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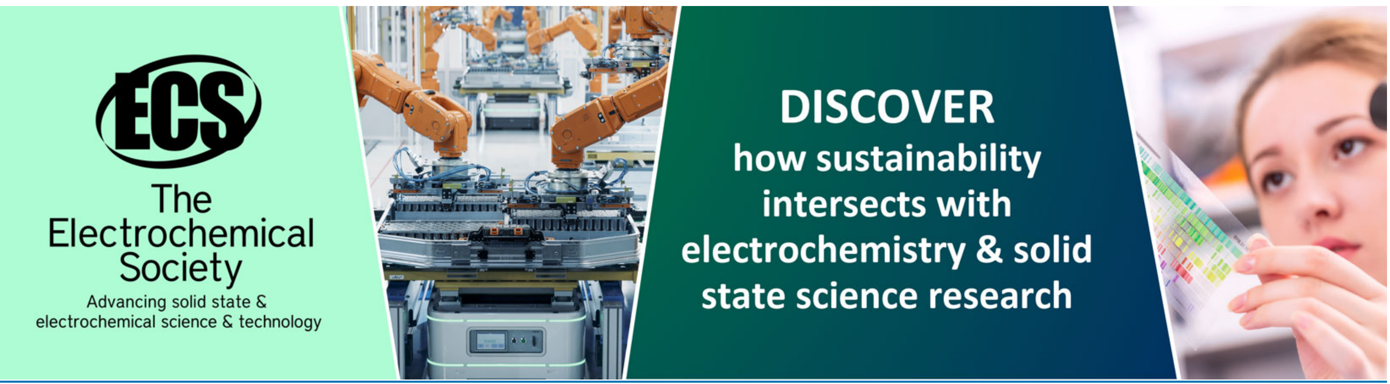

Constructing a background model for DAMIC CCDs

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Abstract. The DAMIC Collaboration uses fully-depleted silicon charge-coupled devices to search for low mass dark matter particles. We present a new analysis of backgrounds in the DAMIC at SNOLAB detector, which is used to construct a background model for an ongoing WIMP search analysis. The formation of this background model reveals new radioactive background components, the presence of which has since been experimentally confirmed. This background model additionally informs how best to proceed in meeting the lower background constraints of the DAMIC-M detector.

1. Introduction

The DAMIC (Dark Matter In CCDs) experiment uses silicon charge-coupled devices (CCDs) to search for dark matter interactions, such as from a weakly interacting massive particles (WIMPs), at the SNOLAB underground observatory [1]. DAMIC CCDs are made from thick ($\sim$1 mm) high-resistivity silicon wafers, enabling sufficiently high exposures for a dark matter search [2]. An interaction in the silicon will deposit energy in the detector which will produce a quantized number (on average, one per 3.8 eV$_{\rm ee}$) of charges [3]. As these electrons drift across the fully-depleted silicon, they experience lateral thermal motion, or diffusion, which is proportional to the vertical distance traveled, or depth, before being collected in an array of 15×15 μm^2 pixels. The DAMIC at SNOLAB detector consists of seven 6×6 cm^2 (4k $\times$ 4k pixel) CCDs with a 675 μm thick active region between dead layers of only a few microns.

DAMIC CCDs have already been demonstrated to have excellent discrimination power regarding the progenitor of an energy deposition due to their exceptional position resolution [4]. Below $\sim$10 keV$_{\rm ee}$, all energy depositions are approximately point-like, but the Gaussian spread of an energy deposition on the pixel array due to diffusion is highly correlated with the true depth of the energy deposition in the detector. This correlation is calibrated using muons, which deposit energy uniformly in a straight track, allowing for a precise translation between interaction depth and reconstructed Gaussian pixel spread σ_x [1].

