PHYSICS REPORTS

Physics Reports 307 (1998) 275–282

Dark matter experiments at the UK Boulby Mine

UK Dark Matter Collaboration

P.F. Smith[a,*], N.J.T. Smith[a], J.D. Lewin[a], G.J. Homer[a], G.J. Alner[a], G.T.J. Arnison[a], J.J. Quenby[b], T.J. Sumner[b], A. Bewick[b], T. Ali[b], B. Ahmed[b], A.S. Howard[b], D. Davidge[b], M. Joshi[b], W.G. Jones[c], G. Davies[c], I. Liubarsky[c], R.A.D. Smith[c], N.J.C. Spooner[d], J.W. Roberts[d], D.R. Tovey[d], M.J. Lehner[d], J.E. McMillan[d], C.D. Peak[d], V.A. Kudryatsev[d], J.C. Barton[e]

[a] *Rutherford Appleton Laboratory, Chilton, OX11 0QX, UK*
[b] *Imperial College, Astrophysics, Blackett Laboratory, London SW7 2BZ, UK*
[c] *Imperial College, High Energy Physics, Blackett Laboratory, London SW7 2BZ, UK*
[d] *University of Sheffield, Houndsfield Road, Sheffield S3 7RH, UK*
[e] *Birkbeck College, London WC1E 7HX, UK*

Abstract

The current status is summarised of dark matter searches at the UK Boulby Mine based on pulse shape discrimination in NaI, together with further plans for international collaboration on detectors based on nuclear recoil discrimination in liquid and gaseous xenon. © 1998 Elsevier Science B.V. All rights reserved.

PACS: 95.35. + d

1. Boulby Mine and programme objectives

The Boulby Mine is a working salt and potash mine in the North–East of England. The mine operators, Cleveland Potash Ltd., have provided access to several disused tunnels and caverns in low background salt rock, as a permanent location for the UK underground physics programme. These have been provided with power, lighting, telephone, fibre-optic data links, flooring and control rooms as a basic infra-structure for all experiments, and shielding systems have been installed consisting of (a) a 6 m tank of purified water and (b) a number of shielding castles built from a 20 cm outer lead shield and a 10 cm copper inner shield.

* Corresponding author. E-mail: p.f.smith@rl.ac.uk.

PII: S0370-1573(98)00049-0

The object is to search for a continuous spectrum of nuclear recoil pulses with energies <50 keV from WIMP collisions. This requires methods of distinguishing these from the much higher gamma background. Our current and planned programme includes both NaI and Xe targets to cover the WIMP mass range 10–1000 GeV.

The Boulby facility has so far been used specifically to run WIMP searches based on pulse shape discrimination in sodium iodide targets, summarised in Section 2. The available space is now being increased to accommodate liquid xenon experiments to be carried out in collaboration with the UCLA/Torino groups [1], as described further in Section 3. Future more advanced liquid xenon detectors may involve a larger collaboration including the ITEP group [2]. This is referred to as the ZEPLIN programme. The available space would also accommodate much larger detectors with directional sensitivity, based on observation of tracks in low pressure gases. Studies of this are in progress in collaboration with Temple, UCSD, and other groups [3,4]. This scheme is named DRIFT (directional recoil identification by formation of tracks).

The mine contains many kilometers of disused salt caverns, some of which would be available for neutrino physics experiments. These are outlined in a separate paper. The present paper reports the current and planned dark matter programme.

2. Dark matter searches with NaI targets

Experiments have been based on NaI crystals, 2–10 kg in mass, observed with two photomultipliers and silica light guides, all materials being selected for lowest activity. Calibration with neutron and gamma sources shows that nuclear recoil pulses have a decay constant about 70% that of Compton gamma interactions. The pulse time constant distributions have a significant width due to the small number of photoelectrons (typically 3–6 per keV) so that at low energies the nuclear recoil and gamma distributions overlap. An initial phase of work with a water-shielded 5 kg crystal showed that a factor 10–30 below gamma background could be set as a statistical limit on a population of the shorter pulses [5].

