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A Pilot Experiment with Reactor Neutrinos in Taiwan

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Abstract

A Collaboration comprising Taiwan and mainland Chinese scientists has been built up since 1996 to pursue a experimental program in neutrino and astro-particle physics in Taiwan. A pilot experiment to be performed at the Nuclear Power Station II in Taiwan is now under intense preparation. It will make use of a 600 kg CsI(Tl) crystal calorimeter to study various neutrino interactions. The feasibility of performing a long baseline reactor neutrino experiment will also be investigated. The conceptual design and the physics to be addressed by the pilot experiment are presented.

1 Introduction

Activities in experimental particle physics started in Taiwan in the late 80's. There is intensive participation in a number of international experiments (L3, CDF, Fermilab E871, Belle, AMS, RHIC-PHOBOS), working on various hardware, online software and data analysis projects. A neutrino group was started in 1996, looking into the possibilities and opportunities in reactor neutrino experiments to be performed in Taiwan [1].

At present, the "TEXONO" [1] Collaboration comprises more than 40 scientists with diversified expertise from Taiwan (Academia Sinica, Institute of Nuclear Energy Research, National Taiwan University, National Tsing Hua University, National Chiayi Teachers' College and Nuclear Power Plant II), mainland China (Institute of High Energy Physics, China Institute of Atomic Energy, Nanjing University, Shandong University, University of Science and Technology at Hefei) and the United States (University of Maryland). It

[1] **T**aiwan **EX**periment **O**n Reactor **N**eutrin**O**.

Table 1: Power Reactor Plants in Taiwan and their Parameters

Plant	Type	No. Cores	Power /core GW	Location	Status
I	Boiling Water	2	1.78	North Shore	Operational
II	Boiling Water	2	2.90	North Shore	Operational
III	Pressurized Water	2	2.78	South Shore	Operational
IV	Advanced Boiling Water	2	4.1	North Shore	Expect 2004

is one of the first collaborative efforts in large-scale basic research among Taiwanese and mainland Chinese scientists.

The principal objectives of the Collaboration are to initiate a program in experimental neutrino physics and astro-particle physics, as well as to build up a qualified experimental team for future projects. The goal is to conduct an international-standard particle physics experiment in Taiwan. A good local research program is complementary to the participation of international projects, and is essential to the solid foundation of international collaborative basic research in the country. A local program can serve as a base for training young students and scientists, and a "launch-pad" for more ambitious project beyond, local or abroad.

Given the above implications and considerations, the field of choice is reactor neutrino. There are operational power reactors in Taiwan with parameters shown in Table 1. The mountainous landscape dotted with mines and tunnels makes the construction of an underground laboratory conceivable. The proximity of the reactor locations and the possible underground sites (Nuclear Power Plants I, II and IV are all about 20-30 km from Taipei city, as shown in Figure 1) to the city infrastructures provides an additional advantage.

The Collaboration has been intensely preparing a "pilot" experiment to be performed at a site of about 30 m from one of the reactor cores at Nuclear Power Station II. The location is shown schematically in Figure 2. Meanwhile, the feasibility and conceptual studies of the "next" project will be pursued. A possible direction can be a long baseline reactor neutrino experiment.

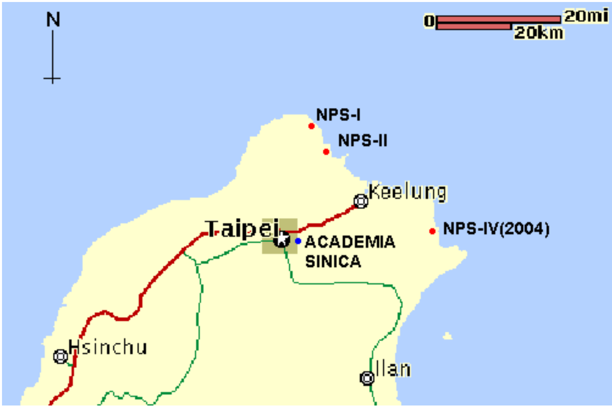

Figure 1: Sketch map of the northern shore of Taiwan, showing the three nuclear power stations and their relative position with Taipei city. The Pilot Experiment will be performed at NPS-II as indicated.

