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UKDMC dark matter search with inorganic scintillators

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Abstract. The status of dark matter searches with inorganic scintillator detectors at Boulby mine is reviewed. Results of a test experiment with CsI(Tl) crystal are presented. The objectives of this experiment were to study anomalous fast events and ways to remove this background. We found clear indications that these events were due to surface contamination of crystals by alphas, probably from radon decay. A new array of unencapsulated NaI(Tl) crystals immersed in liquid paraffin or nitrogen atmosphere is under construction at Boulby. Such an approach allows us to control the surface of the crystals. Preliminary results of WIMP searches with NaI(Tl) detectors at Boulby are presented.

1 Introduction

The UK Dark Matter Collaboration (UKDMC) has been operating encapsulated NaI(Tl) detectors at the Boulby Mine underground site for several years (Smith et al. (1998)). Competitive limits on the flux of weakly interacting massive particles (WIMPs), that may constitute up to 90% of mass in the Galaxy, have been set by one of these detectors using pulse shape analysis (PSA) to distinguish scintillation arising from background electron recoils from that due to nuclear recoils (Smith et al. (1996)). Discrimination is possible because the sodium and iodine recoils expected from elastic scattering by WIMPs have faster mean pulse decay time than for electrons (Tovey et al. (1998)). Traditionally, because NaI is hygroscopic, detectors are fabricated using an outer copper encapsulation with glued-in quartz windows plus additional thick (typically $>$ 100 mm) quartz lightguides to shield the crystal from photomultiplier activity. However, this design limits detector sensitivity because it prevents access to potential background sources on crystal surfaces. The importance of NaI(Tl) surfaces has been highlighted recently by indications that they might be a source of anomalous fast time constant events seen so far at similar rates in many dark matter experiments with encapsulated NaI(Tl) crystals (Smith et al. (1998); Gerbier et al. (1999); Kudryavtsev et al. (1999); Smith et al. (2000)). Greater access would allow improved control of potential contaminants there and hence a possible reduction in such events, leading to greater sensitivity to WIMPs.

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2 Anomalous fast events

The observation of anomalous fast events in the UKDMC encapsulated NaI(Tl) detectors was first reported by Smith et al. (1998). These events are faster than typical electron recoil pulses and even faster than nuclear recoil pulses (Smith et al. (1998)). Similar fast events with similar rate have been seen also by the Saclay group (Gerbier et al. (1999)).

Smith et al. (1998) suggested that the anomalous fast events could be due to MeV alphas. To account for the rate at low energies (10-100 keV) the alphas would need to deposit a small fraction of their initial energy at the crystal surface. Intrinsic bulk contamination of the crystal by uranium and thorium (measured to be at the level of about 0.1 ppb) is certainly not enough to explain the observed high rate at low energies. External incoming alphas from surrounding materials (PTFE, quartz windows) cannot easily explain the observed spectrum: fine tuning of model parameters, such as a dead layer of scintillator, is needed and a very high contamination of the material by uranium or thorium (about 1 ppm) is required as well. Moreover, the time constant of the incoming alphas is not matched well to that of the fast events (Kudryavtsev et al. (1999)).

Intrinsic surface contamination of the crystal by an alpha-emitting isotope has recently been discussed as a source of the anomalous fast events (Smith et al. (2000)). Recoiling nuclei from radon decay can be implanted into the crystal surface. This creates a thin (0.1-0.2 microns) alpha emitting layer. Although a high concentration of radioactive nuclei (0.1-1 ppm) is needed to account for the observed rate, the predicted spectrum agrees quite well with observations. Note that it is not known how such a large concentration of radioactive nuclei can appear on the surface of an encapsulated crystal. Similar hypotheses on the source of the anomalous fast events have been suggested by Saclay groups (Chardin et al. (2000)) and by Cooper et al. (2000).

