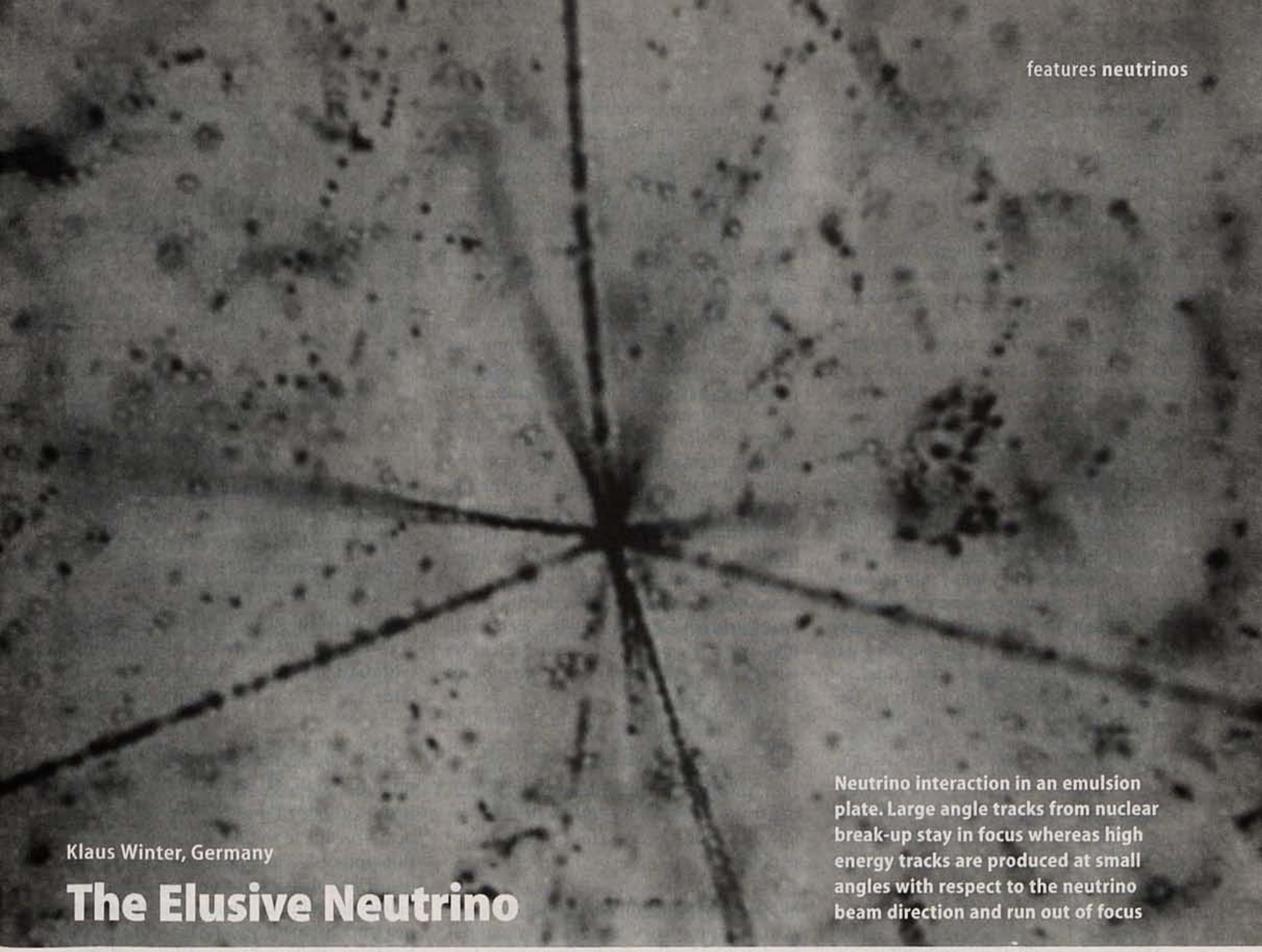


Neutrino interaction in an emulsion plate. Large angle tracks from nuclear break-up stay in focus whereas high energy tracks are produced at small angles with respect to the neutrino beam direction and run out of focus

