Prospects for a direct dark matter search using high resistivity CCD detectors

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The possibility of using CCD detectors in a low threshold direct detection dark matter search experiment is discussed. We present the main features of the DECam detectors that make them a good alternative for such an experiment, namely their low noise and their large depleted volume. The performance of the DECam CCDs for the detection of nuclear recoils is discussed, and a measurement of the ionization efficiency for these events is presented. Finally the plans and expected reach for the CCD Experiment at Low Background (CELB) are discussed.

I. INTRODUCTION

The current results from observations in astronomy and astrophysics strongly favor the concordance model for cosmology \cite{1}, where $\sim$25\% of the total energy in the universe is in the form of dark matter. Direct detection of dark matter is a possible interpretation for the annual modulation signal in the DAMA/LIBRA and DAMA/NaI experiments described in \cite{2} and references therein, but has not yet been confirmed by other. The only confirmed evidence for dark matter comes from its gravitational effects in space. The imminent turn-on of the Large Hadron Collider (LHC) high energy physics collider could change this situation dramatically by confirming the existence of new a particle having the properties needed to be a good dark matter candidate. Such a discovery, however, will not tell us if the new particle is indeed the dark matter unless we directly detect it in the Galactic halo.

The Weakly Interactive Massive Particles (WIMP) are the leading candidate dark matter particle. The search for dark matter in the halo of our galaxy by direct detection experiments has been a very active field in recent years, with the limits on WIMP-nucleon cross section improving significantly with time (for a review see Refs. \cite{3} and \cite{4}). In general, these experiments are performed by measuring the rate of nuclear recoils in a detector above a certain energy threshold. By doing the experiments with appropriate shielding and in an underground facility, a very low rate ( $\approx$1 eV/kg/day ) for nuclear recoils coming from non-WIMP events can be achieved. These low measured rates are used to establish upper limits for the WIMP-nucleon cross section as a function of WIMP mass. However, typical searches of this kind have a poor sensitivity for low mass WIMPs because of the high thresholds ($\approx$1 keV) established for the detection of the nuclear recoils. These high thresholds produce weaker experimental limits for WIMP masses below 10 GeV, as can be seen in Fig. 1. The most popular models for dark matter particles predict masses above 10 GeV (for a review see Ref. \cite{5}) for which a low threshold dark matter search is not needed. There are however some models for which the dark matter particles have lower mass \cite{6} \cite{7} and in those cases a low threshold for nuclear recoil detection is needed for a direct search. A low mass dark matter candidate could also arise in the most simple extension of the Minimal Supersymmetric Standard Model as discussed in Ref. \cite{8}. The possibility of detecting sub-GeV dark matter candidates in colliders is discussed in Ref. \cite{9}. Models for which the typical velocity of the dark matter particles with respect to the earth is lower have also been considered \cite{10} \cite{11}, and those cases also require a low threshold in a direct search experiment. One of the limitations for setting a lower threshold in the direct dark matter searches is the readout noise of the detectors used for the experiments. There has been a continuing effort in reducing the readout noise for the detectors typically used in direct dark matter searches to overcome the high threshold issue \cite{12}.

In this work, we discuss the idea of using Charge-Coupled Devices (CCDs) for a direct dark matter search with a low detection threshold for nuclear recoils. The CCDs considered here present an extremely low readout noise $\sigma = 2e$ and could easily be stacked in an array to produce a detector with significant active mass.

II. HIGH RESISTIVITY CCD DETECTORS

Recent advances in CCD technology \cite{13} allow the fabrication of high resistivity ($\sim$ 10 k$\Omega$/cm$^2$) detectors, up to $\sim$ 300 $\mu$m thick which are fully depleted at relatively low voltages. These CCDs have a significantly higher efficiency in the near-IR and for this reason are the optical detectors chosen by several groups building new mosaic cameras for astronomy, such as DECam \cite{14} \cite{15}, SNAP \cite{16} and HyperSuprime \cite{17}.

In this work we discuss the features of the DECam detectors \cite{14} \cite{15} \cite{16} that will make then good candidates for a low threshold direct dark matter search. DECam is the instrument currently being built for the Blanco 4m Telescope at CTIO \cite{21} that will be used for the Dark Energy Survey (DES) and will be available as a facility instrument at CTIO. For a general description of CCDs see Ref. \cite{20}.

A cartoon of the devices developed by Lawrence Berke-
FIG. 1: Examples of cross section limits from existing and planned direct dark matter searches. The limits are very weak for WIMP mass below 10 GeV.

The main features that make the DECam detectors good candidates for a direct dark matter search are: i) their low electronic noise and ii) their thickness. These two features combined would allow building an experiment with significant mass (given by the large thickness) and with a very low threshold for nuclear recoils.