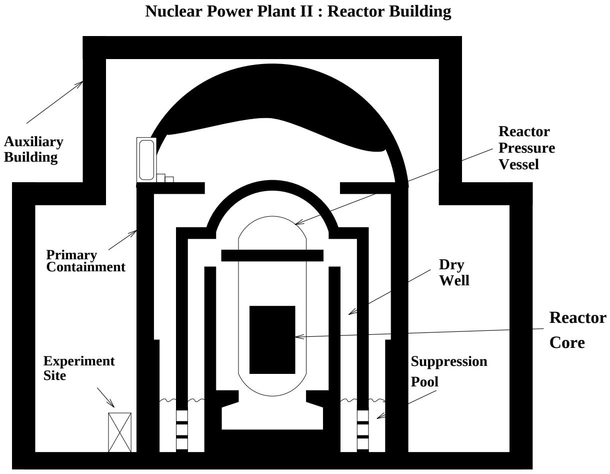

Figure 2: Schematic side view, not drawn to scale, of the NPS-II Reactor Building, indicating the experimental site. The reactor core-detector distance is about 30 m.

2 The Pilot Experiment

2.1 Considerations and Constraints

The most important subject in the field of reactor neutrino physics at present is undoubtedly a long baseline neutrino oscillation experiment [2]. The next generation experiment will have to be at a location of at least O(10 km) from the reactor cores at a depth of at least 500 m of rock underground and with a detector target mass of O(1000 ton). Taiwan does have the geographical advantage to perform such an experiment. However, the magnitude of resources required (in terms of funding, expertise, manpower, time and international credibility) to launch such an experiment is considered to be too large as the first project of a starting group. It would be more appropriate to first pursue a smaller experiment located close to the reactor cores.

Such a "pilot" experiment will be an important learning exercise and team-building efforts for the new Collaboration, preparing ourselves for the more ambitious projects beyond, whatever exactly they may be. In addition, it should have its stand-alone and independent physics motivations, while being the first efforts towards a long-term visions. It is essential that the experiment itself will produce interesting and new physics results, with a detector that can be built, and hence the production of physics output possible, in a relatively short time.

2.2 Physics and Detector Motivations

Almost all previous reactor neutrino experiments were based on liquid scintillator techniques to study the ($\bar{\nu}_e$ p) "Reines" interactions, but with different neutron-capture isotopes. An experiment focusing on gamma detection has never been attempted.

However, gamma-ray spectroscopy has been a standard technique in nuclear sciences (that is, in the investigations of physics at the MeV range). Gamma-lines of characteristic energies give unambiguous information on the presence and transitions of whichever isotopes, allowing a unique interpretation of the physical processes. The experimental difficulties of building a high-quality gamma detector for MeV neutrino physics have been the large target mass required. However, in the past few years, big electro-magnetic calorimeter systems (with mass up to 40 tons of crystals, in the case for the forthcoming B-factories experiments [3]) have been built for high energy physics experiments, using CsI(Tl) crystals with photo-diodes readout.

Properties	CsI(Tl)	NaI(Tl)	BGO	Liquid	Plastic	Glass
Density	4.51	3.67	7.13	0.9	1.0	$\sim$3.5
Relative Light Yield	0.45	1.00	0.15	0.4	0.35	0.15
Radiation Length (cm)	1.85	2.59	1.12	$\sim$45	$\sim$43	4
Emission Peak (nm)	565	410	480	425	425	395
Decay Time (ns)	1000	230	300	2	2	100
Refractive index	1.80	1.85	2.15	1.5	1.6	1.55
Hygroscopic	slightly	yes	no	no	no	no

Table 2: Characteristic properties of the common crystal scintillators and their comparison with typical liquid, plastic and glass scintillators.

The properties of CsI(Tl) crystals, together with those of a few common scintillators, are listed in Table 2. The CsI(Tl) crystal offers certain advantages over the other possibilities. It has relatively high light yield and high photon absorption (or short radiation length). It is mechanically stable and easy to machine, and is only weakly hygroscopic. It emission spectra well matches the response of silicon photo-diode as depicted in Figure 3, thus making a compact design with minimal passive volume and efficient shielding configuration possible.

The CsI-crystal production technology is by now well matured and the cost has been reduced enormously due to the large demands. It become realistic and affordable to build a CsI detector in the range of 1-ton in target mass for a reactor neutrino experiment. The detector mass can be further scaled up if the first experiment would yield interesting results or lead to other potential applications.