The stability and resolution of this detector has been improved by larger PMTs, shorter light guides, and a stabilised and reduced operating temperature ($10^{\circ}C \pm 0.1^{\circ}C$). Gamma sources are lowered automatically into the shielding tank to provide energy calibration once a week and Compton calibration for 5 h each day. A running period of 4000 h (excluding calibration periods) between August 1996 and October 1997 has been analysed. The improved resolution reveals a small population of pulses of shorter time constant (mean ~ 230 ns), distinct from the gamma time constant distribution (mean 360 ns) and close to the time constant observed for neutron-induced recoils. The shorter pulses are absent in the periods of Compton calibration (Fig. 1) suggesting that they are not an analysis artefact. For further confirmation, these are also seen in a second crystal (made from the same material) but with less good resolution. The shorter pulses are otherwise normal in shape, with photoelectrons distributed equally between PMTs so they could in principle be low-energy alpha events. Fig. 2 shows the energy spectrum of these events together with the spectrum of normal high energy alphas (due to U & Th impurities) from a data run extended to 5 MeV. Their number appears much larger than would be expected from photodisintegration of iodine by gammas above 2.6 MeV. Neutron events at this rate are excluded by the water shielding and low flux of muons at 1100 m.

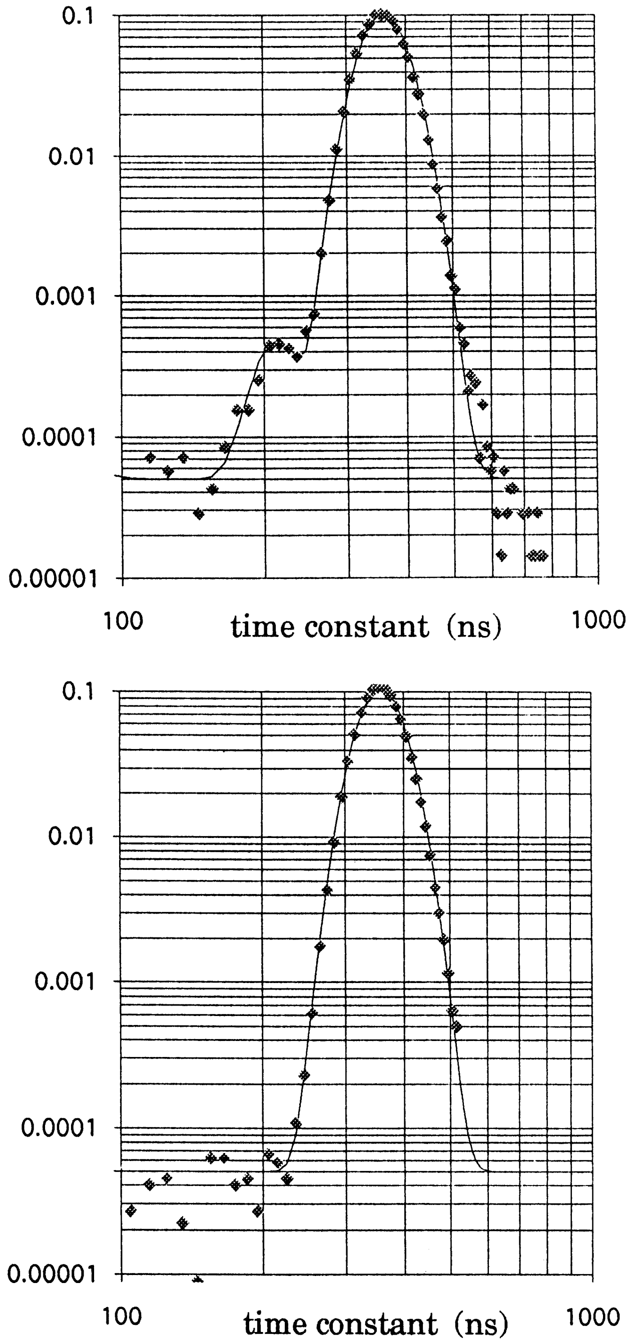

Fig. 1. Time constant distributions (normalised to unity) for 5 kg NaI crystal: (*upper graph*) Background distribution showing additional population of shorter pulses; (*lower graph*) Compton calibration with ^{60}Co source (5 h each day).

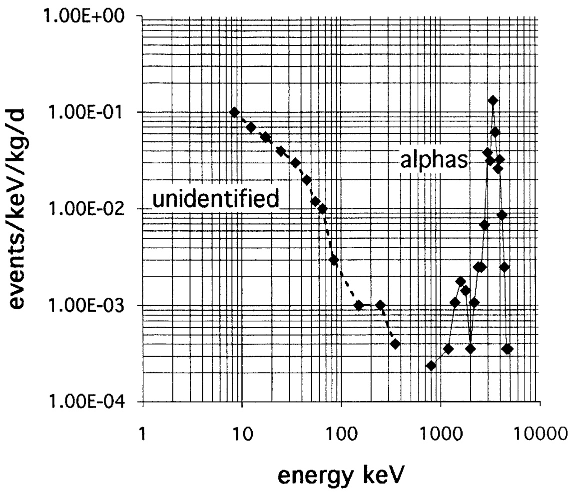

Fig. 2. Energy spectrum of unidentified events compared with high-energy alpha spectrum.

