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NSC Research Proposal (2005-2006) on the TEXONO Research Program in Low Energy Neutrino Physics

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Abstract & Summary [4]

The TEXONO Collaboration comprising scientists from Taiwan, China, Turkey and the U.S.A has been pursuing an experimental program in neutrino and astro-particle physics, and in the studies of other novel phenomena. The "Kuo-Sheng (KS) Reactor Neutrino Laboratory" has been commissioned and made operational since 2001. Period I data taking has completed with which we have achieved world-level sensitivities and international recognition in neutrino magnetic moments and the radiative decay lifetimes. Various other analysis projects are being pursued. Period II data taking was completed in June 2004 and analysis towards (a) a measurement of the neutrino-electron scattering cross-section, and (b) first-ever background studies with a 100 eV threshold ultra-low-energy germanium (ULEGe) detector are under way. Period III data taking started in September 2004. Various R&D projects are being pursued. In particular, we are investigating the scientific issues of adapting the ULEGe detector technology towards full-scale experiments on the first observation of neutrino-nucleus coherent scattering, as well as Dark Matter searches. This article presents the highlights of our recent achievement, current status and future plans, and serves as supporting materials for the funding request from the National Science Council in the period August 2005 till July 2006. We request support in funding and positions to operate, maintain, upgrade the KS reactor experiment and to perform the data analysis, as well as to procure equipment and materials for the the R&D programs.

[4] Following suggestions from the NSC convener, funding request on another branch of our activities – an inter-disciplinary program on Sonoluminescence – is submitted as a different proposal.

1 Highlights of Status and Results

An overview of our program can be referred to a recent article [AS-TEXONO/03-19; Mod. Phys. Lett. **A 19**, 1207 (2004)] titled " The TEXONO Research Program on Neutrino and Astroparticle Physics", available from our Home Page, under link "Public Domain Articles".

A summary on the highlights in 2003-04 period:

1. **Personnel:**
   A group from the Middle East Technical University in Turkey, under Prof. Mehmet Zeyrek, joined the Collaboration. A starting Ph.D. student, Muhammed Deniz, is now stationing at AS to work on his thesis. Adding to Lin Shin-Ted (NTU/AS, started 2002, on KS Physics), and Ke-Jun Dong (CIAE, started 2003, on AMS trace radio-purity measurement), there are three current Ph.D. students working on the neutrino part of the TEXONO program. Four new M.Sc. students joined: Heng-Yi Liao (NTU) , working on KS experiment monitoring system and analysis on neutrino-induced nuclear transitions, Hsi-Ming Chang (NTU), working on reactor axion searches, with Dao He and Xin Li (THU, Beijing), working on Dark Matter searches with ULEGe. Another notable development is that Mr. Feng-Shieuh Lee, formerly research assistant at AS, is now pursuing Ph.D. studies at Imperial College London, working on Dark Matter searches.

2. **Professional Recognitions:**
   Extensive press coverage on our history and research program were featured in various media in 2003 (including the prestigious Science Magazine and the well-subscribed America Institute of Physics' Weekly "Physics News Update"). Our results on neutrino magnetic moments were reported by our members in many major international meetings, and cited in the summary talks in the most important ones (in EPS03, LP03, ICHEP04). Our PI, Henry Wong, was invited to present a plenary subject review at the "Neutrino 2004" Conference in College de France, Paris in June 2004. The TEXONO program was selected to be one of the ten "Highlight Achievement" in Academia Sinica in 2004.

   We have received very positive external review in December 2003 conducted at the Institute of Physics. The particle physics panel included Prof. Y. Totsuka, Spokesman of Super-Kamiokande Collaboration and Director of KEK High Energy Physics Laboratory, and Prof. S. Olsen, co-Spokesman of the Belle Collaboration. They noted that:

   " The IOP-led TEXONO experiment is noteworthy because it produced the best direct experimental limit on the electron neutrino magnetic moment. This is the first

world-class particle physics result to come from an experiment based in Taiwan. ..... This group has also shown that germanium detectors can be operated with a very low energy threshold (~100 eV).

