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Feasibility Studies of WIMP Searches with CsI(Tl) Scintillating Crystals

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1 Introduction

The detection of weakly interacting massive particle (WIMP) [1] has gathered a lot of interests in past years. Its discovery will have a huge impact on both cosmology and particle physics. There are many experiments booming for the WIMP search and there are a long list of different methods proposed already. So far the detection of the nuclear recoil energy, down to 10 keV level, by using scintillation material is probably the most established technique, while cryogenic detectors offer enhanced sensitivities at the expense of target size.

The simplicity of operation and possibility of having massive detectors make scintillating crystals like NaI(Tl) an attractive method for WIMP searches. A recent report [2] from DAMA has claimed observing some positive WIMP signatures by using NaI crystals. However, an upper limit [3] set by CDMS may rule out the DAMA region, depending on assumptions and procedures adopted in setting the limits.

The verdict are still open and there are strong motivations to probe DAMA results and even to improve further on the sensitivities with new experiments. Massive detectors

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have the merits of statistics which are crucial to establish *positive* results (as contrast to setting stringent limits) via the detection of the annual 8% modulation due to the difference of the relative velocity of the Earth relative to the WIMP sea.

The scintillating crystal CsI(Tl) is an attractive alternative to NaI(Tl). The crystal is an extremely good active target at keV scale since it has enough scintillation light yield ($\sim$52 photons per keV). The purification process of CsI is currently reaching a level of ppm to ppb. There are experience in constructing and operating massive CsI(Tl) calorimeters to the scale of 50 tons. (Cryogenic detectors of of scales 100 g or less!) The TEXONO Collaboration reactor experiment has built up much expertise and connections related to this technique, offering an convenient and important “launch lad” for this approach. In fact, the electronics, data acquisition, monitor and control systems developed and constructed successfully for the reactor experiment can be readily adapted to a potential WIMP search experiment.

A feasibility study for WIMP search was proposed by utilizing a prototype CsI crystal from TEXONO CsI detector. The plan was supported by the CosPA II project under the collaboration between National Taiwan University and the TEXONO group. The first step of this project is to study the light collection efficiency because it is crucial to set the threshold as low as possible. A lower threshold means much higher sensitivity. This information will be very important for detector design of optimized crystal geometry. Another important task is to determine the observed nuclear recoil energy. The purpose of this is two-fold. First, we need to calibrate the detector energy scale by x-ray source (e.g. ^{55}Fe) from time to time. However, the detector response for nuclear recoil with the same amount of x-ray energy is different. It is much smaller by a factor, quenching factor. This factor can be determined by a neutron beam test. Second, the pulse shapes obtained from nuclear recoil and x-ray are also different. The information can be used to reject low energy background which is dominant by x-rays.

The final test will be done in an underground site to determine the actual counting rate level after background vetoing. The competitive rate is something like 1 count per day per kg per keV. Site searching is a nontrivial thing because it should be deep enough with easy access.

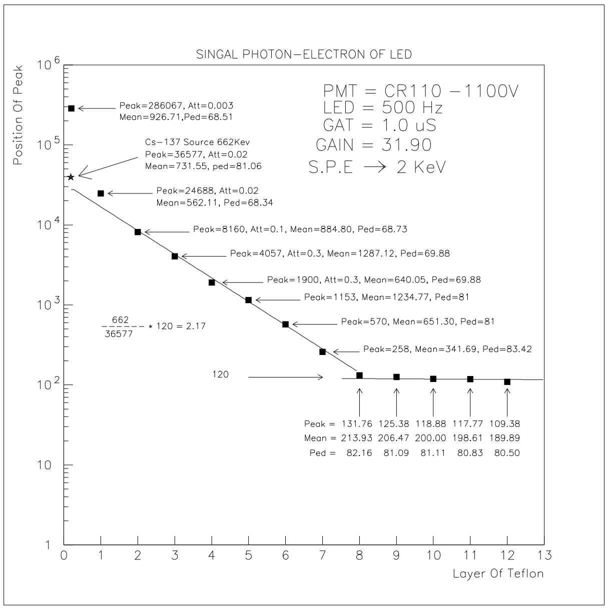

Figure 1: Light intensity versus teflon wrapping layers.

