5 Searching for Dark Matter and Neutrinos with CCD Detectors

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(DAMIC Collaboration)

Using thick, fully-depleted, low-noise CCDs, we are able to search for low-energy nuclear recoils which produce a small number of ionization electrons. The DAMIC (Dark Matter in CCDs) experiment uses this technology to provide high sensitivity for directly detecting weakly interacting dark matter (DM) particles (WIMPs) with mass below 5 GeV. The CONNIE (Coherent Neutrino Nucleus Interaction) experiment uses the same type of detector to search for the process of neutrinos scattering coherently off nuclei, a process which is predicted by the standard model, but has currently never been experimentally observed.

5.1 DAMIC

DAMIC searches for low-mass DM which is motivated by the similar abundances of baryons and DM, and the disparity of the matter-antimatter densities [1–3]. First results for DAMIC were obtained from data collected in 2011 [4]. At that time, these DAMIC results constituted the best limits for DM mass below 4 GeV, but have been superseded since. 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 [5] originally for the Dark Energy Camera (DECam) [6, 7]. DECam CCDs [8] are 30 times thicker (500 - 650 µm) than commercial CCDs, leading to correspondingly higher detection efficiencies. 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 [9].

In 2015, the upgraded DAMIC experiment collected data in SNOLab, which boasts 6000 meter-water-equivalent of overburden that provides shielding from backgrounds induced by cosmic ray muons. This new DAMIC experiment took 0.6 kg·days of data using four 5.5-gram CCDs, each 5 times the mass of those used in the previous experiment. The CCDs 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. Lead and polyethylene shield against γ-rays and neutrons. 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. Results of this data run were published in 2016 [10], showing that DAMIC is competitive with other low-mass DM searches.

Given the low energy threshold and excellent energy resolution to resolve low energy signals, DAMIC has discovered a niche for searching for different types of DM candidates. One such candidate is known as the hidden photon [11]. Like an ordinary photon, a hidden photon can be absorbed by an electron in a detector material. However, the hidden photon would have a mass and be non-relativistic, allowing it to clump in DM halos in the manner of weakly interacting massive particles. One interesting difference of hidden photons with respect to

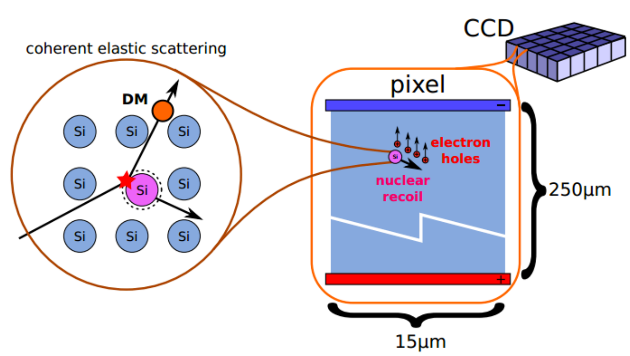

Fig. 5.1 – DAMIC detection principle: hypothetical DM particles scatter coherently off silicon nuclei, producing a nuclear recoil that is recorded as charge on pixels in the CCD. A prototype setup with a CCD thickness of 250 µm is shown.

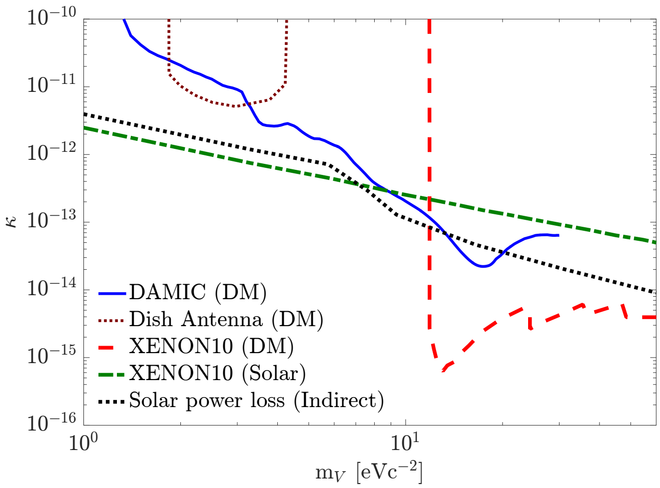

FIG. 5.2 – DAMIC exclusion plot (90% C.L.) for the hidden-photon kinetic mixing κ as a function of the hidden-photon mass m_V.

WIMPs is that the interaction does not depend on the velocity distribution of the particles. Using 6.25 days of data acquired in 2016, DAMIC was able to set the best direct limits on hidden photons within the mass range of 3 - 12 eV/c^2 as in Fig. 5.2 [12]. DAMIC is currently collecting data with an even-lower background rate, and will publish these new results in the next year.

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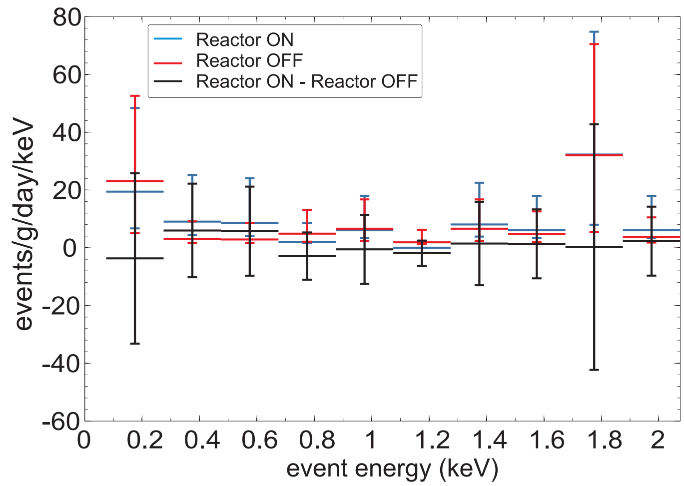

FIG. 5.3 – A comparison of CONNIE data, collected with the reactor on and off, demonstrates that there are no additional backgrounds present during reactor operation.

