Low-threshold WIMP search at SuperCDMS

E. Lopez Asamar, on behalf of the SuperCDMS Collaboration

Instituto de Física Teórica UAM/CSIC, Universidad Autónoma de Madrid, 28049 Madrid, Spain

Abstract

The Super Cryogenic Dark Matter Search (SuperCDMS) experiment aims to detecting nuclear recoils from weakly-interacting massive particles (WIMPs) by measuring phonon and ionization energy in crystalline Ge. It has been operating at the Soudan Underground Laboratory in Minnesota (USA) since March 2012 with improved background rejection capabilities with respect to CDMS II. A low-threshold analysis of the SuperCDMS data has been performed, allowing to explore WIMP masses below 30 GeV/$c^2$. This is the first analysis using the full background rejection capabilities of SuperCDMS. In particular both phonon and ionization signals are used for defining a fiducial volume excluding events near any of the surfaces of the detectors. In addition, the background discrimination includes multivariate techniques optimized for several WIMP masses. The results are competitive with other low-threshold WIMP searches, and probe new parameter space for WIMP-nucleon scattering for WIMP masses between 4 and 6 GeV/$c^2$.

Keywords: Direct dark matter search, light WIMP, SuperCDMS, low threshold.

1. Introduction

A wide variety of astronomical and cosmological observations are consistently described by assuming that ~85% of the mass content of the Universe is non-luminous and of non-baryonic nature[1]. This particular contribution is generically referred to as dark matter (DM), and the properties of its fundamental components remain unknown. Weakly-interacting massive particles (WIMPs) allow to explain DM as a relic from the early Universe, and have the additional interest of being inherent to some definite extensions of the Standard Model of particle physics. In this context, the study of WIMP masses below 30 GeV/$c^2$ is motivated by the fact that this interval is still allowed in some models given the current constraints from DM searches[2, 3, 4, 5, 6, 7, 8, 9, 10]. Furthermore, the DAMA[11], CDMS II (Si)[12] and CoGeNT[13] experiments report excesses of events that can be interpreted as the signal of a WIMP with mass between 8 and 20 GeV/$c^2$.

2. The SuperCDMS experiment

The purpose of the Super Cryogenic Dark Matter Search (SuperCDMS) experiment is to measure the phonon and ionization signal produced by a Ge nucleus recoiling after a WIMP interaction. In general, the ionization energy, $E_Q$, is only a part of the total recoil energy, $E_R$. The ratio between $E_Q$ and $E_R$ is called ionization yield, $Y$:

$$E_Q \equiv YE_R.$$ (1)

The ionization yield depends on the type of the recoiling particle. For a recoiling electron $Y$ is equal to unity, i.e., the full recoil energy produces ionization, and for a recoiling Ge nucleus $Y$ ranges approximately between 0.15 and 0.3 depending on the recoil energy. This property allows to use the ionization yield for discriminating nuclear recoils (NRs) against electron recoils (ERs). The full recoil energy is eventually converted into phonon energy. There is an additional contribution to the phonon energy if an external electric field is applied. In this case, the charge carriers caused by the ionization move within the crystal along the lines of the...
electric field, producing additional phonons[14]. Denoting the voltage difference induced in the crystal as $V$ the total phonon energy reads

$$E_P = E_R + \frac{V}{\epsilon} E_Q.$$ 

The constant $\epsilon$ depends on the material, being equal to 3.0 V for Ge. Note that the measured values of $E_P$ and $E_Q$ allow to determine $E_R$ and $Y$ uniquely.

The SuperCDMS experiment operates fifteen instrumented cylinders of monocrystalline Ge called detectors, arranged in five stacks of three detectors each, and operating in a thermal bath of 50 mK. The mass of each detector is 0.6 kg. An external electric field is applied to each detector in order to separate positive charge carriers from negative charge carriers and to define a fiducial volume, see Figure 1. Electrodes at +2 and -2 V located on the top and bottom sides of the detector respectively create an electric field in the bulk that is almost parallel to the detector axis. This configuration causes negative and positive charge carriers produced by recoils occurring in the bulk to move respectively towards the top and bottom sides. Additional interleaved electrodes at 0 V located on both sides modify the electric field near those surfaces while keeping the electric field in the bulk practically unaltered. Hence this change only affects the propagation of charge carriers produced by recoils occurring near the top and bottom surfaces, that move towards the same side regardless of being negative or positive. For this reason, by instrumenting the top and bottom sides of the SuperCDMS detectors and requiring symmetry between both ionization measurements it is possible to reject events occurring near those surfaces. In addition, events occurring at high radius are rejected by segmenting the readout channels on each side along the radial direction and requiring the ionization measurements from the outer channels to be consistent with noise. Since part of the phonon signal is produced by the propagation of the charge carriers across the Ge crystal, phonons carry some information about the position of the recoil, and hence allow complementary fiducialization.