The noise performance of these detectors has been studied in detail as part of the characterization effort done by the DECam CCD team [18] [19]. The detectors have 8 million, 15 µm square pixels and are read in by two amplifiers in parallel, each amplifier sitting on opposite ends of a serial register towards which the charge is clocked. The signal is digitized after correlated double sampling (CDS) of the output. Each sample used for the CDS operation is the result of an integration during a time τ. This integration acts as a filter for high frequency noise. The noise measured for a DECam detector as a function of readout time is shown in Fig. 3. The noise observed for pixel readout times larger than 50 µs is σ < 2e (RMS). At large readout times τ is one half of the pixel readout time. The detectors have an output stage with a electronic gain of ∼ 2.5 µV/e. These results were obtained using a Monsoon [20] CCD controller.

A commonly used tool in the characterization of CCD detectors is low energy X-rays from an $^{55}$Fe source [20]. We present here the results obtained with $^{55}$Fe in DECam CCDs to demonstrate their performance. The main emission of the $^{55}$Fe source is a 5.9 keV X-ray. By reconstructing the ionization charge produced by the X-ray hits, one can measure a conversion factor between charge and energy. This factor can be used to translate the noise measured in units of charge to the noise in units of energy for X-ray ionization. This conversion factor is known to be 3.64 eV/e [20] and has been measured extensively for CCD detectors in general. An example of the energy spectrum measured for an $^{55}$Fe X-ray exposure in a DECam CCD is shown in Fig. 4, which confirms the conversion factor.
FIG. 3: Noise as a function of pixel readout time for DECam CCDs. At slow readout speeds a noise below $\sigma = 2$ e is achieved.

The study of the size of X-ray hits in a back illuminated CCD provides a measurement of the diffusion. Since the detectors are back illuminated, a 5.9 keV X-ray produced by an $^{55}$Fe source will penetrate only about 20 $\mu$m into the silicon before producing a charge pair [20]. The charge produced will have to travel most of the Si thickness before it can be stored under the potential well for later readout. As a result of this process, $^{55}$Fe X-rays will produce diffusion limited hits in the detector corresponding to a known energy deposition. When considering these detectors for a dark matter search, diffusion is an important parameter because it determines the size of the reconstructed nuclear recoil events. The nuclear recoils will produce a very localized charge cloud ($\ll 15$ $\mu$m), and the signature in the CCD detectors will be a diffusion limited charge deposition, similar to the X-ray hits. The diffusion measurement for DECam CCDs using X-rays is shown in Fig. 5. This measurement done with X-rays is consistent with measurements done with optical methods on the same detectors [22], and on other thick detectors developed by LBNL [24] [25].

III. NUCLEAR RECOIL DETECTION WITH CCDs

In order to demonstrate the nuclear recoil detection with CCDs, a DECam detector was exposed to a $^{252}$Cf neutron source, an example of the resulting images is shown in Fig. 6. The image shows ionization tracks that can be up to a few hundred pixels long and diffusion limited hits, typically occupying only a few pixels. The nuclear recoil candidates are the diffusion limited hits and are selected according to the diffusion measured for these detectors shown in Fig. 5. The image was produced using a substrate voltage of 80 V. Shape parameters for the hits are measured using the astronomical image analysis package SExtractor [29], and only those hits with a principal axis smaller than 1 pixel are selected as nuclear recoil candidates. We used the X-ray data to prove that this selection is efficient for separating diffusion limited hits from the rest of the ionization events in the Si.

The energy spectrum from the $^{252}$Cf neutron source has been measured in previous work [30], where it was
shown to be properly described by the function

\[ N(E) = N_0 \exp(-\alpha E) \sinh \sqrt{\beta E}, \]

where \( N(E) \) is the number of neutrons emitted with kinetic energy \( E \), \( N_0 \) is a normalization constant and the parameters \( \alpha = 0.88 \) and \( \beta = 2 \). The DECam detectors used in this work operate at -100°C and, for this reason, they are inside a vacuum dewar with 2.5 cm thick Al walls. To understand the spectrum of the neutrons inside the dewar, we ran a Geant4 [34] simulation. The expected spectrum for neutrons inside the dewar as calculated with Geant4 is shown in Fig. 7. The simulation was performed for a wall thickness of 2.5 cm and 5.0 cm. The thicker case was considered for neutrons crossing the Al wall with a large angle. The expected neutron spectrum inside the dewar can also be described by Eq.(1) with somewhat different parameters. The spectrum parameters for the different dewar wall thickness are shown in Table I. Once the spectrum of the neutrons inside the dewar is calculated as shown in Fig. 7, the energy distribution of the nuclear recoils produced by a beam of neutrons with energy distribution given by \( N(E) \) in Eq.(1) can be expressed as

\[ P(E_r) = P_0 \int_{E_r}^{\infty} N(E)F(q)dE \]

where \( E_r \) is the recoil energy, \( P_0 \) is a normalization factor and \( F(q) \) is the nuclear form factor correction given as a function of the momentum transfer, see Ref. [31] for details. The results of the nuclear recoil energy distribution calculated in Eq.(2) are shown in Fig. 8 in order to compare them with the spectrum observed in the CCD the data is fitted to a fourth order polynomial

\[ P(E_r) = A_0 + A_1E_r + A_2E_r^2 + A_3E_r^3 + A_4E_r^4 \]

with the parameters shown in Table II.

