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A Feasibility Study of Using Crystal Scintillator for Cold Dark Matter Search : A Proposal

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Abstract

The identification and study of Dark Matter is a major research subject and experimental challenge in the decades to come. Based on the experience and infrastructures already built up, we propose to conduct a feasibility study to investigate the various experimental issues in the use of CsI(Tl) crystal scintillator for a Cold Dark Matter Search. If the conclusion would be positive, a full-scale experiment will be proposed.

1 Introduction

There are very solid evidence based on a wide spectrum of observations for the existence of Dark Matter in the Universe [1]. Big Bang Nucleosynthesis arguments require that most of these missing mass must be non-baryonic. Many Dark Matter candidates have been proposed : the leading ones being neutrinos for "Hot" Dark Matter, and Weakly Interacting Massive Particles (WIMP, denoted as χ) for "Cold" Dark Matter. The exact properties of the Dark Matter have very profound consequence to particle physics (inevitably requiring physics beyond the Standard Model) and cosmology (evolution of the Universe and the structure formation).

Experimental searches for Dark Matter [2] started at around late 1980's, and in many different directions. Baryonic dark matter components have been observed in the form of massive compact halo objects (MACHOs).

Direct WIMP searches have been pursued by many groups in the world. A variety of techniques are considered. The central idea is to look for nuclear recoil from χ-N elastic scattering, and to monitor the annual modulation of the recoil spectra as the Earth traverses the WIMP sea with different relative velocities [3].

The recoil kinetic energy is of the range of 10 keV. This is a new frontier experimentally demanding state-of-the-art background control and low detection threshold over large target mass.

At present, the most sensitive experiments are from the underground NaI(Tl) crystal scintillator experiments, deploying the range of 100 kg of target [4]. A host of intensive R&D projects are underway on various new and challenging cryogenic detection techniques, which are important detector development in their own rights. The DAMA group recently reported preliminary results [5] which are consistent with WIMP signatures.

2 Motivations of Proposal

We propose to initiate some research efforts and to conduct a feasibility study for a Dark Matter experiment. There are several motivations, or equivalently goals, behind this move.

1. **Dark Matter is a very important subject:** It is very likely that this subject will remain in the research spotlight in the coming decade and beyond. Being several

years behind in getting into the field need not be a major drawback in the long run. There are still much room for innovative ideas. The experimental investigations are very challenging and rich, with potential spin-offs for other applications. We would like to study the case seriously, that is, to learn the physics and basics, to develop a taste of the various proposed detector techniques and to formulate a vision for future evolutions.

2. **Coherence with research development in Taiwan:** The National Taiwan University is establishing a "Cosmology and Astro-particle physics" program. Meanwhile, the Academia Sinica group is pursuing a program in low-energy neutrino physics, with the intention of a next-generation solar neutrino experiment. A Dark Matter project carried out under the collaboration of both groups is coherent with these development, and will greatly enhance the vitality of both programs. It will also enrich the inter-disciplinary interactions among the particle physics, astrophysics and cosmology communities in Taiwan.

3. **A base already built up by both groups:** Through the activities in the past few years, both groups have established the necessary facilities, infra-structures and connections which can serve as an efficient "launch-pad" for the studies, and to explore a new subject together.

It should be emphasized that the Proposal is on a "Feasibility Study", rather than a rigidly-defined and carefully-formulated experiment. The resource requested is rather modest, and the studies will be pursued in parallel to the on-going program of both groups.

3 Feasibility Studies

3.1 Baseline Project

The baseline project will be to study the case of using a CsI(Tl) detector for WIMP searches. A realistic experiment will be of the target mass range of 500 kg to 1 ton. Meanwhile, we would follow the development on other promising possibilities, which can be with a different crystal scintillator or with an alternative detector technology altogether.

