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Status on the Searches of Neutrino Magnetic Moment at the Kuo-Sheng Power Reactor

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Abstract

The TEXONO collaboration has been built up among scientists from Taiwan and China to pursue an experimental program in neutrino and astro-particle physics. The flagship efforts have been the study of low energy neutrino physics at the Kuo-Sheng Power Reactor Plant in Taiwan. The Reactor Laboratory is equipped with flexibly-designed shieldings, cosmic veto systems, electronics and data acquisition systems which can function with different detector schemes. Data are taken during the Reactor Period June-01 till April-02 with a high purity germanium detector and 46 kg of CsI(Tl) crystal scintillator array operating in parallel. A threshold of 5 keV has been achieved for the germanium detector, and the background level comparable to those of Dark Matter experiments underground is achieved. Based on 62/46 days of analyzed Reactor ON/OFF data, a preliminary result of $(\mu_{\bar{\nu}_e}/10^{-10}\mu_{\rm B})^2 = -1.1 \pm 2.5$ can be derived for neutrino magnetic moment $\mu_{\bar{\nu}_e}$. Sensitivity region on neutrino radiative decay lifetime is inferred. The complete data set would include 180/60 days of ON/OFF data.

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1 Introduction and History

The TEXONO Collaboration has been built up since 1997 to initiate and pursue an experimental program in Neutrino and Astroparticle Physics [1]. The Collaboration comprises more than 40 research scientists from major institutes/universities in Taiwan (Academia Sinica†, Chung-Kuo Institute of Technology, Institute of Nuclear Energy Research, National Taiwan University, National Tsing Hua University, and Kuo-Sheng Nuclear Power Station), China (Institute of High Energy Physics†, Institute of Atomic Energy†, Institute of Radiation Protection, Nanjing University, Tsing Hua University) and the United States (University of Maryland), with AS, IHEP and IAE (with †) being the leading groups. It is the first research collaboration of this size and magnitude among major research institutes from Taiwan and China.

The research program [1] emphasizes on the the unexplored and unexploited theme of adopting detectors with high-Z nuclei, such as solid state device and scintillating crystals, for low-energy low-background experiments in Neutrino and Astroparticle Physics[2]. The "Flagship" program [3] is a reactor neutrino experiment to study low energy neutrino properties and interactions at the Kuo-Sheng (KS) Neutrino Laboratory. It is the first particle physics experiment performed in Taiwan. In parallel to the reactor experiment, various R&D efforts coherent with the theme are initiated and pursued.

This article focuses on the magnetic moment data taking and analysis with a germanium detector during the Reactor Period June 2001 till April 2002.

2 Electromagnetic Properties of the Neutrinos

The strong and positive evidence of neutrino oscillations implies the existence of neutrino masses and mixings [4, 5], the physical origin, structures and experimental consequences of which are still not thoroughly known and understood. Experimental studies on the neutrino properties and interactions which may reveal some of these fundamental questions and/or constrain certain classes of models are therefore of interests. The coupling of neutrino with the photons are consequences of non-zero neutrino masses. Two of the manifestations of the finite electromagnetic form factors for neutrino interactions [6, 7] are neutrino magnetic moments and radiative decays.

The searches of neutrino magnetic moments are performed in experiments on neutrino-electron scatterings [8]:

$$\nu_{l_1} + \mathrm{e}^- \rightarrow \nu_{l_2} + \mathrm{e}^- . \qquad (1)$$

The experimental observable is the kinetic energy of the recoil electrons(T). The differential cross section for the magnetic scattering (MS) channel can be parametrized by the neutrino magnetic moment (μ_l), often expressed in units of the Bohr magneton(μ_{B}). Its dependence on neutrino energy E_ν is given by [6]:

$$(\frac{\mathrm{d}\sigma}{\mathrm{dT}})_{\mathrm{MS}} = \frac{\pi \alpha_{\mathrm{em}}^2 {\mu_l}^2}{\mathrm{m_e^2}} [\frac{1 - \mathrm{T/E_\nu}}{\mathrm{T}}] . \qquad (2)$$

The process can be due to *diagonal* and *transition* magnetic moments, for the cases where $l_1 = l_2$ and $l_1 \neq l_2$, respectively. The MS interactions involve a flip of spin and therefore do not have interference with the Standard Model (SM) cross-section. The μ_l term has a 1/T dependence and hence dominates at low electron recoil energy over the SM process.

