Limits on the Neutrino Magnetic Moment using 1496 Days of Super-Kamiokande-I Solar Neutrino Data

D.W. Liu,[4] Y. Ashie,[1] S. Fukuda,[1] Y. Fukuda,[1] K. Ishihara,[1] Y. Itow,[1] Y. Koshio,[1] A. Minamino,[1] M. Miura,[1] S. Moriyama,[1] M. Nakahata,[1] T. Namba,[1] R. Nambu,[1] Y. Obayashi,[1] N. Sakurai,[1] M. Shiozawa,[1] Y. Suzuki,[1] H. Takeuchi,[1] Y. Takeuchi,[1] S. Yamada,[1] M. Ishitsuka,[2] T. Kajita,[2] K. Kaneyuki,[2] S. Nakayama,[2] A. Okada,[2] T. Ooyabu,[2] C. Saji,[2] S. Desai,[3] M. Earl,[3] E. Kearns,[3] M. D. Messier,[3,*] J. L. Stone,[3] L. R. Sulak,[3] C.W. Walter,[3] W. Wang,[3] T. Barszczak,[4] D. Casper,[4] J. P. Cravens,[4] W. Gajewski,[4] W. R. Kropp,[4] S. Mine,[4] M. B. Smy,[4] H.W. Sobel,[4] C.W. Sterner,[4] M. R. Vagins,[4] K. S. Ganezer,[5] J. Hill,[5] W. E. Keig,[5] J. Y. Kim,[6] I. T. Lim,[6] R.W. Ellsworth,[7] S. Tasaka,[8] A. Kibayashi,[9] J. G. Learned,[9] S. Matsuno,[9] D. Takemori,[9] Y. Hayato,[10] A. K. Ichikawa,[10] T. Ishida,[10] T. Ishii,[10] T. Iwashita,[10] J. Kameda,[10] T. Kobayashi,[10] T. Maruyama,[10,†] K. Nakamura,[10] K. Nitta,[10] Y. Oyama,[10] M. Sakuda,[10] Y. Totsuka,[10] A. T. Suzuki,[11] M. Hasegawa,[12] K. Hayashi,[12] T. Inagaki,[12] I. Kato,[12] H. Maesaka,[12] T. Morita,[12] T. Nakaya,[12] K. Nishikawa,[12] T. Sasaki,[12] S. Ueda,[12] S. Yamamoto,[12] T. J. Haines,[13,4] S. Dazeley,[14] S. Hatakeyama,[14] R. Svoboda,[14] E. Blaufuss,[15] J. A. Goodman,[15] G. Guillian,[15] G.W. Sullivan,[15] D. Turcan,[15] K. Scholberg,[16] A. Habig,[17] M. Ackermann,[18] C. K. Jung,[18] T. Kato,[18] K. Kobayashi,[18] K. Martens,[18,‡] M. Malek,[18] C. Mauger,[18] C. McGrew,[18] E. Sharkey,[18] B. Viren,[18,§] C. Yanagisawa,[18] T. Toshito,[19] C. Mitsuda,[20] K. Miyano,[20] T. Shibata,[20] J. Ishii,[21] Y. Kajiyama,[21] Y. Kuno,[21] Y. Nagashima,[21] M. Takita,[21] M. Yoshida,[21] H. I. Kim,[22] S. B. Kim,[22] J. Yoo,[22] H. Okazawa,[23] T. Ishizuka,[24] Y. Choi,[25] H. K. Seo,[25] Y. Gando,[26] T. Hasegawa,[26] K. Inoue,[26] J. Shirai,[26] A. Suzuki,[26] M. Koshiba,[27] T. Hashimoto,[28] Y. Nakajima,[28] K. Nishijima,[28] H. Ishino,[29] M. Morii,[29] R. Nishimura,[29] Y. Watanabe,[29] D. Kielczewska,[30,4] J. Zalipska,[30] R. Gran,[31] K. K. Shiraishi,[31] K. Washburn,[31] and R. J. Wilkes[31]

(Super-Kamiokande Collaboration)

