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)

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 (Dark Matter in CCDs) aims at the search for WIMPs in the mass region below 5 GeV by detection the feeble ionization signals produced by WIMPs colliding with nuclei inside low noise CCDs. DAMIC uses CCDs with an electronics noise of σ=7.2 eV. This leads 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 (see Fig. 5.1). The DAMIC CCD detectors were fabricated by Lawrence Berkeley National Laboratory [1] originally for the Dark Energy Camera (DECam) [2, 3]. DECam CCDs [4] are good candidates for a DM search since they are 30 times thicker (500 - 650 μm) than commercial CCDs, leading to proportionally higher interaction rates. Each CCD has up to 16 million 15 μm x 15 μm pixels and is read 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 [5].

First results were obtained with a single 0.5 g CCD, installed ≈100 m underground in the NuMI [6] 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 [7], 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.

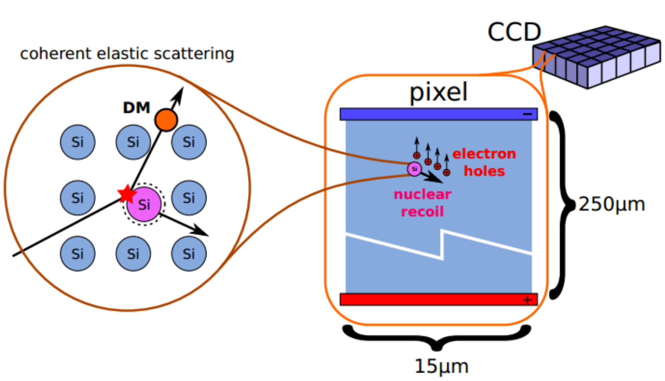

FIG. 5.1 – DAMIC detection principle: hypothetical dark matter particles scatter coherently off silicon nuclei, producing a nuclear recoil that is recorded as charge on pixels in the CCD.

[1] S.E. Holland *et al.*, IEEE Trans. Electron Dev., **50** 225 (2003).

[2] B. Flaugher, *Ground-based and Airborne Instrumentation for Astronomy*, Ian S. McLean editor; Iye, Masanori, Proceedings of the SPIE, Volume 6269, (2006).

[3] Dark Energy Survey Collaboration, astro-ph/0510346.

[4] J. Estrada and R. Schmidt, *Scientific Detectors for Astronomy 2005*, J.E. Beletic, J.W. Beletic and P. Amico editors, Springer (2006).

[5] Estrada *et al.*, Proceedings of SPIE 2010.

[6] http://www-numi.fnal.gov/PublicInfo/forscientists.html.

[7] J. Barreto *et al.* (DAMIC Collaboration), Phys. Lett. B **711**, 264 (2012).

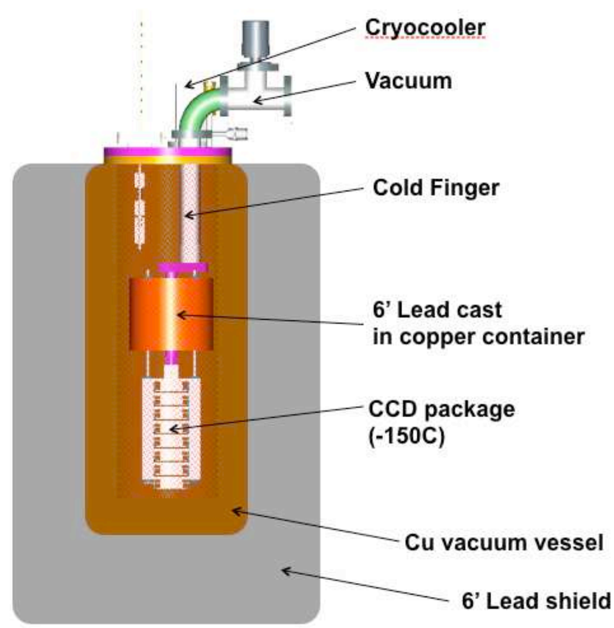

FIG. 5.2 – Schematic of the DAMIC-100 vacuum vessel with copper and lead shielding.

