Limits On the Neutrino Magnetic Moment Using 1496 Days of Super-Kamiokande-I Solar Neutrino Data

The Super-Kamiokande Collaboration

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A search for a non-zero neutrino magnetic moment has been conducted using 1496 live days of solar neutrino data from Super-Kamiokande-I. Specifically, we searched for distortions to the energy spectrum of recoil electrons arising from magnetic scattering due to a non-zero neutrino magnetic moment. In the absence of clear signal, we found $\mu_\nu \leq 3.6 \times 10^{-10} \mu_B$ at 90% C.L. by fitting to the Super-Kamiokande day/night spectra. The fitting took into account the effect of neutrino
oscillation on the shapes of energy spectra. With additional information from other solar neutrino and KamLAND experiments constraining the oscillation region, a limit of $\mu_{\nu} \leq 1.1 \times 10^{-10}$ $\mu_B$ at 90% C.L. was obtained.

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In the Standard Model, neutrinos are massless and do not have magnetic moments. There is now strong evidence from recent experiments [1,2,3,4] that neutrinos undergo flavor oscillations and hence must have finite masses. Introducing neutrino masses to the Standard Model results in neutrino magnetic moments [5]. How-ever, such moments are at least eight orders of magnitude below currently accessible experimental limits. These limits are derived from reactor $\bar{\nu}_e$'s [6,7,8] and are in the range of $(1 - 4) \times 10^{-10}$ $\mu_B$, where $\mu_B$ is Bohr magneton. Therefore, a positive observation of such large magnetic moments would imply additional physics beyond the Standard Model.

The general interaction of neutrino mass eigenstates $j$ and $k$ with a magnetic field can be characterized by constants $\mu_{jk}$, the magnetic moments. Both diagonal ($j = k$) and off-diagonal ($j \neq k$) moments are possible. While there have been attempts to use the neutrino magnetic moments to explain the solar neutrino problem [11], e.g. spin flavor precession (SFP) [12], SFP cannot explain the suppressed reactor anti-neutrino flux detected at KamLAND [8]. Under the assumption of CPT invariance, KamLAND’s results give independent support to neutrino oscillations [1,2,3], not SFP [13], being the solution to the solar neutrino problem.

In this paper, we report a search for neutrino magnetic moment using the high statistics solar neutrino data obtained by Super-Kamiokande-I. Super-Kamiokande (SK) is a water Cherenkov detector, with a fiducial volume of 22.5 kton, located in the Kamioka mine in Gifu, Japan. Descriptions of the detector can be found elsewhere [14]. SK detects solar neutrinos via the elastic scattering of neutrinos off electrons in the water. The scattered recoil electrons are detected via Cherenkov light, allowing their direction, timing and total energy to be measured. SK measures the spectrum of the recoiling electrons with high statistical accuracy. To control energy-related systematic effects, the number of hit photomultiplier tubes (PMT) is related to the total electron energy using electrons injected by an electron linear accelerator (LINAC) [15]. The number of hit PMTs in the Monte Carlo simulation of those LINAC electrons is tuned to agree with LINAC data. As a result of this tuning, the systematic uncertainty of the reconstructed energy of electrons between 5 and 20 MeV is less than 0.64%. The uncertainty of the energy resolution is less than 2%. This absolute energy scale is monitored and cross checked by (1) muon decay electrons, (2) spallation products induced by cosmic ray muons, and (3) decay of artificially produced $^{16}$N [16]. The data used for this analysis were collected from May 31, 1996 to July 15, 2001 with a livetime of 1496 days. The results are binned in 0.5 MeV bins of the total electron energy from 5 to 14 MeV and one bin combining events from 14 to 20 MeV. As a real time detector, SK can divide the data sample into day and night data samples which give the day/night spectra. The number of events in each energy bin is extracted individually by utilizing the directional correlation between the recoil electrons and the Sun. The angular distribution in the region far from the solar direction is used to estimate the background. The estimation of the backgrounds, along with the expected angular distributions of the solar neutrino signals, are incorporated into an extended maximum likelihood method to extract the number of solar neutrino events [8].

