

# Proposed search for signals from non-baryonic Galactic dark matter by observation of low energy nuclear recoil events in a new liquid xenon detector with high background rejection.

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## 1 Introduction & project description

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. Observational evidence, in particular searches for gravitational lensing events, continues to support the hypothesis that non-baryonic matter may constitute the majority of the 90% non-luminous component of our Galaxy.

This proposal is based on a major advance in the detection of low energy nuclear recoils, which would result from interaction with weakly interacting massive particles. With neutron background reduced to a negligible level in an underground location, observation of such nuclear recoils would provide clear evidence of a flux of new neutral particles. Moreover, a theoretical candidate exists in the form of the lightest particle ('neutralino') of supersymmetry theory, which would be formed in the early universe and subsequently cluster in Galaxies with normal matter. Estimates of interaction rates are in the range 0.001- 1 events/kg/d, the most favored region being 0.01-0.1 events/kg/d.

No experiments are yet running which could reach such low event rates. It has been known for several years that this level of sensitivity is possible in principle by using combined scintillation and ionization processes in liquid xenon to discriminate the nuclear recoil events from background gamma or beta decay events. This formed the basis of a previous proposal to NSF from this collaboration. The major advance since then, made by members of the ICARUS collaboration, including the UCLA group, has been to demonstrate conclusively this discrimination process in liquid xenon test chambers of 150g and 2kg. This now makes it possible to proceed with a full low background underground experiment using a detector of 20kg target mass and improved energy threshold capable of observing a flux of Galactic neutralinos, or any other type of massive particle, at an interaction rate below 0.1 events/kg/d.

The interaction with a target nucleus may be either spin-dependent or spin-independent (scalar). All nuclei would respond to the latter, but only nuclei with spin will respond to the former. Moreover, in the case of a neutralino either form of interaction may dominate, depending on the parameters of the theory (Jungman et al 1996, Phys Rep 267)). Liquid xenon satisfies all of the basic requirements for a dark matter target:

- (a) It is available in sufficiently large quantities with high purity.
- (b) It scintillates via two mechanisms, stimulated differently by nuclear and electron recoil events.
- (c) It contains both odd and even isotopes, suitable for both spin-dependent and scalar interactions, offering the further possibility of using enriched odd or even isotopes to identify the type of interaction for any suspected signal.

The 20kg detector proposed here is an order of magnitude larger than the recent test chamber constructed at CERN and has 5x better light collection achieved by larger photomultipliers. This module could subsequently be replicated to achieve a total target mass 100-1000kg. This would allow exploration of lower event rates (0.001-0.01/kg/d) and may also be needed to detect the annual modulation (of both rate and energy spectrum) to confirm the Galactic origin of any signal.

**Fig 1** summarizes progress in improving the sensitivity of dark matter experiments. Underground Ge ionization detectors have set some important limits to the event rate from dark matter particle candidates such as heavy neutrinos, but do not have the nuclear recoil discrimination needed to reach the neutralino event rate levels. Recently some significant improvements in sensitivity have been made by means of pulse shape discrimination in low background NaI scintillating targets, giving event rate limits of order 10/kg/d for both spin-dependent and scalar interactions. These will soon fall further, to 1/kg/d and below, with improved light collection and longer running, but the rather small pulse shape differences between recoil events and gamma background makes it difficult and perhaps impossible to reach 0.1-0.01/kg/d with this target material.

There are two distinct approaches to discriminating nuclear recoil events in liquid xenon

- (1) Analyzing the total scintillation pulse shape (or, at low energy, the individual photon arrival times) - which differs significantly for nuclear recoil and electron recoil events.
- (2) By applying an electric field to inhibit recombination and (a) measuring the 'primary scintillation' S<sub>1</sub> and (b) drifting the ionization component into a strong electric field in the anode region to produce a 'secondary scintillation' signal S<sub>2</sub> with a time delay of up to 50  $\mu$ s. The mean ratio S<sub>1</sub>/S<sub>2</sub> differs for nuclear recoil and electron recoil events, with an 'overlap' which is typically only 1% at a gamma energy of 10 keV and 0.1% at a gamma energy of 20 keV.

Method (2) is more powerful and is the one proposed here. Discrimination between alphas and gammas was first demonstrated in 1994 within the ICARUS collaboration by a small team which included members of the UCLA group. More recent tests have used neutron scattering to confirm, firstly that liquid xenon will give a scintillation response to recoil of its own nuclei, and secondly that the above discrimination processes remain effective down to background energies of a few keV, as required for a dark matter experiment. These tests are shown in more detail in §3 below. In addition, a monoenergetic neutron beam at Padua has been used to measure the relative scintillation efficiency for nuclear recoils and background.

This quantitative demonstration of discrimination by method (2) above is a crucial step towards the goal of operational detectors. The results show that nuclear recoil events could be identified at only 0.01-0.001 of the gamma background within a 1 year running period. Thus since reported gamma/electron backgrounds in underground liquid xenon tests (at Gran Sasso) are at the level 10/kg/d, a 20kg underground experiment based on the new technique proposed here could identify a population of rare nuclear recoils at the level 0.1-0.01/kg/d in a running period of 1-2 years.

We refer to liquid noble gas detectors with a field-defined target zone generically as 'ZEPLIN' configurations, which may optionally include an outer self-shielding zone. The present design does not utilize the latter but contains several other unique features, including excellent light collection from direct contact between the photomultipliers and liquid xenon and a surrounding Compton veto (plastic scintillator) to reject > 90% of low energy background from photomultiplier radioactivity.

Construction of this detector would proceed in parallel with small scale tests, at UCLA and in the UK, of relative scintillation efficiency, light collection efficiency, operating parameters and background discrimination criteria. The full low background design, together with underground operation of the experiment, would be carried out in collaboration with the UK dark matter program in the 1100m deep Boulby salt mine. This is currently running the above-mentioned NaI scintillation experiments and thus already established as a fully operational dark matter laboratory, equipped with all necessary services, low background shielding, data acquisition, remote communication facilities, and operating manpower.

This project will be the first of its kind and will achieve three important goals:

- (1) First full scale demonstration of a low background experiment based on nuclear recoil identification by primary and secondary scintillation.
- (2) Continuous underground running for 1-2 years to search for signals from neutralinos or other particles in the 10-1000GeV range.
- (3) Assessment of design improvements and possibilities for scale-up to 100-1000 kg targets.

Achievement of event rates in the range 0.01-0.1/kg/d will be a major landmark in dark matter searches, reaching the most favored predicted neutralino range for the first time. Moreover, by combining the recent UCLA liquid xenon R&D results and engineering experience with the UK low background experience and existing underground facilities, this unique experiment can now be constructed and operated at a comparatively low cost. It would provide also the basis for international collaboration on further experiments to study any positive signal of Galactic origin.

