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Neutrino Physics with the KamLAND Detector

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We present the initial design of a very large liquid scintillator detector to be installed in the underground cavity where Kamiokande was once sited. The experiment is optimized to detect low-energy anti-neutrinos and will perform unique measurements in the fields of neutrino physics, geophysics and astrophysics. KamLAND is conceived as a "scalable" detector that will be able to start in a very short time. This first stage detector will be able to deliver results on a number of essential physics issues that only require present day technology. This first running period will also establish backgrounds and detector requirements for a second ultra-low background running phase. One of the initial aims will be to perform a very long baseline oscillation experiment using several nuclear reactors. This can be considered the "ultimate" neutrino mass test using the oscillation technique. The observation of neutrinos from the Earth, supernovae, atmosphere and nucleon decay will also be part of a very ambitious initial program, while in a later stage the observation of solar neutrinos will become the main focus.

1. Introduction

KamLAND is a 1000 ton liquid scintillator detector. The main goal of the experiment is to search for the oscillation of anti-neutrinos emitted by several nuclear power plants. The Large Mixing Angle solution of the solar neutrino problem ($\triangle m^2 = 10^{-5}\text{eV}^2$ and $\sin^2 2\theta$ larger than 0.6) will be verified or rejected. Anti-neutrinos with energies above 1.8 MeV are measured by detecting the reaction $\overline{\nu}_e + p \rightarrow n + e^+$. The time coincidence, the space correlation and the energy constraint between the e^+ signal and the 2.2 MeV gamma-ray signal produced by the capture of a thermal neutron on a free proton make it possible to identify this reaction unambiguously, even in the presence of a rather large background. The collaboration expects to begin to take data in April 2001.

2. The KamLAND Construction

2.1. The Underground Laboratory

The 3000 ton water Cerenkov detector, known as Kamiokande, has been dismantled. A thousand 20" PMTs and their mountings have been saved. The mine tunnel from Super-Kamiokande to KamLAND has been enlarged. The new dimensions are 4.3 meters wide by 3.8 meters high. The cavity has also been enlarged. The new dimensions are 20 meters high by 20 meters in diameter. The rock surface was lined with a polyurethane resin. A new power station and new 3kV power lines were installed as of March 1999. A radon-free ventillation system and various monitoring systems (fire, heat , gases) will be completed by March 2000. A set of compensating coils will be installed along the wall of the cavity to reduce the magnetic field to less than 50 mGauss.

2.2. The Buffer Oil Tank

An 18-meter diameter stainless spherical tank is currently built inside the cavity. This sphere is supported by 10 legs anchored to the floor. Special care is taken to avoid contamination by radioactivity during the welding procedure. A 4-meter diameter and 2-meter high nozzle is located at the top of the tank to allow the presence of various recirculation pipes as well as access for several calibration devices.

2.3. The Plastic Balloon

A 13-meter diameter plastic balloon is centered in the spherical tank. This balloon separates the buffer oil from the liquid scintillator. The buffer oil is an equal mixture of isoparaffin and paraffin which almost matches the density of the scintillator, but is slightly lighter (0.5%). The role of the buffer is to shield the scintillator from the

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radiation emitted by the tank and PMTs. The attenuation length of 400 nm light is about 30 meters. The material of the balloon is a sandwiched film EVOH/Nylon/EVOH. EVOH (Polyvinyl alcohol) has a low permeability for Radon, less than 10 μmeter/sec. The transparency of a 75 μm is found to be about 96% at 400 nm. Thicker films are currently being produced. Since the scintillator is heavier than the buffer oil, the balloon is wrapped in a plastic rope net and suspended from the nozzle.

2.4. The 17" PMT

1280 17" PMTs will be uniformly mounted on the inner wall of the spherical tank. This corresponds to a surface coverage of 22%. These PMTs have been specially developed by Hamamatsu for the KamLAND experiment. They have the same shape and size as the 20" Hamamatsu PMTs. However, the photocathode sensitivity is restricted to the central 17" of the front face. (A black acrylic cap has been attached to mask the outer part of the cathode.) Compared to the 20" PMT, a major improvement has been achieved in the transit-time-spread which is about 3ns FWHM at a gain of 10^7. All the 17" PMTs have been delivered to Tohoku University. They are currently being stored at Honda-Seiki where their detailed characteristics were measured.

