DAMIC-M Experiment: Thick, Silicon CCDs to search for Light Dark Matter

N. Castelló-Mor[a,*], on behalf of the DAMIC-M Collaboration

[a] *Instituto de Fisica de Cantabria (Universidad de Cantabria/CSIC), Av. de los Castros s/n 39005 Santander, Spain*

Abstract

This report presents an overview of the unconventional use of charge-coupled devices (CCDs) to search for Dark Matter (DM). The DArk Matter in CCDs (DAMIC Experiment) employs the bulk silicon of thick, fully-depleted CCDs as a target for ionization signals produced by interations of particle dark matter from the galactic halo. The DAMIC collaboration has engaged in an extensive campaign of characterization efforts to understand the response of these CCDs to low-energy nuclear recoils and their unique capabilities, including the use of high spatial resolution for both the rejection and study of backgrounds. The preliminary results of DAMIC prove the performance of the detector, provide measurements of the background contamination and demonstrate the potentiality for DM searches, with only ~40 grams of detector mass. The next phase of the experiment, DAMIC-M (DArk Matter in CCDs at Modane), will consist of a kg-sized detector, implementing the most massive CCDs ever built. These CCDs will feature sub-electron noise and will be deployed in a low-radioactivity environment at the *Laboratoire Souterrain de Modane* in France.

Keywords: dark matter detectors, solid state detectors, very-low energy charge particle detectors, CCD

1. State-of-the-art in DM searches

The mistery of dark matter (DM) is one of the most fundamental questions in physics. Significant efforts have been made to understand the nature of dark matter and theories have been formulated to explain its existence. Some of these include *Modified Newtonian Dynamics* in the context of Einstein's General Relativity [1], existence of yet undetected fundamental particles with all sort of possible signatures in the context of Particle Physics [2] and Dark Fluid theoris [3]. A well-motivated theoretical model is that DM is composed of a new class of particle(s) that was also produced in an early phase of our universe and interacts (in some "unknown" way) with ordinary matter to dramatically influence the shape of the universe as it is. For instance, Weakly Interacting Massive Particles (WIMPs), the main focus of the vast majority of the DM detectors, were produced together with Standard Model (SM) particles in the hot bath of the early universe, ultimately escaping thermal equilibrium. No technique (scintillation crystals [4, 5, 6], noble liquids [7, 8, 9], bubble chambers [10], cryogenic calorimeters [11, 12]) has been successful yet in the effort to detect the low-energy nuclear recoils induced by the interactions of these theorized particles. The nature of the DM, so far elusive, constitutes one of the most fundamental open questions in Physics.

Hidden Sector (HS) particles have been proposed by the international community as an alternative approach to go beyond the WIMP paradigm [13]. In this scenario, DM is made of particles from one of the many "hidden sectors" that are thought to exist outside of the "visible sector" (made of ordinary matter) that encompasses our entire visible world. Whilst the nuclear recoil induced by light DM is albeit undetectable, energy transfer in the scattering with electrons or the absorption of a dark photon are much more efficient [14], allowing DM direct detection experiments to probe as low as eV.

Independently of the theoretical motivations, it is important to recognize that current experiments have limited sensitivity to DM-electron interactions, and a light DM particle may have well escaped detection. Most of the interactions result in the production of few charges, requiring the *detector to be able to resolve individual electrons*. An ubiquitous challenge for DM experiments is also different sources of background (natural radioactivity, airbone radon, neutrons α particles, neutrinos, etc.) which must be really low for a signal to be recognizable. The sensitivity of Si based detectors are limited by the dark current. A low dark current is a prerequisite to building a detector to search for light DM using DM-electron interactions.

The best limits on the DM mass are reached with the noble liquid technique with XENON10 data [15], but the results are limited by background-induced noise and were not improved with the tenfold increase in the mass of XENON100. SuperCDMS will perhaps reach single-electron sensitivity by operating in high-voltage mode[16], however, the required improvements in phonon resolution and leakage current have not been demonstrated (so far).

In this context, innovative technology of a single-electron detection, already demonstrated in CCDs, will enable DAMIC-M to achieve unprecedented sensitivity to the DM hidden sector. DAMIC-M capitalizes on the DAMIC experience at SNOLAB (see sec. 2) and, at the same time, greatly improves in sensitivity by further innovating the detector technology (see section 3). In fact, the measurement and mitigation of ^{32}Si and tritium that will be achieved with DAMIC-M are a necessary step to demonstrate the feasibility of a next-generation detector aiming

*Corresponding author. Tel.: +41 22 76 71657
Email address: castello@ifca.unican.es (N. Castelló-Mor)

to reach the neutrino floor.

