The TEXONO Research Program on Low Energy Neutrino and Astroparticle Physics

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This article reviews the research program and efforts of the TEXONO Collaboration on neutrino and astro-particles. The main program is on reactor-based low energy neutrino physics at the Kuo-Sheng (KS) Power Plant in Taiwan. The facilities of the laboratory are described. A limit on the neutrino magnetic moment of $\mu_\nu(\nu_e) < 1.3 \times 10^{-10}~\mu_B$ at 90% confidence level has been achieved from measurements with a high-purity germanium detector. Other research program at Kuo-Sheng are surveyed.

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I. INTRODUCTION

The TEXONO (**T**aiwan **EX**periment **O**n **N**eutrin**O**) 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 Taiwan, China, United State of America and Turkey. The "flagship" program is on reactor-based low energy neutrino physics at the Kuo-Sheng (KS) Power Plant in Taiwan [2]. The KS experiment is the first large-scale particle physics experiment in Taiwan. The TEXONO Collaboration is the first research collaboration among scientists from Taiwan and China [3].

Results from recent neutrino experiments strongly favor neutrino oscillations which imply neutrino masses and mixings [4, 5]. Their physical origin and experimental consequences are not fully understood. There are strong motivations for further experimental efforts to shed light on these fundamental questions by probing standard and anomalous neutrino properties and interactions. The results can constrain theoretical models necessary to interpret the future precision data – or may yield surprises which have been the characteristics of the field. In addition, these studies will also explore new neutrino sources and novel detection channels to provide new tools for future investigations.

The TEXONO research program is based on 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 [6]. The theme of this paper is to present the efforts of TEXONO Collaboration on neutrino and astro-particle physics. Subsequent sections highlight the results and status of the program.

II. KUO-SHENG NEUTRINO LABORATORY

The "Kuo-Sheng Neutrino Laboratory" [2] is located at a distance of 28 m from the core #1 and 108 m from the core #2 of the Kuo-Sheng Nuclear Power Station at the northern shore of Taiwan. A multi-purpose "inner target" detector space of 100 cm×80 cm ×75 cm is enclosed by 4π passive shielding materials with a total weight of 50 tons. Different detectors can be placed in the inner space for different scientific goals. The detectors are read out by versatile electronics and data acquisition systems [7] based on 16-channel per module, 20 MHz sampling rate, 8-bit dynamic range Flash Analog-to-Digital-Convertor (FADC) modules. 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 Academia Sinica (AS), where remote access and monitoring are performed regularly. Data are stored and accessed with a cluster of multi-disks arrays each with 800 Gbyte of memory.

The measure-able nuclear and electron recoil spectra due to reactor $\bar{\nu_e}$ are depicted in Figure 1, showing the effects due to Standard Model [$\bar{\nu_e}e^-$(SM)] and magnetic moment [$\bar{\nu_e}e^-$(MM)] in $\bar{\nu_e}$-electron scatterings [8], as well as in neutrino coherent scatterings on the nuclei ($\bar{\nu_e}$N(SM) and $\bar{\nu_e}$N(MM), respectively). The uncertainties in the low energy part of the reactor neutrino spectra

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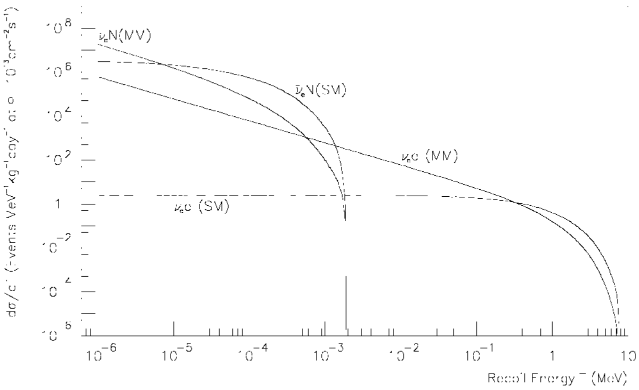
require that experiments to measure $\sigma[\bar{\nu}_e e^-(SM)]$ should focus on higher electron recoil energies (T>1.5 MeV), while MM searches should base on measurements with T<100 keV [9]. Observation of $\bar{\nu}_e$N(SM) would require detectors with sub-keV sensitivities.



