**AS-TEXONO/97-01**

# A Pilot EXperiment On Neutrino Oscillation (EXONO) in Taiwan : A Status Report

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the Academia Sinica
for
the EXONO Collaboration

# 1 Overview

A pilot experiment on reactor neutrinos have been intensely pursued during the past year in Taiwan. Its motivation is to conduct a feasibility study on an ultimate full scale long baseline EXperiment On Neutrino Oscillation (the EXONO proposal) from the nuclear power reactors of the Taiwan Power Company in Taiwan.

The collaboration comprises a wide spectrum of expertise from various fields : nuclear and particle physicists from the Academia Sinica, the University of Maryland, Nanjing University and the Institute of High Energy Physics at Beijing; chemists from the National Taiwan University; as well as nuclear engineers from the National Tsing Hua University, the Taiwan Electric Company and the Institute of Nuclear Energy Research-Atomic Energy Council. The Academia Sinica has been taking the leadership and coordination role in these efforts.

In our first proposal to the National Science Council in 1996, we have prepared a detailed report summarizing the current status of neutrino physics and astrophysics with emphasis on the experiments with reactor neutrinos; we have described the first experimental studies leading to a conceptual design of the pilot experiment, and have outlined future visions of the project which may bring us to the international frontiers. We include this document for reference.

In the following notes, we present a summary of the progress and status on the project. Future plans and strategies are also discussed.

# 2 Current Status

The success of the pilot experiment involves many complex and modern experimental techniques which the collaboration has to learn to master, while the building up of a qualified collaboration from the various groups of diversified background adds to the dimension of the challenge. Nevertheless, enormous progress have been achieved on the various fronts, and the highlights are summarized as follows.

- Manpower : New members at the level of faculties and postdoctorate associates have joined the collaboration, and will take up some of the important roles of the experiment.
- Collaboration : The collaborative efforts have been further consolidated, with various groups attacking different aspects of the experiment based on their research interest and expertise.

- Simulation Studies : Software have been developed to enable us to study and understand the problem of light collection of cells with different geometry and internal reflection properties, as well as the question of neutron transport in matter.
- Liquid Scintillator (NTU, AS, IHEP) : Progress have been made in our attempt to produce our own boron-loaded liquid scintillator (in particular, the "$HO_1 + TMB$") with comparable performance as the commercial product BC-523A from Bicron. Details on the measurements of attenuation length, light yield and pulse shape discrimination are presented in the appendix of this report. The separation of $(\alpha, \gamma)$ has been successively achieved with $HO_1 + TMB$ with small sized samples. A master thesis (by graduate student Miss Ribi Leung of National Cheng Kung University done at Academia Sinica with $HO_1 + TMB$ produced in National Taiwan University) has been produced.
- Trigger and Data Acquisition (AS) : This is the area where local expertise and resources have been the strongest based on past experience. Various options and alternatives have been studied, and will be finalized when we have the final detector design.
- Neutron Background (NTHU) : Using an array of $^3$He-filled proportional counters, the background neutron fluxes near the power reactors as well as that along the water fronts in the city of Yeh Lu, 10 kilometer north of Taiwan Power Company's Nuclear Power Reactor Plant-II, have been measured.
- Low Background Components (TPC, NTHU, AS): The radioactive impurities of the liquid scintillator $HO_1 + TMB$, and that of other materials such as the photo-multipliers, cell wall materials etc., to be used as construction materials for the EXONO detectors have been measured at the low background counting facilities of the Taiwan Power Company, the National Tsing Hua University and the Academia Sinica.
- Production of Photo-multipliers (NU) : Twenty photo-multiplier tubes (PMT) of two inch in diameter are produced by the PRC under the coordination of Nanjing University. These PMTs perform well and cost less than one fifth of their international market prices in the United States, Japan or Europe. They are potential candidates to be used in EXONO from our PSD studies. We continue to look for PMTs with larger diameter, higher quantum efficiency and lower radioactive impurities in the PRC.
- Prototype Construction (INER-AEC) : A prototype module (a matrix of 3 x 3 cells) of the EXONO detector has been designed and is being constructed through the Institute of Nuclear Energy Research. The expected delivery time is March 1997. With it, many operational experiences and the performance of the detector such as light collection, Winston Cone, FEP teflon, and thermal neutron capture efficiecy etc. can be studied in detail.

- Experimental Site and Infra-structure (TPC) : The possible sites for the pilot experiment and the associated infra-structures have been studied in conjunction with the Taiwan Power Company, with safety issues being taken seriously.