Klaus Winter, Germany

The Elusive Neutrino

Do neutrinos have mass? Last year's results from the Superkamiokande detector say yes. But we can not be sure. Two CERN experiments are looking for answers

Do neutrinos have non-zero rest mass? Gershtein and Zel'dovich were the first, in 1966, to ask this question and to appreciate the consequences for cosmology: even a neutrino mass equivalent to an energy of just 10 eV—almost a million times smaller than that of the electron—would mean that neutrinos completely dominates the mass of the universe. The neutrino contribution could then be large enough not only to stop the expansion of the universe but also to reverse it, to cause the Big Crunch.

We know that there exist three families of neutrinos in nature. Two of them have been detected by their capture on neutrons, the electron-neutrino and the muon-neutrino. The third, the tau-neutrino, has remained undetected. But there are undisputable reasons why it must exist. Do these families mix in a way similar to quarks allowing them to make transitions into other families? If so they can spontaneously change their flavour. This phenomenon is called neutrino oscillation and would in itself, if confirmed, be evidence that neutrino's have mass.

These two questions belong to the most fundamental questions of elementary particle physics. Theories which attempt to unify the description of all forces between elementary particles postulate non-zero neutrino masses and predict a hierarchy in terms of quark masses (generated by a "see-saw" mechanism which creates small masses proportional to the mass of the charged lepton or quark of the same family). Results from recent experiments on solar neutrinos favour a muon-neutrino mass of 3×10^{-3} eV. Recent results on the anisotropy of the cosmic microwave background radiation favour a tau-neutrino mass of ~ 7 eV and the baryon asymmetry of the universe can be explained by a tau-neutrino mass of ~ 0.1 eV. Non-zero neutrino mass is a necessary condition for neutrino mixing.

There is a very sensitive way of weighing neutrinos. It is analogous to well-known examples of two base quantum states, *eg* that of the ammonium maser or of the K^0 - $\bar{K}^0$ system. In reactions induced by the weak force the family eigenstates ν_e, ν_μ or ν_τ are produced, *eg* the ν_μ in pion decay: $\pi \rightarrow \mu\nu_\mu$.

Their propagation is governed by the mass eigenstates providing that the flavour eigenstates mix by common mass eigenstates. If their masses are different these states will display the well-known properties of quantum mechanical superposition and interference of amplitudes. This will lead to time dependent appearance and disappearance of the flavour eigenstates. Neutrinos can spontaneously change their flavour if they mix and have non-zero and different rest masses. The frequency of oscillation is given by the difference of the neutrino masses squared (Δm^2). This phenomenon, called neutrino oscillation, was first predicted by Bruno

Pontecorvo in 1957 and independently by Z. Maki in 1967. If neutrino oscillation is confirmed, it will be evidence for non-zero neutrino mass.

The search for oscillation

Several experiments are being conducted in the search for the spontaneous disappearance of muon-neutrinos and the appearance of tau-neutrinos ($\nu_\mu \rightarrow \nu_\tau$). The experimenters are investigating neutrinos produced by cosmic rays in the atmosphere of the earth and neutrinos produced in accelerators. These two sources of neutrinos are sensitive to very different neutrino masses. It depends on the ratio of the distance (L) the neutrinos travel from their point of creation (which is pion and muon decay) to their point of interaction, and of their energy (E). At the point of creation they are muon-neutrinos because they are created together with a muon. But on their way they may spontaneously change their flavour—almost like a chameleon changing its colour—and become a tau-neutrino. The interaction of the neutrino in a detector will probe its flavour; if it remained a muon-neutrino it will produce a muon, but if it changed its flavour to a tau-neutrino it will produce a tau-lepton. The probability of this oscillation (p) depends on the product of L/E and Δm^2, and on the mixing probability, $\sin^2 2\theta_{\mu\tau}$

$$p(\nu_\mu - \nu_\tau) = \sin^2 2\theta_{\mu\tau} \times \sin^2 (\Delta m^2 L / 4E)$$