The next goal for the Kuo Sheng neutrino program is the development of a low-background detector with an energy threshold that is low enough so that coherent neutrino-nucleus scattering could be measured. ..... a definitive observation on coherent neutrino-nucleus scattering would be an experimental tour-de-force and an important milestone for neutrino physics and searches for dark matter WIMP searches. ..... there is some possibility of surprises. ..... this seems to be a very good activity for the group. "

3. **KS Period II data taking completed and analysis under way:**
   Period II data taking at KS was performed from February 2003 till May 2004. Detector configuration started with a 186 kg CsI(Tl) crystal scintillator array and the 1 kg HPGe detector. The HPGe sub-detector was improved shielding configurations. An additional ant-Compton detector was added. General infrastructures of the KS Lab have been improved. Hardware failure on the HPGe during the run terminated the DAQ of this sub-detector prematurely. A 5 g "Ultra-Low-Energy" (ULE)-HPGe with 100 eV was installed in November 2003. Intense efforts on data analysis are under way. Goals include: (a) improvement on the magnetic moment sensitivity with HPGe, (b) performing the first measurement of the $\bar{\nu}_e$-e cross-section, and (c) performing the first-ever sub-keV low background measurement, towards the future project of neutrino-nucleus coherent scattering.

4. **Period III data taking started:**
   The HPGe was subsequently repaired and installed on-site. Period III data taking started on September 2004. The target mass for the CsI array was increased to 296 kg, with some shielding and gas system improvement. The major change is the commissioning of a new data acquisition system which runs on the latest Linux version (such that it can benefit from the latest PCs), operates more robustly, and with DMA (direct memory access) data transfer. Through this project, we have successfully built in an in-house DAQ expertise. Goals of the data are to further enhance and improve on the magnetic moment and neutrino-electron scattering sensitivities.

5. **Low Energy HPGe Prototype Detector:**
   We are studying a 5 g prototype "Ultra Low Energy" HPGe, and the results indicate a threshold better than 100 eV is possible. Considerable interests on this result are generated among the international communities. We have the data for a first-ever background measurement at the sub-keV range at the KS Lab. When

demonstrations are made that both the threshold and background levels can meet the requirements of a first-ever measurement and observation of the neutrino coherent scattering on the nucleus, we will prepare a proposal for a bigger 1 kg range detector built as multi-channel array. An AS "Pilot Theme Project" was approved for the August 2004 to July 2005 period to pursue an R&D program towards this goal. Such a detector concept may also find applications in Dark Matter searches.

6. **Independent (but inter-correlated) Projects for the Chinese Groups:**
As a sign of maturity of the Collaboration, part of the Chinese groups are now engaging in independent projects where they are taking the leading roles and supplying the major funding and manpower and expertise resources – such that the Taiwan groups will play supporting roles in return. TEXONO PI Henry Wong remains the overall supervising person and retains good controls on how the projects will intellectually evolve even though they are not based in (and funded by) Taiwan. The Beijing-led TEXONO projects include:
(1) The Accelerator Mass Spectrometry (AMS) techniques for trace radio-purity measurements is an approved project in China, headed by the CIAE group with established expertise and facility in AMS;
(2) The CIAE group has organized the first neutron beam measurement of quenching factor for Ge in Oct 2004: this is a necessary supporting experiment for the ULEGe project, for both neutrino and Dark Matter applications. Further improvements and lower threshold are foreseen in the next test beam measurement, scheduled in 2005;
(3) The Beijing Tsing Hua University (THU) group is preparing to bring the ULEGe prototype to the YangYang Underground Lab(Y2L) in Korea to conduct the first survey on application of this detector technology to Dark Matter searches. This measurement is also complementary to the sub-keV background studies at KS, being located at an underground site with 700 m water-equivalence overburden. The Korean host team (KIMS Collaboration) is providing support of the infrastructures and technical expertise. It is expected that the move to Y2L will further strengthen regional collaboration in non-accelerator particle physics.

2 Schedules and Goals : 2005-06

2.1 Analysis and Scientific Results of KS Reactor Experiment.

The different channels of reactor neutrino interactions, as well as their spectral shape and relevant energy range, is depicted in Figure 1.