- International Communications : Critical comments and peer reviews on EXONO from the experts in the field have been seriously solicited. Through personal contacts, we have benefited much from discussions with the Gösgen, Bugey, Chooz, Palo Verde and SNO groups, as well as with a few other leading neutrino physicists. While our collaboration is still inevitably new and immature, our efforts and visions have been received with a fair amount of attention and anticipation from the international community.

# 3 Future Plans

Continuing efforts will be pursued in all the items mentioned above. The major tasks can be summarized as follows :

- Recruitment of more good graduate students and postdoctoral associates remains a key issue for the future of the Collaboration. The wide spectrum of questions being addressed requires new and young blood to ensure continuity and to inject new vigor to the investigations.

- The coordination and communication within the various groups of the Collaboration will be made more solid and efficient.

- The R&D program on the development and improvement of liquid scintillator and the light collection of the cells will continue. Meanwhile, studies of alternative liquid scintillator and new conceptual design of the experiment are also under way.

- When we are satisfied with the test-bench results, the design of the pilot experiment will be finalized, and the construction of the detector will start. The detector will then be installed at the reactor where the pilot experiment will be performed.

- In parallel, the world-arena in the fields of neutrino physics and astrophysics will be followed closely. Important new data are expected in the next few years from the present generation of major neutrino experiments : Super-Kamiokande, CHORUS, NOMAD, Chooz, Palo Verde and SNO which will inevitably define the future landscape of the field. First investigations will be carried out on the potential physics program of a long baseline reactor neutrino facility, the conceptual design of the detector, the site requirements, ... and so on.

# 4 Conclusion

The investigations of neutrino masses and mixings remain a major experimental challenge in fundamental research, the outcome of which will have significant impact in particle physics, astrophysics and cosmology. There may be a unique opportunity to perform a long baseline neutrino oscillation experiment in Taiwan, profiting from the power reactors which provide an abundant supply of neutrinos and the local mountainous geography where an underground laboratory can be built.

The EXONO Collaboration is preparing to carry out a pilot experiment at the power reactors, the first step towards this goal. It is expected that this experience will equip us with the necessary experimental techniques in this field and will help us to build up a qualified team to make major contributions in such future efforts. This report summarizes the status and the achieved progress of the project, and discusses plans for the future efforts.

# 5 Appendix : Results on the R&D program on Liquid Scintillator

## 5.1 Overview on Liquid Scintillator for EXONO

EXONO measures the $\bar{\nu_e}$ flux and its energy spectrum via the detection of the reaction:

$$\bar{\nu_e} + p \longrightarrow e^+ + n \quad . \tag{1}$$

With a hydrogen rich liquid scintillation (LS) target, the possible signals are:

(1) An $e^+$ of $E_{e^+} = (E_{\bar{\nu_e}} - 1.8)$ MeV.

(2) Two 511 keV $\gamma$ rays following the annihilation of the $e^+$ in the scintillator:

$$e^+ + e^- \longrightarrow \gamma + \gamma \tag{2}$$

(3) A delayed signal characterizing the capture of the neutron.

Thus, a four-fold coincidence with their special time and space sequence is available, which allows us to detect the rare neutrino initiated signal above background. EXONO selected its target liquid scintillator based on the following criteria:

(i) It must be hydrogen-rich, i.e., with a very high H/C ratio. The hydrogen nucleii, the protons, serve as the target of the neutrinos in reaction (1), as well as a convenient scattering center for the cooling of the neutron produced.

(ii) It must have good performance in terms of high light yield and long bulk attenuation length (BAL).

(iii) It must be cost effective and safe to handle in large quantity.

(iv) It must allow the loading of elements with high capture cross sections for thermal neutrons.

(v) It is preferred to have an enhanced slow emission component for the induced luminescence allowing pulse shaping discrimination on $(n, \gamma)$ separation.

