ISSN 1063-7788, Physics of Atomic Nuclei, 2006, Vol. 69, No. 11, pp. 1956–1961. © Pleiades Publishing, Inc., 2006.

NEUTRINO PHYSICS AND ASTROPHYSICS
(Elementary Particles and Fields. Experiment)

The TEXONO Research Program on Low-Energy Neutrino and Astroparticle Physics*

V. Singh** and **H. T. Wong*****

Institute of Physics, Academia Sinica, Taipei, Taiwan

Received October 13, 2005

Abstract—This article reviews the research program and efforts of the TEXONO Collaboration on neutrino and astroparticles. The main program is on reactor-based low-energy neutrino physics at the Kuo-Sheng Power Plant in Taiwan. The facilities of the laboratory are described. A limit on the neutrino magnetic moment of $\mu_\nu(\bar{\nu}_e) < 1.3 \times 10^{-10}\mu_{\rm B}$ at 90% C.L. has been achieved from measurements with a high-purity germanium detector. Other research programs at Kuo-Sheng are surveyed.

PACS numbers: 13.15.+g, 95.85.Ry
DOI: 10.1134/S1063778806110214

1. INTRODUCTION

The TEXONO (Taiwan EXperiment On NeutrinO) 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, the 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 devices 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 astroparticle physics. Subsequent sections highlight the results and status of the program.

2. KUO-SHENG NEUTRINO LABORATORY

The Kuo-Sheng Neutrino Laboratory [2] is located at a distance of 28 m from core no. 1 and 108 m from core no. 2 of the Kuo-Sheng Nuclear Power Station at the northern shore of Taiwan. A multipurpose "inner target" detector space of $100 \times 80 \times 75$ cm is enclosed by 4π passive shielding materials with a total weight of 50 t. 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 milliseconds 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 multidisk arrays each with 800 Gbyte of memory.

The measureable nuclear and electron recoil spectra due to reactor $\bar{\nu}_e$ are depicted in Fig. 1, showing

*The text was submitted by the authors in English.

**E-mail: vsingh@phys.sinica.edu.tw

***E-mail: htwong@phys.sinica.edu.tw;http://hepmail.phys.sinica.edu.tw/texono

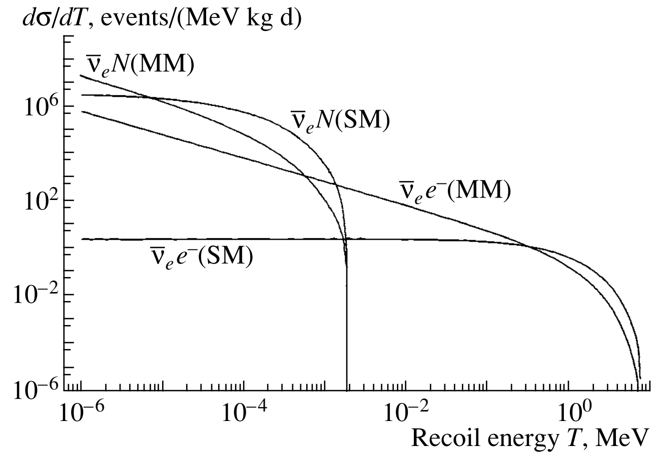

Fig. 1. Differential cross section showing the recoil energy spectrum in $\bar{\nu}_e e$ and coherent $\bar{\nu}_e N$ scatterings, at a reactor neutrino flux of 10^{13} cm^{-2} s^{-1}, for the Standard Model (SM) processes and due to a neutrino magnetic moment (MM) of 10^{-10} μ_{B}.

the effects due to the Standard Model [$\bar{\nu}_e e^-$(SM)] and magnetic moment [$\bar{\nu}_e e^-$(MM)] in $\bar{\nu}_e$ 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 require that experiments to measure $\sigma[\bar{\nu}_e e^-(\mathrm{SM})]$ focus on higher electron recoil energies ($T > 1.5$ MeV), while MM searches should be based on measurements with $T < 100$ keV [9]. Observation of $\bar{\nu}_e N$(SM) would require detectors with sub-keV sensitivities.

