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Skipper CCDs for the search of a daily modulation of Dark Matter signal in the DMSQUARE experiment

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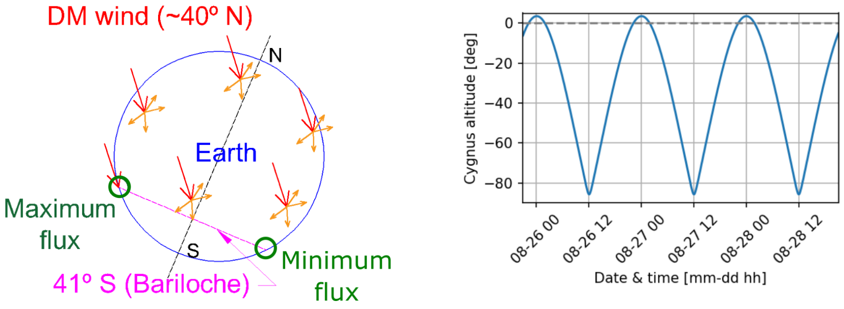
Abstract. The Dark Matter Daily Modulation experiment (DMSQUARE) seeks for dark matter interactions with a Skipper CCD. It is currently running at surface level in Bariloche, Argentina, and will be moved to a shallow underground site at Sierra Grande, Argentina in November 2021. The low threshold achieved by Skipper CCDs allows to search for electron recoil events with an ionization energy down to 1.2 eV. In order to extract a potential dark matter signal from noise at the single electron level, we propose to search for a diurnal modulation of events, resulting from the potential interaction of the dark matter wind with the particles in the Earth. Depending on the model, mass and cross-section, this modulation can be maximum at 40 deg of latitude in the Southern Hemisphere, where DMSQUARE is operated. In this article we present the experiment, report preliminary results with a prototype Skipper CCD taking data at surface level and comment on future prospects.

1. Introduction

Although there is wide evidence for the existence of Dark Matter (DM) in the universe, its microscopic properties remain elusive to this day. Many experiments are being conducted in order to detect interactions of the DM particles with ordinary matter. The Dark Matter Daily Modulation Experiment (DMSQUARE) uses a Skipper CCD to search for DM-electron interactions in a similar way as SENSEI [1], and future DAMIC-M and Oscura. These detectors allow for a low threshold of 1.2 eV thanks to the Skipper technology, at the cost of a long readout time. They exhibit, however, at low energy deposits (1 or 2 electrons) an apparently irreducible background that is hard to model [2].

Because of the movement of the solar system around the galaxy center, the DM particles of the galactic halo have a velocity distribution with nonzero mean when seen from the solar system rest frame. This effect is known as the DM wind and the mean velocity of the particles point towards the Earth from the direction of the Cygnus constellation. While these DM particles go across the Earth, if they interact through any means with the nuclei or electrons that conform the planet, they may scatter or lose energy. A detector fixed on the surface may therefore receive a flux of DM particles that changes over time in a diurnal period. Fig. 1 illustrates this effect, described in more detail in refs. [3, 4, 5]. DMSQUARE is located at 41° South in Bariloche, while the main direction of the DM wind is at 40° North. At some point of the day, Cygnus is barely above the horizon, meaning that the incoming DM particles only need to get across the atmosphere. Twelve hours later the wind comes from below and has to get across the whole Earth, so each particle has more chances to scatter away. An advantage of the search for this modulation is that the period is one sideral day in contrast with a solar day. Therefore if a signal is detected with the correct period and phase, then the same signal should be detected six months later but with opposite phase to be accounted as DM.



(a) (b)

Figure 1: (a) Schematic of the main direction of the DM wind and the scattering of its particles when getting accross the Earth. A detector located in Bariloche would receive a maximum flux when Cygnus is barely above the horizon and a minimum flux 12 hours later. (b) Altitude of Cygnus for a certain time and date in August. Six months later the altitude will be shifted by 12 hours.

