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# A Pilot Experiment With Reactor Neutrino in Taiwan : A Status Report submitted to the National Science Council

Prepared by

the Academia Sinica

on behalf of

the TEXONO Collaboration

**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. This report summarizes our status, plans and visions, and serves as a supporting document to our request to the National Science Council funding for the 1998-99 financial year.

# A Pilot Experiment With Reactor Neutrino in Taiwan

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# 1 Neutrino Project in Taiwan

## 1.1 History

In 1996, under the initiation of the Academia Sinica, a Collaboration was built up to pursue the goal of performing a world-standard particle physics experiment in Taiwan. A proposal [1] of doing a pilot experiment with the power reactor was submitted and subsequently approved by the National Science Council under the contracts NSC 86-2811-M-001-001R- and NSC 87-2112-M-001-034.

The principal objectives of the Neutrino Collaboration are to initiate a program in experimental neutrino physics and astro-particle physics in Taiwan, as well as to build up a qualified experimental team for future projects. A good local research program is complementary to the participation of international projects elsewhere, and is essential to the solid foundation of international collaborative basic research in the country. As the field grows and matures, the community has to acquire the experience of conceiving, formulating, fighting for, and then implementing and coordinating a big project (that is, the experience of being responsible to "generate an experiment and make it work" in its totality). A local program also serves as a base for training young students and scientists, as well as promoting the discipline of large-scale basic research to the public.

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 to the city infrastructures and comfort provides an additional advantage (Nuclear Power Plants I, II and IV are all about 20-30 km from Taipei city, as shown in Figure 1). Since the project is started afresh, there are more flexibilities to optimize the various parameters like the reactor-detector distance and the detector target mass to the specific physics we would like to address.

The immediate research efforts are to perform a pilot experiment at the nuclear power reactor in Taiwan. On a longer time-frame, the Collaboration will conduct a feasibility study on an ultimate full scale long baseline neutrino oscillation experiment using the reactor neutrinos.

## 1.2 The Neutrino Collaboration

The Neutrino Collaboration (TEXONO) has been growing steadily since its foundation. Our plans and visions have been well received by local students and scientists. Students find our program attractive since it can be done at home and they can have more thorough and balanced exposure to the wide spectrum of techniques deployed in a big modern particle physics experiment. Local scientists, especially those from the existing nuclear physics and nuclear engineering community, appreciate the inter-disciplinary approach of the Project. They contribute tremendously with their expertise and infrastructures, while finding the new ingredients (for instance, large-scale detector systems, modern electronics applications, modern software practices, collaboration in a big and diversified group ... etc.) beneficial to their own research program. In a positive sense, the Neutrino Project serves as a means where Taiwan can build up an experimental high energy/particle physics foundation based on the existing nuclear physics experience and resources, while the nuclear scientists can be exposed to the the technical and organizational sophistications on how to conduct big international collaborative research efforts thereby enhancing the vigour of their program. Students and young scientists being trained in the process would eventually contribute further to both fields as their careers proceed.

By early 1998, there are more than 40 collaborators with the diversified expertise, as shown in Table 2, from Taiwan, mainland China and the United States. Besides being the first "high-energy-physics-style" experiment to be performed in Taiwan where local scientists are taking the major and defining role, this is also one of the first collaborative efforts in basic research among Taiwanese and mainland Chinese physicists. Tremendous pioneering spirits are involved in launching and realizing such an experiment. Our efforts are not only about "doing basic science", and also about the "foundation" and "development" of it.

Internationally, critical comments and reviews on our plans have been seriously solicited from the world-leaders in the field. 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. We have been invited to present reports on "The Starting-Up of a Neutrino Project in Taiwan" [2] in three international meetings in 1997 [3] while another one is already scheduled in 1998 [4]. In particular, our well-received talk at the "Weak Interaction Conference 1997" was scheduled alongside with the most discussed-of future projects and most active researchers in the field (see Figure 2 for the program and speakers). This can serve as a testimonial of international attention and interests on our efforts.

## 1.3 Starting Considerations

With the goal of performing a world-class particle physics experiment in Taiwan, a valid and perhaps natural choice is to pursue experiments with reactor neutrinos. There are world-standard and operational nuclear power reactors in Taiwan which provide an intense flux of electron anti-neutrinos ($\bar{\nu_e}$). The Taiwan Power Company has officially approved the availability of sites, the access to reactor raw data and the provision of technical support at the Nuclear Power Plant II at Kuo-Sheng.

Reactor neutrino experiments have been carried out many years world-wide [5]. In fact, neutrino was first observed by Reines and Cowan in 1956 using reactor neutrinos [6]. The central topics in reactor neutrino physics has been the search for neutrino oscillation. A list of previous and current reactor neutrino oscillation experiments [7] is given in Table 3. These experiments all made use of the "Reines" reaction :

$$\bar{\nu_{\rm e}} \ + \ {\rm p} \ \rightarrow \ {\rm e}^{+} \ + \ {\rm n}$$

followed by the delayed capture of the neutron, as its detection mechanism. Almost all experiments used liquid scintillator to provide an active proton-rich target. They differed in their selected means of neutron capture : $^{3}$He proportional counters for Gösgen, lithium-loaded liquid scintillator for Bugey, and gadolinium-loaded liquid scintillator for Rovno, Savannah River, Chooz and Palo Verde. After almost twenty years of efforts and two generations of experiments, the reactor neutrino spectrum is now measured [8] and consistent with theoretical calculations to better than a few % [9]. The best sensitivity in oscillation parameters achieved to date is from Chooz [10], a 5-ton fiducial mass detector at a distance of 1 km from the cores, which has excluded the $\Delta{\rm m}^2 > 10^{-3}$ eV$^2$ region.

The most important and glamourous subject of the field of reactor neutrino physics is undoubtedly a long baseline neutrino oscillation experiment. 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 more than 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. (That is, its worth should be in the physics achieve-able by itself but not solely in what we may or may not do as the next step.) It is essential that the experiment itself will likely to 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.

There is little or no physics along the line of neutrino oscillation that can still be achieved with an experiment close to the reactor cores. A new experiment on neutrino oscillation is still worthwhile only if a new and improved detector technology is deployed. This has been our initial "line-of-attack" where the goal is to develop large-scale liquid scintillator loaded with boron. These efforts are discussed in Section 2.

Meanwhile, a host of other physics topics involving reactor neutrinos remain valid and well-motivated. Some of these topics can be addressed by a crystal calorimeter experiment which is both resource-wise affordable and technically manage-able for our new Collaboration. This experiment is discussed in Section 3.

# 2 R&D Efforts on Liquid Scintillator

The Collaboration started off with an R&D project on liquid scintillator. The goal is to measure the well-studied reactor neutrino spectrum using a new liquid scintillator technique. The task will be to develop large-scale ($> 1$ m in the initial phase) detector system of liquid scintillator loaded with $^{10}$B, and with pulse-shape discrimination (PSD) ($\alpha/\gamma$ separation) capabilities.