2 Light collection study

The crucial experimental challenge for WIMP searches is to achieve low detection threshold (order of 1−10 keV), preferably with "recoil/γ" pulse shape discrimination – and yet with a massive enough detector with low enough background. In CsI(Tl) crystal scintillator, this is the problem of light collection.

The work of light collection study can be summarized in the following two plots.

Figure 1 shows the light intensity observed by PMT from a LED source with different Teflon wrapping layers. The observed light peak eventually reaches a level of single photon-electron after 8 layers. From the first point without Teflon to the second point with one Teflon layer, the light was blocked by 90%. After 3 layers of Teflon, the light intensity dropped relatively by 50% for adding one more layer. This is due to the multi-reflection effect in between layers. Then the intensity reached a plateau which is the single photon-electron range. Since the 662 keV peak of ^{137}Cs is well known, this determines that we will have one photo-electron, in the average, per 2 keV energy deposition.

Since both ends of the crystal bar have PMTs attached, the observed signal size for a radioactive source may vary depending on the source position. The reasons to cause this nonuniformity is mainly due to geometrical acceptance and the light lose during propagation to PMT. The results of a ^{137}Cs source at different positions are shown in

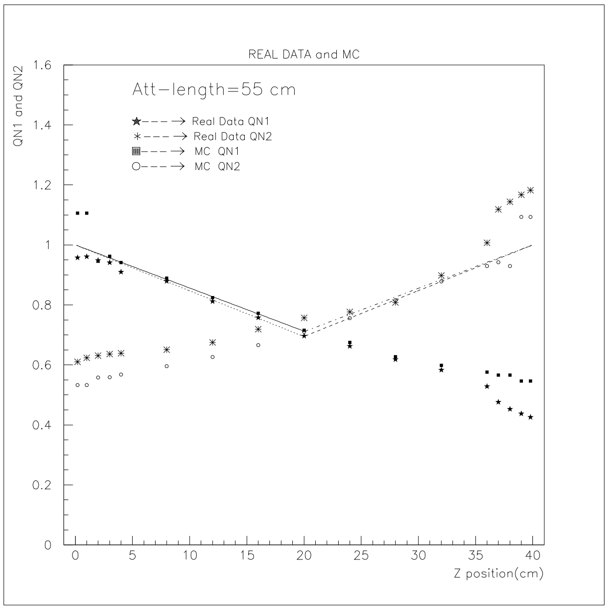

Figure 2: Measured light yield from a ^{137}Cs source and the comparison with simulation.

Figure 2. The prototype bar was wrapped with 4 layer thick of Teflon. The surface lose of light is assumed to be 1% according to Figure 1. A simple Monte Carlo was written which performs photon bouncing inside the crystal. The polarization of light is assumed to be random in order to handle the reflection and refraction between boundaries of different materials. The CsI scintillation spectrum and the PMT quantum efficiency curve are taken from the Hamamatsu PMT manual. An average of 520 scintillation photons were generated for a 10 keV x-ray. The reflection at Teflon surface is assumed to have random direction. If the light bulk attenuation length is assumed to be 55 cm, the MC predicted nonuniformity is also plotted in Figure 2. Note the simulation near edges has bigger discrepancy because that the aperture effect of radioactive source is not properly simulated. Not only the nonuniformity agrees well with our MC prediction but also the expected photo-electrons at one end agree well with data (5 in this case). This confirms that we will have one photo-electron per 2 keV at one end if the source is put in the center.

This threshold, 2 keV, can be improved easily by using a different type of PMT. The TEXONO PMT is CR110 with standard bi-alkali photo-cathode. The quantum efficiency at 500 nm (near CsI scintillation peak) is less than 10%. If we use a different multi-alkali photo-cathode of PMT R5800G, the Q.E. is improved to 27%. The detector geometry is not optimized because of the long bar option. If we choose a wider cross-section area and a shorter bar, the light collection can be improved by factor of 2. A 10 cm bar is tested