[1]*Kamioka Observatory, Institute for Cosmic Ray Research, University of Tokyo, Kamioka, Gifu, 506-1205, Japan*
[2]*Research Center for Cosmic Neutrinos, Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba 277-8582, Japan*
[3]*Department of Physics, Boston University, Boston, Massachusetts 02215, USA*
[4]*Department of Physics and Astronomy, University of California, Irvine, Irvine, California 92697-4575, USA*
[5]*Department of Physics, California State University, Dominguez Hills, Carson, California 90747, USA*
[6]*Department of Physics, Chonnam National University, Kwangju 500-757, Korea*
[7]*Department of Physics, George Mason University, Fairfax, Virginia 22030, USA*
[8]*Department of Physics, Gifu University, Gifu, Gifu 501-1193, Japan*
[9]*Department of Physics and Astronomy, University of Hawaii, Honolulu, Hawaii 96822, USA*
[10]*High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305-0801, Japan*
[11]*Department of Physics, Kobe University, Kobe, Hyogo 657-8501, Japan*
[12]*Department of Physics, Kyoto University, Kyoto 606-8502, Japan*
[13]*Physics Division, P-23, Los Alamos National Laboratory, Los Alamos, New Mexico 87544, USA*
[14]*Department of Physics and Astronomy, Louisiana State University, Baton Rouge, Louisiana 70803, USA*
[15]*Department of Physics, University of Maryland, College Park, Maryland 20742, USA*
[16]*Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
[17]*Department of Physics, University of Minnesota, Duluth, Minnesota 55812-2496, USA*
[18]*Department of Physics and Astronomy, State University of New York, Stony Brook, New York 11794-3800, USA*
[19]*Department of Physics, Nagoya University, Nagoya, Aichi 464-8602, Japan*
[20]*Department of Physics, Niigata University, Niigata, Niigata 950-2181, Japan*
[21]*Department of Physics, Osaka University, Toyonaka, Osaka 560-0043, Japan*
[22]*Department of Physics, Seoul National University, Seoul 151-742, Korea*
[23]*International and Cultural Studies, Shizuoka Seika College, Yaizu, Shizuoka, 425-8611, Japan*
[24]*Department of Systems Engineering, Shizuoka University, Hamamatsu, Shizuoka 432-8561, Japan*
[25]*Department of Physics, Sungkyunkwan University, Suwon 440-746, Korea*
[26]*Research Center for Neutrino Science, Tohoku University, Sendai, Miyagi 980-8578, Japan*
[27]*The University of Tokyo, Tokyo 113-0033, Japan*
[28]*Department of Physics, Tokai University, Hiratsuka, Kanagawa 259-1292, Japan*
[29]*Department of Physics, Tokyo Institute for Technology, Meguro, Tokyo 152-8551, Japan*
[30]*Institute of Experimental Physics, Warsaw University, 00-681 Warsaw, Poland*
[31]*Department of Physics, University of Washington, Seattle, Washington 98195-1560, USA*

(Received 7 February 2004; published 6 July 2004)

0031-9007/04/93(2)/021802(5)$22.50

A search for a nonzero 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 nonzero neutrino magnetic moment. In the absence of a 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.

DOI: 10.1103/PhysRevLett.93.021802 PACS numbers: 14.60.Pq, 13.15.+g, 13.40.Em, 26.65.+t

In the standard model, neutrinos are massless and do not have magnetic moments. There is now strong evidence from recent experiments [1–5] that neutrinos undergo flavor oscillations and hence must have finite masses. Introducing neutrino masses to the standard model results in neutrino magnetic moments [6]. However, such moments are at least 8 orders of magnitude below currently accessible experimental limits. These limits are derived from reactor $\bar{\nu}_e$'s [7–10] and are in the range of $[(1\text{–}4) \times 10^{-10}]\mu_B$, where μ_B is the Bohr magneton. Various astrophysical observations also yield limits on the neutrino magnetic moment in the range from $10^{-12}\mu_B$ to $(4 \times 10^{-10})\mu_B$ [11]. 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 μ_{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 [12], e.g., spin flavor precession (SFP) [13], SFP cannot explain the suppressed reactor antineutrino flux detected at KamLAND [5]. Under the assumption of *CPT* invariance, KamLAND's results give independent support to neutrino oscillations [2,3], not SFP [14], being the solution to the solar neutrino problem.