## 2 Scientific case

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. In this proposal we are concerned specifically with the problem that the rotation curves of most galaxies, including our own, indicate that the visible stars constitute only 10% of the Galactic mass, immersed in non-luminous matter which constitutes the remaining 90%. The candidate explanations for Galactic dark matter are in two main classes

- (a) Baryonic: eg non-luminous stars of less than 1 solar mass, referred to as MACHOs.
- (b) Non-baryonic: eg light neutrinos, new weakly interacting massive particles (WIMPs), or new light bosons (eg axions)

Dynamical observations alone cannot distinguish between (a) and (b), so other types of observational search are in progress on each. For the particle candidates, 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 low energy (keV-range) nuclear recoils from elastic scattering in low background underground detectors. This is the subject of the present proposal. Elsewhere, there are also experimental plans for light axion searches, through conversion to microwave photons in a magnetic field. Light neutrinos are less-favored from a galaxy-formation viewpoint, but remain possible in principle, requiring one neutrino to have a mass of order 20-30eV. Relic neutrinos, because of their low energy ( $10^{-4}$ - $10^{-2}$ eV) are not experimentally detectable at the present time, though with improved technology future detection ideas can be envisaged.

The case for particle searches has been strengthened in recent years by a number of astronomical developments:

- (1) There is continuing evidence that the total density parameter of the universe is in the range  $0.2 < \Omega < 1$  (critical density) while at the same time estimates of the baryonic contribution have narrowed to the range  $0.02 < \Omega_b < 0.06$ , (Carswell 1994 MNRAS 268,L1, Songaila 1994, Nature 368,599, Galli 1995, ApJ 443, 536) This strengthens the evidence for a dominant non-baryonic component in the universe as a whole.
- (2) The possible microlensing detections of 0.01-1 solar mass baryonic objects ('MACHOS') in the halo can probably only account for  $\approx 20\%$  of the halo mass (Carr 1994 ARAA 32, 531, Gates & Turner 1994 PRL 72, 2520, Adams & Laughlin 1996 preprint) with a rather large uncertainty at present. From the EROS CCD searches for short time-scale lensing events, there are strong constraints on any significant contribution to  $\Omega$  from baryonic objects in the mass-range  $10^{-7}$  -  $10^{-3}$  solar masses. The Hubble space telescope has provided strong limits on any contribution from normal low mass stars to the halo density (Graff & Freese, Flynn et al, 1996 preprints). These observations leave a particle explanation still favored to account for the majority of the halo density.

Supersymmetry continues to be an important candidate theory for accounting for particle mass hierarchy in a 'natural way'. In particular, it predicts the existence of a lightest (stable) supersymmetric particle - the neutralino - with mass probably  $> 20$ GeV (from accelerator searches) and  $< 1000$ GeV (from theoretical considerations). 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. For more detailed discussions of supersymmetry in relation to dark matter see Jungman et al 1996 Phys Rep 267, Treille 1994 RPP 57,1137, Ellis 1991 Phys Scripta T36,142, Nojiri & Drees Phys Rev D48,3483, Arnowitt & Nath, Wisc HEP-PH 9408226, 9409301.

Nevertheless, experiments based on nuclear recoil are virtually free from assumptions about the nature of the particles or their theoretical basis. This is because 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. Moreover the interaction rates themselves can be estimated on rather general grounds to be in the range 0.01-100 events/day/kg of target, with neutralino rates predicted to be at the lower end of this range (see above references).

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. Nevertheless it is customary for experimental limits to be displayed separately for spin-dependent and spin-independent interactions (as shown in **Fig 1**). In the latter case, the rate for low momentum transfer will be proportional to the square of the number of neutrons and/or protons in the nucleus (eg 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 the interaction rates, for both types of interaction, are reduced by a form factor correction (see §3). 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  $>100\text{kg}$ ) 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 this results in a  $\pm 5\%$  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 ( $\sim 1\text{-}5\text{ }\mu\text{g/cm}^2$ ) directionality will be difficult to achieve in a solid or liquid, but there are longer term ideas for achieving this, and also for large-scale low pressure gaseous track detectors which could observe the recoil direction, and hence definitively correlate the signal with Galactic motion.

### 3 Detection principles and discrimination in liquid xenon

#### 3.1 Energy spectrum, event rates, background discrimination

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

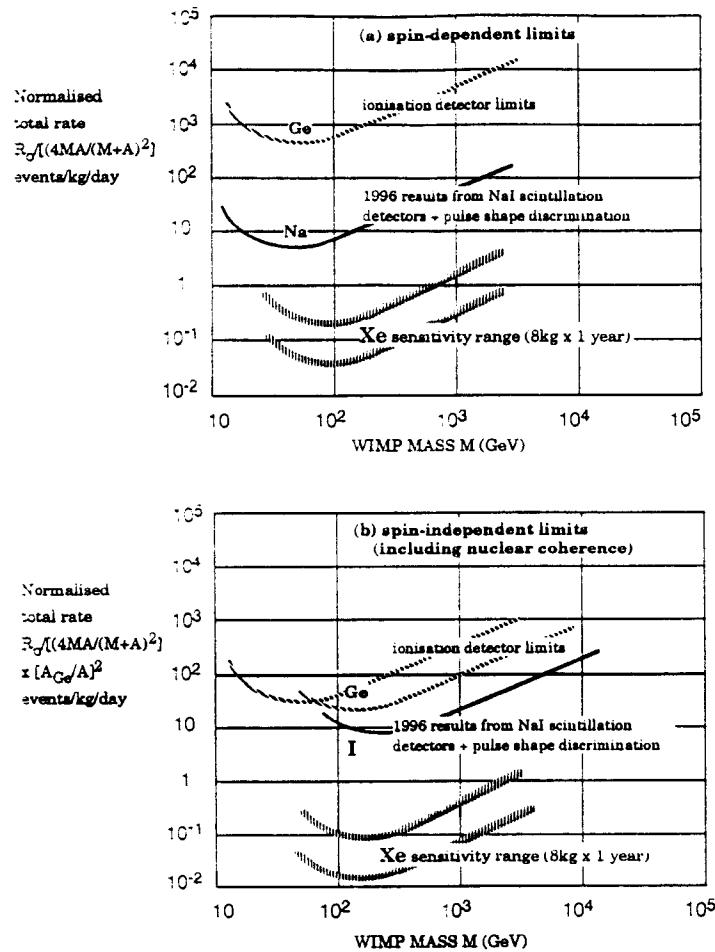
$$dR/dE_R = c_1 (R_0 / E_{0r}) [\exp(-c_2 E_R / E_{0r})] [F(E_R)]^2 \quad (1)$$

where  $r = 4M_D A / (M_D + A)^2$  for target element A and incident particle mass  $M_D$ ,  $E_0 = M_D v_0^2 / 2$  ( $v_0$  = Galactic velocity dispersion  $\approx 210$  km/s,  $E_0$  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 (eg only about 50% of a xenon target has nuclear spin). The coefficients  $0.5 < c_1, c_2 < 1$  allow for the motion of the earth relative to the Galaxy. For a stationary earth,  $c_1=c_2=1$  giving total event rate  $R_0$ . The motion of the sun modifies this to  $c_1 \approx 0.78$ ,  $c_2 \approx 0.58$  with further  $\pm 5\%$  annual variations arising from the orbital motion of the earth (for a full discussion of the mathematics of dark matter experiments see review Smith & Lewin RAL-TR-95-024).

