NEUTRINO EXPERIMENTS : HIGHLIGHTS

HENRY TSZ-KING WONG
Institute of Physics, Academia Sinica, Nankang 11529, Taipei, Taiwan.
E-mail: htwong@phys.sinica.edu.tw

This article consists of two parts. The first section presents the highlights on the goals of neutrino physics, status of the current neutrino experiments and future directions and program. The second section describes the theme, program and research efforts for the TEXONO Collaboration among scientists from Taiwan and China.

1 Introduction

With the strong evidence presented by the Super-Kamiokande experiment on neutrino oscillations [1], there are intense world-wide efforts to pursue the next-generation of neutrino experiments.

The aims of the first section of this article is to "set the stage" for students and researchers not in the field by summarizing the key ingredients and highlights of the goals, status and future directions in neutrino physics experiments. It is not meant to be a comprehensive lecture or detailed review article. Interested readers can pursue the details from the listed references on textbook accounts [2], latest status [3] and Web-links [4].

The second part of this article presents an account of the research program of the TEXONO Collaboration.

2 Neutrino Physics Experiments

2.1 Why Neutrino Physics

Neutrino exists – and exists in large quantities in the Universe, comparable in number density to the photon. It is known that there are three flavors of light neutrino coupled via weak interaction to the Z gauge boson. Yet the fundamental properties : (1) masses, denoted by $\mathrm{m_i}$ for mass eigenstate ν_i, and (2) mixings, denoted by U_{li} for mixing matrix elements between flavor eigenstate ν_l and mass eigenstate ν_i (alternatively by θ_ij for mixing angles between mass eigenstates ν_i and ν_j), remains unknown or at least not accurately known enough.

In field theory language, this translates to the crucial question on the structure (or even the possible existence) of a "neutrino mass term" L(ν-mass) in the total Lagrangian. Standard Model sets this to be identically

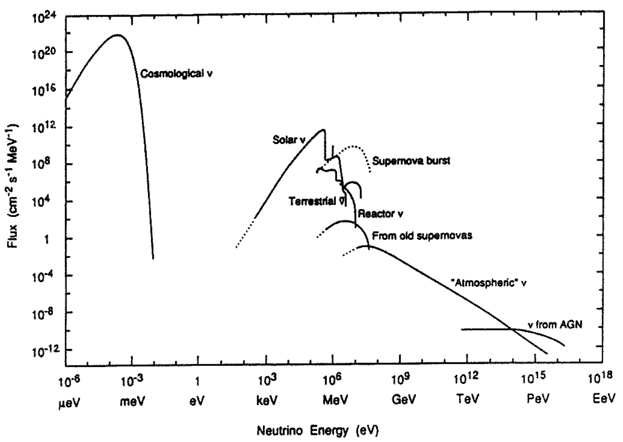

Figure 1. The expected neutrino spectra from various celestial and terrestrial sources. Neutrinos from man-made accelerators, typically at the range of 10 MeV to 100 GeV, are not shown here since accelerator parameters differ.

zero, but without any compelling reasons – in contrast to the massless-ness of the photons being dictated by gauge invariance. The detailed structures and values of this term can reveal much about the Grand Unified Theories.

At the large length-scale frontier, neutrino mass is related to the composition and structural evolution of the Universe. Neutrino has been a candidate of Dark Matter [3]: in fact it is the only candidate within the list that is proven to exist.

Experimentally, the probing of L(ν-mass) is carried out by studying various processes related to neutrino masses and mixings, such as direct mass measurement through the distortion of β-spectra, neutrinoless double beta decays, neutrino oscillations, neutrino magnetic moments, neutrino decays ..... and so on. These investigations are realized by a wide spectrum of experimental techniques spanned over several decades of energy scale with different neutrino sources. The expected neutrino spectrum due to terrestrial and astrophysical sources are shown in Figure 1.

