“**Liquid Xenon R&D for Future Large-Scale Dark-Matter Detectors**”

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ABSTRACT

A strong theoretical candidate for weakly interacting massive particles (WIMPs) is the neutralino. The neutralino is the lightest supersymmetric particle (LSP), from supersymmetry (SUSY) theory, that would be formed in the early universe and subsequently cluster in galaxies with normal matter. This could account for the ~90% non-luminous mass inferred in our Galaxy from the motion of stars and gas, and forming a dark halo extending to 150-200 kpc. If the dark matter consists of nuetralinos, these could in princple be detected by collisions with normal matter, producing nuclear recoil typically in the range 1-30 keV and with predicted rates 10^{-1} – 10^{-3}/kg/day.

Experiments so far have achieved sensitivities down to ~ 1/kg/day without observing a nuclear recoil signal, although the DAMA group have abserved a seasonal variation in background which they claim could be caused by dark matter events. There are therefore intensive efforts to reach lower levels of sensitivity in the direct observation of nuclear recoils. The ZEPLIN-II detector (with 35-kg of liquid xenon medium), which currently has the best possibility of reaching the lowest limit, will be installed and taking data at the UK Boulby Mine next year (2002). The current research and development program (for which an NSF proposal is pending) comprises the operation of the 35-kg ZEPLIN-II detector at Boulby. ZEPLIN II will cover well below the DAMA regions. However, to cover completely the predicted SUSY dark matter regions, a large one-ton scale detector with low background, low energy threshold and high background discrimination is needed. With supplemental funding from the DOE Advanced Detector Research Program, we will be able to study the performance of the ZEPLIN-II detector and carry out a series of tests to optimize the design for the one-ton detector. These tests will include:

1. photon amplification in liquid and gas xenon using a CsI internal photo-cathode,
2. ionization yield in liquid and gas xenon due to recoil nuclei at low energies.
3. low radioactive background photon readout devices R&D and, ^{85}Kr removal from xenon.
4. optimization of the ZEPLIN-II operation and combine 1, 2, 3, for the ZEPLIN II scale up.

If accomplished, the one-ton xenon detector (with low energy threshold, extremely low background, ^{85}Kr free and large mass) will be the best option for the future US national underground science laboratory for dark matter search.

Liquid-noble-gas time-projection-chamber (TPC) technology has been utilized for a couple of key frontiers in high-energy physics experiments, including the ICARUS experiment. The ZEPLIN-II detector that is under construction at the UCLA Dark Matter Laboratory fully utilizes this technology. The UCLA group's participation in the ICARUS experiment (using liquid Ar) and in its R&D on a liquid xenon dark matter detector, has shown that the UCLA group is best suited to carry out the next generation dark matter detector R&D and operation. In addition, with new institutions (TAMU, Princeton) joining the quest, we are forming the best team with expertise from various high-energy physics experiments for this effort.

A preliminary test at CERN in the gaseous xenon chamber showed that a CsI internal photo-cathode produced approximately 10 times overall amplification, taking CsI quantum efficiency into account. With repeated measurements of the experiment, the firm limit of amplification ratio can be achieved for the double-phase (liquid and gas) detector. This will lower the detector energy threshold significantly.

Large Area Avalanche Photo Diode (LAAPD) and Gas Electron Multipliers (GEM) are of new devices, which if carefully optimized, could be used as single photon readout devices with very low radioactive background. PMTs currently used in ZEPLIN II may become the limiting background sources in the

detector for the future. To fully explore the SUSY region, this option should be investigated to achieve extremely low background detector.

ZEPLIN II will have 0.1% intrinsic dead region in the design. If the nuclear recoil produce insufficient ionization, this is the limiting factor for background rejection in ZEPLIN II. In order to fully utilize the xenon background rejection power, dead regions should be completely eliminated. The possibility of ionization yield due to recoil nuclei at low energies will provide the key to the design of a detector not limited by dead regions. The current ZEPLIN II detector is an ideal device for such studies.

Overall, it is very promising with all the new technologies available today that a next generation detector for future dark matter search can be built in the near future. It is very important that the US participation in the search for dark matter be expanded. It is very clear that a two-phase xenon detector has a scientific and technological edge for detecting the undiscovered dark matter particles. We believe that these proposed studies will solidify the position of future US participation in the worldwide dark matter searches. Successful test results, combined with the ZEPLIN-II system, would produce an ideal dark matter detector for the future Underground Laboratory in the US.

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1 Project Objectives

Since the on-going ZEPLIN-II project (described below in detail) (and also the CDMS-II) has currently the best possibility of reaching the lowest limit of neutralino detection, it could be best viewed as R&D for the ultimate scale-up dark-matter detector. Although the ZEPLIN-II detector has been optimized vastly for maximum performance to reach well below the DAMA region, there is room for improving the technique, for example, to lower the detector energy threshold to reduce the form factor effect, to reduce radioactivity in the detector itself (including ^{85}Kr removal in the xenon liquid) to keep the initial background at a ultra low level and, to eliminate dead regions to improve discrimination. These are the key issues if we want to have a large-scale dark matter detector to explore completely the SUSY dark matter region.

The proposed R&D program has the following objectives:

a) Primary scintillation photon amplification to reduce energy threshold

We want to set a firm limit of electroluminescent photon amplification through the careful measurement of a proven amplification method, a CsI internal photocathode in a simple two-phase xenon setup. Preliminary test in xenon gas with a CsI internal photo-cathode for the primary-scintillation photon amplification at CERN showed that a possible amplification factor of ten could be achieved. A further study of this research effort should be carried out for the current two-phase xenon detector with a better precision of the amplification.

b) Low radioactive photon readout device R&D and ^{85}Kr removal

If SUSY dark matter is not in the DAMA region and even lower limit need to be reached, extremely low radioactive materials should be used in the detector construction, including removal of ^{85}Kr from the target (xenon) itself. All electronics and photon readout devices must also be constructed with low radioactive materials. The PMT readout system in current design may become the limiting factor even with careful veto system. The LAAPD or GEM variant may be the best option. They are all capable of single photo counting. It is very important to study the possibility of optimizing such devices.

c) Determine ionization yield due to recoil nuclei at low energies in liquid and gas xenon

ZEPLN II detector has 0.1% dead region intrinsic to the design. Any background events in these regions will lose ionization charge hence look like recoil events. By requiring secondary signal from recoil, those events in dead regions having a single pulse will be rejected. This will completely eliminate the dead regions so that the discrimination power will depend only on the xenon properties, which is expected much higher than 99.9%. The current ZEPLIN II design has the capability to have a very high electric field in the drift region for ionization electron extraction. We propose to study this during ZEPLIN II operation at Boulby mine and at TAMU using the CsI test system on a neutron beam.

The UCLA group's research efforts have been carried out extensively at CERN in collaboration with P. Picchi (the Torino group) using the ICARUS R&D facility. The successful operation of ICARUS T600 will lead the shift in objective at the CERN lab. We would like to request funding to shift the R&D work back to the US (including a possible transfer of equipment from CERN) to achieve the outlined project objectives, considering the significance of having these types of experiment on the US soil. We believe that the proposed research program is crucial as an R&D program for the ultimate liquid-xenon dark-matter detector to be built possibly at a US national underground science laboratory.

We will describe the objective in the following section separately.

The search for SUSY WIMPs may also require a very sensitive detector capable of reaching 10^{-4} events/kg/day (or less), which will require very powerful discrimination and a massive detector. **Figure 2** shows a range of models for SUSY WIMPs and the expected rates. Note that very low rates are possible in these models. We also show in **Figure 2** the expected sensitivities of CDMS-II and ZEPLIN-II. In order to improve the sensitivity of the liquid xenon detector, the above listed objectives must be tested. If all of these can be accomplished, we may reach the level of sensitivity labeled as ZEPLIN-IV in **Figure 2**. Note that this would be very complementary to that of CDMS-II and could help confirm any signal CDMS-II may claim in the near future using a totally different technique. For this reason we believe that the objectives proposed here are very important for the ultimate search for dark matter WIMPs.

The goal of this proposal is to realize a large xenon discriminating detector. Results of these studies could be used in the current ZEPLIN-II upgrade in the future and/or applied to a future large-scale dark-matter detector. A future large-scale detector based on ZEPLIN-II and the CsI internal photocathode could be realized as shown in **Figure 1**. It is only 500 kg and already is sensitive to most SUSY regions, as shown in **Figure 2**. New single photon-readout devices may replace the PMT tubes.

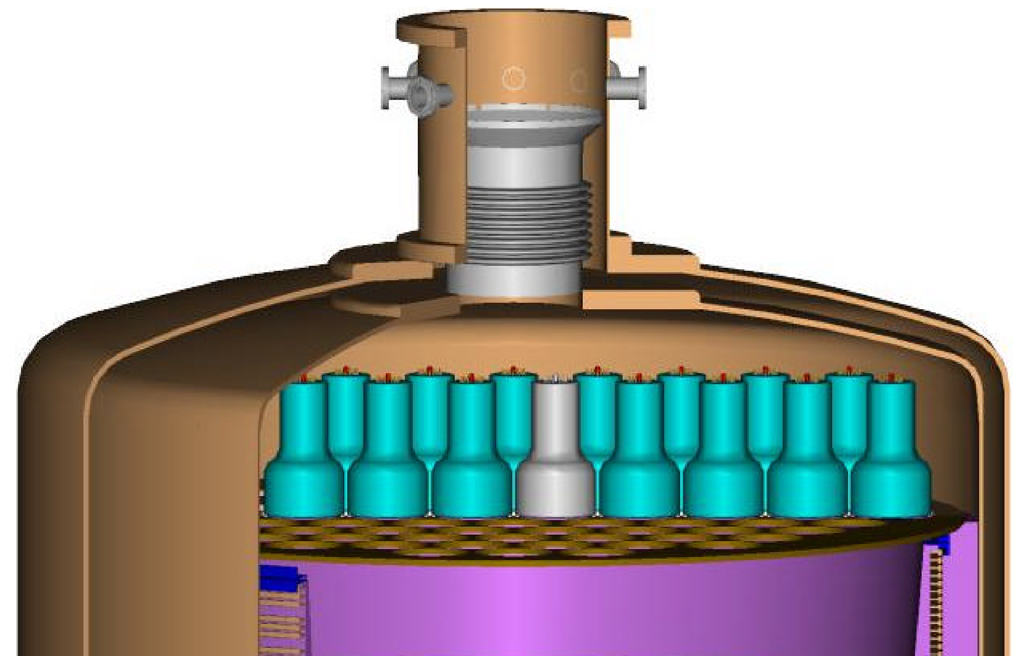


Figure 1 The conceptual drawing of the ZEPLIN-IV detector (500-kg liquid-xenon target) based on the ZEPLIN-II design and the expected CsI internal photocathode results. (Electronics are not shown.) New single photo readout devices may replace the PMTs.

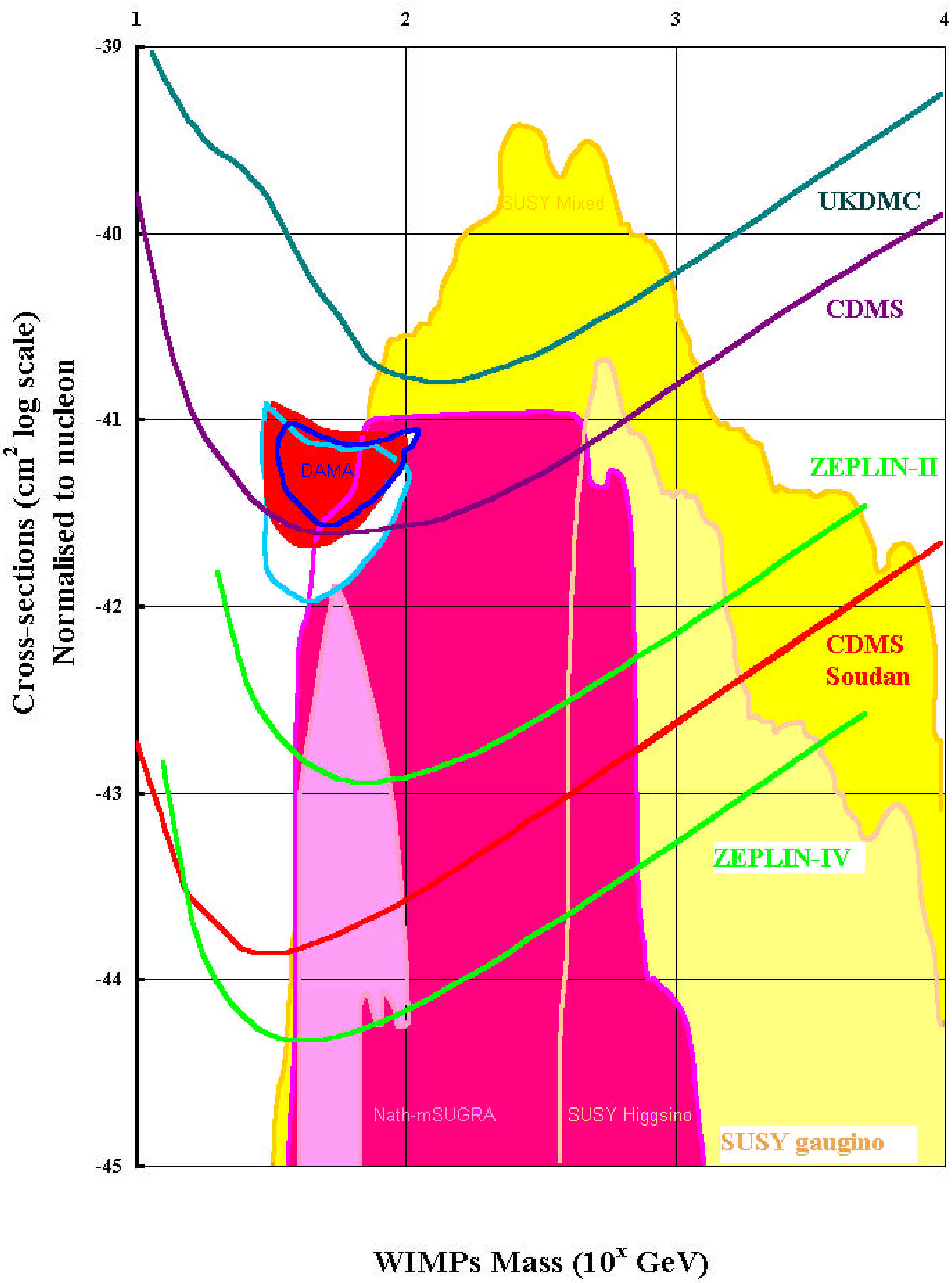


Figure 2 Summary of sensitivities in current experiments (CDMS & DAMA) and expectations from future experiments (CDMS & ZEPLIN-II). Curve labeled as ZEPLIN-IV shows the expected sensitivity with improved energy threshold (in this proposal) and scaled-up design, using scintillation techniques, showing objectives of the liquid-xenon ZEPLIN program. The CDMS collaboration has similar objectives, using a cryogenic phonon + ionization technique with semi-conducting Ge & Si as targets (in the Soudan Mine, Minnesota from 2001). A muon veto is required for rates below 0.1/kg/d at Soudan and for rates below 0.01/kg/d at the greater depth of the Boulby Mine, UK.

2 Introduction

2.1 Neutralino as the strongest WIMP dark matter candidate

The experimental search for cold dark matter is one of the most exciting challenges of the next few years, for both cosmology and particle physics. Increasing observational evidence continues to indicate that the majority of dark matter in galaxies and galaxy clusters is in a non-baryonic form. Moreover, the strongest theoretically suggested dark matter candidate is WIMP (Weakly Interacting Massive Particle) in the form of the lightest supersymmetric particle (LSP or 'neutralino' in this proposal) of supersymmetry theory, which would be formed in the early universe and subsequently clustered in Galaxies with normal matter. Scattering with normal matter would produce detectable nuclear recoils. Estimates of interaction event rates are in the range 0.001- 1 events/kg/d, the most favored region being 0.01 - 0.1 events/kg/d.

No experiment is yet running, which could observe such low event rates. Intensive world development work has been in progress to reach a level of sufficient sensitivity to observe these theoricially proposed neutralino-normal matter interaction signals. Following such detection, a scaled-up or an array of small existing detectors with other types of detectors, which might have different detection schemes would constitute a `dark matter telescope' to study the astrophysical properties of the dark matter (including density and Galactic velocity distribution) in addition to determining the basic particle properties (mass, spin-dependence, and etc.).

2.2 Case for non-baryonic dark matter and experimental efforts

The nature of the non-luminous matter in the universe continues to be a major unsolved problem at the interface of astronomy and particle physics. The motion of stars and gas out to >100 kpc allows the mass profile of the Galaxy to be estimated, and shows that the visible stars constitute only 10% of the Galactic mass, immersed in non-luminous matter which constitutes the other 90%. Similar conclusions result for other galaxies. The candidate explanations for Galactic dark matter are in two main classes

(a) Baryonic: e.g. non-luminous stars of less than 1 solar mass, referred to as MACHOs.