The SuperCDMS detectors are protected from the environmental radioactivity by an outer active shielding consisting of pannels of scintillating plastic, acting as muon veto, and an inner passive shielding consisting of two layers of polyethelene and two layers of lead. Both the active and passive shielding cover the full solid angle. In addition, ultra-radiopure Cu is used for the structures inside the shielding. The full setup is located in the Soudan Underground Laboratory (Minnesota, USA) at a depth of 713.5 m (~2100 mwe).

3. Analysis of low-threshold data

Light WIMPs were searched for in SuperCDMS by using the full background rejection capabilities of the Ge detectors in the limit of their resolution[15], that corresponds to recoil energies between 1.5 and 10 keV. This enables to probe WIMP masses between 5 and 15 GeV approximately. Only data taken between October 2012 and July 2013 in the seven detectors with the lowest trigger thresholds were considered for this search, totalling 577 kg days of raw exposure. Data in the signal region were blinded until the event selection was completely finalized.

Two dominant background sources were identified: surface events from nuclear decays occurring in the vicinity of the detectors; and electron recoils induced by $\gamma$- and X-rays. The first category includes recoils produced by charged particles from the decay of $^{210}$Pb nuclei implanted on the surface of the detectors themselves or on the inner surface of the copper housings. Due to the microscopic mean free path of such charged particles in solids, decays of $^{210}$Pb nuclei located elsewhere are irrelevant. The events in the second category have two origins: Compton scattering of $\gamma$-rays from nuclear decays occurring in the Cu structures or the passive shielding, that have energies in the MeV scale; and X-rays produced by L-shell capture in Ge atoms inside the detector themselves, that have energy equal to 1.29 keV. Note that a 1.29 keV photon has a microscopic mean free path in Ge and hence in the second case all its energy is deposited inside the detector. The backgrounds were modelled using Monte Carlo (MC) simulations and data from the signal sidebands only, and included resolution effects by adding measured noise to

![Figure 1: Schematic view of the section of a SuperCDMS Ge detector, showing lines of the applied electric field (blue lines) and the propagation of charge carriers (red arrows) produced in three recoils (green stars) occurring respectively in the bulk, near the bottom surface and at high radius.](image-url)
perfect pulses.

Only data satisfying a set of quality criteria were considered in the analysis. WIMP candidates were required to satisfy fiducial volume cuts based on the ionization signal, and to have ionization yield consistent with NRs. In addition, events with activity above noise in the muon veto or in any of the fifteen detectors other than that containing the WIMP candidate were rejected. Finally, four quantities related to the ionization yield and the fiducial volume defined by the phonon signal were used to construct multivariate discriminators. In particular, the discriminators were implemented as boosted decision trees\[16\], see Figure 2. A total of four BDTs were developed, assuming WIMP masses equal to 5, 7, 10 and 15 GeV/c^2 respectively, and in each case a cut value was set such that the expected Poisson upper limit at 90% C.L. is minimized. Events were accepted if at least one of such cuts is satisfied.

The background satisfying all selection cuts was predicted to be equal to 6.2^{+1.1}_{-0.8}. This estimation included the systematic uncertainties in the background model. Upon unblinding, eleven events were found to pass all the selection requirements, see Figure 3. This represents a discrepancy slightly below the two-sigma level with respect to the predicted background, and hence no evidence of WIMP signal can be claimed. In general, a good agreement is found between the background prediction and the observed number of events in all the considered detectors except T5Z3, see Table 1, in which 0.13^{+0.06}_{-0.04} background events were predicted and 3 events were observed. This particular detector had one electrode shorted to ground and hence the applied electric field differed to that for the remaining detectors considered in this analysis. The origin of the discrepancy in T5Z3 is currently under study, and the most credible hypothesis is that the altered electric field affected the selection of event used for modelling the backgrounds in this detector.