Maximum oscillation probability occurs if $(\Delta m^2 / 4) \times (L / E) \sim \pi / 2$ where Δm^2 is in units of eV^2, E in GeV and L in km. The two sources of ν_μ, cosmic rays and accelerators, can be used to investigate vastly different domains of Δm^2. Atmospheric neutrinos travel distances of 10 km or 10 000 km to an underground detector—depending on which side of the earth they were created—and have energies between 0.5 and 10 GeV, and can explore the domain of $\Delta m^2 \sim 0.01$ to $0.0005\ eV^2$. Accelerator-made neutrinos in present configurations travel ~ 1 km and have energies between 0.5 and 50 GeV and can therefore explore the domain $\Delta m^2 \sim 1$ to $30\ eV^2$.

The search for $\nu_\mu \rightarrow \nu_\tau$ oscillation consists of detecting the tau-neutrino induced reaction: $\nu_\tau N \rightarrow \tau^- X$ (N is a neutron) which produces the tau-lepton, its charged brother. Tau-leptons are 3500 times heavier than their electron relatives. Their mean life is very short: 3×10^{-13} s which corresponds to a mean decay length of 0.09 mm in their rest frame.

Standard electronic detectors such as wire chambers or scintillation counters cannot recognize such short-lived particles. The two experiments at CERN being used to search for tau-neutrinos in beams of muon-neutrinos are CHORUS and NOMAD. They use different methods to detect the tau-leptons. CHORUS uses the classical pictorial method of nuclear emulsion (*see figure 2*) to observe the dominant decay topology of a kink—a sudden change of direction in the tau-lepton track. This "stone-age" method has been revitalised by the use of modern computer-assisted automatic microscopes which can measure more than 1000 neutrino events per month. This modern technique was developed at the University of Nagoya, Japan, one of the CHORUS institutes. There are now several automatic microscopes at the European institutes of the CHORUS collaboration. Using the classical human-operated microscope only one event per month could be measured. Nomad is using electronic methods to recognize events in which the energy is carried away by neutrinos in tau-lepton decay.

The CERN neutrino beam is the most intense of its kind and has one essential feature in the search for $\nu_\mu \rightarrow \nu_\tau$ oscillation: purity. Its contamination with tau-neutrinos is six orders of magnitude below the muon-neutrino flux and therefore negligible.

The Superkamiokande experiment

If the appearance of tau-neutrinos cannot be detected by the production of tau-leptons, the disappearance of muon-neutrinos can be investigated. This method is applicable for the atmospheric neutrino experiment. The Superkamiokande detector in Japan is detecting muons produced by the interaction of muon-neutrinos in a large water tank. In water, muons produce light through the Cerenkov effect. The light cone is detected by photomultipliers covering the walls of the water tank. If the muon stops, its energy is determined by its range. The distance the neutrino travelled is given by the direction of the incident neutrino and its intersection with the atmosphere. This direction is closely related to the direction of the produced muon which is measured by the direction of the cone of Cerenkov light.

Neutrino interactions are detected in a cylinder filled with water 50 metres in diameter and 30 metres in height. The walls have been covered with 10 000 photomultipliers. From their location and from the arrival time of the light detected, the Cerenkov cone opening angle, its direction and its origin and endpoint are measured. The quantities E and L are determined for each contained event which is produced

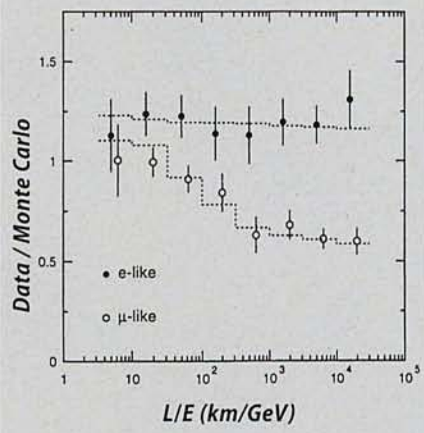


Fig 1 The points show the ratio of the number of fully contained observed events to Monte Carlo events versus the reconstructed L/E. For e-like events the ratio is nearly independent of L/E whereas for μ-like events it agrees with the distribution (dotted line) for $\nu_\mu \rightarrow \nu_\tau$ oscillation for $\Delta m^2 = 2.2 \times 10^{-3}\ eV^2$ and $\sin^2 \theta = 1$

