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Paving the path to Dark Matter detection

Adoquinando el camino para la detección de materia oscura

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ABSTRACT

In order to detect Dark Matter (DM), scientists in the Dark Matter In CCDs (DAMIC) Collaboration have set an experimental array of Charge-Coupled Devices (CCDs) in a nickel mine underground, and have developed all analysis tools to discern any known trace of conventional matter from what they expect to find in case a DM particle crosses the CCDs. In order to calibrate the signals from the CCDs, they have also designed experiments to quantify neutron-silicon interactions, assuming that neutrons can mimic DM interactions in the CCDs. Here we present preliminary results from the analysis of data obtained in these experiments.

RESUMEN

Para poder detectar materia oscura (DM, por sus siglas en inglés), científicos de la Colaboración DAMIC (*Dark Matter In CCDs*) han puesto un arreglo experimental de dispositivos de carga acoplada (CCDs, por sus siglas en inglés) en una mina subterránea de niquel, y han desarrollado todas las herramientas necesarias para discernir entre las trazas que pudieran dejar en ellos partículas de materia convencional, para comparar con las que podrían ser encontradas si una partícula de DM atravesara al arreglo de CCDs. Con el objeto de calibrar las señales de los CCDs, también han desarrollado experimentos para cuantificar las interacciones neutrón-silicio, suponiendo que los neutrones pueden imitar las interacciones de DM en los CCDs. Aquí presentamos resultados preliminares del análisis efectuado.

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The DAMIC experiment

At two kilometers underground, the Vale InCo's Creighton nickel mine in Ontario, Canada, hosts the Sudbury Neutrino Observatory Laboratory (SNOLAB). There, after riding an elevator at 50 km/h, walking another 1.5 km, and bathing and changing clothes to prevent dust to come into the laboratory, physicists, astronomers and engineers who have already been certified as miners, can visit the charged coupled devices (CCDs) array constructed by the Dark Matter In CCDs (DAMIC) Collaboration to study *Dark Matter* (DM). In fact, DAMIC is the acronym for Dark Matter in CCDs, (Tiffenberg, 2013) and it is one of the international collaborations which has deployed experiments in underground mines to conduct these studies. Another example is the Large Underground Xenon Collaboration (LUX) (Akerib *et al.*, 2013), which uses a 1.4 km underground gold mine in South Dakota, United States, to also study DM.

According to scientists, in order to understand galaxies' rotation, large structure formation, and gravitational lensing, there must exist about 5.5 times more DM than ordinary baryonic matter. Furthermore, models predict that the DM local density should be around 0.3 GeV/cm^3, with velocities in the Earth's reference frame of hundreds of km/s. There exist different candidates to DM particles, and one of these is the so called *weakly interacting massive particle* (WIMP). DAMIC is an experiment dedicated to study WIMP-nucleon spin independent interactions, where the nucleons are those of silicon conforming a CCD, which are low threshold and low background particle

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detectors. The scientific grade CCDs used by DAMIC are three 3 cm $\times$ 6 cm silicon wafers, two of them 500 microns thick and the other one 675 microns (2.2 g and 2.5 g, respectively), similar to those that were originally designed to construct the Dark Energy Survey experiment (DES) (Salles, 2013). DES studies the origin of the universe since 2012. In the near future, DAMIC will be upgraded to DAMIC 100, which will consist of 24 CCDs, 16 Mpixel, 675 μm CCDs, each 5.5 g of weight.

The experimental setup consists of a copper box where the CCDs are assembled, which is immersed in a vacuum vessel (VV) where the temperature is kept at about -131 °C (figure 1). Since even dust includes radioactive particles, this array has to be very well blinded from ambient radiation. Therefore, the VV is protected by a 22 cm thick lead shield to protect from gamma rays, and a 46 cm thick poliethylene shield to protect from neutrons from radioactive decays.

The way DAMIC CCDs are used to detect particles is the following. When a particle hits the Si nucleus, part of the recoil nucleus' energy, E_R, is used to produce ionization. This ionization energy, E_I, produces a charge Q deposit in the Si net, which is then collected and read bin by bin in a timed sequence. A schematic of the CCD operation is given in figure 2.

