Limit on the Electron Neutrino Magnetic Moment from the Kuo-Sheng Reactor Neutrino Experiment

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A search of neutrino magnetic moment was carried out at the Kuo-Sheng Nuclear Power Station at a distance of 28 m from the 2.9 GW reactor core. With a high purity germanium detector of mass 1.06 kg surrounded by scintillating NaI(Tl) and CsI(Tl) crystals as anti-Compton detectors, a detection threshold of 5 keV and a background level of 1 $\mathrm{kg^{-1}\,keV^{-1}\,day^{-1}}$ at 12–60 keV were achieved. Based on 4712 and 1250 h of reactor ON and OFF data, respectively, the limit on the neutrino magnetic moment of $\mu_{\bar{\nu}_e} < 1.3 \times 10^{-10} \mu_B$ at 90% confidence level was derived. An indirect bound of the $\bar{\nu}_e$ radiative lifetime of $m_\nu^3 \tau_\nu > 2.8 \times 10^{18}$ eV^3 s can be inferred.

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Results from recent neutrino experiments can be explained by neutrino oscillations due to finite neutrino masses and mixings [1,2]. Their physical origin and experimental consequences are not fully understood. Experimental studies on the neutrino properties and interactions can shed light on these fundamental questions and/or constrain theoretical models. The coupling of neutrinos with the photons are consequences of finite neutrino masses and electromagnetic form factors [3]. The manifestations include neutrino magnetic moments and radiative decays. In this paper, we report new limits on these parameters from a reactor neutrino experiment where a lower energy threshold compared to those of previous efforts is achieved.

The searches of neutrino magnetic moments are performed by experiments on neutrino-electron scatterings [4]: $\nu_{l_1} + e^- \rightarrow \nu_{l_2} + e^-$. Both *diagonal* and *transition* moments are allowed, corresponding to the cases, where $l_1 = l_2$ and $l_1 \neq l_2$, respectively. The experimental observable is the kinetic energy of the recoil electrons (T). A finite neutrino magnetic moment (μ_l), expressed in units of the Bohr magneton (μ_B), will contribute to a differential cross-section term given by [3]

$$\left(\frac{d\sigma}{dT}\right)_\mu = \frac{\pi \alpha_{em}^2 \mu_l^2}{m_e^2}\left[\frac{1 - T/E_\nu}{T}\right], \tag{1}$$

where E_ν is the neutrino energy. The magnetic scattering has a $1/T$ dependence such that measurements at low recoil energy provide higher sensitivities. The quantity μ_l is an effective parameter which can be expressed as [5] $\mu_l^2 = \sum_j |\sum_k U_{lk}\mu_{jk}|^2$, where U is the mixing matrix and μ_{jk} are the coupling constants between the mass eigenstates ν_j and ν_k with the photon. In this paper, we write $\mu_{\bar{\nu}_e} = \kappa_e \times 10^{-10} \mu_B$ for simplicity. The neutrino-photon couplings probed by ν-e scatterings are related to the decay rates Γ_{jk} for the neutrino radiative decays [6]: $\nu_j \rightarrow \nu_k + \gamma$, via $\Gamma_{jk} = [\mu_{jk}^2 (m_j^2 - m_k^2)^3]/[4\pi m_j^3]$, where m_i is the mass of ν_i.