In addition, neutrino has been used as probe (as "beam" from accelerators and reactors and even astrophysical sources) to study electroweak physics, QCD, structure function physics, nuclear physics, and to provide otherwise inaccessible information on the interior of stars and supernovae.

Therefore, the study of neutrino physics and the implications of the results connect many disciplines together, from particle physics to nuclear physics to astrophysics to cosmology.

2.2 Current Status and Interpretations

Neutrino interactions are characterized by cross-sections at the weak scale (100 fb at 100 GeV to $< 10^{-4}$ fb at 1 MeV). As an illustration, the mean free path in water for $\bar{\nu_e}$ from power reactors at the typical energy of 2 MeV is 250 light years! The central challenge to neutrino experiments is therefore on how to beat this small cross section and/or slow decay rate. Usually massive detectors are necessary to compensate by their large target size. Then the issue becomes how to keep the cost and background low.

After half a century of ingenious experiments since the experimental discovery of the neutrinos by Cowan and Reines, there are several results which may indicate the existence of neutrino masses, and hence physics beyond the Standard Model. All these results are based on experimental searches of neutrino oscillation, a quantum-mechanical effect which allows neutrino to transform from one flavor eigenstate to another as it traverses in space. This process depends on the mass difference ($\Delta \mathrm{m}^2 = |\mathrm{m}_\mathrm{i}^2 - \mathrm{m}_\mathrm{j}^2|$) rather than the absolute mass, resulting in enhanced sensitivities. A simplified summary of the results of neutrino oscillation experiments is shown in Figure 2.

The "allowed regions" are due to anomalous results from experiments in:

1. **Atmospheric Neutrinos:**
Data from the Super-Kamiokande experiments [1], supported by other experiments, indicates a smaller $(\nu_\mu + \bar{\nu_\mu})/(\nu_\mathrm{e} + \bar{\nu}_\mathrm{e})$ ratio than would be expected from propagation models of cosmic-ray showering. The "smoking gun" for new physics is that the deficit has a statistically strong dependence with the zenith angle, meaning the effect depends on the propagation distance of the neutrinos from the production point to the detector. The combined fit supports a scenario of $\nu_\mu \to \nu_\tau$ oscillation.

2. **Solar Neutrinos:**
All solar neutrinos to date reported an observed solar neutrino flux less than the predictions of Standard Solar Model. The deficit is different among the experiments, suggesting an energy dependence which is difficult to be explained by standard solar models. However, within an individual experiment, the potential "smoking gun" effects (day-night variation, seasonal variation, spectral distortion) are absent or statis-

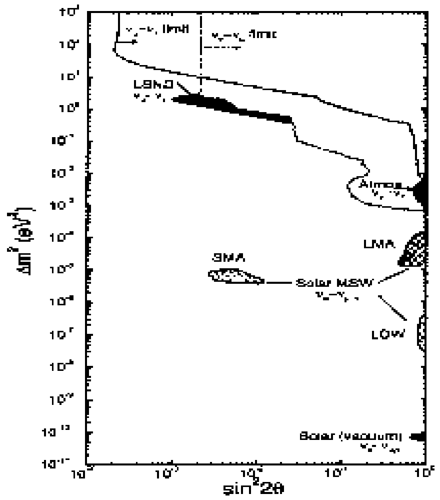

Figure 2. A summary of results of neutrino oscillation experiments in (Δm^2,$\sin^2 2\theta$) parameter space. The allowed regions are shaded.

tically weak. The combined data favors neutrino oscillations of ν_e to another species, active or sterile: $\nu_e \to \nu_x$, either in vacuum or due to matter-enhanced oscillation (the "MSW" Effect) in the Sun.

3. **LSND Anomaly:**
The LSND experiment with accelerator neutrinos reported unexpected excess of ν_e and $\bar{\nu_e}$ in a $\nu_\mu + \bar{\nu_\mu}$ beam, which can be explained by $\nu_\mu \to \nu_e$ oscillation. The results are yet to be reproduced (or totally excluded) by other experiments.