The quantity μ_l is an effective parameter which, in the case of $\bar{\nu_e}$ and large mixings between the mass eigenstates, can be expressed as [9]:

$$\mu_{\mathrm{e}}^2 = \sum_{\mathrm{k}} | \sum_{\mathrm{j}} \mathrm{U_{ej}} \mu_{\mathrm{jk}} |^2 \qquad (3)$$

where U is the mixing matrix and μ_{jk} are the fundamental constants that characterize the couplings between the mass eigenstates ν_{j} and ν_{k} with the electromagnetic field. The ν-γ couplings probed by ν-e scatterings is the same as that giving rise to the neutrino radiative decays [10]:

$$\nu_{\mathrm{j}} \rightarrow \nu_{\mathrm{k}} + \gamma \qquad (4)$$

between ν_{j} and ν_{k}. The decay rate Γ_{jk} is related to μ_{jk} by:

$$\Gamma_{\mathrm{jk}} = \frac{\mu_{\mathrm{jk}}^2}{4\pi} \frac{(\Delta \mathrm{m_{jk}^2})^3}{\mathrm{m_j^3}} \qquad (5)$$

where $\mathrm{m_j}$ is the mass of ν_{j} and $\Delta \mathrm{m_{jk}^2} = \mathrm{m_j^2} - \mathrm{m_k^2}$. The total decay rate is given by

$$\Gamma_{\nu_{\mathrm{e}}} = \sum_{\mathrm{k}} | \sum_{\mathrm{j}} \mathrm{U_{ej}} \Gamma_{\mathrm{jk}} |^2 \qquad (6)$$

Reactor neutrinos provide a sensitive probe for "laboratory" searches of μ_{e}, taking advantages of the high $\bar{\nu_e}$ flux, low E_ν and the better experimental control via the reactor ON/OFF comparison. Neutrino-electron scatterings were first observed in pioneering experiment [11] at Savannah River. However, a reanalysis of the data by Ref [6] with improved input parameters on the reactor neutrino spectra and $\sin^2\theta_{\mathrm{W}}$ gave a positive signature consistent with the interpretation of a finite magnetic moment at $(2-4)\times 10^{-10}$ $\mu_{\rm B}$. Other results came from the Kurtchatov [12] and Rovno [13] experiments which quoted limits of $\mu_{\bar{\nu}_e}$ less than 2.4×10^{-10} $\mu_{\rm B}$ and 1.9×10^{-10} $\mu_{\rm B}$ at 90% confidence level (CL), respectively. However, the lack of experimental details and discussions in the published work make it difficult to assess the robustness of the results.

Theoretically, a minimally-extended Standard Model would give rise to μ_ν's for Dirac neutrinos too small to be of interest [14]. However, there are models [4] which can produce large μ_ν by incorporating new features like right-handed currents and transition moments. Neutrino flavor conversion induced by resonant or non-resonant spin-flip transitions in the Sun via its transition magnetic moments has been considered as solution to the Solar Neutrino Problem [15]. Stimulated by the new results from the Super-Kamiokande and SNO experiments, recent detailed work [16] suggested that this scenario is also in excellent agreement with the existing solar neutrino data. Alternatively, the measured solar neutrino $\nu_\odot$-e spectra has been used to set limits of $\mu_\nu^\odot < 1.5\times 10^{-10}$ $\mu_{\rm B}$ at 90% CL for the "effective" $\nu_\odot$ magnetic moment [9], which is in general different from that of a pure ν_l state derived in laboratory experiments. In addition, there are astrophysical arguments [4] from nucleosynthesis, stellar cooling and SN1987a which placed limits of the range $\mu_{\rm e} < 10^{-12} - 10^{-13}$ $\mu_{\rm B}$. However, care should be taken in their interpretations due to the model dependence and assumptions on the neutrino properties implicit in the derivations.

These discussions show that further laboratory experiments to put the current limits on more solid grounds and to improve on the sensitivities are of interest. Beside the Kuo-Sheng (KS) experiment [1] reported in this article, there is another on-going experiment MUNU [17] at the Bugey reactor using a time projection chamber with CF_4 gas.

