1404: Status report and recent results from the UK Dark Matter Collaboration

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Abstract. The UK Dark Matter Collaboration (UKDMC) has an ongoing programme of detector development and operation with the eventual aim of reaching dark matter rates below 0.1/day/kg. Limits for the interaction rate have been set by this group and others using pulse shape discrimination in sodium iodide scintillation detectors. Methods for improving these limits through increased light output will be discussed, including avalanche photodiode R&D. To reach the lowest interaction rates we are collaborating with members of ICARUS on liquid xenon systems and this work is briefly reported.

1 Introduction

Dark matter (DM) in the form of weakly interacting massive particles (WIMPs) can be detected via the very small (<50keV) energy deposit of a nuclear recoil resulting from the elastic scatter of the incoming WIMP. Such collisions will be rare, 1-0.01 c/kg/day [1]. DM detectors are in general located underground to exclude cosmic rays. Though the ambient radioactivity can be reduced by high purity shielding, the irreducible radioactive contamination in the target/detector itself ultimately limits the sensitivity. Thus new detectors must be able to distinguish the nuclear recoil signal events from the background electron recoils resulting from gammas and beta decay. This discrimination has been studied by several groups in both room temperature and cooled sodium iodide (NaI) and liquid xenon (LXe) [2][3][4][5]. Neutron sources can be used to produce similar nuclear recoils as would dark matter particles. We discuss results from a 6kg room temperature NaI(Tl) target which exploits the difference in the pulse shape between nuclear recoils and background. For full details see [6]. We have also operated pure NaI detectors underground and are developing LXe detectors.

2 Experimental Assembly

The UKDMC’s experiments are situated 1100m underground (2900m water equivalent) in the Boulby salt mine. We employ two types of shielding, either a 6m by 6m cylindrical high purity water tank, which also removes neutrons from radioactivity in the rock, or low activity electroformed copper and lead which have been stored underground.
The 6kg device was operated in the water tank and read out by two PMTs in coincidence.

## 3 Data sample

The integrated pulse from each incident pulse was recorded on disk after digitisation with a LeCroy 9430 oscilloscope. The sensitivity was 1.6 photo-electrons (p.e)/keV and the threshold set at 2.4 p.e./PMT. The data reported here are for 173 days running. The temperature was measured but not stabilised during this period and drifted slowly in the range $32 \pm 1 ^\circ$C. A correction was made for this slow deviation $^1$. Energy calibrations were carried out using a $^{57}$Co source; gamma pulse shape calibration was achieved both with a $^{60}$Co source and by raising the detector to expose it to the gamma background from the cavern; neutron pulse shape calibration was achieved by lowering a Cf source to 1m from the detector.

## 4 Data analysis

The data set in the range 4-25keV was grouped into 8 energy bins: 4-5keV, 7-10keV and thereafter in 3keV intervals. Discrimination occurs in NaI(Tl) at ambient temperature through a variation in a single time constant. Normalised calibration distributions for the 6kg crystal are shown in fig.1 (left) for the 7-10keV energy range, together with 6 months data from the fully shielded underground detector.

Time constants ($\tau$) were obtained by fitting to a single exponential and the distribution in $\tau$ was well described by a Gaussian in $\ln \tau$. At energies below 10keV this distribution overlaps a distribution of faster PMT noise pulses. The noise-free portion of the spectrum was used to give an accurate estimate of the true number of events in these energy bins. See curves (a) and (b) in fig. 1 (left).

Any dark matter signal would be expected to follow the shape of the neutron calibration spectrum. Thus a combination of dark matter signal (or neutrons) and radioactive background would result in a spectrum lying somewhere between the neutron and gamma calibration spectra. In fact the data can be expressed as a linear combination of these. The most likely fraction of nuclear recoils and gammas can then be found. We see from fig. 1 that the data are consistent with being entirely radioactive background. A 90% confidence level (c.l.) upper limit on the nuclear recoil signal can be obtained by running Monte Carlo simulations of the data [$^7$]. This process was carried separately for each energy bin.

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$^1$ Temperature stabilisation is now in operation for all systems and in fact the detectors are run below ambient to enhance the discrimination.
Fig. 1. Time constant distribution for neutrons and gammas in the 7-10keV range for the 6kg target (left). Background differential spectra (right): (a) observed rate; (b) after subtraction of fast noise pulses; (c) 2σ limits on nuclear recoil events for energy spans shown by horizontal bars.

We conclude, at the 90% c.l., that we have discrimination gain factors of 0.025-0.18 depending on which bin is considered. This enables us to reduce the 90% c.l. upper limit on the dark matter counting rate for each bin. See curve (c) in fig. 1 (left).

5 Results

We are thus able to set dark matter limits for each of the 8 energy bins, labeled by the index k (k=1 to 8). Following [8], the differential nuclear recoil rate, \( S_{nk} \), where R is the nuclear recoil rate for dark matter of mass, \( m_D \), and energy, \( E_\text{r} \), with a target nucleus of mass, \( m_T \), \( R = m_T E_\text{r} \) is the recoil energy and form factor, \( F \), is given by: \( S_{nk} \propto R \propto (R_0 / r) (c_1 / E_\text{r}) \exp(-c_2 E_\text{r} / E_\text{r}) F^2 dE_\text{r} \), where \( R_0 \) is the total rate unit in c/kg/day and \( r \) is \( 4(m_T m_D) / (m_T + m_D)^2 \).

Thus energy span k yields a limit curve of rate (or cross-section) versus mass, with the minimum \((R_0 / r)_k \) at higher \( m_D \) for higher k. Since each limit is statistically independent the best result is obtained by forming a single weighted \((R_0 / r)_k \). The 90% c.l. in \( R_0 / r \) is shown in fig. 2 for the spin dependent and coherent \((A^2) \) interactions.

6 Developments towards lower event rates

Further gains can be achieved by improved light collection via alternative light detectors, such as avalanche photodiodes; indeed we have an programme with Silicon Sensors in Germany to develop suitable drift devices.

The group, in collaboration with UCLA and members of ICARUS at CERN, is also investigating the use of LXe, which appears to offer far greater
discrimination [9][10]. By extrapolating higher energy data for electrons and alphas (which approximate to a nuclear recoil) simulations show that it is possible to reduce the background by factors of ~100, even at low energies, by timing measurements on the scintillation light [4]. Alternatively, the LXe can be operated in the proportional scintillation mode. This method has been used to separate 5.5MeV alpha particles and 122keV gammas [5]. Preliminary results with neutron sources indicate that very significant discrimination is possible using this technique [10]. We suggest that such a detector could reach event rates below 0.1/day/kg.

References