An estimation of the relative WIMP-nuclei cross-sections between CsI(Tl) and NaI(Tl), based on theoretical models [5, 8], is shown in Figure 1. For Dirac-type WIMPs with spin-independent interactions, $\sigma \propto \mathrm{M_r^2 n^2}$, where $\mathrm{M_r} = \frac{\mathrm{m_\chi m_N}}{\mathrm{m_\chi + m_N}}$ is the reduced mass of the system and n is the neutron number. For Majorana-type WIMPs with spin-dependent interactions, $\sigma \propto \mathrm{M_r^2} \lambda^2 \mathrm{J(J+1)}$ where J is the nuclear spin and λ are factors depending on nuclear matrix elements. It can be heavy nuclei with non-zero spins like ^{133}Cs and ^{127}I have favorable cross-sections and event rates, especially for heavy WIMPs, relative to the lighter or spin-zero elements.

The prospective sensitivity curves in the "$\sigma_{\chi \mathrm{p}}$ Vs M_χ" parameter space for a 500 kg CsI(Tl) target mass, with the assumption of achieving a similar background level as the NaI(Tl) experiments, are given in Figures 2 and 3 for the spin-independent and spin-dependent interactions, respectively.

3.2 Motivations

CsI(Tl) may offer potential advantages to the other existing WIMP detection schemes :

1. Unlike NaI(Tl), it is only weakly hygroscopic and need not be placed in a hermetically sealed container. This would minimize passive dead volume in the target area, thereby enabling better background control.

2. It is relatively inexpensive due to large demands in recent years from the many high-energy-physics experiments, where electromagnetic calorimeter of up to 50 ton are being built. A 1 ton range of target mass is readily affordable and technically manage-able. Indeed, there are much room to be further scaled up. The world does have much experience in producing and operating large quantities of CsI(Tl) detectors.

3. It has superb pulse shape discrimination (PSD) properties differentiating the dominant gamma/electron background from the nuclear recoil signals.

4. Much experience have been accumulated by both the AS and NTU groups on the crystal scintillator technique. The NTU group is constructing a BGO very-forward-calorimeter for Belle in KEK, while the AS group is pursuing an experiment with 500 kg CsI(Tl) for studying reactor neutrino physics [6]. A lot of the tools have been developed (like measurement systems, electronics system, simulation software

....), as well as good working relationships have already been established with manufacturers, providing us an excellent base to start.

A Technical Report [7] which describes all the experimental aspects of the AS reactor neutrino experiment ("TEXONO") is attached to this Proposal. As illustrations on their relevance, the PSD between α's and γ's down to 100 keV is shown in Figure 4, demonstrating the capabilities for picking up nuclear recoil signatures from the gamma-background. The TEXONO electronics system, designed and developed all by the Collaboration, is depicted in Figure 5. The amplified signals from the photo-diode are fully digitized by FADC modules read out by the VME protocols. This system can be readily adopted in the Dark Matter feasibility studies or even the eventual experiment. Besides technical experience, the AS group is also well-connected to the high energy and nuclear physics expertise, as well as crystal manufacturers, in Beijing.

(Perhaps NTU can quote a couple of their relevant work here)

3.3 R&D Program

A rigorous feasibility study on the baseline project would include the following ingredients:

1. Study on the physics of WIMPs and their interactions, and on the various proposed experimental schemes to detect them, i.e. learn the basics and really get ourselves familiar with this discipline.

2. Study the various underground site options: It can be local or abroad. Some preliminary inquiries have already been made by the AS group.

3. Construction of a prototype module to investigate the various experimental issues:

    - What is the optimal crystal dimensions ?
    - Is light guide necessary to bring out the scintillation light?
    - What is the optimal detector configuration ?
    - What are the readout device to adopt - photo-multipliers or avalanche photo-diode ?
    - How low one can achieve in the detection threshold ?
    - What is the PSD performanace at the O(10 keV) energy range?

- Development of simulation packages on light transmission within crystals and on nuclei recoil effects.

4. Studies of the Background issues and addressing the various issues:

   - Physics of the various background processes, and an evaluation/estimation of their contributions;
   - Study of intrinsic radiopurity of the crystal, teflon wrap, and the readout device;
   - Study of radiopurity of various experimental components (support structure, cables ... etc), and the effects of the ambient background;
   - What is the necessary overburden of the underground site, and the effects from the residual cosmic muons.