2. Background Model

Previously, DAMIC at SNOLAB set limits on WIMP-nucleon coupling with an 0.6 kg-day exposure [1]. Since then, the DAMIC at SNOLAB detector has been upgraded with reduced backgrounds and increased detector mass, and operated for a substantially larger cumulative exposure of 13 kg-days. The previous SNOLAB analysis relied on a fiducial cut in sigma to isolate the "bulk" of the CCD from the surfaces, where the background rate is highest. This cut was effective at high energies, but inefficient at removing un-modeled back-side events at lower

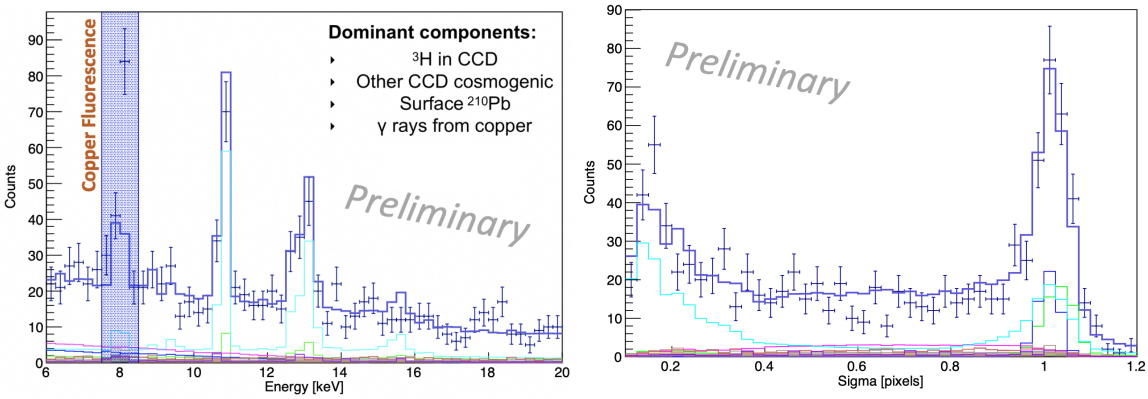

Figure 1. Results of the two-dimensional fit to data projected onto energy (left) and σ_x (right).

energies, resulting in a weakened limit on low-mass dark matter. In this analysis, we utilize information at higher energies to model radioactive backgrounds in the DAMIC at SNOLAB detector, enabling sensitivity down to energies as low as 50 eV$_{ee}$without needing a fiducial cut in reconstructed variables.

We start by simulating all long-lived isotopes in detector components using GEANT4 [5] and record the deposited energy E_{G4} and depth z_{G4} of each interaction. We then apply our diffusion model to each simulated energy deposition, bin the resulting energy spread into pixels, apply noise and saturation according to our best model of each CCD, and run a clustering algorithm to produce reconstructed variables E and σ_x. We simulate a total of 23 isotopes across 65 detector volumes, which are grouped together by decay chain and material origin into 53 two-dimensional templates in E and σ_x. The normalization of each of these templates is determined from the corresponding isotope activity, which has typically been determined by either ICP-MS or germanium gamma counting, depending on the material. To account for this, we construct a template fit wherein the normalization of each template is either (1) weighted by a nuisance parameter applying a Gaussian penalty if the activity of the isotope for a given template is known, (2) allowed to float freely down to zero if the activity for a given template is constrained by an upper bound, or (3) unconstrained and unbound.

In order to fit to data, we consider clusters with $E > 6$ keV$_{ee}$to be background dominated, as previous silicon experiments have excluded such WIMP masses at cross-sections accessible with our exposure [6]. We perform quality cuts on the data to eliminate badly reconstructed clusters, including whether any pixels were touching a masked pixel or if any clusters are not well described by a Gaussian, resulting in a bad σ_x. The simulations either have the same cuts applied or are corrected for the efficiency of the cut. We then perform a binned likelihood fit in reconstructed energy (between 6–20 keV$_{ee}$) and σ_x for of these 53 templates against the DAMIC at SNOLAB data. This is done by assuming the number of events observed k_{ij} in the i^{th} energy and j^{th} sigma bin are described by a Poisson distribution, with the expected number of counts ν_{ij} coming from the sum of all simulated templates. Each template is assigned a normalization scale factor, thus effecting the total number of expected counts ν_{ij}. Finally, we add a Gaussian penalty to all bound scale parameters for each constraint $N_n \pm \sigma_n$ on the activity of a template isotope. Thus, we can write the overall log-likelihood as

$$LL = \sum_i \sum_j \left(k_{ij} \log(\nu_{ij}) - \nu_{ij} - \log(k_{ij}!)\right) - \sum_n \left(\frac{(N_n^0 - N_n)^2}{2\sigma_n^2}\right). \quad (1)$$