The ionization efficiency for nuclear recoils is not the same as that for X-rays, as has been demonstrated in previous work [27]. For this reason the energy scale for

\[ \begin{array}{c|c|c}
\text{Mean} & 2.188 & 2.053 \\
\text{RMS} & 1.686 & 1.608 \\
\end{array} \]

FIG. 6: Image resulting from an exposure of a DECam CCD to an $^{252}$Cf neutron source. The total width of the image corresponds to 1000 pixels.

FIG. 7: Spectrum of neutrons inside the dewar obtained using Geant4 simulation (black histogram). The blue dashed line shows the best fit to Eq.(1) with \( \alpha = 0.88 \) and \( \beta = 2 \), the red curve is the best fit to Eq.(1) with free \( \alpha \) and \( \beta \).

FIG. 8: Spectrum of nuclear recoils expected according to the simulation for 2.5 cm wall thickness (top) and 5.0 cm wall thickness (bottom).
The detectors discussed above show features that make them ideal for a CCD Experiment at Low Background (CELB), to conduct a direct dark matter search optimized for low mass dark matter candidates. The mass of each DECam CCD is 1 g (18 cm² and 250 µm thick) and we envision a 10 g array to be operated underground in the near future. In the meantime, we collected data for 2 g-day exposure of a DECam CCD, and the spectrum is shown in Fig. 10 and Fig. 11. A study of radiation events in astronomical images was presented in Ref. [35] for thick CCDs, similar to the DECam detectors. The rate of diffusion limited hits, characterized as “spots” in Ref. [35], was measured to be ~1 cm⁻² min⁻¹ for an unshielded detector at sea level. These measurements include the full dynamic range of the CCDs, corresponding to energies up to 400 keV. In these units, we measured 0.8 cm⁻² min⁻¹ for our unshielded detectors at Fermilab, which means that our results are consistent with those presented in [35].

The current best limit published for WIMP masses below 5 GeV corresponds to Ref. [36], giving a limit for the spin independent nucleon-WIMP cross section σ < 10⁻¹⁵ cm². This limit was established with a threshold of ~600 eV for nuclear recoils and an exposure of 338 g-day. We expect to have a 300 g-day exposure underground during 2008 with a threshold of 135 eV (corresponding to 5 sigma of the electronic noise). To estimate the reach of a CCD based search for dark matter, we assume that the background observed in our 2 g-day run can be reduced by 4 orders of magnitude by going to an underground facility and building a proper shield around our detector. The expected cross section upper limits for a 300 g-day exposure are shown in Fig. 12. The results expected with a threshold ten times higher are also shown for comparison.

| parameter | ²⁵²Cf | 2.5 cm Al | 5.0 cm Al |
|-----------|-------|-----------|-----------|
| α         | 0.88  | 0.98 ± 0.02 | 1.10 ± 0.03 |
| β         | 2.0   | 2.5 ± 0.3  | 3.1 ± 0.5  |

TABLE I: Spectrum parameters in Eq. (1) for ²⁵²Cf spectrum, and after the neutrons crossed an Al wall of 2.5 cm and 5.0 cm.

| parameter | 2.5 cm Al | 5.0 cm Al |
|-----------|-----------|-----------|
| A₀        | 2.7 ± 0.2 | 2.8 ± 0.2 |
| A₁        | -13.0 ± 0.6 | -13.5 ± 0.6 |
| A₂        | 25.5 ± 1.0  | 26.5 ± 1.0  |
| A₃        | -24.1 ± 1.6 | -25.0 ± 1.6 |
| A₄        | 9.2 ± 1.8  | 9.5 ± 1.8  |

TABLE II: Parameters for the polynomial fit to the nuclear recoil spectrum in Fig. 8

| wall thickness | Vsub | f (e/MeV) | χ²/nd.f. | Q |
|----------------|------|-----------|----------|---|
| 2.5 cm         | 80 V | 74083 ± 1034 | 2.6 | 3.71 ± 0.05 |
| 5 cm           | 80 V | 68934 ± 1047 | 2.7 | 3.98 ± 0.06 |

TABLE III: Parameters for the polynomial fit to the nuclear recoil spectrum in Fig. 8. The results assuming a 5cm thick wall are also presented.
FIG. 10: Background spectrum measured for an unshielded DECam CCD at FNAL (sea level). The line is an exponential fit $f_1(E) = \exp(a + bE)$, with $a = 11.44$ and $b = -0.053$.