and stops in a central volume, more than 2 metres away from the walls. The distribution of observed events (normalised to that expected if muon-neutrinos disappear—neutrino oscillation) is shown as a function of L/E in *figure* 1. For large values of L/E the distribution of μ-like events is below the value of 1 indicating the disappearance of neutrinos. This observation has been attributed to neutrino oscillation with a mixing probability of ~ 0.8. This very exciting result may indeed be the discovery of neutrino oscillation. A statistical fluctuation is excluded by 6 standard deviations. But it remains to be confirmed independently. Do the muon-neutrinos which seem to disappear appear as tau-neutrinos? This is an open question.

In contrast to the apparent disappearance of muon-neutrinos there is no evidence for electron-neutrino disappearance. Electron-neutrinos are produced in muon decay. In their interaction they produce electrons which can be discriminated from muons by the more diffuse Cerenkov cone due to the development of an electromagnetic shower in the water.

The CHORUS experiment

The neutrino target and tau-lepton detector is a large 800-kg block of nuclear emulsion. A minimum ionising particle produces 300 silver grains per mm of track length. The position of the grains can be measured with a resolution of ~ 1 μm. The emulsion target is therefore the ideal detector for short-lived particles such as the tau-lepton. It is subdivided in-

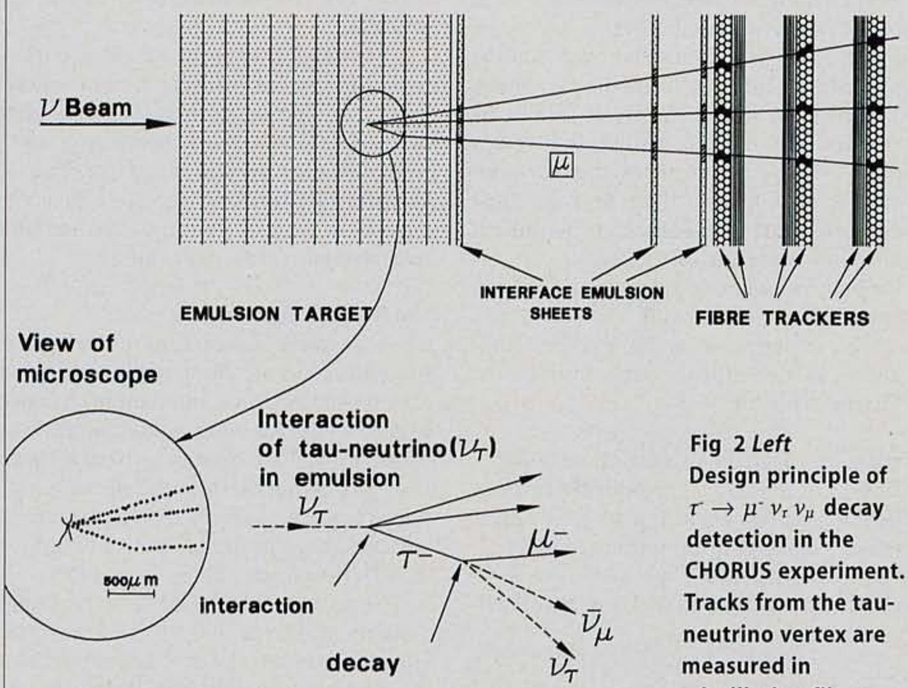


Fig 2 ***Left*** **Design principle of $\tau^- \rightarrow \mu^- \nu_\tau \nu_\mu$ decay detection in the CHORUS experiment. Tracks from the tau-neutrino vertex are measured in scintillating fiber trackers and extrapolated towards the emulsion target with the help of three interface emulsion sheets. The tau lepton decay is identified by the kink, a change of track direction at the decay point, and the negative charge of that track**