Electron anti-neutrinos from the reactor interact with proton from the liquid scintillator via the standard reaction :

$$\bar{\nu_e} + \mathrm{p} \rightarrow \mathrm{e}^+ + \mathrm{n} \quad .$$

The emitted neutron will be thermalized and captured by $^{10}$B with a typical delay of less than a few $\mu$s :

$$\mathrm{n} + {}^{10}\mathrm{B} \rightarrow {}^{7}\mathrm{Li}^* + \alpha \quad (\mathrm{Q} = 2.3 \ \mathrm{MeV})$$

$$^{7}\mathrm{Li}^* \rightarrow {}^{7}\mathrm{Li} + \gamma \quad (\mathrm{E}_\gamma = 480 \ \mathrm{keV}).$$

The large cross section ($\sigma \sim 4000$ barn) and high isotopic abundance (20%) makes $^{10}$B an interesting isotope to provide thermal neutron capture. In particular, liquid scintillator can be produced with a concentration up to the range of 1% $^{10}$B by weight (or up to 5%

$^{10}$B if the isotopic abundance is further enriched). Indeed, though expensive, commercial liquid scintillator with enriched-$^{10}$B loading [11] does exist. This leads to a much shorter capture time (a few $\mu$s) with >99% capture efficiency compared to other good isotopes adopted in previous and current reactor neutrino experiments where the capture time is of the range of 30-100 $\mu$s: $^{3}$He in Goesgen (inhomogeneous detector), $^{6}$Li in Bugey (0.1% by weight), and $^{157}$Gd in Chooz and Palo Verde (0.1% by weight). The capture time in unloaded liquid scintillation is typically 180 $\mu$s. The capture time distribution for neutrons with an initial energy of 0.5 keV in a liquid scintillation with different amount of $^{10}$B by weight, based on a full neutron transport simulation [12], is depicted in Figure 3, showing a mean capture time of 2.3 $\mu$s for a $^{10}$B concentration of 1%.

Modest success have been achieved and the liquid scintillator developed (a pseudocumene + trimethyl-borate (TMB) based solution) has similar performance in terms of light yield, attenuation length and PSD capabilities as the commercial product [11], whereas the cost is much reduced. Their comparisons are shown in Table 4.

In the course of our R&D efforts, however, we come across several technical problems which may make a large-scale (tonnes) deployment of such a liquid scintillator difficult and impractical.

- The "electron-equivalence" energy of the neutron capture by $^{10}$B is only about 50 keV, making PSD at such a low light yield extremely difficult, even more so for large systems. The background at such a low energy is also a major concern.
- The chemical TMB is extremely hygroscopic. On exposure to air, it turns into boric acid (a white powder) immediately, and severely degrade the light attenuation length. This will make large-scale handling difficulty or at best, messy and complicated.

Nevertheless, we manage to develop a boron-loaded liquid scintillator which gives PSD at the neutron capture energy of 50 keV, a technical achievement in its own right. The measured energy spectrum and the PSD separation on n/$\gamma$ are depicted in Figure 4 and Figure 5, respectively. This is at the expense of the addition of a large quantity of wavelength-shifter, which also affects the attenuation length of the liquid. Optimization between light transmission and the PSD capabilities is currently underway.

A technical paper on our liquid scintillator R&D efforts is now under preparation for publication.

# 3 A Crystal Calorimeter for Reactor Neutrinos

## 3.1 Motivations

Almost all previous reactor neutrino experiments were based on liquid scintillator techniques to study the ($\bar{\nu}_e$ p) interactions, but with different neutron-capture isotopes. An experiment capable of high-quality 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 system (with mass up to 40 tons of crystals, in the case for the forthcoming B-factories experiments [13]) have been built for high energy physics experiments, using CsI(Tl) crystals with photo-diodes readout.

The CsI-crystal production technology is by now well matured and the cost has been reduced enormously due to these 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.

Since a precision gamma-detection with a crystal calorimeter is a new approach to neutrino experiment, it does offer a wide spectrum of physics (and thesis!) 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.

One can envisage using the CsI crystals both as "active target" and as a gamma detector where passive target materials are inserted in between, shown schematically in Figure 6 and Figure 7, respectively.

## 3.2 Physics Menu

In this section, we discuss the various physics items which can be potentially addressed by a 500 kg-CsI detector.

Previous experiments with reactor neutrinos primarily focused on the ($\bar{\nu}_e$ p) interactions to look for neutrino oscillations. 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 [14] and have blossomed into a matured field. There are rooms for interesting physics with reactor neutrino experiments along this direction.

### 3.2.1 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 ($\mu_\nu$) and the mean square charge radius ($< r^2 >$) [15]. Scatterings of the ($\nu_e$ 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 8.

In an experiment, what can be measured is the recoil energy of the electron (T), the differential cross section can be expressed as :

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

where

$$g_V \ = \ \begin{cases} 2\ \sin^2\theta_W + \frac{1}{2} & \text{for} \ \ \nu_e \\ 2\ \sin^2\theta_W - \frac{1}{2} & \text{for} \ \ \nu_\mu \ , \ \nu_\tau \end{cases} ,$$

$$g_A \ = \ \begin{cases} \frac{1}{2} & \text{for} \ \ \nu_e \\ -\frac{1}{2} & \text{for} \ \ \nu_\mu \ , \ \nu_\tau \end{cases} ,$$

and

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

while replacing

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

The $g_A$ Vs. $g_V$ parameter space where ($\bar{\nu_e}$ e) scatterings are sensitive to is depicted in Figure 9. The complementarity with ($\nu_\mu$ e, $\bar{\nu_\mu}$ e) can be readily seen. The expected recoil energy spectrum is displayed in Figure 10, showing standard model expectations and the case with an anomalous neutrino magnetic moment at the present limit. The $\mu_\nu$ 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 (measurement of $\sin^2\theta_W$) at the MeV range, to test electron-muon universality (that is, whether ($\bar{\nu_e}$ e) can be described by the same $g_{V/A}$ as ($\nu_\mu$ e) and ($\bar{\nu_\mu}$ e)), and to look for an anomalous neutrino magnetic moment if one can reduce background at low (less than 1 MeV) energy.

A 500 kg CsI crystal calorimeter will have more target electrons than previous experiments [16], and thus can potentially improve the sensitivities of these studies. The signature for ($\bar{\nu_e}$ e) will be a single hit out of the several hundred channels in the active target configuration.

### 3.2.2 Neutrino Charged and Neutral Currents on $^{127}$I and $^{133}$Cs

Neutrino interactions on nuclei have not been studied experimentally beyond a few light ones ($^1$H, $^2$H, $^{12}$C). The charged-current (CC) interactions

$$\bar{\nu_e} \ + \ ^{127}\mathrm{I} \ (^{133}\mathrm{Cs}) \ \rightarrow \ e^+ \ + \ ^{127}\mathrm{Te}^* \ (^{133}\mathrm{Xe}^*)$$

have signatures of 2 back-to-back 511 keV $\gamma$s from the positron annihilation, plus the characteristic $\gamma$-lines from the daughter nuclei, while the neutral current (NC) interactions

$$\bar{\nu_e} \ + \ ^{127}\mathrm{I} \ (^{133}\mathrm{Cs}) \ \rightarrow \ \bar{\nu_e} \ + \ ^{127}\mathrm{I}^* \ (^{133}\mathrm{Cs}^*)$$

will have the characteristic $\gamma$-lines as signatures. Investigations of these interactions will provide important input to the considerations of future deployment of even larger scale CsI-calorimeter as neutrino detectors. The isotope $^{127}$I has been proposed as a target material to study solar neutrinos [17].

There is no theoretical calculations on the cross sections of the CC and NC cross-sections mentioned above. The Collaboration will co-ordinate with the Taiwanese and mainland Chinese theorists to pursue such calculations. Conventional expectations, however, would suggest that the CC is suppressed since the parent nuclei $^{133}$Cs and $^{127}$I are both neutron-rich, so that the conversion to $^{133}$Xe and $^{127}$Te, respectively, will be "Pauli-blocked". Nevertheless, the physics analysis is an essentially free by-product from the active target data taking where the major focus will be on $\bar{\nu_e}$ e scatterings. Their investigations will still be worthwhile.