Among the astronomical community the possibility of developing a zero-noise CCD readout system has been extensively discussed [37] [38]. In addition, devices using an electron multiplication stage (CCDEM) giving zero noise performance have been fabricated, although much thinner than the high resistivity detectors considered here (see for example the L3 Vision products from e2v [39]). A zero readout noise detector will allow setting a threshold for nuclear recoils at 14 eV (corresponding to 1e), the reach of an experiment with such a low threshold is also shown in Fig. 12.

V. CONCLUSION

The prospects for a direct dark matter search using CCDs have been discussed, demonstrating that the new high resistivity detectors fully depleted with a thickness of 250 $\mu$m are good candidates for such an experiment.

A demonstration of the technology with a 10 g CCD array is planned using the DECam CCDs, and we expect that this experiment will set the best limit for WIMPs of masses below 5 GeV. The development of a zero noise CCD readout could extend this reach below the 1 GeV region. We believe that an experiment of these characteristics would be a good complement to the currents dark matter searches because of its extremely low threshold.

FIG. 11: Same as Fig. 10 but now showing low energy region. For this region of the energy spectrum an additional term is added, the curve corresponds to $f_2(E) = f_1(E) + \exp(c+dE)$.

FIG. 12: Cross section limit expected for a 300 g-day exposure of DECam CCDs underground to be done during 2008. Red) with a threshold set at 13.5 eV, Green) with threshold set at 135 eV. Black) reach with a 1.35 keV threshold is shown for comparison.
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[1] A. Kogut et al., The Astrophysical Journal, 665 355 (2007).
[2] Bernabei, R et al., arXiv:0804.2741
[3] J.R. Gaitskell, Annu. Rev. Nucl. Part. Sci., 54 315 (2004).
[4] G. Chardin, "Cryogenic Particle Detection", edited by Christian Enss, Springer (2005), arXiv:astro-ph/0411503
[5] B. W. Lee and S. Weinberg, Phys. Rev. Lett., 39 165 (1977).
[6] D. Hooper and K.M. Zurek, arXiv:0801.3686v1
[7] X. He, T. Li, X. Li and H. Tsai, Modern Physics Letters A, 22 2121 (2007).
[8] J.F. Gunion, D. Hooper, B. McElrath, Phys.Rev., D73 015011 (2006)
[9] C. Bird, R. Kowalewski & M. Pospelov, Modern Physics Letters A, 21 457 (2006).
[10] Gondolo, P. and Gelmini, G., Phys. Rev., D 71 123520 (2005).
[11] T. Damour and L.M. Krauss, “Proceedings of the 3rd International Workshop on the Identification of Dark Matter”, edited by N. J. C. Spooner & V. Kudryavtsev. World Scientific (2001), arXiv:astro-ph/9806165v3
[12] P.S. Barbeau, J.I. Collar and O. Tench. Journal of Cosmology and Astroparticle Physics, 09 009 (2007).
[13] S.E. Holland, D.E. Groom, N.P. Palacio, R. J. Stover, and M. Wei, IEEE Trans. Electron Dev., 50 225 (2003), LBNL-49992.
[14] Flaugher, B., Ground-based and Airborne Instrumentation for Astronomy, Edited by McLean, Ian S.; Iye, Masanori. Proceedings of the SPIE, Volume 6269, (2006)
[15] Dark Energy Survey Collaboration, [astro-ph/0510346]
[16] “Supernova / Acceleration Probe: A Satellite Experiment to Study the Nature of the Dark Energy”, SNAP Collaboration, G. Aldering et al., submitted to Publ. Astr. Soc. Pac., astro-ph/0405232 SNAP Collaboration, astro-ph/0507459
[17] M. Satoshi et al., Ground-based and Airborne Instrumentation for Astronomy. Edited by McLean, Ian S.; Iye, Masanori. Proceedings of the SPIE, Volume 6269, (2006)
[18] J. Estrada & R. Schmidt, Scientific Detectors for Astronomy 2005, Edited by J.E. Beletic, J.W. Beletic and P. Amico, Springer, (2006).
[19] J. Estrada et al., Ground-based and Airborne Instrumentation for Astronomy. Edited by McLean, Ian S.; Iye, Masanori. Proceedings of the SPIE, Volume 6269, (2006).
[20] J.R. Janesick, Scientific Charge Coupled Devices, SPIE press (2001).
[21] T. M. C. Abbott et al., Ground-based and Airborne Instrumentation for Astronomy. Edited by McLean, Ian S.; Iye, Masanori. Proceedings of the SPIE, Volume 6269, (2006)
[22] H. Cease, H. T. Diehl, J. Estrada, B. Flaugher and V. Scarpine, Experimental Astronomy, Online First (2007)