In this Letter, 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 [15]. 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) [16]. 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 [17]. The data used for this analysis were collected from May 31, 1996 to July 15, 2001 with a live time 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 [2].

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) [18].

$$\left(\frac{d\sigma}{dT}\right)_{WK} = C\left[g_L^2 + g_R^2\left(1 - \frac{T}{E_\nu}\right)^2 - g_L g_R \frac{m_e T}{E_\nu^2}\right], \quad (1)$$

where $C = 2G_F^2 m_e/\pi$, $g_L = \sin^2\theta_W + 1/2$ for ν_e, $g_L = \sin^2\theta_W - 1/2$ for ν_μ and ν_τ, and $g_R = \sin^2\theta_W$.

$$\left(\frac{d\sigma}{dT}\right)_{EM} = \mu_\nu^2 \frac{\pi\alpha_{em}^2}{m_e^2}\left(\frac{1}{T} - \frac{1}{E_\nu}\right), \quad (2)$$

where μ_ν is in units of μ_B, E_ν is the neutrino energy, $T = E_e - m_e$, and $T(E_e)$ is the kinetic (total) energy of the recoil electrons.

In a method first pioneered by Beacom and Vogel to extract the neutrino magnetic moment from Super-Kamiokande's early solar data [18], 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 the 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.

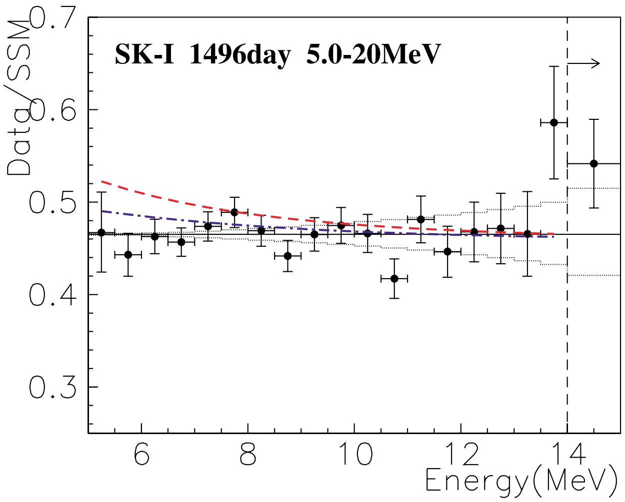

FIG. 1 (color online). Ratio of SK-I observed recoil electron energy spectrum and the expected nonoscillated weak scattering spectrum. The error bars are the results of the statistical and energy noncorrelated systematic errors being added in quadrature. The dotted lines are the correlated systematic errors. The dash-dotted line is the expected oscillated weak scattering spectrum for $\Delta m^2 = 6.6 \times 10^{-5}$ eV^2 and $\tan^2\theta = 0.48$. The dashed line shows the addition of magnetic scattering with $\mu_\nu \leq (1.1 \times 10^{-10})\mu_B$ on top of the oscillated weak spectrum. (The zero has been suppressed).

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 χ^2, similar to the one used in SK's standard solar spectrum analysis [19] with the addition of the oscillation effects and the contribution of magnetic scattering:

$$\chi^2 = \sum_{a=d,n} \sum_{i=1}^{18} \left[\frac{\frac{\alpha}{1+\beta\delta_i}(W_i^a + \mu_{10}^2 M_i) - D_i^a}{\sigma_i^a} \right]^2 + \beta^2, \quad (3)$$

where $W_i^{d,n}$ is the ratio of the oscillated day-night weak scattering spectra to the nonoscillated weak scattering spectrum. We approximate the solar neutrino oscillations by a two-neutrino description with parameters θ (mixing angle) and Δm^2 (difference in mass squared between mass eigenstates) [2]. M_i is the ratio of the magnetic scattering spectrum to the nonoscillated weak scattering spectrum assuming $\mu_\nu = 10^{-10}\mu_B$. $D_i^{d,n}$ is the ratio of the measured day-night spectra to the nonoscillated weak scattering spectrum. δ_i is the energy bin correlated systematic error, and $\sigma_i^{d,n}$ is the day-night statistical and uncorrelated systematic errors added quadratically. α is the normalization factor of the measured ^{8}B flux to the expected flux; the ^{8}B flux is not constrained in this analysis. μ_{10}^2 is the magnetic moment squared in units of $(10^{-10}\mu_B)^2$. β is a parameter used to constrain the variation of correlated systematic errors that come from the uncertainties in the energy scale, resolution, and ^{8}B neutrino energy spectrum. Considering neutrinos with only diagonal magnetic moments [18], the survival probability of neutrinos passing through the magnetic field in the Sun is independent of neutrino energy [20]. Thus the shape of the ^{8}B neutrino spectrum will not be changed by the magnetic field in the Sun. In this Letter we use the SK day-night spectra from 5 to 14 MeV and consider only the ^{8}B solar neutrino flux. Furthermore, we assume $\mu_{\nu 1} = \mu_{\nu 2}$, so the magnetic scattering spectrum would not be affected by neutrino oscillations.