(b) Non-baryonic: e.g. new weakly interacting massive particles (WIMPs) or new light bosons (eg axions), light neutrinos.

Dynamical observations alone cannot distinguish between (a) and (b), but there are other observations which now strongly favor (b). In particular,

(i) The majority of dark halos in spiral galaxies are not known to extend to radii of at least 100-200 kpc. If baryonic (e.g. in the form of molecular hydrogen or ionized hydrogen as sometimes suggested), this would give a density parameter $\Omega_b > 0.1$, which would then exceed by a substantial margin the nucleosynthesis limit $\Omega_b = 0.4 \pm 0.2$ (Weinberg et al., 1998 ApJ, Copi et al., 1995 PRL 75, 3981). Many astronomers regard this in itself as a convincing argument for non-baryonic dark matter as the dominant component of our Galaxy.

(ii) The behavior of off-axis visible matter and gas can be used to infer that the dark halos are not flattened like the baryonic disk, but are in the form of an ellipsoid of eccentricity ~ 31. This shows that the halo material did not relax into a disk, as would be expected if it were weakly interacting.

(iii) Measurements of the Suntaev-Zeldovich effect on the CMB can be used to estimate the electron density in galaxy clusters, and hence the corresponding baryon density. Latest results (Birkinshaw, IAU2000) show only 7±1% of the dark matter in clusters to be in baryonic form. Thus it is regarded as a firm conclusion that the majority of cluster dark matter is non-baryonic. A substantial amount of this must also be in the individual galaxies, since these must contain at least a component due to infall from the cluster.

(iv) Searches for MACHOs in our Galaxy by gravitational lensing continue to see too few events to account for more than about 20% of the total Galactic dark matter .

The case for a particle explanation is thus now strengthened. The most experimentally accessible are the WIMPs, with the particular theoretical possibility of a lightest, stable, supersymmetric particle. At typical Galactic velocities (0.001c) these would be observable as keV-range nuclear recoils from elastic scattering in low background underground detectors.

Other classes of particle are more difficult experimentally, and perhaps also less favored theoretically. One experiment is in progress in the US to search for light axions, through conversion to microwave photons in a magnetic field. Light neutrinos are difficult to reconcile with galaxy formation models but remain possible in principle, requiring one neutrino to have a mass ~20 - 50 eV. Because of their low energy (10^{-4} - 10^{-2} eV) these are not experimentally detectable in the foreseeable future, although a neutrino mass in the 10 - 50 eV range is not definitively excluded and could be directly verified by time of flight from a supernova. Recent indications from SuperKamiokande of atmospheric neutrino oscillations appear to suggest a neutrino mass scale (< 1 eV) too low to account for a significant fraction of the dark matter.

Supersymmetry continues to be an important candidate theory for accounting for a natural particle mass hierarchy. In particular, it predicts the existence of a lightest (stable) supersymmetric particle - the neutralino - with mass > 40 GeV (from accelerator searches) and most probably < 200 GeV from theoretical considerations (Roszkowski 1997 Dubna workshop) Such particles would be created in large numbers in the early universe and would subsequently cluster in association with normal matter. The neutralino has thus become a leading candidate for the dark matter, with the merit that the theory makes order-of-magnitude predictions of the event rates expected in specific target nuclei. Dependent on model parameters, event rate estimates are in the range 0.001-1/kg/d, with the narrower range 0.01 - 0.1/kg/d most favored. For detailed discussions of supersymmetry and dark matter see Jungman et al. (1996 Phys Rep 267, 195), Kane et al. (1994 PRD 49, 6173), Treille (1994 RPP 57, 1137), Roszkowski (1997 Dubna workshop), Ellis (1991 Physica Scripta T36, 142), Nojiri & Drees (Phys Rev D48, 3483), Arnowitt & Nath (1995 MPL A10, 1257, PRL 74, 45992).

Nevertheless, experiments based on nuclear recoil cover a wider range of possible particles, since they are free from any assumptions about the nature of the particles or their theoretical basis. The outcome of low energy scattering from a nucleus depends purely on kinematics, and the expected nuclear recoil spectrum follows in a simple way from the incident and target masses, together with the expected Galactic velocity distribution. Thus any particle in the 10 - 1000 GeV mass range, including a heavy neutrino for example, would be detectable in these experiments.

An additional consideration is that some types of interaction may be spin-dependent, so it is important to include target nuclei with non-zero spin. In the case of the neutralino a mixture of spin-dependent and spin-independent interactions is expected, so that any target material should be sensitive to such particles. In the spin-independent case, the rate for low momentum transfer will be proportional to the square of the number of neutrons and/or protons in the nucleus (for example only neutrons contribute significantly in the case of Dirac neutrinos) but with increasing recoil energy the inverse momentum transfer (fermi) becomes comparable to or less than the nuclear radius and all interaction rates are reduced by a form factor correction (see below). This provides an important incentive for achieving the lowest possible detection energy threshold, which in addition maximizes the fraction of events collected for a wide range of particle masses.

In the event of observation of a positive signal there are in principle two methods of proving this to be of Galactic origin. The first would be to scale-up to a sufficiently large target mass (typically >100 kg) to observe the annual modulation in rate and energy spectrum arising from the motion of the earth around the sun, combined with the sun's motion through the Galaxy. The mathematics of these results in a ± 5% rate modulation (dependent on energy threshold) with a maximum in June and minimum in December. The second possibility is to develop a detector capable of measuring recoil direction, for which there is a typical 4:1 forward:back ratio relative to the direction of motion through the Galaxy, so that the earth's rotation gives a diurnal modulation an order of magnitude larger than the annual modulation. Because low energy recoils have a short range (~1-5 $\mu g/cm^2$) directionality will require sub-micron target layers, or low pressure gas detectors to record recoil direction as tracks, and hence observe individual events correlated with Galactic motion.

In either case it is essential that the events shown specifically to be nuclear recoils. A recent claim by the DAMA (Rome) collaboration to have observed seasonal modulation in count rate from NaI crystals has the defect that the modulation is observed in the total count rate - which includes gamma, beta and alpha background (plus any systematic error including that observed in the UK NaI detectors) and is also close to the electronic noise threshold. There is no analysis offered to show the modulation as a function of pulse shape. Our ZEPLIN-II detector will search for seasonal modulation specifically in an identified population of nuclear recoil events (with neutron events excluded) and hence would be definitive.

Figure 2 shows the expected sensitivity of the ZEPLIN-II detector along with other world programs, notably the CDMS cryogenic experiment to be installed in the Soudan Mine, have similar objectives.

2.3 Underground laboratory for low background

In order to keep the level of background noise from the already known particles (neutron, gamma, alpha, beta and etc.) as low as possible, a deep underground laboratory to facilitate any developed detector is necessary with a large veto system. In a deep underground location, neutron background can be reduced to a level below the expected event rate so that observation of nuclear recoil events would provide clear evidence of a flux of new neutral particles. Since the majority of detector types will also detect electron recoils, it is also essential to devise methods, which discriminate nuclear recoil events from beta & gamma background.

For the ZEPLIN-II detector, we chose the UK Boulby Salt Mine for the installation. Our UK collaborators for the ZEPLIN-II project have been developing excellent facilities and infrastructure for dark matter searches in the 1100m deep Boulby Mine. Low backgrounds have been demonstrated in the initial program based on pulse shape discrimination in NaI. The UK program has now been funded to include liquid xenon targets, and a preliminary small xenon detector (5-kg target) using only pulse shape discrimination has been installed underground with its associated cryogenic, purification, and safety systems.

The UK and US programs are now formally linked by an MOU, in which the combined expertise of the two groups would be used to construct and operate a scaled up version of the proven UCLA test chamber, with liquid xenon mass 35kg and referred to as ZEPLIN-II. The initial hardware funding for this, including a surrounding veto and shielding system, is being provided largely by the UK. The key central chamber is under construction at UCLA by UCLA/Torino group.

3 Detection Principles and Background Discrimination

In order to better describe our proposed R&D work for two-phase xenon detector for the dark matter search, understanding principles of basic detection scheme and discrimination methods for nuclear recoil signal are necessary. We summarize them in the following.

3.1 Energy spectrum, event rates, background discrimination

The nuclear recoil signal is expected to be in the form of a continuous spectrum with differential counting rate (events/keV/kg/day) as a function of recoil energy E_R (keV) approximated by

$$dR/dE_R = c_1 (R_o / E_o r) [\exp(-c_2 E_R/E_o r)] [F(E_R)]^2, \quad (1)$$

where $r = 4M_D A/(M_D+A)^2$ for target element A and incident particle mass M_D , $E_o = M_D v_o^2/2$ (v_o = Galactic velocity dispersion $\approx$ 210 km/s, E_o converted to keV) and F^2 is a nuclear form factor correction. There may be further correction factors to allow for detection efficiency and the fraction of a given element in a compound target (e.g. only about 50% of a xenon target has nuclear spin). The coefficients $0.5 < c_1, c_2 < 1$ provide a convenient way of modifying the formula for the motion of the earth relative to the Galaxy. For a stationary earth, $c_1 = c_2 = 1$ giving total event rate R_o. The motion of the sun modifies this to $c_1 \approx 0.78$, $c_2 \approx 0.58$ with further ±5% annual variations arising from the orbital motion of the earth (for a full discussion of the mathematics of dark matter experiments see Smith & Lewin, Astroparticle Physics 6 (96) 87).

Thus a limit on, or measurement of, the differential rate dR/dE_R for a given E_R leads to a corresponding limit or value for R_o for each assumed particle mass M_D. This is the basis of the limit curves in **Figure 2**, the minimum of the curves occurring approximately when $M_D \approx A$. Because the above spectrum falls sharply with energy, a low energy threshold (< 10-keV) is important. Moreover, scintillation detectors will in general respond to nuclear recoils with a light output, which is less than the electron or gamma-equivalent energy. This relative scintillation efficiency, or 'quenching factor' f_A, has to be measured for any target element A by using neutron scattering to produce the nuclear recoils. The importance of this is that a detector is calibrated with gammas (electron recoils) then any nuclear recoil event of observed energy E_{obs} corresponds to a true recoil energy $E_R = E_{obs} / f_A$ and it is this value which applies throughout eq.(1). Examples of well-established measured values of f_A are ~ 0.3 for Na in NaI, and ~ 0.09 for I in NaI. Recent measurements of f_A for xenon by this collaboration, using neutron beam facilities at Legnaro, Italy and at Sheffield, have given the value $f_{Xe} = 0.22 \pm 0.02$. The recoil efficiency affects experimental sensitivity in particular through the form factor correction, which follows approximately a Bessel function in qR_A where R_A = nuclear radius and momentum transfer $q \approx \sqrt{(2AE_R)} = \sqrt{(2AE_{obs}/f_A)}$. Form factors are discussed further in **§3.5**.

The left hand side of eq. (1) will contain the detector background plus any signal. Discrimination in liquid xenon allows an upper limit to be placed on the signal content as a fraction of background events. Substitution of this upper limit on the left side of eq. (1) then allows an upper limit on R_o to be plotted as a function of the hypothetical particle mass M_D.

3.2 Statistical enhancement of discrimination

There will in general be an overlap between signal and background event distributions as a function of some discriminating parameter *p* (such as pulse time constant). A 'cut' on *p* to include, say, 90% of the signal events, will also include some (energy-dependent) fraction f_g of misidentified background events. Thus a straight 'cut' to the data would be limited to a factor f_g gain in sensitivity. However much larger gains are possible by statistical analysis of a long run of data. By calibrating a detector with gammas and neutrons, event distributions for nuclear recoils and gammas can be obtained as a function of energy and of the discriminating parameter p.

These are determined separately for discrete energy intervals E_1 to E_2 (typically a few keV) and will in general vary slowly with energy, determined from the calibration data. For zero nuclear recoil signal, the experimental background distribution is expected to coincide with the gamma calibration distribution. An upper limit to the signal can then be estimated from the 90% confidence level fluctuations on the background, giving a 90% confidence level for the ratio of signal events S to background events N:

$$S/N \leq C\ N^{-0.5} \quad \text{with} \quad C = 1.3\,[f_g\,(1-f_g\,)]^{0.5} / [\,f_n - f_g]\,, \qquad (2)$$

where f_n , f_g are the fractions of nuclear recoil and gamma events below some value of p.

Thus the signal sensitivity in events per unit time improves not only linearly with reduction in background rate but also inversely as the square root of the number of counts in any specified energy interval. The numerical factor C which can be called a ‘coefficient of discrimination’. From the distributions in p a value of p can in general be found for which C is optimum (i.e., minimum). This provides a basic 'figure of merit’ with which to compare discrimination techniques. With actual data from an operational experiment a full chi squared analysis can be used to place a limit on the existence of a second population, but the use of the discrimination coefficient C provides a convenient means of assessing in advance any given technique or experiment.

3.3 Liquid xenon as a dark matter target

Liquid xenon satisfies the following basic requirements for a dark matter target:

(a) It is available in sufficiently large quantities with high purity.

(b) It scintillates via two mechanisms, responding differently to nuclear and electron recoil events.

(c) It contains both odd and even isotopes, suitable for spin-dependent and scalar interactions, offering the possibility of using enriched odd or even isotopes to identify the type of interaction.

(d) Its high atomic number provides a good kinematical match to the most theoretically favored particle mass range 100-200 GeV.

Target masses 100-1000 kg may be needed to reach the lowest predicted event rates. The 35 kg detector proposed in the ZEPLIN-II (under construction now) project represents a major step towards this, being a factor >10 larger than previous test chambers built at CERN and could subsequently be replicated to give a total target mass 100-1000 kg. This would achieve sensitivity to the lowest neutralino event rates (0.001-0.01/kg/d) and could also detect the annual signal modulation, which would confirm the Galactic origin of any signal.

The need for detectors based on a new target material and principle is highlighted by recent unexplained results. Following initial signal limits set by underground Ge detectors, some significant advances in sensitivity were made initially by means of pulse shape discrimination in low background NaI scintillating targets. Recently both the Rome and UK groups have encountered signal-like anomalies at the level 0.5-1 events/kg/d. Rome report a seasonal modulation of total count rate, while the UK see a separated population of recoil-like pulses. We believe both have natural explanations (e.g. a source of low energy alphas) but this emphasizes the need for new detectors with higher sensitivity with different target elements.

With liquid xenon, signal discrimination can be achieved in two basic ways:

(1) By analyzing the total scintillation pulse shape - which differs by a factor ~2-3 in time constant for nuclear recoil and electron recoil events.

(2) By applying an electric field to inhibit recombination and (a) measuring the 'primary scintillation' S1 and (b) drifting the ionization component into a strong electric field in the anode region to produce a 'secondary scintillation' signal S2 with a time delay (electron drift velocity in liquid xenon at 500V/cm is about 2mm/μs).

Method (2) is more powerful, involving a comparison of two distinct signals associated with each individual event. The mean of the ratio S1/S2 differs for nuclear recoil and electron recoil events and provides the parameter p in §**3.2**, leading to a statistical signal/noise of order $\sqrt{(C/N)}$ where N is the number of background events and C is typically ~1% at a gamma energy of 10-keV. Sensitivity thus progressively improves by extended running (and larger target masses) subject to the elimination of any systematic errors that may be encountered.

Members of the ICARUS collaboration including the UCLA and Torino groups demonstrated discrimination between alphas and gammas using this technique in 1994. Further tests used neutron scattering confirmed for the first time (a) that liquid xenon will give a scintillation response to recoil of its own nuclei, and (b) that the above discrimination processes remain effective down to energies < 5-10 keV, as required for a dark matter experiment.

3.4 Nuclear recoil discrimination in liquid xenon

3.4.1 Single phase pulse shape discrimination

An extensive literature on basic excitation mechanisms in liquid xenon has shown that Xe_2^*excited states are produced which decay with two time constants 3-ns and 27-ns, emitting 175-nm photons. In addition an ionized state Xe_2^+ is produced which can recombine to $Xe_2^*$and decay as before. The proportions of these decay processes are different for excitation by electrons (from gamma interactions) and alphas (equivalent to nuclear recoil) giving effective pulse decay times ~ 45-ns for gamma interactions and ~ 15-ns for alphas (**Figure 3**). These results are for small-scale laboratory tests. In the past year, tests in the UK on a 5-kg single-phase xenon have shown that these results can be approximately reproduced on a larger scale. A ^{60}Co source was used to produce gamma interactions and an Am-Be source was used to produce a mixture of neutron and gamma interactions. Pulse analysis showed a time constant in the region 40-ns for gamma interactions and ~20-ns for neutron interactions, in reasonable agreement with the published small scale tests.

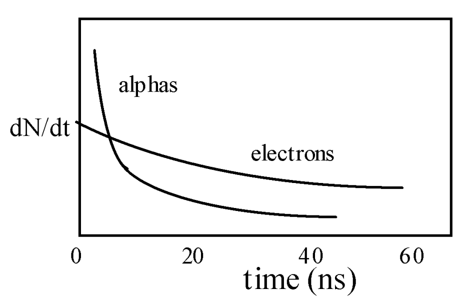


Figure 3 Scintillation pulse shape difference between alphas and electrons in liquid xenon.