2. CCDs as a Dark Matter detector

Recent advances in CCD technology due to the increase in the purity of the silicon have allowed the fabrication of thicker devices, e.g. 250 μm-thick used by the Dark Energy Survey[17] for efficient detection of near-infrared light from astrophysical objects. Motivated by its potential, Lawrence Berkeley National Laboratory developed a high-resistivity silicon CCD for the DAMIC experiment with the idea to increase sensitivity to search for DM particles. This new prototype of CCD achieved a record thickness of 675 μm with an area of 6cm×6cm and a mass of 5.8 grams. Furthermore, the CCD also presents high spatial resolution and an excellent energy response in very effective background identification techniques. All this makes the DAMIC CCDs a well-suited detector to identify and suppress radioactive background. DAMIC is an initiative to search for dark matter through direct search based on these technology. It employs the bulk silicon of the CCD as a target for interactions of particle DM [18]. Ionization signals may be produced in the active bulk of the device by recoiling nuclei or electrons following the scattering of a dark matter particle. By virtue of the low readout noise of the CCD technology, and the relatively low mass of the silicon nucleus, DAMIC is particularly sensitive to the signal from low mass WIMPs (2–10 GeV/c^2), which induce nuclear recoils of keV-scale energies (bottom panel Fig. 4, violete-dotted line).

DAMIC CCDs were fabricated from n-type, high-resistivity silicon wafers, and are fully depleted (i.e., active over their full volume) by applying a potential ($\geq$ 40V) to a thin back-side contact. Each CCD is epoxied onto a silicon backing, together with a flex cable that is wire bonded to the CCD and provides the voltage biases, clocks and video signals required for its operation. These components are supported by a copper frame to complete the CCD module. The modules are installed into slots of a copper box that is cooled to ~130K inside a vacuum chamber.

The response of DAMIC CCD to ionization radiation has been extensively characterized in the laboratory. The linear response of the amplifier has been demonstrated with optical photons for ionization signals as small as 10 e^-, and with mono-energetic X-ray and gamm ray sources for energies in the range 0.5−60keV$_{ee}$ (where 3.8 eV$_{ee}$ = 1e^-) [19]. The energy scale for recoiling nuclei, which produce a smaller electron-hole pairs than a recoiling electron of the same kinetic energy, was calibrated with neutron sources [20]. DAMIC CCDs present some unique properties when is compared to other dark matter detectors:

1. *An unprecedented charge resolution* of a pixel charge r.m.s. noise of ~ 2 e$^-$, dominated by the noise of the readout amplifier. This allows for the positive identification of as little as 40 eV of ionization energy deposited in a pixel. DAMIC-M will have a much smaller noise allowing for high-resolution detection of a single electron, being sensitive to extremely small energy transfers from a DM-electron interaction.

2. *The lowest leakage current ever measured in a silicon detector* of a level of 4e^-/mm^2/day. This extremely low dark current allowed to place experimental constraints on dark matter interactions that produce as little as a single electron, improving the ionization threshold over previous dark matter searches by an order of magnitude. Figure 1 shows the observed pixel distribution, consistent with the expected distribution of leakage current convolved with a white pixel readout noise of 1.6e^-. This capability allows DAMIC CCDs technology to place the most stringent direct-detection on hidden-photon dark matter in the galactic halo with masses 3 − 12 eVc^{-2}[21].

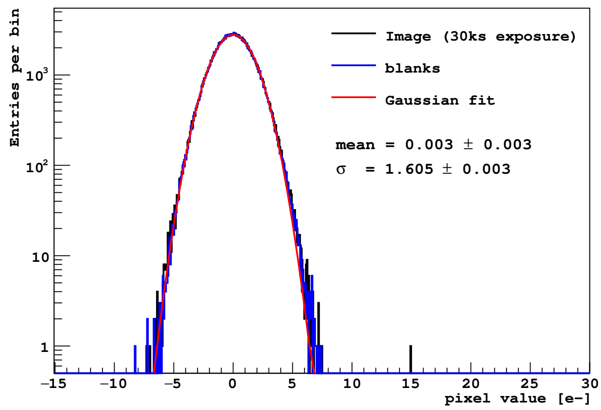

Figure 1: Distribution of pixel values in blanks images (white noise) and in 8 hours exposure (white noise, leakage current and sigma) when operating at 140 K.

