5 DAMIC: search for dark matter using CCD detectors

J. Liao, B. Kilminster, and P. Robmann

in collaboration with: Fermi National Accelerator Laboratory, University of Chicago, University of Michigan, Universidad Nacional Autónoma de México, Universidad Nacional de Asunción de Paraguay

(DAMIC Collaboration)

DAMIC (Dark Matter in CCDs) is an experiment designed to provide high sensitivity to direct detection of weakly interacting dark matter particles (WIMPs) with mass below 5 GeV. There are a number of theoretical models favoring such low mass WIMPs, which offer an explanation for the coincidence of dark matter (DM) and baryon abundance, and the matter-antimatter densities [1–3].

The main challenge in searching for low mass DM is measuring the low energy deposit of the associated nuclear recoils in the detection material. DAMIC uses CCDs with an electronics noise of σ=7.2 eV corresponding to a 5σ=36 eV threshold, which is the lowest of any current DM detector. CCD detectors are silicon pixel detectors that shift charge from the capacitor of one pixel to the next by generating potential wells until reaching a charge amplifier which converts the charge to voltage (Fig. 5.1). The DAMIC CCD detectors were fabricated by Lawrence Berkeley National Laboratory [4] originally for the Dark Energy Camera (DECam) [5, 6]. DECam CCDs [7] are 30 times thicker (500 - 650 μm) than commercial CCDs, leading to correspondingly higher detection eficiencies. Each CCD has up to 16 million 15 μm x 15 μm pixels and is read out by two amplifiers in parallel. The electronic gain is $\sim$ 2.5 μV/e. The signal is digitized after correlated double sampling and the noise performance improves by reducing the readout speed. The lowest noise, $\sigma <$ 2e$^-$ (R.M.S.) per pixel, was achieved with readout times of 50 μs per pixel [8].

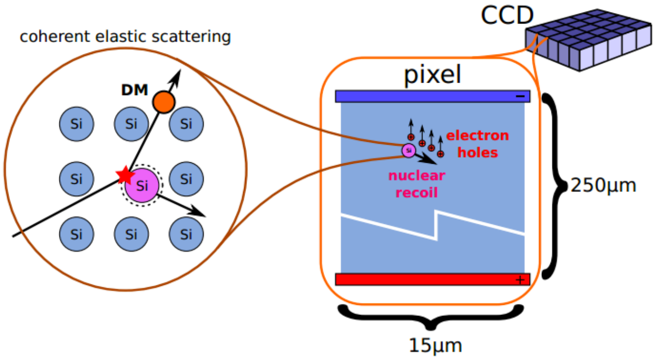

FIG. 5.1 –
DAMIC detection principle: hypothetical dark matter particles scatter coherently off silicon nuclei, producing a nuclear recoil that is recorded as charge on pixels in the CCD.

First results were obtained with a single 0.5 g CCD, installed ≈100 m underground in the NuMI [9] near-detector hall at Fermilab. Data were collected during 11 months in 2011. Standard techniques were used to interpret the results as a cross section limit for spin-independent DM interactions [10], and parameterizations were used allowing the direct comparison with other limits on low mass DM particles. At the time, the DAMIC results constituted the best limits for dark matter mass below 4 GeV.

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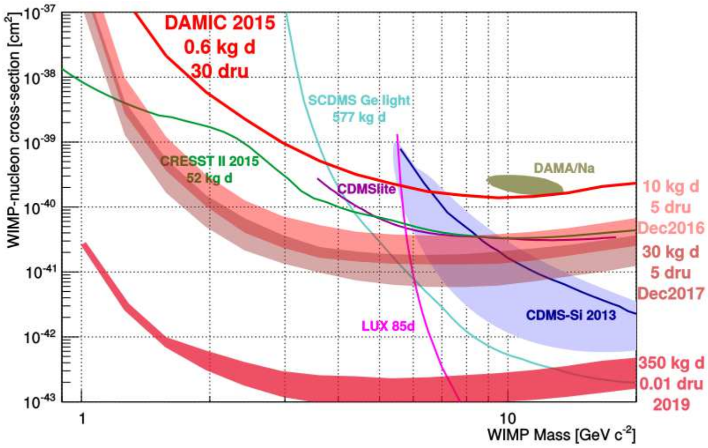

FIG. 5.2 –
The limit of DAMIC 0.3 kg day and DAMIC-100(2016).