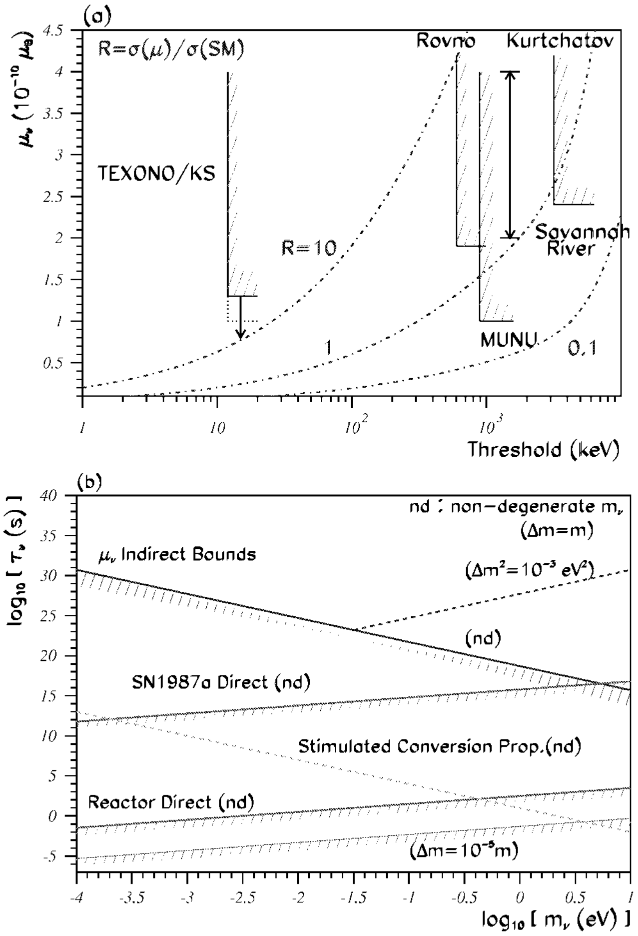
Hình 1: Differential cross section showing the recoil energy spectrum in ν_e-e and coherent ν_e-N scatterings, at a reactor neutrino flux of 10^{13} cm^{-2}s^{-1}, for the Standard Model (SM) processes and due to a neutrino magnetic moment (MM) of 10^{-10} μ_B.

Accordingly, data taking are optimized with these strategies. An ultra low-background high purity germanium (ULB-HPGe) detector started taking data since June 2001, while 200 kg of CsI(Tl) crystal scintillators were added from January 2003. Both detector systems operate in parallel with the same data acquisition system but independent triggers. A R&D program is pursued in parallel to develop detectors with ~100 eV threshold, towards the goal of observing for the first time neutrino-nucleus coherent scattering.

III. NEUTRINO MAGNETIC MOMENT SEARCHES WITH GERMANIUM DETECTOR

Neutrino magnetic moments characterize the neutrino electromagnetic couplings which involve the spin-interactions [10]. The ULB-HPGe is surrounded by NaI(Tl) and CsI(Tl) crystal scintillators as anti-Compton detectors, and the whole set-up is further enclosed by another 3.5 cm of OFHC copper blocks, and housed in a radon shield. After suppression of cosmic-induced background, anti-Compton vetos and convoluted events by pulse shape discrimination, a background level at 20 keV at the range of 1 keV^{-1}kg^{-1}day^{-1} and a detector threshold of 5 keV were achieved. These are the levels comparable to underground Dark Matter experiment. Comparison of the measured spectra for 4712/1250 hours of Reactor ON/OFF data [11] shows no excess of event and limits of the neutrino magnetic moment $\mu_\nu(\bar{\nu}_e) < 1.3(1.0) \times 10^{-10}$ μ_B at 90(68)% confidence level (CL) were derived. Data taking continues and the $\mu_\nu(\bar{\nu}_e)$ sensitivities down to the $\sim 10^{-10}$ μ_B range can be expected.