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5.2 CONNIE

Although coherent neutrino-nucleus scattering (CNNS) is the neutrino process with the largest standard-model cross-section and already predicted in 1974 [13] it has not yet been observed yet due to the difficulty in its detection. The process is an important input to supernova simulations, and a deviation from the expectation could indicate new physics [14]. Neutrino-nucleus scattering would be observed by neutrinos in the MeV-range scattering off nuclei and providing them with keV-range energy recoils, resulting in an ionization signal of less than 100 eV. The CCDs used in the DAMIC experiment are well-suited for identifying this process due to their low energy threshold, and we have designed a new experiment using many of the same technologies as in DAMIC to search for CNNS.

An ongoing experimental effort called CONNIE, which consists of an array of CCD detectors located 30 m outside a 3.8 GW_{th} nuclear reactor in Brazil, is currently collecting data in order to measure the coherent neutron scattering process. The detection of the coherent scattering of neutrinos is done by comparing data collected with the reactor on (RON) and the reactor off (ROFF). The radiation background is the ultimate limit for the sensitivity of the experiment. The backgrounds include cosmic-ray muons, which typically deposit 80 keV of minimum ionizing energy in a 250 µm-thick CCD. They are easily identified as straight tracks and removed from data providing they do not produce secondary particles by interacting with the shielding. A comparison of ROFF and RON data show that there is no significant extra background component from the reactor (Fig. 5.3). The current radiation background observed in the engineering array is ∼3000 events/kg/day/keV (d.r.u.) at 0.5 keV. Preliminary results from an engineering run in 2015 using two CCDs, with an active mass of 4 grams of silicon and 19 days of RON and 15 days of ROFF data, indicate that backgrounds from fission products of the nuclear reactor are manageable, and provide first estimates of the sensitivity to coherent neutrino scattering using this detection technology of two orders of magnitude above standard model predictions [15]. These results indicate that the CONNIE experiment can feasibly yield a first observation of the CNNS process.

In July of 2016, the CONNIE experiment was upgraded to contain fourteen 6-gram CCDs, yielding a total mass of 83.6 grams. The CCDs have less defects than in the previous run, and some charge-injection problems that led to higher electronics noise during readout were solved. The noise is now verified to be 50% lower, allowing the experimental energy threshold to decrease by 50%. A further improvement has been the reduction of radio-impurities in the CCD packaging. The combined improvements in terms of mass, energy threshold, and lower background rates mean that the signal yield expected by the upgraded CONNIE experiment is 130 times greater. This greatly improves the expected signal significance, such that evidence for CNNS could be achieved within two years.

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5.2.1 Calibration and testing

Of vital importance to both DAMIC and CONNIE is a correct energy calibration of nuclear recoils. This calibration for DM or neutrinos in the detector is factorized into the ionization energy calibration as determined from direct and fluorescent X-rays, and the signal quenching observed for ionizing nuclear recoils. The quenching factor has been measured in Si for recoil energies above 4 keV [16], showing good agreement with the Lindhard model [17, 18].

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 detector target. The scattering angle and neutron time-of-flight are used to determine the nuclear recoil energy, and the ionization energy is measured in the silicon detector. The scattered neutrons are detected with a set of ∼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).

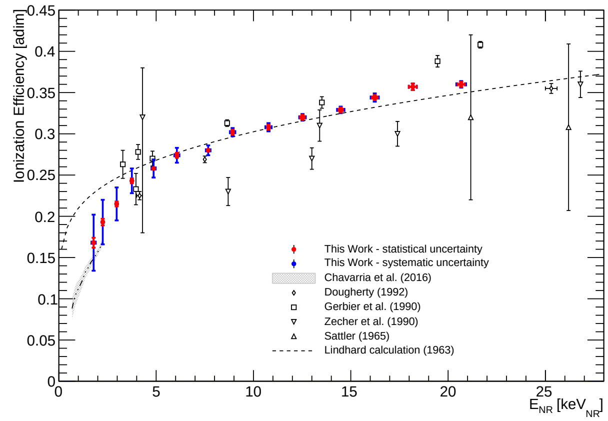

FIG. 5.4 – Results from Antonella data compared to the Lindhard model [17, 18] and testing the consistency with [21].

Besides designing and testing the detector for this calibration experiment, our group developed a GEANT [19] 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, and the results have been submitted for publication in 2017 [20]. Some of our collaborators have measured the quenching factor in the range from 680 eV to 2.3 keV using an independent technique [21], and have observed a deviation from the Lindhard model. Our result measures the quenching factor in the 1.8 to 20 keV range, showing agreement with this new calibration in the lower energy range, but also showing consistency with previous measurements in the upper energy range. The implication is that experiments using the Lindhard model at low energies could be overestimating the energy deposited in their detector, thereby overestimating their sensitivity to nuclear recoils from dark matter or neutrino scattering.

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