### 3.2.3 Neutrino Charged and Neutral Currents on Deuteron

The interactions

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

and

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

have been observed [18], and there are already theoretical work studying them [19, 20]. Improved measurements will be of interest, especially since the NC reaction is the detection channel adopted by the forthcoming SNO experiment [21] 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. The SNO experiment will pursue this CC/NC ratio measurements for solar neutrino, and it would be desirable to have a laboratory experiment demonstrating the validity of the technique.

In a realistic experiment, the CsI crystal slabs will be put into a tank with 500 kg of heavy water ($D_2O$) with good neutron capture isotopes (like gadolinium or cadmium) either as dissolved salts or as inserted sheets. The CC signatures will be rather spectacular: back-to-back 511 keV $\gamma$s followed by two separate bursts of high energy $\gamma$s produced in neutron capture by Gd or Cd. The NC detection will rely on a single $\gamma$-burst.

### 3.2.4 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 $\gamma$-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 :

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

and

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

There are theoretical works [19, 22] suggesting that these cross sections [23] are sensitive to the axial isoscalar component of NC interactions and the strange quark content of the nucleon. Therefore, $\nu$N NC scattering may provide a complementary approach to the investigations of nucleon structure physics comparing to the eN scattering systems.

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.

#### 3.2.5 NC Excitation on Other Nuclei

If a CsI calorimeter proves itself to be optimal for studying NC excitations on nuclei [19, 22], where the experimental signatures are the characteristic $\gamma$-lines, one can insert other passive materials to measure their cross sections, and turns the experiment into a longer-term program. Theoretical efforts in evaluating these cross-sections can be organized to complement the experimental program to "cover the field".

### 3.3 Experimental Details

A complete Technical Report is under preparation by the Collaboration. It will contain all the technical details we know about the CsI experiment : neutrino source, prototype CsI(Tl) modules and photo-diode readout, mechanical design of the target assembly, electronics, trigger, data acquisition system, calibration and monitoring system, shielding designs, software organization, data analysis, as well as background discussions and sensitivities estimates.

The reported is expected by April 1998, and copies will be forwarded to the National Science Council as further supporting documents.

## 4 Organization and Task Sharing

One of the important motivations of performing the CsI experiment is to acquire the experience of conceiving, formulating, and then constructing and executing a modern complex high-energy-physics style experiment in its completeness. The successful design, construction and operation of the CsI experiment requires the efficient coordination and the coherent involvement of expertise from many diversified fields : particle physics, nuclear physics, nuclear engineering, low background techniques, mechanical engineering design, modern electronics design, data acquisition systems, modern software packages and large-scale computation in simulations and analysis. In addition, communications and working experience with certain key industrial manufacturers will be established.

Collaboration meetings are held once every three months, the venues alternating between Taiwan and mainland China, to review the progress status, to identify areas of focus and to define the next immediate goals. Regional co-ordination are under the responsibilities of Academia Sinica (for Taiwan groups), Institute of High Energy Physics, Beijing (for mainland Chinese groups), and University of Maryland (for U.S. participation). Adminstrative and financial issues are discussed among the "Collaboration Board" made up of one representative per institute.

The regional co-ordinators follow closely the progress and ensure efficient task distributions among the groups. A internal newsletter is prepared once a month to review the status and is broadcast to all members via the Internet. Web-sites [2] are set up both in Taiwan and in the mainland to centralize and store all relevant information on the experiment, and to ensure their easy access by all members of the Collaboration.

The principal tasks among the groups are summarized in Table 5. The task sharing between the collaborating institutes follow the experience and interest among them.

# 5 Estimated Budget and Schedule

The estimated budget required for the CsI experiment is rather modest in the typical high energy physics scale. The breakup of the major items are listed in Table 6. The estimate does not include travels, personnel and labour expenses and operational cost. Assuming that a loan arrangement for the heavy water will be realized, we hope to be able perform the experiment with a 1 MUSD budget ceiling.

By the end of 1997, we have secured about 400k USD funding from the National Science Council, Taiwan and from the Institute of Physics at the Academia Sinica. Further request for support will be submitted to other possible channels, such as the Atomic Energy Agency and the Taiwan Power Company in Taiwan as well as the various funding agencies in mainland China and the United States.

[2] Home Page in Taiwan - http://hep3.phys.sinica.edu.tw/EXONO/index.html

The schedule we hope to be able to achieve is shown in Figure 11. By the end of 1997, the conception and formulation of the project is mostly completed. We are heavily involved in the optimization of the prototype module and its readout, the understanding and measurements of the potential background sources, as well as the engineering design of the mechanics, electronics, data acquisition and software systems. The first running version, with about 100 kg of crystal, is expected be operation by the end of 1998 and the whole detector completed by Spring 1999. When the construction and installation of the experiment have reached a certain matured and steady state, first physics and conceptual studies on the next project will be initiated.

# 6 Request to the National Science Council

We request the continuing support of the National Science Council on the Reactor Neutrino Pilot Experiment. The detailed funding request is listed in the accompanying application forms.

The project has evolved from the R&D and preparation phase to the full-scale construction phase in 1998. Support in the personnel expenses (both as research assistant and postdoc positions, as well as labour cost in construction and installation) will be particularly crucial.

Our purchasing power have also been adversely affected by the recent changes in exchange rates. Further funding support to enhance our equipment and raw material budget will ensure the efficient construction of the experiment.

# 7 Conclusion

The experimental investigation of neutrino physics and astrophysics is an exciting and active field, and remains a major experimental challenge in fundamental research, the outcome of which will have significant impact in particle physics, astrophysics and cosmology [24]. A wide spectrum of pioneering techniques have been devised and deployed, and there are much room for surprises in their outcomes. There may be some "hints" that new physics may be round the corner in this sector, based on the anomalous results in solar, atmospheric and accelerator neutrinos. The present generation of experiments will put these "hints" to further scrutiny, and will define the future landscape of the field [25].

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.

A collaboration comprising physicists from Taiwan, mainland China and the United States have been built up to perform a pilot, yet independent, experiment at Nuclear Power Plant II in Taiwan, the first step towards this goal.

We are constructing a CsI crystal detector to study reactor neutrino interactions close to the cores of NP2. A high-performance gamma-detector for neutrino physics is new and may bring along many physics opportunities. It is technically manage-able and resource-wise afford-able for our Collaboration as a new group.

Besides having the potentials of addressing a wide spectrum of physics topics, this "experiment" and "experience" will equip us with the necessary techniques in the field and will help us to build up a qualified team to make major contributions in the more ambitious future projects at the international arena. Both the science as well as the collaborative method of pursuing it are new to Taiwan. In addition to being a pioneering effort on the development of large-scale basic research in Taiwan, it is also one of the first collaborative efforts among scientists on both sides of the Taiwan Strait. The importance of the outcomes of such an "experiment" will lie beside, if not beyond, neutrino physics.

# 8 Appendix

Enclosed with this article are our publications in 1997 : (a) Ref. [2] on "The Starting-Up of a Neutrino Project in Taiwan" published in two international conference proceedings and (b) Ref. [24] on "Neutrino Physics : An Overview" (in Chinese), published in "Natural Sciences Newsletter" and "Physics Bi-Monthly Magazine".