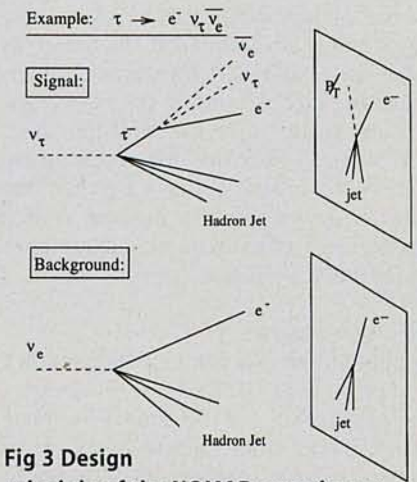


Fig 3 Design principle of the NOMAD experiment. Electrons produced in tau lepton (τ) decays are weakly correlated in transverse momentum with the hadron jet. Shown are the angles projected onto a plane perpendicular to the neutrino beam direction. The missing transverse momentum (P_T) carried away by the undetected neutrinos causes an imbalance. In the reaction induced by an electron neutrino (ν_e) the electron is produced back to back with the hadron jet

to four stacks, each composed of 35 plates of 800 μm thickness.

The tracks associated with neutrino interactions in the emulsion target are measured with scintillating fiber techniques. The position and the direction of the tracks at the emulsion exit face are predicted with a high accuracy (~ 150 μm, ~ 2 mrad). As emulsions are integrating all tracks crossing it, individual tracks have to be related with a particular neutrino interaction by spatial accuracy.

This scheme is depicted in *figure* 2 together with an enlarged microscope view of a tau-neutrino interaction. It shows two hadron tracks coming from the tau-neutrino vertex and the track of a tau-lepton which changes direction at the point of its decay, which here is into a μ^- and two neutrinos. This change of direction is called a "kink" in emulsion language and is the topology characterizing a tau-lepton decay. Two other requirements are that the kink daughter, here a muon, has negative charge and that there is no other muon coming from the vertex. With these requirements the background of events which could mimic a tau-neutrino interaction are negligible. That is the essential point and advantage of the CHORUS experiment. Evidence for $\nu_\mu \rightarrow \nu_\tau$ oscillation and hence for a non-zero tau-neutrino mass can be obtained at the level of single events.

Other electronic parts of the CHORUS detector serve to identify muons, and to measure their momentum and charge. They also measure the charge of hadrons which can be daughters of tau-lepton decays and the direction of the hadron shower produced in the neutrino interaction.

The golden events searched for have a

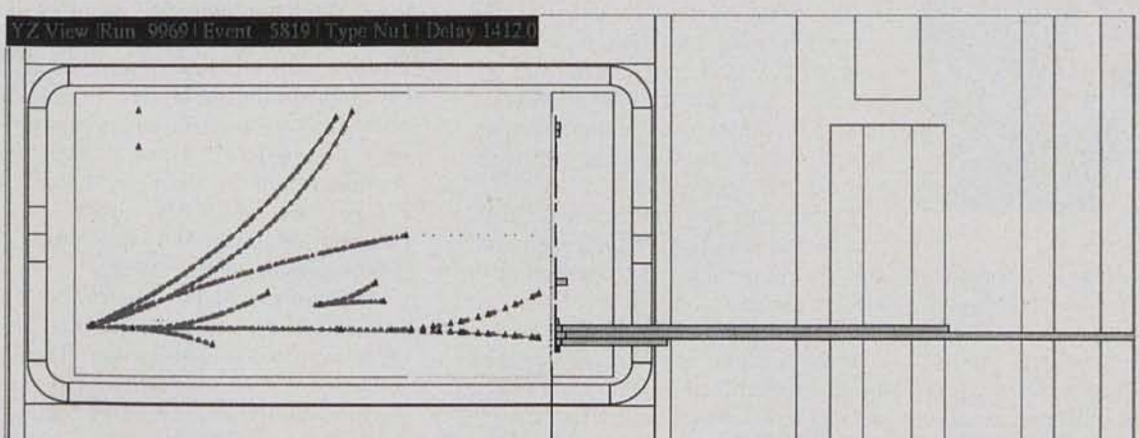


Fig 4 Electron neutrino induced event in the NOMAD detector. The electron is identified in the transition radiation detector and its energy is confined to three lead glass counters

negative muon or hadron as the daughter of the tau lepton track and a kink, a sudden change of direction at the tau decay, of at least 250 MeV/c transverse momentum. The tracks found in the fiber trackers and in the interface emulsion sheets are followed back into the emulsion target. The emulsion is like a gigantic data storage device, and the method used to access these data was improved immensely for this experiment.