There is so far no explanation of this additional population of events. Further data runs are being made, with different sized crystals, to establish whether the spectrum and events/mass is similar for all crystals. It is of interest that there appears to be a significant summer–winter difference. In the energy range 20–60 keV there are approximately 700 events in 70 days in the summer period, compared with 600 events in 70 days in the winter period. This demonstrates that the care is needed in investigating annual modulation, since any spurious signal (for example alphas) could also show differences over several month periods for a variety of reasons. A second winter run is currently in progress.

The energy spectrum of the anomalous events falls less rapidly than expected for a dark matter spectrum based on a Galactic velocity dispersion 230 km/s. Summing predicted Na and I spectra with appropriate form factors [6]) approximate agreement can be achieved only with a high velocity dispersion > 300 km/s for the Galactic dark matter, together with a dark matter particle mass > 200 GeV. This differs from the mass < 100 GeV deduced from the marginally significant annual modulation reported by the Rome group [7]. Thus we continue to search for an explanation in terms of normal particles.

A number of ideas are being investigated to further improve the performance of NaI detectors, including optical coupling of unencapsulated crystals with liquid paraffin [4].

3. The sodium iodide diagnostic array ('NaIaD')

The above situation emphasises the need for dark matter experiments to have good diagnostic capability, to allow investigation of spurious events which may mimic a dark matter signal. In particular, one needs:

(a) A principal target with good energy resolution and minimum background.
(b) Targets of different size, to investigate proportionality with mass.

(c) Targets with data acquired over different energy ranges – e.g. 0–50, 0–500, 0–5 MeV, to investigate energy cut-off and higher-energy background, such as MeV-range alphas.
(d) Targets of the same size in different shielding systems, to investigate internal origin.
(e) A larger multi-crystal array for faster data acquisition and annual modulation search.
(f) Where possible different target nuclei, or isotopic variations, to study spin-dependence.

Our present underground array contains (a), (b), (c), (d) but not yet (e) due to funding limits (Fig. 3). Item (f) is not currently possible with NaI targets (since the Na and I recoils cannot be distinguished), but can be achieved more easily in experiments using Ge [8] and Xe [9] targets where stable odd and even isotopes can be separated.

4. Liquid xenon detectors

Liquid xenon allows a variety of ways of separating nuclear recoils from background, owing to the production of both scintillation light and ionisation:

1. the ionisation may be allowed to promptly recombine, adding to the scintillation light and giving differences in scintillation pulse shape [10],
2. an electric field can be used to prevent recombination, the charge being drifted to create a second scintillation pulse S2 in addition to the primary pulse S1. The ratio S2/S1 differs for nuclear recoils and gammas [11],
3. the charge in (ii) can be extracted from the liquid surface to the gas phase, and accelerated to give a larger secondary scintillation pulse [1],
4. all signals may be enhanced by TEA amplification, the shape of the initial charge distribution producing a difference in geometric light distribution [1].

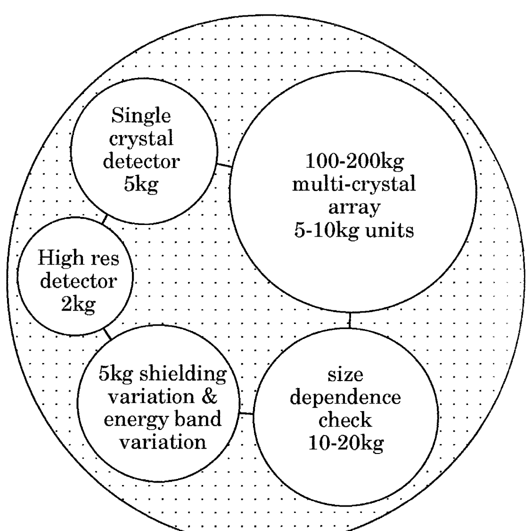

Fig. 3. Array of NaI detectors for diagnostic studies of signal-like events.