If all experimental results are correct and to be explained by neutrino oscillations, one must incorporate a fourth-generation sterile neutrino. If one takes the conservative approach that LSND results must be reproduced by an independent experiment before they are incorporated into the theoretical framework, then the favored scenario would be a three-family scheme with:

- **Neutrino Mass Differences:**
Atmospheric neutrino oscillation is driven by $\Delta m^2_{23} \sim 10^{-2} - 10^{-3}$ eV^2 which is much bigger than the scale which drives solar neutrino oscillation at $\Delta m^2_{12} \sim 10^{-4} - 10^{-5}$ eV^2 due to matter-enhanced oscillation, as depicted in Figure 3. The sign of Δm^2_{23} remains undetermined.

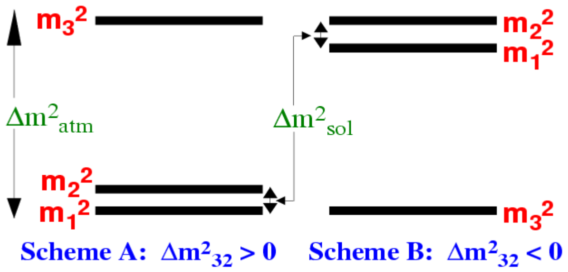

Figure 3. The favored hierarchical structures of the neutrino mass matrix to explain atmospheric and solar neutrino results.

- **Mixing Angles:**
  Surprisingly when compared to the quark sector, the atmospheric neutrino data supports strongly large mixing angles (order of 1) for $\sin^2 2\theta_{23}$. Combining all data from solar neutrinos also statistically favors large $\sin^2 2\theta_{12}$. The 1-km baseline reactor neutrino experiments set limits on $\sin^2 2\theta_{13} < 0.1$.

2.3 Future Experimental Program

Among the various neutrino sources depicted in Figure 1, only a relatively small window from $\sim$1 MeV to $\sim$100 GeV is detectable by present techniques. The future of neutrino experiments will therefore evolve along various directions:

(I) Further Exploration of the Measured Window

- **Long Baseline (LBL) Neutrino Oscillation Experiments:**
  There is a running experiment with accelerator neutrinos produced by "proton-on-target" (PoT) from KEK to the Super-Kamiokande detector (250 km), while two others (both 730 km) in construction: Fermilab to MINOS experiment at Soudan, and CERN to ICANOE and OPERA experiments at Gran Sasso. The goals will be to reproduce and improve on the $\nu_{\rm atm}$ parameters, to observe the E/L oscillation pattern, and to detect ν_τ appearance explicit by observing ν_τ charged-current interactions leading to the production of τ-lepton.
  In addition, there are two experiments, KamLAND and BOREXINO, with capabilities of performing LBL experiments with reactor neutrinos

from power plants $\sim$100 km away. Their goals will be the probe the "Large Mixing Angle" MSW solution to the solar neutrino data.

- **Detection of Weak/Rare Signals:**
Various big underground experiments are sensitive to neutrinos from supernovae, with the hope of detecting thousands of events from the next supernova, as compared to the 20 events from SN1987a. The LBL reactor neutrino experiments will also try to observe "terrestrial neutrinos" produced by the radioactive (mainly ^{232}Th and ^{238}U series) from the Earth's crust.

- **Further Double Beta Decay Searches:**
Neutrinoless Double Beta Decay is sensitive to the absolute scale of $\mathrm{m_i^2}$ rather then $\Delta\mathrm{m_{ij}^2}$. Many R&D projects are underway to try to achieve the interesting range of $\mathrm{m_3} \sim 0.1 - 0.01$ which is a scenario suggested by atmospheric neutrino results.