Emulsion analysis

A photograph of a neutrino interaction is *shown on page 121*. The neutrino beam is perpendicular to the emulsion plate. Black tracks from nuclear break-up recoiling at large angles stay within the focal depth of ~ 3 µm whereas the forward going tracks of a muon and of hadrons quickly run out of focus. The image is digitized in a tomographic way by a CCD camera every 7 µm of depth. A fast processor selects grains in successive views within the predicted angular range; out of 17 views at least 11 grains have to be found to form a track. The track finding procedure continues from sheet to sheet. The plate in which the track cannot be verified anymore is called the vertex plate—the neutrino interaction or a decay vertex is located here. And the most enjoyable part of the search is played out here. An eye scan of this region is performed, to look for a decay kink. No kink event has yet been found.

The experiment at its present stage gives a 90% confidence upper limit for the mixing probability of

$$\sin^2 2\theta_{\mu\tau} < 1.2 \times 10^{-3}$$

averaging over the oscillation term for large $\Delta m^2 > 40$ eV². This sensitivity can be improved by analyzing all events and the efficiency of event finding to give

$$\sin^2 2\theta_{\mu\tau} < 2 \times 10^{-4}$$

or a discovery potential of ~ 6 tau-neutrino events with negligible background taking the mixing probability at its present limit.

The NOMAD experiment relies entirely on the kinematical selection of events. Special emphasis is put on the detection of the decay of the tau-lepton into an electron and two neutrinos. As the flux of electron-neutrinos is only ~ 1 % compared to that of muon-neutrinos the background is potentially lower.

The NOMAD experiment

The transverse momentum of the neutrinos emitted in the decay of the tau-lepton affects the transverse momentum balance of the visible reaction products. Events induced by ν_e are expected to have a sharp 180° correlation between the electron produced and the hadron shower direction, whereas this correlation is very broad for the electron from τ decay (*figure* 3).

The set-up of the NOMAD experiment consists of a large magnet used for measuring the momenta of charged particles produced by neutrino interactions in target foils between drift chambers. Electrons are identified by transition radiation. A calorimeter measures the direction and energy of the photons. Muons are identified behind an iron filter and their charge and momentum is measured in the large magnet. An electron-neutrino induced event is shown in *figure* 4.

Several effects weaken the kinematical correlation between the electron and the hadron shower transverse momentum. One is related to the Fermi motion of nucleons in the target nuclei. Others are due to resolution effects in measuring the hadron shower direction. As a result, a background is expected in this experiment, weakening the statistical significance of the potential observation of tau-neutrino induced events compared to the CHORUS experiment.

However, the information is available in real time, whereas for CHORUS additional time for emulsion handling and scanning is required. Events have been kinematically analysed in terms of all decay modes of the tau-lepton. No candidate events for tau-neutrino interactions have been detected so far and a limit (90% confidence) on the mixing probability of

$$\sin^2 2\theta_{\mu\tau} < 0.92 \times 10^{-4}$$

has been established. By how much can this first result be improved?

A silicon strip decay detector has been added to the set-up to add information on the decay topology and further data is being taken. A final sensitivity for the mixing probability of ~ 6 × 10^{-4} may be reached.

The observations of the Superkamio-

Gran Sasso Laboratories

The Grand Sasso, a mountain range of unsurpassed beauty at a distance of 120 kilometres from Rome is one of Italy's best known scenic landmarks. A complex of buildings at the foot of the mountain may pass for a modern hotel complex at a ski resort. But these buildings house the offices of one of Italy's scientific flagships, the Gran Sasso National Laboratories, located in the heart of the mountain under a 1400-metre cover of rock.