The resulting fit captures all key features in the data between 6–20 keV$_{ee}$, as shown in Figure 1, with the exception of the copper fluorescence peak at ∼8 keV$_{ee}$. Consequently, we choose to

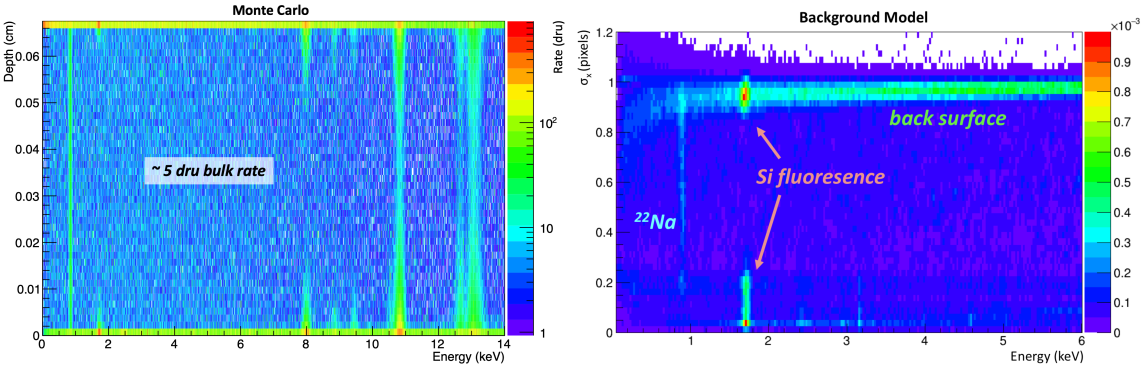

Figure 2. Left: Monte Carlo template sum in $[E_{G4}, z_{G4}]$ weighted by the results of the two-dimensional fit to data. **Right:** Background model in $[E, \sigma_x]$ constructed from energy depositions drawn from the Monte Carlo (left), diffused, and pasted onto CCD images.

mask this energy range (7.5–8.5 $\mathrm{keV_{ee}}$) in the fit. Here, we use this fit to higher energies to generate a background model for our WIMP region of interest (ROI) below 6 $\mathrm{keV_{ee}}$.

To create a pdf for the profile likelihood ratio limit calculation, we take the best fit template sum (shown in Figure 2 in $[E_{G4}, z_{G4}]$ space) and sample fake events from this distribution. These fake events are then fed through our diffusion model and pasted randomly onto blank images (real short-exposure images which are expected to have zero background but contain detector read-out noise). The same clustering algorithm and analysis chain that is used on the data is then run on these fake images to produce a set of clusters with reconstructed variables E and σ_x. The resulting pdf's in $[E, \sigma_x]$ are used to produce a limit in the energy ROI of 0.05–6.0 $\mathrm{keV_{ee}}$. Both the original $[E_{G4}, z_{G4}]$ and final $[E, \sigma_x]$ pdf's are shown in Figure 2. A complete paper on these results is in preparation and will be submitted for publication shortly after the release of new limits on WIMP dark matter.

3. Discussion of Results

We are able to isolate various background components, with significant confidence above 1 dru (defined as 1 event $\mathrm{kg^{-1}\ day^{-1}\ keV_{ee}{}^{-1}}$). The dominant contribution to the roughly 12 dru rate observed in the detector (between 6–7.5 keV) comes from ^{210}Pb on the various surfaces of the detector and in the oxygen-free (OFC) copper (3 dru). The exact distribution of this ^{210}Pb is the major source of uncertainty in our analysis and will be addressed below. The next major component comes from tritium, and exhibits both a bulk and back component in σ_x. The bulk component (2 dru) is attributed to direct cosmogenic activation of the silicon CCDs during storage on the surface. The back component (2 dru) is attributed to hydrogen trapped in the backside dead layer during CCD manufacturing. A subsequent analysis using secondary ion mass spectrometry, shown in Figure 3, finds order 10^{21} H/cm^3 on the back of the CCD, which is consistent with the measured rate of tritium decays under the assumption that the tritium fraction in trapped hydrogen is of the same order of magnitude as in water (10^{-18} ^{3}H/H). The remaining 6 dru is composed mainly of copper activation, impurities in the OFC copper components and kapton flex cables, and ^{32}Si in the CCD itself.