There is much overlap in the crystal prototyping and the background studies parts with the current AS program. For instance, a radiopurity level better than 10^{-12} g/g of ^{238}U and ^{232}Th in the CsI(Tl) crystal has been demonstrated [7]. Background processes at the 1 MeV range at shallow depth have been surveyed, and one has to base on these knowledge to extend the studies to the 10 keV range at an underground site. Much of the experience, information and know-how that we would learn (site options, background channels and their control, radiopurity of equipment) during the feasibility studies will be useful in any future discussions of underground low-background experiments, which do not necessarily restrict to WIMP searches.

An important milestone of the feasibility study would be to demonstrate that the crystal is capable of detecting WIMP, that is, observing nuclear recoils using a MeV neutron source like ^{241}Am/Be or ^{252}Cf. A technical report will be prepared at the completion of the feasibility studies.

3.4 Resource Requested

The Proposal is on a "Feasibility Study" and hence the request of funding is rather modest. The more important part is the commitment of additional and dedicated manpower to carry out this program. The existing AS and NTU groups will participate at a part-time basis, in parallel with the on-going programs.

The request can be summarized as follows :

Funding: We request the funding for equipment and materials at 1 MNT per year for two year. The major expense items will be on crystal fabrication, readout (PMT, APD) device, electronics and data acquisition equipment. Computing power can be provided by existing facilities.

Manpower: We request a full-time post-doc position and a visitor position for two years. We hope to get one or two NTU students for thesis work. We may also invite some crystal expertise from IHEP-Beijing to collaborate.

We envisage a time-scale of 1 to 1.5 year to carry out this feasibility study, upon availability of the above-mentioned resources.

4 Scenarios for Future Evolution

The "feasibility study" is an exploratory effort. There is a "baseline project" on CsI(Tl) detector, but meanwhile, we would keep our options open for the other detection schemes, already proposed or totally new. For instance, the AS high energy physics group has been involved in a R&D project with a French group on the superheated superconducting granule detector [9], which is a recognized contender for WIMP searches.

There are various scenarios where the future may evolve.

1. If the conclusion of the feasibility studies would be positive, that is, we demonstrate that the CsI(Tl) detection scheme is resource-wise affordable, technically manageable and physics-wise competitive, we will then submit a full-scale proposal for the actual experiment.

2. If we conclude that the baseline scheme is not the most optimal way to pursue, there are various alternatives to proceed :

   - We may choose to work on another subject. Much expertise would have been acquired that there are many options in the arena of low-background experiments alone.
   - We would have learned the subject well enough and developed a matured taste on the various techniques, such that we can focus on a new idea and/or identify a good experiment in the world to participate in.

The feasibility R&D studies will enable us to involve in a topical subject and equip us with the experience and know-how which have general applications in non-accelerator low-background physics. It will enrich the physics and astrophysics research scenes in Taiwan. The resources requested are modest. Whatever the outcomes, we believe that the efforts would be worthwhile.

5 Outlook

Dark Matter is a very important subject in particle physics and cosmology, and will remain so in the coming decades and beyond. There are much intellectual contents both in the physics and in the detection schemes.

The NTU and AS groups propose to pursue a feasibility study on the use of CsI(Tl) crystal scintillator to look for Cold Dark Matter. We have built up a substantial base and infrastructure to make such a research program possible. We hope that this will be the first step towards a long-term program in an exciting field.