3.4.2 Proportional scintillation in single phase test chambers

If an electric field is applied, the recombination process in §**3.4.1** is inhibited, and the ionization can be drifted into a stronger field to produce a second scintillation pulse, proportional to the amount of ionization. Thus a double scintillation pulse is produced - a primary pulse S1 from the initial excitation, followed a few 10-s of μs later by a secondary scintillation pulse S2 from the drifted charge. From published data on the interaction of electrons, protons and heavy ions with liquid xenon, the ratio S1/S2 is predicted to be 0.1 - 0.3 for incident nuclei and 1-10 for electrons, with an overlap between these estimated to be only a few % at 10-keV.

These expectations were confirmed by tests carried out at CERN by members of the ICARUS collaboration, in particular H. Wang of UCLA. To demonstrate the basic principle, a small (50-g) liquid xenon chamber, containing an electric field and coupled to a photomultiplier was irradiated with 5-MeV alphas and 120-keV gammas. Drift voltages of several kV suppressed recombination and a secondary scintillation signal was produced (see **Figure 4**, from Benetti et al., NIM A327(1993) 203). The ratio S2/S1, as shown in **Figure 5** and **Figure 6**, was >1 for gammas and <1 for alphas, as predicted. Subsequently, the double pulses were observed also with a larger (1-kg) chamber and two coincident photomultipliers.

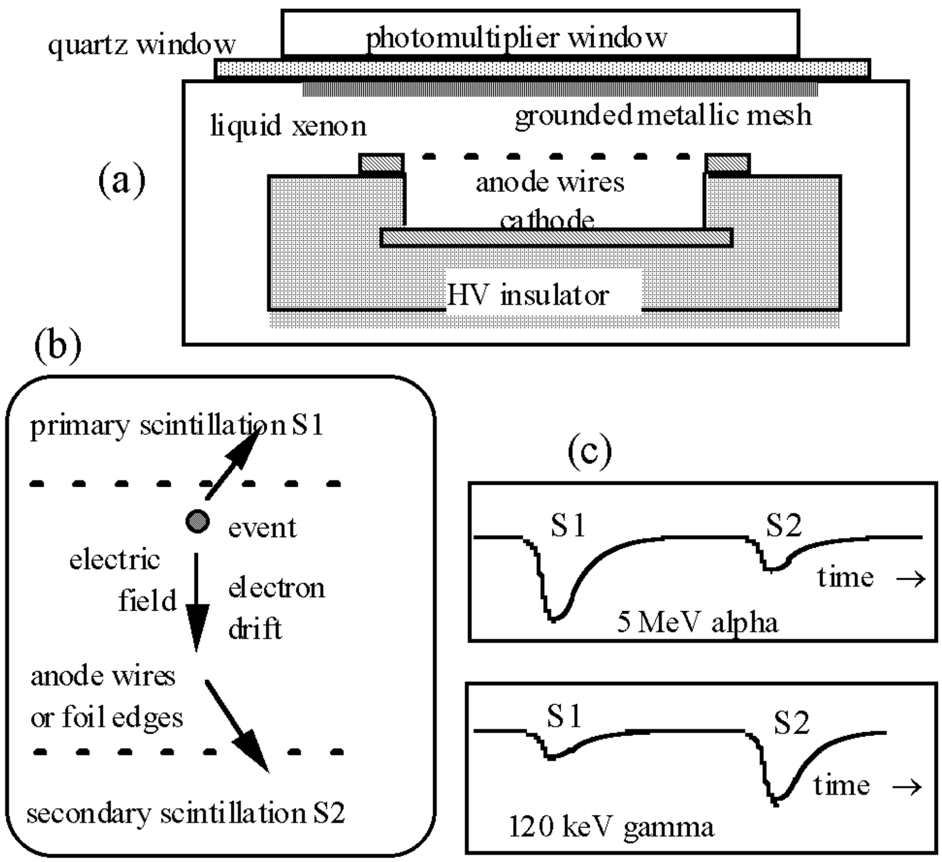


Figure 4 (a) Single phase test chamber, (b) processes following collision, and (c) S1 & S2 pulses for alpha and gamma interactions (the actual picture of (c) is shown in **Figure 7**).

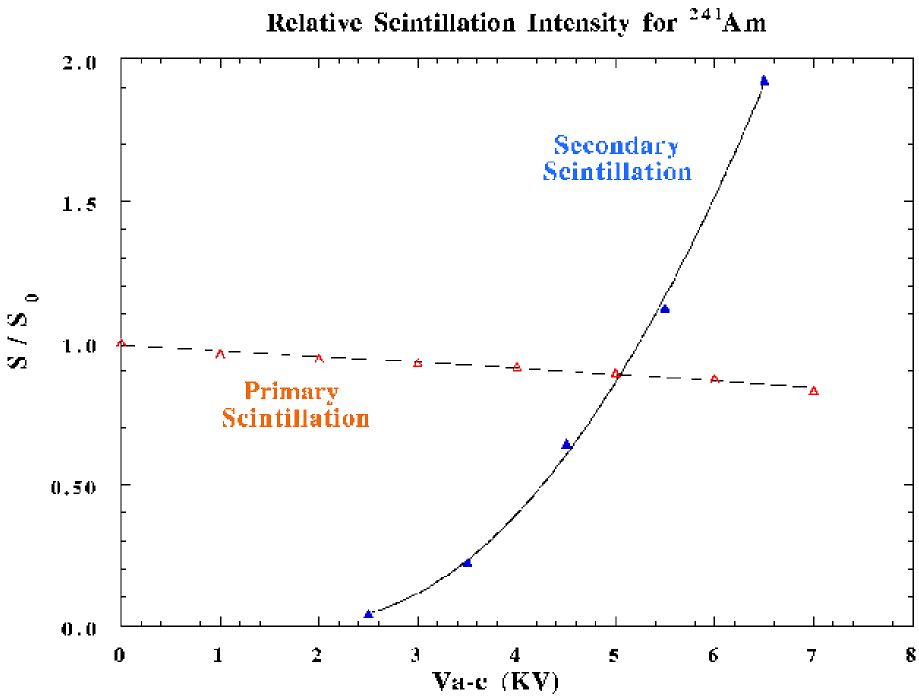


Figure 5 Normalized primary and secondary scintillation vs. applied electric field for a 5.4-MeV alpha.

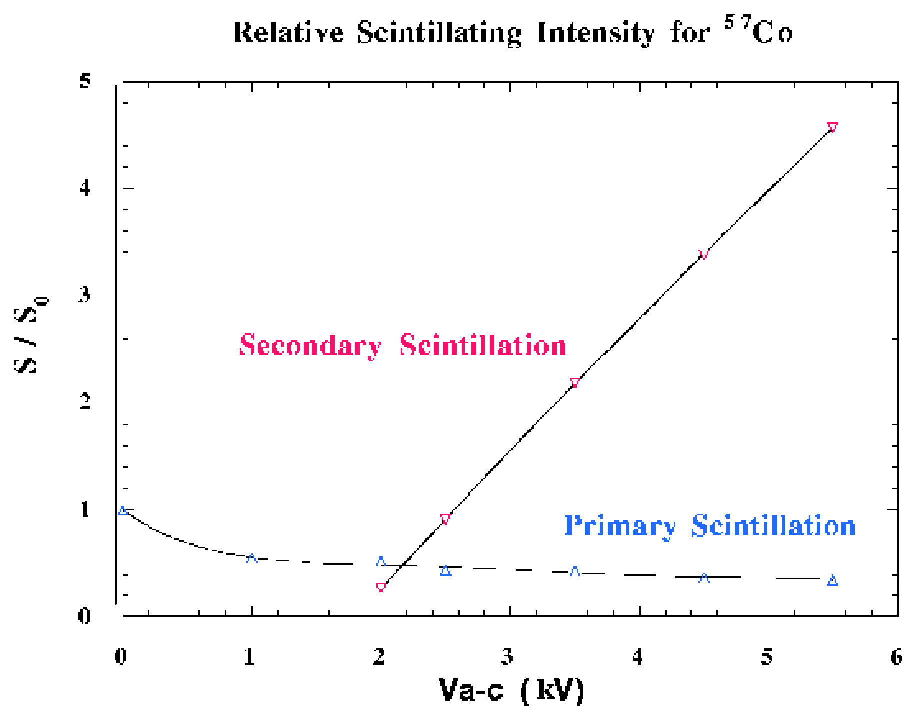
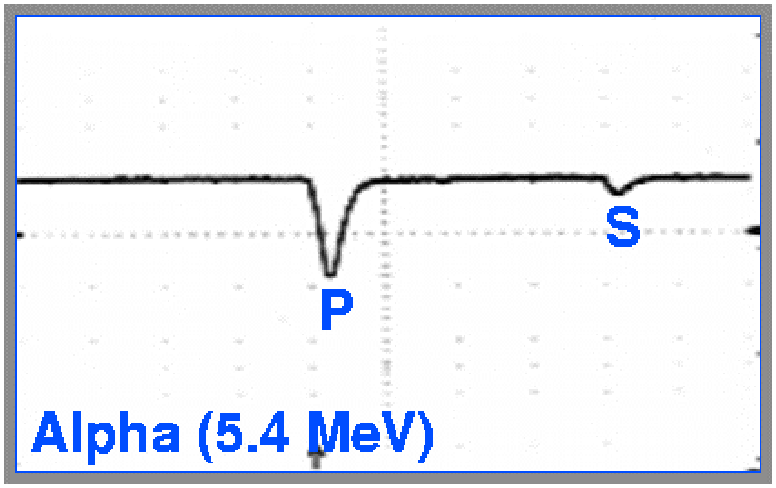


Figure 6 Normalized primary and secondary scintillation vs. applied electric field for a 100-keV gamma.



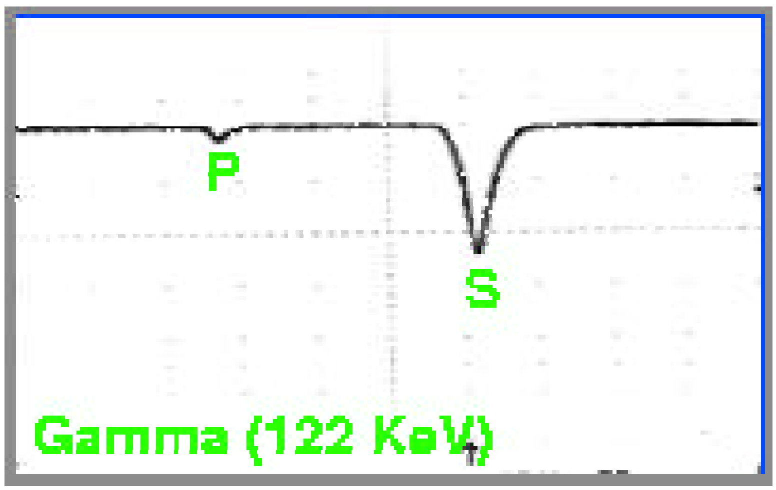


Figure 7 Waveform of alpha and 122-keV gamma scintillation and proportional scintillation signal from PMT. (P is primary scintillation, and S is secondary scintillation.)

3.4.3 Enhanced proportional scintillation using two-phase xenon

In 1997 an important improvement was made to this technique. By introducing a liquid surface into the chamber, with the electric field extending into the gas phase, the charge can be pulled into the gas and accelerated to give a much larger proportional scintillation signal, while the primary scintillation pulse remains unchanged. This improves background rejection in two ways:

(i) Since the nuclear recoils produce relatively little ionization, a larger difference between signal and background events is created.

(ii) Most background events are effectively amplified out of the low energy region and can be rejected by a cut on total signal amplitude.

Error! Reference source not found. shows a 0.5-kg test chamber recently constructed using the two-phase principle. Initial test results are shown in **Figure 9**, in which the relative values of signals S1, S2, defined above, are plotted for events from an Am-Be source (which emits both neutrons and gammas). The separation of nuclear recoil events (from the neutrons) and Compton scattering events is clearly demonstrated and is in accordance with expectation from the principles discussed above. An energy calibration of the neutron events was made from a Monte Carlo simulation using the known Am-Be source spectrum, which when matched to the observed event number distribution provides the energy scale shown in **Figure 9**. This is also consistent with simple kinematic estimates.

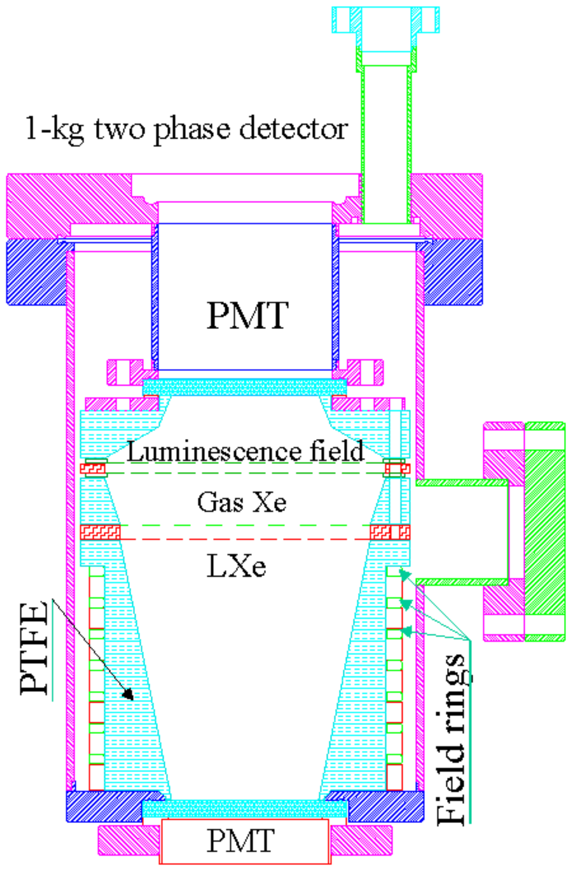


Figure 8 Two-phase xenon test detector

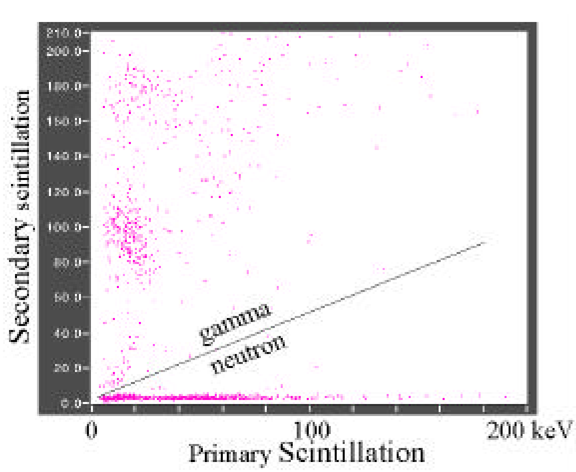


Figure 9 Separation of nuclear and electron recoils into two populations by primary and secondary scintillation in two-phase system.

With the setup shown in **Figure 8**, the drift and proportional fields are isolated. This means that by varying drift or proportional field, one can control the extraction and drift of the ionization electrons independently from the control of proportional gain. The test results of the separation are shown in **Figure 10** in single phase (liquid). Notice that the primary scintillation decreases with increased drift field because of the recombination decrease. At 250 V/cm, the secondary scintillation pulse height under 2.5 kV (potential on the 3-μm-diameter wires) proportional field is already higher than that of primary scintillation. It is a perfect match with the constant electron drift velocity as shown below in §**4.2**, while, in the case of electroluminescence, the secondary is much higher, see §**4.3**. **Figure 11** shows a direct waveform of a 22-keV signal from PMT taken from this set up.

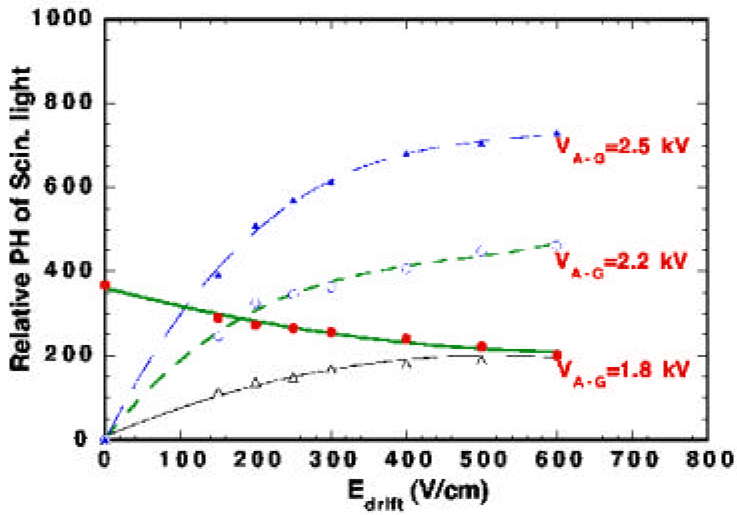


Figure 10 Primary and secondary scintillation vs. drift field with secondary scintillation under three different proportional fields with 122-keV gammas.