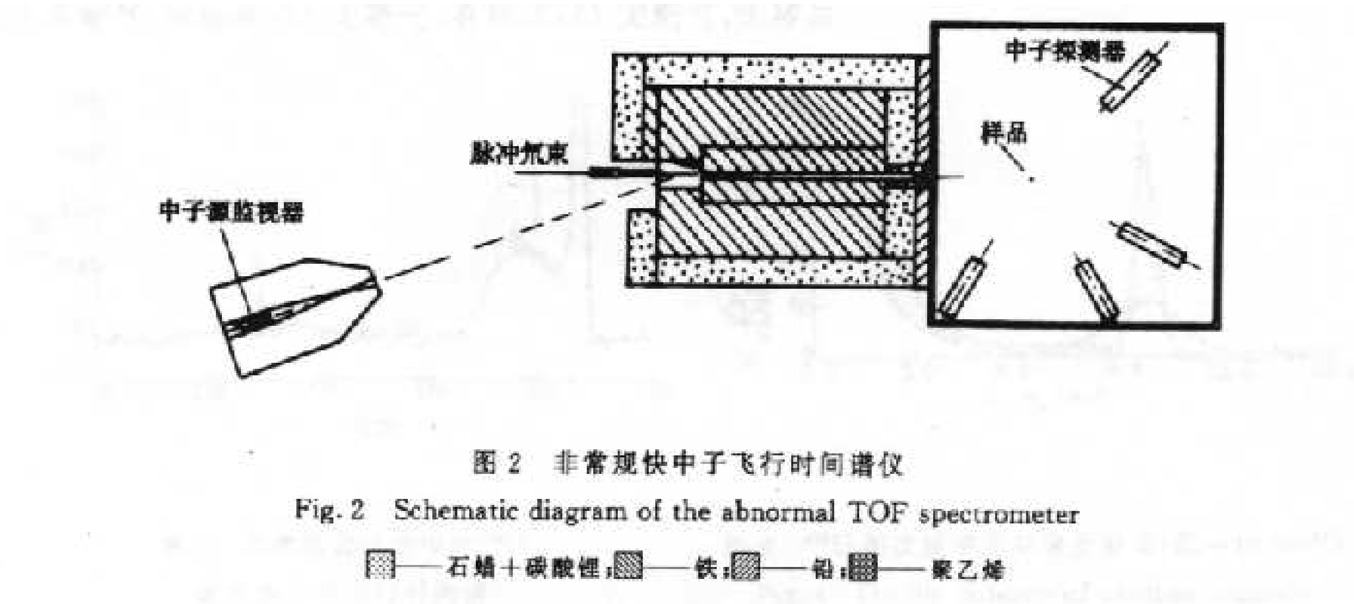

Figure 3: Neutron Test Beam Facility at CIAE.

and the result agrees well with MC prediction.

3 Neutron beam test

Another important aspect to determine in the feasibility studies is the actual detector response of the nuclear recoils due to WIMP elastic interactions. A neutron beam calibration measurement was therefore arranged at the China Institute of Atomic Energy (CIAE) TANDEM accelerator in October 2000 (neutron and WIMP gives similar response in the detector level). Forward neutrons were selected from collisions between accelerated deuteron beam and deuteron target. The beam energy is 8 MeV. A schematic diagram of the beam line set-up is shown in Figure 3. The sample is a ϕ 3 cm by 3 cm cylindrical CsI crystal wrapped with Teflon, aluminum foil and black tapes. It has only one end read-out by a CR110 PMT. The TEXONO read-out system was used in the test except the trigger was taken from Time of Flight (TOF) system externally. We used the timing information formed by the neutron detector and the pulsed beam at the target to define each event.

The TOF spectrum of triggered events with neutron detector at 50^o scattering angle from CsI sample is shown in Figure 4. There are two peaks and a rather flat layer underneath. The right peak (at TOF unit=142) corresponds to the elastic scattering between neutrons and heavier nuclei (e.g. Cs, I or even C). The lower peak is from

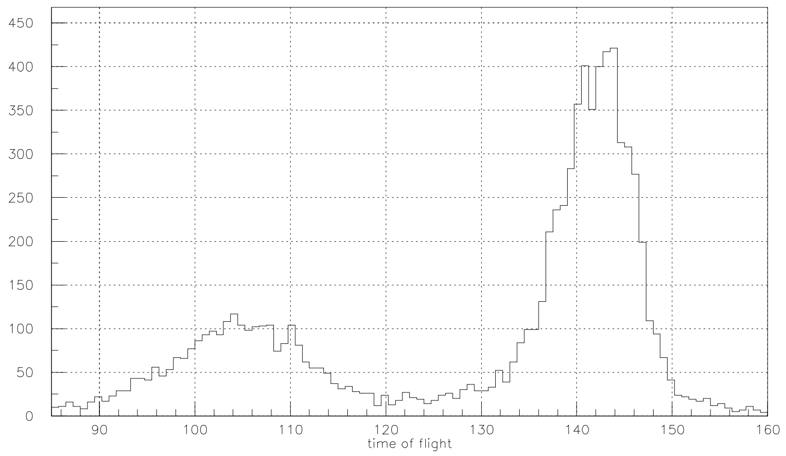

Figure 4: Time of flight spectrum, in arbitrary time unit, of time between neutron production and detection.