If the source of fast events is indeed on the surface of the crystal, then it can be removed by polishing the surface. This is hard to do with encapsulated NaI(Tl) crystals but such an experiment can be done with CsI(Tl), providing it shows fast events. The advantages of CsI(Tl) crystals are: a) they are only slightly hygroscopic and can be easily handled; b) they show better discrimination between electron and nuclear recoils (Kudryavtsev et al. (2001); Pécourt et al. (1999)).

3 Test with CsI(Tl) crystal

Tests were performed with an 0.8 kg CsI(Tl) Harshaw crystal previously studied in the laboratory to evaluate its characteristics such as quenching factor for recoils and discrimination power, relevant to dark matter searches. The results have been reported elsewhere (Kudryavtsev et al. (2001)).

The crystal was subsequently moved to the underground laboratory at Boulby and tested for background rate and anomalous fast events. In all tests we applied the standard procedure of pulse shape analysis adopted by the UK Dark Matter Collaboration for NaI(Tl) dark matter detectors (Smith et al. (1996); Kudryavtsev et al. (1999); Spooner et al. (2000); Kudryavtsev et al. (2001)). Pulses from both PMTs were integrated using a buffer circuit and then digitised using a LeCroy 9350A oscilloscope driven by a Macintosh computer running Labview-based data acquisition software. Final analysis was performed on the sum of the pulses from the two PMTs. Our standard procedure of data analysis involves the fitting of a single exponential to each integrated pulse to obtain the index of the exponent. Although scintillation pulses from CsI(Tl) have an additional second component (Kudryavtsev et al. (2001)), the pulses can nevertheless be well fitted by a single exponential if fits are restricted to data below 1500 ns. This fraction of the pulse contains the major contribution to the integrated pulse amplitude so that the distortion of the fit due to the presence of the second exponential at large time scales was found to be insignificant (Kudryavtsev et al. (2001)).

In the low background conditions of the underground laboratory at Boulby, the CsI(Tl) crystal was found to show an anomalous population of fast events. Figure 1a shows time constant distribution of events with visible energy 30-50 keV together with a fit to a log(Gauss) function (14.3 kg $\times$ days of exposure). Note a "bump" of fast events at the left edge of the time constant distribution.

There is an excess of observed events over the log(Gauss) fit also at high values of time constant. This can be explained assuming stochastic pile-up of single thermal photoelectrons (Tovey (1998)), occasional afterpulses and fluorescence of the crystal after the scintillation pulse. The effect is seen for both "data" and "calibration" runs and does not interfere

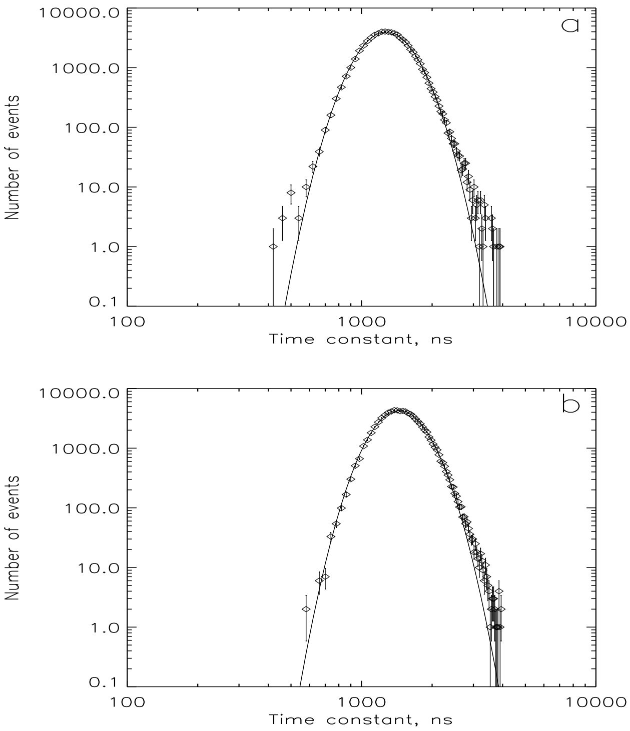

Fig. 1. a) Time constant distribution for events with visible energy 30-50 keV from the CsI(Tl) crystal; b) similar distribution after crystal polishing. Solid curves show fits to a log(Gauss)-function.

with the search for events faster than electron recoil events, such as nuclear recoils from WIMP interactions with matter or other kinds of fast events.