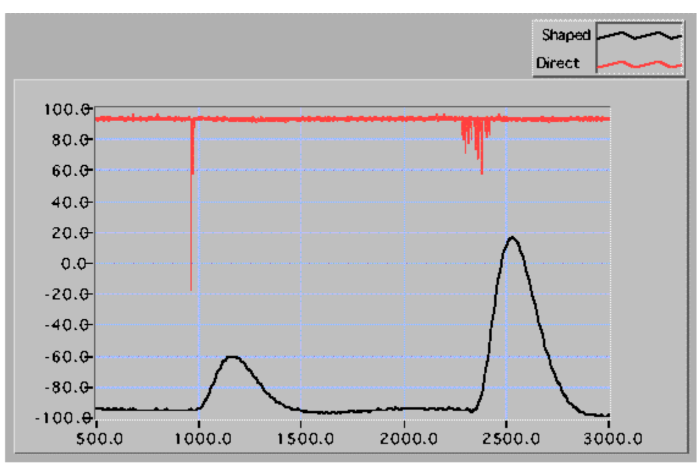


Figure 11 Direct and shaped signals from a 22-keV gamma. (X-axis is plotted as the number of sampling points with 10-ns sampling rate.)

From these initial tests it is thus possible

(a) to conclude that the neutron and gamma events are separated down to < 10-keV actual recoil energy and

(b) to estimate approximately the neutron/gamma separation (i.e. the fraction gamma events overlapping with 90% of neutron events) as a function of energy (**Figure 12**) showing a factor ~10 improvement over the corresponding overlap achieved using NaI pulse time constant differences.

3.5 Form factor correction

The discrimination gain has to be considered in conjunction with the form factor correction, plotted in **Figure 13** as a function of true recoil energy. This shows the importance of achieving an observed energy threshold as low as 5 keV, corresponding to a recoil energy of 23 keV. Performance is best estimated by a direct comparison between xenon detectors and existing scintillation detectors based on NaI (and for which the achieved event rate sensitivity is known). From the viewpoint of coherent interactions we can consider just the I component of the NaI (since it is 80% of the mass and has an A^2 factor 30 times higher). Moreover xenon and I have similar size nuclei, and hence similar form factor corrections for a given recoil energy. xenon gains over I in NaI for the following reasons:

(i) The recoil efficiency is higher for Xe (22%) than for I in NaI (9%), so will be sensitive to a lower recoil energy for a given energy threshold.

(ii) The discrimination factor and figure of merit C is better for Xe by an order of magnitude (**Figure 12**).

(iii) The intrinsic background in xenon (with sufficiently reduced ^{85}Kr) will be lower than that in NaI due to contamination with U and Th (for which significant reduction has not been achieved, despite efforts to do so).

Taking account of these three factors, and allowing for the factor 2 lower scintillation light output from xenon, simulations suggest a possible gain factor 100 in potential sensitivity of xenon detectors compared with NaI detectors. Since the latter have achieved a sensitivity level ~ 1 event/kg/day, this indicates that two-phase xenon detectors are in principle capable of achieving sensitivities down to 0.01 events/kg/day for the same mass and running time, and below that if scaled up to larger mass.

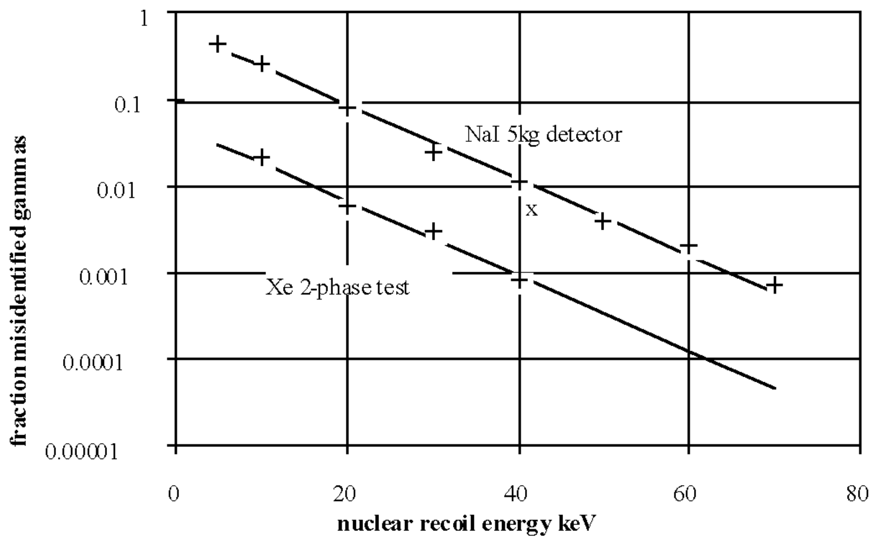


Figure 12 Dimensionless figure of merit, C(E), as a function of true recoil energy estimated from liquid-xenon test results, compared with corresponding values for pulse shape analysis in NaI. Background rejection factor is vC/N for N event in given energy range.

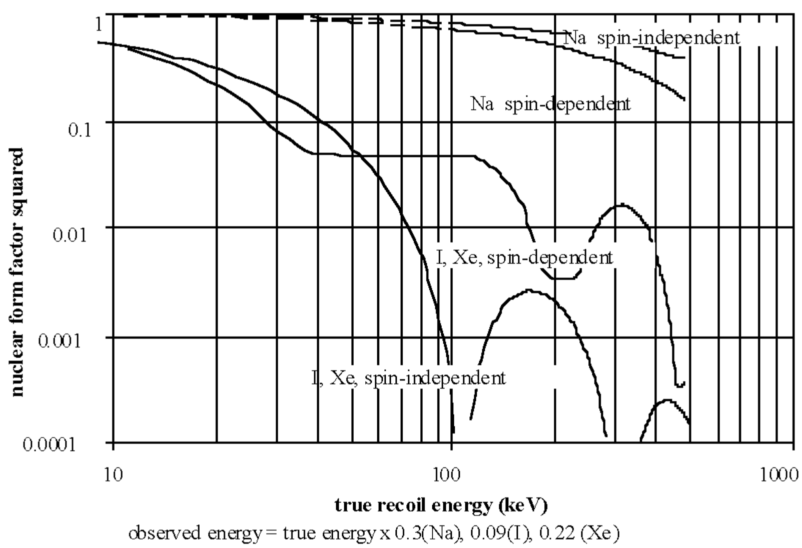


Figure 13 Nuclear form factor correction for Na, I, and xenon recoils, plotted against gamma-equivalent energy. Note that for weakly interacting particles the Bessel function zeros will be smoothed for spin-dependent interactions, but will remain as large dips in the case of spin-independent interactions (in contrast to nuclear scattering of e or n).

3.6 Background

The basic feature of the detector is that it is able to discriminate a nuclear recoil signal from background signal of gammas and betas, with some overlap which can be reduced statistically by longer running and or a larger target mass. However, low energy nuclear recoils can also be produced by neutron interactions, so it is of prime importance to ensure that these are reduced to below the expected neutralino signal level. Nuclear recoils in the range 1-30 keV can arise from neutrons in the range $E_n = 0.1 - 10$ MeV. There are three main sources of neutron background:

(1) U and Th in the rock produce neutrons mainly via alpha interactions with the rock elements. The predicted rates in an underground cavern are typically a factor 10^5 lower than the background gamma flux (i.e. typically $10^{-6}/cm^2/s$). These neutrons can be thermalized and absorbed by hydrogenous materials giving a factor 10 attenuation per 20-cm shielding.

(2) Within the shielding, further neutrons can arise from U and Th in the target and detector materials, but again at only 10^{-5} of the local gamma flux. The achieved gamma flux at Boulby after shielding is of order 100/kg/day, part of which may arise from U/Th contamination. Thus the neutron background from this must be < 0.001/kg/day. This would be reduced further with development of higher purity materials.

(3) Cosmic ray muons produce neutrons in all materials by both spallation and capture. From the cross section and multiplicity of those processes, and the muon flux, the neutron production cross-section can be estimated as a function of depth. A Monte Carlo simulation gives a rate in a shielded target ~0.01 event/kg/day below 20-keV at the Boulby mine. This is already low for the present experiment and could be further reduced by a muon veto. This could be done with > 99% efficiency, reducing the muon-produced neutron events to 0.0001 event/kg/day.

Gamma and beta background should also be as low as possible, in order that the discrimination factor acts on a lower starting value and reaches the lowest possible signal level.

More important sources of background in this experiment are U and Th in the photo-multipliers, and intrinsic beta decay in the target materials, e.g. ^{85}Kr in xenon. Typical current ^{85}Kr contamination for 20-ppm purity xenon gas is $5x10^{-17}$atom/atom, giving a low energy beta decay rate of ~50 event/keV/kg/day. However, this can be reduced by cryogenic distillation or by centrifuging.

The UK Boulby Salt Mine of our choice is a working mine at a uniform level of 1100-m, with a network of many km of underground tunnels and caverns. The natural radioactivity is as low as any other underground sites in the world, and the background is further shielded as discussed above. Several adjacent caverns and tunnels are dedicated to the UK dark matter program. Full electrical services, telephone and fiber optic data links are installed, and the UK contribution to this project will include installation and manpower for commissioning, continuous running, and data acquisition.

4 The ZEPLIN II Detector

Based on the R&D experience over the past years, we are confident that a two-phase xenon detector is the best for a WIMP dark matter search covering the current interested SUSY region. The central detector is currently under construction at UCLA, and Columbia and the UK dark-matter group will provide active veto and shielding. We describe the design of the ZEPLIN II detector below. ZEPLIN-IV, the future large-scale detector, will have the same overall structure.

4.1 Central detector

The key to the background rejection power in this detector, as described above, is the observation of the ionization components of the background events by looking at the luminescent photons produced by the ionization electrons in the xenon gas phase. Hence, the collection efficiency of these ionization electrons must be close to 100%. Any background event in the detector must not lose its ionization charges or it will be miss-identified as a recoil event. With this in mind, the central detector design is designed as shown in **Figure 14**. Note that 100% of the active xenon used is confined to the region within which ionization electrons will drift up to the interface of the liquid and gas phases. An extraction field is present at the interface so that electrons will continue to drift into the gas phase. Electron drifting in the gas region will undergo the electroluminescent process and produce over 200 photons per electron (discussed in detail in §**4.3**). To avoid photon loss due to window materials, all seven PMTs are placed inside the vacuum vessel for better light collection efficiency and will face the scintillation photons directly. A copper plate above this luminescence region holds the PMTs. Teflon spacers are used both to isolate the PMTs from the copper plate and to block all scintillation photons from above the copper plate. This is to prevent the photons from the background events in the gas region in the upper part of the detector from entering the PMT readout.

The 3-D view of the detector is shown in **Figure 14** and it will be housed in a double-layer vacuum thermal insulation vessel (as shown in **Figure 15**). The estimated thermal loss is about 20 W. It is important to keep the thermal loss low for safety and low-cost operation. A low-power cooling system will be used to keep the system at liquid xenon temperature. A frustum-shaped cup made of Teflon (PTFE) confines the active liquid xenon. Electric-field-shaping rings are placed outside the PTFE cup to avoid a fringing field effect on the ionization charge.

Special care is taken at all boundaries near the active region and wire frames, where the drift field for ionization electrons is configured, so that all electrons must drift to the gas electroluminescence region. For regions where it is impossible to form such drift field (dead regions), they have been reduced to less than 0.1% of the total active volume. **Figure 16** shows the static electric field near the PTFE, as well as a charged-up condition in this setup. The surface charge in this calculation is arbitrary and is only intended to show the effect of the charge up. As shown, it is clear that the charge-up effect tends to modify the equipotential line such that in the worst case the equipotential lines will be perpendicular to the PTFE surface. This is because once the equipotential lines are perpendicular to the surface, ions will move only in the direction parallel to the PTFE surface. The actual charge up will depend on the purity of liquid xenon and on the PTFE surface conductivity. The higher the xenon purity, the longer the ions will stay on the surface. The ions will be carried away by the surface current, because the conductivity of the PTFE surface is non-zero. The charge up will obviously distort the event location near the surface. The background rejection power does not depend on tracking or on location of the event. So even if the worst charge-up condition happens, it will not degrade the capability of the detector.

Two fine mesh frames are used to generate the electron extraction and electroluminescence fields. One of the frames is placed in the liquid and the other in the gas phase. The strong field (>3 kV/cm) between the two wire sets is enough to extract electrons near the surface. Once electrons get out of the surface, they will undergo the electroluminescence process under this field.

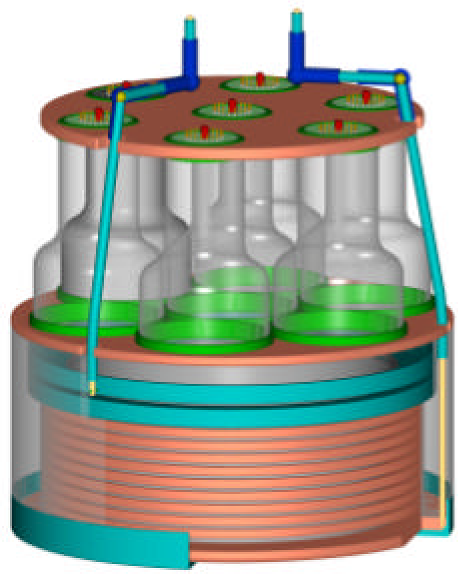


Figure 14 3-D view of the ZEPLIN-II central detector. Seven 5-in.-diameter PMTs are placed on a copper plate support. A PTFE cup is used to confine the liquid xenon; field-shaping rings are placed outside the Teflon. The luminescent-field structure is shown between the top copper plate and the PTFE cup (meshes are not shown).

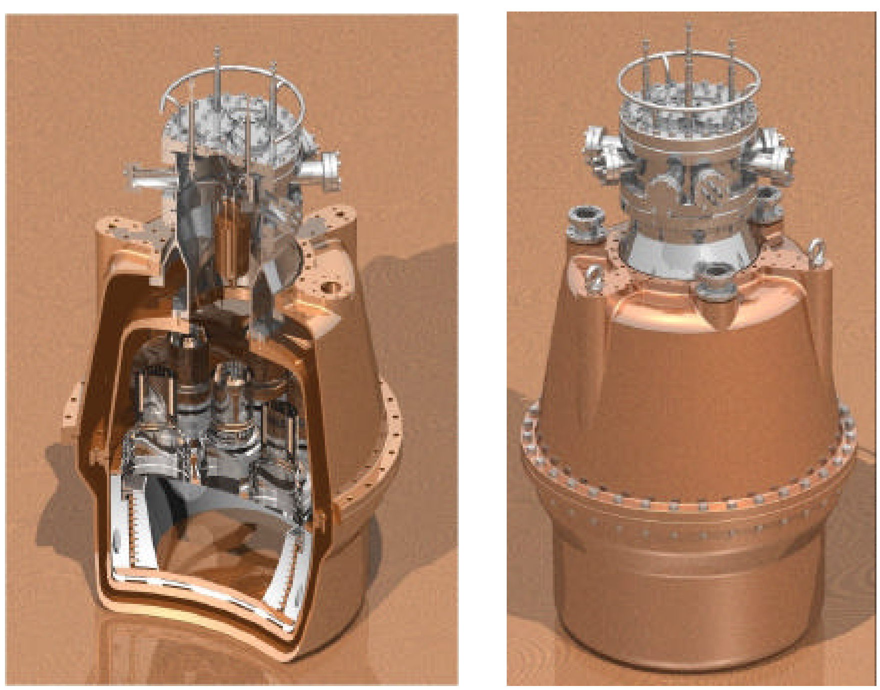


Figure 15 The ZEPLIN-II cryogenic vacuum vessel. The central detector will be placed at the bottom of the inner vessel. Estimated thermal loss is about 20 W. Feedthroughs for HV, signals, and all pipelines are placed on top for easy installation and to minimize background.

