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THE TEXONO RESEARCH PROGRAM ON NEUTRINO AND ASTROPARTICLE PHYSICS

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This article reviews the research program and efforts for the TEXONO Collaboration on neutrino and astro-particle physics. The core program is on reactor-based low energy neutrino physics at the Kuo-Sheng (KS) Power Plant in Taiwan. The facilities of the laboratory is described. A limit on the neutrino magnetic moment of $\mu_{\bar{\nu}_e} < 1.3 \times 10^{-10}\ \mu_B$ at 90% confidence level was derived from measurements with a high purity germanium detector. Other physics topics at KS, as well as the various R&D program, are discussed

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1. Introduction and History

The TEXONO[a] Collaboration[1] has been built up since 1997 to initiate and pursue an experimental program in Neutrino and Astroparticle Physics[2]. 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 scientists from Taiwan and China[3].

Results from recent neutrino experiments strongly favor neutrino oscillations which imply neutrino masses and mixings[4]. 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 which will be necessary to interpret the future precision data. In addition, these studies would also explore new detection channels to open up new avenues of investigations.

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[a] Taiwan **EX**periment **O**n **N**eutrin**O**

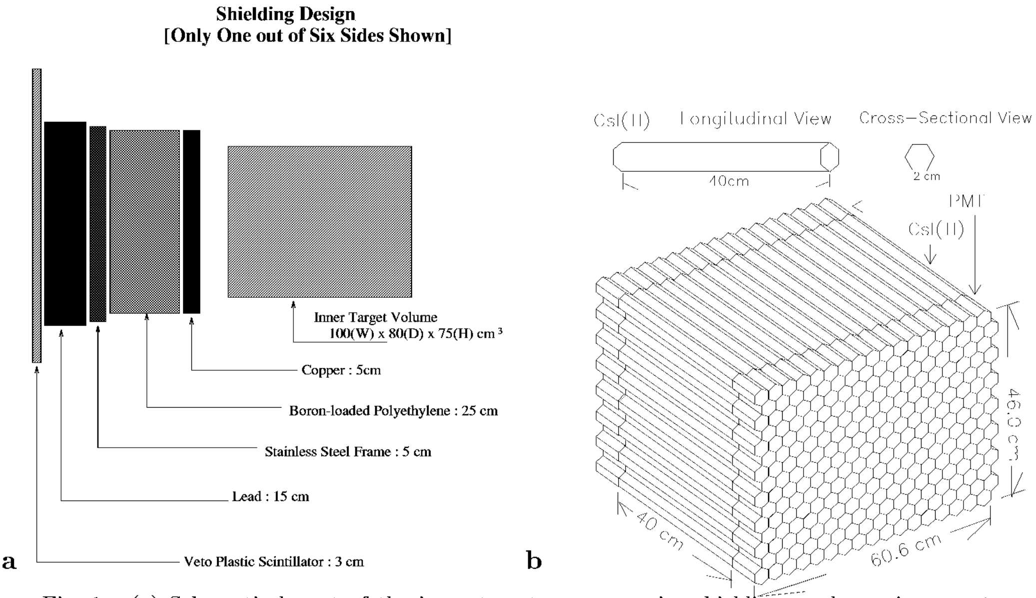

Fig. 1. (a) Schematic layout of the inner target space, passive shieldings and cosmic-ray veto panels. The coverage is 4π but only one face is shown. (b) The CsI(Tl) target configuration where a total of 93 modules (186 kg) is installed for Period II.

The TEXONO research program is based 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[5]. The main effort is a reactor neutrino experiment at the Kuo-Sheng (KS) Nuclear Power Station in Taiwan to study low energy neutrino properties and interactions[6]. The Kuo-Sheng experiment is the first particle physics experiment in Taiwan. In parallel to the reactor experiment, various R&D efforts coherent with the theme are initiated and pursued.

Subsequent sections highlight the results and status of the program.

2. Kuo-Sheng Neutrino Laboratory

The "Kuo-Sheng 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[6]. A multi-purpose "inner target" detector space of 100 cm×80 cm×75 cm is enclosed by 4π passive shielding materials which have a total weight of 50 tons. The shielding provides attenuation to the ambient neutron and gamma background, and consists of, from inside out, 5 cm of OFHC copper, 25 cm of boron-loaded polyethylene, 5 cm of steel, 15 cm of lead, and cosmic-ray veto scintillator panels. The schematic layout of one side is shown in Figure 1a.

