FERMILAB-CONF-07-606-E

CDMS experiment : current status and future

Jonghee Yoo
(for CDMS collaboration)
Fermi National Accelerator Laboratory, PO Box 500
Batavia, IL 60510, USA
E-mail: yoo@fnal.gov

We present the current status of the Cryogenic Dark Matter Search (CDMS). The five tower detector array, total 30 detectors, are running stable since October 2006. We have accumulated more than 900 kg-days of low background data. We also summarize the prospect of SuperCDMS project.

Keywords: Dark matter, WIMP, CDMS, SuperCDMS

1. Introduction

The observations of rotational curve of galaxies, cosmic microwave background, large scale structure, galaxy clusters, gravitational lensing, bullet clusters provide that nonluminous, nonbaryonic mass components may constitute most of the matter in the Universe.[1] Cosmological relic abundance arguments suggests that it is reasonable to probe weak interaction scale and around 100 GeV of mass. Weakly interacting massive particles (WIMPs) are currently the most popular dark matter candidate. Interestingly, supersymmetric scenarios provide stable massive neutral particles, the neutralinos, in the weak interaction scale. Future collider experiments such as LHC and ILC may reveal the characteristics of the supersymmetirc particles. However it should be pointed out that the dark matter is not necessarily a supersymmetric particle, and need not to have an electro-weak interaction[2].[3] Therefore direct detection of the dark matter is a crucial step to understand its nature.

The Cryogenic Dark Matter Search (CDMS) experiment is designed to detect WIMP signal through nuclear recoil by elastic scattering. The detector is capable of reading out both phonon-energy and ionization-energy of an interaction in Ge or Si crystals. The CDMS-I experiment was carried out in Stanford underground laboratory and the performance of detectors had been demonstrated. The CDMS-II experiment moved to the Soudan underground laboratory which substantially reduced cosmic-ray induced neutron background. There are three phases to the CDMS-II experiment. The first phase was a single tower (4 Ge and 2 Si detectors) operation and the second phase was a two tower (6 Ge and 6 Si detectors) operation. The third and current phase of the CDMS-II experiment, five tower detector array and total 30 detectors, are running stable since October 2006. We accumulated more than 900 kg-days of data. The five tower operation will be kept until the summer of 2008.

2. CDMS experiment

CDMS ZIP detectors (depth(Z)-sensitive Ionization and Phonon detectors) is able to discriminate WIMP-nucleus recoil energy by measuring both ionization and phonon signal from the crystal.[6] The ZIP detector is made of pure Ge (250 g) or Si (100 g) crystal in a cylindrical shape of 1 cm thickness and 7.6 cm in diameter. A tower consists of a vertically stacked 6 ZIP detector-array. The detectors are cooled by a dilution refrigerator down to 50 mK. The low temperature configuration prevents background fluctuations from thermal excitations in the crystal. The ionization signal is the interaction that excite the electron-hole pairs of the semiconductor crystal. The electron and hole pairs are separated by an electric field through the crystal. The ionization signals are then read out by inner and outer electrodes. The inner electrode covers 85% of ionization side of the detector. The outer electrodes provides discrimination power of the edge events. The outer electrode is used to discriminate those edge-events. The phonon signals that are produced by vibration of crystal lattice are read out by total 4144 per detector of Quasiparticle-assisted Electrothermal-feedback Transition-edge sensors (QETs). Each QET consists of a 1 μm wide strip of tungsten connected to 8 superconducting aluminum collection fins which cover the phonon sensor side of the crystal. The tungsten strips from the Transition-Edge-Sensors (TESs) are voltage biased, with the current through them monitored by a high-bandwidth SQUID array.

When an interaction occurs in the crystal, huge amount of phonons are produced. Almost half of the phonon energy goes into thermal phonons which may not read out by the QETs. Most of the athermal phonons that reach the surface of phonon sensor area can scatter into the aluminum fins. The phonons, energetic enough (above 340 μeV) to break Cooper pairs in a superconducting state of aluminum fins, produce quasiparticles. The