These permit a much greater degree of background discrimination than in the case of NaI pulse shape. As a first step we are constructing a 5 kg detector based on (i) for running experience at Boulby (Fig. 4). Following this, the objective is to construct and operate a 20–30 kg detector based on method (iii) in collaboration with the UCLA and Torino groups (Fig. 5). This is planned to be running by the year 2000. Each detector will be located inside a 30 cm thick liquid scintillator Compton veto, to reduce both photomultiplier and ambient background. Discussions are in progress for a further detector based on method (iii) or other design variations [2].

5. The Xe diagnostic array (ZEPLIN collaboration)

As in the case of NaI, it is essential to be able to view any candidate signal or anomalous event population in Xe in several different detectors, in order to investigate its behaviour and origin. The above principles allow not only different types of Xe detector, but also diagnostic procedures in a given detector, in particular varying the electric field used to drift the charge. It would also be possible to run the detectors with different Xe isotopes. Fig. 6 shows the array of detectors which

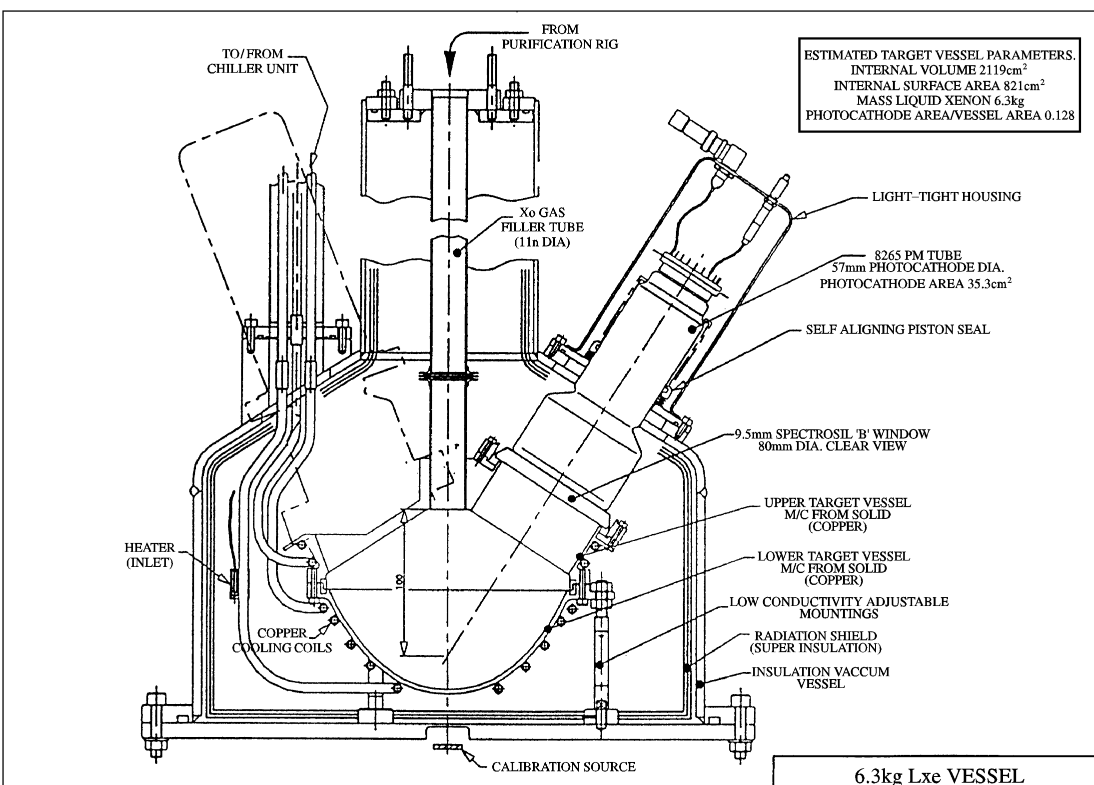

Fig. 4. Single-phase liquid Xe detector.