^{210}Pb gets embedded on detector surfaces from plate-out following radon decay. For the DAMIC at SNOLAB detector, we consider ^{210}Pb on the copper surfaces, in the OFC copper volumes, on the silicon frame, on the CCD surfaces, and on the back inside surface of the active region. The last location was included after finding that the back surface of the wafer is not polished during manufacturing, despite substantial (multiple years) exposure of the wafer to air prior to CCD production. By manually removing some of the ^{210}Pb templates and repeating

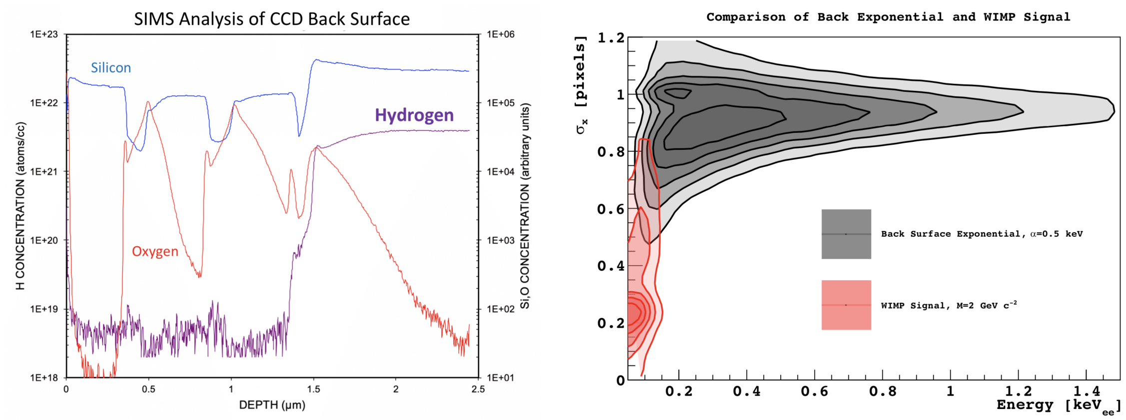

Figure 3. Left: Results of a secondary ion mass spectrometry measurement on the back of a CCD, confirming the presence of hydrogen in the innermost backside dead layer. **Right:** Comparison of a back exponential in energy with exponential constant $\alpha = 0.5$ keV (black), representing the systematic uncertainty due to ^{210}Pb, against a 2 GeV c^{-2} WIMP signal (red).

the fit, we are able to quantify our systematic uncertainty in the background model due to the location of ^{210}Pb in our detector. We find that the resulting difference at low energies is mainly restricted to a back exponential in energy, as shown in Figure 3.

4. Implications for DAMIC-M

DAMIC-M is the next phase of the DAMIC experiment, consisting of 1 kg of silicon CCDs to be deployed at the Laboratoire Souterrain de Modane in France. In order to maximize sensitivity to dark matter, DAMIC-M must meet a design goal of 0.1 dru, a factor of $\sim$100 reduction from the radioactive background levels measured in DAMIC at SNOLAB. The background model for DAMIC at SNOLAB (presented here for the first time) directly informs this effort, specifically with regards to background contributions above 1 dru. Most importantly, this analysis reveals that the backside dead layer of the CCDs must be removed, due to unexpected tritium content revealed through this analysis. Additionally, this analysis emphasizes the importance of wafer handling controls prior to CCD production. Since the backside of the wafer is not polished before production, any radon-daughter plate out will result in a ^{210}Pb background rate greater than the design specifications. Most other dominant contributions, such as impurities in the copper, cable, and other detector materials can be controlled through more careful material selection and handling.

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