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| Plant | Type | No. Cores | Power/core (GW) | Location | Status |
|---|---|---|---|---|---|
| I | Boiling Water | 2 | 1.78 | Northern Shore | Operational |
| II | Boiling Water | 2 | 2.90 | Northern Shore | Operational |
| III | Pressurized Water | 2 | 2.78 | Southern Shore | Operational |
| IV | Advanced Boiling Water | 2 | 4.1 | Northern Shore | Compl. 2004 |

Table 1: Power Reactor Plants in Taiwan and their Parameters. The Pilot Experiment will be performed at a distance of 30 m from the core in Nuclear Power Plant II.

| **Institutes** | **Experience and Expertise** |
|---|---|
| **<u>Taiwan</u> :** | |
| Academia Sinica | High Energy Physics, Particle Physics, Nuclear Physics |
| Institute of Nuclear Energy Research | Nuclear Physics and Engineering, Mechanical Engineering |
| National Central University | Theory Support |
| National Chiayi Teachers' College | - |
| National Taiwan University | Chemistry, Particle Physics |
| National Tsing Hua University | Nuclear Engineering, Health Physics Atomic Science |
| Nuclear Power Plant II | Nuclear Engineering, Site Provision |
| **<u>China</u> :** | |
| China Institute of Atomic Energy, Beijing | Nuclear Physics |
| Institute of High Energy Physics, Beijing | High Energy Physics |
| Nanjing University | High Energy Physics |
| Shandong University | Particle Physics, Cosmic Ray Physics |
| University of Science and Technology, Hefei | Electronics |
| **<u>U.S.A.</u> :** | |
| University of Maryland | High Energy Physics |

Table 2: Collaborating institutes in the Neutrino Project as of November 1997, and their areas of experience and expertise.

| Experiment | Neutron Capture Isotopes | Target Mass | Distance from Core (max.) | $\Delta m^2$ (90% CL) (min.) | Status |
|---|---|---|---|---|---|
| Gösgen | $^3$He | 320 kg | 65 m | 0.019 | completed 1986 |
| Rovno | Gd | 190 kg | 25 m | 0.05 | completed 1988 |
| Krasnoyarsk† | $^3$He | 458 kg | 231 m | 0.008 | completed 1994 |
| Bugey | $^6$Li | 555 kg | 95 m | 0.01 | completed 1995 |
| Savannah River | Gd | 250 kg | 24 m | 0.1 | completed 1996 |
| Chooz | Gd | 5 ton | 1 km | 0.0009 | first results 1997, continuing |
| Palo Verde | Gd | 12 ton | 750 m | - | in preparation |

† All experiments except the Krasnoyarsk detector adopted liquid scintillator as a proton-rich active target. The Krasnoyarsk experiment used polyethylene as passive target.

Table 3: A summary of all previous and current reactor neutrino oscillation experiments

| | Commercial [11] | Homemade |
|---|---|---|
| Mean attenuation length | 4 m | 3.2 m |
| Relative light yield | 1.00 | 1.06 |
| PSD (relative figure of merit) ¶ | 0.9 | 1.0 |
| % $^{10}$B by weight | 4.4% (90% enriched) | 0.4% (natural) |
| Cost | USD 4600 /l | USD 60 /l |

¶ On $\alpha$'s from $^{241}$Am.

Table 4: Comparison between the Commercial and Homemade Liquid Scintillator

| **Institutes** | **Tasks and Responsibilities** |
|---|---|
| AS | Overall coordination, physics, photo-diode readout,<br>shielding designs, electronics design and construction,<br>data acquistion system, software coordination, simulations,<br>R&D on liquid scintillator. |
| INER | Shielding design and construction,<br>mechanics and workshop facilities,<br>trace radiopurity measurements (neutron activation),<br>construction of $B_4C$ plates from powder<br>with the plasma combustion technique,<br>provision or raw materials. |
| NCU | Theory support and coordination<br>on the calculations of neutrino cross sections. |
| NCTC | Student participation, simulations,<br>electronics tests and assembling. |
| NTU | Student participation,<br>R&D project on liquid scintillator. |
| NTHU | Nuclear engineering, neutron transport calculation,<br>radioactivity measurements,<br>trace radiopurity measurements (germanium detectors). |
| NP2 | Site provision, provision of shielding materials,<br>installation logistics, mechanics workshop. |
| CIAE | Mechanics and workshop,<br>trace radiopurity measurements (accelerated mass spectroscopy). |
| IHEP | Physics, CsI production and quality monitor,<br>tests and measurements of prototypes,<br>inner detector engineering design,<br>electronics design and construction,<br>simulations, R&D on liquid scintillators. |
| Nanjing | Shieldings design and construction. |
| Shandong | Simulations. |
| Hefei | Electronics design and production. |
| UMD | Simulations, provision of plastic scintillators. |

Table 5: Major items in the task sharing among the collaborating institutes. Many groups will participate in the physics and data analysis.

| **Items** | **Amount** | **Unit Price/USD** | **Cost/kUSD** |
|---|---|---|---|
| CsI(Tl) Crystal | 700X200 cc | 2.3 | 322 |
| Photo-Diodes | 700 pieces | 100 | 70 |
| Electronics Components | 700 channels | 100 | 70 |
| DAQ+Computers | | | 70 |
| Power Supplies, Cables ... | | | 30 |
| $B_4C$ powder | 500 kg | 20 | 10 |
| Polyethylene | 3 tons | | 10 |
| Lead Shielding | 30 tons | | 30 |
| Plastic Scintillator | | | On Loan |
| Iron Shielding | | | On Loan |
| Heavy Water | | | Loan Expected |
| **Total** | | | 612 |
| Contingency 20% | | | 122 |
| Seed Funds for R&D | | | 50 |
| **Grand Total** | | | 784 |

Table 6: An estimate of the budget for the CsI(Tl) equipment experiment. The figures do not include positions, labour cost and travels.

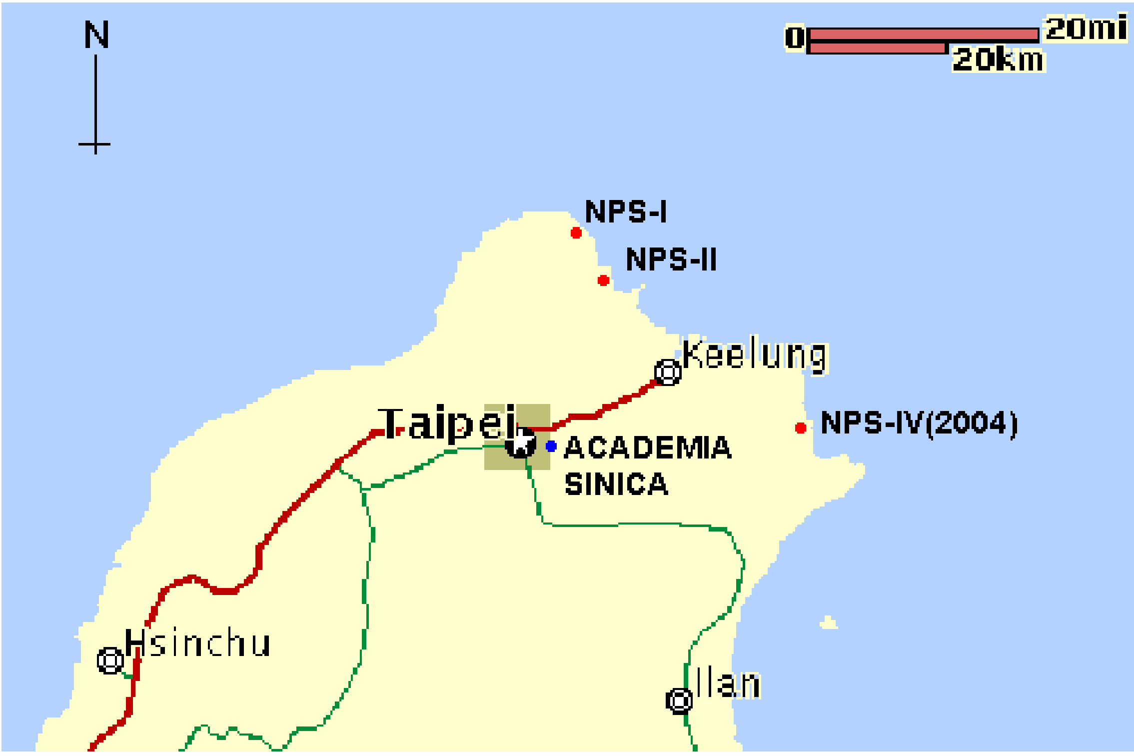


Figure 1: Sketch map of the northern shore of Taiwan, showing the three nuclear power stations and their relative position with Taipei city. The Pilot Experiment will be performed at NPS-II as indicated.