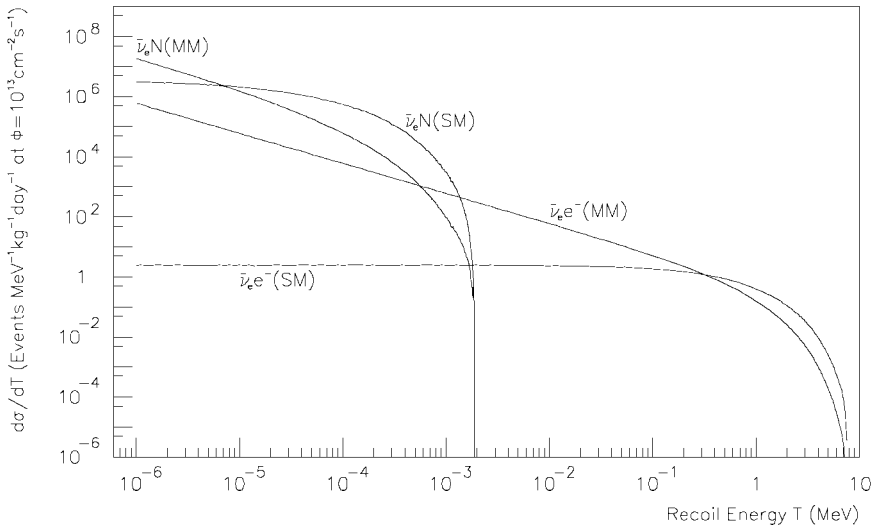

Figure 1: Summary of the various neutrino interaction channels, their differential cross-section and relevant energy scales, with the typical reactor neutrino flux. The KS Period I data taking focused on $\bar{\nu_e}$e(MM) at 1-100 keV. The Period II data taking will focus on $\bar{\nu_e}$e(SM) greater than 1 MeV. The goal of the ULE HPGe project will be to probe the coherent $\bar{\nu_e}$N(SM) below 1 keV.

2.1.1 ULB-HPGe Detector

The ULB-HPGe data is unique for its low threshold, high Z and in an intense neutrino flux. The various topics under pursuit are:

1. Magnetic moments (μ_ν) and radiative lifetimes of $\bar{\nu_e}$: we have achieved world-level sensitivities in these important parameters of intrinsic neutrino properties. First results from Period I data was published. We collected about 50% more data in Period II (where the run was terminated pre-maturely due to hardware failure). These have been analysed showing similar level of sensitivities. We intend to collect factor of two more data in Period III so allow the μ_ν sensitivities surpassing the benchmark 10^{-10} μ_B range, after which data taking of this physics channel with this detector will be finished, and a long paper will be prepared.

2. Calculation of ν_e flux from reactor, and therefore magnetic moments and radiative lifetimes and other unexplored parameters regarding ν_e. Extending the idea further, the scenario of loading a power reactor core with selected isotopes to enhance the ν_e flux has been explored. Potential applications are studied, including high accuracy cross-section measurements, searches for the mixing parameter θ_{13} and as a means

to monitor plutonium production We are at the fine-polishing stage by end of 2004, and a paper will be submitted soon.

3. Cross Sections of $\bar{\nu}_e$ on nuclei, like neutral current excitation processes, where the signature are distinct lines corresponding to the Q-values of transitions. We have selected events where the ^{73}Ge meta-stable excited state is populated. Studies were made to identify the excitation channels and Reactor ON/OFF comparison will be made. We expect to make enough advances by summer 2005 for the Master Thesis of Liao HY.

4. Reactor Axion Searches – Following suggestions from a prominent theorist abroad, we are initiating an analysis of our HPGe data towards a reactor axion searches. Axion models favor axion productions in electromagnetic M1 transitions (e.g. from ^{7}Li following neutron capture by ^{10}B at the reactor core). Detections are via axion "Primakoff conversion" or Compton scattering at the detector. Our data are unique in the world for having such low (10 keV) threshold at a reactor site, and hence well-suited to conduct such searches. We expect to complete this study by end of 2005.

2.1.2 CsI Array

The Period II CsI(Tl) data analysis are under way. This includes a factor of 100 larger data volume than the HPGe system, and is therefore a substantially more complicated system Especially challenging are issues like DAQ dead time evaluation, system calibration and stability, data processing and background. We are getting most of these technical challenges in good control.