Reactor neutrinos provide a sensitive probe for "laboratory" searches of $\mu_{\bar{\nu}_e}$, taking advantage of the high $\bar{\nu}_e$ flux, low E_ν, and better experimental control via the reactor ON/OFF comparison. A finite $\mu_{\bar{\nu}_e}$ would manifest itself as excess events in the ON over OFF periods, which have a $1/T$ energy spectrum. Neutrino-electron scatterings were first observed in the pioneering experiment [7] at Savannah River. A revised analysis of the data by Ref. [3] with improved input parameters gave a positive signature consistent with the interpretation of a finite $\mu_{\bar{\nu}_e}$ at $\kappa_e = 2$–4. Other results came from the Kurtchatov [8] and Rovno [9] experiments which quoted limits of $\kappa_e <$ 2.4 and $<$1.9 at 90% confidence level (C.L.), respectively. However, many experimental details, in particular, the effects due to the uncertainties in the standard model (SM) "background," were not discussed. An on-going experiment MUNU [10] is performed at the Bugey reactor using a time projection chamber with CF_4 gas. A preliminary result of $\kappa_e < 1.3$ (90% C.L.) was obtained, while an excess of events below 1 MeV during reactor ON was also reported.

Neutrino flavor conversion induced by magnetic scattering in the Sun via its transition moments has been considered to explain the solar neutrino measurements [3,11], though this scenario would be disfavored by the recent KamLAND results [12]. Alternatively, the measured solar neutrino $\nu_{\odot}$-e spectral shape has been used to set a limit of $\kappa_{\odot} < 1.5$ at 90% C.L. for the "effective" $\nu_{\odot}$ magnetic moment [5] which is different from that of a pure $\bar{\nu}_e$ state derived in reactor experiments. Astrophysical arguments [1,3] placed bounds of $\kappa_{astro} < 10^{-2}$–10^{-3}, but there are model dependence and implicit assumptions on the neutrino properties involved.

Further laboratory experiments to put the current limits on more solid grounds and to improve the sensitivities are therefore necessary. The Kuo-Sheng (KS) results presented in this article are based on data from an ultralow-background high purity germanium detector (HPGe) from June 2001 until April 2002. The HPGe is optimal for magnetic moment searches [13,14] because of its low detection threshold, excellent energy resolution, and robust stability. The strategy is to focus on energy <100 keV [15], where the SM background is negligible at the $10^{-10}\mu_B$ range considered here. A CsI(Tl) scintillating crystal array of mass 46 kg was operating in parallel, and data were taken by a single readout system.

The KS neutrino laboratory [13] is located at a distance of 28 m from Core No. 1 of the Kuo-Sheng Power Station in Taiwan. The nominal thermal power output is 2.9 GW. The laboratory is on the ground floor of the reactor building at a depth of 12 m below sea level and with about 25 m water equivalence of overburden. The primary cosmic ray hadronic components are eliminated while the muon flux is reduced by a factor of 4. The laboratory is equipped with an outer 50-ton shielding structure, consisting of, from outside in, 2.5 cm of plastic scintillators with photomultipliers (PMTs) readout for cosmic ray veto (CRV), 15 cm of lead, 5 cm of stainless steel support structures, 25 cm of boron-loaded polyethylene, and 5 cm of oxygen-free high-conductance (OFHC) copper. The innermost space has a dimension of $(100 \times 80 \times 75)$ cm^3 where both the HPGe and CsI(Tl) detectors and their inner shielding were placed. The ambient neutron background is similar to that of a typical surface laboratory, while the γ background is about 20 times higher, predominantly from radioactive dust with ^{60}Co and ^{54}Mn. The dust can get settled on exposed surfaces within hours and is difficult to remove. Some earlier prototype detectors were contaminated this way. Attempts to clean the surfaces on site resulted in higher contaminations. Accordingly, the various detector and inner shielding components were wrapped in plastic sheets during transportation, which were removed on site only prior to installation. There are no indications of this background source in the present data. There are also no observable differences between the ON and OFF periods for both the ambient γ and neutron background.