# Neutrino Oscillation:
**WORKING GROUP AGENDA :**

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**Friday 27th June | 9:00 - 12:30 MORNING SESSION**

**All times include 5 minute for questions unless otherwise indicated.**

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**Future Experiments**

| Talk # | Title | Speaker | Time |
|---|---|---|---|
| 1. | KEK to Super-Kamiokande | C.K. Jung | 20 |
| 2. | Start-up of a Neutrino Project in Taiwan | H. Wong | 15 |
| 3. | Progress of COSMOS | W. Reay | 20 |
| 4. | TOSCA - A Short Baseline Experiment at CERN | J.J. Gomez-Cadenas | 20 |
| 5. | BOONE at the MI Booster | G.Mills | 15 |
| 6. | OPERA - An Emulsion Long Baseline Experiment | A. Ereditato | 20 |
| 7. | NOE - A Long Baseline Neutrino Oscillation Experiment | E. Scapparone | 15 |
| 8. | The Status of MINOS | D. Michael | 20 |
| 9. | ICARUS | C. Rubbia | 20 |
| 10 | Neutrino beams at CERN and Fermilab | V. Palladino | 15 |
| 11. | Plans for Neutrino Experiments at CERN and FNAL: discussion | G. Rameika | 20 |

Figure 2: Program for the “Weak Interaction 1997” Conference, where the Taiwan Neutrino Project was reported.

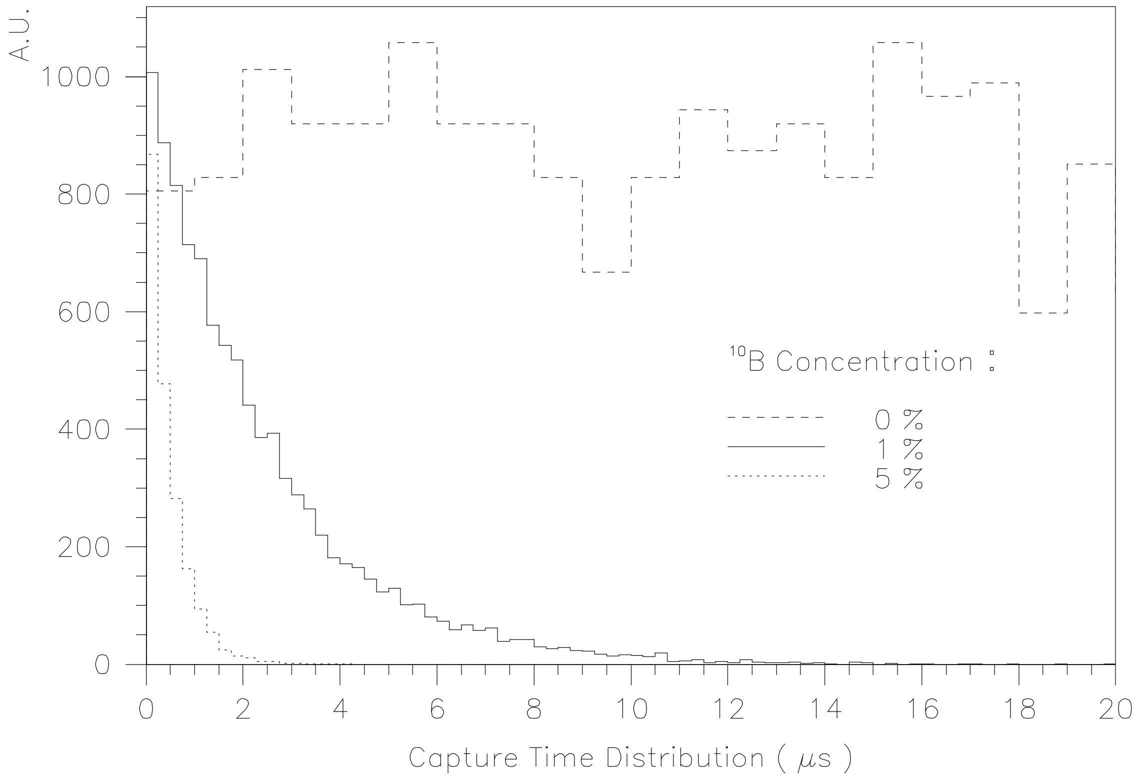



Figure 3: Full simulation of the capture time distribution of neutron with 0.5 keV initial energy in a liquid scintillator medium with 0%, 1% and 5% $^{10}$B by weight. The mean capture time is 2.3 $\mu$s for a $^{10}$B concentration of 1%.