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

In Fig. 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 include 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 χ^2. As

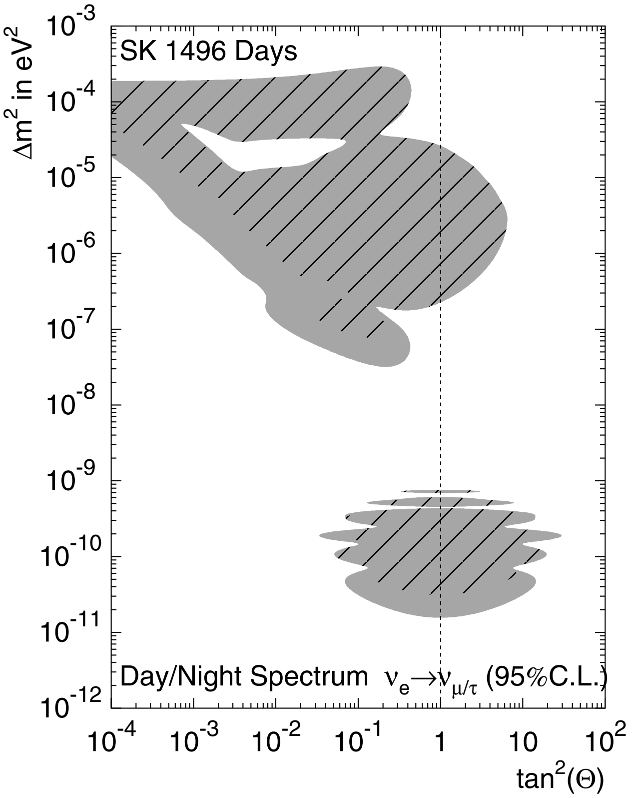

FIG. 2. The 95% C.L. exclusion regions using the SK day-night spectra shape. The shaded area assumes only weak scattering. The hatched region takes into account the contribution from magnetic scattering.

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 $\Delta\chi^2 = \chi^2 - \chi^2_{\rm min}$ as a function of the square of the magnetic moment is used. Figure 3 shows the probability distributions of $\Delta\chi^2$ as a function of μ_ν^2 for some oscillation parameters.

A 90% C.L. upper limit μ_0 on the neutrino magnetic moment is obtained by Equation (4) for each point in the oscillation parameter space.

$$\mathrm{Prob}(\Delta\chi^2(\mu^2 \geq \mu_0^2)) = 0.1 \times \mathrm{Prob}(\Delta\chi^2(\mu^2 \geq 0)). \tag{4}$$

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 $\Delta m^2 = 3.13 \times 10^{-11}$ eV^2 and $\tan^2\theta = 0.91$, which is in the vacuum oscillation (VAC) region.

Results from other solar neutrino experiments can further constrain the allowed regions in the oscillation parameter space. Radiochemical experiments Homestake [21], SAGE [22], and Gallex/GNO [23] (combined into a single "Gallium" rate) detect solar neutrinos via charged current interactions with nucleons. The presence of a nonzero neutrino magnetic moment would not affect their measurements of solar neutrino flux rates. Sudbury Neutrino Observatory Collaboration (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 a nonzero neutrino magnetic moment on the SNO neutral current interaction are estimated to be very small [24]. 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 nonzero 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 Fig. 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 $\Delta m^2 = 2.8 \times 10^{-5}$ eV^2 and $\tan^2\theta = 0.42$.