3 Kuo-Sheng Reactor Neutrino Laboratory

The "Kuo-Sheng Reactor Neutrino Laboratory" is located at a distance of 28 m from the core #1 of the Kuo-Sheng Nuclear Power Station at the northern shore of Taiwan [3]. A schematic view is depicted in Figure 1.

A multi-purpose "inner target" detector space of 100 cm$\times$80 cm$\times$75 cm is enclosed by 4π passive shielding materials and cosmic-ray veto scintillator panels, the schematic layout of which is shown in Figure 2. The shieldings provide attenuation to the ambient neutron and gamma background, and are made up of, inside out, 5 cm of OFHC copper,

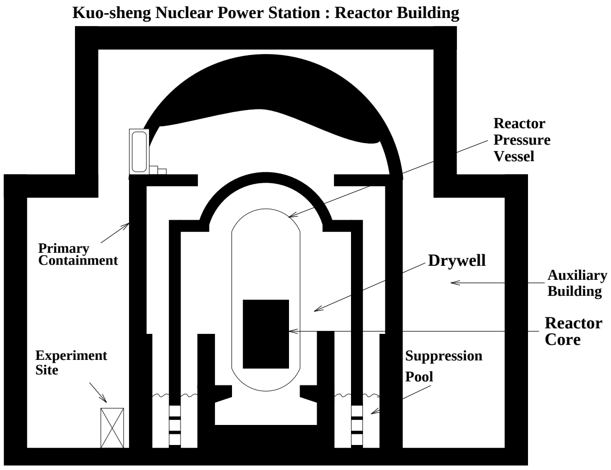

Figure 1: Schematic side view, not drawn to scale, of the Kuo-sheng Nuclear Power Station Reactor Building, indicating the experimental site. The reactor core-detector distance is about 28 m.

25 cm of boron-loaded polyethylene, 5 cm of steel and 15 cm of lead.

Different detectors can be placed in the inner space for the different scientific goals. The detectors are read out by a versatile electronics and data acquisition systems [18] running on a VME-PCI bus. Signals are recorded by Flash Analog-to-Digital-Convertor (FADC) modules with 20 MHz clock and 8-bit resolution. The readout allows full recording of all the relevant pulse shape and timing information for as long as several ms after the initial trigger. The reactor laboratory is connected via telephone line to the home-base laboratory at AS, where remote access and monitoring are performed regularly. Data are stored and accessed in a multi-disks array with a total of 600 Gbyte memory via IDE-bus in PCs.

It is recognized recently [19] that the low energy part of the reactor neutrino spectra is not well modeled or experimentally checked. Consequently, the uncertainties induced in the SM $\bar{\nu_e}$-e cross-sections can limit the sensitivities of magnetic moment searches at the domain where they are comparable or larger than the MS interactions. Therefore, experiments intended for measure Standard Model cross sections with reactor neutrinos should focus on higher energies (T>1.5 MeV) while μ_ν searches should base on measurements with T<100 keV.

Accordingly, data were taken for Period I Reactor ON/OFF from June 2001 till April 2002 with these strategies. Two detector systems are running in parallel using the same data acquisition system but independent triggers: (a) an Ultra Low Background High

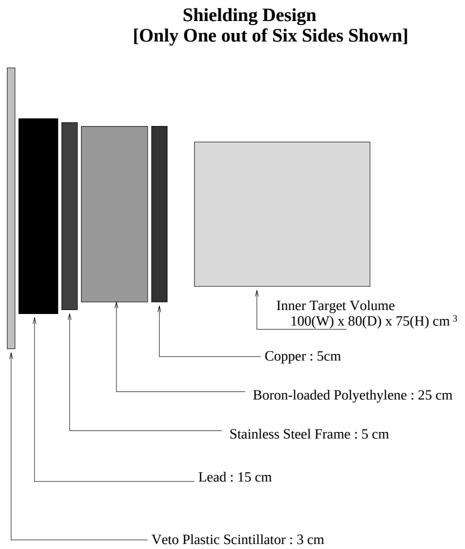

Figure 2: Schematic layout of the inner target space, passive shieldings and cosmic-ray veto panels. The coverage is 4π but only one face is shown.