Since a crystal calorimeter with improved γ-detection capabilities is a new approach to neutrino experiment, it does offer several physics opportunities with a rather modest investment of cost, manpower and time, well suited for a starting group. It is also technically much simpler to build and to operate than, for instance, gas chambers and liquid scintillators. The background processes for such novel applications are not thoroughly understood. It is a new research domain the experiment will explore and will require state-of-the-art techniques in its control, identification and suppression.

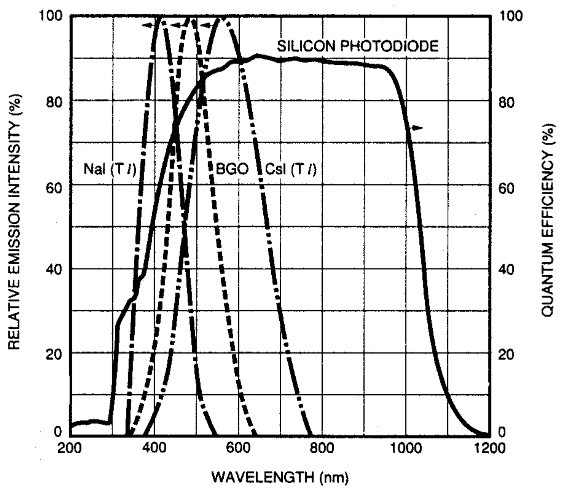

Figure 3: The sensitivities as a function of wavelength for typical silicon photo-diode, and the emission spectra of several common crystal scintillators, showing that CsI(Tl) matches best among them.

2.3 Physics Menu

Previous experiments with reactor neutrinos primarily focused on the ($\bar{\nu_e}$ p) interactions to look for neutrino oscillations [5]. However, the use of low energy (MeV) neutrino as a probe to study particle and nuclear physics has not been well explored - although high energy (GeV) neutrino beams from accelerators have been very productive in investigating electroweak, QCD and structure function physics [4] and have blossomed into a matured field. There are rooms for interesting physics with reactor neutrino experiments along this direction, some of which can be explored by a crystal calorimeter.

2.3.1 Neutrino-Electron Scattering

The cross section for the process

$$\bar{\nu_e} + e^- \rightarrow \bar{\nu_e} + e^-$$

gives information on the electro-weak parameters (g_V, g_A, and $\sin^2\theta_W$), and are sensitive to small neutrino magnetic moments (μ_ν) and the mean square charge radius ($< r^2 >$) [6]. Scatterings of the (ν_e e) and ($\bar{\nu_e}$ e) are two of the most realistic systems where the interference effects between Z and W exchanges can be studied, as shown by the Feynman diagrams in Figure 4.

In an experiment, what can be measured is the recoil energy of the electron (T). The

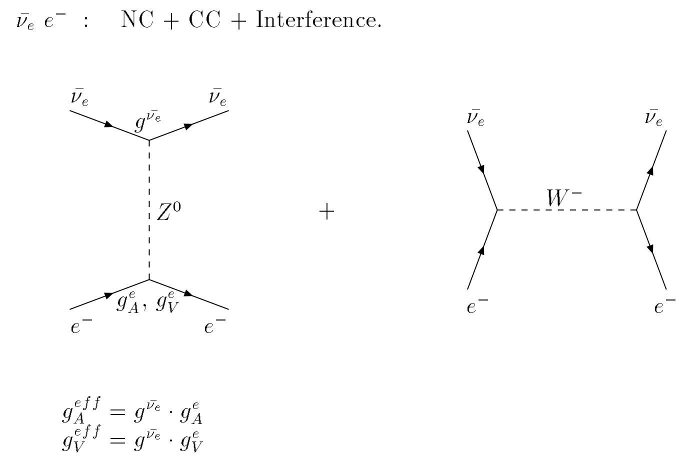

Figure 4: Feynman diagrams for ($\bar{\nu_e}$ e) interaction, showing there exists charged and neutral current components, as well as their interference term.