For instance, as shown in Table 1, the liquid scintillator BC-523A produced by Bicron meets almost all the criteria mentioned above. It therefore has been used as a standard reference for our R&D program in the development of LS for EXONO.

| Properties | |
|---|---|
| $^{10}$B Content | 4.41% |
| Density | .916 g/cc |
| Light yield | 65% anthracene |
| Decay time | 3.7 nsec. |
| $\lambda_{max.emission}$ | 424 nm |
| Bulk light att. length | $> 4$ m |
| Refractive index | 1.414 |
| No. H per cc | $4.98 \times 10^{22}$ |
| No. C per cc | $2.86 \times 10^{22}$ |
| No. O per cc | $0.81 \times 10^{22}$ |
| No. $^{10}$B per cc | $0.243 \times 10^{22}$ |
| No. $^{11}$B per cc | $0.027 \times 10^{22}$ |

Table 1: Properties of BC-532A of Bicron (Enriched Boron-loaded Liquid Scintillator)

Since the energy of the neutron produced in (1) ranges from a fraction of a keV to several keV and very rarely reaches 18 to 20 keV. These fast neutrons will be thermalized via (n,p) collisions in the hydrogen-rich liquid scintillator. The thermal neutrons (E=0.025 eV) can be efficiently identified by loading elements of high thermal neutron absorption cross sections. All the common reactions used to detect slow neutrons result in either heavy charged particles or a burst of high energy gamma rays in their final states. In particular, heavy charged particles can provide a unique signal distinguishable from the background due to $\gamma$ radiations. Table 2 compiles the most promising elements which can be used for such a purpose.

For instance, in the case of $^{10}$B loaded LS, one has the n-capture reactions:

$$^{10}\mathrm{B} + \mathrm{n} \longrightarrow {}^{7}\mathrm{Li} + \alpha + 2.792\ \mathrm{MeV} \tag{3}$$

or

$$^{10}\mathrm{B} + \mathrm{n} \longrightarrow {}^{7}\mathrm{Li} + \alpha + 2.310\ \mathrm{MeV} \tag{4}$$

where the $^{7}$Li may be either left in its ground state (10%, in 3) or in its first excited state(90%, in 4). From conservation of energy and momentum, one can deduce that

$$\mathrm{E}_{^7\mathrm{Li}} = 0.84\ \mathrm{MeV} \quad \mathrm{E}_{\alpha} = 1.47\ \mathrm{MeV}$$

for the capture reaction (4).

The possibility of using pulse shape discrimination (PSD) to achieve $(\alpha, \gamma)$ separation makes a $^{10}$B-loaded liquid scintillator potentially superior to the commonly used gadolinium-loaded scintillators used in the present generation of reactor neutrino experiments. The 8 MeV $\gamma$ ray burst resulting from the neutron capture by gadolinium

| Element | Natural Abundance (%) | $\sigma_{n-capture}$ (barns) | Adapted by | $E_{signal}$ (MeV) |
|---|---|---|---|---|
| $^{155}$Gd<br>$^{157}$Gd<br>Gd$_{natural}$ | 15<br>16<br>100 | $\gamma$ burst,$6.1 \times 10^4$<br>$\gamma$ burst,$2.5 \times 10^5$<br>$\gamma$ burst, $1.7 \times 10^4$ | San Onofre | 8<br>$E_{ee}$ =<br>.07 to .182 |
| $^3$He | $10^{-4}$ | $\sigma_p = 5.3 \times 10^3$ | SNO | $E_p = .574$<br>$E_t = .191$ |
| $^{35}$Cl | 76 | $\sigma_p = 0.5$ | SNO | |
| $^6$Li | 7.5 | $\sigma_{alpha} = 9.4 \times 10^2$ | Bugey | $E_\alpha = 2.05$<br>$E_t = 2.73$ |
| $^{10}$B | 20 | $\sigma_\alpha = 3.8 \times 10^3$ | EXONO | $E_\alpha = 1.47$<br>$E_{Li} = .84$ |
| $^{113}$Cd | 12 | $\gamma$ burst,$2 \times 10^4$ | Savannah | |

Table 2: Properties of elements good for thermal neutron identification

manifest itself as a group of scattered low energy electrons and hence can easily be confused by background noises, while a heavy charged particle usually deposit its whole energy in a localized region of production. To avoid buying BC-523A at $1100 per liter, EXONO decided to develop its own LS at the National Taiwan University. After an intense R&D program, a candidate $HO_1 + TMB$ was produced ($HO_1 + TMB$ is a LS consisting of 4 g/l PPO and 100 mg/l POPOP in o-xylene, and is loaded with 0.41% $^{10}$B by weight). Although there remains some gap between the performance of BC-523A and $HO_1 + TMB$, one needs to be reminded that Bicron must already have spent decades and millions of dollars in R&D efforts on their products.

The major results from our R&D program on LS are summarized in the following notes. Further details can be referred to the Thesis of Miss Ribi Leung (National Cheng Kung University, 1996).