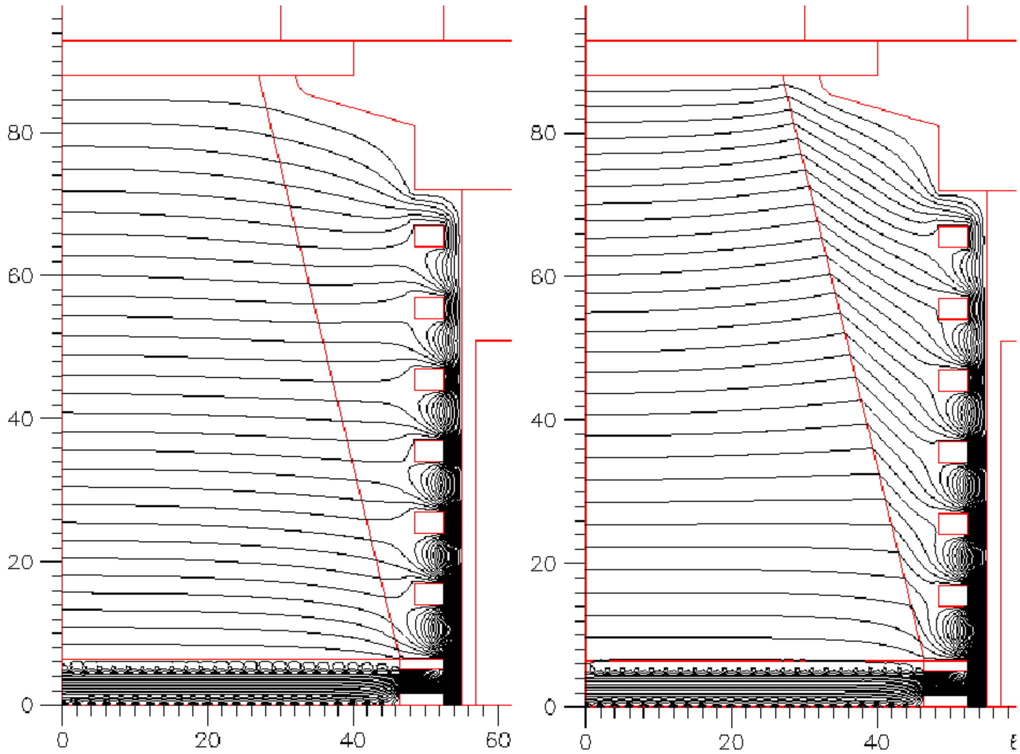


Figure 16 Drift field calculated with simplified model: Left -- normal condition; Right -- Charged-up condition. Electrons will drift downwards. The tilted line is the boundary between the liquid xenon and the Teflon cone.

4.2 Xenon purification

The most important milestone of the UCLA--Torino dark-matter search was the successful test result of the liquid xenon purification (P. Benetti et al., NIM **A**329, 1993, 361-364). Based on the ICARUS purification technique, we have developed a special procedure for xenon purification that yields a purity of less than 0.1-ppb electron negative impurities. This is equivalent to over a few milliseconds of electron lifetime in liquid xenon or a few meters of electron drift distance under normal electric fields (250 V/cm).

The lifetime measurement setup is shown in **Figure 17**. Both anode and cathode are shielded by metal grid mesh. Between the two meshes is the region where electrons drift. A UV laser pulse shining on the photocathode in the chamber produces a large number of electrons. Then the known quantity of charge (measured by the cathode) was injected into the purity test chamber and was collected by the anode after it drifted some distance in the chamber. **Figure 18** shows the lifetime result. No charge loss was observed after 200-µs drifts. The rising edge is the charge injected and the falling edge represents the collected charge. In this particular case, the electrons were drifting under a 10-V/cm electric field. With this highly purified liquid xenon, we are in principal able to design a liquid xenon detector with large volume for the case where long electron drift is needed.

Electron drift velocities in liquid xenon under different electric fields and different temperatures (pressure) were measured with the same chamber. The results are shown in **Figure 19**. Notice that the electron drift velocity is independent of the temperature at a drift field around 250 V/cm.

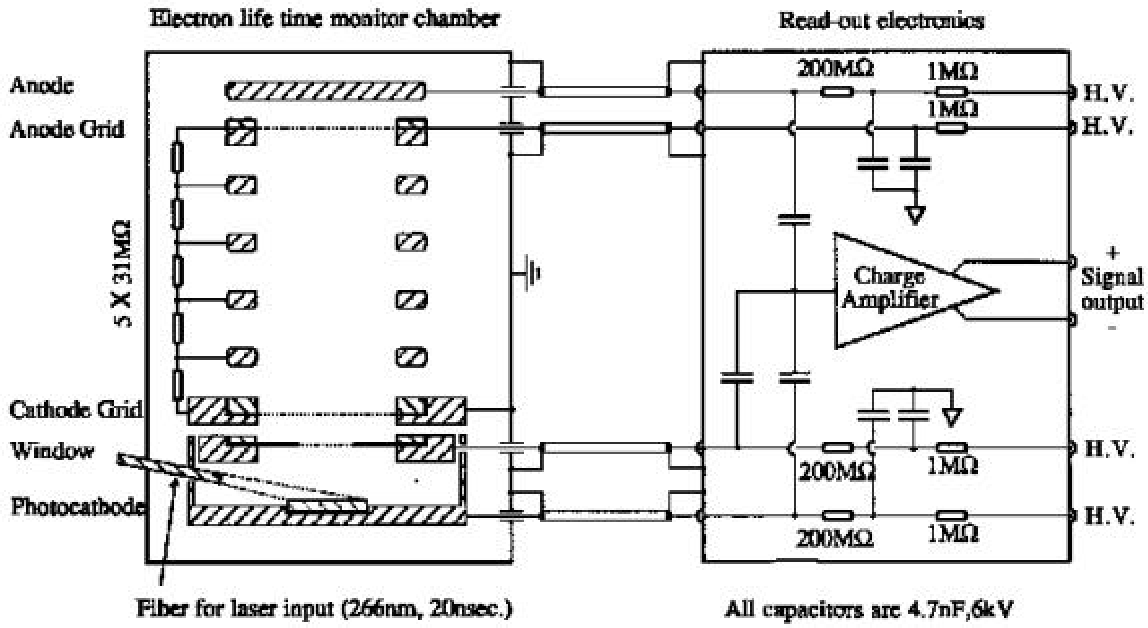


Figure 17 Electron lifetime measurements setup. Purified liquid xenon was filled in the chamber (left box). A laser pulse produces charges. The cathode box is specially made to shift the laser trigger noise. The charges leaving the cathode box and those arriving at the anode are both measured with the same amplifier (right).

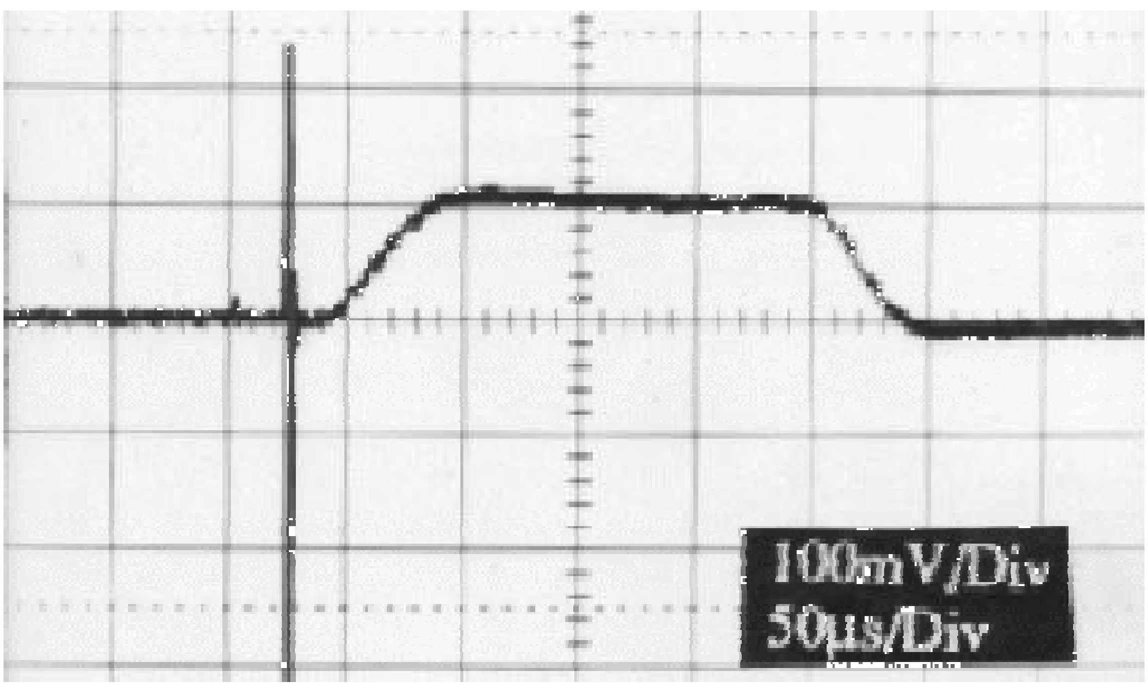


Figure 18 Lifetime measurement results. Electrons drift under an electric field of 10 V/cm. The first big spike is the noise from the laser trigger.

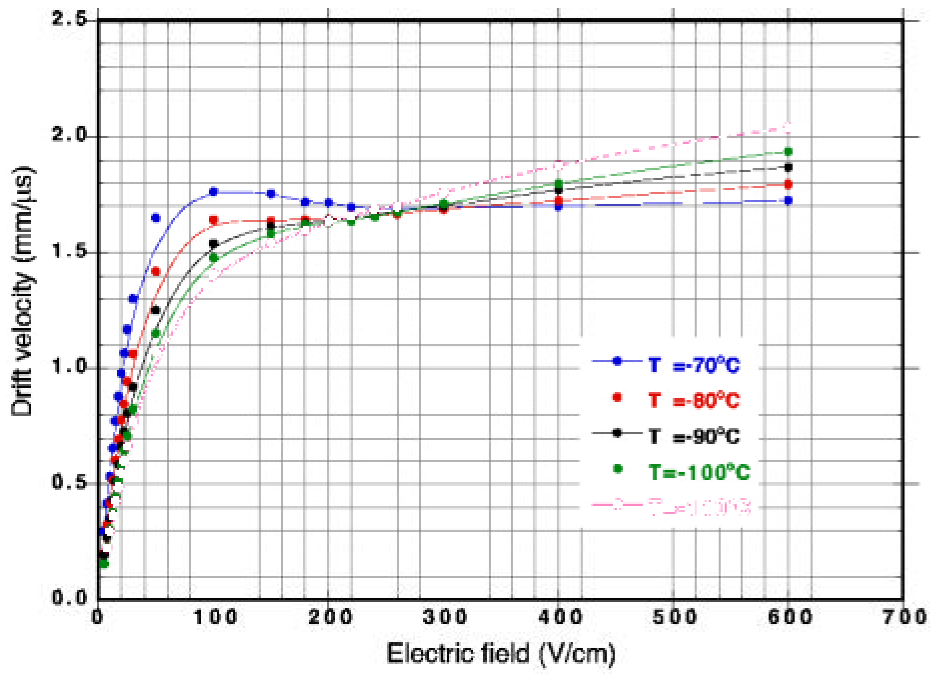


Figure 19 Electron drift velocities under different drift fields, *E*, and temperature. Notice that the constant speed at ~ 250 V/cm.

4.3 Electroluminescence

When electrons drift under high electric field in gas xenon, electroluminescence will take place. The number of electroluminescent photons, N_{ph}, produced by a single electron under the field of E (kV/cm) at pressure P,and drift distant X can be well approximated by the experimental formula:

$$N_{ph} = 70 \times \left(\frac{E}{P} - 1.3 \right) \times X \times P \,. \quad (3)$$

In the pure liquid case, proportional scintillation was produced with very thin wire (3 µm in diameter) at high potential. When electrons drift very near the thin wire, because of the very high field near the wire surface, proportional scintillation takes place in liquid xenon. The gain in proportional scintillation depends on several factors, e.g., the surface smoothness of the wire, uniformity of the wire diameter, etc. In the case of 3-µm wire, the surface defect due to gold coating can be as big as the wire diameter (seen under electron microscope). In the case of gas luminescence, the gain N_{ph} depends only on E, P, and X in Eq. (3), so a very uniform and high gain can be obtained.

Figure 20 shows the results of two-phase xenon compared with single-phase results. Because of the high gain in luminescence, the separation of gamma and recoil is significantly improved. The background rejection power is better than 99.8% in the pure liquid case and is expected to be much better in the two-phase detector.

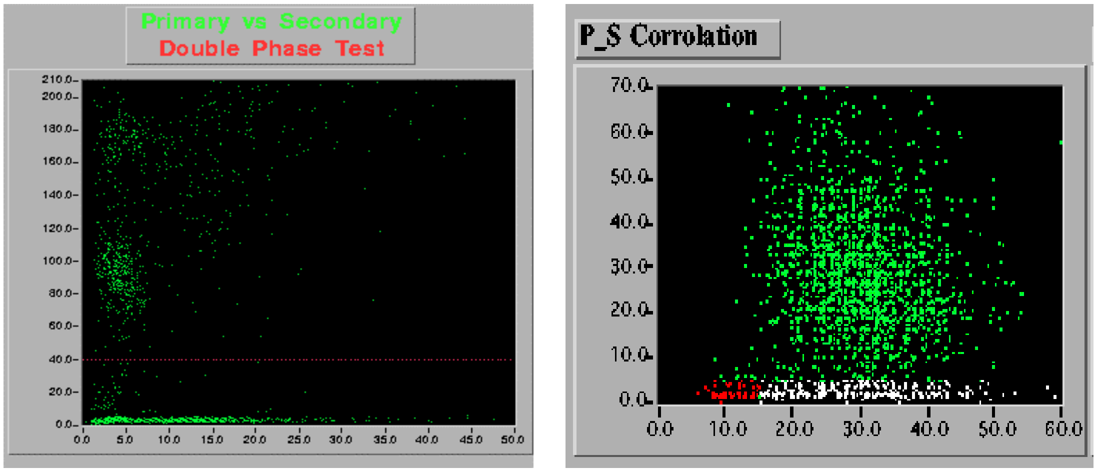


Figure 20 Primary versus secondary plot in two-phase (left) and single-phase (right) xenon.

4.4 Status of ZEPLIN-II project

The central detector is under construction at the UCLA Dark Matter Laboratory. We have a dedicated laboratory space for constructing the detector, and the main components have arrived **Figure 21**. The construction of the central detector will take about four months. Some initial tests will be made at UCLA, and the system integration will be completed during early 2002 at RAL in the UK.

Figure 21 PTFE sitting on copper plates (keys supply scale). The cup in the ZEPLIN-II design will be made from this PTFE. All field shaping rings, the copper plate holding the PMT, and the bottom copper plate will be made from these plates.

5 CsI Internal Photocathode for Signal (Primary Scintillation) Amplification

5.1 Principles of the CsI luminesence plate

The typical photon wavelength of xenon scintillation is 175 nm. It is hard to collect such hard VUV light with high efficiency. To reduce the photon loss that occurs when photons pass through a window, all PMTs are placed inside the detector (thereby eliminating the need for a window) as close as possible to the luminescence region to maximize the light collection efficiency. To get an even lower energy threshold, one must develop high Q.E. PMTs or increase the light collection efficiency. The ZEPLIN-II design already maximized the light collection efficiency. If the primary signal can be amplified before it reaches the PMT, then the photon collection efficiency can be significantly improved. Incorporating this into the ZEPLIN-II design will produce a perfect detector for dark matter searches.

A CsI photocathode in liquid xenon has been tested by E. Aprile et al. (NIM **A**343 1994, 129-134). The typical I-V curves of the CsI internal photocathode measured in liquid xenon show a high photocurrent production under a strong electric field (**Figure 22**). Notice that the photocurrent in liquid xenon at field above 1.8 kV/cm is greater than that in vacuum. To use CsI as an internal photocathode, we need a very special design to combine the photocathode with the luminescent field.

The UCLA group has developed a primary-scintillation photon-amplification method using a CsI internal photocathode luminescence plate (**Figure 23**). The plate is a simple, thick PCB board with uniformly distributed holes (1.4 mm in diameter). In order to coat the plate with CsI, the surface has to be treated as shown in **Figure 24**. To prevent CsI deposition in the holes, all holes are filled with pins, as shown in **Figure 26**.

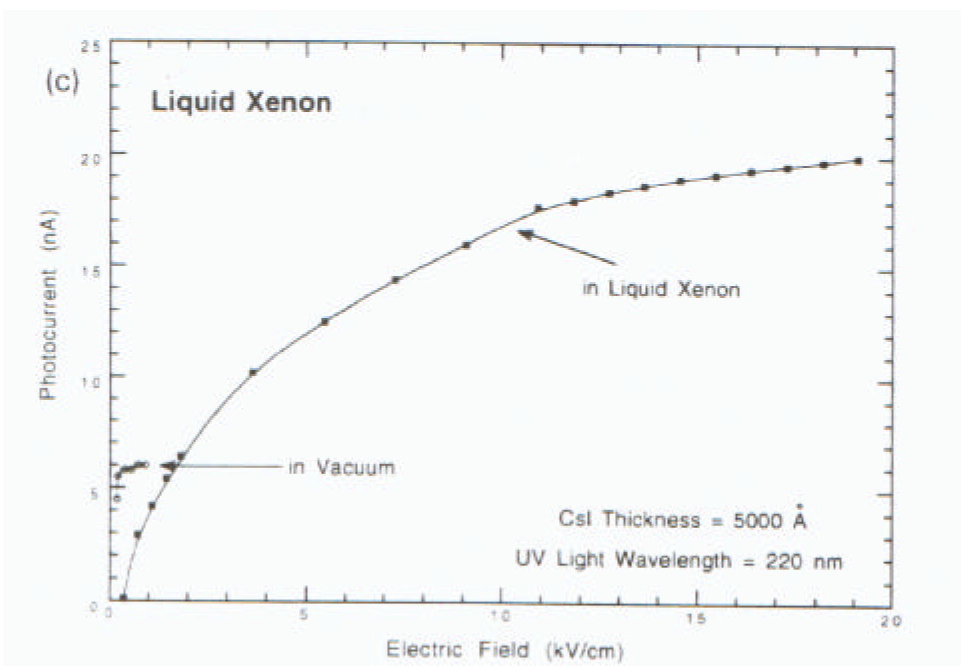


Figure 22 Typical I-V curves of the CsI photocathode measured in liquid xenon and vacuum (E. Aprile et al. NIM **A**343 1994, 129-134).