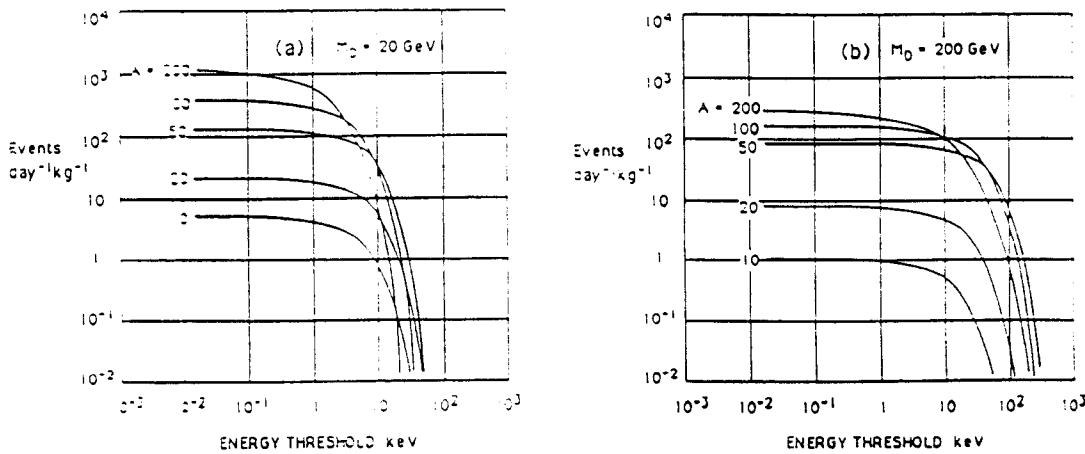
Thus a limit on, or measurement of, the differential rate  $dR/dE_R$  for a given  $E_R$  leads to a corresponding limit or value for  $R_0$  for each assumed particle mass  $M_D$ . This is the basis of the Ge limits in **Fig 1**, the minimum of the curves occurring approximately when  $M_D \approx A$ . Because the above spectrum falls sharply with energy, the sensitivity depends on energy threshold. **Fig 2** shows the variation of total events observable as a function of energy threshold for two illustrative values of  $M_D$ . It can be seen that the energy threshold has a greater effect for smaller values of  $M_D$  but nevertheless remains important even for  $M_D > 100$  GeV. Scintillation detectors will in general respond to nuclear recoils with an output signal which is smaller per keV than for electron recoils. This is known as the relative scintillation efficiency  $f_A$ , and 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  $E_{\text{obs}}$  corresponds to a true recoil energy  $E_R = E_{\text{obs}} / f_A$  and it is this value which applies throughout eq.(1).

This affects the sensitivity both through the number of events which occur above  $E_{\text{obs}}$  and in particular through the form factor correction, which follows approximately a Bessel function in  $qR_A$  where  $R_A$  the nuclear radius and  $q \approx \sqrt{2AE_R} = \sqrt{2AE_{\text{obs}}/f_A}$  is the momentum transfer. The effect of the form factor on experiment design is discussed further below.

The left hand side of eq.(1) will contain the detector background plus any signal, so that progressive reduction of background would in principle allow observation of any constant signal. However, the best available shielding and detector materials have not so far reduced differential backgrounds below about  $1/\text{keV/kg/d}$  for energies  $< 10$  keV, in underground tests on Ge, NaI, and liquid Xe targets, corresponding to integrated dark matter limits in the region  $10\text{-}100/\text{kg/d}$ . Thus to reach counting rates  $R_0 = .01\text{-}1/\text{kg/day}$  it is necessary to achieve discrimination between nuclear recoil and background events, to reject the latter by a factor 100-1000. Several methods of doing this are being developed. These include simultaneous measurement of ionization and phonon signals in semiconductors at low temperature, pulse shape or wavelength discrimination in scintillators, and the double-pulse signal in liquid xenon proposed here and described in more detail in §4.



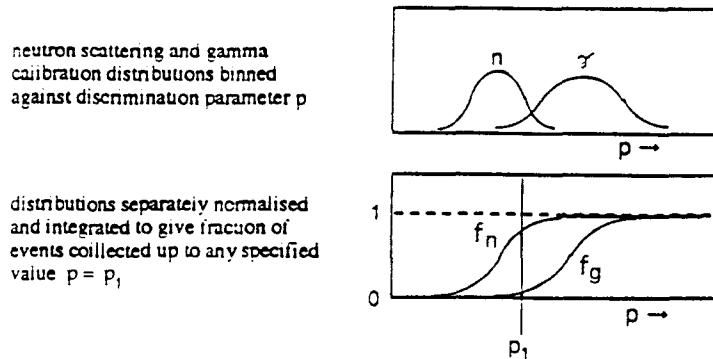
**Fig 1** Dark matter rate limits for (a) spin-dependent and (b) spin-independent interactions, showing limits from Ge double-beta decay detectors, recent improved limits from the UK program using pulse shape discrimination in NaI, and the region achievable with the liquid Xe detectors in this proposal. The normalized rate plotted is equivalent to cross section reduced mass squared, which is proportional to the fundamental couplings.



**Fig 2** Total event rate versus detector recoil energy threshold for weakly interacting dark matter particles of mass (a) 20 GeV and (b) 200 GeV incident on target atomic number A. The coherent Dirac neutrino cross section (modified by the energy dependent nuclear form factor) is taken for illustration.

With all discrimination techniques, there will in general be, at least near energy threshold, some overlap between signal and background event distributions as a function of a discriminating parameter  $p$ . A range of  $p$  which includes, 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 will be limited to a factor  $f_g$  gain in sensitivity.

However further 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 background are first obtained as a function of the discriminating parameter  $p$ .



These apply to some small energy interval  $E_1$  to  $E_2$  (typically a few keV) and will in general vary slowly with energy, determined from the calibration data. For no 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. For assessment purposes this can be usefully quantified in terms of a 'figure of merit, derived as follows:

If, in the specified energy interval there are  $N$  (total) events consisting of  $S$  true signal events and  $N-S$  background events, then the number  $N_1$  below some value  $p = p_1$  is

$$N_1 = f_n S + f_g (N-S) \quad (2)$$

If there is no real signal but only statistical fluctuations in the background then the number below  $p_1$  is  $f_g N$  plus a possible statistical fluctuation  $1.3 s$  (one-sided, 90% confidence):

$$N_{\text{obs}} = f_g N + 1.3 [f_g (1-f_g) N]^{0.5} \quad (3)$$

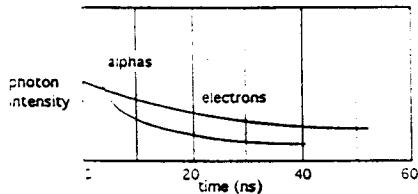
Equating (1) and (2) the 90% confidence signal background limit is

$$S/N \leq C N^{-0.5} \text{ with } C = 1.3 [f_g (1-f_g)]^{0.5} / [f_n - f_g] \quad (4)$$

This shows that the signal limit improves inversely as the square root of the number of counts in the energy interval, multiplied by a numerical factor  $C$  which can be called a 'coefficient of discrimination'. From the integral curves one can in general find a value of  $p$  for which  $C$  is optimum (ie minimum). This provides a basic "figure of merit" with which to compare discrimination techniques. In practice a slightly better limit may be obtainable by using a full chi squared analysis of the data, but the above approximation is fully adequate for discussion and design purposes.

The possibility of substantial statistical gains from even a small signal difference between nuclear recoils and background has been already demonstrated by using pulse shape discrimination in a 6kg NaI detector running in the UK Boulby Mine. Six months data was sufficient to give a nuclear recoil sensitivity a factor 10 below background at 5 keV, improving to a factor 40 at 20 keV (Smith et al., Phys. Lett. B June 1996). The pulse shape analysis was also used to reject PMT noise pulses.