- **Neutrino Factories from Muon Storage Rings:**
There are intense pilot efforts to study the feasibilities of performing LBL experiments with a "Neutrino Factory" where the neutrinos are produced by muons decay in a muon storage ring. Unlike conventional PoT neutrino beam, μ-decay gives beams which are selectable in ν_{e}, $\bar{\nu_e}$ ν_μ and $\bar{\nu_\mu}$, and with well-known spectra and compositions. Coupled to the high luminosity and small beam size, they can be powerful tools to study neutrino physics. The goals for the LBL program, where the baseline will have to be the 1000-10000 km range, would be to do precision measurements on the ν_{atm} parameters, to probe $\sin^2 2\theta_{13}$ to $\mathrm{O}(10^{-4})$ (from $\nu_{\mathrm{e}} \rightarrow \nu_\mu$), to determine the signs of $\Delta\mathrm{m}_{23}^2$ (from the asymmetric $\nu_{\mathrm{e}}/\bar{\nu_{\mathrm{e}}}$ matter effects), and to probe CP-violation in the lepton sector (comparing $\nu_{\mathrm{e}} \rightarrow \nu_\mu$ & $\bar{\nu_{\mathrm{e}}} \rightarrow \bar{\nu_\mu}$). There are many technical challenges which must be addressed towards the realization of such projects.

(II) Extension of Detection Capabilities:

- **High Energy Frontiers:**
There are several "neutrino telescope" projects (Lake Baikal, AMANDA, NESTOR, ANTARES) whose objective is towards the construction of an eventual "km^3" detector. The scientific goals are (a) to identify and understand the astrophysics of high-energy (TeV to PeV) neutrino sources from active galactic nuclei, gamma-ray bursts, neutron stars and other astrophysical objects, and (b) to use these high-energy neutrinos for neutrino physics like very long baseline studies.

- **Low Energy Frontiers:**
  There are a host of new solar neutrino experiments: SNO is taking data while Borexino and KamLAND are under construction, as well as many R&D ideas and projects. Their goals are to measure the solar neutrino spectrum and particularly those from the dominant sub-MeV pp and ^{7}Be neutrinos, and to study the details of spectral shape, day-night and seasonal variations, as well as the neutral-current to charged-current ratios, so as to identify a unique solutioin to "solar neutrino problem", and to measure the $(\Delta m^2, \sin^2 2\theta)$ parameters. The low-energy solar neutrino spectrum also provides a probe to the other inaccessible physics at the interior of the Sun.
  Weakly Interacting Massive Particles (WIMP) are candidates for Dark Matter. Their experimental searches also employ the techniques of low-background low-energy experiments. Many experiments are running or being planned, based on crystal scintillators, cryogenic detectors and other techniques.
  Finally, the relic "Big Bang" neutrino, the counterpart to the 2.7 K cosmic microwave photon background (CMB), has large number density (110 cm^{-3} for Majorana neutrinos, comparing to 411 cm^{-3} for CMB) but extremely small cross sections due to the meV energy scale at an effective temperature of 1.9 K. The relic neutrinos decouples from matter at a much earlier time (1 s) than the CMB (3×10^5 years), and hence are, in principle, better probes to the early Universe. A demonstration of its existence and a measurement of its density is a subject of extraordinary importance. Though there is no realistic proposals on how to detect them, it follows the traditions of offering a highly rewarding challenge to and pushing the ingenuity of neutrino experimentalists.

3 Research Program of the TEXONO Collaboration

Since 1997, the TEXONO[a] Collaboration has been built up to initiate and pursue an experimental program in Neutrino and Astroparticle Physics [5]. By the end of 2000, 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), Mainland China (Institute of High Energy Physics†, Institute of Atomic Energy†, Institute of Radiation Protection, Nanjing University) and

[a] **T**aiwan **EX**periment **O**n **N**eutrin**O**

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 Taiwanese and Mainland Chinese scientists

The research program [6] is based on the the unexplored and unexploited theme of adopting the scintillating crystal detector techniques for low-energy low-background experiments in Neutrino and Astroparticle Physics [7]. The "Flagship" experiment [10] is based on CsI(Tl) crystals placed near the core of the Kuo-Sheng Nuclear Power Station (KSNPS) at the northern shore of Taiwan to study low energy neutrino interactions. It is the first particle physics experiment performed in Taiwan where local scientists are taking up major roles and responsibilities in all aspects of its operation: conception, formulation, design, prototype studies, construction, commissioning, as well as data taking and analysis.