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[7] based on 16-channel, 20 MHz, 8-bit 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. Software procedures have been devised to extend the effective dynamic range from the nominal 8-bit measurement range provided by the FADC[8]. The reactor laboratory is connected via telephone line to the home-base laboratory, 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 2, 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[9], 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 $\sigma[\bar{\nu}_e e^-(\mathrm{SM})]$ should focus on higher electron recoil energies (T>1.5 MeV), while MM searches should base on measurements with T<100 keV[10]. Observation of $\bar{\nu}_e$N(SM) would require detectors with sub-keV sensitivities.

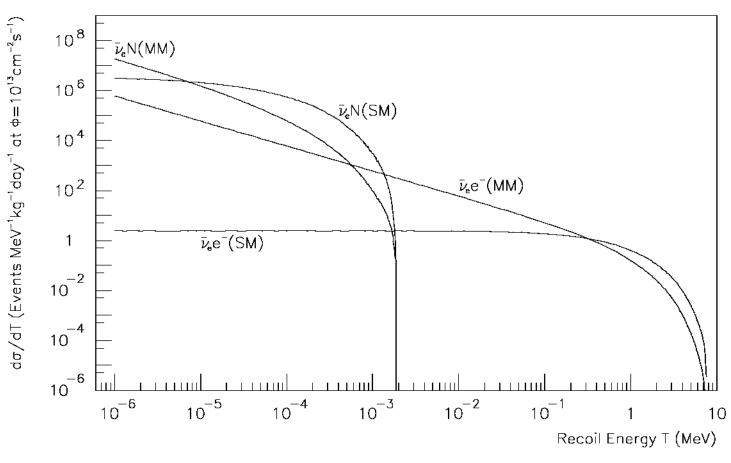

Fig. 2. Differential cross section showing the recoil energy spectrum in $\bar{\nu}_e$-e and coherent $\bar{\nu}_e$-N scatterings, at a reactor neutrino flux of 10^{13} cm^{-2}s^{-1}, for the Standard Model (SM) processes and due to a neutrino magnetic moment (MM) of 10^{-10} μ_B.

Accordingly, data taking were optimized with these strategies. An ultra low-background high purity germanium (ULB-HPGe) detector of mass 1 kg was used for Period I (June 2001 till May 2002) data taking, while 186 kg of CsI(Tl) crystal scintillators were added in for Period II (Jan 2003 till Sept 2003). Both detector systems operate in parallel with the same data acquisition system but independent triggers.

3. Low Energy Neutrino Physics at Kuo-Sheng

We have achieved in the Period I data-taking using the ULB-HPGe a background level at 20 keV at the range of 1 $\text{keV}^{-1}\text{kg}^{-1}\text{day}^{-1}$. These are the levels comparable to underground Dark Matter experiments. Comparison of the measured spectra for 4712/1250 hours of Reactor ON/OFF data in Period I[11] shows no excess. Limits on the neutrino magnetic moment of $\mu_{\bar{\nu}_e} < 1.3(1.0) \times 10^{-10}$ $\mu_{\rm B}$ and on the neutrino radiative decay lifetime[12] of $\tau_\nu \text{m}_\nu^3 > 2.8(4.8) \times 10^{18}$ eV^3s in the non-degenerate case, at 90(68)% confidence level (CL) were derived. Details of this work are given in an accompanying article in these Proceedings[13].

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. The subsequent decays of these isotopes by electron capture would produce mono-energetic ν_e. A realistic neutron transfer simulation has been carried out to estimate the flux. Physics analysis on the μ_ν and Γ_ν of ν_e will be performed, while the potentials for other physics applications will be studied. In additional, potentials for an *inclusive* analysis of the anomalous neutrino interactions with matter, as well as studies on neutrino-induced nuclear transitions will be pursued.