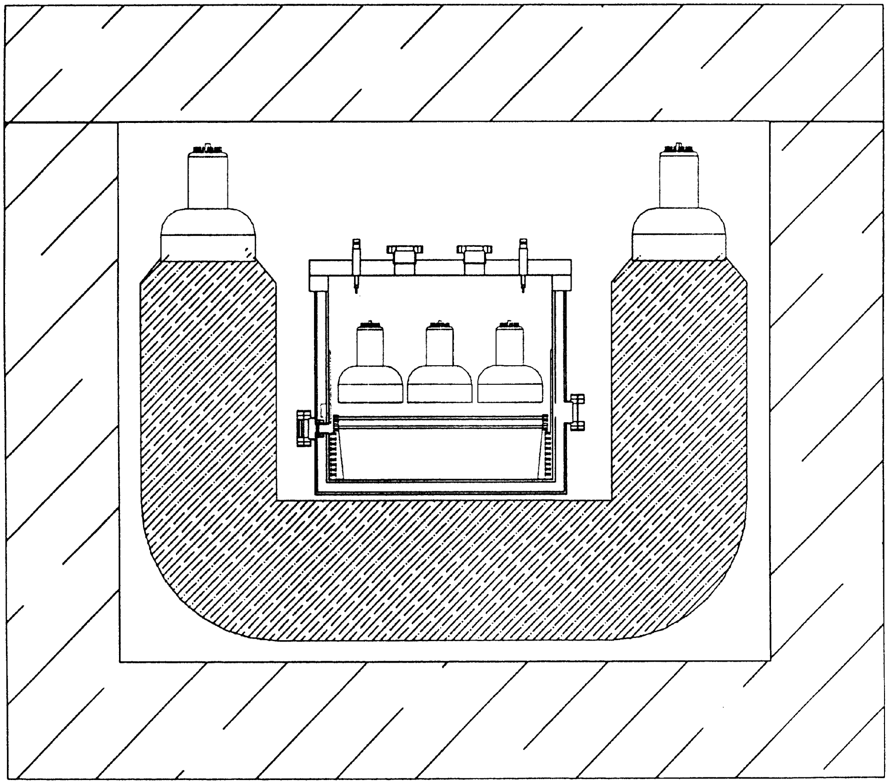

Fig. 5. Two-phase ZEPLIN detector in scintillator veto.

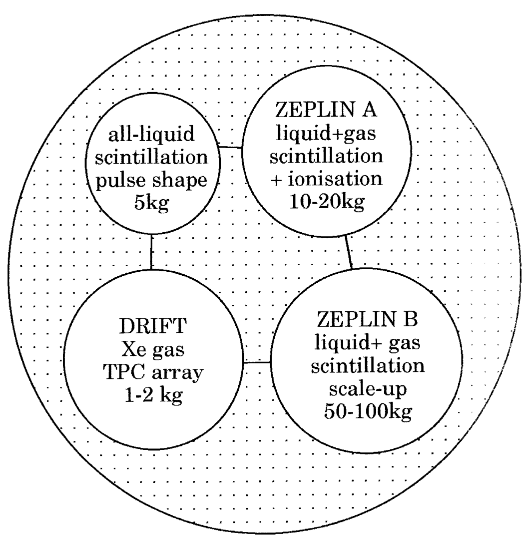

Fig. 6. Proposed array of Xe detectors for signal diagnosis.

could result from our programme and which would provide varying target mass and discrimination technique, giving excellent overall diagnostic capability.

Included in Fig. 6 is the possibility of ultimately adding a Xe gas target to verify directionality in the Galaxy, through the collaborative DRIFT programme mentioned in Section 1. In this connection it is of interest that the Boulby Mine happens to be located at the ideal latitude for directional experiments, the rotation of the earth automatically providing orientations parallel, anti-parallel and perpendicular to the Galactic motion for a detector placed with axis horizontal relative to the earth's surface [12].

Acknowledgements

We are grateful to Cleveland Potash Ltd., UK for their co-operation in permitting the use of the surface and underground facilities of the Boulby Mine for this programme.

References

[1] H. Wang, Phys. Rep. 307 (1998), this issue.
[2] D. Akimov et al., This conference.
[3] P.F. Smith et al., This conference.
[4] N.J.C. Spooner, Phys. Rep. 307 (1998), this issue.
[5] P.F. Smith et al., Phys. Lett. B 379 (1996) 299.
[6] J.D. Lewin & P.F. Smith, Astropart. Phys. 6 (1996) 87.
[7] P. Belli et al., This conference.
[8] R. Schnee et al., This conference.
[9] P. Belli et al., Nuovo Cimento 19C (1996) 537.
[10] G.J. Davies et al., Phys. Lett. B 320 (1994) 395.
[11] P. Benetti et al., Nucl. Instr. Meth. Phys. Res. A 327 (1993) 203.
[12] M. Lehner, K. Buckland, personal communication.