In parallel to the flagship reactor experiment, various R&D efforts coherent with the theme are initiated and pursued.

3.1 Scintillating Crystal Detector for Low-Energy Experiments

One of the major directions and experimental challenges in neutrino physics [3] is to extend the measurement capabilities to the sub-MeV range for the detection of the p-p and ^{7}Be solar neutrinos, Dark Matter searches and other topics. For instance, while high energy (GeV) neutrino beams from accelerators have been very productive in the investigations of electroweak, QCD and structure function physics, the use of low energy (MeV) neutrino as a probe to study particle and nuclear physics has not been well explored. Nuclear power reactors are abundant source of electron anti-neutrinos ($\bar{\nu_e}$) at the MeV range and therefore provide a convenient laboratory for these studies.

On the detector technology fronts, large water Cerenkov and liquid scintillator detectors have been successfully used in neutrino and astro-particle physics experiments. New detector technology must be explored to open new windows of opportunities. Crystal scintillators may be well-suited to be adopted for low background experiments at the keV-MeV range [7]. They have been widely used as electromagnetic calorimeters in high energy physics [8], as well as in medical and security imaging and in the oil-extraction industry. There are matured experience in constructing and operating scintillating crystal detectors to the mass range of 100 tons.

This technique offer many potential merits for low-energy low-background experiments. In particular, they are usually made of high-Z materials which provide strong attenuation for γ's of energy less than 500 keV, as indicated in the photon attenuation plot in Figure 4. As an illustration, 10 cm of CsI(Tl)

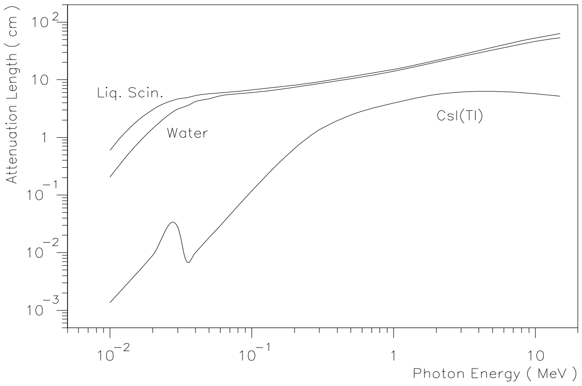

Figure 4. The attenuation length, as defined by the interactions that lead to a loss of energy in the media, for photons at different energies, for CsI(Tl), water, and liquid scintillator.

has the same attenuating power as 5.6 m of liquid scintillators at γ-energy of 100 keV. Consequently, it is possible to realize a compact detector design with minimal passive materials equipped with efficient active veto and passive shielding. Externally originated photons in this energy range from ambient radioactivity or from surrounding equipment cannot penetrate into the fiducial volume. Therefore, the dominating contribution to the experimental sensitivities is expected to be from the internal background in the crystal itself, either due to intrinsic radioactivity or cosmic-induced long-lived isotopes, both of which can be identified and measured such that the associated background can be subtracted off accordingly. The experimental challenges are focussed on the understanding and control of the *internal background*. Pioneering efforts have already been made with NaI(Tl) crystals for Dark Matter searches [9].