2. Experimental setup

The DMSQUARE detector is a Charge Coupled Device with Skipper-type readout (Skipper CCD). The prototype Skipper CCD used for the science runs reported in this article is a 200 μm thick array of 1248×724 pixels. Its total mass is 0.095 g and has four readout amplifiers, one on each corner of the CCD, which enable a simultaneous readout of each quarter of the detector. The size of the active region is approximately 2 cm^2 and is packaged inside a copper housing. The detector is placed inside a vacuum chamber, which allows it to be at a working temperature of around 105 K without having air condensating around it. Fig. 2 shows a photography of the setup and a schematic of the cooling mechanism. The detector is thermally coupled to a ~ 1 m long copper cylinder referred to as “cold finger”. Its lower end is in direct contact with liquid nitrogen. The temperature of the Skipper CCD is measured via a Pt100 resistor coupled to the detector mounting base. A Low Threshold Acquisition (LTA) board is placed on the outside of the vacuum chamber (red box in the photograph). The DAQ and the monitoring of the CCD temperature are controlled using a Raspberry Pi mini computer.

Our Skipper CCD has proven to work properly at temperatures below 135 K. Above that threshold, the dark current (DC) begins to play an important role and single-electron events

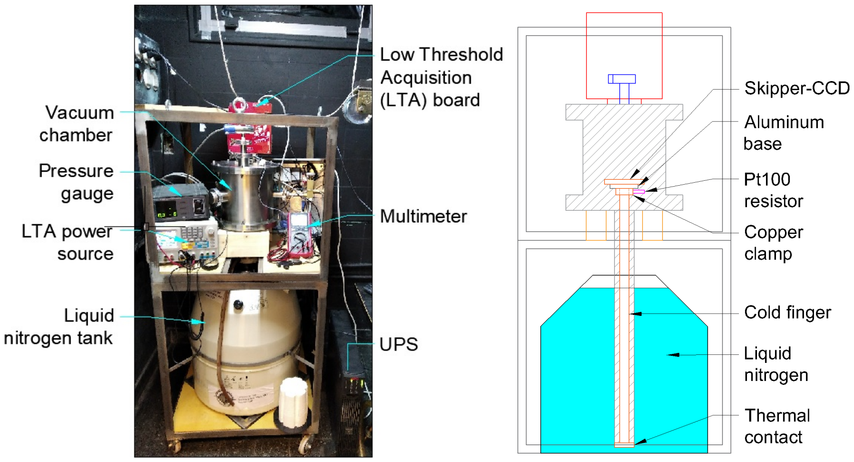


Figure 2: DM-SQUARE setup at Bariloche.

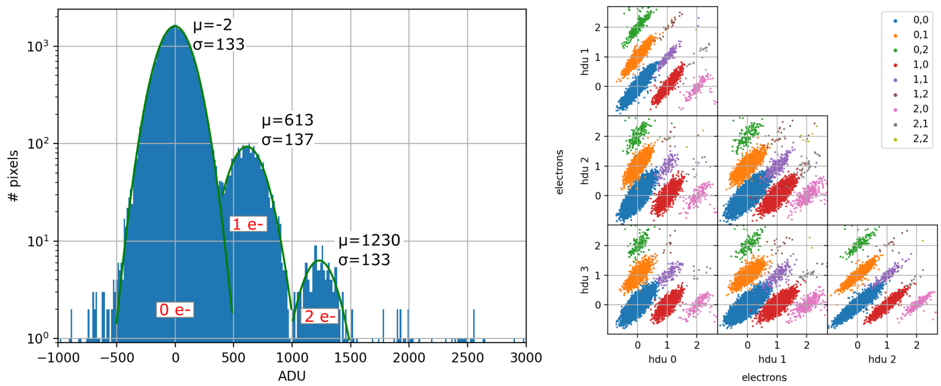
increase in quantity. The temperature of the Skipper CCD increases when the tank runs out of liquid nitrogen. If that happens, an automatic script turns off the bias voltage, effectively turning off the detector and preventing it from malfunctioning. We also have a double conversion UPS that protects the equipment from instabilities in the electric power supply and provides with about two hours of extra battery in case there is a power cutoff. This allows to complete an acquisition and shut down the Skipper CCD properly.