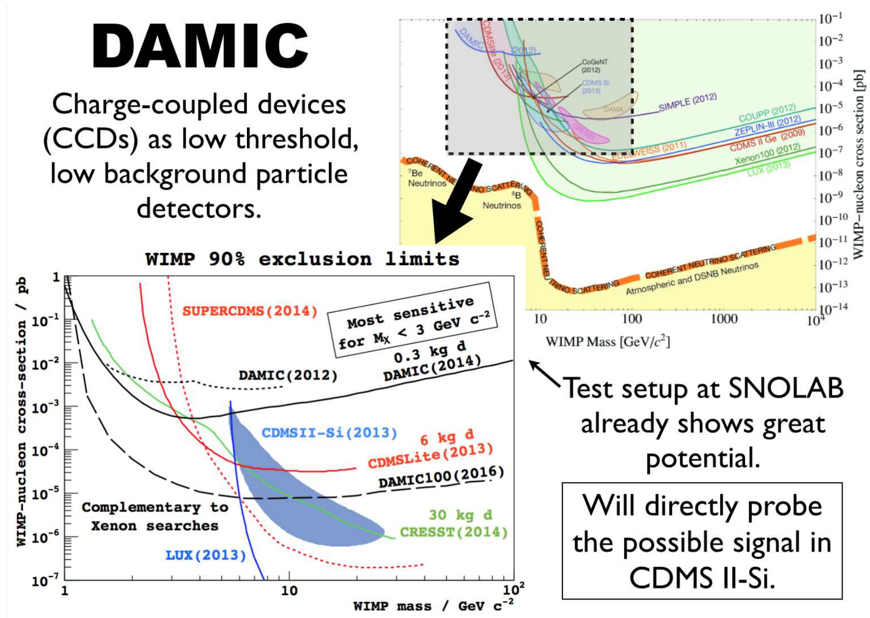

FIG. 5.3 – Result of DAMIC 0.3 kg · days and the expected sensitivity of DAMIC-100 (2016).

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. A schematic of the new setup is shown in Fig. 5.2. 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 in 2014, with a low background lead shield machined at the University of Zurich, and newly designed readout cables provided by the University of Zurich. Using 0.3 kg·day of DAMIC data taken from three CCDs in 2014, DAMIC has obtained a preliminary limit which constitutes the best constraint on DM particles with mass below 4 GeV, Fig. 5.3. Expectations with the full 100 grams of CCDs, and some additional reductions of backgrounds are also shown as DAMIC 100.

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 [1], showing good agreement with the Lindhard model [2, 3].

We have helped design and test 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 19 scintillating bar counters placed at angles between 20 and 70 degrees (see Fig. 5.4) corresponding to the low recoil energies of interest between 1 and 30 keV.

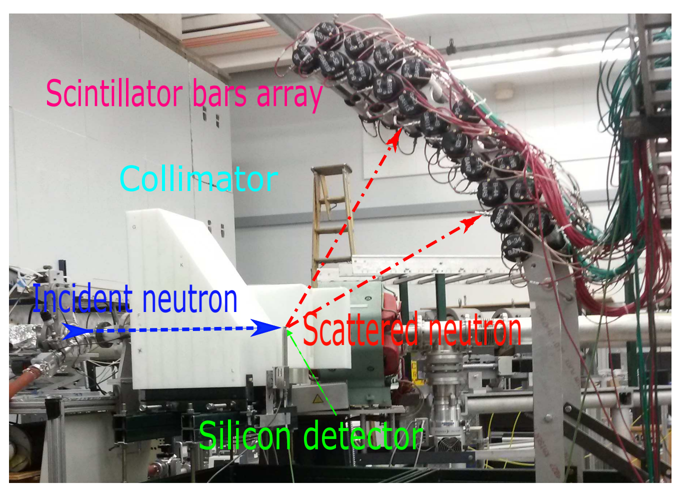

FIG. 5.4 – The setup of the quenching factor measurements at Notre Dame.