The spectrum of these events presented in Figure 2 (crosses) has been traced up to MeV energies. The rate and shape of the spectrum are similar to those observed in the NaI(Tl) encapsulated detectors (Smith et al. (1998)). A peak at about 3 MeV corresponds to the 5.3 MeV alphas from ^{210}Po $\rightarrow$ ^{206}Pb α-decay, assuming a quenching factor for alphas of about 0.6. Note the absence of higher energy events which may be associated with the decay channels prior to ^{210}Po. This contradicts the hypothesis by Cooper et al. (2000).

After 2 months of running at various dynamic ranges the crystal was removed, polished and put into a sealed vessel with nitrogen atmosphere. After polishing, the crystal was exposed to air for only a few hours during the installation procedure.

The subsequent runs revealed a decrease in the rate of fast events by about a factor of 4 (squares in Figure 2). The first two points below 100 keV show an upper limit to the rate. An accurate measurement of the rate at these energies is difficult because of the small mass of the crystal and the high rate of γ-background observed due to internal contamination of ^{137}Cs. The time constant distribution for events of 30-50 keV after polishing is shown in Figure 1b (22.3 kg $\times$ days of exposure). It can be seen that the rate of anomalous fast events is significantly reduced (see Figure 1a), though not completely suppressed probably due to the difficulty of re-

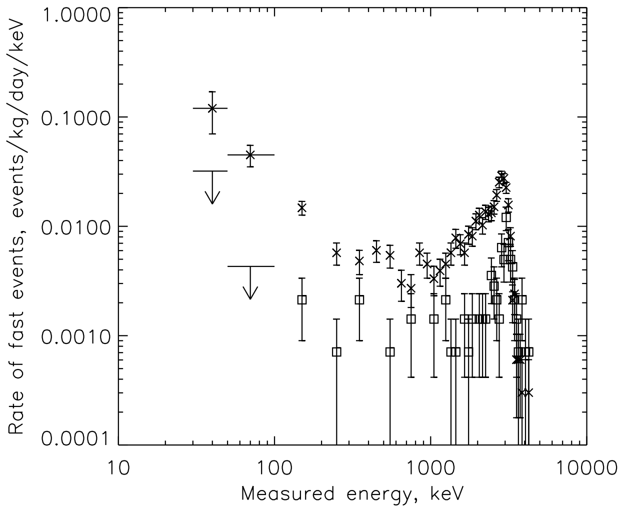

Fig. 2. Rate of fast events (αs) in CsI(Tl) crystal before (crosses) and after (squares) polishing. The first two points after polishing show limits at 90% confidence level.

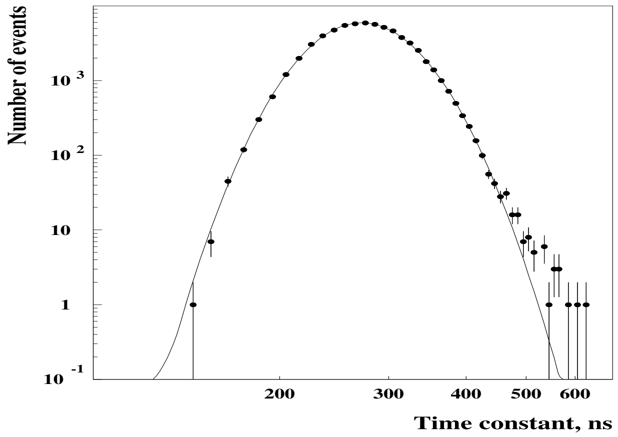

Fig. 3. Time constant distribution for events with visible energy 35-40 keV from the first NAIAD module (DM74). Solid curve shows a fit to a log(Gauss)-function.

moving the hard surface layer of CsI.