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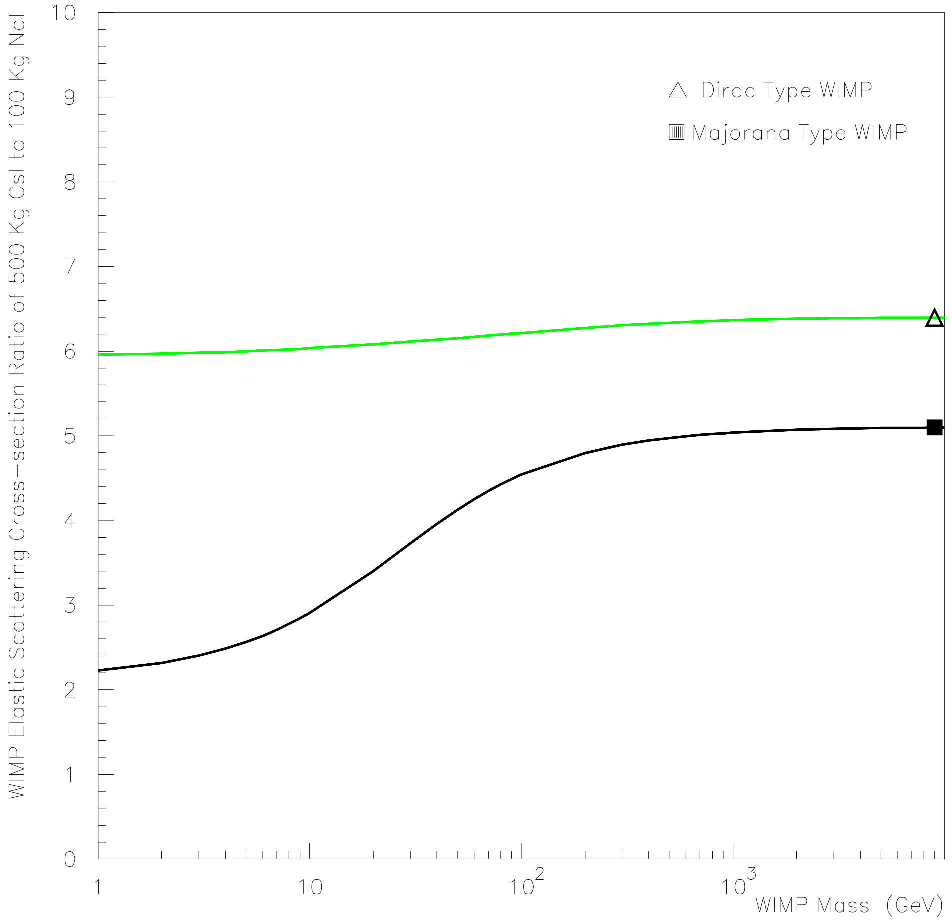


Figure 1: The relative merit in signal rates between 500 kg of CsI(Tl) with 100 kg of NaI(Tl), for both Dirac and Majorana-type WIMPs.