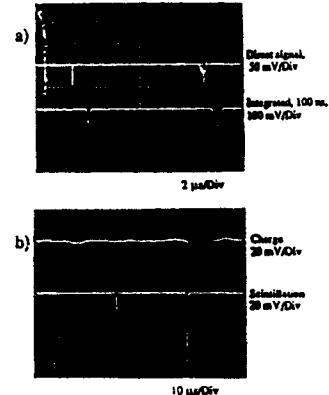
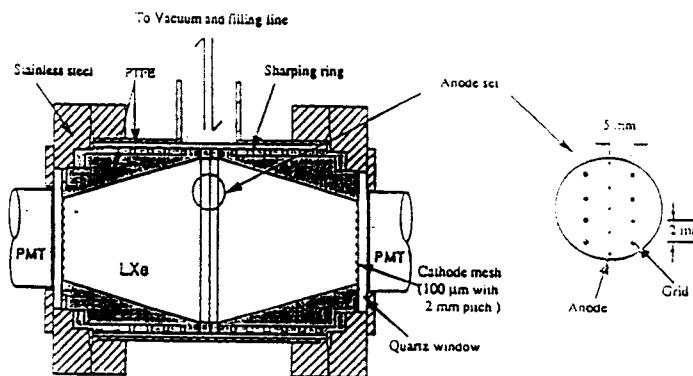
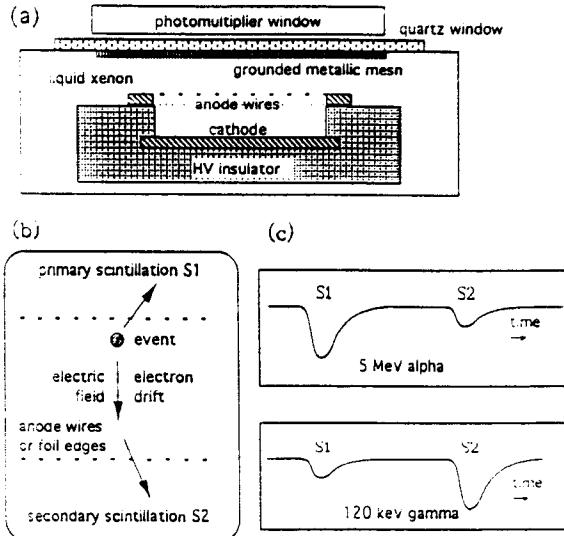
The present proposal is based on recent test results which confirm that proportional scintillation in liquid xenon is capable of much better discrimination than pulse shape discrimination in NaI - ie substantially lower values for the parameters  $f_g$  and  $C$ . We show these results in the next section.



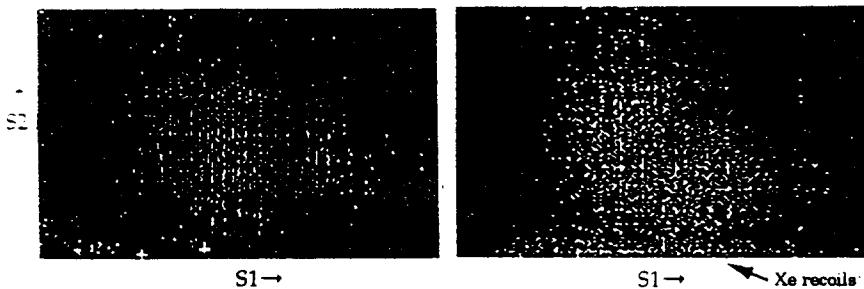
**Fig 3** Scintillation pulse shape differences for alphas and electron recoils in liquid Xe

**Fig 4** Discrimination by proportional scintillation

- (a) Liquid xenon test chamber
- (b) Processes following scattering event
- (c) Integrated S1 and S2 pulses:  
 $S2/S1=0.3\pm 0.2$  for  $\alpha$ ,  $S2/S1=3\pm 2$  for  $\gamma$



**Fig 5** Two-PMT liquid xenon test chamber and typical pulses  
 (a) direct and integrated primary and secondary scintillation pulses.  
 (b) scintillation pulses and associated anode charge signal



**Fig 6** Correlation plots of signals S1 and S2 for irradiation with 22 keV gamma source (left) and mixed n +  $\gamma$  source (right) showing additional population of Xe recoils at low S2 with only 0.1% overlap with  $\gamma$  events of the same energy.

#### 4 Nuclear recoil discrimination in liquid xenon - recent experimental studies

Discrimination between signal and background arises from the fact that liquid Xe scintillates by several mechanisms, stimulated differently by nuclear and electron recoil (for a summary and references see G Davies et al. Phys Lett B 320 (1994) 395). These mechanisms are:

- (1) Production and decay of  $\text{Xe}_2^*$  excited states, which decay with time constants 3ns and 27ns, emitting 175nm photons. The proportions of these differ for electron and nuclear recoils, giving significantly different pulse shapes (**Fig 3**).
- (2) Production of an ionized state  $\text{Xe}_2^+$ . If this recombines, it also leads to  $\text{Xe}_2^*$  states which decay as before. However, recombination can be inhibited with an electric field, and the charge can be drifted into a strong field near fine anode wires to produce a second (proportional) scintillation pulse (see **Fig 4**).

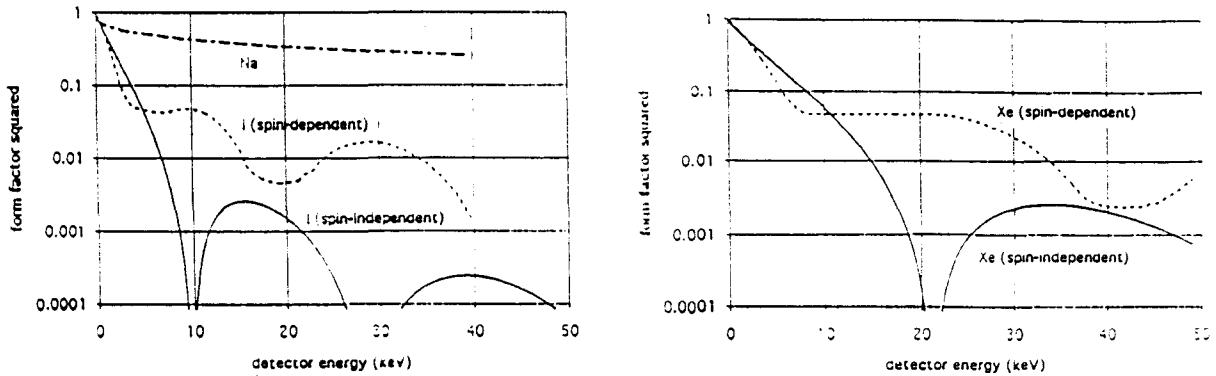
Thus a double scintillation pulse can be created - a primary scintillation pulse S1 from (1), followed a few  $\mu\text{s}$  later by a secondary scintillation pulse S2 from (2). From published data on the interaction of electrons, protons and heavy ions with liquid xenon the average ratio S2/S1 is predicted to be 0.1-0.3 for incident nuclei and 1-10 for electrons, with an overlap between the two classes of events estimated to be only a few % at 10 keV.