3.2 Flagship Experiment with Reactor Neutrinos

An experiment towards a 500 kg CsI(Tl) scintillating crystal detector to be placed at a distance of 28 m from a core in KSNPS is under construction to study various neutrino interactions at the keV-MeV range [10], and to establish and explore the general techniques for other low-energy low-background applications. The layout of the experimental site is shown in Figure 5

The physics objectives of the experiment are to improve on or to explore the subjects of: (1) Neutrino-electron scatterings, which is a fundamental interaction providing information on the electro-weak parameters

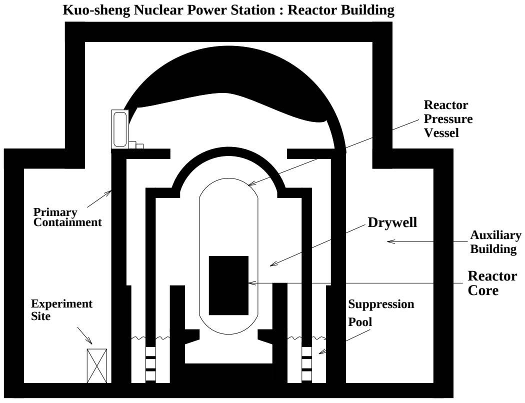

Figure 5. Schematic side view, not drawn to scale, of the Kuo-sheng Nuclear Power Station Reactor Building, indicating the experimental site. The reactor core-detector distance is about 28 m.

(g_V, g_A, and $\sin^2\theta_W$), and are sensitive to small neutrino magnetic moments ($\mu\nu$) and the mean square charge radius, as well as the W-Z interference effects; (2) Neutrino interactions on nuclei such as ^{133}Cs and ^{127}I, and in particular the neutral current excitation (NCEX) channels where the signatures are gamma-lines at the characteristic energies $-$ their cross-sections are related to the physics of nucleon structure, and are essential to explore the scenario of applying these interaction channels in the detection of low energy solar and supernova neutrinos; (3) Matter effects on neutrinos, since this is the first big high-Z detector built for reactor neutrino studies.

To fully exploit the advantageous features of the scintillating crystal approach in low-energy low-background experiments, the experimental configuration should enable the definition of a fiducial volume with a surrounding active 4π-veto, and minimal passive materials. This is realized by a design shown schematically in Figure 6. One CsI(Tl) crystal unit consists of a hexagonal-shaped cross-section with 2 cm side and a length 20 cm, giving a mass of 0.94 kg. Two such units are glued optically at one end to form a module. The modules will be installed in stages towards an eventual 17×15 matrix configuration. The light output are read out at both ends by custom-designed 29 mm diameter photo-multipliers (PMTs) with low-activity glass, whose signals will pass through amplifiers and shapers to be digitized by 20 MHz FADCs [11]. The sum and difference of the PMT signals gives information on the energy and the longitudinal position of the events, respectively. The passive shieldings

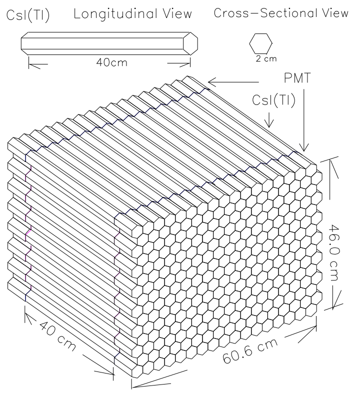

Figure 6. Schematic drawings of the CsI(Tl) target configuration.

consist of, from inside out, 5 cm of copper, 25 cm of boron-loaded polyethylene, 5 cm of steel, 15 cm of lead and finally plastic scintillators as cosmic-ray veto. The target is housed in a nitrogen environment to prevent background events due to the diffusion of the radioactive radon gas.