This is the first time CsI(Tl) detectors are used in low energy low background experiment, where a three-dimensional position information is measured. Besides demonstrating an understanding the performance and background parameters of this novel detector concept, the physics goal is to perform a measurement of the Standard Model cross-section on $\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$. This fundamental interaction has been observed but not measured for reactor neutrinos. In fact, there is no measurement of $\sin^2\theta_W$ at the MeV momentum transfer range, and this attempt may contribute to the first such effort. (We note also that there are reports on anomalous $\sin^2\theta_W$ at the GeV range from measurements with accelerator neutrinos). The range of interest is above 3 MeV electron recoil energy. The first-iteration analysis of one-month data indicates that the background is still "a factor of a few" too high. The after-cut spectrum is displayed in Figure 2. Further work are necessary to understand and suppress the background, including improved analysis cuts and pulse shape analysis, better energy calibration for the *tail events*, as well as measurements intrinsic radio-purity of ^{238}U/^{232}Th through temporal-and-spatial correlations

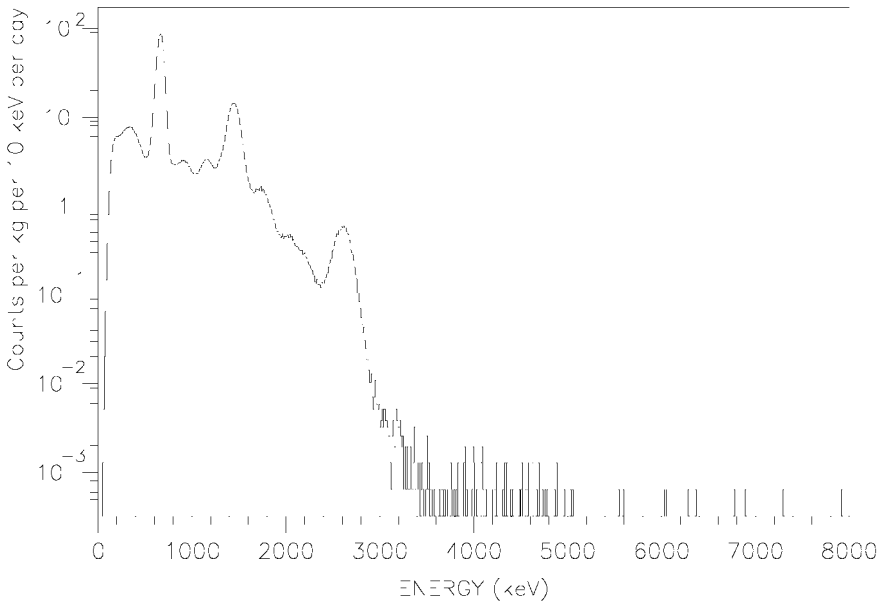

Figure 2: The first iteration *after-cut* spectra for 1550 kg-day of CsI data. It can be seen that the signal region above 3 MeV is still contaminated by anomalous tail of the ^{208}Tl 2.6 MeV peak, the end-point for natural radioactivity.

of the α-events.

2.2 Ultra Low Energy Germanium (ULE-Ge) Detectors

Prototype measurements of the 5 g ULE-Ge indicate a detector threshold of less than 100 eV can be achieved. This novel detector and the first-ever measurements have attracted considerable interests from the world community. The KS on-site measured spectra are depicted in Figure 3, with an equivalent one from the 1 kg HPGe overlaid. The data represents the first-ever low-background measurement (anywhere!) at this low threshold.

The two spectra are normalized by "per unit mass", and it shows a factor of 10 deviations in the common range of 20-40 keV. Further simulation studies will be done to understand the scaling behaviour, necessary for future scale-up. An intriguing and interesting structure is the bump above threshold but below 200 eV. The the Standard Model cross-section for νN is too small to account for this rate, we interpret it as possible γN coherent elastic-scattering at this point and will conduct further measurements to study it. If confirmed, it would (a) be the first measurement of this mode (and another world-class result), (b) provide *in situ* calibration in the future νN experiment , and (c) mean that γ-tagging will be of paramount importance in the νN experiment.