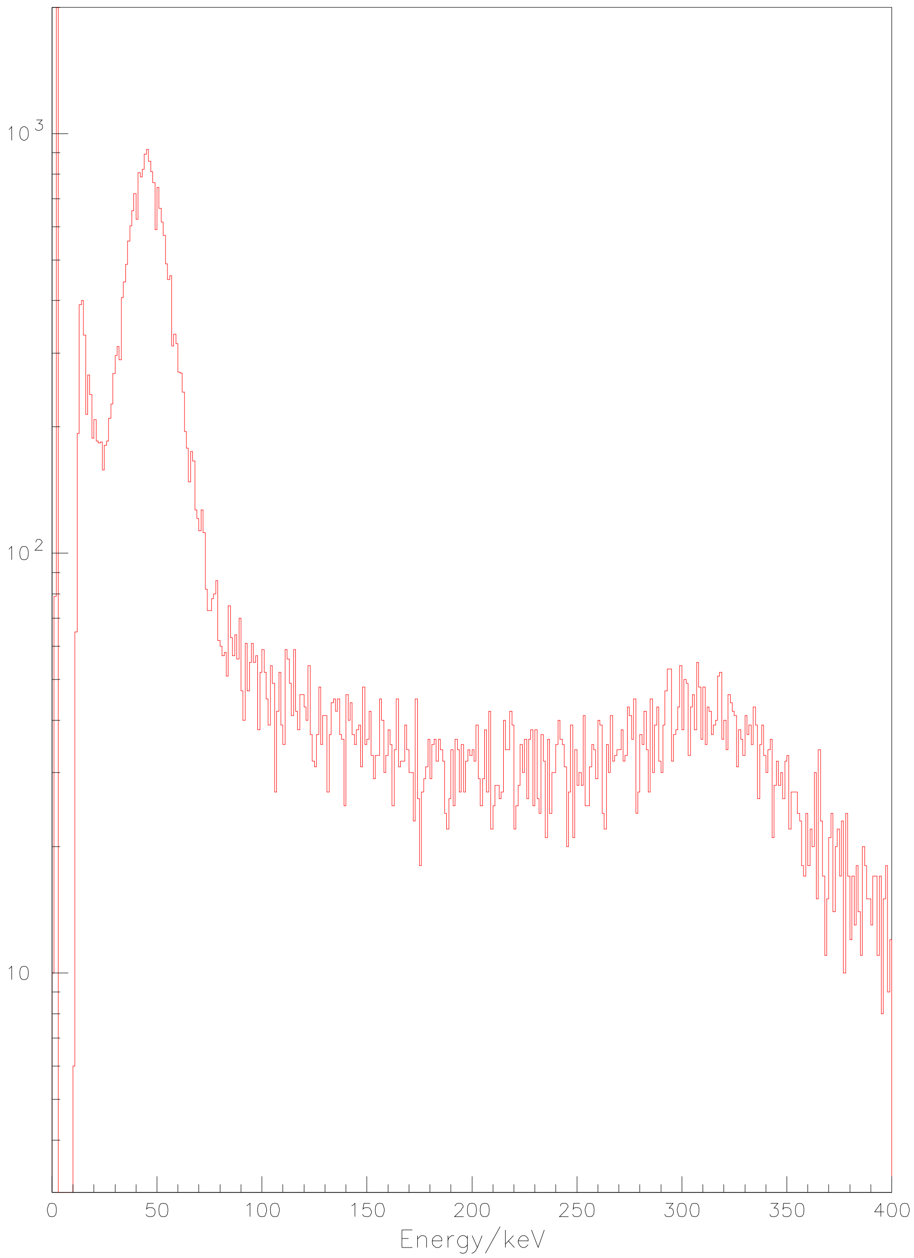



Figure 4: Energy spectrum measured with our homemade liquid scintillator exposed to a neutron source. The peak at 50 keV comes from neutron capture by $^{10}$B while the Compton edge is due to the 480 keV $\gamma$ from the $^7$Li$^*$ final state.

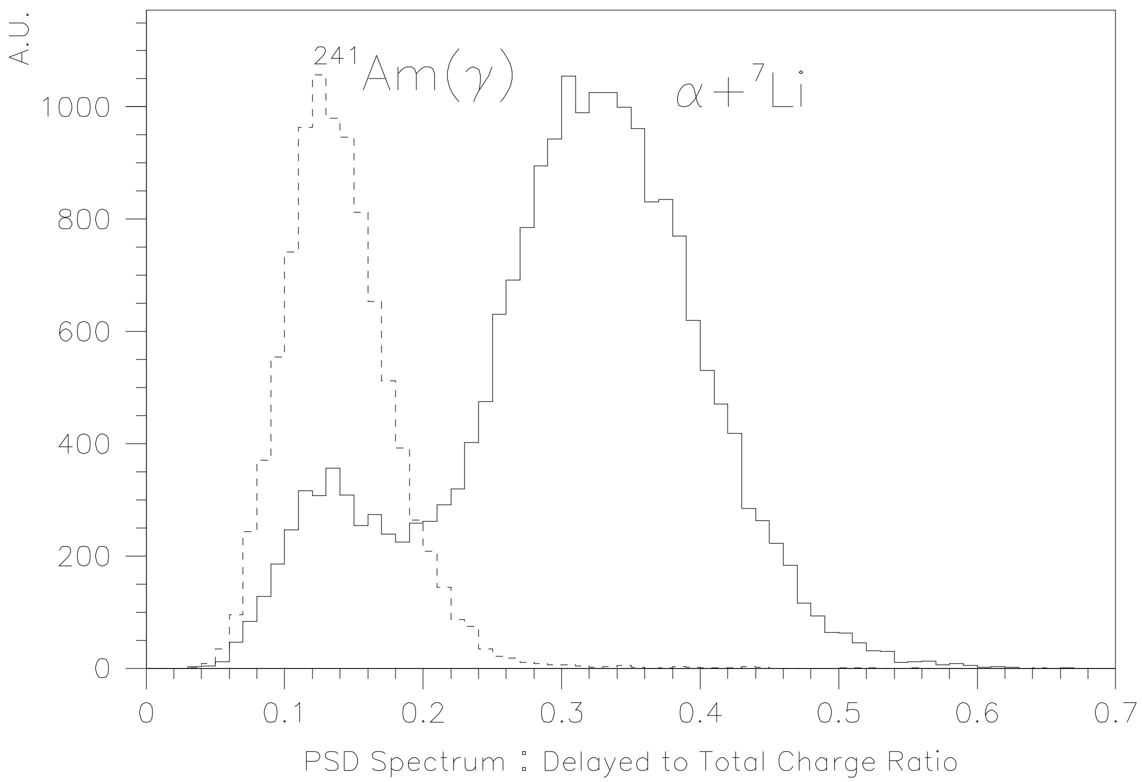



Figure 5: Measured PSD spectrum of the homemade liquid scintillator loaded with 1.0% $^{10}$B by weight : $\gamma$ from $^{241}$Am (60 keV) and $\alpha +^7$ Li from the neutron capture of $^{10}$B (50 keV).

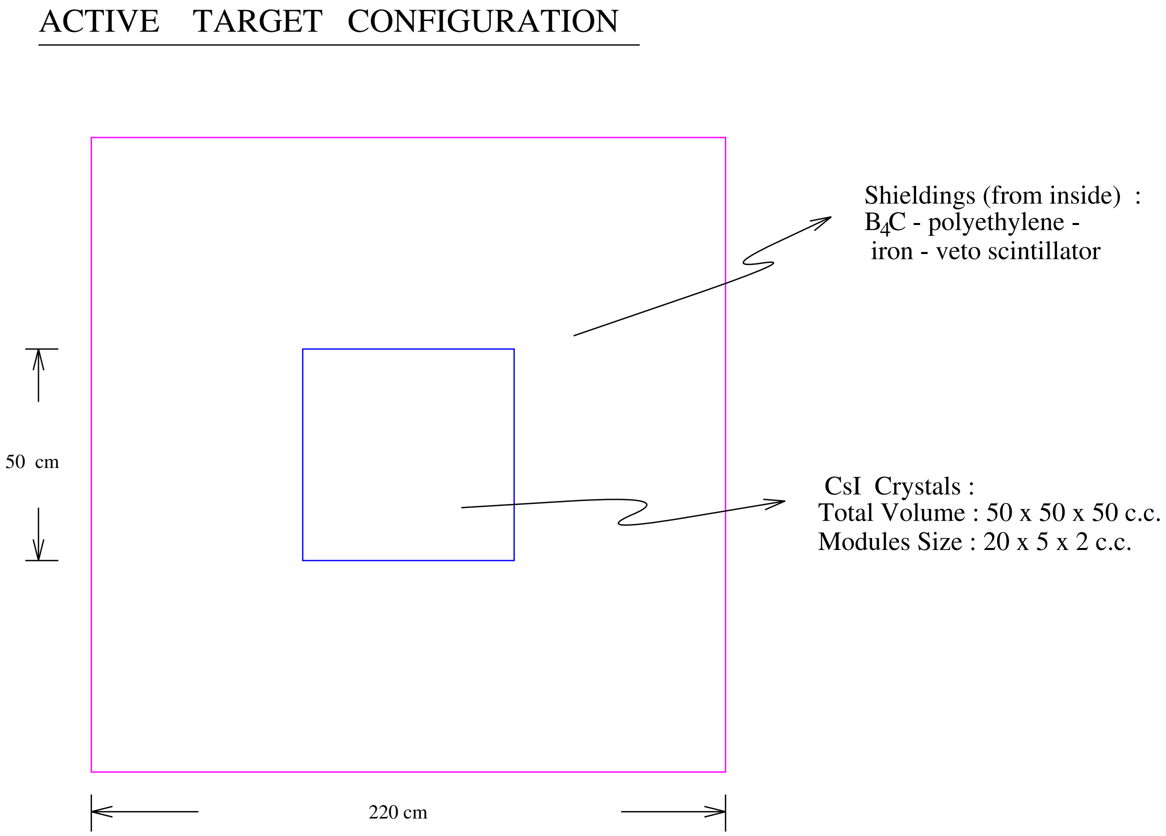



Figure 6: Schematic layout of the experiment using CsI crystals as active target.