## 5.2 The Bulk Attenuation Length of $HO_1 + TMB$

The "Effective Light Attenuation Length" (EAL) of a LS in a particular detector design depends on:

- the bulk attenuation length (BAL) of the scintillator,
- the geometrical configuration of the cell, and
- the reflective properties of the cell walls.

| LS Sample | BAL(cm) at 420 nm | BAL(cm) at 440 nm | BAL(cm) at 450 nm |
|---|---|---|---|
| HO-1 | 140 | 723 | 868 |
| $HO_1$ + TMB (new) | 124 | 310 | 434 |
| $HO_1$ + TMB (after 3 months) | 79 | 140 | 155 |
| o-xylene | 543 | 1085 | 1447 |
| 1119A | 207 | 868 | 1085 |
| 1119C | 136 | 620 | 868 |
| 1119D | 89 | 255 | 362 |
| 1119E | 22 | 723 | 1085 |
| NE213 | 28 | 197 | 271 |
| BC501 | 35 | 543 | 868 |
| BC-517H | 217 | 434 | 482 |
| BC-519 | 255 | 868 | 1085 |

Table 3: The BAL of LS measured at the Academia Sinica.

Therefore, the developement of a LS with the longest possible BAL is one of the key issues in our R&D program. The BAL of LS prepared by EXONO are measured with UV visible light spectrometer using air as a reference. The results are summarized in Table 3. The measured BAL values as a function of wavelength are shown in Figure 1.

The compositions of the various LS samples are:

- HO-1 : 4g/l PPO, 100mg/l POPOP in o-xylene
- $HO_1$ + TMB: 4g/l PPO, 100mg/l POPOP in o-xylene which is loaded with 0.41% $^{10}B$ by weight. TMB in $HO_1$ + TMB stands for trimethylborate which is the boron component soluble in xylene. The concentration of TMB in $HO_1$ + TMB is about 21% giving rise to 0.42% of $^{10}B$ by weight.
- 1119A: 4g/l PPO, 50mg/l POPOP in o-xylene
- 1119C: 2g/l PPO, 100mg/l POPOP in o-xylene
- 1119D: 4g/l PPO, 100mg/l POPOP in p-xylene
- 1119E: 4g/l PPO, 100mg/l 1,4-bis(4-methyl-5-phenyl-oxazol-2-yl) benzene in o-xylene
- BC517H, BC519, BC523A, BC501 are all LS from Bicron based with 1,2,4-trimethylbenzene. BC517H and BC519 are mixed with 70% and 60% of mineral oil by weight, respectively.

| Formula | PMP $C_{18}H_{20}N_2$ | POPOP $C_{24}H_{16}N_2O_2$ |
|---|---|---|
| Molar Mass(g $mol^{-1}$) | 264.37 | 364.40 |
| Stokes shift($cm^{-1}$ | 10370 | 3540 |
| Peak emission (nm) | 425 | 418 |
| Quantum efficiency | 0.88 | 0.93 |

Table 4: Comparison of the photophysical properties of PMP with the widely used POPOP (used by EXONO in $HO_1$ + TMB).

- NE213 is xylene based.

We have demonstrated that the performance of $HO_1$ + TMB is close to the industrial standard. For instance measured BAL of $HO_1$ + TMB has reached more than 430 cm in the wavelength region 450 nm as compared to the $>$ 400 cm at the blue region (424 nm) for BC-523A produced by Bicron (See Table 1). We believe that the gap in quality between $HO_1$ + TMB and BC-523A may have been caused by appreciable self absorption of the emissions in the loaded PPO and POPOP mis-matched with the base solvent, o-xylene. In addition, the presence of the TMB may provide more scattering centers as well. Therefore, it is expected that further improvement on $HO_1$ + TMB can be made by:

- further optimizing compositions of PPO and POPOP, since LS-1119A is also a candidate with good performance.
- doping the boron-loaded LS with the a suitable wavelength shifter such as 1-pheny-3-mesityl-2-pyrazoline (PMP). PMP makes a large separation between the absorption and emission spectra (large Stokes shift). The comparison between PMP and POPOP is shown in Table 4, while their absorption and emission spectra are displayed in Figure 2.
- cleaning up (deoxygenation) of the LS by bubbling it with dry nitrogen gas.
- doing spectral analysis on the LS at each stage.
- matching the PMT response with the LS emission spectra.