These expectations have been fully 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 liquid xenon chamber, containing an electric field and coupled to a photomultiplier was irradiated with 5 MeV alphas and 120 keV gammas (see **Fig 4**, taken from Benetti et al., NIM A327(1993)203). Drift voltages of several kV suppressed recombination and a secondary scintillation signal was produced. The ratio S2/S1 was  $>1$  for gammas and  $<1$  for alphas, as predicted. Subsequently, the double pulses have been observed with a larger (2kg) chamber and two coincident photomultipliers (**Fig 5**). During the past year further tests at CERN with a 150g chamber have enabled more precise measurements to be made of the discrimination factor, this time for true Xe recoils from neutron scattering. **Fig 6** shows S1-S2 correlation plots for events at 22 keV with clear separation of the populations of gamma and neutron scattering events.

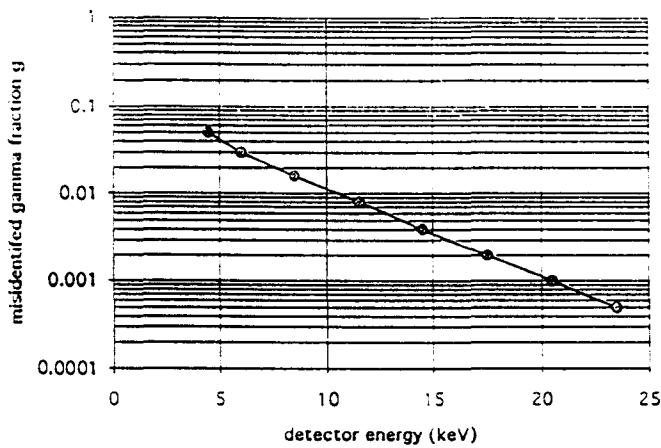
In addition, the 150g chamber has been used to make the first Xe recoil efficiency measurements using a 6MeV monoenergetic neutron beam with known scattering angles. Their preliminary result of 20% is similar to that expected from a Lindhard estimate, but lower than expected theoretically with recombination (50%) and will be repeated. Nevertheless this value is much better than the 9% measured for iodine in NaI. This in turn gives a less severe form factor correction, as plotted versus measured energy  $E_{\text{obs}}$  in **Fig 7**. This is another feature which makes Xe clearly superior to NaI in sensitivity. After removal of PMT noise pulses the overlap  $f_g$  in **Fig 6** is about 0.1%, from which a Monte Carlo interpolation allows  $f_g$  to be estimated as a function of energy (**Fig 8**). This can then be used to calculate the energy-dependent figure of merit  $C(E)$  and compare this with the corresponding values of  $C$  for Na and I in NaI, already known from the UK program (**Fig 9**). These curves include the measured values of relative scintillation efficiency. Taking into account the various form factor corrections in **Fig 7**, the gain would be greater for scalar interactions than for spin-dependent, but always in the range 10-100. Thus liquid xenon is expected to have a higher sensitivity for both types of interaction. Using the estimated  $C$  values, **Fig 10** shows the dark matter sensitivity in events/kg/d achievable as a function of the product (target mass  $\times$  running time) compared with projected improvements for NaI experiments. The lower Xe curve is for improved light collection from replacement of PMTs by low noise avalanche photodiodes currently under development, as discussed below in §5

This work has provided, for the first time

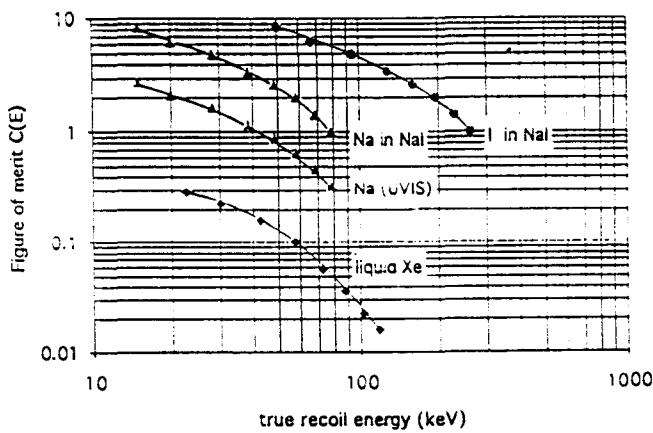
- (a) a demonstration of the technical feasibility of the proportional scintillation technique.
- (b) confirmation that liquid Xe will register low energy recoils of its own nuclei.
- (c) the first quantitative estimates of the discriminating power of the technique. The calculations show that the use of primary and secondary scintillation offers a clear prospect for discriminating a dark matter signal from background at rates 0.01-0.1 events/day/kg - and hence to observe a neutralino signal at this level.



**Fig 7** Nuclear form factor correction for Na, I and Xe recoils, plotted against observed detector energy, using measured relative scintillation efficiencies 0.3, 0.09, 0.2, respectively. It is established theoretically 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).



**Fig 8** Approximate fraction of gamma events misidentified as nuclear recoils as a function of observed energy in liquid Xe, for the system of Fig 5-6.



**Fig 9** Dimensionless figure of merit  $C(E)$  as a function of true recoil energy estimated from liquid xenon test chamber results, compared with corresponding values for pulse shape discrimination in NaI. UK neutron beam measurements of  $C$  for discrimination in cooled NaI (UVIS technique) are also shown.

## 5 Design concepts, detector configurations

The objective is to implement the preceding discrimination principle into an operational detector.

Experimental sensitivity is governed in particular by

(a) increasing target mass, giving

- (i) increased data rate per unit running time
- (ii) self-shielding - ie decreased background/kg from detector components and PMTs

(b) improved light collection, giving

- (i) more photoelectrons/keV, improving signal/background discrimination statistics.
- (ii) lower energy threshold, collecting more signal events (through eq.1 and Fig 2).
- (iii) lower energy threshold, reducing the form factor correction (Fig 7).

The test chambers ,used to study the basic discrimination mechanism and recoil efficiency, are not suitable for dark matter searches and require scale-up in both (a) and (b) to achieve sensitivities  $< 0.1$  event/d/kg. In arriving at an optimum design, (b) is found to have at least equal priority to (a), in view of the rapid fall in the form factor with energy for the large Xe nucleus (Fig 7). Our proposed design has

- (1) Target mass 20kg, which is a factor 10 larger than the test chamber and would provide a realistic basic module for larger mass arrays if required in the future.
- (2) A light collection improved by a factor 5 from the 2kg prototype, by using the largest available quartz-window photomultiplier (12cm photocathode diameter). Magnesium fluoride windows are available only on small PMTs, and the 170nm transmission of quartz ( $> 70\%$ ) is sufficient to ensure that the 12cm PMT will give better overall performance.

The essential features of the design are shown in **Fig 11**, which also shows the arrangement of gamma and neutron shielding. Also shown is a plastic scintillator Compton veto, aimed at rejecting low energy gamma background from the PMTs. The principle, verified by Monte Carlo simulation, is that those gammas from U,Th, K in the PMTs which deposit only a small fraction of their energy in the xenon carry away most of their energy (typically 100-1000keV and can then be registered in the outer veto. If the latter has an energy threshold of 30-100keV, then 90% of the low energy background events can be rejected, the remaining 10% then being subject to the discrimination analysis to search for a possible signal component.