In order to pick out DM signals from those of conventional matter, DAMIC has undergone detailed background studies from all possible sources, including for example, that coming from the epoxy used in the CCD package assembly. Also, this Collaboration has dedicated great efforts to understand the E_I to Q conversion, and the E_R to E_I ionization efficiency, sometimes referred to as *quenching factor*. Leonel A. Villanueva and Marco A. Reyes, a student and a professor of the Department of Physics of the Sciences and Engineering Division of the University of Guanajuato, have participated in these efforts, which we shall describe below.

Charge and time characterization of phototube EMI-9954KB with a 0.2 photoelectron threshold

Due to the searches of very low mass WIMPs as DM candidates, conducted by DAMIC or other experiments, measurement of nuclear recoil quenching factors for energies of about 1 KeVs - 10 KeVs has become very important in the past few years. DAMIC Collaboration is setting up a neutron scattering experiment on a silicon target to measure nuclear recoil quenching factor. Scintillator bars and phototubes (PMTs) are used to measure angular distribution of the scattered neutrons. Description of this experiment is given in the following section.

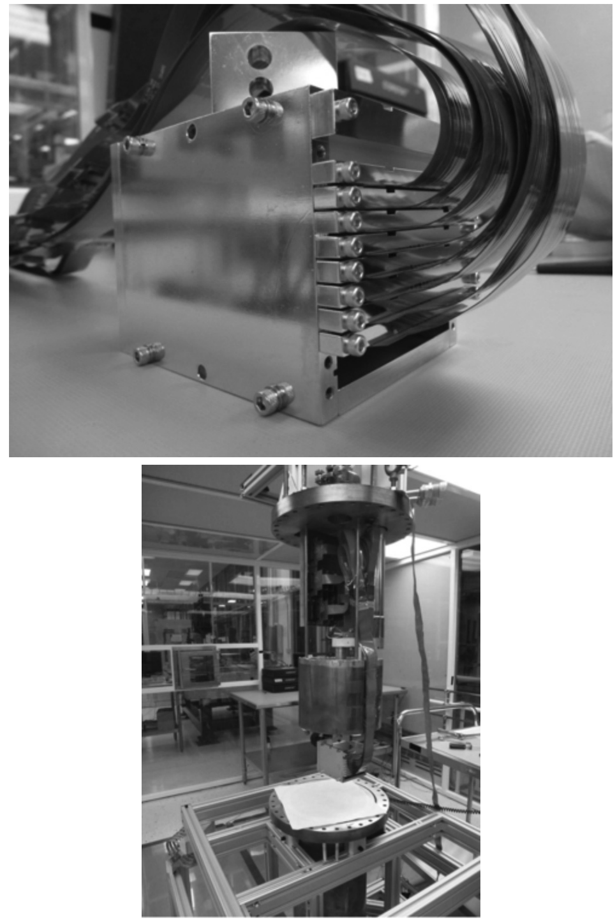

Figure 1. The DAMIC CCD array (top) and the vacuum vessel with vacuum and temperature controlers (bottom).
Source: Author's own elaboration.

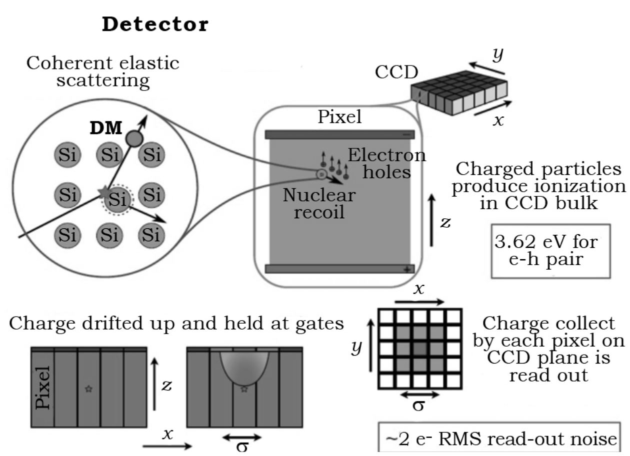

Figure 2. The DAMIC CCD operation.
Source: Author's own elaboration.