KamLAND uses inverse β-decay interactions to detect reactor $\bar{\nu}_e$'s [5]. The signature of magnetic scattering with nonzero neutrino magnetic moment bears no similarity to that used to detect the inverse β-decay interactions. Therefore, KamLAND's detection of antineutrinos would not be affected by a nonzero neutrino magnetic

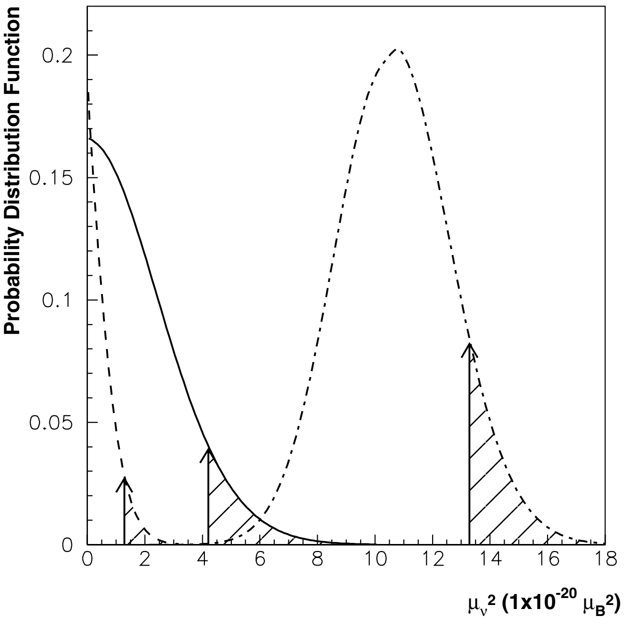

FIG. 3. The probability distribution of $\Delta\chi^2$ as a function of μ_ν^2. The solid line is for the case of no oscillation. The dashed line is for $\Delta m^2 = 2.8 \times 10^{-5}$ eV^2 and $\tan^2\theta = 0.42$ (LMA). The dash-dotted line is for $\Delta m^2 = 3.13 \times 10^{-11}$ eV^2 and $\tan^2\theta = 0.91$ (VAC). The arrows point to the place where the 90% C.L. limits are. The hatched areas to the right of the arrows are 10% of the total areas under the curves.

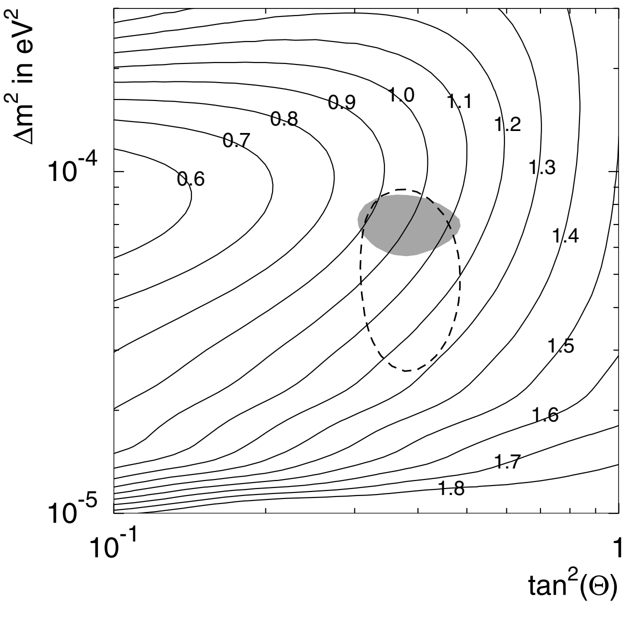

FIG. 4. The 90% C.L. μ_ν limit contours (in units of $10^{-10}\mu_B$) and neutrino oscillation allowed regions. The area within the dashed lines is the solar neutrino experiments' allowed region considering both weak and magnetic scattering. The shaded area shows the allowed region for solar experiments plus KamLAND.

moment. Assuming *CPT* invariance, the inclusion of the KamLAND results further constrains the neutrino oscillation solutions in the LMA region (the shaded area in Fig. 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 $\Delta m^2 = 6.6 \times 10^{-5}$ 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) [9] 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}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 [14,25], so the same limits on the neutrino magnetic moment in the LMA region would be obtained.