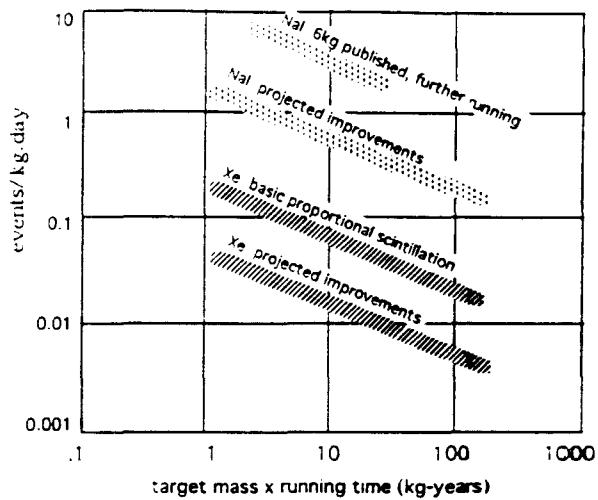
In accordance Fig 10, this design is capable of observing (in the absence of systematic errors) event rates 0.03-0.1/kg/d within a 1-2 year running time.

Further improvements in light collection and background may be possible through the use of wavelength shifting coatings on the chamber walls. This converts the 170nm light to a visible wavelength, for which the reflection losses are lower and the photocathode sensitivity greater.

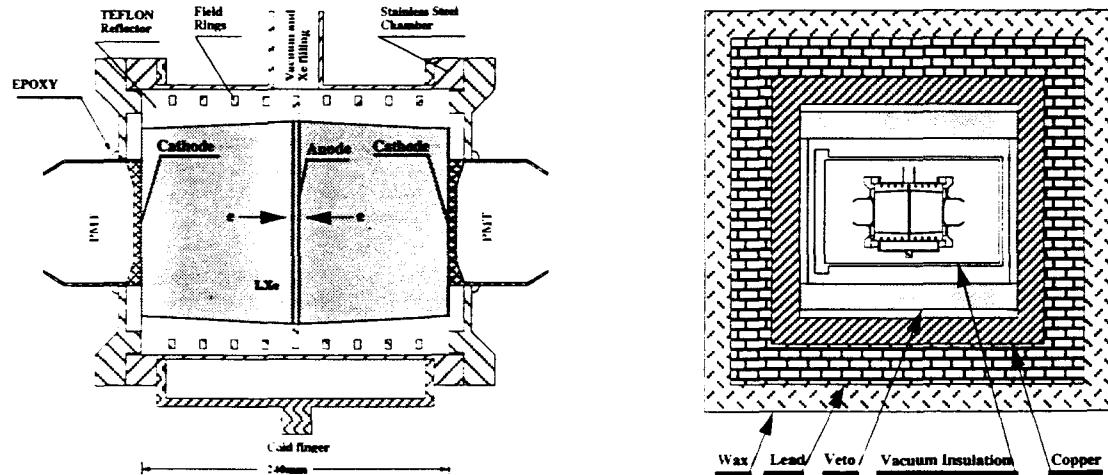
The drift voltage (optimum at 250V/cm) provides an important diagnostic variable, which can be used to vary the relative primary and secondary pulse heights, and this provides a unique method of studying backgrounds and any suspected signal. An additional feature of the design is that it can be run without the electric field, giving background rejection by simple pulse shape discrimination (Fig 3). This mode of operation sacrifices the self-shielding, relying on the surrounding veto for PMT background reduction, but provides a second, independent, method of confirming any apparent signal. In practice we plan to use both the proportional scintillation signal and the pulse shape of each to maximize the signal discrimination.

For gamma shielding, the UK Boulby Mine has utilized shields either of a 3m thickness purified water or more conventional low activity copper and lead enclosures. From previous experience of testing a cryogenic system at Boulby, it will be more convenient to use a metallic shield for liquid xenon, rather than attempt to construct a sealed system for the water shielding tank. In this case, wax shielding will also be added to attenuate neutrons from the cavern walls (see **§6**). It should be noted that all of the recent experience with NaI detectors at Boulby, relating to light collection, low background, data acquisition and cryogenics is directly relevant to the xenon experiments. First trials (summer 1996) of underground operation with the 2kg prototype in gamma shielding at Mont Blanc (**Fig 12**) have shown no new technical difficulties, and the background level is consistent with that expected from the adjacent photomultiplier activity as the dominant component.

Associated with the underground experiments, laboratory performance studies will be continued at UCLA and in the UK, using smaller chambers and portable neutron sources, to optimize operating parameters. Improved nuclear recoil efficiency measurements will also be possible, using a monoenergetic neutron beam which will be available within the UK program (at Sheffield, UK) in the near future. The proposed experiment, test program, and R&D items, provides a significant opportunity for the involvement of both graduate and undergraduate students.



**Fig 10** Predicted sensitivity versus (target mass x running time) for proposed liquid Xe detectors, with existing & projected sensitivity of NaI detectors shown for comparison



**Fig 11** Principal features of proposed liquid xenon detector:  
 (left) 20kg liquid xenon chamber, showing electric field and light collection system.  
 (right) Detector installed in veto shield, gamma shielding, and neutron shielding.

## 6 Backgrounds and underground site.

In this section we show that neutron backgrounds, which would produce low energy nuclear recoils indistinguishable (in a non-directional detector) from dark matter interactions, can be reduced to below the expected neutralino signal level. Nuclear recoils of 1-30keV can arise from neutrons in the 0.1-10 MeV range (since the energy transfer to a nucleus A is typically  $2A/(A+1)^2$  times the incident energy). 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 cross sections are known or estimated, and the predicted rates in the cavern are typically a factor  $10^5$  lower than the background gamma flux, ie of order  $10^{-6} \text{ /cm}^2\text{/s}$  in agreement with neutron measurements in several underground laboratories. These neutrons can be thermalized and absorbed by hydrogenous materials (water or polythene) giving a factor 10 attenuation per 20cm shielding. Our Monte Carlo studies show that lead or copper shielding > 20cm thick also effectively attenuates neutrons, by rescattering a large fraction of them back to the cavern walls.

(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 undiscriminated  $\gamma$  background in shielded NaI and liquid Xe detectors (the latter from tests at Gran Sasso) is of order 100/kg/day, part of which may arise from U and Th contamination. Thus the n background from this source must be < 0.001/kg/d, and this upper bound would reduce further with development of higher purity materials.

(3) Cosmic ray muons produce neutrons in the shielding by both spallation and capture. Combining the cross section and multiplicity of those processes with the muon flux and spectrum as a function of depth, the neutron production cross section can be estimated as a function of depth. Some of those scatter into the target, producing nuclear recoils. A Monte Carlo simulation gives a rate in the 4-20 keV region of about 0.01/kg/d at the Boulby depth of 1100m. This could be further reduced by a muon veto. With only 100 muons/day, this could be done with 99% efficiency, reducing the muon-produced neutron events to 0.0001/kg/d. To summarize:

|                            | unreduced rate (/kg/d) | reducible to (/kg/d)       |
|----------------------------|------------------------|----------------------------|
| (1) neutrons from rock     | 10                     | < 0.0001 (H shielding)     |
| (2) neutrons from detector | 0.001                  | < 0.0001 (by purification) |
| (3) neutrons from muons    | 0.01                   | < 0.0001 (by veto)         |

Gamma and beta backgrounds 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. Underground rates from U, Th, K in the walls of a salt cavern are typically  $\sim 10/\text{kg/s}$ , attenuated to < 10/kg/d by 250g/cm<sup>2</sup> low activity shielding (Pb+Cu, or H<sub>2</sub>O, at Boulby). The inner layer of copper will in general contain some induced (cosmogenic) activity, which can be improved by electrolysis if necessary. However, larger sources of background are U and Th in the PMTs and, potentially, intrinsic beta decay in the target material - eg <sup>85</sup>Kr in Xe. However, it is now known that the latter is not a serious problem, since a liquid xenon chamber operated by Rome at Gran Sasso has a reported differential background  $\sim 1/\text{keV/kg/d}$  at 10 keV, similar to that of NaI detectors and hence probably due mainly to the activity in the adjacent PMTs. Thus all background problems are sufficiently understood, with levels confirmed by underground tests at Boulby and Gran Sasso.