Purity Germanium (ULB-HPGe), with a fiducial mass of 1.06 kg, and (b) 46 kg of CsI(Tl) crystal scintillators.

Preliminary results of the HPGe system is presented in the following sections. The performance of the CsI(Tl) modules is discussed elsewhere [1, 20].

4 Low Background Germanium Detector

The low threshold and excellent energy resolution of the germanium detector make it optimal for μ_ν searches [1, 21]. The set-up of the KS-Ge experiment is schematically shown in Figure 3. 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. Both of these features provide total suppression to ambient γ-background below 60 keV, such that events below this energy are either due to internal activity or external high energy γ's via Compton scattering. The HPGe was surrounded by an anti-Compton (AC) detector system made up of two components: (1) an NaI(Tl) well-detector of thickness 5 cm that fit onto the end-cap cryostat, the inner wall of which is also made of OFHC copper, and (2) a 4 cm thick CsI(Tl) detector at the bottom. Both AC detectors were read out by photo-multipliers (PMTs) with low-activity glass. The assembly was surrounded by 3.7 cm of OFHC copper inner shielding. Another

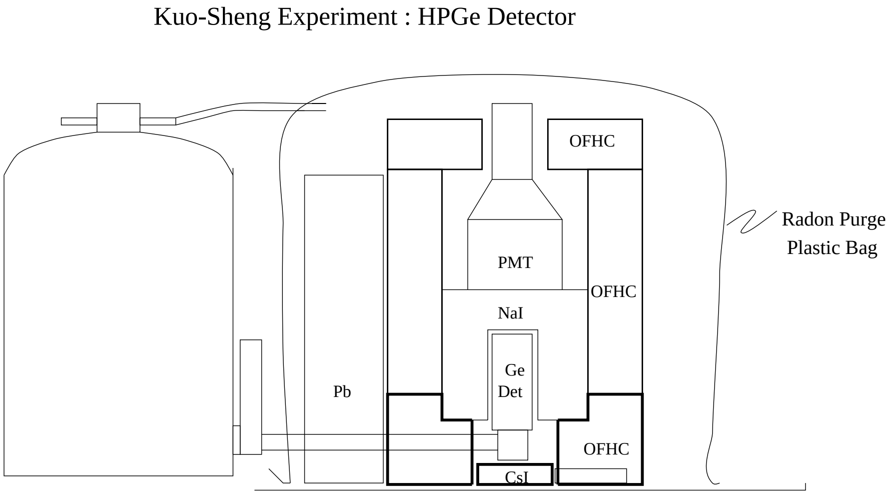

Figure 3: Schematic drawings of the ULB-HPGe detector with its anti-Compton scintillators, passive shieldings and radon purge system.

10 cm of lead provided additions shieldings on the side of the liquid nitrogen dewar and pre-amplifier electronics. The inner shieldings and detectors were covered by a plastic bag connected to the exhaust line of the dewar, serving as a purge for the radioactive radon gas.

The HPGe pre-amplifier and AC PMT signals were distributed via 10 m cables to two spectroscopy amplifiers at the same 4 μs shaping time but with different gain factors. A very loose amplitude threshold on the SA output provided the on-line trigger, ensuring all the events down to the electronics noise edge were recorded. The SA output, as well as the PMT signals from the AC detectors, were recorded by the FADC for a duration of 25 μs after the trigger. The discriminator output of the Veto PMTs were also recorded. A *random* trigger was provided by an external clock once per 10 s for sampling the background level and evaluating the various efficiency factors. The DAQ system remains active for 2 ms after a trigger to record possible time-correlated signatures. The activities in any part of the detector systems within 10 μs prior to the trigger were also recorded. The typical data taking rate for the HPGe sub-system was about 1 Hz. The accurately recorded DAQ dead time was about 10-20 ms per event.