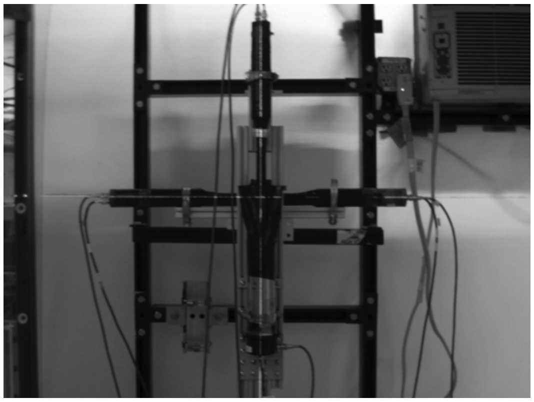

Figure 3. The two scintillator bar experimental setup at the Fermilab Test Beam Facility. Laser light is used to align the array with the proton beam direction.
Source: Author's own elaboration.

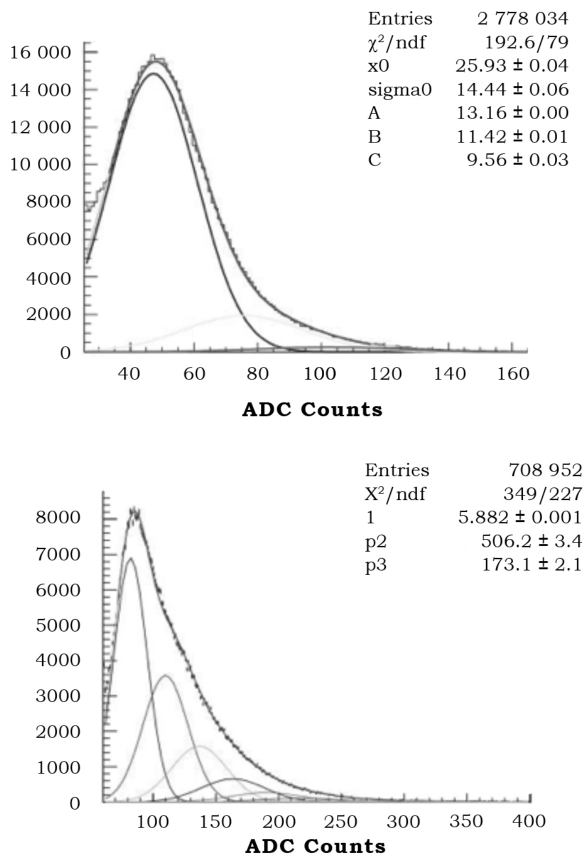

Figure 4. Top panel: Fit to the one *p.e.* ADC distribution using a tiny hole: the histogram shows the data, the first gaussian curve from shows the one *p.e.* distribution, and the second and third gaussian curves from the left show the two and three *p.e.* distributions. The on top of the histogram bars is the sum of these distributions. Bottom panel: The ADC distribution and the several *p.e.* fits for a mask with two holes of 1.19 mm of radius.
Source: Author's own elaboration.

In such experiment, to increase the neutron detection efficiency, the phototubes are operated with a very low threshold, of the order of 0.2 photoelectrons (*p.e.*'s). A group of scientists from DAMIC carried out an experiment at the Fermilab Test Beam Facility (FTBF) to characterize the charge and time resolution behavior of the PMTs that would be used in the neutron scattering experiment.

For this PMT characterization experiment, the experimental setup consisted of two crossed Eljen EJ-200 scintillator bars, with two PMTs attached at the ends of each bar (figure 3). One bar had two FEU-115M PMTs, and the other had one FEU-115M PMT and one EMI-9954KB PMT, which is of the type of PMT to be used by the neutron scattering experiment. The three FEU-115M PMTs were used as a trigger, and the response of the EMI-9954KB PMT to low light intensity was studied. The light intensity was controlled by using a series of black paper masks with very small holes of calibrated sizes.

For this experiment, the FTBF provided a beam of 120 GeV protons, which was aligned to cross the center of the scintillator bars array. These protons produced ionization in the scintillator bars which then emit light which is collected by the PMTs, and converted to an electronic signal. The charge distributions shown here correspond to paper masks with one tiny hole in the paper mask, of radius 0.035 mm in radius (top panel in figure 4), and two small holes of radius 1.19 mm (bottom panel of figure 4).