Depicted in Figure 2a is the summary of the results in $\mu_\nu(\bar{\nu}_e)$ searches versus the achieved threshold in various reactor experiments [11]. The dotted lines denote the $R = \sigma(\mu)/\sigma(SM)$ ratio at a particular [T,$\mu_\nu(\bar{\nu}_e)$]. The KS(Ge) experiment has a much lower physics 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. The neutrino-photon couplings probed by μ_ν searches in ν-e scatterings are related to the neutrino radiative decays (Γ_ν) [12]. Indirect bounds on Γ_ν can be inferred and are displayed in Figure 2b for the simplified scenario where a single channel dominates the transition. It corresponds to $\tau_\nu m_\nu^3 > 5.6(9.6) \times 10^{18}$ eV^{3}s at 90(68)% CL in the non-degenerate case. Superimposed are the limits[11] from the previous direct searches of excess γ's from reactor and supernova SN1987a neutrinos, as well as the sensitivities of proposed simulated conversion experiments at accelerators. It can be seen that ν-e scatterings give much more stringent bounds than the direct approaches.



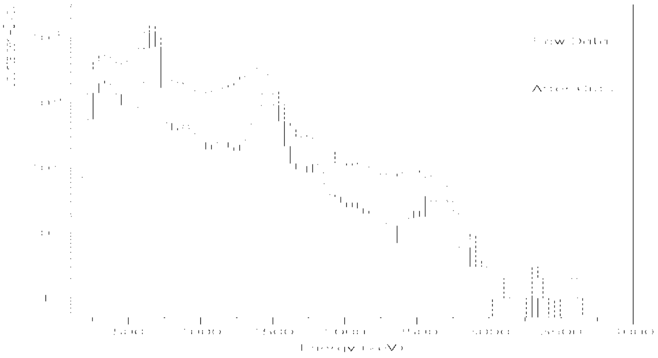
Hình 2: Summary of the KS results in (a) the searches of neutrino magnetic moments with reactor neutrinos, and (b) the bounds of neutrino radiative decay lifetime.

IV. OTHER RESEARCH PROGRAM AT KUO-SHENG (KS)

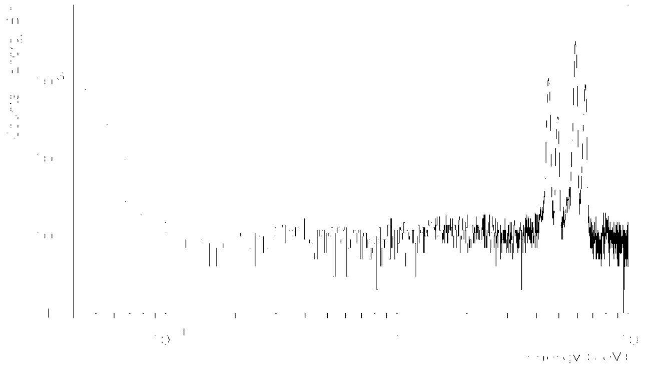
The KS data with ULB-HPGe are the lowest threshold data so far for reactor neutrino experiments, and therefore allow the studies of several new and more speculative topics. Nuclear fission at reactor cores also produce electron neutrino (ν_e) through the production of unstable isotopes, such as ^{51}Cr and ^{55}Fe, via neutron capture. A realistic Monte Carlo Nucler Physics (MCNP) simulation studies on the neutron transport and capture at the reactor core were performed [13]. The subsequent decays of these isotopes by electron capture give rise to monoenergetic ν_e's at Q-values of 753 keV and 231 keV and fluxes of 8.3×10^{-4} and 3.0 $\times10^{-4}$ ν_e/fission, respectively. Using data from a ULB-HPGe detector, we derived direct limits on the ν_e magnetic moment and the radiative lifetime of $\mu_\nu(\bar{\nu_e}) < 1.3 \times 10^{-8}$ $\mu_{\rm B}$ and $\tau_\nu/m_\nu > 0.11$ s/eV at 90 % CL, respectively [14]. Using the simulation sofware as mentioned above, we investigated the merits of inserting selected materials to the reactor core to enhance the ν_e-flux. The optimal choice of suitable isotope is ^{50}Cr(pure). We estimated that in the case of a P_{th} = 4.5 GW reactor and maximal loading of ^{50}Cr(pure) will emit a total of 4.2×10^{19} of ν_e's per second from the core, equivalent to the activity of a 1.1 GCi source. The ν_e-flux at 10 m is $3.3 \times 10^{12} cm^{-2}s^{-1}$. We have also proposed at least two potential applications of this study. The first potential application is on the study of the mixing angle θ_{13}. We have demonstrated that ~1% sensitivity can be statistically achieved with five years of data taking. Another possibility is on the monitoring of unwarranted plutonium production during reactor operation an issue of paramount importance in the control of nuclear proliferation [15].