17 high-energy events (visible energy of 5-6 MeV) were also detected during the first day after polishing. These are double-pulse events where the first pulse corresponds to the β-decay of ^{212}Bi (half-life 1 hour) and the second due to the α-decay of ^{212}Po (half-life 0.3 μs). These events are probably caused by contamination of the crystal surface during installation. No more of these events were seen after the first day.

Only one prominent peak is seen in the spectra shown in Figure 2. The peak is likely due to $^{210}\mathrm{Po} \rightarrow {}^{206}\mathrm{Pb}$ α-decay (5.3 MeV αs). No decay chains $^{222}\mathrm{Rn} \rightarrow {}^{218}\mathrm{Po} \rightarrow {}^{214}\mathrm{Pb}$ or $^{224}\mathrm{Ra} \rightarrow {}^{220}\mathrm{Rn} \rightarrow {}^{216}\mathrm{Po} \rightarrow {}^{212}\mathrm{Pb}$ were seen before or after polishing. This suggests that the concentration of U, Th and Ra in the bulk of the crystal is very low (less than 0.1 ppb).

At least several months of exposure to Rn is needed to explain the rate of α-events in CsI(Tl) and NaI(Tl) detectors. This is not surprising for an unencapsulated CsI crystal but is hard to explain for NaI sealed detectors.

4 Array of unencapsulated NaI(Tl) detectors - NAIAD

The results obtained with the CsI(Tl) crystal at Boulby clearly indicate the importance of having access to the crystal surface for polishing and control. Such access can be granted by running unencapsulated crystals in high purity mineral oil or dry air inside sealed plastic or copper vessels. Laboratory tests have shown also that high light yield (up to 10 photoelectrons per keV) can be reached with the aforementioned detectors (Spooner et al. (2000)).

Since 1999 the UKDMC has been developing a programme to run several unencapsulated NaI(Tl) crystals mounted in an array – NAIAD (NAI Advanced Detector). The NAIAD array is designed to be flexible enough to allow various modes of operation with crystals. To-date two types of module have been constructed: a "vertical" module filled with high purity mineral oil to protect crystals from moisture, and a "horizontal" module in which either a liquid or dry nitrogen is used around the crystal. Operation of an encapsulated crystal is also possible in the horizontal module. Design details and predictions of sensitivity to WIMPs are given by (Spooner et al. (2000)).

The first vertical module of NAIAD has been running since February 2000. It contains a 14 cm diameter $\times$ 15 cm length crystal (termed DM74) with mass of about 8.5 kg. The crystal was polished before installation. The total exposure (excluding calibration runs) is 996 kg $\times$ days. Figure 3 shows a typical distribution of time constants for events with 35-40 keV visible energy together with a fit to a log(Gauss) function. As with the polished CsI(Tl) crystal the rate of anomalous fast events is greatly suppressed (by a factor of 2-3 at least) with respect to the rate in encapsulated detectors.

A second (horizontal) module containing 4 kg unencapsulated and polished crystal in nitrogen (DM72) also does not show the presence of fast events. This second detector is currently running underground at Boulby.

The data from the first NAIAD module have been analysed using our standard procedure (Smith et al. (1998, 1996); Kudryavtsev et al. (1999); Spooner et al. (2000)) to search for possible presence of events due to nuclear recoils. These events are expected to be faster than electron recoils but not as fast as anomalous events. The calibration of the detectors with gamma (^{60}Co) and neutron (^{252}Cf) sources has been done before moving them to the mine. Detectors are also calibrated daily with gamma sources in the mine. Temperature stability is checked every minute by DAQ slow control and the value of temperature is written to disk for each event. Off-line analysis includes fitting of each pulse to an exponential and analysis of time constant distributions for various visible energies. Only those events which survive tempera-