In the early 1980s, when the highway tunnel through the Gran Sasso linking Rome to the Adreatic Sea was reaching completion, Antonio Zichichi, who was

Alessandro Bettini

then the President of Italy's National Institute for Nuclear Physics (INFN), convinced the government to fund the creation of the largest physics underground laboratory in the world. Three huge 100 meter-long halls excavated in dolomite, a rock with very low natural radioactivity, now house several huge detectors that listen to the particles that almost do not interact with matter at all and that can only be detected in absolute "cosmic silence." One of the halls is almost completely filled by MACRO, a 10 000-cubic-metre detector. It looks for muons and neutrinos produced by cosmic-ray particles interacting with the atmosphere. It also attempts to detect the enigmatic weakly interacting massive particles (WIMPs) that would make up part of the missing mass in the universe, and for the supermassive magnetic monopoles. However, none of these exotic particles have been found during the five years of its operation.

Another large detector, BOREXINO (*see cover*), will be completed in 2001 and will look for neutrinos coming from the beryllium chain in the fusion reactions of the sun. According to Alessandro Bettini, the laboratory's director, solar oscillations can only be measured with precision if you also control the neutrino source, and his hopes are high that CERN will approve later this year the construction of an artificial source that will beam neutrinos towards the Gran Sasso.

Bettini says that the source at CERN has been costed at 44 million euros and that the proposal for the first module of one of the detectors at Gran Sasso has been approved. Bettini hopes also that one day a muon accumulator operated by an international collaboration will be able to shoot neutrinos at Gran Sasso.

Alexander Hellemans

kande experiment are surprising. The mixing probability for muon-neutrinos is nearly a maximum whereas for electron-neutrinos it is small, less than 0.02 as shown by the CHOOZ experiment (in the French Ardennes, detecting nuclear power station-produced neutrinos). The mass difference is very small, indicating either near degeneracy of masses or very small neutrino masses.

An independent confirmation of these results is needed. It may come from new results obtained in the same detector, produced by a beam of accelerator muon-neutrinos of $E \sim 1$ GeV and $L \sim 235$ km which will be sent from the KEK proton accelerator (near Tokyo) which starts up this year, if Δm^2 is 10^{-2} - (3×10^{-3}) eV^2. The investigation of atmospheric neutrinos will probably be repeated at the Gran Sasso Laboratory in Italy in 2004 (*see box*). An attempt to detect tau-neutrinos will be made with a high energy ($E \sim 15$ GeV) muon-neutrino beam sent from CERN. The detector (called OPERA) will use the emulsion method developed in the CHORUS experiment at CERN to detect tau-neutrino interactions producing a tau-lepton.

Sterile neutrinos

It has been suggested that the disappearance of tau-neutrinos may lead to the appearance of so-called sterile neutrinos ν_s, left-handed antimuon-neutrinos which do not interact. This special case can in principle be distinguished from $\nu_\mu \rightarrow \nu_\tau$ oscillation by a measurement of neutral current neutrino interactions, muon-less events identified by neutral pion production. Tau-neutrinos will interact by neutral current and produce neutral pions whereas sterile neutrinos will not. This search can also in principle be conducted with the 235 km-long beam line from the KEK Laboratory to the Superkamiokande detector.

The CHORUS and NOMAD experiments will further improve their sensitivity and are expected to reach a mixing probability of 2. In a three-neutrino mixing scenario some $\nu_\mu \rightarrow \nu_\tau$ events can be expected in compatibility with a $\nu_\mu \rightarrow \nu_s$ Superkamiokande effect.

If the Superkamiokande effect is confirmed future neutrino oscillation experiments will need extremely large and costly detectors, which will require very large collaborations. The full exploration of the mixing matrix and mass structure of all neutrino flavours will lead us into the third millenium.