If $\mu_{\nu} \neq 0$, the differential cross section of neutrino-electron scattering is an incoherent sum of weak scattering (1) and magnetic scattering (2).

\[
\frac{d\sigma}{dT} = C \left[ g_1^2 + g_2^2 \left( 1 - \frac{T}{E_{\nu}} \right)^2 - g_L g_R \frac{m_T^2}{E_{\nu}^2} \right] \tag{1}
\]

where $C = 2G_F^2 m_e / \pi$, $g_L = \sin^2 \theta_W + 1/2$ for $\nu_e$, $g_L = \sin^2 \theta_W - 1/2$ for $\nu_\mu$ and $\nu_\tau$, and $g_R = \sin^2 \theta_W$.

\[
\frac{d\sigma}{dT} = \mu_{\nu}^2 \frac{\pi \alpha_{em}^2}{m_e^2} \left( \frac{1}{T} - \frac{1}{E_{\nu}} \right) \tag{2}
\]

where $\mu_{\nu}$ is in units of $\mu_B$, $E_{\nu}$ is the neutrino energy, $T = E_{\nu} - m_e$, and $T(E_{\nu})$ is the kinetic (total) energy of the recoil electrons.

We search for the effects of the neutrino magnetic moments by looking for distortions in the shape of the recoil electron spectrum relative to the expected weak scattering spectrum. Figure 1 shows the ratio of SK measured recoil electron energy spectrum and the expected weak scattering spectrum assuming no oscillation. It is flat, with no obvious increase of event rates in the lower energy bins. As neutrino oscillation could change the expected weak scattering spectrum, the flatness could be due to a combination of a decrease of the weak scattering rate by oscillation and an increase of the magnetic scattering rate at lower energies. To investigate this the observed SK day/night energy spectra are examined using the following $\chi^2$, similar to the one used in SK’s standard solar spectrum analysis [18] with the addition of the oscillation
neutrino spectrum will not be changed by the magnetic field in the Sun. In this paper we use the SK day/night spectra from 5 to 14 MeV and consider only the $^8$B solar neutrino flux. Furthermore, we assume $\mu_{e1} = \mu_{e2}$, so the magnetic scattering spectrum would not be affected by neutrino oscillations.

The $\chi^2$ is minimized with respect to the parameters $\alpha$, $\beta$ and $\mu^2_B$ in the whole oscillation parameter space. We impose the physical condition $\mu^2_B \geq 0$ in the process of minimization. As there is no strong distortion of the observed energy spectra, this $\chi^2$ can be used to exclude certain regions in the oscillation parameter space.

In Figure 2 the shaded regions are excluded by SK day/night spectra at 95% C.L. considering only weak scattering, while the hatched regions are excluded at the same confidence level but including the contribution from the magnetic scattering. The exclusion regions shrink with the addition of the magnetic scattering because there is one more parameter with which to minimize the $\chi^2$. As there is no obvious increase of event rates at lower energies, we instead derive a limit on the
neutrino magnetic moment. For each point in the oscillation parameter space, the probability distribution of \(\Delta \chi^2 = \chi^2 - \chi^2_{\text{min}}\) as a function of the square of the magnetic moment is used. Figure 3 shows the probability distributions of \(\Delta \chi^2\) as function of \(\mu^2\) for some oscillation parameters.

A 90% C.L. upper limit on the neutrino magnetic moment is obtained by Equation 4 for each point in the oscillation parameter space.

\[
\text{Prob}(\Delta \chi^2(\mu^2 \geq \mu^2_0)) = 0.1 \times \text{Prob}(\Delta \chi^2(\mu^2 \geq 0)) \quad (4)
\]

The overall limit on the neutrino magnetic moment is obtained by finding the maximum of the aforementioned limits in the oscillation parameter space. Discarding the regions excluded by SK day/night spectra, we found at 90% C.L. \(\mu_\nu \leq 3.6 \times 10^{-10} \mu_B\) with the limit at \(\Delta m^2 = 3.13 \times 10^{-11} \text{eV}^2\) and \(\tan^2 \theta = 0.91\) which is in the VAC region.