In 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 when analyzing energy spectra. A limit of $(3.6 \times 10^{-10})\mu_B$ 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 by the Japanese Ministry of Education, Culture, Sports, Science and Technology, the U.S. Department of Energy, and the U.S. National Science Foundation. This work was partially supported by the Korean Research Foundation (BK21) and the Korea Ministry of Science and Technology.

---

*Present address: Harvard University, Cambridge, MA 02138, USA.

†Present address: Enrico Fermi Institute, University of Chicago, Chicago, IL 60637, USA.

‡Present address: Department of Physics, University of Utah, Salt Lake City, UT 84112, USA.

§Present address: Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA.

[1] Y. Fukuda *et al.*, Phys. Rev. Lett. **81**, 1562 (1998).
[2] S. Fukuda *et al.*, Phys. Rev. Lett. **86**, 5656 (2001); S. Fukuda *et al.*, Phys. Lett. B **539**, 179 (2002).
[3] Q. R. Ahmad *et al.*, Phys. Rev. Lett. **89**, 011301 (2002); Q. R. Ahmad *et al.*, Phys. Rev. Lett. **89**, 011302 (2002).
[4] S. N. Ahmed *et al.*, Phys. Rev. Lett. **92**, 181301 (2004).
[5] K. Eguchi *et al.*, Phys. Rev. Lett. **90**, 021802 (2003).
[6] B. W. Lee and R. E. Shrock, Phys. Rev. D **16**, 1444 (1977); W. J. Marciano and A. I. Sanda, Phys. Lett. B **67**, 303 (1977).
[7] F. Reines, H. S. Gurr, and H. W. Sobel, Phys. Rev. Lett. **37**, 315 (1976); P. Vogel and J. Engel, Phys. Rev. D **39**, 3378 (1989).
[8] A. I. Derbin *et al.*, JETP Lett. **57**, 768 (1993).
[9] H. B. Li *et al.*, Phys. Rev. Lett. **90**, 131802 (2003).
[10] Z. Daraktchieva *et al.*, Phys. Lett. B **564**, 190 (2003).
[11] Particle Data Group, K. Hagiwara *et al.*, Phys. Rev. D **66**, 010001 (2002), and references therein.
[12] J. Schechter and J. W. F. Valle, Phys. Rev. D **24**, 1883 (1981); **25**, 283(E) (1982); L. B. Okun, M. B. Voloshin, and M. I. Vysotsky, Sov. Phys. JETP **64**, 446 (1986).
[13] C. S. Lim and W. J. Marciano, Phys. Rev. D **37**, 1368 (1988); E. Kh. Akhmedov, Phys. Lett. B **213**, 64 (1988).
[14] J. Barranco *et al.*, Phys. Rev. D **66**, 093009 (2002); hep-ph/0207326 v3.
[15] Y. Fukuda *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **501**, 418 (2003).
[16] M. Nakahata *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **421**, 113 (1999).
[17] E. Blaufuss *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **458**, 638 (2001).
[18] J. F. Beacom and P. Vogel, Phys. Rev. Lett. **83**, 5222 (1999).
[19] Y. Fukuda *et al.*, Phys. Rev. Lett. **82**, 2430 (1999).
[20] R. Mohapatra and P. B. Pal, *Massive Neutrino in Physics and Astrophysics* (World Scientific, Singapore, 1998).
[21] B. T. Cleveland *et al.*, Astrophys. J. **496**, 505 (1998).
[22] V. N. Gavrin, contribution to TAUP 2003, 8th International Workshop on Topics in Astroparticle and Underground Physics, Seattle, WA, USA, 2003, http://int.phys.washington.edu/taup2003/.
[23] E. Bellotti, contribution to TAUP 2003, 8th International Workshop on Topics in Astroparticle and Underground Physics, Seattle, WA, USA, 2003 (Ref. [22]).
[24] E. Kh. Akhmedov and V. V. Berezin, Z. Phys. C **54**, 661 (1992); K. Tsuji, S. Nakamura, T. Sato, and K. Kobodera (to be published).
[25] O. G. Miranda *et al.*, Phys. Lett. B **521**, 299 (2001); Nucl. Phys. **B595**, 360 (2001); W. Grimus *et al.*, Nucl. Phys. **B648**, 376 (2003).