An exclusion limit was calculated applying the optimal interval method[17, 18] without background subtraction, assuming the standard halo model, see Figure 4. Under these conditions, the WIMP interpretation of the CDMS II (Si), DAMA and CRESST results is disfavoured. In addition, the WIMP interpretation of the CoGeNT result is excluded independently of the halo

| Detector | Number of observed events | Predicted background |
|----------|--------------------------|----------------------|
| T1Z1     | 0                        | 0.03^{+0.03}_{-0.01} |
| T2Z1     | 2                        | 1.4^{+0.2}_{-0.2}    |
| T2Z2     | 2                        | 1.8^{+0.4}_{-0.3}    |
| T4Z2     | 0                        | 0.04^{+0.02}_{-0.02} |
| T4Z3     | 0                        | 1.7^{+0.4}_{-0.3}    |
| T5Z2     | 4                        | 1.1^{+0.3}_{-0.3}    |
| T5Z3     | 3                        | 0.13^{+0.06}_{-0.04} |

Table 1: Number of observed events (second column) and predicted background (third column) in each detector.
parameters and the nature of the WIMP-nucleon couplings. New WIMP-nucleon cross sections are explored for WIMP masses between 4.5 and 6 GeV. Note that the limit is consistent with the sensitivity expected before unblinding below 10 GeV/c², while the discrepancy seen above this point reflects the tension between the background prediction and the observed number of events in T5Z3.

4. Conclusions

The low-threshold WIMP search is the first study using the full rejection capabilities of the SuperCDMS detectors. The backgrounds were modelled using MC simulations and data in the signal sidebands only, and are able to provide predictions in good agreement with data, with the exception of one detector with a modified applied electric field. In addition, this analysis presented the first application of multivariate techniques in direct DM searches, demonstrating that such approach greatly improves the performance of the discriminant quantities in the limit of their resolution. The result obtained in this study is competitive with other DM searches, and along with those from CDMSlite and LUX set severe constraints to the WIMP interpretation of event excesses reported by DAMA, CDMS II (Si) and CoGeNT.

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References

[1] J. L. Feng, Ann. Rev. Astro. Astrophys. 48 (2010) 495.
[2] D. B. Kaplan, Phys. Rev. Lett. 68 (1992) 741.
[3] D. E. Kaplan, M. A. Luty, K. M. Zurek, Phys. Rev. D 79 (2009) 115016.
[4] C. Cheung, J. T. Ruderman, L.-T. Wang, I. Yavin, Phys. Rev. D 80 (2009) 035008.
[5] R. Essig, J. Kaplan, P. Schuster, N. Toro, arXiv:1004.0691.
[6] A. Falkowsky, J. Ruderman, T. Volansky, J. High Energy Phys. 1105 (2011) 106.
[7] K. Zurek, arXiv:1308.0338.
[8] D. Hooper, W. Xue, Phys. Rev. Lett. 110 (2013) 041302.
[9] K. Petraki, R. R. Volkas, Int. J. Mod. Phys. A 28 (2013) 1330028.
[10] D. G. Cerdeno, M. Peiro, S. Robles, JCAP 1208 (2014) 005.
[11] R. Bernabei, et al., Eur. Phys. J. C 73 (2013) 2648.
[12] R. Agnese, et al., Phys. Rev. Lett. 111 (2013) 251301.
[13] C. E. Aalseth, et al., Phys. Rev. D 88 (2013) 012002.
[14] P. Luke, J. Appl. Phys. 64 (1988) 6858.
[15] R. Agnese, et al., Phys. Rev. Lett. 112 (2014) 241302.
[16] A. Hocevar, et al., arXiv:physics/0703039.
[17] S. Yellin, Phys. Rev. D 66 (2002) 032005.
[18] S. Yellin, arXiv:0709.2701.
[19] G. Angloher, et al., Eur. Phys. J. C 72 (2012) 1971.
[20] Z. Ahmed, et al., Science 327 (2010) 1619.
[21] Z. Ahmed, et al., Phys. Rev. Lett. 106 (2011) 131302.
[22] R. Agnese, et al., Phys. Rev. Lett. 112 (2014) 041302.
[23] D. Akerib, et al., Phys. Rev. Lett. 112 (2014) 091303.
[24] J. Angle, et al., Phys. Rev. Lett. 107 (2011) 051301.
[25] E. Armengaud, et al., Phys. Rev. D 86 (2012) 051701.
[26] E. Aprile, et al., Phys. Rev. Lett. 111 (2013) 021301.