Extensive measurements on the crystal prototype modules have been performed [12]. The response is depicted in Figure 7, showing the variation of collected light for Q_1, Q_2 and Q_{tot} as a function of position within one crystal module. The error bars denote the FWHM width of the ^{137}Cs photo-peaks. The discontinuity at L=20 cm is due to the optical mis-match between the glue (n=1.5) and the CsI(Tl) crystal (n=1.8). It can be seen that Q_{tot} is only weakly dependent of the position and a 10% FWHM energy resolution is achieved at 660 keV. The detection threshold (where signals are measured at both PMTs) is <20 keV. The longitudinal position can be obtained by considering the variation of the ratio $R = (Q_1 - Q_2)/(Q_1 + Q_2)$ along the crystal. Resolutions of 2 cm and 3.5 cm at 660 keV and 200 keV, respectively, have been demonstrated.

In addition, CsI(Tl) provides powerful pulse shape discrimination capabilities to differentiate γ/e from α events, with an excellent separation of >99% above 500 keV. The light output for α's in CsI(Tl) is quenched less than that in liquid scintillators. The absence of multiple α-peaks above 3 MeV in the prototype measurements suggests that a ^{238}U and ^{232}Th concentration (assuming equilibrium) of $< 10^{-12}$ g/g can be achieved.

By early 2001, after three and a half years of preparatory efforts, the "Kuo-Sheng Neutrino Laboratory", equipped with flexibly-designed shield-

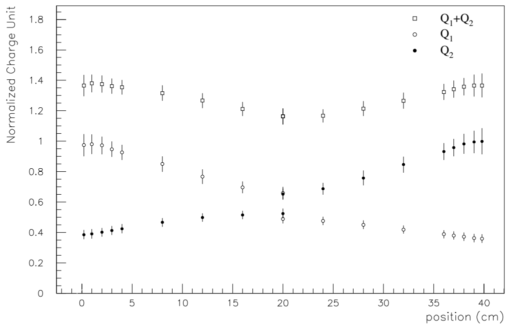

Figure 7. The measured variations of Q_1, Q_2 and $Q_{tot} = Q_1 + Q_2$ along the longitudinal position of the crystal module. The charge unit is normalized to unity for both Q_1 and Q_2 at their respective ends.

ings, cosmic-ray 4-π active veto, complete electronics which allow full digitization of multi-channel detectors for a 10 ms long duration, data acquisition and monitoring systems, as well as remote assess capabilities, was formulated, designed, constructed and commissioned. Prototype CsI(Tl) detector has been operating in the home-base laboratory. The first Reactor ON/OFF data taking period will be based on a 1 kg low-background germanium detector with 100 kg of CsI(Tl) running in conjunction.

3.3 R&D Projects

Various projects with stronger R&D flavors are proceeding in parallel to the flagship reactor experiment. A feasibility study of using boron-loaded liquid scintillator for the detection of $\bar{\nu_e}$ has completed [13]. The cases of using of GSO [14] and LiI(Eu) [15] as well as Yb-based scintillating crystals for low energy solar neutrinos are explored. The adaptations of CsI(Tl) crystal scintillator for Dark Matter WIMP searches are studied, which includes a neutron beam measurement to study the response due to nuclear recoils [16].

A generic and convenient technique to measure trace concentration of radio-isotopes in sample materials is of great importance to the advance of low-energy low-background experiments. A R&D program is initiated to adapt the techniques of Accelerator Mass Spectrometry(AMS) with the established facilities at the 13 MV TANDEM accelerator at IAE [17]. The goals are to device methods to measure ^{238}U, ^{232}Th, ^{87}Rb, ^{40}K in liquid and crystal scintillators beyond the present capabilities [18].

Complementary to these physics-oriented program are detector R&D efforts. Techniques to grow CsI(Tl) mono-crystal of length 40 cm, the longest in the world, have been developed and are deployed in the production for future batches.

4 Outlook

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 Taiwan, Mainland China and U.S.A. collaboration has been built up with the goal of playing a major role in this field. It is the first generation collaborative efforts in large-scale basic research between scientists from Taiwan and Mainland China. The technical strength and scientific connections of the Collaboration are expanding and consolidating. The flagship experiment is to perform the first-ever particle physics experiment in Taiwan. Many R&D projects are being pursued.

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

Acknowledgments

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