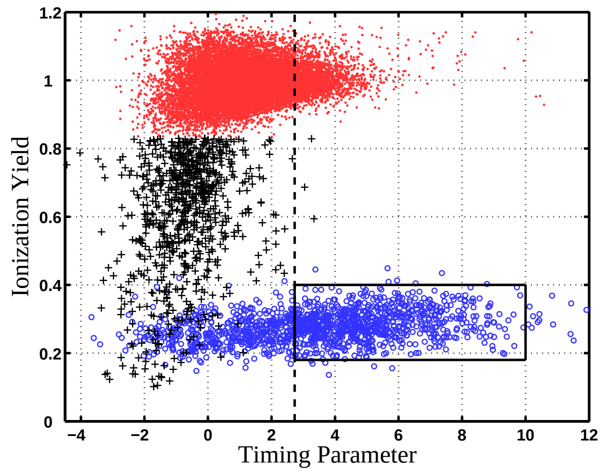

Fig. 1. Ionization yield versus timing parameter for calibration data in a Ge detector with the recoil energy range 10–100 keV. The ionization yield shows clear separation between bulk-electron recoil events (dots and yield near 1.0; from ^{133}Ba calibration source) from nuclear recoil events (circles and yield near 0.3; from ^{252}Cf calibration source). The surface-electron recoil events (crosses) from ^{133}Ba show wide distribution along the ionization yield and non-negligible amount of events are leaked into nuclear recoil area. The timing parameter has discrimination power of those electron leak events. The vertical dashed line shows the minimum allowed timing parameter for WIMP candidate event. The squared area is an allowed region of nuclear recoil.

quasiparticles enter into TESs. The interaction between the quasiparticles and conduction electrons in the TESs increase the system temperature and hence increase the tungsten resistance. The increase of resistance decreases the current supplied by the voltage bias. The reduction of Joule heating from the voltage bias lowers the tungsten temperature. This strong electro-thermal-feed-back guarantees that the power deposited into the TES is exactly compensated for by a reduction in Joule heating. The energy deposited can then be measured by reading out change of currents.

Detector calibrations are carried out during the normal data-taking period. A ^{133}Ba gamma-ray source is used to calibrate energy scale and to characterize detector response to electron recoils. A ^{252}Cf neutron source is used to characterize the detector response of nuclear recoils produced by neutrons. The nuclear recoil characteristics is important to determine WIMP signal region. Results of Monte Carlo simulations of ^{133}Ba and ^{252}Cf calibration show excellent agreement with data.

3. Backgrounds

The CDMS detectors demonstrated excellent performance of the particle identification. The ionization signals producing a nuclear recoil, which WIMPs may cause, are suppressed compared to electron recoils while phonon signals are not. The ratio between ionization and phonon (recoil) energy, termed as ionization yield, provides strong discrimination power of background events. However, the events in the detector surface suffer ionization yield suppression, therefore some of those events could be misidentified as nuclear recoils. The phonon pulse time information, such as start and rise of phonon pulse, helps to reject 97% of these surface events while keeping 70% of true nuclear recoils. Figure 1 shows ionization yield versus timing parameter for calibration data of ^{133}Ba and ^{252}Cf sources. The ionization yield shows clear separation between bulk-electron recoil events from nuclear recoil events. The surface-electron recoil events can be excluded by setting a timing parameter cut. The squared area in the figure is defined as a WIMP signal region before looking at WIMP search data sample.

The WIMP is supposed to interact weakly ($<10^{-42}$cm^2) and the mean free path in Ge is order of 10^{10} m. Therefore WIMP will scatter a single time while neutrons can multiple scatter in the detector array. Choosing only single scatter events, the neutron events can be reduced. Since WIMPs are assumed to transfer small momenta to the nucleus they will scatter off coherently with whole nucleus. Therefore the interaction rate of WIMPs in nuclei is expected to be proportional to mass-square ($\propto$A^2) of the target nuclei. Accordingly the WIMP interaction rate in ^{73}Ge is $\sim$6 times larger than ^{28}Si while neutron interaction rates are similar for both crystals. Once we observe handful amount of WIMP candidate events in several detectors, by comparing event rates between Ge and Si detectors will provide statistical discrimination power between neutrons and WIMPs.