Results from other solar neutrino experiments can further constrain the allowed regions in the oscillation parameter space. Radiochemical experiments Homestake [20], SAGE [21] and Gallex/GNO [22] (combined into a single “Gallium” rate) detect solar neutrinos via charged current interactions with nucleons. The presence of a non-zero neutrino magnetic moment would not affect their measurements of solar neutrino flux rates. SNO [4] extracts the charged current, neutral current and elastic scattering rates by utilizing their distinctive angular distributions. Inclusion of the neutrino magnetic moment will not affect the charged current interaction. The effects of non-zero neutrino magnetic moment on the SNO neutral current interaction are estimated to be very small [23]. Such a magnetic moment could change the elastic scattering rates but would not change the angular distribution of the elastic scattering events. Therefore, SNO’s charged current and neutral current rates will be essentially unaffected by a non-zero neutrino magnetic moment. The combination of these charged current rates with SNO’s neutral current rate and SK’s day/night spectra constrains the neutrino oscillation to an area in the large mixing angle (LMA) region as shown in Figure 4 (the area within the dashed lines).

Limiting the search for the neutrino magnetic moment within the region allowed by solar neutrino experiments, we get an upper limit on the neutrino magnetic moment of \(\mu_\nu \leq 1.3 \times 10^{-10} \mu_B\) at 90% C.L. with the limit at \(\Delta m^2 = 2.8 \times 10^{-5} \text{eV}^2, \tan^2 \theta = 0.42\).

KamLAND uses inverse \(\beta\)-decay interactions to detect reactor \(\bar{\nu}_e\)’s [5]. The signature of magnetic scattering with non-zero neutrino magnetic moment bears no similarity to that used to detect the inverse \(\beta\)-decay interactions. Therefore, KamLAND’s detection of anti-neutrinos would not be affected by a non-zero neutrino magnetic moment. Assuming CPT invariance, the inclusion of the KamLAND results further constrains the neutrino oscillation solutions in the LMA region (the shaded area in Figure 4). This results in a limit on the neutrino magnetic moment at 90% C.L. of \(\mu_\nu \leq 1.1 \times 10^{-10} \mu_B\).
with the limit at $\Delta m^2 = 6.6 \times 10^{-5}\text{eV}^2$ and $\tan^2 \theta = 0.48$. This result is comparable to the most recent magnetic moment limits from reactor neutrino experiments of $1.3 \times 10^{-10} \mu_B$ (TEXONO) [8] and $1.0 \times 10^{-10} \mu_B$ (MUNU) [10], albeit for neutrinos and not antineutrinos.

If neutrinos have off-diagonal moments, the magnetic field in the Sun can affect the $^8\text{B}$ neutrino flux spectrum, so the results on the limits of neutrino magnetic moment could in principle be changed. But for the LMA region, the effect of the solar magnetic field is negligible [13, 24], so the same limits on the neutrino magnetic moment in the LMA region would be obtained.

**Conclusion.** – Limits on the neutrino magnetic moment have been obtained by analyzing the SK day/night energy spectra. The oscillation effects on the shape of the weak scattering spectrum have been taken into account using Super-Kamiokande-I’s 1496 days of solar neutrino data is obtained. By constraining the search to only the regions allowed by all neutrino experiments, a limit of $1.1 \times 10^{-10} \mu_B$ is obtained.

The authors gratefully acknowledge the cooperation of the Kamioka Mining and Smelting Company. Super-Kamiokande has been built and operated from funding of the Kamioka Mining and Smelting Company. Super-Kamiokande-I’s 1496 days of solar neutrino data is obtained. By constraining the search to only the regions allowed by all neutrino experiments, a limit of $1.1 \times 10^{-10} \mu_B$ is obtained.

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