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Dark matter experiments at the UK Boulby Mine

UK Dark Matter Collaboration

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Abstract

The current status is summarised of dark matter searches at the UK Boulby Mine based on pulse shape discrimination in NaI, together with future plans for international collaboration on detectors based on nuclear recoil discrimination in liquid and gaseous xenon.

1. Boulby Mine and programme objectives

The Boulby Mine is a working salt and potash mine in the NorthEast 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 infrastructure for all experiments, and shielding systems have been installed consisting of (a) a 6 m diameter 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.

The object is to search for a continuous spectrum of nuclear recoil pulses with energies < 50 keV from WIMP collisions, expected at a rate of ≤ 1.0/d/kg for WIMP masses ~ 100 GeV dominating Galactic gravity. This requires methods of distinguishing these signals 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 NaI 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 and ITEP groups, as described further in Section 3. 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. This scheme is named DRIFT (Directional Recoil Identification by Formation of Tracks).

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 (Quenby et al., 1996, Smith et al., 1996) These results are shown in figures 1 and 2 for spin-dependent and spin-independent interactions as cross sections for WIMP-nucleon interaction. They are a factor 10 above the top of the range of most predictions of the MSSM model.

The stability and resolution of this detector has been improved by larger PMTs, shorter light guides, and a stabilised and reduced operating temperature (10°C $\pm$ 0.1°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 $\sim$ 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. 3) 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.4 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. Experiments with an alpha source inducing surface layer effects seem to give an additional time constant which does not fit the anomaly (Kudryatsev et al., 1999). Betas have also been excluded as a possible source (Smith,N.J.T., et al., 1999). Their number appears much larger than would be expected from photodisintegration of iodine by gammas $>$ 2.6 MeV. Neutron events at this rate are excluded by the water shielding and the low flux of muons at 1100 m. Sumner et. al., (this conf.) also considers the problem in terms of a multi-time constant analysis.

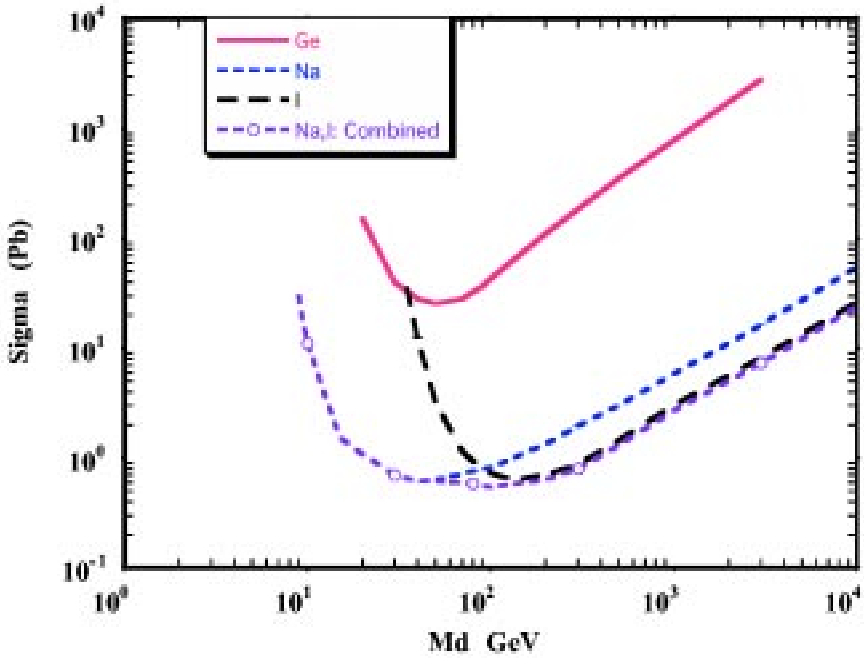

Figure 1: Dark matter cross section limits in picobarns, corrected to the equivalent proton cross section, as a function of LSP mass for the combined data

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 year cycle 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 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 (Bernabei et al., 1998). 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.

