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Measurement of Reactor Anti-Neutrino Disappearance in KamLAND

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The flux of $\overline{\nu}_e$ from distant nuclear reactors has been measured using Kamioka Liquid scintillator Anti-Neutrino Detector (KamLAND). The long baseline, typically 180 km, enables KamLAND to probe the oscillation solution of the "solar neutrino problem" using reactor anti-neutrinos under laboratory conditions. Correlated positron-neutron events from the reaction $\overline{\nu}_e p \rightarrow e^+ n$ were recorded for a period of 145.1 days (162 ton·year). Instantaneous thermal power generation, burn-up and fuel exchange records for all Japanese commercial power reactors are provided by the power companies. The fission rate for each fissile element is calculated from these data, resulting in a systematic uncertainty in the $\overline{\nu}_e$ flux of less than 1 %. Averaged over the present live-time period, the relative fission yields from the various fuel components are $^{235}\mathrm{U}$: $^{238}\mathrm{U}$: $^{239}\mathrm{Pu}$: $^{241}\mathrm{Pu}$ = 0.568 : 0.078 : 0.297 : 0.057. The thermal power generation data is checked by comparison with the independent records of electric power generation, and the systematic uncertainty is taken as 2% from the regulatory specification for safe reactor operation. The $\overline{\nu}_e$ spectra per fission from $^{235}\mathrm{U}$, $^{239}\mathrm{Pu}$, and $^{241}\mathrm{Pu}$ are taken from the direct measurement of β spectra of fission fragments, and the calculated spectrum is used for $^{238}\mathrm{U}$. The uncertainty of $\overline{\nu}_e$ spectrum per fission is taken as 2.5% by convolving the uncertainty of the data and the $\overline{\nu}_e$ spectra. There are geo $\overline{\nu}_e$s below 2.6 MeV, which comes from the β decay of $^{238}\mathrm{U}$, $^{232}\mathrm{Th}$ branches in the earth, and whose flux has not been measured yet. To avoid the flux ambiguity, energy cut larger than 2.6 MeV is applied. Expected number of reactor $\overline{\nu}_e$ events for 145.1 days in KamLAND is 86.8 events.

The KamLAND detector is located at the site of the earlier Kamiokande, with an average rock overburden of 2,700 m.w.e., resulting 0.34 Hz of cosmic-ray muons. The main target is 1 kton of ultra-pure liquid scintillator (LS) contained in a 13m-diameter spherical balloon made of 135-μm-thick transparent nylon/EVOH composite film. The components of the LS is 80% dodecane, 20% pseudocumene (1,2,4-Trimethylbenzene), and 1.52 g/liter of PPO (2,5-Diphenyloxazole) as a fluor. Surrounding the LS is 2.5 m thick paraffin oil buffer, which shields the LS from external radiation. The LS is viewed by an array of 1,879 photomultiplier tubes (PMTs) supported on a 9m radius stainless steel spherical vessel. 1,325 specially developed fast PMTs with 17-inch diameter among them are used for this analysis, which corresponds to 22% coverage. A 3.2 kton water-Cherenkov outer detector with 225 20-inch PMTs are used for tagging cosmic-ray muons. e^+ from $\overline{\nu}_e \mathrm{p} \rightarrow \mathrm{e}^+ \mathrm{n}$ emits scintillation lights and neutron is thermalized and finally after $\sim$210μsec captured by proton, followed by 2.2 MeV γ-ray. The delayed coincidence with timing, space, and energy correlation is a powerful tool for reducing background.

The selection criteria for $\overline{\nu}_e$ events are as follows. Fiducial volume <5 m to remove external γ-rays. The number of target protons is 3.46×10^{31}. Time correlation $0.5\mu sec < dT <$ 660μsec, space correlation dR <160 cm, E_{prompt} >2.6 MeV, 1.8 MeV< $E_{delayed}$ <2.6 MeV, the distance from central vertical axis >1.2 m for delayed events are applied. Overall detection efficiency is estimated to be (78.3±1.6)%. Delayed neutron emitters like ^{8}He ($\mathrm{T}_{1/2}$=119msec) and ^{9}Li ($\mathrm{T}_{1/2}$=178msec) of muon spallation products are critical backgrounds because of β decay plus neutron captured signal. These backgrounds are eliminated by the two type spallation cut. Two seconds of full volume cut after showering muon whose extra charge is larger than 10^6p.e. ($\sim$3 GeV), and two seconds of track correlation cut within 3m for delayed events after non-showering muon are applied. The remaining ^{8}He and ^{9}Li background is estimated to be 0.94 ± 0.85. The dead time due to the spallation cuts is 11.4%. Single neutrons can be reduced sufficiently by 2ms veto following muons. Fast neutrons mimic the $\overline{\nu}_e$ events. The number of events of fast neutrons from muons through OD is measured by the delayed coincidence + OD hits. That from muons not through OD is estimated using the production rate from OD muon data and relevant neutron shielding properties. Total fast neutron background is estimated to be less than 0.5 events. Finally, the number of selected $\overline{\nu}_e$ events is 54 in entire data set, and that of the backgrounds is 0.95 ± 0.99. The systematic uncertainty of the fiducial volume is estimated to be 4.6% by reproducing the uniform distribution of spallation neutron data. The uncertainty of energy scale at 2.6 MeV is estimated to be 1.9%, which corresponds to 2.1% of $\overline{\nu}_e$. As the estimated total systematic uncertainty is 6.4%, the expected number of $\overline{\nu}_e$ events is 86.8 ± 5.6. The ratio of the number of observed $\overline{\nu}_e$ events to the expected number of events without disappearance is 0.611 ± 0.085(stat.) ± 0.041(syst.). The deficit of evens is inconsistent with the expected rate for standard $\overline{\nu}_e$ propagation at the 99.95 % confidence level. In the context of two-flavor neutrino oscillations with CPT invariance, these results exclude all oscillation solutions but the 'Large Mixing Angle' solution to the solar neutrino problem.