The analog-to-digital converter (ADC) signal distributions from the EMI PMT were accurately fit by a Poisson distribution with the amplitudes determined by a Landau modulation. This allowed us to fit all different ADC distributions of different paper masks with only three parameters. The ADC distributions then were fit with the function

$$f(x)=\sum_{n=1}^{N} p_n\, G_n(x) \tag{1}$$

where $G_n(x)$ are Gaussian functions. For $n = 1$, single electron response distribution (SER), the Gaussian is truncated at the pedestal, and is given by (Dossi, Ianni, Ranucci & Smirnov, 2000)

$$G_1(x) = \frac{1}{\sqrt{2\pi}\sigma_0 g_N}\ \exp\left[-0.5\left(\frac{x-(x_0+x_p)}{\sigma_0}\right)^2\right], \tag{2}$$

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with $g_N = 1/2\left[1 + erf\left(x_0/\sqrt{2}\sigma_0\right)\right]$, and where x_p is the pedestal position, and x_0 and σ_0 are the first Gaussian mean (measured from this pedestal) and width. This SER corresponds to the one *p.e.* charge distribution. For $n \geq 2$, the mean position and width of the Gaussians are given by

$$x_n = nx_1, \sigma_n = \sqrt{n}\sigma_1, \tag{3}$$

where

$$x_1 = x_0 + \frac{1}{\sqrt{2\pi}g_N} \exp\left[-0.5\left(\frac{x_0}{\sigma_0}\right)^2\right], \sigma_1{}^2 = \sigma_0{}^2 + x_1(x_0 - x_1).$$

The top panel of figure 4 shows the fit to the ADC distribution in the case of a tiny hole mask, the histogram shows the data, the first gaussian curve from the left shows the one *p.e.* distribution, and the second and third gaussian curves from de left show the two and three *p.e.* distributions. The curve on top of the histogram bars is the sum of these distributions. The bottom panel of figure 4 shows the ADC distribution and the several *p.e.* fits for a mask with two holes of 1.19 mm of radius.

The time resolution was also studied as a function of the number of photoelectrons, and found to improve with the number of *p.e.*s in the ADC distribution. The results of these measurements will be presented in the degree dissertation of Leonel Villanueva (2015) but we can assert that the EMI-9954KB PMTs satisfy the time resolution required for the neutron scattering experiment described below, and that we were able to fully understand their ADC distributions.

A neutron scattering experiment to determine the Si ionization efficiency

When an energetic particle —perhaps a DM particle— interacts with the nucleus of an atom, the nucleus can recoil. Some fraction of the energy transferred to the recoiling nucleus E_R, disturbs electrons in adjacent atoms, producing free electric charge. This fraction is called ionization efficiency. The bigger this number, the larger the signal in the detector and the easier it is to detect nuclear recoils.

Ionization efficiency measurements at low energies are important to calibrate the energy measurement of the silicon detectors used in DM direct detection experiments, like DAMIC or CDMS (Ahmed *et al.*, 2011). The calibration will also help experiments trying to observe coherent neutrino scattering, such as Coherent neutrino-nucleus interaction experiment (CONNIE) (Fernández *et al.*, 2014) which is at a nuclear power plant in Angra dos Reis, Brazil.

At low energies, the current best measurements of the ionization efficiency in silicon have considerable uncertainty (Gerbier *et al.*, 1990). However, since the scientific CCDs used by DAMIC are able to detect a few electronvolts of ionization energy, these detectors can detect low energy nuclear recoils where the ionization efficiency has never been measured. Hence, a group of scientist from the DAMIC Collaboration decided to perform a ionization efficiency measurement, aimed to measuring low recoil energies, in the range of 1 KeV to 30 KeV.

For this experiment, the test beam was located at the Institute for Structure and Nuclear Astrophysics at the University of Notre Dame, where protons from the Tandem Van de Graaff accelerator collide in a lithium target to provide a 30 KeV to 600 KeV neutron beam. The neutrons scatter off an X-ray silicon detector and are measured by an array of plastic scintillators and PMTs.

The full apparatus will consist of 21 scintillator bars plus PMTs, in a circular array around the silicon target, as shown in the top panel of figure 5. The scientific team has called this apparatus the Antonella array, and it will run for two weeks in February 2015. However, a preliminary, proof-of-concept run of seven hours using only two scintillator bars has already been performed in March 2014.