The HPGe setup is schematically shown in Fig. 1. It is a coaxial germanium detector with an active target mass of 1.06 kg. The lithium-diffused outer electrode is 0.7 mm thick. The end-cap cryostat, also 0.7 mm thick, is made of OFHC copper. The HPGe was surrounded by an anti-Compton (AC) detector system made up of two components: (1) a 5 cm thick NaI(Tl) well detector that fits onto the end-cap cryostat, and (2) a 4 cm thick CsI(Tl) detector at the bottom. All inner surfaces were made of OFHC copper. Both AC detectors were read out by PMTs with low-activity glass. The assembly was surrounded by 3.7 cm of OFHC copper inner shielding. Another 10 cm of lead provided additional shielding against the liquid nitrogen Dewar and preamplifier electronics. The assembly was covered by a plastic bag connected to the exhaust line of the Dewar, serving as a purge for the radioactive radon gas.

The electronics and data acquisition (DAQ) systems of the KS laboratory have been described elsewhere [16]. The HPGe preamplifier signals were distributed to two spectroscopy amplifiers at the same 4 μs shaping time but with different gain factors. A low threshold on the output provided the online trigger, ensuring that all the events down to the electronics noise edge of 5 keV were recorded. The amplifier and the PMT signals from the AC detectors were recorded by 20 MHz flash analog to digital convertor modules for a duration of 10 and 25 μs before and after the trigger, respectively. The discriminator output of the CRV PMTs was also recorded. A random trigger was provided by an external clock at 0.1 Hz for sampling the pedestals and for accurate measurements of the efficiency factors. The DAQ system remained active for 1 ms after a trigger to record possible time-correlated signatures. The combined DAQ rate for the HPGe and CsI(Tl) systems was about 2–3 Hz and the dead time was 10–20 ms per event, such that the typical system live time was 96%. The various residual γ lines such as that of ^{40}K provided the energy calibration.

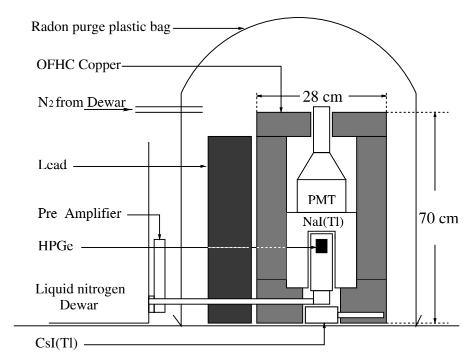

FIG. 1. Schematic layout of the HPGe with its anti-Compton detectors as well as inner shielding and radon purge system.

TABLE I. Summary of the event selection procedures as well as their background suppression and signal efficiency factors.

Event selection	Suppression	Efficiency
Raw data	1.0	1.0
Anti-Compton (AC)	0.06	0.99
Cosmic-ray veto (CRV)	0.96	0.95
Pulse shape analysis	0.86	1.0
Combined efficiency	0.05	0.94

Scatterings of $\bar{\nu}_e$-e inside the Ge target would manifest as "lone events" uncorrelated with other detector systems. The selection procedures, background suppression, and signal efficiency factors are summarized in Table I. The AC and CRV cuts suppressed Compton scattering and cosmic ray-induced events. The pulse shape analysis identified background due to electronic noise and the delayed "cascade" events.

The lone-event spectra from 4712/1250 live time hours of reactor ON/OFF data are displayed in Fig. 2(a). The ON data were taken in 1282 and 3430 h of run time before and after the OFF period, respectively. The spectra are stable with time between finer subperiods. A detector threshold of 5 keV and a background of $\sim 1\ \text{keV}^{-1}\,\text{kg}^{-1}\,\text{day}^{-1}$ above 12 keV were achieved. This background level is comparable to those in underground cold dark matter experiments. Several lines can be identified: Ga x-rays at 10.37 keV and $^{73}\text{Ge}^*$ at 66.7 keV from internal cosmic-induced activities, and ^{234}Th at 63.3 and 92.6 keV due to residual ambient radioactivity from the ^{238}U series in the vicinity of the target. The ON and OFF spectra differ only in the Ga x-ray peaks, which originate from the long-lived isotopes (^{68}Ge and ^{71}Ge with half-lives of 271 and 11.4 d, respectively) activated by cosmic rays prior to installation. The time evolution of the peak intensity can be fit to two decay constants consistent with the two known half-lives. A threshold of 12 keV was therefore adopted for physics analysis. This is also above the energy range where corrections due to atomic effects have to be considered.