The potential merits of crystal scintillators for low-background low-energy experiments were recently discussed[5]. The CsI(Tl) detector configuration for the KS experiment is displayed in Figure 1b. Each crystal module is 2 kg in mass and consists of a hexagonal-shaped cross-section with 2 cm side and a length 40 cm. The light output are read out at both ends (Q_R and Q_L) by custom-designed 29 mm diameter photo-multipliers (PMTs) with low-activity glass. The sum and difference of the PMT signals gives information on the energy and the longitudinal position of the events, respectively. A total of 186 kg (or 93 modules) have been commissioned for the Period II data taking, where more than 3×10^4 kg-day of reactor ON data were collected. The physics goal is to measure the Standard Model neutrino-electron scattering cross sections, and thereby to provide a measurement of $\sin^2\theta_\text{W}$ at the untested MeV range. The strategy[10] is to focus on data at high (>2 MeV) recoil energy where the uncertainties due to the reactor neutrino spectra are small. The large target mass compensates the drop in the cross-sections at high energy.

The typical Q_L versus Q_R distributions for single-site events after cosmic and pulse shape vetos are depicted in Figure 3a. There are evidence of contamination of internal radioactivity due to residual ^{137}Cs, such that the distributions of the 662-keV events are uniform across the 40 cm crystal length. Events due to γ-background from ^{40}K (1460 keV) and ^{208}Tl (2612 keV), on the other hand, occur more frequently near both edges, indicating that they are from sources external to the crystals. The raw and "after-selection" energy spectra for 14 kg-day of data taking are depicted in Figure 3b. It can be seen that the background is very low above 2.6 MeV, making this a favorable range to provide a measurement of σ(SM).

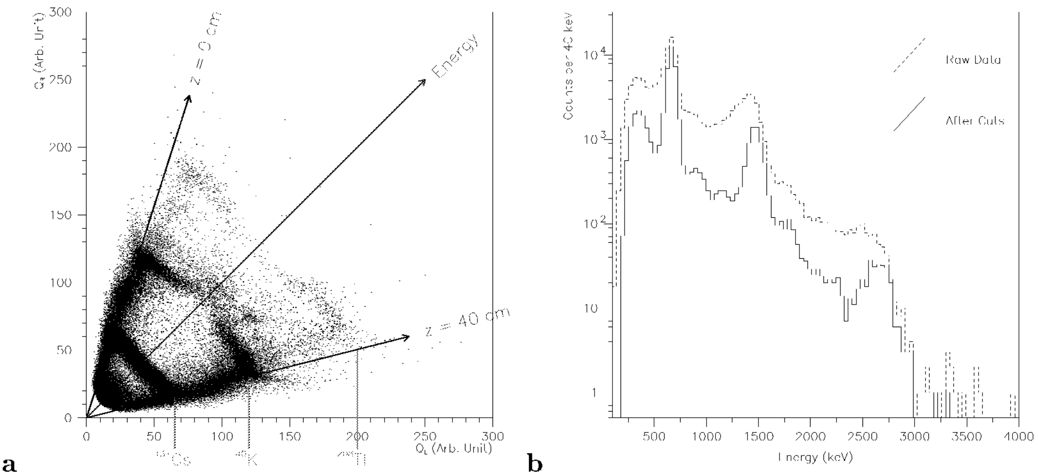

Fig. 3. (a) Q_L versus Q_R distributions for single site events. (b) The raw and the "after-selection" energy spectra from 14 kg-day of data taking, represented by the dashed and solid histograms, respectively.

In addition, a prototype ultra-low-energy germanium (ULE-HPGe) detector of 5 g mass is being studied, with potential applications on Dark Matter searches and neutrino-nuclei coherent scatterings. A hardware energy threshold of better than 100 eV has been achieved, as illustrated in Figure 4. The ULE-HPGe is placed inside the shieldings at the KS laboratory where the goal will be to perform the first-ever background studies at the sub-keV energy range. It is technically feasible to build an array of such detectors to increase the target size to the 1 kg mass range.

4. R&D Projects

Various R&D projects[6] are proceeding in parallel to the KS reactor neutrino experiment. Besides the ULE-HPGe already mentioned, the other highlights are:

4.1. *Dark Matter Searches with CsI(Tl)*

Experiments based on the mass range of 100 kg of NaI(Tl) are producing some of the most sensitive results in Dark Matter "WIMP" searches[15]. The feasibilities and technical details of adapting CsI(Tl) or other good candidate crystal like CaF_2(Eu) for WIMP Searches have been studied. A neutron test beam measurement for CsI(Tl) was successfully performed at IAE 13 MV Tandem accelerator[16]. We have collected the lowest threshold data for nuclear recoils in CsI(Tl), enabling us to derive the quenching factors, as well as to study the pulse shape discrimination techniques at the realistically low light output regime[17]. The measurements also provide the first confirmation of the Optical Model predictions on neutron elastic scatterings with a direct measurement on the nuclear recoils of heavy nuclei. A full scale Dark Matter