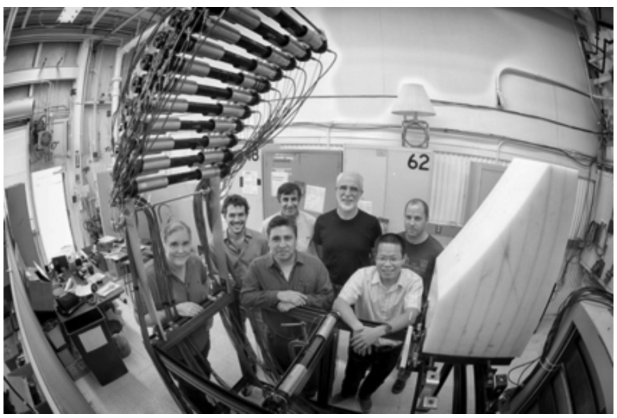
In this preliminary run, a total of 69 scattering neutron events were collected and used to obtain a preliminary measurement of the silicon ionization efficiency. We used a templates analysis to compare the data with Geant4 simulations, and the theoretical model developed by Lindhard, Nielsen, Scharff & Thomsen (1963). In that model, the ionization efficiency is predicted to be:

$$Q = \frac{\kappa\, g(\varepsilon)}{1 + \kappa g(\varepsilon)} \tag{4}$$

where $g(\varepsilon) = 3\varepsilon^{0.15} + 0.7\varepsilon^{0.6} + \varepsilon$, $\varepsilon = 11.5\ E_R Z^{-7/3}$, $\kappa = 0.133\ Z^{2/3}/\sqrt{A}$, and for silicon, $Z = 14$ and $A = 28$.

The measurement produced the preliminary result shown by the red solid line in the plot in the bottom panel of figure 5. In the analysis, events were divided into six data bins, which were then compared to Geant4 events selected with the same analysis cuts as the data. In the fits, κ was left as a parameter for the data fit. The red line shows the model Q for the fit with best χ^2. The dotted red bands represent the one sigma error bands of the fit. The dots come from the best experimental measurement, by Gerbier *et al.* (1990) and the black line represents their fit to that data.

The team will soon run for two weeks, with a full setup of 21 scintillator bars. Calculations and simulations predict a collection of about 1000 neutron events. With these statistics the error bars will be reduced from the red dashed lines to the yellow band shown in the plot.



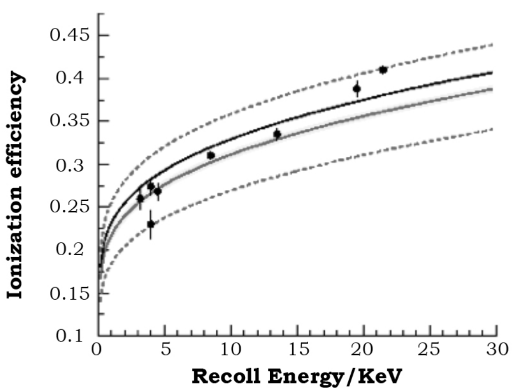


Figure 5. Top panel: The full Antonella array to be used by DAMIC to measure N-Si interactions, and part of the scientific group involved in the construction and physics analysis. Bottom panel: The ionization efficiency for silicon is plotted as a function of nuclear recoil energy, from preliminary Antonella data with two scintillator bars. The black line and dots with error bars show the best measurements to date. The solid red line shows our fit to preliminary new data, from 2 KeV to 20 KeV. The dashed lines display the 1 sigma error bands of a single parameter χ^2 fit to the model (developed by Lindhard *et al*., 1963). In our next run we expect these errors, for points every 1 KeV, to shrink to the yellow band. The recoil energy range will cover from 1 KeV to 30 KeV.
Source: Author's own elaboration.

DISCUSSION

We have shown here that the EMI phototubes satisfy the time resolution and ADC performance needed to perform a high resolution neutron-nucleon scattering experiment, using a proton beam from the FTBF. We have also shown that a preliminary measurement of the silicon ionization efficiency using a reduced model of the Antonella array designed by the DAMIC Collaboration, is compatible with the best measurement up to day, and that the final measurement with the full array should greatly reduce the ionization efficiency uncertainty.

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