The CDMS-I experiment had been carried out at the Stanford Underground Facility (SUF), California, USA at a depth of 10.6 m (17 meters water equivalent). The expected cosmic-ray muon background rate in this shallow site is 50 muons sec^{-1}m^{-2}. Neutrons, the most serious background source at SUF, gave a rate of $\sim$1 event kg^{-1} day^{-1}. A single tower, total 6 detectors (4 Ge + 2 Si), was operated a total of 65.8 detector live days and 28.3 kg-day of net exposure. 20 nuclear recoil events are observed from the WIMP search data sample and those agreed with the expected neutron background rate.[11]

The first phase of the CDMS-II experiment, a single tower operation with the identical detector configuration at SUF, was carried out in the

Soudan Underground Laboratory, Minnesota, USA, at a depth of 780 m from the surface (2090 meters water equivalent). The cosmic muon rate was reduced down to 0.25 muons min^{-1} m^{-2}. Neutron background rate is estimated to be 1 event $\mathrm{kg}^{-1}\,\mathrm{year}^{-1}$. The rate of unvetoed neutron induced recoils is 3×10^{-4} kg^{-1} day^{-1} and is estimated by Monte Carlo simulations. A total of 52.6 detector live days and 19.4 kg-day of net exposure were achieved. The dominant source of background in Soudan Underground Laboratory is surface electrons from the radioactive contaminants. The number of electron-recoil events expected to be misidentified as nuclear recoils were estimated 0.7 ± 0.3 in Ge detectors. The analysis results found one nuclear-recoil candidate event at 64 keV, consistent with the expected background event[12].[13]

The second phase of the CDMS-II experiment, a two tower operation, was carried out with six more detectors. The operation periods was from March 25 to August 8, 2004 total 74.5 detector live days and 34 kg-day (13 kg-day) net exposure for Ge (Si) detectors.

The third phase of the CDMS-II experiment, a five tower operation, is now up and running since October 2006. We have accumulated almost 800 kg-day of detector exposure data. We expect the results of the first half of data analysis in the early 2008.

4. Data analysis

Since the five tower data blind analysis is currently in progress, we describe general schematics of CDMS data analysis based on two tower analysis.

To prepare good WIMP search data samples, we exclude data sets with known problems such as events triggered by noise burst, non-operational channels and fails off-line diagnostics. For recoil energies above ∼10 keV, events due to background photons are rejected with $> 99.99\%$ efficiency. Electromagnetic events very near the detector surface can mimic nuclear recoils because of reduced charge collection. These surface events, however, are rejected with $> 96\%$ efficiency by using additional phonon pulse shape information.

The band-width of the electron-recoil and nuclear-recoil in the ionization yield parameter space (ionization energy / recoil energy) are taken to be $\pm 2\sigma$. The veto coincident events are removed. Then we choose single scatter events, which has a signal only in one detector out of 12 detectors.

Events with low ionization yield in the ^{133}Ba calibration data, which presumably come from surface electron recoils, were used to develop rejection cut criteria. Two phonon pulse timing quantities, the time delay of the

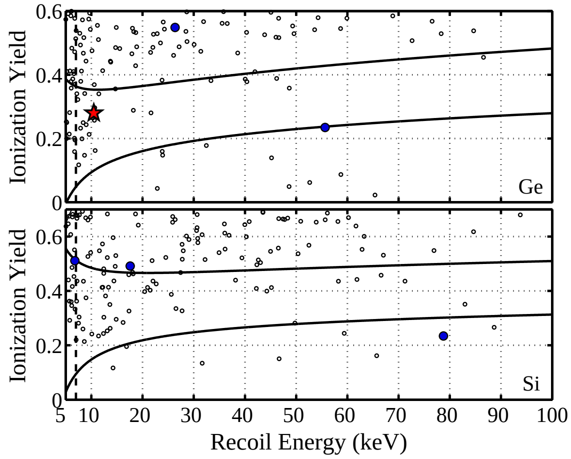

Fig. 2. Ionization yield versus recoil energy events for Ge (upper figure) and Si (lower figure) detectors before (small circles, solid dots and star mark) and after (solid dots and star mark) surface electron recoil rejection cut (timing parameter cut). The 7 keV energy threshold is shown in vertical dashed line in each figure. The ionization yield between curved lines in each figure is WIMP signal region. One candidate event is found in WIMP search signal band in Ge detector with recoil energy of 10.5 keV (shown in star mark in upper figure).

phonon signal relative to the fast ionization signal and the phonon pulse rise time, in the quadrant with the largest phonon signal or local-quadrant phonon signal are used to discriminate surface events. The sum of delay and rise time forms a timing parameter, where energy corrections to the delay and rise time are applied to achieve energy-independence (see figure 1).