differential cross section can be expressed as :

$$\begin{aligned}\frac{d\sigma}{dT}(\nu\ e) &= \frac{G_F^2 m_e}{2\pi}[(g_V + x + g_A)^2 + (g_V + x - g_A)^2[1 - \frac{T}{E_\nu}]^2 + (g_A^2 - (g_V + x)^2)\frac{m_e T}{E_\nu^2}] \\ &+ \frac{\pi \alpha_{em}^2 \mu_\nu^2}{m_e^2}[\frac{1 - T/E_\nu}{T}]\end{aligned}$$

where $g_V = 2\ \sin^2\theta_{\rm W} - \frac{1}{2}$ and $g_A = -\frac{1}{2}$ for $\nu_\mu\ e$ and $\nu_\tau\ e$ scatterings where only neutral currents are involved, and

$$x = \frac{2M_W^2}{3} < {\rm r}^2 > \sin^2\theta_{\rm W} \quad \text{for} \quad \nu,$$

while replacing

$$\begin{matrix} g_A \rightarrow -g_A \\ x \rightarrow -x \end{matrix} \quad \text{for} \quad \bar{\nu}\ .$$

For $\nu_e\ e$ scattering, both neutral and charged currents and their interference terms contribute, so that the cross sections can be evaluated by replacing $g_V \rightarrow g_V + 1$ and $g_A \rightarrow g_A + 1$.

The $\rm g_A^e$ Vs. $\rm g_V^e$ parameter space where ($\bar{\nu_{\rm e}}$ e) scatterings are sensitive to is depicted in Figure 5. The complementarity with (ν_μ e, $\bar{\nu_\mu}$ e) can be readily seen. The expected recoil energy spectrum is displayed in Figure 6, showing standard model expectations

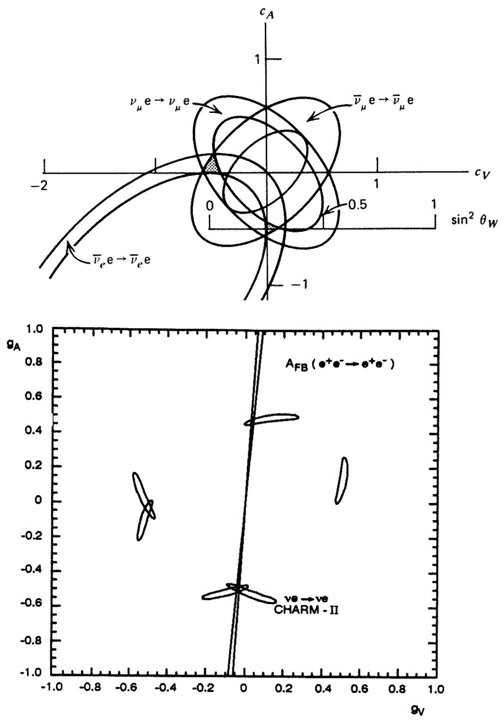

Figure 5: **Top** : Sensitivities of (ν_μ e), ($\bar{\nu_\mu}$ e) and ($\bar{\nu_e}$ e) cross-sections to different regions in the g_A^e-g_V^e parameter space (axes labeled as c_A and c_V), showing their complementarity. **Bottom** : Allowed region of the g_A^e-g_V^e plane from the accelerator (ν e) scattering and the e^+e^- forward-backward symmetry data.

and the case with an anomalous neutrino magnetic moment at the present limit. The μ_ν term have a $\frac{1}{T}$ dependence. Accordingly, experimental searches for the neutrino magnetic moment should focus on the reduction of the threshold (usually background-limited) for the recoil electron energy.

Therefore, investigations of ($\bar{\nu_e}$ e) cross-sections with reactor neutrinos allow one to study electro-weak physics at the MeV range, to probe charged and neutral currents interference, and to look for an anomalous neutrino magnetic moment.

A 600 kg CsI crystal calorimeter will have more target electrons than previous experiments [7] and current projects [8], and thus can potentially improve the sensitivities of these studies. The compact detector size will also allow effective shielding design. The signature for ($\bar{\nu_e}$ e) will be a single hit out of the several hundred channels in the active target configuration. The goal is to achieve a 10% measurement on the cross-section and a physics threshold of 1 MeV to probe neutrino magnetic moment down to 5×10^{-11} μ_B

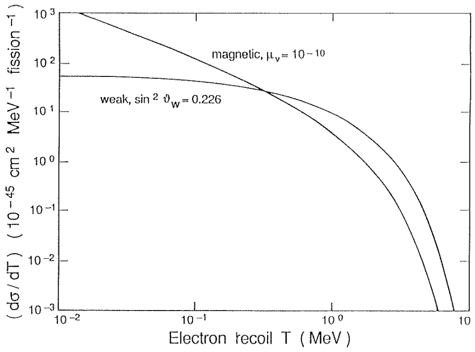

Figure 6: Differential cross section showing the electron recoil energy spectrum in $\bar{\nu_e}$-e scatterings, for of Standard Model processes and for the case with a neutrino magnetic moment of 10^{-10} Bohr magneton, the present experimental limit.