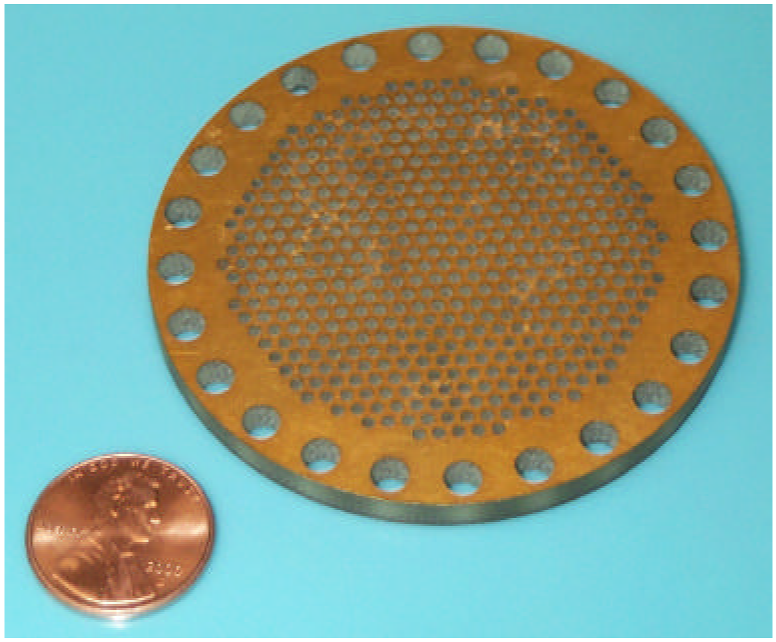


Figure 23 A picture of the CsI luminescence plate with an outer diameter of 66 mm (the active CsI part is 50 mm); the CsI will be coated near the small-hole area.

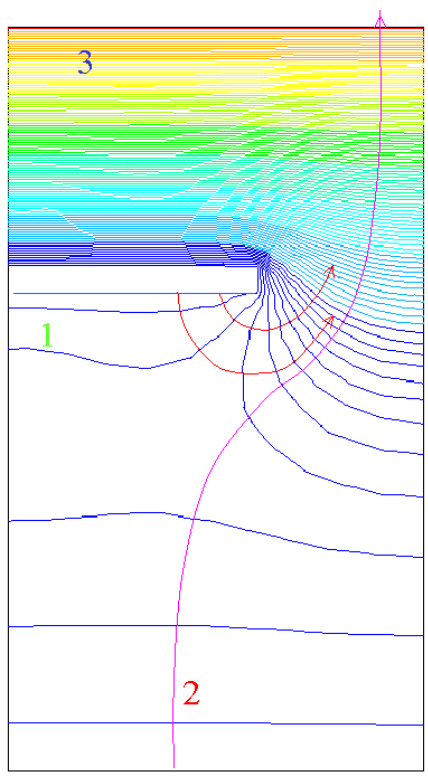


Figure 24 CsI coating on the PCB board and the photoelectron trajectory.

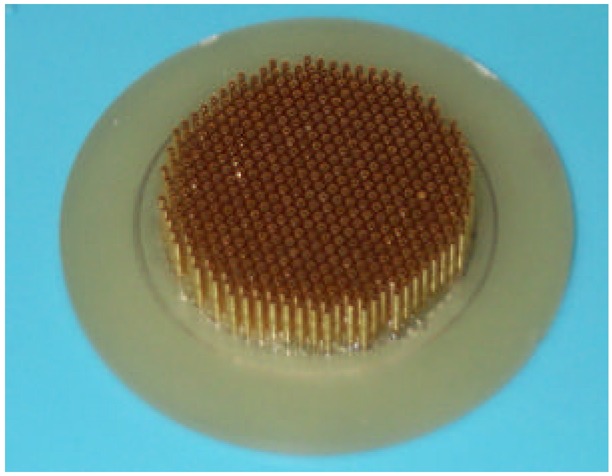


Figure 25 Pin array used to prevent CsI deposition into the holes.

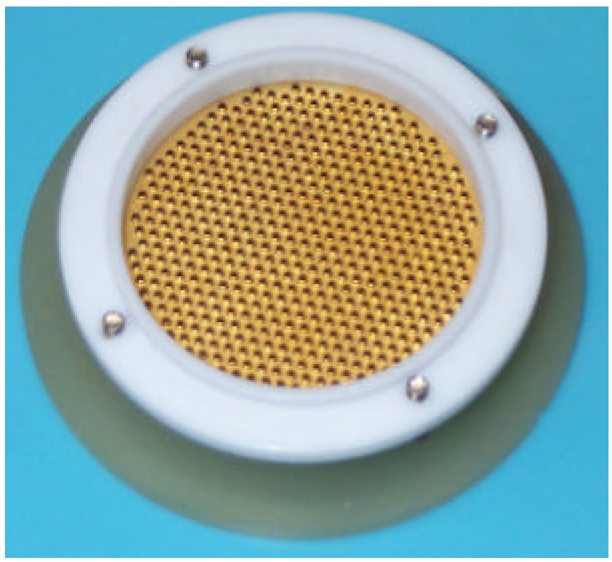


Figure 26 The CsI coating setup, which is placed in a vacuum deposition chamber for coating at CERN.

The CsI internal photocathode luminescence plate will be placed in the chamber with the CsI surface face down; the liquid xenon surface will be controlled just above the bottom surface of the plate. **Figure 27** (left) shows a small portion of the plate in a simplified 3-D model for finite element analysis (ANSYS installed at CERN). The model contains one half-hole and two quarter-holes. The calculation stops at the liquid surface. Above the liquid surface, the result is the same except that the dielectric changed from liquid to gas. **Figure 27** (right) shows the result of the calculation in 3-D with equipotential surfaces. The red lines show the trajectory of electrons coming from the CsI photocathode; the pink lines show the trajectories of electrons from ionization in the active region. It is clear that any electron (ionization or photoelectron) below the plate will drift up through the holes and, since the field at the liquid surface is strong enough, all electrons will continue to drift to the gas phase. Again, the field in the gas phase is strong enough for luminescence to take place.

In order to extract electrons from the CsI surface with high efficiency, the field on the surface should be stronger than 1.8 kV/cm, as suggested from **Figure 22**. With careful arrangement this can be achieved and the calculated results from ANSYS are shown in **Figure 28**. This confirms that the minimum field at the CsI surface is greater than 1.8 kV/cm.

The working process is as follows. The primary scintillation photons from events in the active region will hit the CsI surface and produce photoelectrons. Then the photoelectrons will be extracted by the strong field at the surface and will continue to drift along the trajectories shown in **Figure 27**. So the CsI internal photocathode luminescence plate converts the primary scintillation photon and then amplifies it through electrolumienscence process.

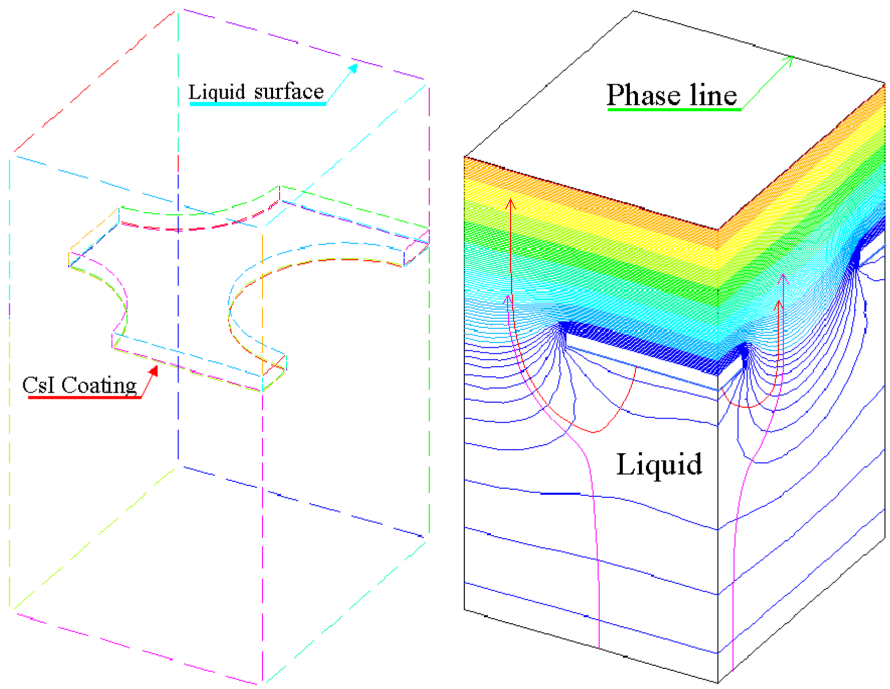


Figure 27 ANSYS finite element analysis: Left: a small portion of the plate in a simplified 3-D model; Right: the drift trajectory of photoelectrons (red from bottom surface) and ionization electrons (pink from below).

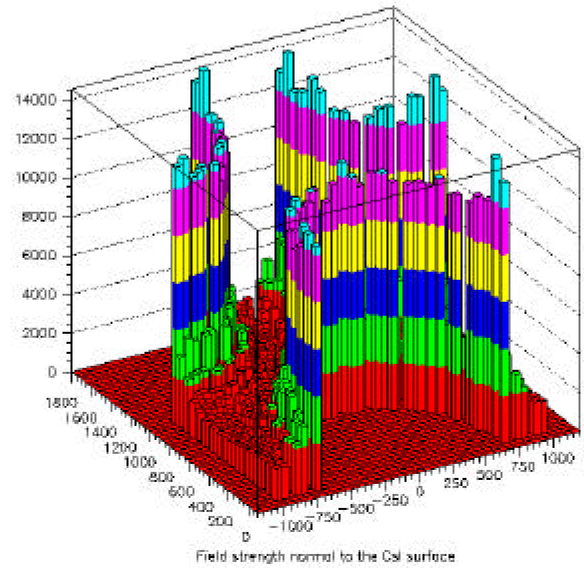


Figure 28 Electric field strength at the surface of CsI. The horizontal axis is the location on the plate; the vertical axis is the field normal to the surface in V/cm.

5.2 Initial test results

A quick test was make at CERN with gas only; there was no need for cryogenic and purification systems. The simple setup is shown in **Figure 29**. Over 2.5 kV was applied between the two surface of the luminescence plate; no special UV lamp was used; we only trigger on the background signals in the chamber filled with gas xenon. Two typical signals are shown in **Figure 30**. Notice that there is no drift field below the plate in this test condition in order to avoid ionization electron drift up, which may be mixed with those photoelectrons.

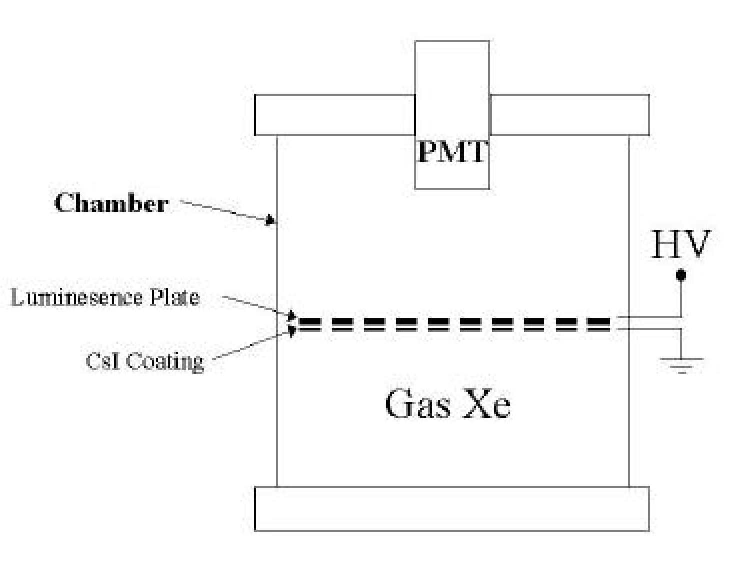


Figure 29 A simple diagram of the experimental setup of the CsI internal photocathode for gas xenon.

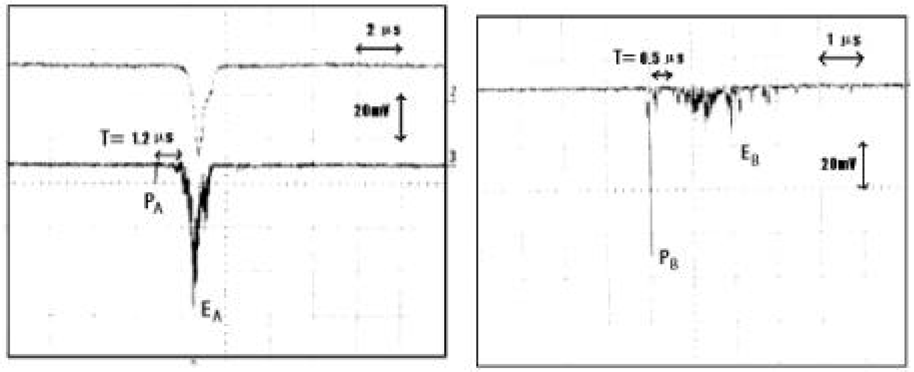


Figure 30 Typical signals from the experimental setup with the CsI internal photocathode in the one-phase xenon test chamber: Normal amplification signal (left) and when large gamma--xenon nucleus interaction occurs near the plate (right).

The typical drift time from the CsI surface to the holes is about 1.2 µs, as shown in the figure. The ratio of secondary-to-primary signal (S/P) is about 20 (**Figure 30** left). Assuming 0.2 as the quantum efficiency of the PMT, the estimated gain (number of photons per photoelectron) is about 200, which is in a good agreement with N_{ph} from Eq. (3) in §**4.3**. **Figure 30 (**right) shows that a large gamma--xenon nucleus interaction occurs near the luminescence plate. Since the electric field is non-zero near the plate, ionization electrons produce electroluminescent photons immediately after the event.

The overall gain when solid angle and other factors are considered is about 10. This is a very encouraging result. A systematic study in two-phase xenon should be carried out to confirm the gain.

5.3 CsI Luminescence Plate and signal amplification test at TAMU

The simple experimental setup at CERN (**Figure 29**) uses only gas phase Xe for the signal amplification, and no cooling or other complicated system was required. This setup for the same test must be significantly improved in order to do the two-phase test, which we propose to carry out at TAMU. The cost of the R&D will be low because most of the equipment (vacuum, temperature control, and readout system) is already in hand at TAMU. We request funding for test chamber fabrication, xenon gas and purification system components. The test chamber will also be used for future R&D work for the ultimate dark-matter detector with a ton-scale liquid-Xe target

The proposed test cell is shown in **Figure 31**. The actual test cell will be placed in a vacuum thermal insulation chamber. All gas, cooling, and signal feed-throughs will be placed on the vacuum chamber's top flange (not show). **Figure 32** is a conceptual drawing of the system setup.

The liquid cell is about 250 cm^3 in volume (about 70-mm-diameter, 13-mm-thick cylinder); the liquid (cost $975/commercial bottle at 99.995% purity) will be purified again before the test. An MgF_2 window is used to seal the chamber and to let the 175-nm UV light through. A 2-in. PMT (with MgF_2 window) placed on top of the window in the vacuum reads the signal. Two HV feed-throughs (at rear, not shown) will be used to set the potential on both sides of the CsI plate. The maximum voltage needed is less than 5000 V (between the CsI plates).

The cyrogenic system includes a "Cryo-Plex 8" cold head from Austin Scientific that is capable of cooling to 9K, along with a LakeShore 330 Temperature Controller. This will allow temperature control with a precision of 0.1 K at 160 K.

Vacuum will be made using a Balzers TU-50 turbo pumping station and Varian Star Cell ion pump. The test system has two separate vacuum cells: the test cell and the vacuum thermal insulation. The two cells can be pumped by the same vacuum pump and, when filling liquid Xe, we simply switch off the pumping of the test cell. Of course this will require equal care when cleaning both inside and outside of the test to avoid contamination to the Xe cell.

Readout of the PMT will be done using a 500 MHz LeCroy 9350A Digital oscilloscope. The sampling rate on each of two channels is 500 MS/s (or 2 ns/sample). The fastest component from the Xe scintillation is above 20 ns for the unshaped signal. With maximum record length of 50-k points per channel, the scope can sample 100 µs in one shot. This will easily accommodate a 13-mm drift with a drift field set at 250 V/cm (see **Figure 19**). For systematic studies of the CsI amplification, we will store all data via GPIB interface to a PC for analysis.