In addition, studies of neutrino-induced nuclear transitions, as well as searches for possible reactor-produced axions, are pursued. We are searching axions by investigating specific nuclear transitions in reactor. Shielded ULB-HPGe detector is used to detect single photons produced by Compton and Primakoff effects inside the detector. The constraints of various axion couplings will be determined from data and expecting better upper limit of axion rate at 478 keV.

The potential merits of crystal scintillators for low-background low-energy experiments were recently discussed [16]. The physics goal for the CsI(Tl) scintillating crystal array is to measure the Standard Model neutrino-electron scattering cross sections, and thereby to provide a measurement of $\sin^2\theta_{\rm W}$ at the untested MeV range. Each crystal module is 2 kg in mass and consists of a hexagonal-shaped cross-section with 2 cm side and a length of 40 cm. The light output are read out at both ends by custom-designed 29 mm diameter photomultipliers (PMTs) with low-activity glass. The sum and difference of the PMT signals give information on the energy and the longitudinal position of the events, respectively. In period II more than 110/45 days ON/OFF data analysis is underway. A total of 200 kg (or 100 modules) have been commissioned for the Period–III data taking. The raw and "single-hit" spectra from 14 kg-day of data are displayed in Figure 3a. The strategy [9] is to focus on high (>3 MeV) recoil energy above those from natural radioactivity, with the additional merit of having good accuracies in the knowledge of the reactor neutrino spectra. The large target mass compensates the drop in the cross-sections. It can be seen that the background is very low above 3 MeV, making this a favorable range to provide a measurement of $\sigma(SM)$.



(a)



(b)

Hình 3: (a) The raw and the "single-hit" energy spectra from 14 kg-day of data taking with he CsI(Tl) array, represented by the dashed and solid histograms, respectively. (b) Energy spectrum with the ULE-HPGe, indicating a detector threshold lower than 100 eV, The peaks are from an ^{55}Fe source and from back-scattering with Ti.

A prototype ultra-low-energy germanium (ULE-HPGe) detector of 5 g mass is being studied. A hardware energy threshold of better than 100 eV has been achieved, as illustrated in Figure 3b. The ULE-HPGe has collected data inside the shieldings at the KS laboratory for the first-ever background studies at the sub-keV energy range. It is technically feasible to build an array of such detectors to the target size of the 1 kg mass range. Such detectors can potentially be adopted for Dark Matter searches and to observe neutrino-nucleus coherent scatterings [2]. Since April 2005, this 5 g ULE-HPGe detector is taking data at Yangyang under ground laboratory in South Korea, having minimum 700 m of rock overburden in supervision of TEXONO-KIMS collaboration. Nowadays we are working with 4 × 5 g ULE-HPGe detectors array with auto- filling of liquid nitrogen system.