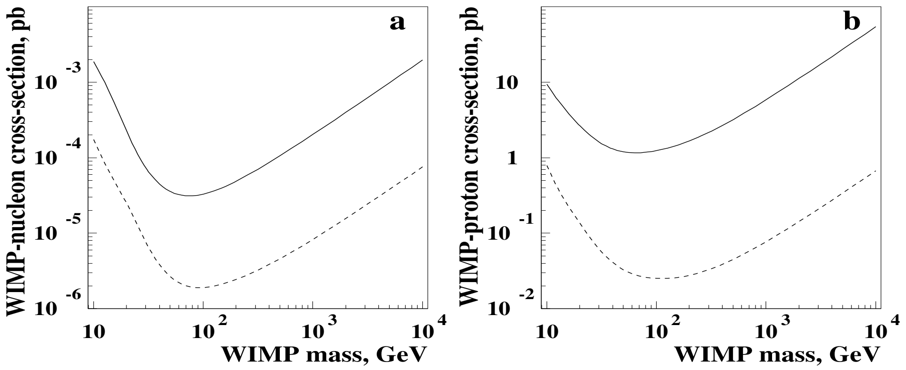

Fig. 4. Preliminary limits on spin-independent WIMP-nucleon (a) and spin-dependent WIMP-proton (for the case of pure higgsino) (b) cross-sections derived from the UKDMC NAIAD experiment (solid curves). Dashed curves show predicted sensitivity for 100 kg × years exposure.

ture cuts and asymmetry cuts (asymmetry between the pulses from two phototubes) have been included in the analysis.

Preliminary limits on the spin-independent and spin-dependent (for the case of pure higgsino) cross-sections are shown in Figure 4 (solid curves). To derive these limits we have used halo model parameters, spin and form factors as in Kudryavtsev et al. (2001) and Spooner et al. (2000) (see references therein). Also shown in Figure 4 is the expected sensitivity of NAIAD with 100 kg × years exposure (Spooner et al. (2000)) (dashed curves) with improved light collection and discrimination power as found for DM72.

5 Pulse shape analysis versus annual modulation

Pulse shape analysis (PSA) is not the only technique used with NaI(Tl) detectors for dark matter searches. The DAMA group (Bernabei et al. (2000)) searches for an annual modulation in the background counting rate of their NaI(Tl) array without PSA (PSA is used only to discriminate between scintillation pulses and PMT noise). Evidence for such an annual modulation in the background rate has been reported by DAMA (see Bernabei et al. (2000) and references therein) indicating a possible signal from WIMPs.

The DAMA group could, in fact, confirm or exclude this possibility using PSA. Bernabei et al. (2000) presented results of the annual modulation analysis (positive signal) together with previous limits on WIMP-nucleon cross-section obtained with PSA. All sets of data (DAMA/NaI-0 analysed using PSA and DAMA/NaI-1 – DAMA/NaI-4 analysed using annual modulation) were obtained with the same experimental set-up and under similar conditions such as background rate etc. PSA applied to the first data set (DAMA/NaI-0) with 4123.2 kg × days exposure allowed DAMA to put limits on WIMP-nucleon interactions (Bernabei et al. (1996)). The subsequent data sets (DAMA/NaI-1 – DAMA/NaI-4) totaling 57986 kg × days showed a positive signal using annual modulation analysis without PSA. Simple statistical considerations show that PSA applied to this 15 times larger exposure from all five data sets (DAMA/NaI-0 – DAMA/NaI-4) compared to the first one (DAMA/NaI-0) could yield a limit on the WIMP-nucleon cross-section improved by a factor of 3.9. Such an analysis would allow DAMA either to confirm the modulated signal or to exclude practically the whole region of parameters that they derive from the observed modulated signal (Bernabei et al. (2000)).

6 Conclusions

Tests with a CsI(Tl) and unencapsulated NaI(Tl) crystals have shown that anomalous fast events seen in several NaI(Tl) detectors at Boulby were probably due to surface αs. Radioactive α-emitting isotopes had been likely implanted into crystal surfaces by radon decay. Polishing the crystal surfaces removed a major part of the fast events. A new array of unencapsulated NaI(Tl) crystals (NAIAD) is being installed in the underground laboratory at Boulby. Data from the first of these modules do not reveal anomalous fast events.

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