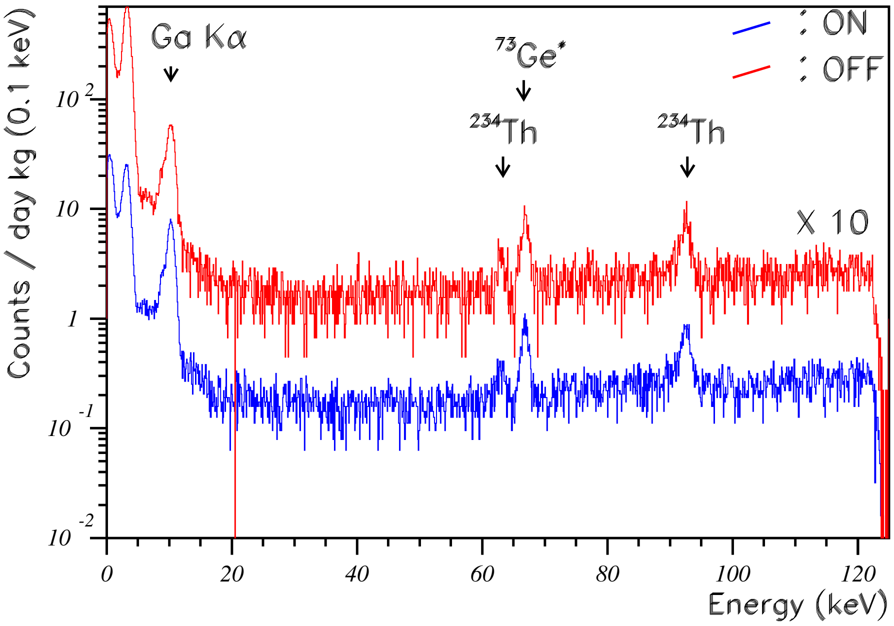

Figure 4: The energy spectra after the anti-Compton and cosmic veto cuts for 60/46 live time days of Reactor ON/OFF data taking. The OFF data set is multiplied by 10 for display purposes.

5 Results

The measured spectra, after cuts of cosmic and anti-Compton vetos, during 60/46 days of reactor ON/OFF data taking are displayed in Figure 4. The background level of 1 $keV^{-1}kg^{-1}day^{-1}$ and a detector threshold of 5 keV, comparable to those of underground Dark Matter experiment, are achieved. Additional cuts based on pulse shape and timing information are expected to further reduce the background level and the threshold.

Several lines can be identified: Ga X-rays at 10.37 keV and $^{73}Ge^{*}$ at 66.7 keV from internal cosmic-induced activities, and ^{234}Th at 63.3 keV 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 in two significant features. The excess of OFF over ON below the noise edge of 5 keV is due to instabilities in the trigger threshold and do not affect the analysis at higher energies. The excess at the Ga X-ray peaks originates from the long-lived isotopes (^{68}Ge and ^{71}Ge with half-lives of 271 and 11.4 days, respectively) activated by cosmic-rays prior to installation. It has been checked that the time evolution of the peak intensity can be fit to two exponentials consistent with the two known half-lives.

The reactor neutrino spectra was evaluated from reactor operation data using the standard prescriptions on from fission $\bar{\nu_e}$ [6] together with a low energy contribution due to neutron capture on ^{238}U [22]. The total flux is $5.6 \times 10^{12}\ \mathrm{cm^{-2}s^{-1}}$. The electron recoil spectra from SM and MS interactions can then be calculated. Background in the energy range of 12 to 60 keV are due to Compton scatterings of higher energy γ's. Accordingly, the Reactor OFF data are fitted to a smooth function

$$\phi_{\mathrm{OFF}} = \alpha_1 \mathrm{e}^{\alpha_2 \mathrm{E}} + \alpha_3 + \alpha_4 \mathrm{E}. \tag{7}$$

A χ^2/dof of 40/46 is obtained indicating this background description is valid. A one-parameter fit is then performed to the Reactor ON data for

$$\phi_{\mathrm{OFF}} + \phi_{\mathrm{SM}} + \mathrm{k}^2 \phi_{\mathrm{MS}} \ , \tag{8}$$

where ϕ_{SM} and ϕ_{MS} are the expected recoil spectra due to weak interactions and MS at $\mu_{\bar{\nu_e}} = 10^{-10}\ \mu_{\mathrm{B}}$, respectively. A best-fit value of

$$\mathrm{k}^2 = -1.1 \pm 2.5 \tag{9}$$

at a χ^2/dof of 55/49 is obtained. The residual plot and the best-fit 1σ region is depicted in Figure 5.