The Boulby Salt Mine is a working mine at a uniform level of 1100m, with two shafts leading to a network of many km of underground tunnels and caverns. The natural radioactivity is at least as low as any other world underground site, and background from this is easily attenuated by shielding as discussed above. Three adjacent caverns are dedicated to the UK dark matter program, as shown in Fig 13, which also indicates an area available for the experiment proposed here. Full electrical services and telephone communications are installed, and the UK manpower will be sufficient for experiments to be run continuously, if necessary with daily attention. The mine is about 250 miles from the participating UK groups, so that the operation of the experiment is generally comparable to that of the UCSB/Oroville double beta decay experiment.

Further comments on communications between the mine, UCLA, and UK groups are given in the next section

Fig 12 2kg liquid xenon test chamber in Mont Blanc laboratory.

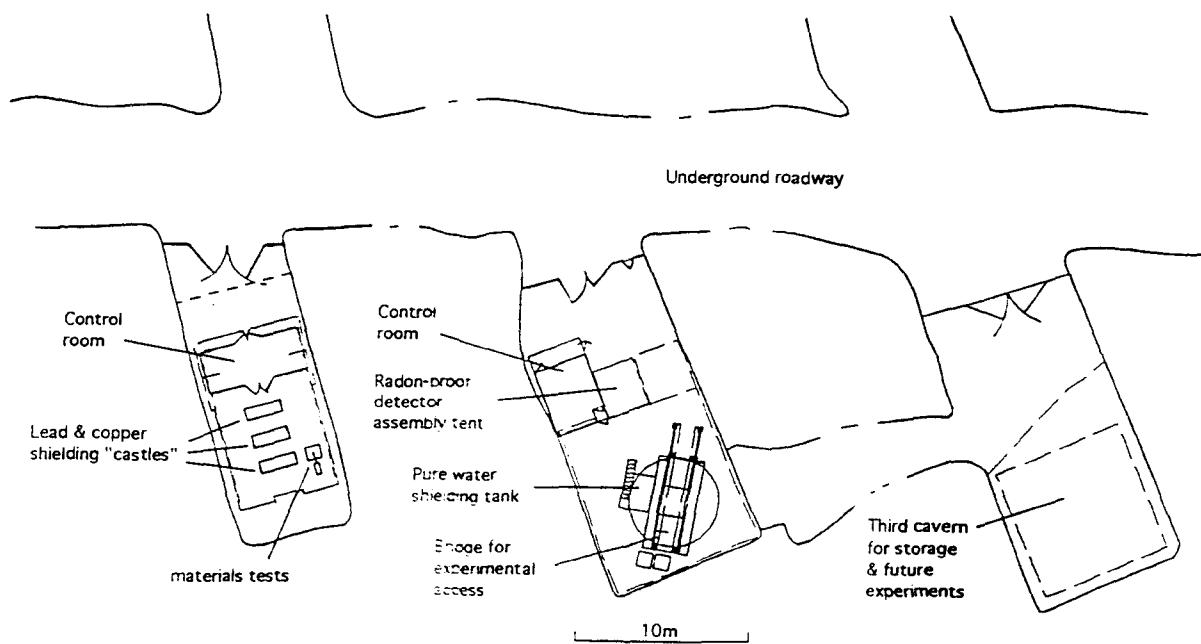


Fig 13 Layout of caverns in Boulby Mine dark matter area

## 7 Communications, collaboration, data analysis

Communications with the mine, and collaboration between the UCLA and UK groups, is straightforward and has been demonstrated in the course of work on this proposal. The basic communications links are

- (a) Direct telephone and Fax links to the underground control rooms. Messages and data have been reliably transmitted between UCLA and the underground control room. Direct file transfer is straightforward between Macintosh computers at Boulby, RAL and UCLA, and can be used to transfer documents, diagrams and data.
- (c) The underground DAQ system is linked by ethernet to a central disk and DAT tape, and via shaft phone line to a surface control computer linked to participating institutes via modem.. UCLA could be added to this system, or receive Macintosh-compatible tapes via a standard courier service. Thus for personnel at UCLA remote interaction with Boulby is as straightforward as at RAL or IC, enabling UCLA to play a major role in data analysis.

Collaboration meetings and discussions have been taking place through regular visits from UK to UCLA, combined with other academic commitments. Together with communication by email and file transfer, these have resulted in a considerable exchange of information and evolution of the project, showing that collaboration between the UK and USA groups is straightforward and effective. Communication has involved both scientific and technical staff. Discussion and new work has taken place on purification problems, light collection, wavelength shifting, optimization of geometry, background problems, self-shielding, veto system, discrimination factors, photomultiplier coupling and additional pulse shape discrimination. Results of these discussions, together with recent operational experience at the Boulby mine, are incorporated in this proposal.

If approved, the project would proceed as an agreed program of work between UCLA and the UK groups, with basic tests set up in the UCLA liquid noble gas laboratory, or in the UK in cases where the existing resources are more appropriate (eg requiring a neutron beam). The UCLA experience on liquid noble gas handling and purification, and the recent successful design and operation of a prototype at CERN, would be central to the project, with the collaborative arrangements ensuring that the UCLA effort can be supplemented by UK engineering and technical manpower where necessary. There would continue to be meetings several times/year for technical and scientific discussions. Installation and continuous running underground can be carried out most cost-effectively by the UK personnel, in parallel with other UK experiments, while the data will be analyzed off-line at UCLA and RAL/IC.

As already mentioned, interaction between UCLA personnel and the experimental data will be immediate and straightforward. Calibration data, from neutron and gamma sources, will be obtained both in laboratory tests and *in situ* from the installed underground detector. Data analysis will involve comparison of the observed events with the calibration data to extract statistically a signal limit at each energy, and then a second stage of processing to convert this into dark matter limits, or to investigate any apparently positive signal. Feedback from this analysis will be used to optimize detector parameters. The range of work on discrimination and signal limits provides an opportunity to involve graduate or undergraduate students, the project providing an excellent teaching tool, linking theoretical, experimental and technical topics.

## 8 Experience of the UCLA & UK groups

### 8.1 Experience of the UCLA group

There is proven capability within the UCLA group for implementing the proposed experiment in collaboration with UK physicists and engineers. The group has previously developed and tested large scale equipment using both liquid Ar and Xe as detector media, including the liquid Ar purification system used in the HGRT project. This can be used for Xe purification with only minor modifications, purity being crucial to the achievement of full light output from liquid noble gases. UCLA also developed the state-of-the-art data acquisition system for a one-tonne imaging liquid argon ionization chamber, which would be available for the proposed experiment if required.