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

3. NEUTRINO MAGNETIC MOMENT SEARCHES WITH GERMANIUM DETECTOR

Neutrino magnetic moments characterize the neutrino electromagnetic couplings which involve spin interactions [10]. The ULB-HPGe is surrounded by NaI(Tl) and CsI(Tl) crystal scintillators as anti-Compton detectors, and the whole setup 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 vetoes, and convoluted events by pulse shape discrimination, a background level at 20 keV at the range of 1 keV^{-1} kg^{-1} d^{-1} and a detector threshold of 5 keV were achieved. These are levels comparable to an underground dark matter experiment. Comparison of the measured spectra for 4712/1250 h of reactor on/off data [11] shows no excess of event, and limits of the neutrino magnetic moment $\mu_\nu(\bar{\nu}_e) < 1.3(1.0) \times 10^{-10}\mu_{\mathrm{B}}$ at 90(68)% C.L. were derived. Data taking continues and $\mu_\nu(\bar{\nu}_e)$ sensitivities down to the $\sim 10^{-10}\mu_{\mathrm{B}}$ range can be expected.

Depicted in Fig. 2*a* is the summary of the results in $\mu_\nu(\bar{\nu}_e)$ searches versus the achieved threshold in various reactor experiments [11]. The dash-dotted curves denote the $R = \sigma(\mu)/\sigma(\mathrm{SM})$ 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 νe scatterings are related to the neutrino radiative decays (Γ_ν) [12]. Indirect bounds on Γ_ν can be inferred and are displayed in Fig. 2*b* 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)% C.L. in the nondegenerate case. Superimposed are the limits [11] from the previous direct searches of excess γ from reactor and supernova SN1987a neutrinos, as well as the sensitivities of proposed simulated conversion experiments at accelerators. It can be seen that νe scatterings give much more stringent bounds than the direct approaches.

4. OTHER RESEARCH PROGRAMS AT KUO-SHENG

The KS data with ULB-HPGe are the lowest threshold data so far for reactor neutrino experiments

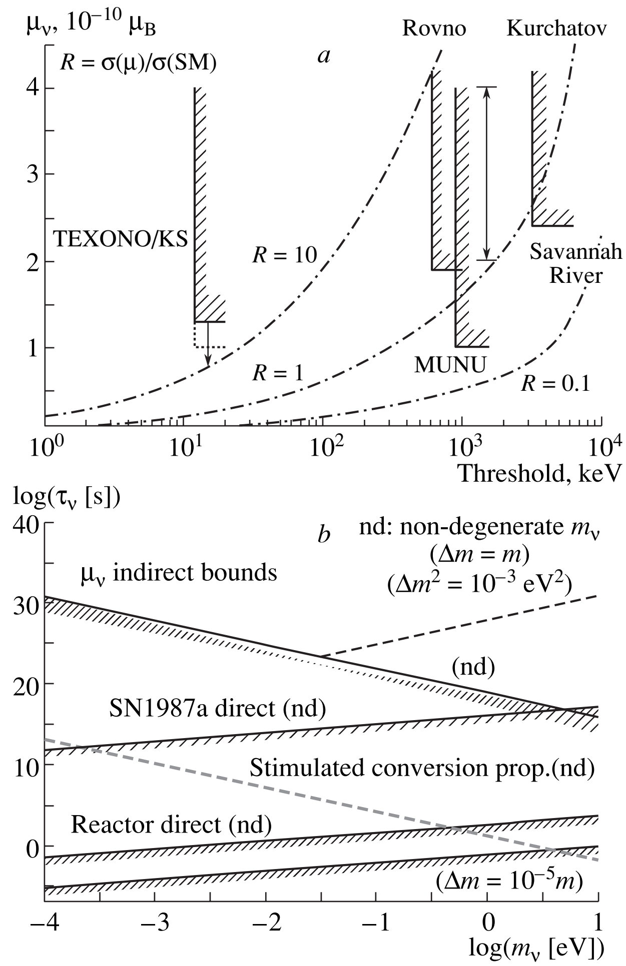

Fig. 2. Summary of the KS results in (*a*) the searches for neutrino magnetic moments with reactor neutrinos and (*b*) the bounds of neutrino radiative decay lifetime.

and therefore allow the study of several new and more speculative topics. Nuclear fission in reactor cores also produces ν_e through the production of unstable isotopes, such as ^{51}Cr and ^{55}Fe, via neutron capture. Realistic Monte Carlo nuclear physics (MCNP) simulation studies on the neutron transport and capture in the reactor core were performed [13]. The subsequent decays of these isotopes by electron capture give rise to monoenergetic ν_e at Q values of 753 and 231 keV and fluxes of 8.3×10^{-4} and 3.0×10^{-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% C.L., respectively [14]. Using the simulation software as mentioned above, we investigated the merits of inserting selected materials into 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 $P_{\rm th} = 4.5$ GW reactor and maximal loading of ^{50}Cr (pure), a total of 4.2×10^{19} ν_e per second will be emitted from the core, equivalent to the activity of a 1.1-GCi source. The ν_e flux at 10 m is 3.3×10^{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 $\sim$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 being pursued. We are searching axions by investigating specific nuclear transitions in the reactor. A 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 a better upper limit of axion rate at 478 keV.