A total of 180/60 days of Reactor ON/OFF are taken for this reactor period. A limit will be derived when the data analysis is improved, complete and finalized. It is expected that the data would give world-level sensitivities in the searches of $\bar{\nu_e}$ magnetic moments. Depicted in Figure 6 is the summary of all the results in $\mu_{\bar{\nu_e}}$ searches with reactor $\bar{\nu_e}$ versus the achieved threshold. The dotted lines are the $\sigma_\mu/\sigma_{\mathrm{SM}}$ ratio at a particular (T, $\mu_{\bar{\nu_e}}$). The KS experiment operated at a much lower threshold of 12 keV compared to previous and current measurements. The large $\sigma_\mu/\sigma_{\mathrm{SM}}$ ratio at low energy implies that effects due to the uncertainties in the SM cross-sections can be neglected such that the limits derived are more robust.

Indirect bounds on the neutrino radiative decay rate are inferred using Eq. 5 and displayed in Figure 7. The sensitivity region of $\mu_\nu = 10^{-10}\mu_{\mathrm{B}}$ is shown for illustration purpose. Superimposed are the limits from the previous direct searches of excess γ's from reactor neutrinos [23] and from the supernova SN1987a [24]. Also shown is the sensitivity level of proposed simulated conversion experiments at accelerator [25]. It can be seen that ν-e scatterings give much more stringent bounds than the direct searches.

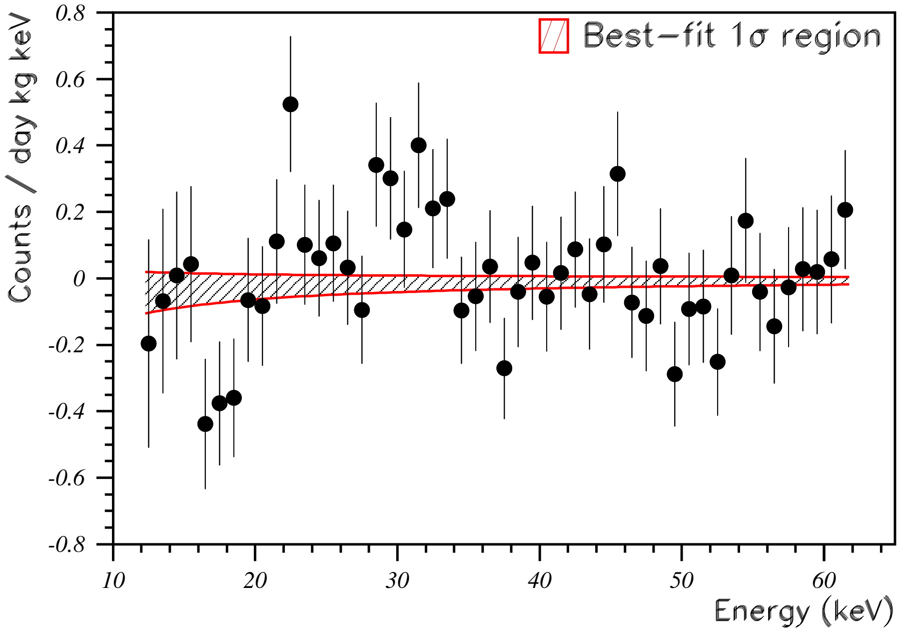

Figure 5: The residual spectrum of the Reactor ON recoil data subtracting $\phi_{\rm OFF}$. The best-fit 1σ region is also shown.