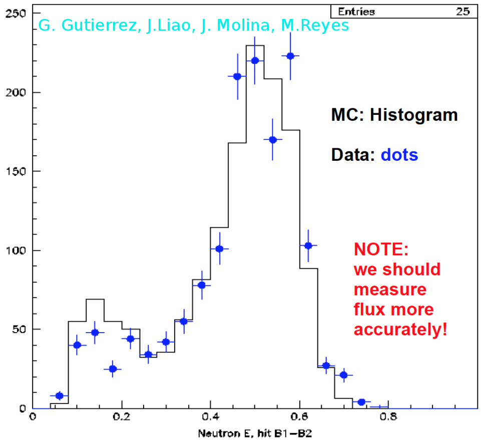

FIG. 5.5 – Neutron flux comparison between data and Geant4 simulation for 2013 beam test.

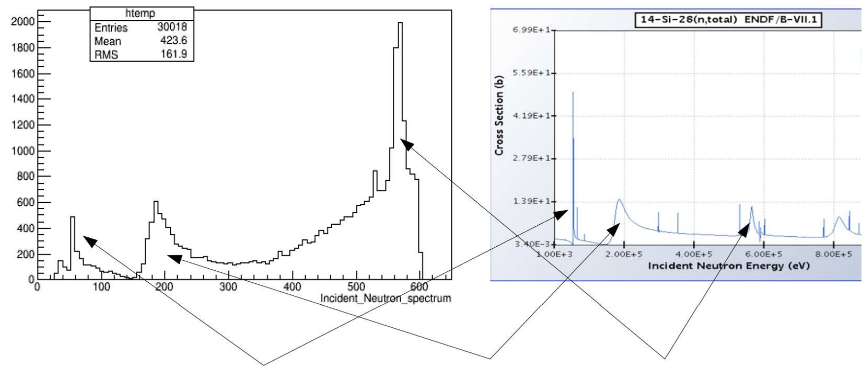

FIG. 5.6 – Neutron resonances shown in Geant4 simulation (left) and NNDC database (right) [4]. Note that the left plot is the convolution of our incident neutron flux (Fig. 5.5) and the neutron silicon cross-section (right plot).

We also developed a Geant simulation of the setup to confirm the neutron beam flux (Fig. 5.5), and to determine the resonance structure for the cross-section of ~100 keV incident neutrons on silicon, as shown in Fig. 5.6. With this model we were able to solve some unexpected discrepancies in the data. Based on the beam test of 2013 and the Geant4 simulation for the 2015 beam test, we expect to produce uncertainties greatly improved compared to previous measurements as in Fig. 5.7.

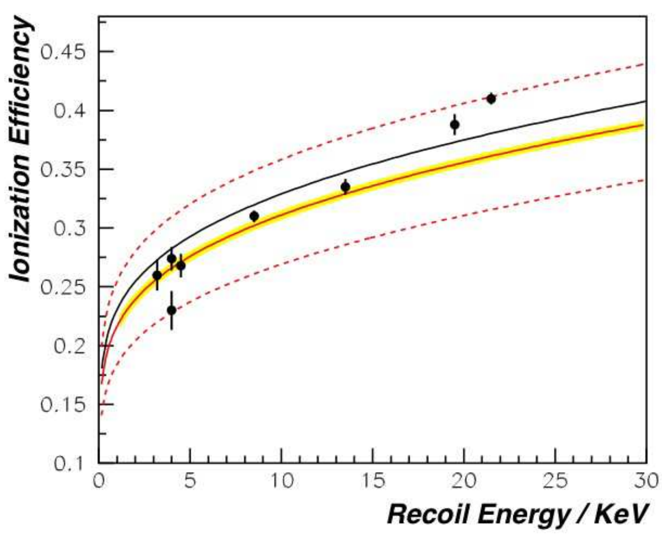

FIG. 5.7 – Silicon quenching factor versus recoil energy. Black dots with error bars: data measured in 2013. Solid red line: single parameter χ^2 fit based on the Lindhard model [2]. Dashed red lines: 1 σ error band of the fit. Yellow band: 1 σ error band expected for 2015, when the recoil energy will cover the region 1 - 30 keV.