The reactor neutrino spectrum and its time evolution were evaluated from reactor operation data with the standard prescriptions on fission $\bar{\nu}_e$ flux [3]. A low energy contribution due to neutron capture on ^{238}U [17] was added. The total flux at the detector is $5.8 \times 10^{12}\ \text{cm}^{-2}\,\text{s}^{-1}$, corresponding to a magnetic scattering event rate of $5.9\ \text{kg}^{-1}\,\text{day}^{-1}$ above 12 keV at $\kappa_e = 2$.

The sources of systematic errors are summarized in Table II. The survival probabilities of the random trigger events along the various analysis stages provided accurate (better than 0.2% statistical errors) measurements of the DAQ live time and the signal efficiencies. The $\bar{\nu}_e$ spectrum above 2 MeV is known to be better than 5%. However, the spectra at low energy are not well studied [15], and we took a conservative range of 30% to be its systematic uncertainties below 2 MeV. These translate to

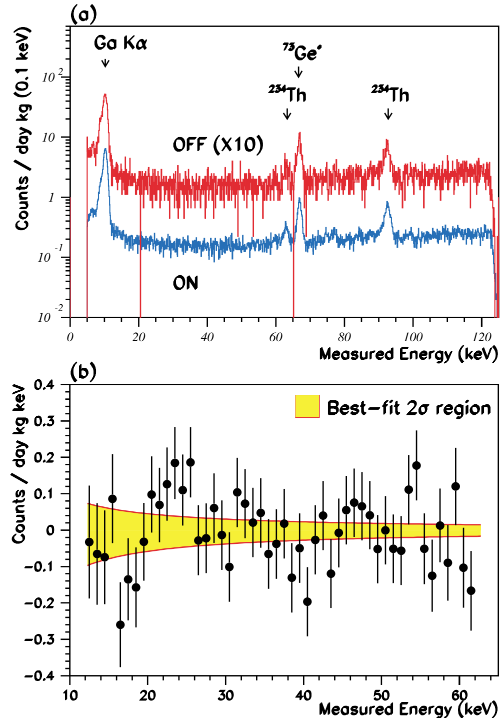

FIG. 2 (color online). (a) The energy spectra for lone events, and (b) the residual of the ON spectrum over the OFF background, from 4712/1250 live time hours of reactor ON/OFF data taking.

23% and 24% uncertainties in the SM and magnetic scattering rates above 12 keV, respectively.

The electron recoil spectra from SM and magnetic interactions at $\mu_{\bar{\nu}_e} = 10^{-10}\mu_B$, denoted by ϕ^{SM} and ϕ^{μ}_{-10}, respectively, were evaluated from the $\bar{\nu}_e$ spectrum. The HPGe provided total suppression to external low energy photons, such that the background between 12 to 60 keV is due to Compton scatterings of higher energy γ and therefore should not exhibit any structures. Accordingly, the OFF spectrum is described by a polynomial function ϕ_{OFF}, and a χ^2/dof of 80/96 was obtained in the best fit. The function ϕ_{OFF} and its uncertainties describe the probable background profile. They are used as input to a fit of the ON spectrum to the relation $\phi_{OFF} + \epsilon(\phi^{SM} + \kappa_e^2 \phi^{\mu}_{-10})$, where $\epsilon = 94\%$ is the analysis efficiency from Table I. Following this relation, the contributions of the various systematic errors to $\delta(\kappa_e^2)$ are given in Table II. The best-fit value of $\kappa_e^2 = -0.4 \pm 1.3(\text{stat.}) \pm 0.4(\text{syst.})$

TABLE II. The various sources of the systematic uncertainties, and their contributions to $\delta(\kappa_e^2)$.