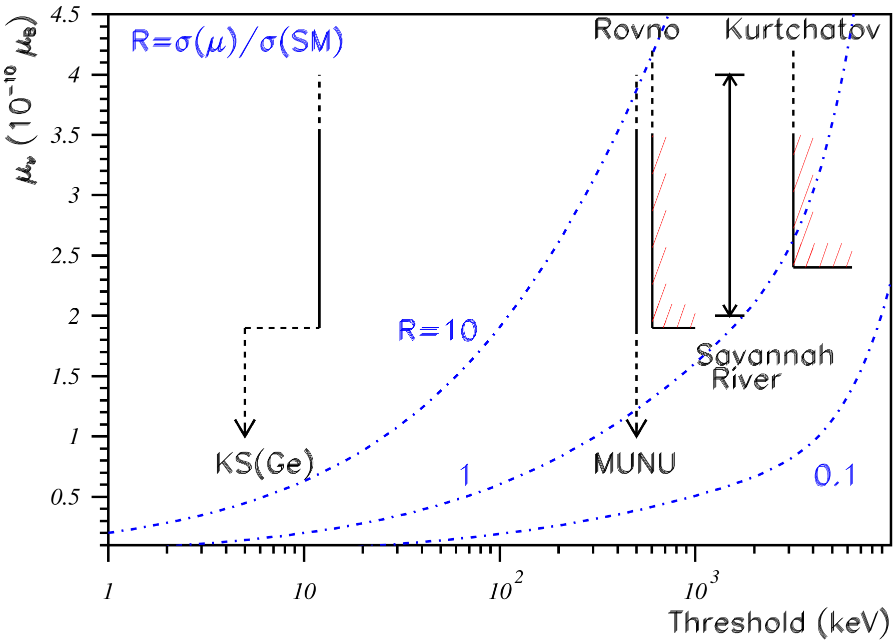

Figure 6: Summary of the results in the searches of neutrino magnetic moments with reactor neutrinos. The dotted line is the ratio between the cross-sections due to magnetic moments and Standard Model weak interactions.

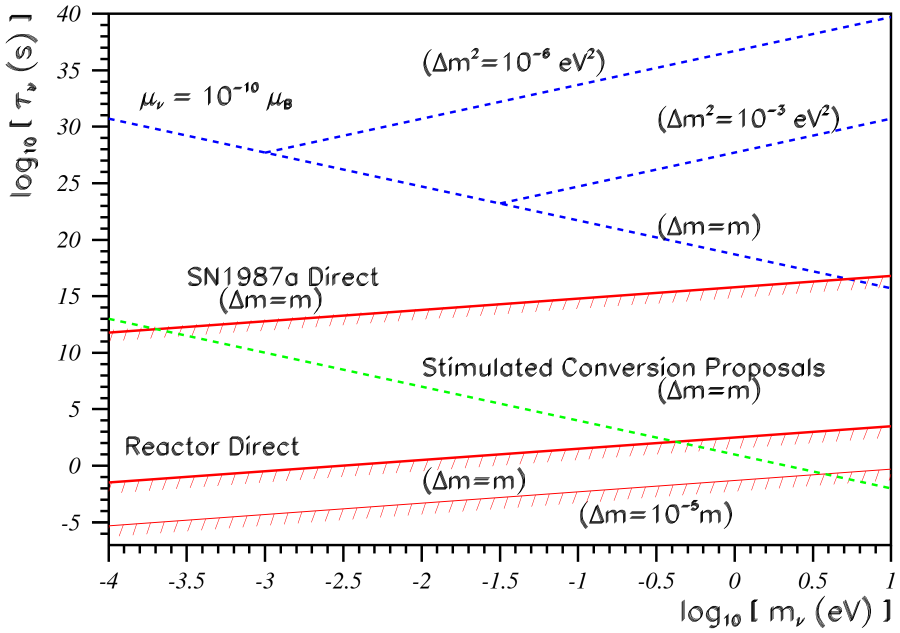

Figure 7: Summary of the results in the bounds in radiative decay lifetime of the neutrino. See text for explanations

6 Summary & Outlook

With the strong evidence of physics beyond the Standard Model revealed in the neutrino sector, neutrino physics and astrophysics remains a central subject in experimental particle physics in the coming decade and beyond. There are room for ground-breaking technical innovations - as well as potentials for surprises in the scientific results.

A Taiwan, China and U.S.A. collaboration has been built up with the goal of establishing a experimental program in neutrino and astro-particle physics. It is the first generation collaborative efforts in large-scale basic research between scientists from Taiwan and China. The flagship effort is to perform the first-ever particle physics experiment in Taiwan at the Kuo-Sheng Reactor Plant. From the Period I data taking, we expect to achieve world-level sensitivities in neutrino magnetic moments and radiative lifetime studies. A wide spectrum of R&D projects are being pursued. New ideas for future directions are being explored.

7 Acknowledgments

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