UKDMC DARK MATTER SEARCH WITH INORGANIC SCINTILLATORS

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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 from the first module 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 [1]. Competitive limits on the flux of weakly interacting massive particles (WIMPs), that may constitute up to 90% of 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[2]. Dis-

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crimination is possible because the sodium and iodine recoils expected from elastic scattering by WIMPs have faster mean pulse decay time than for electrons [3]. At present, 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 surfaces has been highlighted recently by indications that they might be a source of anomalous fast time constant events seen in NaI dark matter experiments [1,4,5,6]. Greater access would allow improved control of potential contaminants there and hence a possible reduction in such events, leading to greater sensitivity to WIMPs.

In this paper we report the results of a study of anomalous fast events with NaI(Tl) and CsI(Tl) detectors, the recipe to suppress their rate and the preliminary results from the first unencapsulated NaI(Tl) detector which does not show this background.

2 Anomalous fast events

The observation of anomalous fast events in the UKDMC encapsulated NaI(Tl) detectors was first reported by Smith *et al.* [1]. Similar events with similar rate have been seen also by the Saclay group [4]. One of the Saclay crystals has been moved to Boulby (as a result of a collaboration between UKDMC and Saclay) and is currently collecting data. We confirm the presence of the population of fast events with a rate similar to that seen in the UKDMC detectors.

Smith *et al.* [1] suggested that anomalous fast events can be due to alphas. To account for the rate at low energies (10-100 keV) a large number of alphas should deposit small energy at the crystal surface. Intrinsic bulk contamination of the crystal by uranium and thorium (usually 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) can hardly explain the observed spectrum: fine tuning of model parameters, such as a dead layer of scintillator, is needed.A very high contamination of the material by alpha-emitting isotope (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 [5].

Intrinsic surface contamination of the crystal by an alpha-emitting isotope has been recently discussed as a source of anomalous fast events [6]. Nuclear recoils 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.

If the source of fast events is 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 a similar rate of 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 capability between electron and nuclear recoils [7].

3 Test experiment with CsI(Tl) crystal

0.8 kg CsI(Tl) crystal has been extensively studied both in the laboratory and underground to evaluate its characteristics such as quenching factor of recoils, discrimination power etc. relevant to dark matter searches. The results have been reported elsewhere [7]. In the low background conditions of the underground laboratory at Boulby, the crystal has shown an anomalous population of fast events with the spectrum presented in Fig. 1 (crosses). The rate and the shape of the spectrum are similar (but not exactly the same) as those observed in the NaI(Tl) encapsulated detectors [1]. After 2 months of running at various dynamic ranges the crystal has been taken out of the detector, polished and put into a sealed vessel with nitrogen atmosphere. The crystal was exposed to air for only a few hours during the installation procedure.

The subsequent runs revealed a decrease of the rate of fast events by about a factor of 4 (squares in Fig. 1). 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. Note, that the anomalous component has not been removed completely during polishing but suppressed significantly. This is due to the difficulty of removing the hard surface layer of CsI.

17 high-energy events (visible energy of 5-6 MeV) were also detected during first day after polishing. These are double-pulse events where the first pulse corresponds to the β-decay of ^{212}Bi and the second one is due to the α-decay of ^{212}Po (half-life is 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.

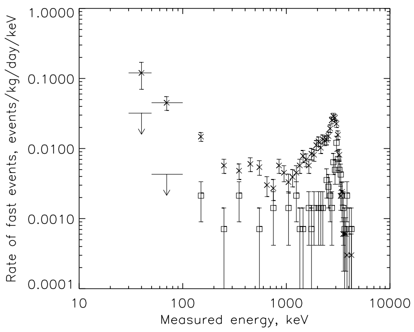

Figure 1. Rate of fast events (α's) in CsI(Tl) crystal before (crosses) and after (squares) polishing. The first two points after polishing show limits at 90% confidence level.