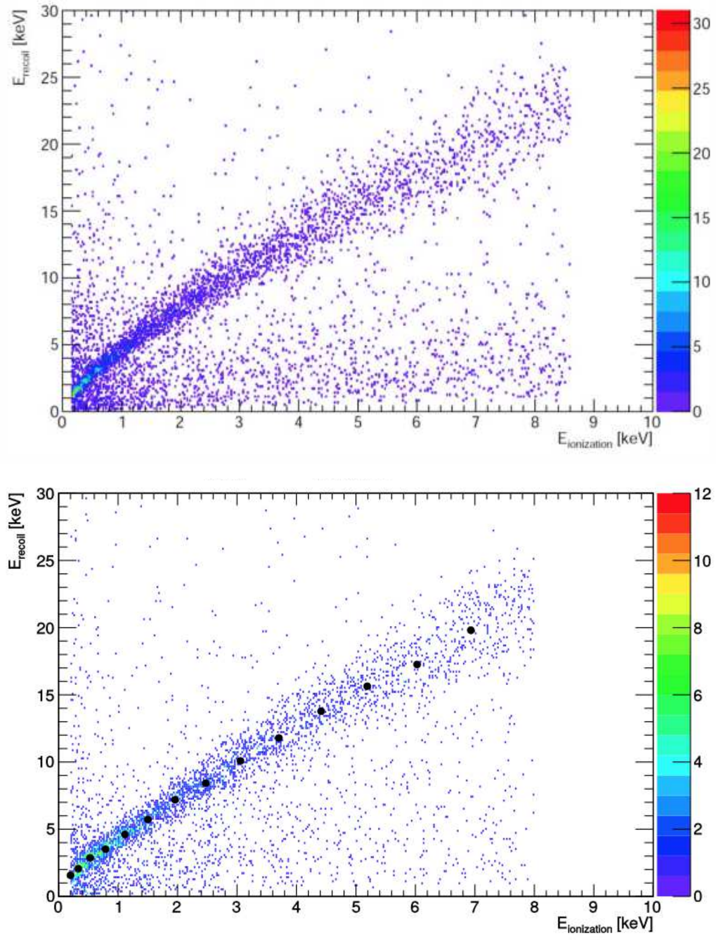

FIG. 5.3 – Distributions of nuclear recoil energy versus ionization energy, from which the quenching factor is determined, for simulation (top) and measurement (bottom). Note a disagreement towards low energy. See next figure too.

5.1 DAMIC-100

The next phase is DAMIC-100, which has begun collecting commissioning data in the summer of 2014. The experiment has been moved underground to SnoLab, which has a 6000 meter water equivalent shielding from cosmic rays, the shielding has been upgraded, and new, thicker detectors have been fabricated. The CCDs, with a total mass of 100 g, are installed inside a copper box cooled to -150°C to reduce dark current. The cold copper also shields the detectors against infrared radiation. A closed cycle helium gas refrigerator is used to maintain the low temperature. The detector is connected through a readout cable to the preamplifiers located outside the lead shield. The detector package is housed in a cylindrical vacuum vessel fabricated with oxygen-free copper, and maintained at 10^{-7} Torr with a turbo molecular pump. Lead and polyethylene shield against γ-rays and neutrons. The detector has been iteratively improved, with a low background lead shield machined at the University of Zurich, and newly designed readout cables provided by the University of Zurich. In 2015, we took 0.6 kg·days of commissioning data using four 5.5-gram CCDs designed for DAMIC-100. The results, in terms of upper limits on the cross-section for spin-independent WIMP - nucleon cross sections, are close to the best results obtained from CRESST II 2015 (Fig. 5.2). Since these DAMIC 2015 results, we have reduced the background from 30 to 5 dru, and we anticipate an order of magnitude improvement in sensitivity by 2016.

5.1.1 Calibration and testing

Energy calibration for DM in the detector is factorized into the ionization energy calibration as determined from direct X-rays and carbon and oxygen fluorescent X-rays from a Fe^{55} source and the signal quenching observed for ionizing nuclear recoils. The quenching factor has been measured in Si for recoil energies above 4 keV [11], showing good agreement with the Lindhard model [12, 13].

We have performed an experiment at the Tandem Van der Graaf of the University of Notre Dame in which monochromatic neutrons are scattered off a silicon target and the scattering angle and neutron time-of-flight are used to determine the nuclear recoil energy. The scattered neutrons are detected with a set of $\sim$20 scintillating bar counters placed at variant angles (from 20 to 70 degree) that correspond to the low recoil energies of interest (1 - 30 keV).