Sources	Uncertainties	$\delta(\kappa_e^2)$
DAQ live time ON/OFF	<0.2%	<0.30
Efficiencies for magnetic scattering	<0.2%	<0.01
Rates for magnetic scattering	24%	0.23
SM background subtraction	23%	0.03
Combined systematic error	···	<0.4

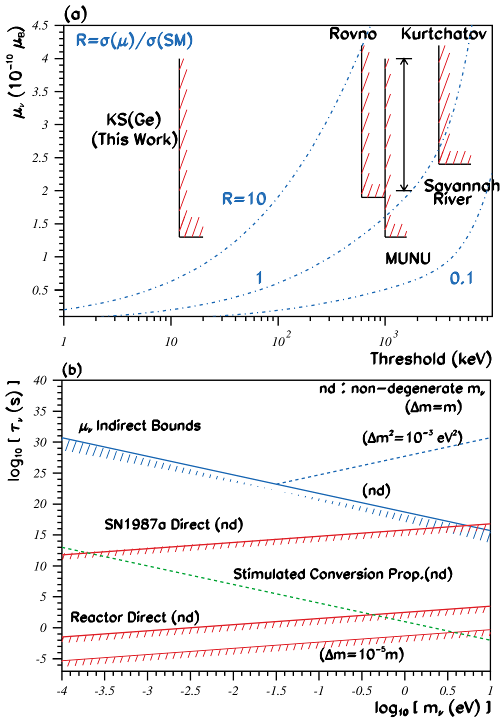

FIG. 3 (color online). Summary of the results in (a) the searches of neutrino magnetic moments with reactor neutrinos, and (b) the bounds of neutrino radiative decay lifetime. See text for explanations.

at χ^2/dof of 48/49 was obtained. Adopting the unified approach [1], the limit on the $\bar{\nu}_e$ magnetic moment of $\mu_{\bar{\nu}_e} < 1.3 \times 10^{-10} \mu_B$ at 90% C.L. was derived. The residual plot of the ON spectrum over the background is depicted in Fig. 2(b), with the best-fit 2σ region for κ_e^2 superimposed. Different choices of ϕ_{OFF} — such as polynomials or exponentials or their combinations — would produce consistent results. It has also been verified that the correct positive signals can be reconstructed from simulated spectra.

Depicted in Fig. 3(a) is the summary of the results in $\mu_{\bar{\nu}_e}$ searches versus the achieved threshold in reactor experiments. The dotted lines denote the $R = \sigma(\mu)/\sigma(\mathrm{SM})$ ratio at a particular $(T, \mu_{\bar{\nu}_e})$. The KS(Ge) experiment has a much lower threshold of 12 keV compared to the other measurements. The large R values imply that the KS results are robust against the uncertainties in the SM cross sections. In particular, in the case where the excess events reported in Refs. [7,10] are due to unaccounted sources of neutrinos, the limits remain valid.

Indirect bounds on the neutrino radiative decay lifetimes are inferred and displayed in Fig. 3(b) for the simplified scenario where a single channel dominates the transition. It corresponds to $\tau_\nu m_\nu^3 > 2.8 \times 10^{18}\ \mathrm{eV}^3\,\mathrm{s}$ at 90% C.L. in the nondegenerate case. Superimposed are the limits from the previous direct searches of excess γ from reactor and supernova SN1987a [18] neutrinos, as well as the sensitivities of proposed simulated conversion experiments at accelerators [19]. It can be seen that ν-e scatterings give much more stringent bounds than the direct approaches.

The KS experiment continues data taking in 2002–2003 using HPGe with improved shielding and 186 kg of CsI(Tl) crystals. Besides enhancing the $\mu_{\bar{\nu}_e}$ sensitivities, the goals are to perform a measurement of the $\bar{\nu}_e$-e cross section at the MeV range, and to study various standard and anomalous neutrino interactions. A prototype HPGe with sub-keV threshold is being studied.

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