Commands are sent to the LTA from the Raspberry Pi using an Ethernet connection and a Python script. In this manner we can control all the voltages applied to the Skipper CCD as well as the size of the images, exposure, number of Skipper samples and hardware binning (HB). In order to achieve enough timing resolution, we read the Skipper continuously without exposure (therefore the exposition time is equal to the total readout time) and apply a 1×5 HB. This allows us to read the whole CCD in 75 minutes at the cost of a small loss in spatial resolution (the information of 5 pixels is compressed into 1 in the vertical direction). A typical image accounts for 0.00494 g day of exposure and consists of 125×430 pixels with 1000 Skipper samples including a prescan region of 8 pixels per row and an overscan of 60 pixels per row. There are four images with these parameters for each readout of the CCD (one for each amplifier).

The data taking began in August 2020 and has been running almost continuously until September 2021, except for some interruptions for technical tests. A total of 3350 images were taken during this period, summing up to 16.5 g day of exposure. For the data analysis presented below some quality cuts were applied however, lowering the total exposure.

3. Data analysis

The output of the Skipper CCD is a `.fits` image consisting of four arrays (one for each amplifier) of pixel values with the several Skipper samples of each pixel. The first step to pre-processing these is averaging the Skipper samples. Then the region called "overscan", which consists of pixels that have not been exposed, is used to find and subtract the baseline. Each amplifier has a cross-talk with the others and in the images it appears as a fake negative signal whenever a physical, high energy event is registered in the same pixel of another amplifier. This is easily corrected by applying a linear matrix to the vector of pixels. The next step is to calibrate the pixel values from ADU to electrons. This is achieved by finding the first two peaks in the charge histogram, fitting them to the sum of two gaussians, finding the gain as the difference of the means of both peaks and then dividing the pixel values by this gain. With the current setup the width of these gaussians is not narrow enough to *a priori* distinguish empty pixels from those which have one electron, but this is due to a correlated noise between all the amplifiers. This correlated noise is evaluated with a Gaussian Mixture algorithm described in [6] and finally the charge of each pixel can be counted individually. Fig. 3 illustrates the last two steps.



(a) (b)

Figure 3: (a) Gain calibration. For each image, a histogram at low energies is drawn and the first three peaks are fit to gaussian curves. The difference between the means of the first two is the gain of the image and the standard deviation provides a measure of the noise. (b) Correlated noise subtraction. Each header data unit (hdu) has the information of the pixels for each amplifier. When we compare the value of a certain pixel of one hdu with the pixel of the same position in the other three, we see a correlation. This is classified by a Gaussian Mixture algorithm into clusters (different colors in the figure) of different number of electrons.

The model tested for this article is a dark photon interacting with nuclei inside the Earth and later with electrons in the detector. The expected number of events in the detector, which depends on the elevation angle of the DM wind, is simulated via Monte Carlo [7, 8]. For the analysis presented in this article we only look at the count of pixels that have a single electron. Other relevant information for each image is the date and time of the start of the readout and the total readout time. With these data we can compute the incidence angle of the DM wind and compare the observed events with the output of the simulations. Finally we compute the p-value of the observed versus simulated data and obtain the limits for mass and cross-section at 90% CL.

We have observed different fluctuations of single electron events in each run, so we applied a gaussianity test to the data of each run. If the data passed this test, then we included them in the analysis and computed the error bars as the standard deviation of the corresponding run. After this quality cut we kept a total exposure of 12.4 g day.