The potential merits of crystal scintillators for low-background low-energy experiments were recently discussed [6]. The physics goal for the CsI(Tl) scintillating crystal array is to measure the SM νe-scattering cross sections and thereby to provide a measurement of $\sin^2\theta_{\rm W}$ in 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 is read out at both ends by custom-designed 29-mm-diameter photomultiplier tubes (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-d 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 d of data are displayed in Fig. 3*a*. 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 σ(SM).

A prototype 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 Fig. 3*b*. The ULE-HPGe has collected data inside the shieldings at the KS Laboratory for the first-ever background studies in the sub-keV energy range. It is technically feasible to build an array of such detectors to a target size of the 1-kg mass range. Such

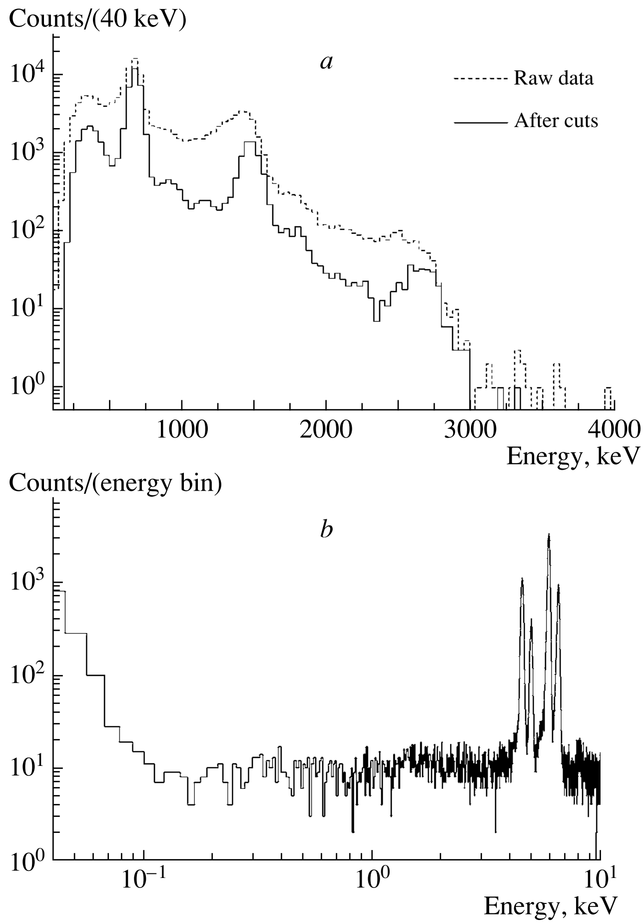

Fig. 3. (*a*) The raw and the "single-hit" energy spectra from 14 kg d of data taking with the CsI(Tl) array, represented by the dashed and solid histograms, respectively. (*b*) Energy spectrum with the ULE-HPGe, indicating a detector threshold lower than 100 eV. The peaks are from an ^{55}Fe source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

detectors can potentially be adopted for dark matter searches and to observe νN coherent scatterings [2]. Since April 2005, this 5-g ULE-HPGe detector has been taking data at the Yangyang underground laboratory in South Korea, having a minimum 700 m of rock overburden under supervision of the TEXONO-KIMS Collaboration. Nowadays, we are working with a 4×5-g ULE-HPGe detector array with autofilling of the liquid nitrogen system.

5. R&D PROJECTS

The 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 as follows:

5.1. Radio-Purity Measurements with Accelerator Mass Spectrometry

Measuring the radio purity of the detector materials as well as other laboratory components is 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) [16]. 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 is 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 CIAE AMS facilities [17] to devise measuring schemes for the other candidate isotopes like ^{238}U, ^{232}Th, ^{87}Rb, and ^{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 sensitivity of 10^{-17} g/g should be achievable by the AMS techniques.