Besides designing and testing the detector for this calibration experiment, our group developed a Geant [14] simulation of the detector setup to confirm the neutron beam flux, to model resonances of neutrons on silicon, and to determine the energy using the timing. The experiment was performed in 2015. The results compared to our simulation are shown in Figure 5.3. The final calibration is compared to the Lindhard

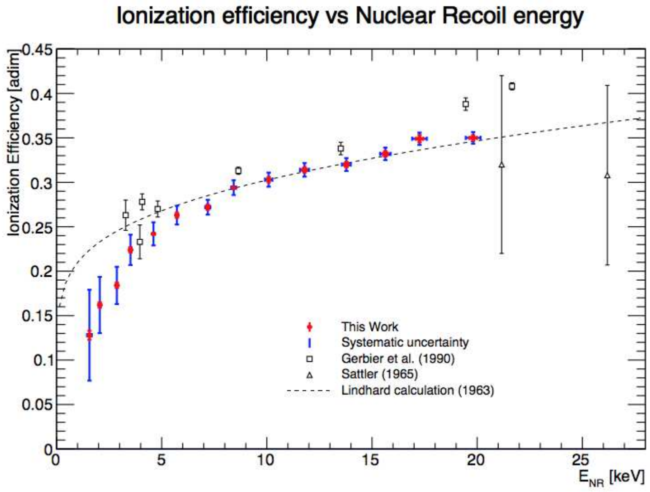

FIG. 5.4 – Results from Antonella data compared to the Lindhard model.

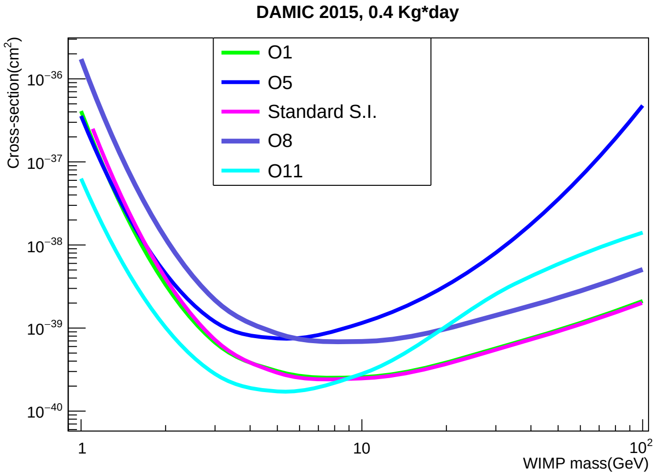

FIG. 5.5 – Limits using 0.38 kg·days of DAMIC 2015 data, comparing various EFT operators with the standard spin-independent interaction.

model and previous measurements in Fig. 5.4. These represent the first measurements of the quenching factor in the 1.5 - 4 keV range, and a deviation from the Lindhard model is observed.

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5.2 Analyzing DAMIC data using EFT

Most models of DM invoke new physics, such as supersymmetry or extra dimensions, associated with electroweak symmetry breaking, where new phenomena can appear at scales of ≥ 100 GeV. However, the momentum transfer in direct detection is much lower, typically a few hundred MeV or less. At this low energy scale, the DM-nucleus scattering in direct detection can be essentially described by a non-relativistic (NR) effective potential with parameters: DM velocity $\beta \equiv v/c \sim 10^{-3}$ and q/Λ, where q is the momentum transfer and Λ some large scale involved, such as the DM mass m_χ, the nucleus mass m_N, or a heavy mediator mass [16]. EFT (Effective Field Theory) provides a general and very efficient way to characterize experimental results with a small set of parameters, such as the mass of the WIMP and the effective coupling constants describing the strength of the contact coupling of the WIMP to the nucleon or nucleus [17–19].

For DM direct detection, there exist 14 "useful" EFT operators with varying powers of v, q and mass scales. We have modeled the expected signals in DAMIC with each of these operators, including detector response and the Lindhard model of energy deposition, and have evaluated the DAMIC 2015 data in terms of these interactions (Fig. 5.5). The $\mathcal{O}1$ operator produces approximately the same results as the standard spin-independent interaction as is expected, and the data is most sensitive to interactions of the $\mathcal{O}11$ operator. The results will be published in a follow-up to our DAMIC 2015 publication this year.

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