This test will determine the photoelectron extraction efficiency and luminescence gain at the gas part in the holes of the luminescence plate. Since all of the principles are already tested in different setups by other authors for different purposes, we believe that the objective of this proposal will have positive results.

James White is a researcher in experimental high energy physics. His primary research the past several years has been the search for evidence of supersymmetry via the tri/di-lepton signals in proton-antiproton collsions at the Fermilab Tevatron while a member of the DZero Experiment. He has also maintained a detector R&D program which has included development of the liquid scintillating fiber calorimetry concept for use at the SSC, investigation of the use of laser induced fluorescence as a new approach for high resolution particle tracking, and studies of the use of cryogenic argon, neon and xenon for cold dark matter detection.

Over the past few years the TAMU group has carried out a number of studies to investigate the possible use of noble gases for dark matter detection. Studies have included: electron extraction from solid and liquid argon; electro-luminescence in argon, xenon, neon and mixtures; the use of phosphors to convert VUV to visible; and purification techniques. The knowledge and experience gained from these studies plus the running of the ZEPLIN II experiment will be added to the considerable expertise of the UCLA and U.K. groups to help develop a ton-scale detector with optimum sensitivity. His future plans are to concentrate full effort on the search for dark matter within the ZEPLIN collaboration, including work on the Zeplin II, 35 kg liquid xenon experiment and R&D for the ton-scale Zeplin IV detector.

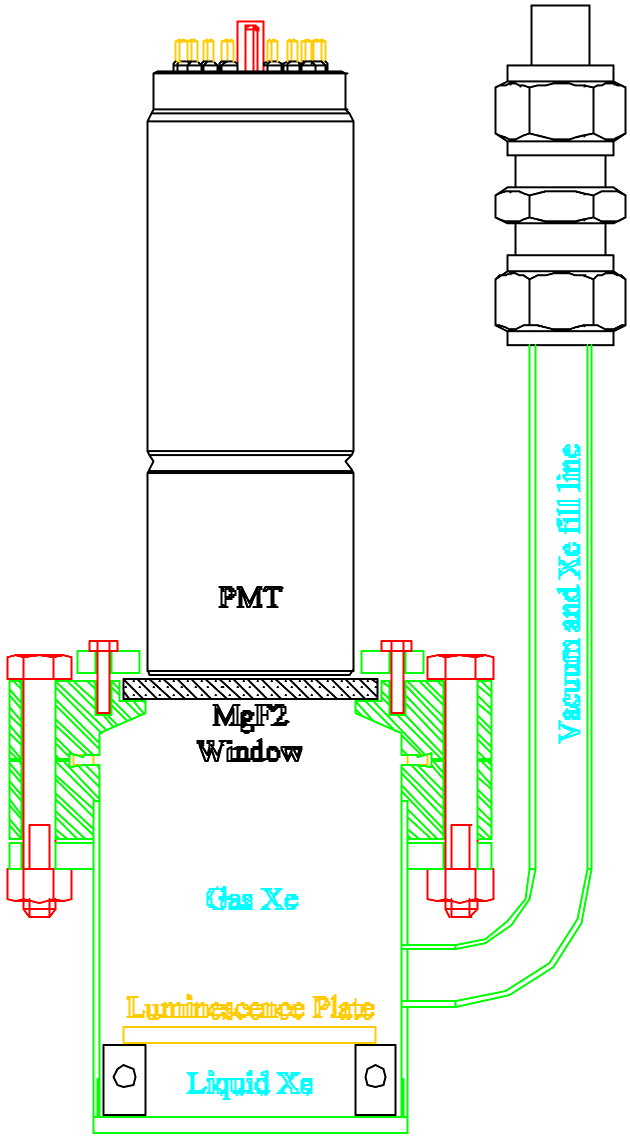


Figure 31 The proposed CsI internal photocathode test cell with two-phase xenon. HV feed-through (on the back, below the liquid line) for the CsI plate is not shown.

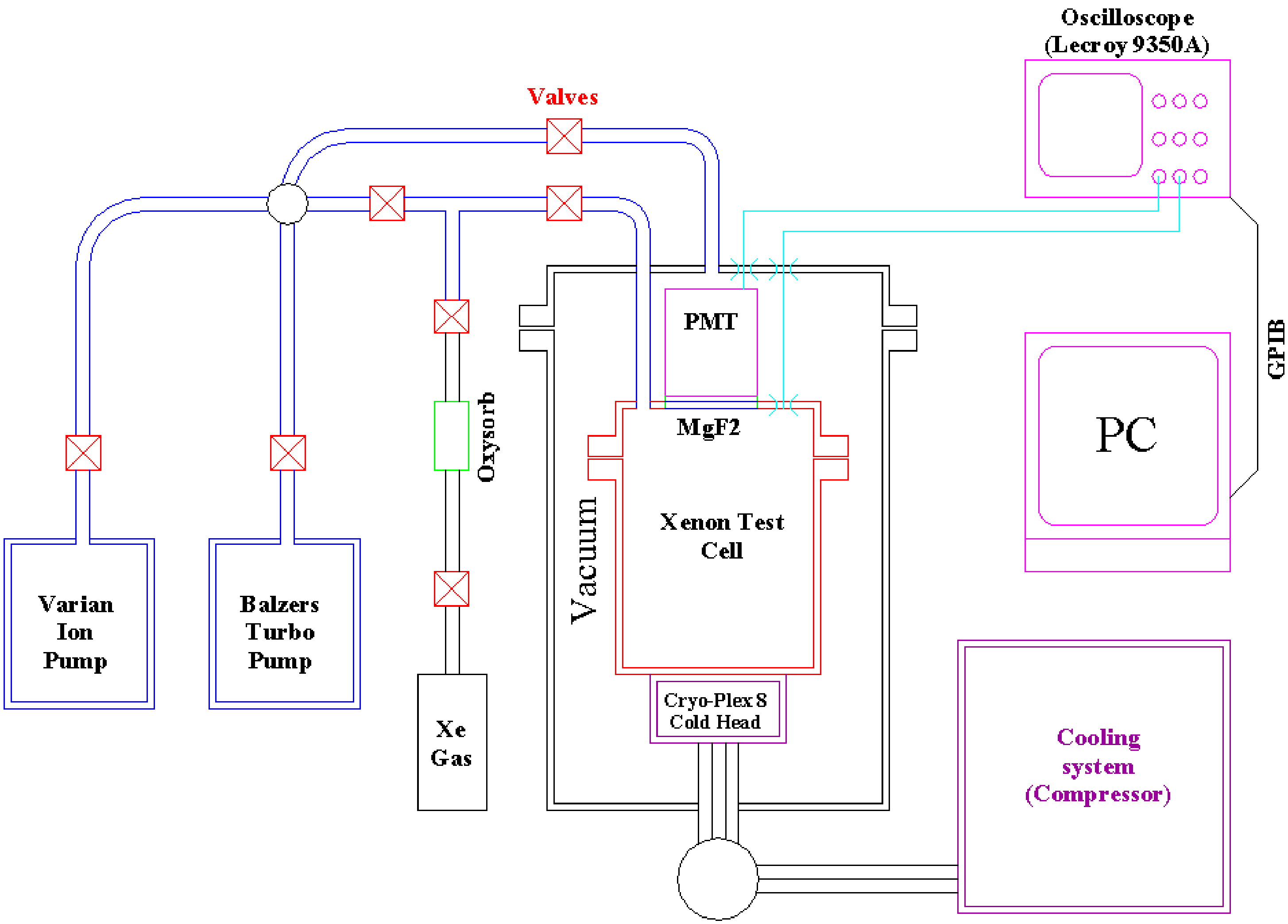


Figure 32 Conceptual drawing of the system setup with complete cryogenic, purification, and DAQ system.

6 Low Radioactive Photon-Readout Device R&D and ^{85}Kr removal

Photo multiplier tubes, while a well known and reliable technology, are very radioactive by the standards of low-background experiments. As an example, the low-activity PMTs used by Borexino have some 4-5 orders of magnitude higher background than what can be expected from 1 cm thick Cu that could serve as the wall of a Xe cryostat. An alternative photon readout technology is crucial to achieving the very low background levels needed for a large-scale experiment.

We propose to explore alternatives to standard PMTs. Our main focus will be on gas electron multipliers, or GEMs (Sauli, 1997 NIM A386, 531). These devices, which are an alternative to wire proportional counters, consist of Cu-Kapton-Cu boards with an array of etched through holes (typically 50 µm in diameter). The fields are designed to be very high in the hole, where proportional gain occurs. This has certain advantages over conventional wire chambers in other applications, but in this case there is the extremely important fact that the basic construction materials, Cu and Kapton, are known to have quite low radioactivity. Recent advances include single photon sensitivity with triple-GEM structures (Mormann *et al.*, 2001, NIM A471, 333), operation of GEMs with relatively high gain in pure Xe (Bondar *et al.*, physics/0103082), and operation with very little photon-feedback and high QE using a CsI photocathode deposited on the GEM surface. A combination of all these factors in Xe gas at our temperature has not yet been demonstrated, but seems feasible, and if successful, would make GEMs an extremely attractive option for readout of both charge and photons. Other alternatives to PMTs include very low-background PMTs based on micro-channel plate technology, and large area avalanche photodiodes (LAAPDs).

At Princeton we propose to study the feasibility of GEMs for single-photon readout in Xe gas at LXe temperatures. The Princeton group has long experience with a wide variety of wire chamber technologies, low noise electronics, and also deposition of CsI. A small chamber, dewar and Xe gas system setup will be set up for testing various GEM configurations, and tackling issues of successful operation with all low-background materials. We may also test new low-background PMTs or LAAPDs, which, at low temperatures, are approaching single-photon sensitivity.

A second issue that Princeton will study is methods to remove 85Kr from Xe. Radioactive ^{85}Kr, a man-made isotope, is present in normal air at a level of typcially 1 Bq/µg. Commercial Xe has roughly 5-10 ppm, ^{85}Kr, so that a large reduction in ^{85}Kr level is needed, even with event-by-event discrimination. The two most promising ^{85}Kr removal possibilities are cryogenic distillation, and chromatographic separation using an activated charcoal adsorption bed operated near the liquification temperature of Xe. Distillation is a common commercial process, but is not readily available optimized for the separation of ^{85}Kr and Xe. Adsorption techniques to separate Rn from air have been developed by the Princeton group for use with the Borexino solar neutrino experiment. Separation of ^{85}Kr from Xe is similar, and in principle should be able to achieve very high efficiency.

We intend to construct a small scale system of the more promising of the two methods. This will consist of either a cryogenic distillation or cryogenic adsorption column and an associated gas system. For this work the Princeton group will use a gas-sampling mass spectrometer that it owns that is capable of roughly 10 ppb detection of ^{85}Kr in Xe.

The proposed budget for the Princeton group is 20 K. Of this, $ 6K will be spent to equip a chamber for Xe work with a dewar and associate hardwared, another $6K will be spent on the Xe gas system, $2K for GEM fabrication, and $7K on a ^{85}Kr removal system.

The Princeton group consists of Tom Shutt and Kirk McDonald. Professor Shutt's thesis work was the development of the first discriminating dark matter detectors, those used by the CDMS experiment. He has extensive experience in dark matter detection, detector development, low-noise electronics, and low-background experiments. Most recently he has been a member of the Borexino solar neutrino experiment, with responsibility for the detector's inner vessels.

Prof. K. McDonald's recent activities have emphasized accelerator R&D towards a neutrino factory and a muon collider. The physics opportunities at a neutrino factory have led him to involvement in studies for future large-scale cryogenic detectors with astrophysical capabilities as well (the LANNDD concept, astro-ph/0105442). In turn, this has led him to an interest in liquid xenon detectors for dark matter searches. Prior to this cycle of activity, McDonald had worked on CsI photocathodes coupled to gas amplification readout, which themes deserve further development in the present project.

7 ZEPLIN II Performance and Ionization Yield Due to Recoil Nuclei

The ZEPLIN II detector, under construction at UCLA, will be installed in Boulby underground facility early 2002. Careful studies of this detector will definitely benefit the design of any future large-scale detector using the same concept. We propose to carry out the ZEPLIN II performance studies, keeping in mind its relevance to the development future detectors.

7.1 Measurement of Scintillation vs. Ionization in Liquid and Gaseous xenon

The background rejection method used in ZEPLIN II, as explained in **section 3**, is to look at the secondary pulse from any events in the target. Since minimum ionizing particles (MIP) will (in addition to primary scintillation) yield ionization in the target xenon and hence produce a secondary signal. Since there is not yet any clear experimental data on the low ionization yield expected from xenon nuclear recoils at low energy, the current ZEPLIN II can alternatively treat single pulse events as candidates for nuclear recoils, while rejecting double-pulse events as beta or gamma background. Additional or confirmatory discrimination can be obtained via pulse shape differences.

Any region where ionization from background events cannot drift and reach the luminescence field region, will be considered as 'dead region' and such regions are carefully minimized. ZEPLIN II will have dead regions not more than 0.1% of the total active volume. These regions are located typically near boundaries of the active liquid xenon volume. This may be a limiting factor if in the future we want to achieve discrimination below 10^{-3}.

If there exists sufficient ionization from recoil at low energies, so that all events give two pulses (primary and secondary), the dead region will be completely eliminated. Then the discriminating power will depend only on the xenon properties. The ratio of ionization to scintillation is the basis for dscrimination between gamma/beta interactions and nuclear recoils (D. B. Cline, Nuc. Phys. B, 51B (1996) 304-313). Our studies shown that the ratio of secondary to primary scintillation of heavy ionizing particles (HIP) is a factor 10-100 smaller than that of a MIP.

Theoretical studies and experiments on ionization yield at low threshold show that there is no sharp threshold cut-off at low energies (Smith & Lewin, Phys Rep 187 (1990) 203-280, Davies et al Phys Lett B 320 (1994) 395). Ionization should be produced below the two-body threshold via virtual momentum transfer to the nucleus or other atoms. This is the basis of the discussion in Lewin & Smith paper (Phys Rev D32, (1985) 1177), and is presumably responsible for the low energy scintillation threshold behavior observed by D Ficinec et. al. (Phys Rev D 36 (1987) 311)

In liquid xenon, extensive measurements have been made for gamma interactions down to low energies, and alpha interactions have been studied in the MeV range (e.g. Exp. Tech. In HEP, T. Ferbel, editor, Addison-Wesley, 1987). The scintillation yield for relatively low energy nuclear recoils in has also been measured (down to ~40 keV)(Nim A, 449, (2000) 147). However, the simultaneous measurement of ionization and scintillation for recoils in the important 10 to 50 keV range has not yet been done for either liquid or gaseous xenon. We propose to carry out these measurements using a neutron beam at Texas A&M University.

The ionization yield can be predicted, in principle, from Lindhard theory (J. Lindhard et al., Mat. Fys. Medd. Dan. Vid. Selsk. 33(1963) 10), and measurements in germanium (ref) and silicon (G. Gerbier et al., Phys. Rev. D 42 (1990) 3211, and A.R. Sattler, Phys. Rev. 138 (1965) A1815.) agree well with this model. The scintillation yield has been shown to follow a similar curve as a function of recoil energy, but the absolute yield is not well predicted. However, at low energies the above references indicate that the Lindhard model needs modification to accommodate a threshold effect arising from the need for the electron to acquire enough energy to cross a finite band gap or ionization potential in the target material (PRL 21, no. 20 (1968)

1430-1433, and Phys. Rep. 187 (190) 203). This potential is expected to be about 7 eV for liquid xenon, but there remains a non-zero probability for sub-threshold ionization via virtual momentum transfer to the atomic nucleus. Thus a sharp cut-off is not expected, as found by Ficinec at al. Estimates of the ionization and light yield using Lindhard theory with and without a threshold effect are shown in **Figure 33**. The primary motivation for including gaseous xenon in our studies is that no threshold effect is predicted for a gas, so the ionization yield at low energies could be larger.

The xenon light and ionization spectra for nuclear recoils will be measured in the range 10 to 50 keV at the Texas A&M Nuclear Science Center with the assistance of Professor Les Brabey. Protons from a 4 MeV Van de Graaff will produce monochromatic neutrons with energies from 0.3 to 2.0 MeV in the $^{7}Li(p,n)^{7}Be$ reaction. The test cell constructed to study the internal CsI photocathode will be employed for these studies as well. We will also investigate ways to improve the light collection for the primary scintillation, such as using tetraphenylbutadiene to shift the light from 175 nm to blue.