2.3.2 Neutrino Charged and Neutral Currents on Deuteron

The interactions

$$CC : \bar{\nu_e} + d \rightarrow e^+ + n + n$$

and

$$NC : \bar{\nu_e} + d \rightarrow \bar{\nu_e} + p + n$$

have been observed [9], and calculated [10, 11]. Improved measurements will be of interest, especially since the NC reaction is the detection channel adopted by the forthcoming SNO experiment [12] for solar neutrino detection. Measurement of the CC/NC ratio provides a complementary method to search for neutrino oscillations, which is independent of the detailed knowledge of the neutrino source - an interesting possibility for long-baseline experiments which may receive neutrinos from many reactor cores and where the conventional "Reactor ON-OFF" subtraction may not be feasible. The SNO experiment will pursue this CC/NC ratio measurements for solar neutrino, and it would be desirable to have a laboratory experiment exploring the systematics of the technique.

In a realistic experiment, the CsI crystal slabs will be put into a tank with 500 kg of heavy water (D_2O). Neutrons produced will mostly be captured via (n,γ) by ^{133}Cs and ^{127}I. The CC signatures will be rather spectacular: two back-to-back 511 keV γs followed by two separate bursts of high energy γs produced in neutron capture. The NC detection will rely on a single γ-burst.

This is a complementary - and improved - technique to the previous experiments [9] which used ^{3}He proportional counters and were therefore sensitive only to neutrons. Accordingly, the CsI detector, with its γ-detection capabilities, can differentiate the signals from the other neutron-producing background channels :

$$\begin{array}{rclcl} \text{“Reines”} & : & \bar{\nu_e} + p & \rightarrow & e^+ + n \; (\text{Threshold} = 1.80 \text{ MeV}) \;\; \text{and} \\ \gamma \text{ Dissociation} & : & \gamma + d & \rightarrow & p + n \; (\text{Threshold} = 2.23 \text{ MeV}) \; , \end{array}$$

and can prevent the CC events with one undetected neutron from contaminating the NC sample. The goals are to achieve 5% and 10% measurements for $\bar{\nu_e}$d-CC and $\bar{\nu_e}$d-NC, respectively.

2.3.3 Neutral Current Excitation on ^{10}B and ^{11}B

If a compact boron-rich object like B_4C (natural boron consists of 20% ^{10}B and 80% ^{11}B) is used as the passive target, characteristic γ-lines (3.59, 5.16 MeV for ^{10}B, and 2.11, 4.45, 5.02 MeV for ^{11}B) will be emitted by the excited daughter nuclei following the NC interactions :

$$\bar{\nu_e} + {}^{10}\text{B} \rightarrow \bar{\nu_e} + {}^{10}\text{B}^*$$

and

$$\bar{\nu_e} + {}^{11}\text{B} \rightarrow \bar{\nu_e} + {}^{11}\text{B}^* \; .$$

There are theoretical works [10, 13] suggesting that these cross sections are sensitive to the axial isoscalar component of NC interactions and the strange quark content of the nucleon. Therefore, νN NC scattering may provide a complementary approach to the investigations of nucleon structure physics comparing to the eN scattering systems. The ν_e NC interaction on ^{11}B has been considered as the detection mechanism in the BOREX solar neutrino proposal [14].

A realistic experiment will consist of about 500 kg of B_4C, either in plate or powder form, inserted into a chamber with CsI crystals at optimized positions. The experimental signature will be gamma-lines of the characteristic energies which show up during reactor ON period.

If a CsI calorimeter proves itself to be optimal for studying NC excitations on nuclei [10, 13], where the experimental signatures are the characteristic γ-lines, one can insert other passive materials to measure their cross sections, and turns the experiment into a longer-term program.