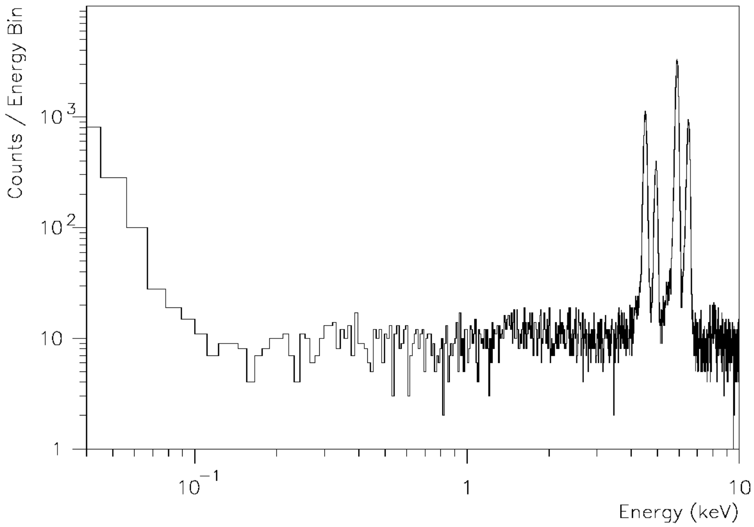

Fig. 4. Energy spectrum with the ULE-HPGe, indicating a detector threshold lower than 100 eV, The peaks are from an ^{55}Fe source and from back-scattering with Ti.

experiment with CsI(Tl) crystals is being pursued by the KIMS Collaboration in South Korea[18].

4.2. *Radio-purity Measurements with Accelerator Mass Spectrometry*

Measuring the radio-purity of detector target materials as well as other laboratory components are crucial to the success of 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 capabilities of radio-purity measurements further with the new Accelerator Mass Spectroscopy (AMS) techniques[19]. This approach may be complementary to existing methods since it is in principle 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 (like single beta-decays from ^{87}Rb and ^{129}I) or where γ emissions are suppressed (for instance, measuring ^{39}K provides a gain of 10^5 in sensitivity relative to detecting γ's from ^{40}K). A pilot measurement of the $^{129}\text{I}/^{127}\text{I}$ ratio ($< 10^{-12}$) in CsI was successfully performed demonstrating the capabilities of the Collaboration. Further beam time is scheduled at the IAE AMS facilities[20] to devise measuring schemes for the other 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 to study is on ^{40}K, where the goal sensitivity of a 10^{-14}g/g should be achieve-able by the AMS techniques.

4.3. *Upgrade of FADC for LEPS Experiment*

Based on the design and operation of the FADCs at the KS experiment, we developed new FADCs for a 1000-channel Time Projection Chamber constructed as a sub-detector for the LEPS experiment at the SPring8 Synchrotron Facilities in Japan[21]. The LEPS FADCs have 40 MHz sampling rate, 10-bit dynamic range, 32 channels per module and are equipped with Field Programmable Gate Array (FPGA) capabilities for real time data processing. The new system will be commissioned at LEPS in summer 2003. The upgraded FADCs will be further optimized and implemented to the KS reactor neutrino experiment for data taking in 2004.

4.4. *Sonoluminescence*

Single-Bubble Sonoluminescence(SL)[22] 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, its studies may provide room for surprises. In particular, there are recent and controversial claims of sonoluminescence-induced nuclear fusion[23]. We are initiating a new program on SL under the TEXONO framework. We will adopt a high-energy-physics-style approach to work on this subject, relying on the collaboration of multi-disciplinary expertise, 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.

5. Outlook

The strong evidence of neutrino masses and mixings[4] lead to intense world-wide 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 are room for ground-breaking technical innovations – as well as potentials for surprises in the scientific results.

A collaboration among scientists from Taiwan and China has been built up with the goal of establishing a qualified experimental program in neutrino and astroparticle 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. 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. Further measurements are pursued at the Kuo-Sheng 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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