3. *An exquisite spatial resolution and 3D reconstruction*. The principle of DM detection with a CCD is illustrated in Figure 2. Ionization charge produced in the substrate, through absorption or a nuclear/electronic recoil, is drifted towards the pixel gate along the direction of the electric field (z axis) and collected on the pixel array ($x - y$ plane), where it is held in place until the readout. Because of thermal motion, the ionized charge diffuses transversely with respect to the electric field direction as it is drifted, with a spatial variance (σ_{xy}) that is proportional to the transit time (i.e. the depth, z, of the interaction point). Hence, there is a positive correlation between the lateral diffusion of the collected charge on the pixel array and the depth of the interaction, which allows for the reconstruction in three dimension of the location of energy depositions in the bulk of the device, as well as the identification of particle types based on the cluster pattern (bottom panel on Figure 2).

4. *Background identification and rejection*. A truly powerful capability of DAMIC is that background can be identified and rejected as spatially correlated events occurring at different times. An example is shown in Figure 3, with three clusters (two electrons and one alpha) detected in the same location but separated in time by several days. The probability for this to occur by change is negligible. The exquisite spatial resolution and the 3D reconstruction are the basis for the rejection of background events produced by low energy gammas and electrons on the surface of the CCD, as well as, for the characterization

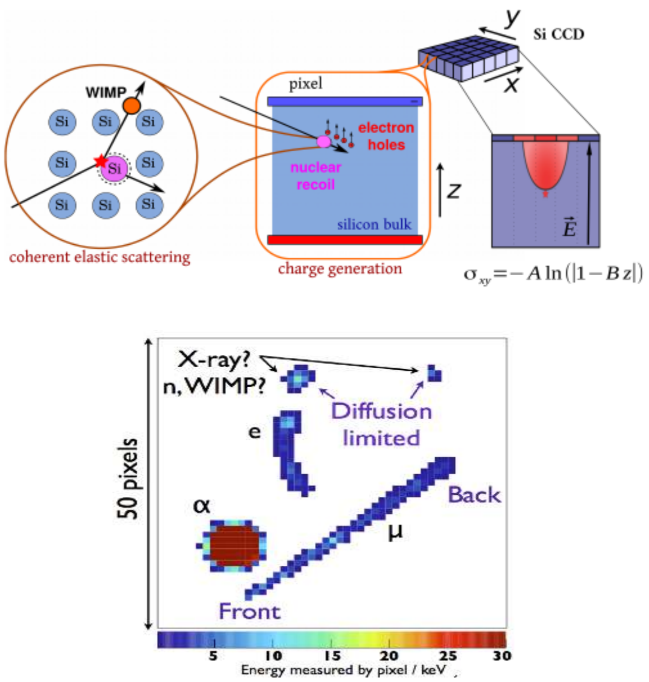

Figure 2: *Top left to right:* Representation of the WIMP-nucleon scattering and of the charge diffusion by a point-like ionization event in the CCD bulk. The $x - y$ coordinates give the position in the CCD whereas the lateral spread positively correlates to the depth of the energy deposit. The diffusion model has been tested with data from radioactive sources and cosmic muons. *Bottom:* Signatures of different ionizing particles in a CCD: a straight track (cosmic ray muon), large blob (alpha particle), "worm" (straggling electron) and small round clusters (low-energy X-ray, nuclear recoil, DM candidate).

of the radioactive background on the surface and in the bulk of the CCD.

3. Prospects of DAMIC-M

DAMIC-M, which is the successor to the DAMIC experiment has received international recognition and has been supported by the European Research Council (ERC-Advanced grant). The new detector will be a low-background 50-CCD array with a mass of 1 kg and a detection threshold of sub-electron. several improvements in the detector design, construction materials and CCD packaging have been foreseen in order to progress further in the search for low-energy dark matter particles, including the GeV-scale WIMPs, the hidden-photon, and to prove a large region of parameter space for dark matter particles in the hidden sector. The most relevant features of the new DAMIC-M CCDs are listed below.

- It will contain the most massive ever built CCD (20 grams), three times more massive than those at SNOLAB. R&D on device packaging and handling already started in order to avoid mechanical stresses on the CCDs during cooldown as this may cause unwanted induced charges to appear an possibly even damage the device.

- An important improvement for DAMIC-M will be the implementation for "skipper" amplifiers on large area 1-mm-thick 36 Mpixel CCDs. The skipper amplifiers perform a large number of uncorrelated measurements of the charge collected by each CCD pixel, significantly decreasing the pixel noise by averaging over a large number of samples. The single electron response of the skipper amplifier has already been demonstrated with a 200 μm-thick 3.6 Mpixel CCD [22], where a readout noise of 0.07 e^- was achieved with 4000 samples per pixel. The single-electron resolution greatly will simplify the calibration since the number of collected electrons per pixel will be counted, providing a direct measurement of the calibration constant.