5.2. Upgrade of FADC for LEPS Experiment

On the basis of the similar design and operation of the FADCs used in the TEXONO experiment, we developed new FADCs for a 1000-channel time projection chamber constructed as a subdetector for the LEPS experiment at the SPring8 synchrotron facilities in Japan [18]. The LEPS FADCs have a 40-MHz sampling rate, 10-bit dynamic range, and 32 channels per module and are equipped with field programmable gate array (FPGA) capabilities for real time data processing. The new system was commissioned at LEPS in the summer of 2003. The upgraded FADC will be further optimized and implemented in the KS reactor neutrino experiment for data taking in Period IV.

5.3. Sonoluminescence

Single-bubble sonoluminescence (SL) [19] is a phenomenon first observed in 1989, where an acoustically trapped and periodically driven gas bubble collapses 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 [20]. We are initiating a new program on SL under the TEXONO framework. We are adopting a high-energy-physics style approach to work on this subject, relying on the collaboration of multidisciplinary expertise, distribution of tasks, advanced multichannel event-by-event measurements, and software analysis techniques. The experience can also serve as a "test case" for the collaboration to venture into interdisciplinary research.

6. OUTLOOK

The strong evidence of neutrino masses and mixings is leading to intense worldwide efforts 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 groundbreaking technical innovations—as well as potential for surprises in the scientific results.

A collaboration among scientists from Taiwan, China, the United States, and Turkey has been built up with the goal of establishing a qualified experimental program in neutrino and astroparticle physics. It is a first-generation collaborative effort in such 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 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 a feasible method for enhancement of the 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 being 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 beside, if not beyond, neutrino physics.

ACKNOWLEDGMENTS

We would like to thank the TEXONO collaborators for the many contributions which "make it happen." Funding support is provided by the National Science Council, Taiwan; the National Science Foundation, China; and by the collaborating institutes.

REFERENCES

1. C. Y. Chang, S. C. Lee, and H. T. Wong, Nucl. Phys. B (Proc. Suppl.) **66**, 419 (1998).
2. H. T. Wong and J. Li, Mod. Phys. Lett. A **15**, 2011 (2000); H. T. Wong, Mod. Phys. Lett. A **19**, 1207 (2004), and references therein.
3. D. Normile, Science **300**, 1074 (2003).
4. Particle Data Group, Phys. Lett. B **592** (2004), and references therein.
5. *Proceedings of XXI International Conference on Neutrino Physics & Astrophys., Paris, 2004*, Nucl. Phys. B (Proc. Suppl.) **143** (2005).
6. H. T. Wong et al., Astropart. Phys. **14**, 141 (2000).
7. W. P. Lai et al. (TEXONO Collab.), Nucl. Instrum. Methods Phys. Res. A **465**, 550 (2001).
8. P. Vogel and J. Engel, Phys. Rev. D **39**, 3378 (1989).
9. H. B. Li and H. T. Wong, J. Phys. G **28**, 1453 (2002).
10. H. T. Wong, Nucl. Phys. B (Proc. Suppl.) **143**, 205 (2005), and references therein.
11. H. B. Li et al. (TEXONO Collab.), Phys. Rev. Lett. **90**, 131802 (2003), and references therein.
12. G. G. Raffelt, Phys. Rev. D **39**, 2066 (1989).

13. *A General Monte Carlo N-Particle Transport Code, Version 4A*, Ed. by J. F. Briesmeister, LA-12625-M (1997).
14. B. Xin et al. (TEXONO Collab.), Phys. Rev. D **72**, 012006 (2005).
15. J. Learned, Nucl. Phys. B (Proc. Suppl.) **143**, 152 (2005).
16. D. Elmore and F. M. Phillips, Science **236**, 543 (1987).
17. S. Jiang et al., Nucl. Instrum. Methods Phys. Res. B **92**, 61 (1994); **52**, 285 (1990).
18. T. Nakano (LEPS Collab.), Nucl. Phys. A **684**, 71c (2001).
19. M. P. Brenner, S. Hilgenfeldt, and Detlef Lohse, Rev. Mod. Phys. **74**, 425 (2002); C.-D. Ohl et al., Philos. Trans. R. Soc. London, Ser. A **357**, 269 (1999); B. P. Barber et al., Phys. Rep. **281**, 65 (1997).
20. D. Shapira and M. J. Saltmarsh, Phys. Rev. Lett. **89**, 104302 (2002); R. P. Taleyarkhan et al., Science **295**, 1868 (2002).