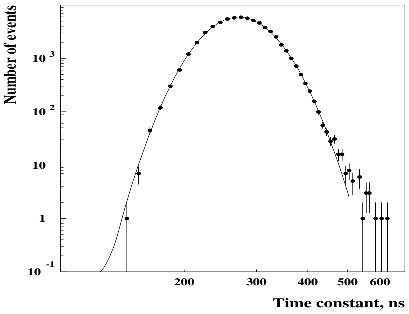

Figure 2. Time constant distribution for events with visible energy 35-40 keV from the first NAIAD module. Solid curve shows a fit to the Gaussian distribution on logarithmic scale.

Only one prominent peak is seen in the spectra shown in Fig. 1. The peak is likely to be due to ^{210}Po $\rightarrow$ ^{206}Pb α-decay (5.3 MeV α's). No decay chains ^{222}Rn $\rightarrow$ ^{218}Po $\rightarrow$ ^{214}Pb or ^{224}Ra $\rightarrow$ ^{220}Rn $\rightarrow$ ^{216}Po $\rightarrow$ ^{212}Pb have been 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 CsI(Tl) crystal in the mine 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 paraffin 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 [8].

Since 1999 the UKDMC has been developing the 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.

The first vertical module of NAIAD has been running since February 2000. It contains a 14 cm diameter $\times$ 15 cm length crystal with mass of about 8.5 kg. The crystal was polished before installation. The total exposure (excluding calibration runs) is about 1000 kg $\times$ days. Fig. 2 shows a typical distribution of time constants for events with 35-40 keV visible energy. It does not show any anomalous fast population. We conclude that the rate of anomalous fast events in the first NAIAD module (DM74) is suppressed by at least a factor of 2-3 with respect to the rate in encapsulated detectors.

One month of running of the second (horizontal) module with 4 kg unencapsulated crystal in nitrogen (DM72) did not reveal the presence of fast events either. This second crystal shows better light collection and better electron/nuclear recoil discrimination than the first one.

The data from the first NAIAD module have been analysed using our standard procedure [1,2,5,8] 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 temperature 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 Fig. 3 (solid curves). To derive these limits we have used halo model parameters, spin and form factors as in Ref. [7,8] (see references therein). Also shown in Fig. 3 is the expected sensitivity of NAIAD with 100 kg $\times$ years exposure [8] (dashed curves) with improved light collection and discrimination power as found for DM72.

5 Conclusions

Tests with a CsI(Tl) crystal have shown that anomalous fast events seen in several NaI(Tl) detectors at Boulby were probably due to surface α's. Radioactive α-emitting isotopes had been likely implanted into the crystal surface

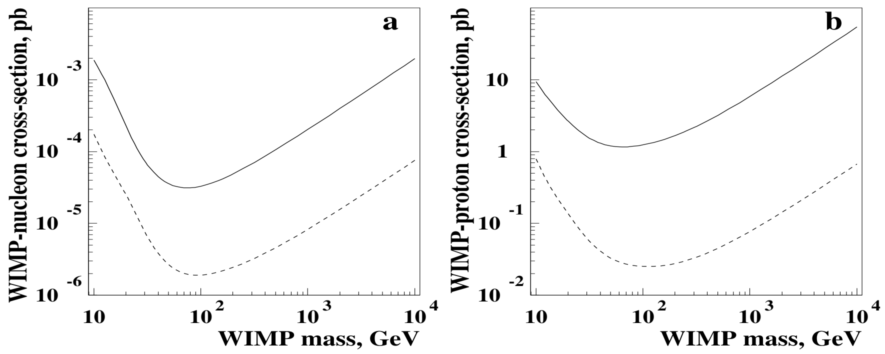

Figure 3. Preliminary limits on spin-independent WIMP-nucleon (a) and spin-dependent WIMP-proton (for the case of pure higgsino) (b) cross-sections derived from the UKDMC NAIAD experiment (solid curves). Dashed curves show predicted sensitivity for 100 kg $\times$ years exposure.

by radon decay. Polishing the crystal surface has removed a major part of the fast events. New array of unencapsulated NaI(Tl) crystals (NAIAD) is being installed in the underground laboratory at Boulby. Preliminary results from the first module are presented.

Acknowledgments

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