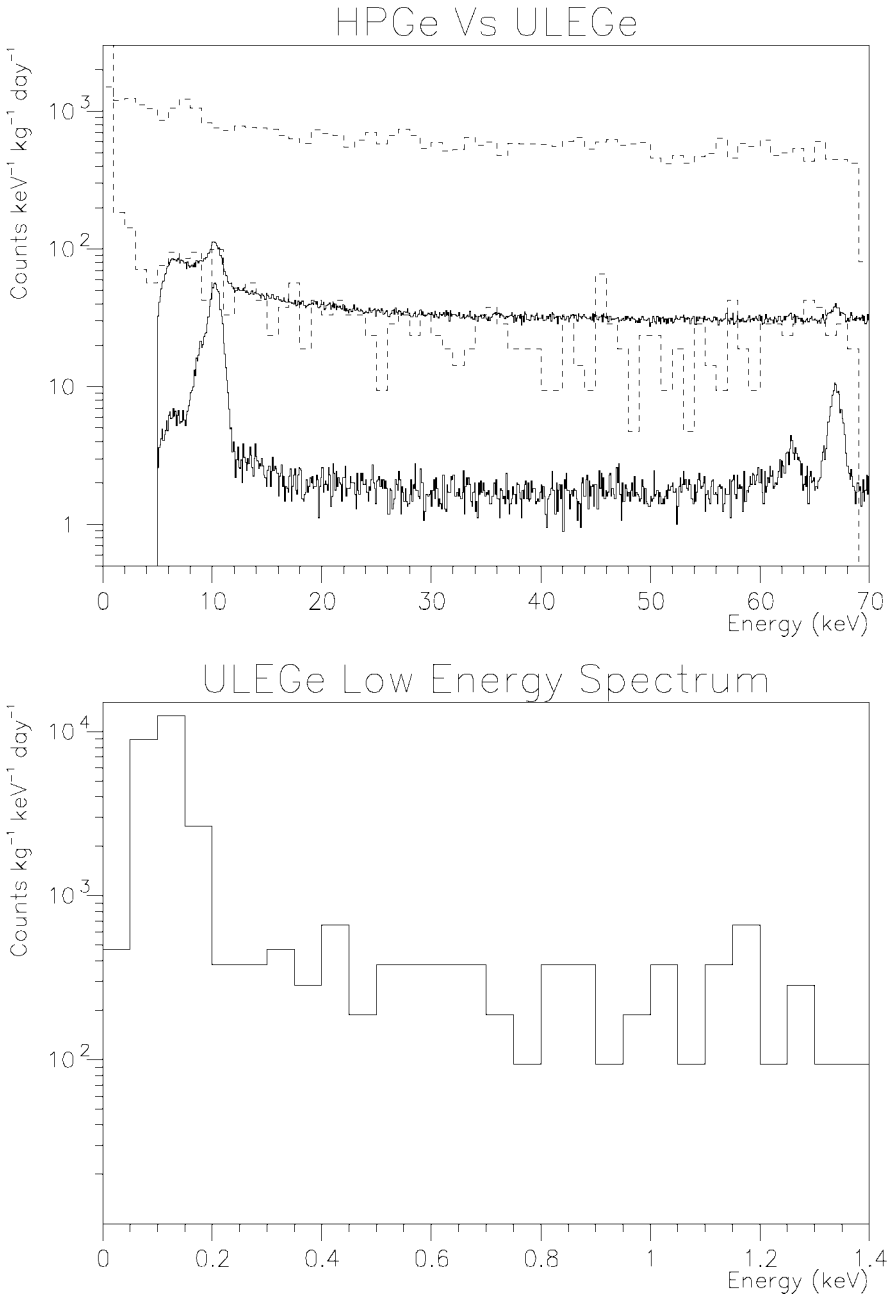

Figure 3: **Top:** Comparison between the *raw* and *after-cut* 1 kg HPGe (solid lines) and 5 g ULEGe (dashed lines) spectra – normalized to the same unit mass. **Bottom:** The ULEGe *after-cut* spectrum showing (a) a threshold of <100 eV is achieved, and (b) anomalous counts at the 100-200 eV regions, still to be clarified.

We expect to build the next prototype with multi-element array (N=4) to address these issues at AS and KS in the period 2005-06, and are discussing with manufacturer on building another single-channel prototype with larger modular mass.

The THU group will prepare a measurement with the 5 g prototype at Y2L in Korea focusing on underground background and Dark Matter searches. Installation and commissioning are foreseen in early 2005. Complementary to the efforts are the CIAE-led Ge quenching factor measurement for the Ge, with the goal of achieving a O(1 keV) threshold. The first neutron beam measurement in 2004 provided the experience to configure a low energy neutron beam at the 13 MV Tandem and to study the trigger and other systematics. Second measurement is scheduled in 2005.