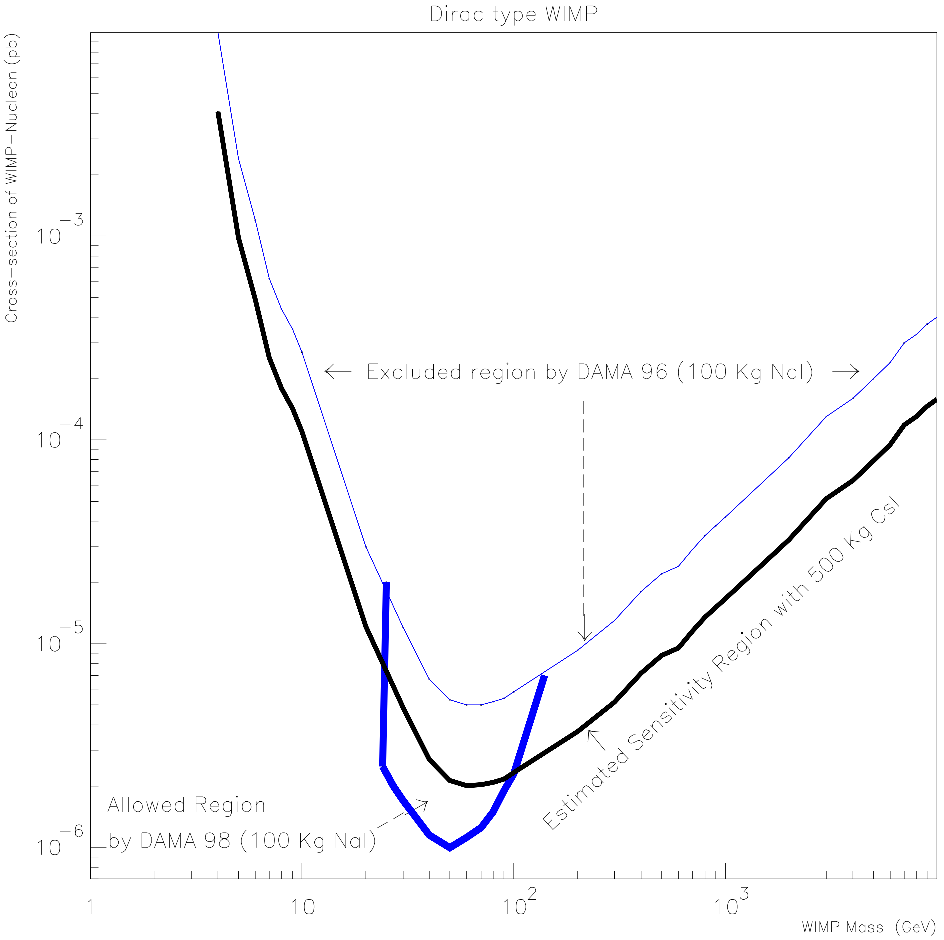


Figure 2: Expected sensitivity region for a 500 kg CsI(Tl) detector in the "$\sigma_{\chi p}$ Vs M_χ" parameter space for spin independent cross section, applicable to Dirac-type WIMPs.

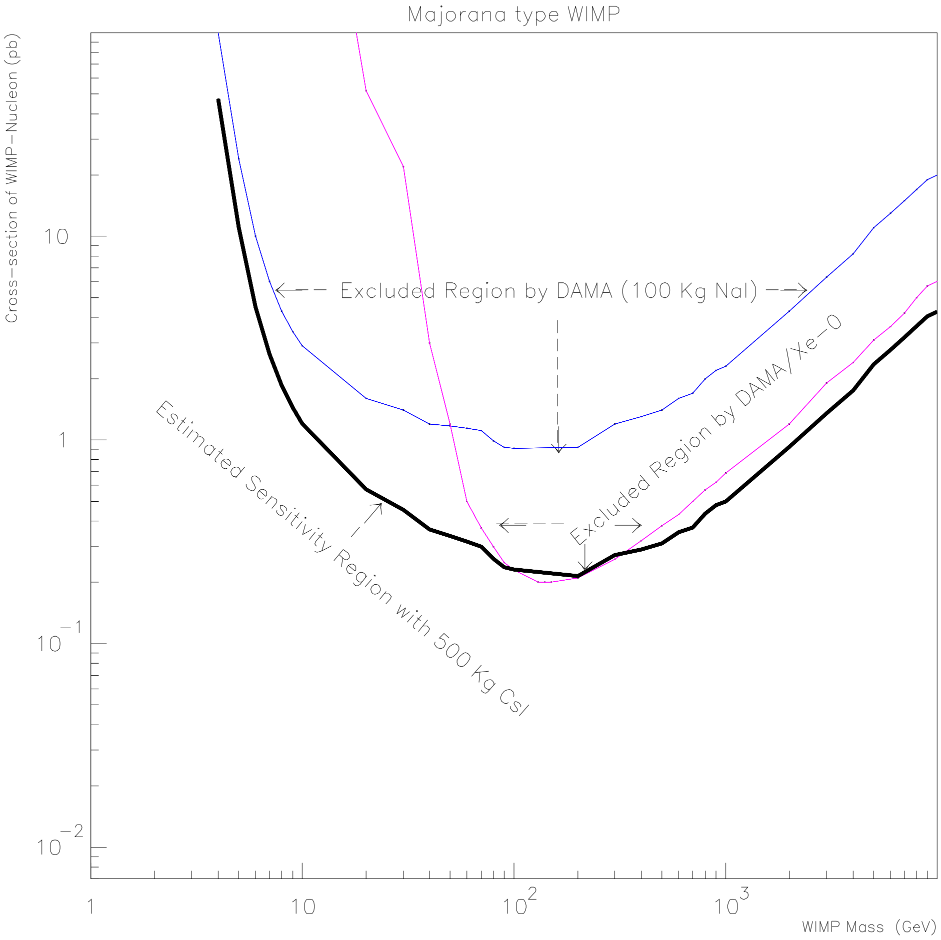


Figure 3: Expected sensitivity region for a 500 kg CsI(Tl) detector in the "$\sigma_{\chi p}$ Vs M_χ" parameter space for spin dependent cross section, applicable to Majorana-type WIMPs.