- DAMIC CCD readout will differ from those at SNOLAB, where CCDs are read out every 8 hours. In DAMIC, the resolution on the pixel charge is dominated by the readout noise, and long exposures are preferable to limit the number of pixels being read out in the experiment's live time. The readout noise is negligible in the skipper CCD, and the leakage current of the device becomes the limiting factor. Thus, continuous readout through four skipper amplifiers will be used to minimize the accumulation of charge from leakage current in a pixel before it is read out.

- A decrease of the radioactive background to a level of $\sim 0.1\mathrm{keV}^{-1}\mathrm{kg}^{-1}\mathrm{day}^{-1}$ will also be necessary. This will require improvements in the design of the detector array and in the handling and packaging of the devices to mitigate surface backgrounds from ^{210}Pb. Also, careful selection of construction materials and procedures and minimizing the exposure of the components to cosmic rays will be implemented to minimize the activation of ^{3}H in the silicon target, which is expected to be the dominant background.

The sensitivity of DAMIC-M to the hidden sector for an integrated exposure of one kg-year is shown in Fig. 4.

DAMIC-M will pioneer the low-mass dark-matter searches with unprecedented sensitivity to DM-electron scattering and hidden-photon DM, by improving by orders of magnitude the sensitivity to the ionization signal from the scattering of dark matter particles with valence electrons. Under these conditions, DAMIC-M will be able to progress furhter in the search for low-energy dark matter particles, including the GeV-scale WIMPS (left panel on the Figure), the hidden-photon, and to probe a large region of parameter space for dark matter particles in the *hidden sectors* (not directly coupling with the ordinary matters) and having masses from 1 MeV/c^2 to 1 GeV/c^2 (right panel on the Figure).

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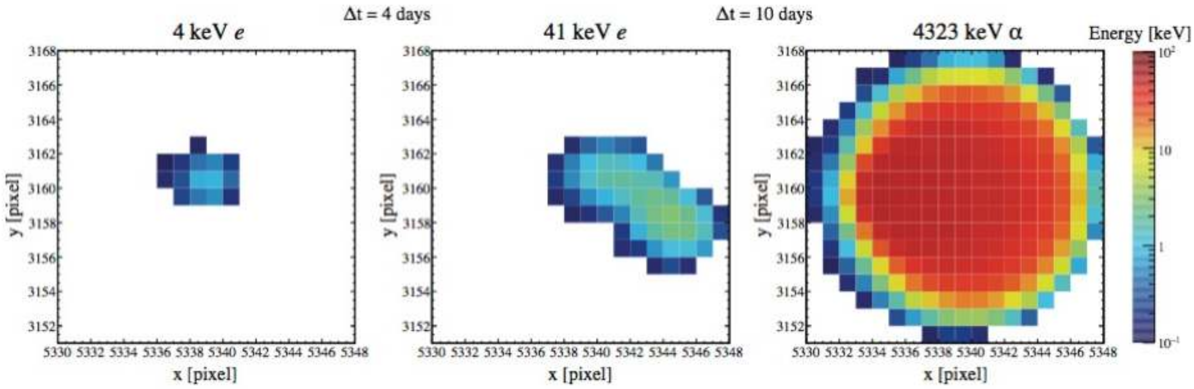

Figure 3: An example of the truly unique capability of DAMIC on background rejections. The three cluster (two electrons and one alpha) detected in the same location but separated in time by several days. The observation is consistent with the decay chain of a single ^{210}Pb nucleus on the CCD surface. A product of the radon decay chain, ^{210}Pb is a major source of surface background in DM experiments caused by material exposure to air.

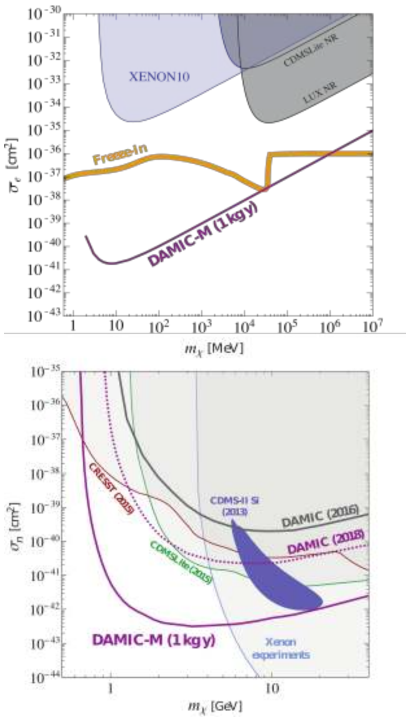

Figure 4: Expected sensitivity of DAMIC-M for DM-electron for a light dark photon mediator (top panel) and WIMP-nucleon spin-independent scattering (bottom panel). Exclusion limits from other dark matter searches are shown for comparison.

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