V. R & D PROJECTS

TEXONO collaboration is intensively involved in various R & D projects, that are proceeding in parallel to the main KS reactor neutrino experiment. Besides the ULE-HPGe already mentioned, the other highlights are:

A. Radio-purity Measurements with Accelerator Mass Spectrometry (AMS)

Measuring the radio-purity of the detector materials as well as other laboratory components are important to the success of low-energy low-background experiments. The typical methods are direct photon counting with high-purity Germanium detectors, α-counting with silicon detectors, conventional mass spectrometry or the neutron activation techniques. We are exploring the capability of radio-purity measurements further with the new Accelerator Mass Spectroscopy (AMS) [17]. This approach may be complementary to existing methods since it is in principal a superior and more versatile method as demonstrated in the ^{13}C system, and it is sensitive to radioactive isotopes that do not emit γ-rays or where γ emission are suppressed. A pilot measurement of the $^{129}I/^{127}I$ ratio ($< 10^{-13}$ g/g) in CsI has been successfully performed, demonstrating the capabilities of the Collaboration. Further beam time is scheduled at the IAE AMS facilities [18] to devise measuring schemes for the other candidate isotopes like ^{238}U, ^{232}Th, ^{87}Rb, ^{40}K in liquid and crystal scintillators beyond the present capabilities by the other techniques. The first isotope study has been on ^{40}K, where we have achieved the preliminary result 12.3×10^{-15} g/g in liquid scintillator, where the goal sensitity of a 10^{-17} g/g should be achievable by the AMS techniques.

B. Upgrade of FADC for LEPS Experiment

Based on the similar design and operation of the FADCs used in the TEXONO experiment, we developed new FADC for a 1000 - channel Time Projection Chamber constructed as a sub-detector for the LEPS experiment at the SPring8 Synchrotron Facilities in Japan [19]. The LEPS FADCs have 40 MHz sampling rate, 10-bit dynamic range, 32 channels per module and equipped with Field Programmable Gate Array (FPGA) capabilities for real time data processing. The new system has been commisioned at LEPS in the summer of 2003. The upgraded FADC will be further optimized and implemented to the KS reactor neutrino experiment for data taking in Period–IV.

C. Sonoluminescence

Single-bubble Sonoluminescence (SL) [20] is a phenomenon first observed in 1989 where an acoustically trapped and periodicaly driven gas bubble collapes so strongly that the energy focusing at collapse leads to light emission. The detailed physics mechanism and potentials have not yet been fully explored. That is, there is much room for research topics and surprises. In particular, there are recent and controversial claims of sonoluminescence-induced nuclear fusion [21]. We are initiating a new program on SL under the TEXONO frame work. We are adopting a high-energy-physics style approach to work on this subject, relying on the collaboration of multi-disciplinary experties, distribution of tasks, and advanced multi-channel event-by-event measurements and software analysis techniques. The experience can also serve as a "test case" for the collaboration to venture into inter-disciplinary research.

Outlook

The strong evidence of neutrino masses and mixings lead to intense world-wide effort to pursue the next-generation of neutrino projects. Neutrino physics and astrophysics will remain a central subject in experimental particle physics in the coming decade and beyond. There is room for ground-breaking technical innovations – as well as potential for surprises in the scientific results.

A collaboration among scientists from Taiwan, China, USA and Turkey has been built up with the goal of establishing a qualified experimental program in neutrino and astro-particle physics. It is the first generation collaborative effort in such a 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 Power Plant. World-level sensitivities on the neutrino magnetic moment and radiative lifetime have already been achieved with the Period–I data using a high-purity Germanium detector. The Collaboration studied the production of electron neutrinos from nuclear power reactors and suggested feasible method for enhancement of electron-neutrino flux and their potential applications and achievable statistical accuracies. These include accurate cross-section measurements, studies of mixing angle θ_{13} and monitoring of plutonium production. Further measurements are pursued at the KS neutrino Laboratory, including the Standard Model neutrino-electron scattering cross-section as well as neutrino coherent scattering with the nuclei. A wide spectrum of R&D projects are being pursued in parallel.

The importance of the implications and outcomes of the experiment and experience will lie besides, if not beyond, neutrino physics.

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