UCLA participants are experienced members of the ICARUS liquid argon project. Within that project they played a key role in the demonstration of proportional scintillation in liquid xenon, and the further development of this principle for discrimination between nuclear recoils and background (Figs 5&6) where practical confirmation was crucial to establishing the feasibility of a detector based on this idea. Further development work would be carried out in the Ultra-Pure Nobel Liquid Laboratory in the Physics Department at UCLA, where 1100 sq ft of laboratory space is dedicated to noble liquid detector studies.

## 8.2 Experience of the UK groups

Dark matter experiments have been studied since 1984 leading to a UK astrophysics/particle physics program since 1989. Theoretical studies have included the effects of energy threshold, form factor, annual modulation, statistical discrimination techniques and Monte Carlo studies of background problems. Underground laboratories in the Boulby salt mine have been established and operated since 1992, with improved dark matter limits (Fig 1) published from low background NaI detectors. This experience in the construction, shielding and operation of low background detectors is directly relevant to the liquid xenon program. The RAL/ICSTM groups also have some experience with liquid xenon, having constructed a small (60g) test chamber for preliminary studies of pulse shape discrimination. Experienced personnel, funded through the UK program, would be available for operation of liquid Xe detectors. Other work has included studies of wavelength-shifting coatings at low temperature. Measurements have been made of nuclear recoil efficiency by neutron scattering in scintillating crystals, and the experience from this would also be applicable to neutron scattering tests on the prototypes proposed here.

## 8.3 Suitability and combined strength of the collaboration

Both groups have a strong background in particle astrophysics topics, which has led to the current collaboration. New ideas for both supernova neutrino detection and dark matter detection have been studied and published by both UCLA and RAL. Astroparticle physics courses and international conferences on these topics are organized by UCLA. This strong scientific background is matched by the technical ability to put ideas into practice. The technical experience of UCLA in liquid noble gases, and in particular the recent detector studies, is complemented by the low background and underground operating experience of the UK groups. In addition the collaboration has a detailed theoretical understanding of the analysis techniques required to optimize the event discrimination and signal limit, or to investigate further any apparent signal.

This collaboration thus represents an optimum partnership for a successful experiment based on this new technique.

## 9 Timescale, costs, existing resources

The program will be focused on the objective of a first operational detector with 20kg fiducial volume, together with ancillary tests to investigate and optimize design and performance - in particular scintillation efficiency, light collection, discrimination and intrinsic radioactivity. Designs will be based on existing experience with the CERN test chamber, plus existing low background experience and Monte Carlo simulations in the UK. Final performance will be confirmed by tests in the Boulby Mine, followed by running periods to search for low level signals from dark matter interactions. The following is the proposed timescale, showing the current preliminary studies, the requested 2-year funding period (Mar 1997 - Mar 1999) for construction and an initial running period. If successful, funding for extended running will be the subject of a separate proposal.

|                        | 1996        | 1997  | 1998  | 1999   |
|------------------------|-------------|-------|-------|--------|
| lab tests              | ----->..... | ..... |       |        |
| detector design        | ----->..... | ..... |       |        |
| manufacture            |             | ..... |       |        |
| instrumentation        |             | ..... |       |        |
| full system test       |             |       | ..... |        |
| install underground    |             |       | ..... |        |
| data taking & analysis |             |       | ..... | -----> |

The funding request attached to this proposal takes account of, and benefits considerably from, substantial equipment and resources already existing at UCLA and in the UK. Thus only salaries and equipment supplementary to this are requested.

*At UCLA there are in particular the following items:*

(a) liquid Ar purification and vacuum system capable of modification for Xe; (b) liquid noble gas test chambers; (c) Laboratory space and facilities; (d) signal readout and data processing equipment. Total value about \$ 600000.

*The UK collaborators offer the following resources:*

(a) underground laboratory at 1100m depth (Boulby Mine, UK) plus services; (b) low activity neutron and gamma shielding; (c) underground materials test facilities; (d) test facilities and laboratory space at RAL & IC; (e) Monte Carlo programs for shielding, light collection, and neutron scattering calibrations; (f) engineering & technical support, plus experimental operating costs. Total value of equipment and facilities in the UK about \$800000, plus \$60000/y underground operating and maintenance costs.

## NSF single-page project summary

This project offers a major step forward in the investigation of the identity of the non-luminous matter that constitutes 90% of our Galaxy. A leading hypothesis is that this dark matter may consist of weakly interacting massive particles, which could be detected as a low rate of nuclear recoil events in various target materials. For the hypothetical neutralino of supersymmetry theory typical event rates would be in the range 0.01-1 event/day/kg, but lower rates, down to 0.001/day/kg are also possible.

The key problem in searching for rates  $< 1/\text{day/kg}$  is to distinguish nuclear recoil events from gamma or beta decay background, resulting from radioactivity in the target and detector materials. Methods of doing this include simultaneous measurement of ionization and phonon energy, pulse shape variations due to different mechanisms in scintillators, and track length differences in low density gaseous targets.

The present proposal is based on an elegant and powerful principle recently demonstrated in liquid xenon by members of the ICARUS collaboration including the UCLA participants. Any interaction in liquid Xe produces both scintillation and ionization, and the latter can be drifted in an electric field to produce a second (proportional) scintillation signal. The mean ratio of the two signals differs considerably for nuclear recoil and electron recoil events, and recent tests with a mixed neutron + gamma source have shown the scattering events separated into two distinct populations, with an overlap of (eg) only 0.1% at 20 keV. This provides an extremely powerful discrimination technique for searching for low event rates from neutralinos or any other weakly interacting particle. Liquid xenon has the additional merit of scale-up capability - target masses can be initially at the 10kg level, and subsequently scaled up to 100-1000kg if required, to reach the lowest predicted neutralino event rates.

Based on the experience already gained we propose to construct a low background experiment with a 20kg liquid xenon target (an optimum size for good light collection and low energy threshold), and to operate this in the UK Boulby Mine dark matter facility, where high-quality shielding systems are available and several years experience exists in running underground low background experiments. An additional new feature of this proposal is a surrounding Compton veto system to reject  $> 90\%$  of low energy background events from photomultiplier activity.

The background rejection capability of the double scintillation pulse improves statistically with time and the prototype would be the capable of searching for a dark matter signal at rates  $0.03-0.1/\text{kg/d}$  within a 1 year running period, for both spin-dependent and spin-independent interactions. Lower rates could then be reached by replicating this optimum-size module to a total mass  $> 100\text{kg}$ .

The groups in this collaboration have a strong background in particle astrophysics, matched by proven technical expertise in implementing new experimental ideas. The experience of the groups is complementary, combining the expertise of the UCLA participants in liquid noble gas techniques, including basic work on proportional scintillation in liquid xenon, with the low background design and underground operating experience of the UK participants, who have already obtained new dark matter limits with long-running NaI experiments. In addition the collaboration has a full theoretical understanding of the analysis techniques required to optimize event discrimination and signal limits, and to investigate further any apparent positive signal.

During the past year, searches for gravitational lensing events in our galaxy continue to set limits of about 20-30% of the dark matter in the form of low mass stars. This strongly suggests that the dominant component may be non-baryonic and increases the urgency for setting up high sensitivity searches for particle dark matter. We believe that the proposed liquid Xe detector offers an excellent route for reaching very low event rates, and that this collaboration represents an optimum partnership for a successful experiment based on this technique.