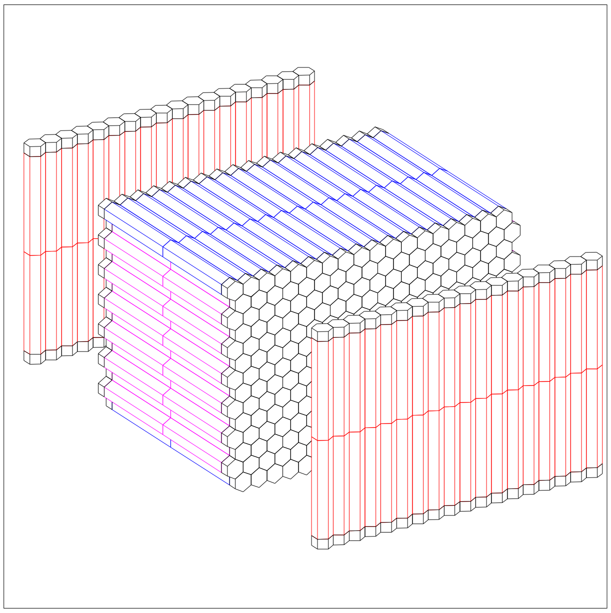

Figure 7: Schematic layout of the CsI(Tl) target in the "active target" configuration, consisting of about 600 crystals, each of which is hexagonal in shape with 2 cm sides, 20 cm length and 1 kg mass.

2.4 Highlights of Experimental Details

Among the various physics items mentioned above, the first to be pursued will be that of neutrino-electron scattering, using the "active target" configuration shown schematically in Figure 7. The detector will consist of about 600 kg of CsI(Tl) crystals. Individual crystal is 1 kg in mass and hexagonal in shape with 2 cm sides and 20 cm length. Each channel is read out by a photo-diode, followed by pre-amplifier, main amplifier and shaper. The entire pulse is digitized by a FADC to be read out with a data acquisition system adopting the VME-bus.

The achieved energy resolution with a prototype module is about 16% FWHM at 660 keV. It is electronic noise-limited and hence improves linearly with energy. Pulse shape discrimination between γ/e and α events, as well as those originated from the photodiodes, can be achieved to better than the 99% level.

The CsI target will be shielded by lead, boron-loaded polyethylene and copper, as depicted in Figure 8. Cosmics will be vetoed by an outermost layer of plastic scintillators. The outer modules of the CsI target can be used as active veto if necessary. The whole inner target will be placed in a dry nitrogen environment to purge the radon gas, and will

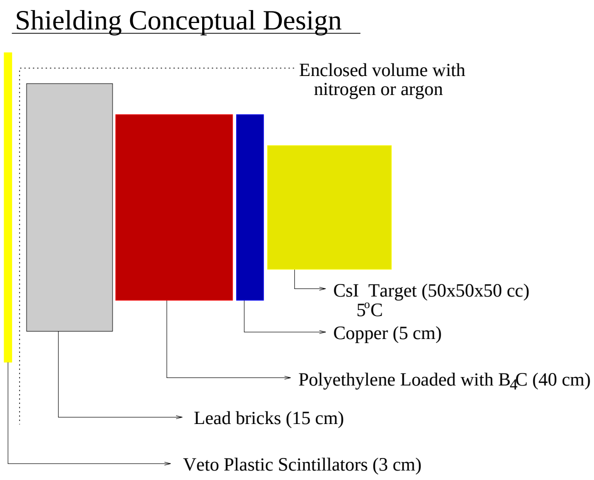

Figure 8: Schematic layout of the target and shielding. The coverage is 4π but only one face is shown.

be kept at 5°C to reduce electronic noise.

The intrinsic radiopurity level of the CsI(Tl) crystal is very crucial to the sensitivities of this experiment, as well as to the future potential applications in low background physics. By the absence of α-peaks above 3 MeV in a measurement using a 3 kg crystal in an underground site, previous work [15] have derived that CsI crystals can be grown to a purity level such that the concentrations of ^{238}U and ^{232}Th are less than the 10^{-12} g/g level.

A detailed technical report is now under preparation. We hope to have a first version of the experiment operational on site by spring 1999.

3 Outlook

A Taiwan and mainland China collaboration has been built up to initiate and pursue a program in experimental neutrino physics and astro-particle physics in Taiwan. A "pilot" experiment to be performed close to the reactor core using CsI(Tl) as detector is now being prepared. Various neutrino interactions at the MeV energy range can be investigated. The feasibility and conceptual studies of the "next" project is under way. A distinct possibility can be a long baseline reactor neutrino experiment.

This is a pioneering "foundation" effort for Taiwan, as well as the first generation collaborative efforts in large-scale basic research between scientists from Taiwan and mainland China. The importance of the outcomes of this experiment and this experience will lie besides, if not beyond, neutrino physics.

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