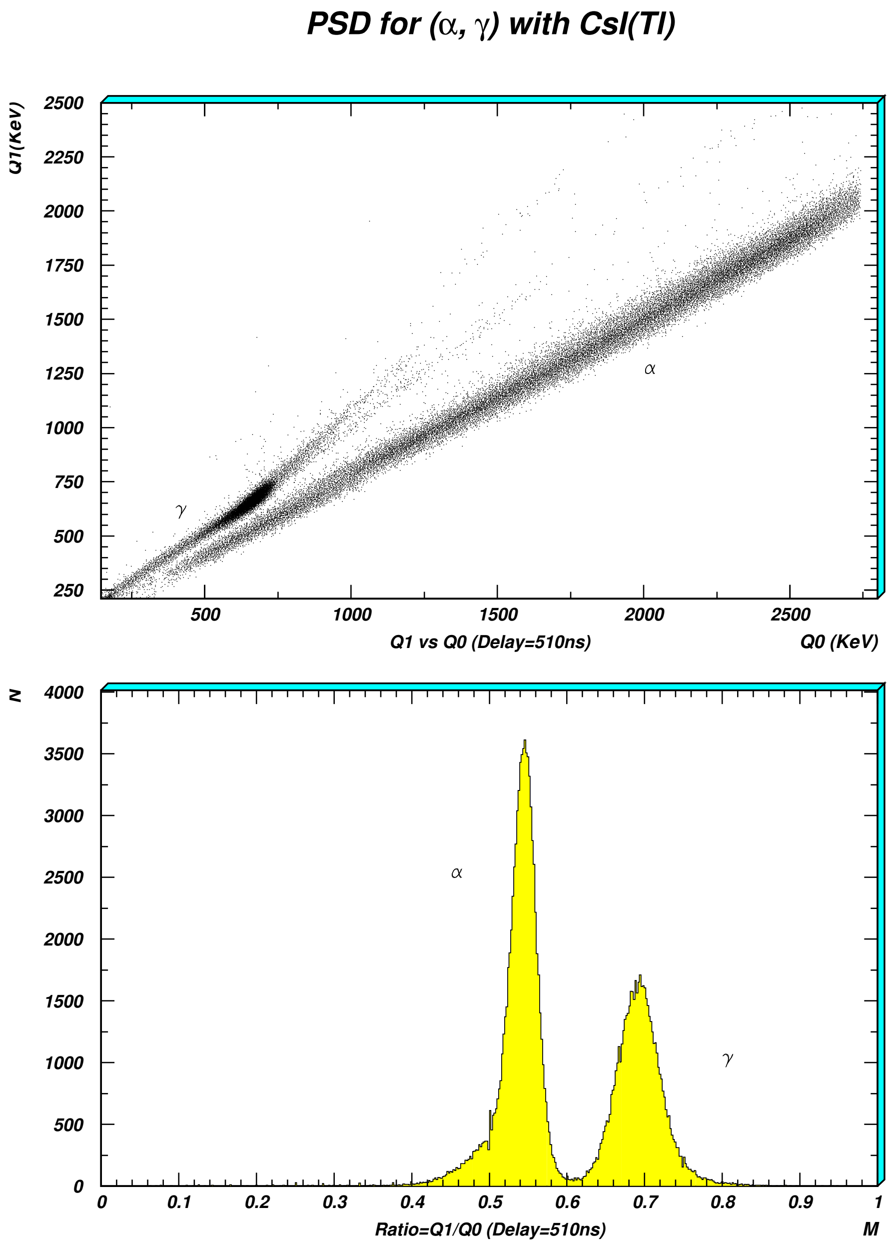
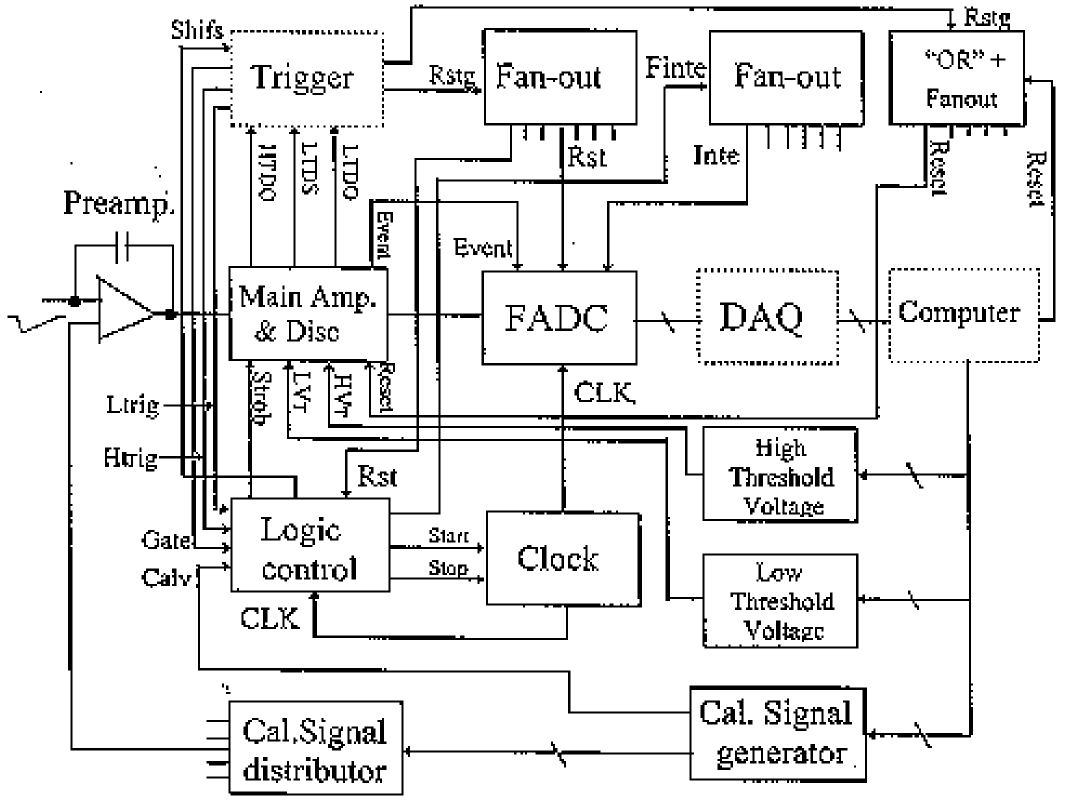


Figure 4: The pulse shape discrimination spectra for α and γ, the separation of which indicates the capabilities of event identification.



Notes:

LTDO – Low Threshold Discrimination "Or" output
HTDO – High Threshold Discrimination "Or" output
LTDS – Low Threshold Discrimination Series output
Strob – Strobe signal
Event – Low Threshold Discrimination "Or" output enabled by strob falling edge.
Finte – FADC INTerrupt Enable
Stop – to stop clock
CLK—CLocK signal
LVT—Low Threshold voltage
HVT – High Threshold voltage
Rstg – Reset signal given by trigger when level-2 trig is negative.
Inte – Interrupt Enable for FADC, which is the fanout of Finte.
RST—ReSeT signal for logic control and FADC, which is the fanout of Rstg.
Calv – Calibration Valid
Shifs – Shift start

Figure 5: Schematic layout of the TEXONO electronics system design for 500 channels of CsI(Tl) detector. Such a system can be readily adapted to a WIMP search experiment.