When *both* the threshold and the on-site sub-keV background level are demonstrated to satisfy the requirements for a neutrino coherent scattering experiment at KS, we will submit proposals to build a multi-element array of the 1 kg mass range to the various funding sources in Taiwan. The cost of this experiment will be of the range of 2-3M NTD, and the funding structures and sharing will have to be worked out by that time. The Dark Matter experiment, if demonstrated to be realizable, will be spearheaded and organized by the THU and funding proposals will be submitted to the respective agencies in China and possibly Korea.

2.3 KS Data Taking, Maintenance and Upgrade

The focus of KS data taking for Period III during the 2005-06 period will be (a) to further optimize the data acquisition of the CsI(Tl) array and to enhance the sensitivities of neutrino-electron scattering studies; and (b) to collect more data for the HPGe to reach the benchmark sensitivities (c) to have on-site experience of operating the N=4 ULE-Ge Array currently being procured, to further enhance the sub-keV background measurement and possible to perform definitive measurement of γN. Part of the study of the γN experiment will be conducted at the AS home-based lab.; (d) possibly to procure another ULEGe prototype with larger modular mass – this allows a more compact final design for the 1 kg array as well as less electronics and readout channels.

The KS electronics, trigger and data acquisition system design will be further upgraded to match the requirements of the future neutrino coherent scattering experiment. These include: (a) design and construction of high-quality shaping amplifiers; (b) inclusion of multi-hit TDCs to the DAQ system to ensure complete collection of neutron-induced background timing; (c) design and construction of FADC readout with online zero-suppression and some pulse shape discrimination capabilities.

2.4 Radio-purity Measurements with Accelerator Mass Spectrometer:

The CIAE team demonstrated in a null measurement that a ^{40}K trace radio-purity sensitivity in *extracted liquid scintillator powder* of a 10^{-13} g/g level can be achieved. Estimating an extracting factor of at least 10^{-2}, the projected sensitivity will be at least 10^{-15} g/g. This would be a very interesting result and already better than the best alternative methods. Further beam time have been scheduled in 2005 to pursue along this direction.

3 Request of This Proposal

In this Proposal to the NSC Research Grant (2005-2006), we focus on several specific items:

3.1 Operation of the KS Reactor Experiment

Most of the hardware up to Period III are already operational on-site. While tasks are distributed among the collaborating institutes during the prototyping and construction phase, additional manpower support to be stationed in AS are necessary in the operation and analysis phase. In the 2005-06 time frame, we request funding for:

1. Operation and "Wear-and-Tear" maintenance of the KS reactor neutrino experiment, including mechanics construction, cables and connectors, data storage disks, computing equipment.

2. Support of and data acquisition system upgrade, as well as the purchase of more advanced amplifier and discriminator NIM-modules and the VME multi-hit TDC.

3. Support of one postdoc scientists: Dr. Venktesh Singh, who is an indispensable member responsible for on-site hardware and CsI data analysis.

4. Support of 12 man-month visiting professorship position to an IHEP senior scientist/engineer is essential to maintain smooth operation of the Collaboration. Application materials will be submitted independently.

5. Support of two research assistants, who have been working with the Collaboration in previous year, and who have played important roles in realizing the status presented in this report.

6. Support of collaboration trips to Beijing, as well as data taking trips to Beijing and Korea.

7. Support of attendance of international meetings where our results will be presented.

3.2 Coherent Scattering Experiment with Multi-Array LE-Ge

The N=4 ULEGe array is already procured with resources from AS, including the aforementioned "Pilot Theme Project". We request partial support from NSC on the cryogenic system for the next ULEGe prototype with larger modular mass.

The γN experiment at AS will required a dedicated high energy γ source. The 2.6 MeV γ-rays from ^{208}Tl is a good candidate. This isotope is a decay product of ^{228}Th (1.9 year half-life). We request the purchase of this source.

3.3 AMS and Neutron Beam Measurements at CIAE, Underground Measurements at Y2L

All these projects are funded by our collaborating groups in China, which provide also the major manpower.

For this NSC proposal, we request minor support on the beam time sharing cost for the CIAE projects as well as data taking trips for AS members to Beijing and Korea.

4 Documents and Articles

Further documents, articles, photos and presentations can be retrieved from our Home Page at http://hepmail.phys.sinica.edu.tw/~texono .

The publication list and selected publications for Henry Wong related to the TEXONO program would provide further information.

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Table 1: The institutes and collaborators list of the TEXONO Collaboration in 2004, for both the reactor experiment and various R&D projects.