The author is an honorary professor at Humboldt University in Berlin and has been performing neutrino experiments at CERN in Geneva since 1975

Neutrino Astronomy

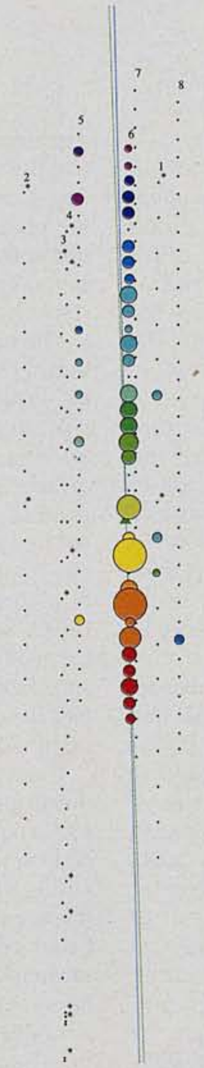
Nature produces cosmic ray particles, probably protons, with energies well above 10^{20} eV. How are they produced? Where do they come from? Gamma rays with energies above 10^{13} eV are produced in jets of active galaxies—are these produced by energetic electrons or protons? What is the correct model of gamma ray bursts? These are just some of the fundamental questions in high energy astrophysics to be answered by observations made with large-area neutrino telescopes.

When gamma rays result from hadronic interactions of protons neutrinos are also produced, but they are not produced when energetic electrons Compton scatter x-rays to gamma-ray energies. So neutrino observations may distinguish between models of active galactic nuclei. Similarly, models for the origin of the highest energy cosmic rays (almost certainly extragalactic)—acceleration of protons in hot spots of giant radio galaxies, acceleration by gamma ray bursts, decay of massive X particles produced by topological defects—may be distinguished as they have very different neutrino signatures, as do different models for gamma ray bursts.

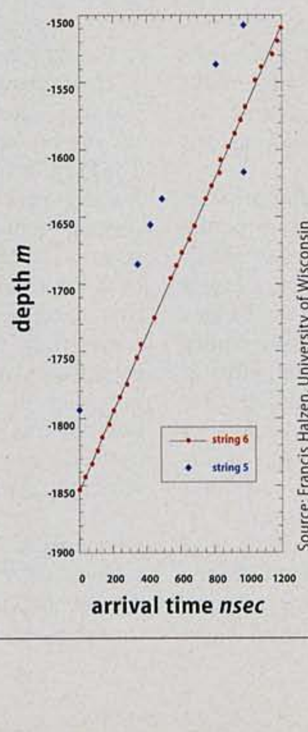
One big advantage of neutrino astronomy is that because of their low interaction cross section, neutrinos can escape from regions opaque to photons, but this is also their biggest disadvantage, as most neutrinos pass unobserved through the Earth.

Predicted fluxes and detection rates are very low, and telescopes of areas approaching 1 km^2 are needed to detect diffuse background intensities. More than three decades ago, Russian and American physicists thought of instrumenting a huge volume of water with photomultiplers to look for Cherenkov light produced by an upward-going muon produced by an interaction, below the detector, of a muon-neutrino which had passed upwards through the Earth.

The AMANDA telescope located at the south pole has recently detected sixteen upward-going neutrino events with energies in the range 10^{11} eV to 10^{12} eV. The detectors used consisted of ten "strings" of photomultipliers (a total of 289) placed in deep vertical holes in the transparent Antarctic ice. Each string extends from 1.5 km to 2 km in depth, and the holes are spread over 10^4 m^2 at the surface. All sixteen events are probably produced by cosmic rays interacting with air nuclei in the northern hemisphere, but they are detected well above any background. The neutrino-induced muon tracks are clearly seen and the angular resolution is very good, currently about 2°. One of the events has a muon track which is nearly vertical and is almost coincident with string 6 (*shown in the diagram where the signal in each detector is indicated by the size of the circle*). The graph *left* shows the time at which each photomultiplier triggered plotted against its depth, giving a perfect correlation for detectors on string 6, and showing the muon's speed was close to the speed of light. This exciting result shows that the goal of constructing viable telescopes for high energy neutrino astronomy is achievable at reasonable cost.



One of 16 neutrino events recently detected by the Amanda south pole telescope



Source: Francis Halzen, University of Wisconsin

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University of Adelaide, Australia