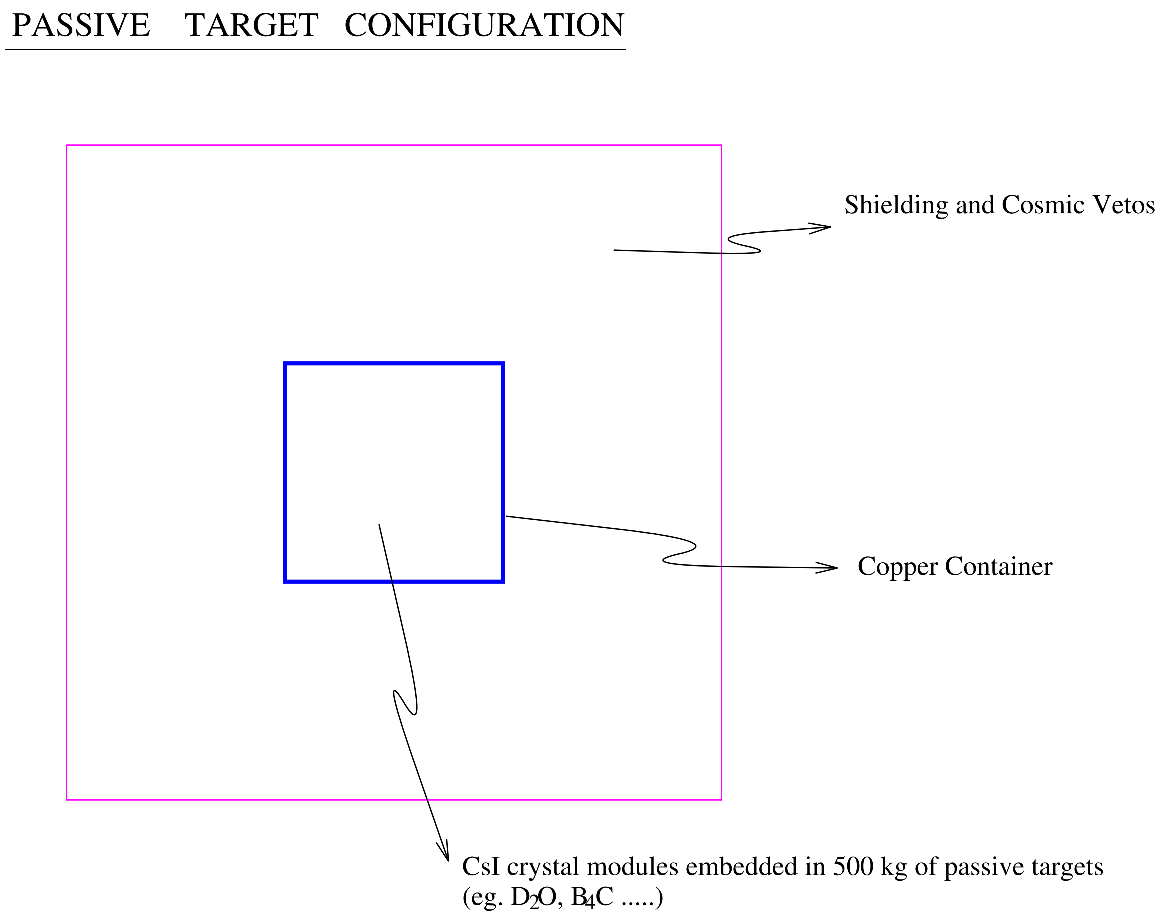
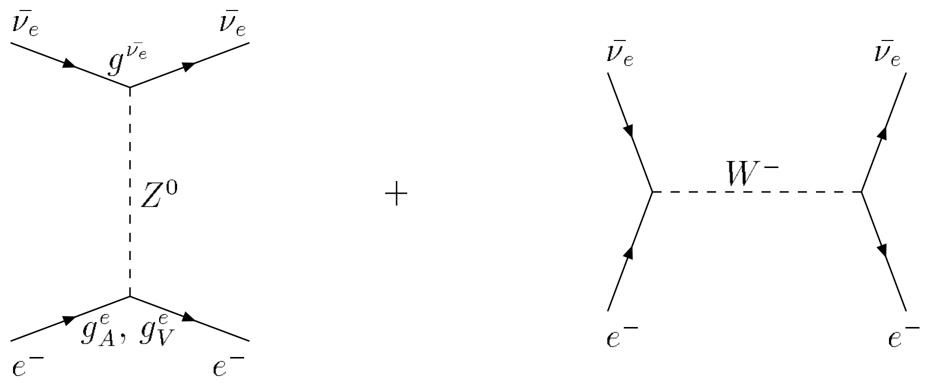


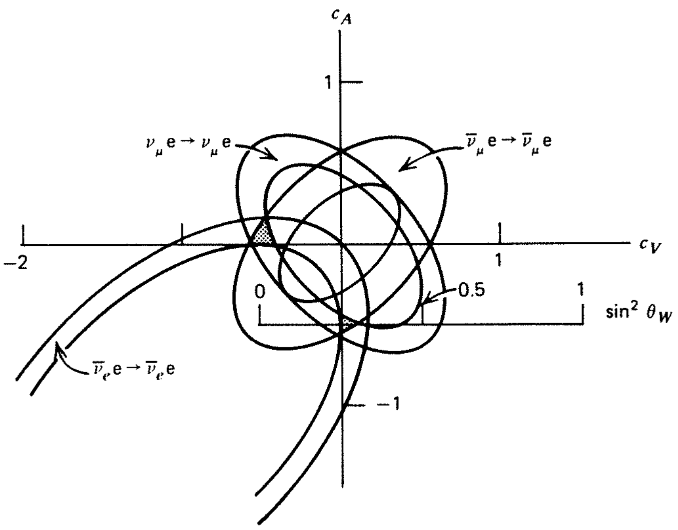

Figure 7: Schematic layout of the experiment using CsI crystals $\gamma$-detector, where passive target materials like $D_2O$ or $B_4C$ are inserted in between.

$\bar{\nu}_e\ e^-$ : NC + CC + Interference.




$$g_A^{eff} = g^{\bar{\nu}_e} \cdot g_A^e$$
$$g_V^{eff} = g^{\bar{\nu}_e} \cdot g_V^e$$

Figure 8: Feynman diagrams for ($\bar{\nu}_e$ e) interaction, showing there exists charged and neutral current components, as well as their interference term.