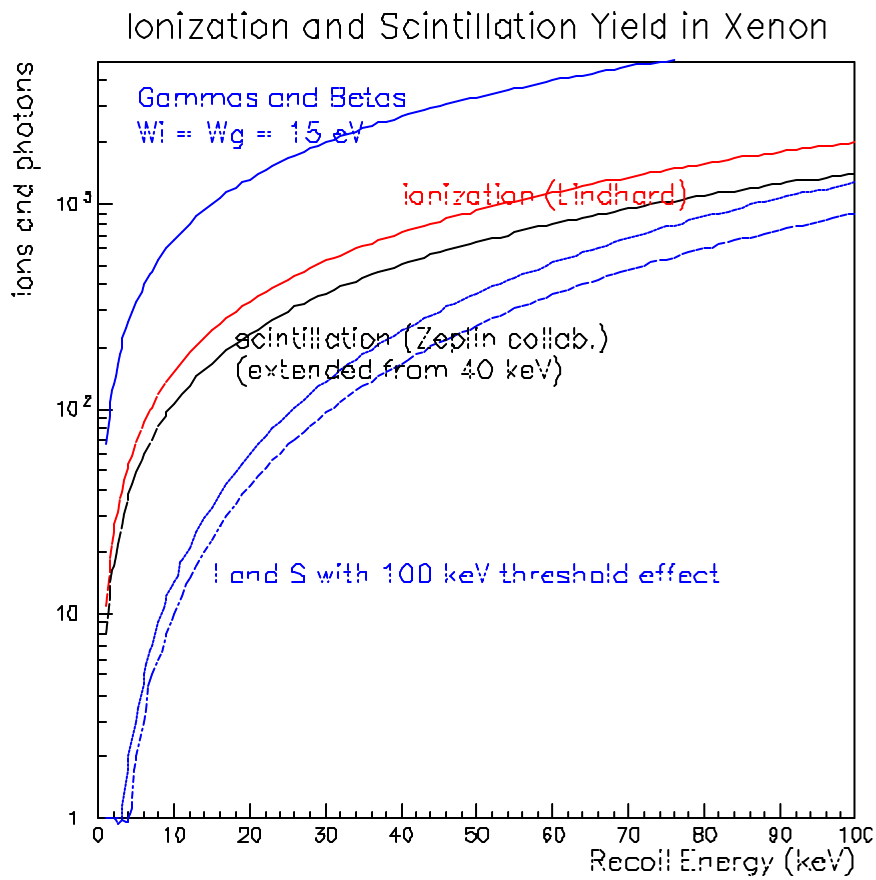


Figure 33 Ionization and scintillation yield for gammas and nuclear recoils in liquid xenon. Ionization is shown for pure Lindhard , and Landhard modified by a 100 keV threshold effect. The scintillation yield related to pure Lindhard is based on the yield measured by the Zeplin collaboration down to a recoil energy of 40 keV. It is extended to lower energies in proportion to the predicted ionization yield. A curve is also shown for the case where the scintillation yield was proportional to, but lower than the ionization with a 100 keV threshold effect. The Zeplin measurement excludes this curve, but the lower ionization has not yet been excluded or confirmed.

8 Budget & Commentary

This project will be directed by Professor David Cline. Dr. HanGuo Wang will help develop test detector hardware and coordinate the research effort. Dr. Wang has eleven years experience developing liquid-noble-gas technology and is extremely well qualified to carry out the research. Three months salary support is being requested for Dr. Wang who will carry out the ZEPLIN II detector performance tests at the Boubly Mine, UK and the neutron beam tests at Texas A&M University. The project is a collaboration between Princeton University and Texas A&M University (TAMU). The statements of work and budget for Princeton University and TAMU are included in this proposal.

Fringe benefits are calculated using standard university tables for this purpose. The current rate for academic appointments is 17% of salary. Fringe benefits on faculty summer salaries are calculated at 9.2%.

The UCLA budget requests $5K for materials to modify the TAMU detector to perform neutron beam tests. These materials includes rings, electronics, vacuum fittings, etc. that go in the chamber.

Foreign travel funds are requested for three trips ($4,500/trip) of one month duration each to the Boulby Mine, UK to carry out ZEPLIN II detector tests and take physics data Travel costs consist of round-trip airfare ($800), 30 days per diem ($3,000) and ground transportation ($700). Domestic travel funds are requested to allow Dr. Wang to travel to TAMU to conduct neutron beam tests. The domestic travel budget consists of three round-trips to TAMU for two week duration each. Travel costs include round-trip airfare ($400/trip), 14 days per diem ($1,400/trip), and ground transportation ($400/trip).

Overhead is calculated on modified total direct costs using the current off-campus rate of 26%. All detector tests and physics data taking for this project will be performed at either the Boulby Mine, UK or the TAMU neutron beam test facility justifying an off-campus overhead rate.

9 Current and Pending Support Statement

David B. Cline

A. Current Support:

Source of Support:	U.S. Department of Energy
Project Title:	Experimental High Energy Physics
Award Amount:	$495,000 (Task B and Task H Univ. Base Program)
	$134,294 (Task H U.S. CMS Project Funding)
	$ 78,000 (Task K – Administrative Core)
Period Covered:	January 15, 2001 through January 14, 2002
Location:	CERN, Fermilab, Gran Sasso, UCLA
Person-Months:	Academic Year: 2.0 Summer: 1.0

Source of Support:	U.S. Department of Energy
Project Title:	Advanced Accelerator Physics Research at UCLA
Award Amount:	$310,000
Period Covered:	November 1, 2001 through October 31, 2002
Location:	BNL, Fermilab, SLAC, UCLA
Person-Months:	Academic Year: 2.0 Summer: 1.0

B. Pending Support:

Source of Support:	U.S. Department of Energy
Project Title:	Experimental High Energy Physics
Award Amount:	$ 330,000 (Task B)
	$ 170,000 (Task H)
	$ 80,000 (Task K)
Period Covered:	January 15, 2002 through January 14, 2003
Location:	CERN, Fermilab, Gran Sasso, UK, UCLA
Person-Months:	Academic Year: 2.0 Summer: 1.0

10 Biographical Sketches

<u>David B. Cline</u>

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Professor David B. Cline received his Bachelor of Science in Physics (Cum Laude) from Kansas State University. He received his Ph.D. in experimental elementary particle physics from the University of Wisconsin – Madison in 1965. He held a brief appointment as a Research Physicist with the National Bureau of Standards in Boulder before being appointed an Assistant Professor of Physics at the University of Wisconsin – Madison. Dr. Cline was promoted rapidly. He became an Associate Professor of Physics at the University of Wisconsin – Madison in 1967 and Professor of Physics in 1968. He was an A. Sloan Fellow between 1967 and 1969. Dr. Cline's career has been ambitious and productive, having held visiting appointments at the University of Hawaii, LBL, Fermilab, and CERN, and serving on High Energy Physics Advisory Panels and Program Committees including those at BNL, Fermilab, Gran Sasso Laboratory, and SLAC. At the University of Wisconsin – Madison, he was Co-Director of the Institute for Accelerator Physics. He serves as an Associate Editor of the Nuclear Physics B. Journal. Dr. Cline joined the faculty at UCLA in 1986, holding a Professorship in the Department of Physics and Astronomy. He initiated the UCLA Center for Advanced Accelerators in 1987 and currently serves as its director. His programs of research include muon cooling for a muon collder at Fermilab, CMS, ICARUS, Accelerator R & D, Astroparticle Physics, and novel flavor factory research and development. He is a member of the New York Academy of Sciences.

<u>Synergistic Activities</u>

a) Associate Editor of Nuclear Physics B
b) Developed the Honors Collegium Course (HC 73) for the Elementary Particles and the Universe
c) Initiated the UCLA Center for Advanced Accelerators
d) Former member of HEPAP and former member of scientific program Committees at BNL, Fermilab, Gran Sasso, and SLAC

List of Persons who are, or have been collaborators in the past 5 years:

M. Atac, P. Chen, P. Picchi, W. Reay, C. Rubbia, P. Smith

List of Graduate Students advised and Postdoctoral Scholars Sponsored:

A. Boden	P. Kwok	D. Ramachandran
D. Chrisman	S. Rajagopalan	C. Ho
W. Hong	H. Wang	L. MacDonald
C. Nantista	Y. Liu	M. Zhou
W. Gabella	S. Masuda	J. Woo

D. Cline Graduate Advisor: William Fry, University of Wisconsin-Madison

RELEVANT PUBLICATIONS:

1) D. B. Cline, "Galactic and Extragalactic Supernova Neutrino-Burst Detection," in Proceedings of Intl. Workshop on the Identification of Dark Matter (The University of Sheffield, UK, Sept. 1996) (World Scientific, Singapore).

2) D. B. Cline, "Fundamentals of Liquid-Xenon SUSY-WIMP Detection," in Proceedings of Intl. Workshop on the Identification of Dark Matter (The University of Sheffield, UK, Sept. 1996) (World Scientific, Singapore).

3) D. B. Cline, "Possible Evidence for Primordial Black Holes," in Proceedings of the 18th Texas Symp. On Relativistic Astrophysics and Cosmology (Chicago, Dec. 15-20, 1996) (World Scientific, Singapore).

4) R. N. Boyd, R. L. Grodzinsky, D. B. Cline (+ 14), "A Supernova Burst Observatory to Study μ and τ Neutrinos," in Proceedings of the 18th Texas Symp. On Relativistic Astrophysics and Cosmology (Chicago, Dec. 15-20, 1996) (World Scientific, Singapore).

5) D. B. Cline, "Progress and Prospects in the Direct Search for Supersymmetric Dark Matter Particles," in Twenty-Five Coral Gables Conferences and their Impact on High Energy Physics (Proc., Intl. Conf. On Orbis Scientiae, Miami Beach, Fl, Jan. 1997) (Plenum Pub. Co.).

OTHER SIGNIFICANT PUBLICATIONS:

1) D. B. Cline, E. Fenyves, G. Fuller, B. Mayer, et al., "A New Method for Detection of Distant Supernova Neutrino Bursts," Astrophys. Lett. **27** (1990) 403-409.

2) D. B. Cline, "Signals of Primordial Black Holes," in Neutrino Telescopes (Proc., Fifth Intl. Workshop, Venice, March 1993), ed. M. Baldo Ceolin (Istituto Veneto di Scienze, Lettere ed Arti, Venice, 1993), pp. 377-385.

3) D. B. Cline and W. Hong, "The Observation of Unusual Gamma Ray Bursts From Primordial Black Hole Evaporation," in Gamma-Ray Bursts (Proc., 2nd Huntsville Symp., Huntsville, AL, Oct. 1993), AIP Conference Proceedings 307, eds. G. J. Fishman, J. J. Brainerd, and K. Hurley (American Institute of Physics, Woodbury, NY, 1994), pp. 557-580.

4) D. B. Cline, "The Supernova Burst Observatory: A Prototype Extra Galactic SN Detector and Supernova Watch," in Sources and Dark Matter in the Universe (Proc., 1st Intl. Symp., Bel Air, CA, Feb. 1994), ed. D. B. Cline (World Scientific, Singapore, 1995), pp. 303-322.

D. B. Cline and G. M. Fuller, "Neutrino Astrophysics," in Particle and Nuclear Astrophysics and Cosmology in the Next Millennium" (Proc., 1994 Snowmass Summer Study, Snowmass, CO, June 1994). eds. E. W. Kolb and R. D. Peccei (World Scientific, Singapore 1995), pp. 247-255.

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Education

1966-1972	Doctor of Philosophy in Physics Caltech
1963-1966	Bachelor of Science in Mathematics and Physics University of Arizona

Employment History

Sep. 1985 –	Professor of Physics, Princeton University
Sep. 1980 – Aug. 1985	Associate Professor of Physics, Princeton University
Sep. 1976 – Aug. 1980	Assistant Professor of Physics, Princeton University
Jan. 1975 – Aug. 1976	Fermi Fellow, University of Chicago
July 1972 – Dec. 1974	Postdoctoral Fellow, CERN

Professional Organizations

Fellow of the American Physical Society

Member of the American Association for the Advancement of Science

Member of the American Association of Physics Teachers

Member of the American Association of University Professors

Member of the Minerals, Metals and Materials Society (TMS)

Member of ASM International

Relevant Publications

C. Lu and K.T. McDonald, *Properties of Reflective and Semitransparent CsI Photocathodes*, Nucl. Instr. and Meth. **A343**, 135 (1994).

C.Lu *et al.*, *Characterization of CsI Photocathodes for Use in a Fast RICH Detector*, Nucl. Instr. and Meth. **A366**, 60 (1995).

C. Lu *et al.*, *Prototype Studies of a Fast RICH Detector with a CsI Photocathode*, Nucl. Instr. and Meth. **A371**, 155 (1996).

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Education

1996-1998	Doctor of Philosophy in Physics University of California, Los Angeles
1992-1996	Master of Science in Physics University of California, Los Angeles
1978-1982	Bachelor of Science in Physics Harbin Institute of Technology (H. I. T.), China

Employment History

Jan. 2000 – Present	Assistant Research Physicist, UCLA
Nov. 1998 – Dec. 1999	Postdoctoral Fellow, UCLA
Sept. 1992 – Oct. 1998	Graduate Student Researcher, UCLA
Jan. 1989 – Aug. 1992	Research Associate, INFN, Frascati, Italy (ICARUS at CERN)
May 1986 – Dec. 1989	Research Associate, U.C. Riverside (at CERN, OPAL)
July 1982 – May 1986	Research and Teaching Assistant, H. I. T. China.

Synergistic Activities

A) Improved the strip production procedure for the OPAL Hardon Calorimeter at CERN. Electronic and Chamber installation and testing.

B) Designed, built, and tested the first 3-ton liquid argon TPC prototype for ICARUS.

C) Developed and perfected the liquid xenon dark matter detection technique as described in this proposal.

Collaborators: M. Atac, D. Cline, P. Picchi, C. Rubbia, B. Shen, P. Smith

Ph.D. Thesis Advisor: David Cline

Relevant Publications

1. ZEPLIN IV: A 1-ton very sensitive ZEPLIN II extension for SUSY dark matter, astro-ph/0108147.
2. Design of the ZEPLIN II detector, in *Proceedings of sources and detection of dark matter and dark energy in the universe: fourth international symposium, held at Marina del Rey, CA, February 23 - 25, 2000*, edited by D. B. Cline (Springer-Verlag Berlin Heidelberg 2001).
3. Measurement of scintillation amplification in a Xenon detector with a CsI-luminescence plate, in *Proceedings of sources and detection of dark matter and dark energy in the universe: fourth international symposium, held at Marina del Rey, CA, February 23 - 25, 2000*, edited by D. B. Cline (Springer-Verlag Berlin Heidelberg 2001).
4. Scintillation Efficiency of Nuclear Recoil in Liquid Xenon. *Nuclear Instruments & Methods in Physics Research*, **A449**, (2000) 147.
5. A WIMP Detector with Two-Phase Xenon. *Astroparticle Physics*, **12**, (2000) 373.
6. Xenon as a Detector for Dark Matter Search. *Physics Reports*, **307**, (1998) 263.
7. Also in *Proceedings of 3rd International Symposium on Sources and Detection of Dark Matter in the Universe (DM '98)* (Marina del Rey, CA, Feb. 1998), ed. D. B. Cline (Elsevier, Amsterdam, 1998).
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10. Operation of a 2kg Discriminating Liquid Xenon Detector for Dark Matter. Talk given at *The Identification of Dark Matter* (Intl. Workshop, University of Sheffield, UK, Sept. 1996).
11. WIMPs Detection using Liquid Xenon Proportional Scintillation. Talk given at *International Workshop on "Aspects of Dark Matter in Astro- and Particle Physics"* (Sept. 16029, 1996, Heidelberg, Germany).
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13. A Simple and Effective Purifier for Liquid Xenon. *Nuclear Instruments & Methods for Physics Research*, **A329**, (1993) 361.
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Positions Held:

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James White is a researcher in experimental high energy physics. His primary research the past several years has been the search for evidence of supersymmetry via the tri/di-lepton signals in proton-antiproton collsions at the Fermilab Tevatron while a member of the DZero Experiment. He has also maintained a detector R&D program which has included development of the liquid scintillating fiber calorimetry concept for use at the SSC, investigation of the use of laser induced fluorescence as a new approach for high resolution particle tracking, and studies of the use of cryogenic argon, neon and xenon for cold dark matter detection. His future plans are to concentrate full effort on the search for dark matter within the ZEPLIN collaboration, including work on the Zeplin II, 30 kg liquid xenon experiment and R&D for the ton-scale Zeplin IV detector.

Recent Presentations

``Dark Matter Detection in Liquid and Solid Noble Gases'', Snowmass 2001-the Future of Particle Physics, Snowmass, CO, July 6, 2001

``Search for Dark Matter'', Conference for the Advancement of Science Teaching, (CAST 2000), Texas A&M University, Oct. 14, 2000

``Dark Matter Detection with Cryogenic Argon'', Sixteenth International Conference on the Application of Accelerators in Research and Industry, (CAARI 2000), Denton, Texas, Nov. 1-4, 2000

Recent Publications

B.Abbott, *et al.* [D0 Collaboration], ``Cross section for b jet production in anti-p p collisions at s**(1/2) = 1.8-TeV," Phys. Rev. Lett. **85**, 5068 (2000) [hep-ex/0008021].

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B. Abbott, *et al.* [D0 Collaboration], ``The isolated photon cross-section in p anti-p collisions at s**(1/2) = 1.8-TeV," Phys.Rev. Lett. **84**, 2786 (2000) [hep-ex/9912017].