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A Search for Anti-electron-neutrinos from the Sun at Super-Kamiokande

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Solar neutrino measurements from Super-Kamiokande and SNO established that the solar neutrino problem (deficit of solar neutrinos) is explained by the transformation of electron neutrinos to the other active neutrinos. The mechanism of this transformation is generally assumed to be via neutrino flavor oscillations from ν_e to some superposition of ν_μ and ν_τ, and the oscillation parameter is indicated in the Large Mixing Angle solution (LMA) region from all solar neutrino experiments. On the other hand, result from a long baseline reactor neutrino experiment, KamLAND, also indicates the oscillation parameter to be in the LMA region in the context of CPT invariance. This good agreement ensures the neutrino oscillation as a solution for the solar neutrino problem. However subdominant Resonant Spin Flavor Precession (RSFP) in which some of the ν_e transform to anti-particles ($\bar{\nu}_\mu$, $\bar{\nu}_\tau$) is not still ruled out. Combination of RSFP and oscillation can transform solar neutrinos to $\bar{\nu}_e$ if the neutrino is Majorana, it has a large magnetic moment, and the Sun has a large magnetic field. In this thesis, we present the result of a $\bar{\nu}_e$ search in SK, study on the neutrino oscillation using the data from solar neutrino measurements and KamLAND (global analysis), study on the neutrino magnetic moment also considering effects of anti-neutrinos on elastic scattering events, and finally perform a global analysis under the RSFP+oscillation hypothesis.

Super-Kamiokande is a 22.5 kton fiducial volume water Cherenkov detector. The data used for this thesis were collected in 1496 live days during 31 May 1996 through 15 July 2001 in SK-I. In the energy region of solar neutrinos (below 20 MeV), neutrinos are detected through following processes ; $\nu+e^- \rightarrow \nu+e^-$ (elastic scattering), $\bar{\nu}_e+p \rightarrow e^+ + n$ (inverse beta decay, if solar neutrinos have $\bar{\nu}_e$ component). Dominant backgrounds are

^{222}Rn in the water, external gamma rays and muon induced spallation products. To remove these background, event selection called 'Reduction' is applied. The reduction is subdivided into four steps, first reduction, spallation cut, second reduction and gamma cut. It has succeeded in background removal of 2 order of magnitude in contrast to ~40% of signal residual efficiency.

The directions of recoil electrons from elastic scattering have strong correlations with incident neutrino directions. Such directional neutrino signals are statistically extracted from the $\cos\theta_{\rm sun}$ distribution of the observed data. The ratio of the observed number of solar neutrino events to the prediction is $N_{\rm elastic}/N_{\rm expect} = 0.465 \pm 0.005({\rm stat.})^{+0.016}_{-0.015}({\rm sys.})$. In another word, the observed ^{8}B neutrino flux $\Phi_{^8{\rm B}}$ is, $\Phi_{^8{\rm B}} = 2.35 \pm 0.02({\rm stat.}) \pm 0.08({\rm sys.}) \times 10^6/cm^2/sec$.

The dominant process of $\bar{\nu}_e$ detection in SK is the inverse β decay, $\bar{\nu}_e + p \rightarrow e^+ + n$. A neutron capture reaction, $n + p \rightarrow d + \gamma(2.2MeV)$, takes place successively. But, 2.2 MeV is below the energy threshold and the γ-ray cannot be used to tag the inverse β decay. Therefore, statistical methods are necessary to subtract the background. For $\cos\theta_{\rm sun} \leq 0.5$ and E $\leq$ 8 MeV region, most of background events are due to radioactivities in the detector materials such as ^{222}Rn and these events have no correlation with the other events. In contrast, for E $\geq$ 8 MeV, most of background events are due to spallation products. By using statistical estimation for spallation backgrounds, for 8 MeV $\leq$ E $\leq$ 20 MeV, we estimated the spallation background is 93% $\pm$ 7% in observed events. No significant excess of $\bar{\nu}_e$ events have been observed and the upper limit on the conversion probability to $\bar{\nu}_e$ of the ^{8}B solar neutrino is 0.8%. We also set a flux limit for monochromatic $\bar{\nu}_e$ for $E_{\bar{\nu}_e}$ = 10 MeV - 17 MeV.

From a global oscillation analysis using all solar flux measurements, SK zenith angle spectra, KamLAND results, and under the two flavor neutrino oscillation hypothesis, only the LMA1 oscillation parameter region is favored at the 99% confidence level.
A global analysis for the RSFP+oscillation hybrid model has been also performed and it turned out that only $\mu_\nu B_{\rm sun} < 1 \times 10^{-4} \mu_B$Gauss is allowed at 90 % C.L. This limit corresponds to $\mu_\nu < 3.3 \times 10^{-10} \mu_B$ for the case B$_{\rm sun}$ is 300 k Gauss. Finally it is pointed out that the RSFP is possible as subdominant process only up to a few % level.