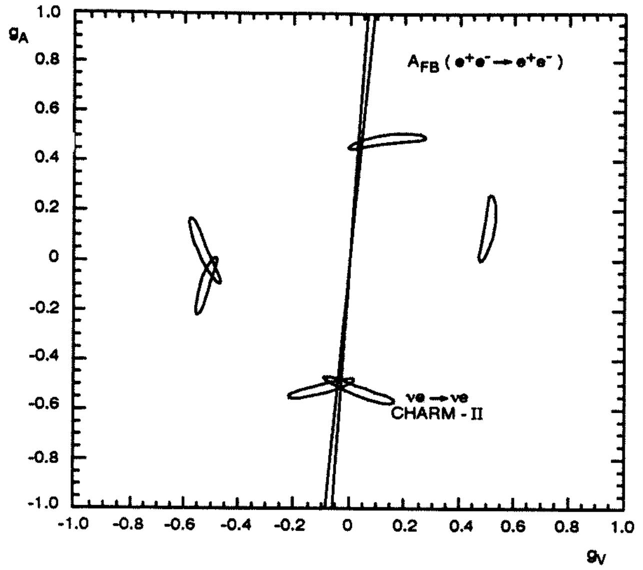




Figure 9: **Top** : Sensitivities of ($\nu_\mu$ e), ($\bar{\nu_\mu}$ e) and ($\bar{\nu_e}$ e) cross-sections to different regions in the $g_A$-$g_V$ parameter space (axes labelled $c_A$ and $c_V$), showing their complementarity. **Bottom** : Allowed region of the $g_A$-$g_V$ plane from the accelerator ($\nu$ e) scattering and the $e^+e^-$ forward-backward symmetry data.

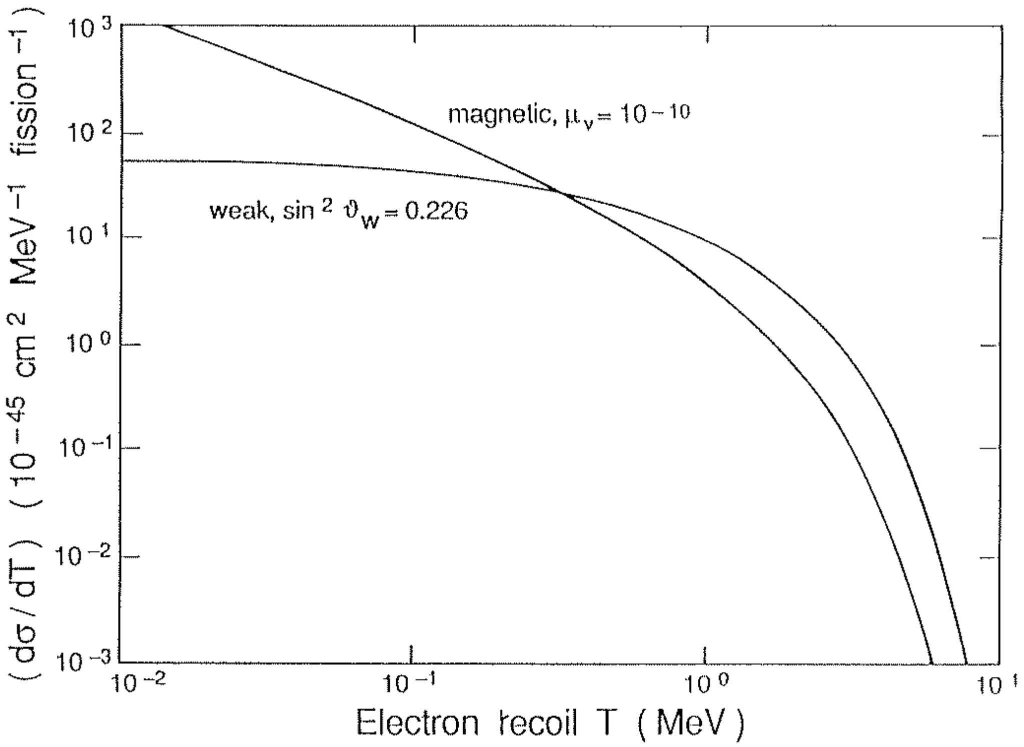



Figure 10: Differential cross section showing the electron recoil energy spectrum in $\bar{\nu}_e$-e scatterings, for of Standard Model processes and for the case with a neutrino magnetic moment of $10^{-10}$ Bohr magneton, the present experimental limit.

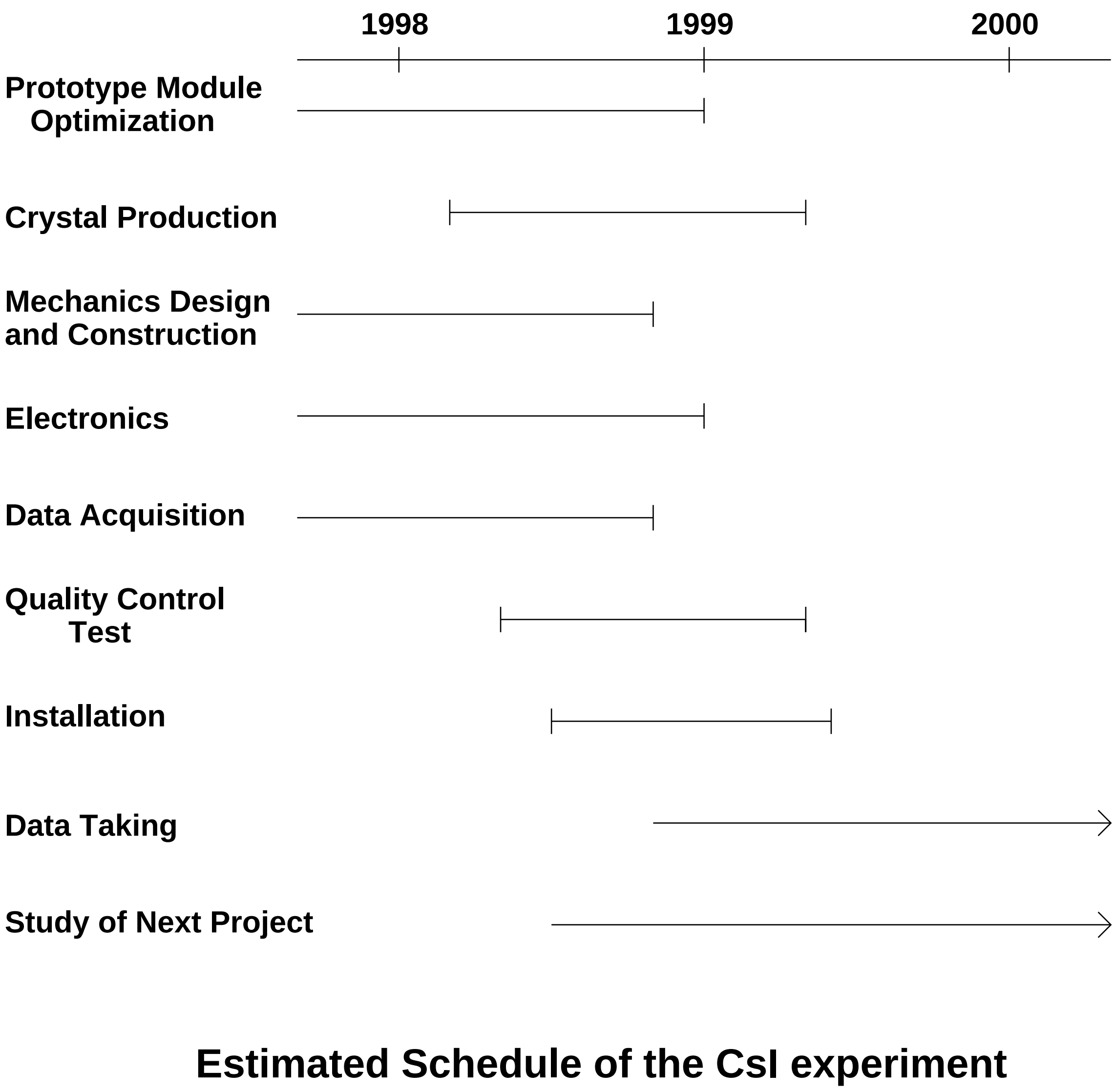



Figure 11: The schedule we would like to achieve for the CsI experiment.