5.1.2 CCD CTI study

The charge deposited in a CCD pixel is shifted across thousands of pixels by row and column to two corners of the CCD and read out by amplifiers. The ratio of lost to total charge is called Charge Transfer Inefficiency (CTI) [5]. We determine the CTI with 5.9 keV X-rays from Fe-55, which produces about 1600 e^-. We found the CTI of DAMIC CCDs to be $3.0E^{-7}$, as compared to a typical CTI from 2001 of $\sim 1.0E^{-6}$ [5].

5.1.3 Monitoring and data analysis

To reach the projected sensitivity of DAMIC-100 we need to determine the noise, dark current, energy response, backgrounds, map of dead and hot pixels for each CCD, with optical light and X-ray sources. We have developed a monitoring system of the data quality which allows to correlate temperature, voltage, and pressure inside the detector cryostat, with dark current, RMS detector noise and X-ray radio-impurities of each individual CCD for each of the thousands of exposures expected during one year of data taking. There is a web page interface to visualize the information in real time, and store everything for off-line data analysis when the signal efficiency and background rejection will be optimized.

5.1.4 EFT analysis of DAMIC data

The momentum transfer q in direct detection is typically a few hundred MeV/c or less so DM-nucleus scattering can be described by a non-relativistic effective potential depending on DM velocity $v \sim 10^{-3}c$ and q/Λ, where Λ is some scale involved, such as the DM mass, the nuclear mass or a heavy mediator mass [6]. Detected energy is affected by quenching, as discussed above, and by the detector response. The quenching factor was calculated using the Lindhard model [2].

EFT (Effective Field Theory) provides a general scheme to characterize the experimental results with a small set of parameters, such as the WIMP mass and the effective coupling constants [7–9]. There exist 14 "useful" EFT operators with varying powers of v, q and mass scales and we have determined the event rate versus detected energy for each of them. Two examples are shown in Fig. 5.8. This will allow us to determine limits on cross-section versus DM mass for the various operators. Thanks to the low energy threshold of DAMIC certain EFT operators will be probed for the first time.

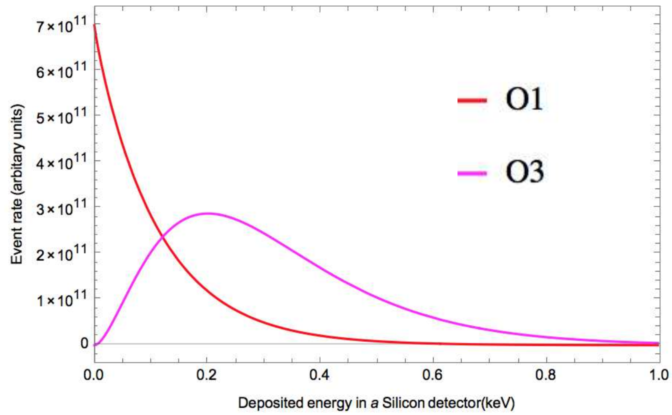

FIG. 5.8 – Comparison of the distributions of deposited energy for the $\mathcal{O}1$ and the $\mathcal{O}3$ operator, assuming a 3 GeV incident WIMP. The DAMIC energy threshold is 0.04 keV.

[1] J.D. Lewin and P.F. Smith, Astropart. Phys. 6, 87 (1996).

[2] J. Lindhard, V. Nielsen, M. Scharff, and P.V. Thomsen, Mat. Fys. Medd. Dan. Selsk **33**, 10 (1963).

[3] H. Chagani *et al.*, JINST 3 (2008) P06003.

[4] http://www.nndc.bnl.gov/sigma/index.jsp .

[5] J. R. Janesick, Scientific Charge-Coupled Devices (SPIE Press, Bellingham, WA), 101 (2001).

[6] J. Fan, M. Reece and L.-T. Wang, JCAP 11 (2010) 042.

[7] B. A. Dobrescu and I. Mocioiu, JHEP 0611, 005 (2006).

[8] Nikhil Anand *et al.*, Phys. Rev. C 89. 065501(2014).

[9] A. Liam Fitzpatrick *et al.*, JCAP (2013) 004.