4. Results

Fig. 4 shows the limits at 90% CL found with the setup and analysis described above. The background plot was extracted from [9]. The orange curve shows the limits found without searching for the modulation and they are similar to the protoSENSEI@Surface results for masses in the $1-3\,\mathrm{MeV}$ range. At higher masses two- and three- electron events set stronger limits and that is why our current analysis is not competitive. The blue curve shows the limits found with the search for the diurnal modulation at DMSQUARE. The limits have been improved by around one order of magnitude in cross-section. This shows that the search described here is useful not only for our experiment but also for other experiments with enough timing resolution.

Searching for a modulation allows us to improve the limits by increasing the exposure even if there is an irreducible background. This will be achieved by installing a bigger Skipper CCD in our setup. On the other hand, limits can also be improved by understanding the source of single-

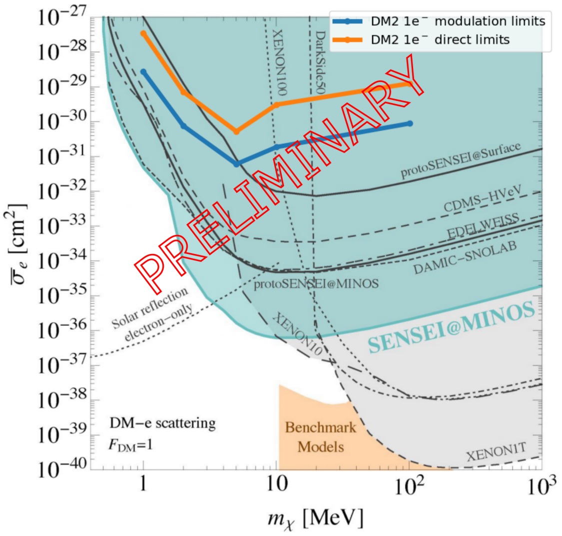


Figure 4: Preliminary DMSQUARE exclusion limits for DM-electron interactions using (blue) and not using (orange) the modulation search. Only single-electron events were used for this analysis. The background plot was extracted from [9].

electron events and reducing them or modeling them as background. Reference [10] describes several possible backgrounds. As DMSQUARE is currently operated at surface and with no shielding, cosmic ray events dominate our background. In order to reduce this, DMSQUARE will be installed by November 2021 at an underground location in Sierra Grande, Argentina. This is the same location of the DM direct detection experiment described in [11, 12], an inactive iron mine with horizontal access to 400 m underground.

5. Conclusions

With a $<$ 100 mg prototype detector operating on surface we were able to improve current surface limits to a dark photon model considering interactions with nuclei inside the Earth and detection via electron recoils. Better results are expected when using a larger Skipper CCD operated at the Sierra Grande underground site. The search for a daily modulation can improve the limits from other DM direct detection experiments in the same energy range should they have enough timing resolution.

Acknowledgements

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References

[1] Crisler M *et al* 2018 *Phys. Rev. Lett.* **121** 061803
[2] Barak L *et al* 2021 *Preprint* arXiv:2106.08347
[3] Collar J and Avignone F 1992 *Phys. Lett. B* **275** 181-5
[4] Collar J and Avignone F 1993 *Phys. Rev. D* **47** 5238-46
[5] Hasenbalg F, Abriola D, Collar J, Di Gregorio D, Gattone A, Huck H, Tomasi D and Urteaga I 1997, *Phys. Rev. D* **55** 7350
[6] Pedregosa F *et al* 2011 *J. Mach. Learn. Res.* **12** 2825-30
[7] Emken T and Kouvaris C 2017 *J. Cosmol. Astropart. Phys.* JCAP10(2017)031
[8] Emken T, Essig R, Kouvaris C and Sholapurkar M 2019 *J. Cosmol. Astropart. Phys.* JCAP09(2019)070
[9] Barak L *et al* 2020 *Phys. Rev. Lett.* **125** 171802
[10] Du P, Egana-Ugrinovic D, Essig R and Sholapurkar M 2020 *Preprint* arXiv:2011.13939v1
[11] Abriola D *et al* 1996 *Astropart. Phys.* **6** 63-69
[12] Abriola D *et al* 1999 *Astropart. Phys.* **10** 133-139