## 5.3 Light Yield of $HO_1$ + TMB

Another important issue is the light yield of $HO_1$ + TMB. With a PMT (Hamamatsu R878) calibrated by a blue LED of known intensity, the absolute light yield of LS samples

| LS Sample | | Relative Light Yield at 450 nm |
|---|---|---|
| HO-1 | | 1.00 |
| $HO_1 + TMB$ | (new) | 1.06 |
| $HO_1 + TMB$ | (after three months) | 1.09 |
| 1204b | 4g/l PPO, 50mg/l, POPOP, o-xylene | 1.22 |
| 1204c | 4g/lPPO, 80mg/l, POPOP, o-xylene | 0.96 |
| 1204e | HO-1(1,2,4-trimethylbenzene) | 0.98 |
| 1119d | HO-1(p-xylene) | 0.98 |
| 1119e | 4g/lPPO,100mg/l solute A,o-xylene) | 1.12 |

Table 5: Relative light yield with respect to that of HO-1) measured by EXONO.

can be measured. Pulse height spectra were measured from samples of $HO_1 + TMB$-loaded LS exposed to the alpha (from $^{241}$Am decay) and gamma sources (from $^{60}$Co decay). Defining the $\alpha$:$\beta$ ratio as

$$r = \frac{\alpha(5.5 \text{ MeV})}{\beta(1.06 \text{ MeV})} \quad ,$$

one measured r=0.084, consistent with a previous measurement [J.B. Czirr, NIM 25, 106 (1963)] of r=0.098. However, the absolute light yield deduced from the measurement would be about 1600-5000 photons per MeV for minimum ionising particles, smaller than the range of 10,000 photon per MeV expected for LS, indicating that there still remains room for improvement in the light yield of $HO_1 + TMB$. Table 5 shows the latest measurements of light yields of various LS samples prepared by EXONO relative to that of HO-1.

## 5.4 Pulse Shape Discrimination.

For the vast majority of organic scintillators, the prompt fluorescence (the fast component in the order of a few nano seconds) represents most of the observed scintillation light. A longer-lived component (the slow component in the order of a few hundred nano seconds), also observed in many cases, corresponds to the delayed fluorescence. The fraction of light which appears in the slow component often depends on the dE/dx values and therefore on the nature of the traversing particles. Pulse Shape Discrimination (PSD) technique takes advantage of this dependence to differentiate between particles of different kinds which deposit the same energy in the LS.

The PSD performance is a function of the emission pulse shape (time characteristics) of the LS, and of its light yield and the number of detected photo electrons. Therefore,

| LS | Energy Cut (keV) | Relative Merit |
|---|---|---|
| NE213 | 450 | 2.2 |
| HO-1 | 290 | 1.56 |
| NE213+TMB (0.5% $^{10}$B) | 29 | 1.58 |
| HO-1+TMB (0.5% $^{10}$B) | 29 | 1.25 |

Table 6: Experimental Results from Charge Ratio PDS analysis, showing the relative merit between various LS

the PSD capability of the scintillator to distinguish between the two particle species depends on both the LS intrinsic characteristics as well as on the actual detector design.

An established mehtod for showing the $(\alpha, \gamma)$ separation via PDS involves the comparison of the integrated total charge ($Q_0$) in the anode pulse to the partial charge ($Q_n$) integrated over some fraction of the same pulse. This is a standard technique in low energy nuclear experimental physics for $(n, \gamma)$ separation, and is refined to the point that a commercial NIM module is available. The output pulse of the PMT is divided by an active splitter and sent to a discriminator for logical signal which generates the gates, and to the ADC's after the delay. The delay constant is chosen to be n $\times$ $\delta$t, with $\delta$t = 10 ns, and n = 0,1,2,..10. Figure 3 shows the scattered plot of $Q_0$ versus $Q_{50\ \mathrm{ns}}$ for alpha and gamma activities due to the $^{241}$Am and $^{60}$Co sources, respectively, for $HO_1$ + TMB. The separation into two different bands is obvious. The figure of merit showing the separation of $Q_{50\ \mathrm{ns}}/Q_0$ given a certain energy threshold is shown in Table 6.

**Figure 1** Measured Bulk Attenuation Length of a few selected samples of liquid scintillator as a function of wavelength.

**Figure 2** Comparison of the absorption and emission spectra between PMP and POPOP.

**Figure 3** The measured scattered plot of $Q_{50\ \mathrm{ns}}$ versus $Q_0$, showing clearly the differentiation of signatures due to $\alpha$ and $\gamma$.