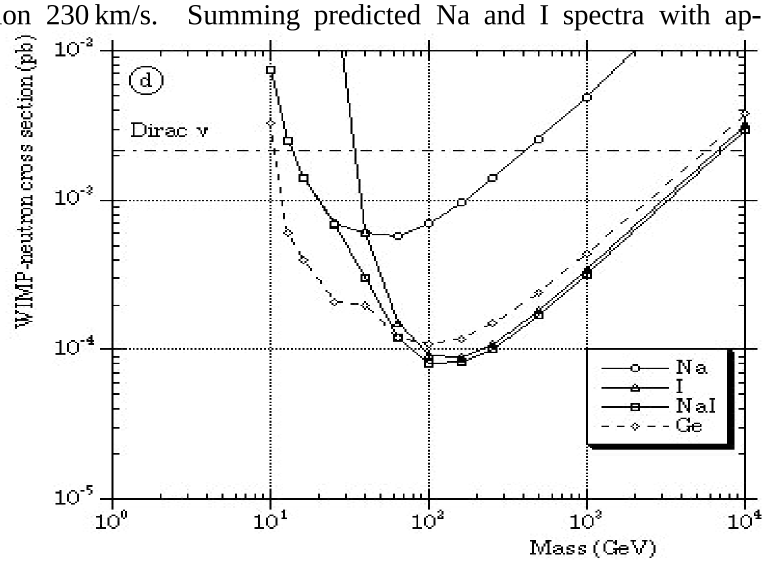

Figure 2: Spin-independent WIMP-neutron cross section (normalised rate divided by $I = (A - Z)^2$; value for Dirac neutrinos would be 0.0021 pb)

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: good energy resolution, minimum background, different target sizes to investigate proportionality with mass, investigation over a wide energy loss range to check high-energy background, different shields for the same target, larger array to search for annual modulation and different target material to check spin-dependence.

Our present underground array contains most of these features but awaits scale-up in size due to funding limits. Investigation of spin-dependence 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 and Xe 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:

(i) the ionisation may be allowed to promptly recombine, adding to the scintillation light and giving differences in scintillation pulse shape (Davies et al., 1994),

(ii) 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 (Benetti et al., 1993),

(iii) the primary ionisation charge can be extracted from the liquid surface to the gas phase, and accelerated to give a larger secondary scintillation pulse (eg Wang, 1998),

(iv) all signals may be enhanced by TEA amplification, the shape of the initial charge distribution producing a difference in geometric light distribution (Wang 1998).