2.5. The Liquid Scintillator

The KamLAND liquid scintillator is composed of paraffin (80%) and pseudocumene (20%) to which 1.5 g/l of PPO is added. The light output is about 50% of Anthracene. The attenuation length of light is 10 meters at 400 nm and 20 meters at 450 nm. The light output has been measured with a 6.5-meter long pipe, the radius of the balloon. Combining the information on the transmission of light through the oil and the balloon, the light output and the photocathode sensitivity and coverage, we expect 160 photoelectrons/MeV in the KamLAND detector. The scintillator has a fast component of 5.4 nsec and a slow component of 37.5 nsec. Therefore, pulse shape discrimination between neutrons and photons might be feasible, which would reduce the background significantly. The radioactivity of the scintillator is of course a serious problem. The contamination of the scintillator by U, Th and R is measured to be 2×10^{-13}, 5×10^{-12} and 7×10^{-11} g/g, respectively. After purification of the scintillator by the water-extraction method, their presence is expected to be reduced to less than 10^{-13} g/g for U and Th and less than 10^{-12} for R. These numbers present no difficulties for the reactor neutrino oscillation search. From Monte-Carlo studies, the signal to background ratio is expected to be 100 to 1. However, an improvement by 2 orders of magnitude is necessary to contemplate the detection of solar ^7Be neutrinos.

2.6. The Cerenkov Outer Detector

Although the radioactivity of the scintillator is not a problem for the reactor experiment, the background induced by high-energy neutrons is potentially dangerous. These neutrons originate from muon-induced spallation. Indeed, they can sneak inside the fiducial volume of the detector, scatter on a proton, slow down and capture on another proton. Due to the difference of light emitted by a proton and an electron, the first proton might be misidentified as an electron and the whole scenario perfectly mimics an anti-neutrino reaction. Fortunately, only the neutrons produced in a 1 meter thick annulus of rock surrounding the experiment contribute to the background, the others have their energy degraded too much to be a problem. Of course, the muons will also create neutrons by spallation in the water surrounding the detector. However, these will be in coincidence with the muon which can be detected because of the Cerenkov light that it produces in the water. Therefore, these events will be actively vetoed. It is evident that the efficiency for this active veto must be high.

There is a major difference between the veto of KamLAND and the veto of the previous experiment Kamiokande. In the Kamiokande design, the Cerenkov light of the muons was detected directly by an array of phototubes looking at the incoming muons. The PMTs are mounted at the boundary of the fiducial volume and they are looking outward. The design of Kamland is different. The PMTs of the veto are mounted against the walls of the pit and they are looking at the tank which is covered with an high reflectivity material (TYVEK). The Cerenkov light emitted by the incoming muons will be detected after it bounces off the diffuser. About 240 PMTs of the Kamiokande experiment will be reused to build this veto; a total coverage of about 3%. Muons will cross the apparatus at a rate of about 0.4 Hz. They will typically go through 1 meter of water before entering the central detector. Assuming a 20% photocatode efficiency, one expects to detect about 100 photoelectons, a number well above what is expected for the dark current counting rate.

2.7. Calibration

The detector calibration and monitoring system for KamLAND will employ LED's, a pulsed UV laser system, and radioactive sources (gamma, positron, neutron, and alpha). The LED's and UV laser systems are primarily for timing and gain measurements while the sources will be used mainly to set the energy scale, measure trigger efficiencies, and improve discrimination between $e\gamma$, recoil protons, and alphas in order to better control and estimate backgrounds. A remotely controlled, retractable arm will be used to position the calibration sources at a wide range of positions within the central detector; this is required because the response of the detector has a marked dependence on position of the energy deposit. For monitoring – which is to be carried out more frequently – a simpler deployment device will be used which lowers sources into the central detector to controlled locations along the vertical diameter.

3. The Long Baseline Neutrino Oscillation Search

Japan relies on nuclear energy for about 30% of its total energy consumption and is therefore populated with many powerful nuclear reactors. It so happens that only a single reactor, of moderate power, is located within a 100 km distance from Kamioka. The flux of anti-neutrinos released by the nuclear plants is a rather well-understood function of the initial fuel abundances and the cycling time. Moreover, the $\bar{\nu}$s are detected via the reaction $\bar{\nu}_e + p \to e^+ + n$ which is the inverse beta decay of the neutron and is therefore also well understood. Thus, it is possible to make a precise determination of the total number of events which will be recorded in a year in the absence of any oscillation mechanism. For a 600-ton fiducial mass and assuming 80% of the maximum reactor power, about 450 $\bar{\nu}$s will be recorded. It is quite amazing that 85% of these events correspond to nuclear plants located from 140 to 200 km away from Kamioka. As a result, the experiment is almost equivalent to a neutrino oscillation search with a single 65 GWatt thermal power reactor located 170 km from the detector. Because of this distance, the sensitivity of KamLAND in Δm^2 will increase by 2 orders of magnitude compared to current experiments such as Chooz and Paolo Verde. Finally, the experiment is definitely sensitive to the parameters allowed by the Large Mixing Angle solution of the solar neutrino puzzle.

4. Acknowledgements

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