the scattering of hydrogen. The flat layer is from the random coincidence between two counters. The nuclear recoil energy is calculated to be 43 keV for neutron scattering off Cs/I at 50^o.

The genuine neutron events scattering of CsI can be selected by using the pulse shape discrimination technique. We define "PSD" as the ratio of the integrated charge of the first 50 FADC samplings and the first 100 FADC samplings. Another parameter used is the energy weighted time. The scatter plot of these two quantities, shown in Figure 5, demonstrate there is a cluster which contains the genuine CsI recoil events consistent with the CsI-reoil-like TOF profile. The event selection is done by a box cut with this two parameters. The energy spectrum of these events is shown in Figure 6. Calibration to "electron-equivalence energy" was done with ^{55}Fe X-ray sources. These information can determine the quenching factors for different recoil energy. We select the events by the same box cut and obtained the quenching factor plots in Figure 7. The two lowest energy points at the recoil energy of 7 keV and 16 keV, respectively, are the lowest world-threshold achieved for the nuclear recoil measurements. This allows better determination of the quenching factor in the form of Birk's Law, and provides very useful data to study PSD at the very small photo-electron regime.

The prototype studies [4] and the neutron calibration work [5] will be summarized into publications.

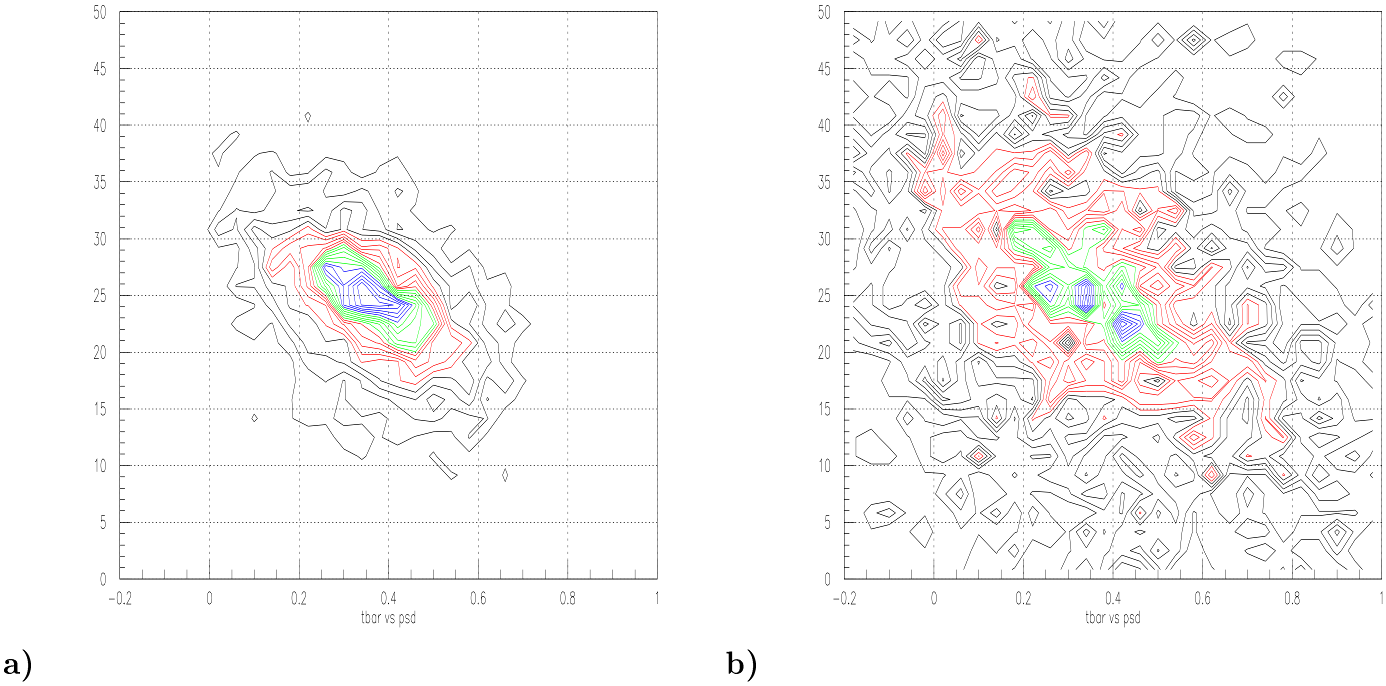

Figure 5: PSD distributions of the two related variables for (a) CsI-recoil-like and (b) light-element-like TOF events.

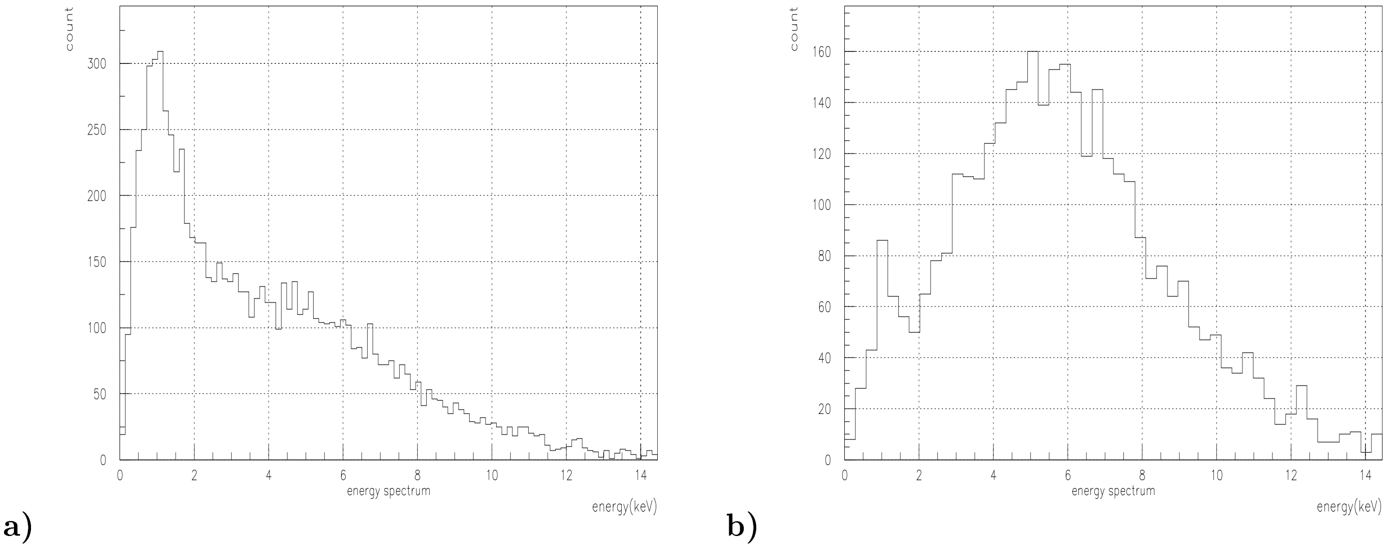

Figure 6: Energy spectra at 50^o, (a) before and (b) after the neutron-ID cuts.

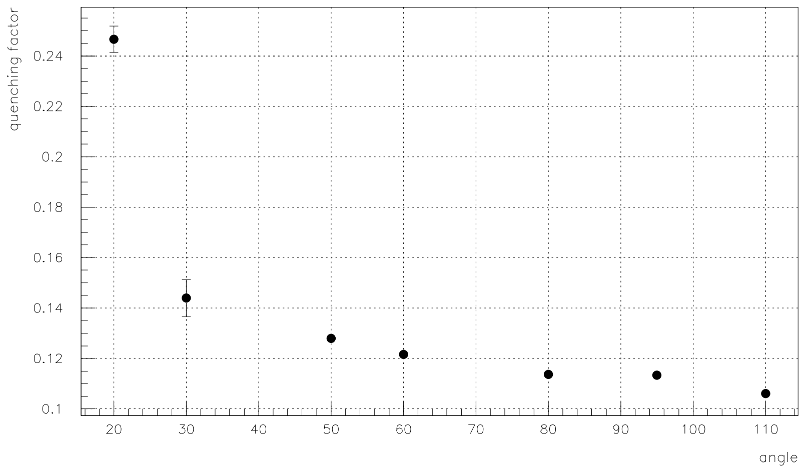

Figure 7: Measured quenching factor of nuclear recoils in CsI(Tl).