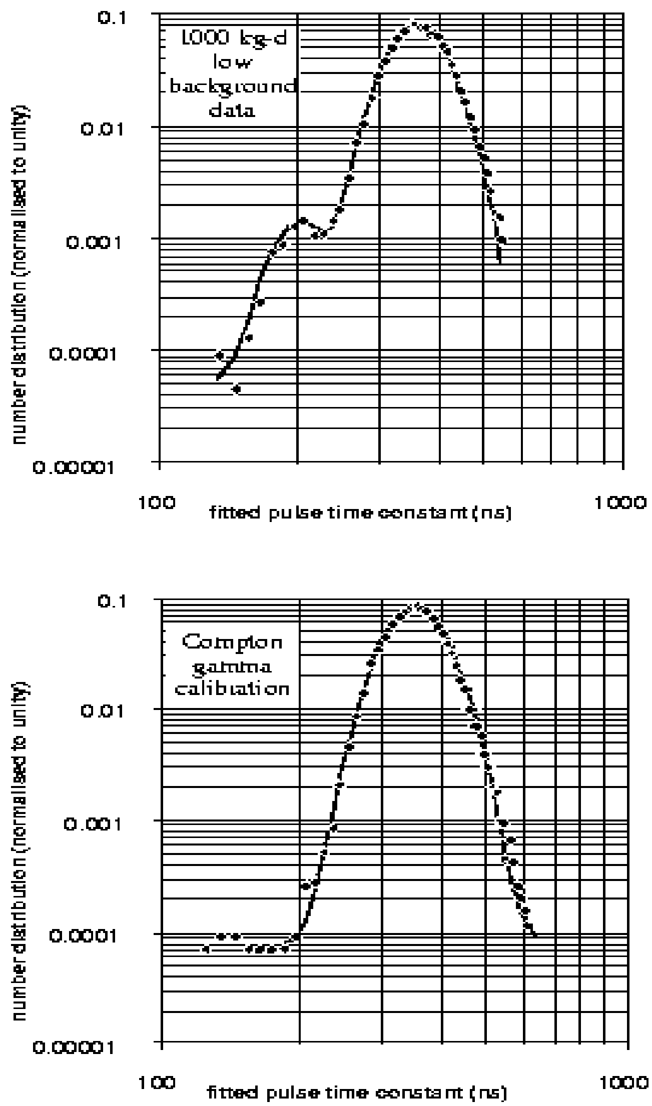

Figure 3: Time constant distributions (normalised to unity) for 5 kg NaI crystal: $(upper graph)$. Background distribution showing additional population of shorter pulses; $(lower graph)$. Compton calibration with ^{60}Co source (5 hours each day).

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 primary scintillation pulse shape for running experience at Boulby. Following this, the objective is to construct and operate a 20–30 kg detector based on a two phase double scintillation method in collaboration with the UCLA, Torino and ITEP 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.

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 and alternative discrimination techniques, giving excellent overall diagnostic capability.

The possibility of ultimately adding a Xe gas target to verify directionality in the Galaxy, through the collaborative DRIFT programme was 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.

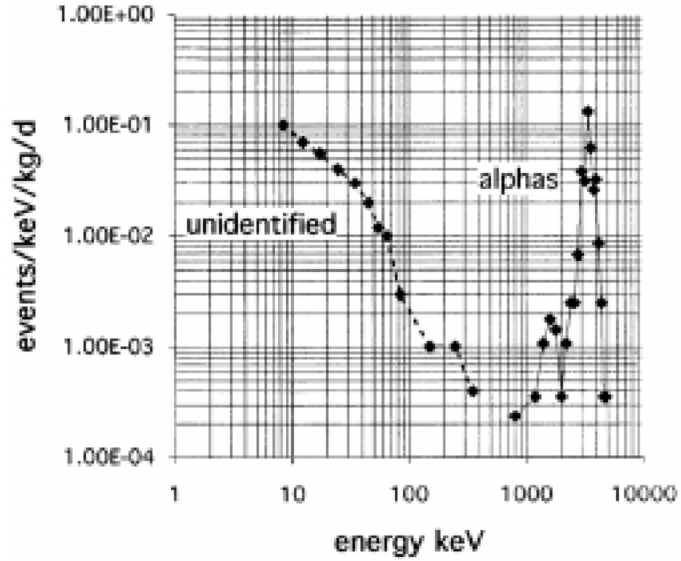

Figure 4: Energy spectrum of unidentified events compared with high energy alpha spectrum

Acknowledgements

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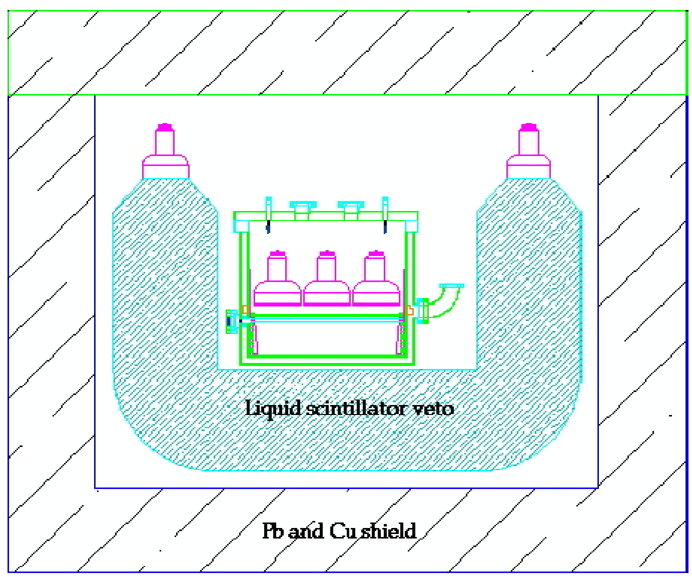

Figure 5: Two-phase ZEPLIN detector in scintillator veto