4 Proto-Collaboration with KIMS Group

The study of light collection and neutron calibration indicates good potentials for using CsI(Tl) in WIMP searches. However, the crystal size and the type of PMT used in TEXONO reactor experiment is not optimized for this very low energy. Another important task is to determine the actual background level in an underground site.

We learned that In October 2000, a Seoul-based group [Korean Invisible Mass Search (KIMS)] was funded in WIMP search by using CsI(Tl) crystals. They have an underground Lab in a power plant about 2 hours drive from Seoul. The study they did focused on background level study with CsI crystals from different vendors. So far, the level they achieved is about 100 counts per day per kg per keV. Low energy electrons/photons are believed to the dominant background.

A meeting was organized prompted at Seoul National University (SNU) in December 2000 to exchange experience. Both groups can match the work of feasibility study very well. There remains issues to be settled before a real experiment can be launched full-swing. Particularly important are (I) the realization of a prototype module (crystal plus readout device) which can deliver low threshold and adequate PSD and (II) the demonstration of a competitive background level. The second meeting will take place in March 2001 at IHEP-Beijing.

The possibility of long term collaboration and the joint-efforts of performing an experiment will be addressed in the case where the results of these studies are positive. The entire electronics, data acquisition and monitoring system for the TEXONO reactor experiment can be readily adopted to such a full-scale Dark Matter experiment.

5 Project Organization

This research program will be carried out under the framework of the TEXONO Collaboration which, since 1997, has successfully opened up channels of communication and collaboration among the Taiwan and Mainland China Groups. Channels of movements of research personnel, equipment as well as funding are by now well-established by the Collaboration. This enables efficient and flexible operation and sharing of resources and expertise in the future projects.

Dr. Wang Ming-Zu (NTU) is the Project Leader of this R&D program, while TEXONO Taiwan-PI Dr. Wong Tsz-King (AS) co-ordinates the operation of the project within the extended TEXONO Collaboration, and in connection with the Korean KIMS group. Dr. Li Jin (IHEP) is the leader of the TEXONO Mainland China groups. Neutron beam at CIAE is under the co-ordination of Dr. Zhou Zu-Ying (CIAE). Dr. Lai Wen-Pin (CKIT) is the scientific interface person from TEXONO. Dr. Ng Kin-wan (AS) is the "in-house" theorist supporting the experimental program. If the project would evolve into a full experiment, two students : Tang Chia-Hsin (NTU) and Yue Qian (IHEP) are expected to work on this subject as their theses.

6 Request of NSC-2001 Proposal

The NTU participation to this R&D studies is supported by the CosPA scheme. The TEXONO group based at AS request the support of : (1) material and operation cost and beam time sharing at the CIAE Tandem for performing further neutron test beam calibration measurements (300k NTD); (2) sharing of equipment cost on new readout devices, including the Flat-Panel PMT, Hamamatsu's New Product (120k NTU); and (3) travels to Beijing IHEP and CIAE for meetings and data taking (2 person-week).

Further proposal may be submitted if the results of the feasibility studies indicate the potentials of a competitive experiment.

7 Summary

The presence of Dark Matter is one of the most important problem facing particle physics and cosmology, which indicates something very fundamental we do not understand. This subject will definitely be in the world's spotlight for many years to come. There are good motivations for Taiwanese groups to "get into the field".

Since mid-1997, the TEXONO Collaboration has built up a broad-based infrastructure and extended connections in Taiwan and Mainland China to pursue the subject of neutrino and astro particle physics. The leadership of NTU group in spear-heading a Dark Matter program further consolidates and substantiates our efforts.

It is fortunate (and a compliment to our generic theme of low-energy experiments with crystal scintillators) that the Korean group are pursuing the same subject with identical approach. There are much room for establishing schemes of regional collaboration (Taiwan, China, Korea, possible extension to Japan) whose implications may lie beyond this present project.

The feasibility study is in its final stage and all groups are working closely together. We hope that the results and experience can lead to a solid experimental program.

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