The surface event backgrounds at WIMP search signal region (nuclear recoil band) are estimated and the expected background rate is based on the passing fraction between 10–100 keV in the WIMP-search data. The number of surface events expected to pass the timing cuts are $0.4\pm0.2(\mathrm{stat})\pm0.2(\mathrm{syst})$ between 10–100 keV in Ge detectors and $1.2\pm0.6(\mathrm{stat})\pm0.2(\mathrm{syst})$ between 7–100 keV in Si detectors. From simulations, the expected background from unvetoed nuclear recoils due to impinging cosmogenic neutrons is 0.06 events in Ge and 0.05 events in Si.

Figure 2 shows the unmasked WIMP search data in ionization yield versus recoil energy for both Ge (upper figure) and Si (lower figure). We observe one WIMP candidate event which turned out to have occurred in a detector while it suffered inefficient ionization collection. Therefore the single event indeed not a WIMP signal. Although we count the event as a WIMP candidate, it is still consistent with the rate of expected background. The results exclude WIMP-nucleon cross section above $1.6\times10^{-43}\,\mathrm{cm}^2$ from Ge detectors and $3\times10^{-42}\,\mathrm{cm}^2$ from Si detectors, for WIMP mass $60\,\mathrm{GeV/c}^2$ with 90%C.L..[14]

The five tower (19 Ge and 11 Si, total 5.85 kg) detector array is currently running stable. The accumulated detector exposure is more than 900 kg-day and it is planned to operate until the summer of year 2008. The five tower operation will provide additional factor ten in sensitivity of WIMP-nucleon cross section in near future.

5. SuperCDMS

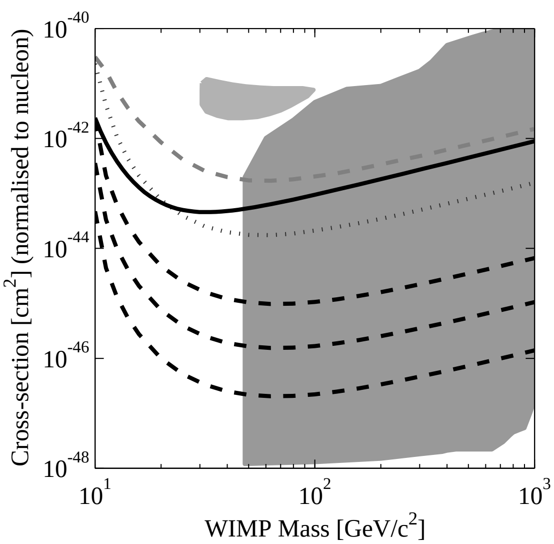

Fig. 3. WIMP search sensitivity (projected). The gray-dashed line at the top is the CDMS-II two tower limit. The black-solid line is the XENON10 limit. The gray-dotted line at the second is the projected limit for third phase (five tower) of CDMS-II. The consecutive dotted, dashed and solid lines are projected sensitivity for SuperCDMS phase A (25 kg), B(120 kg) and C(1 ton) respectively.

The CDMS experiment is currently the most proved equipment to carry out Dark Matter search with background free configuration. The background rejection power provides the sensitivity of the experiment directly proportional to the mass of the detector and exposure time (MT) rather than square root of them ($\sqrt{MT}$). Therefore increasing mass of the detector is the most efficient way to prove smaller WIMP-nucleon cross sections.

In the summer of 2008, we are planning to replace the first two towers of the normal detector to two towers of the super detector (1 inch thick) arrays. The experiment is to focus more on the detector performance test for the 25 kg operation at the existing Soudan facility. The two SuperTowers with $\sim$8 kg of Ge operated during 2008-09 will have the WIMP-nucleon cross section sensitivity down to $\sim 7 \times 10^{-45}$ cm^2 at 60 GeV of WIMP mass.

The SuperCDMS[15] project proposes to install super towers in the SNO-Lab, total mass 25 kg, the seven SuperTowers of six 2.5-cm-thick ZIP detectors during 2011-13. With advanced surface rejection analysis technique and radio active background handling, the SuperCDMS 25 kg SNOLab phase is expected to reach a sensitivity of cross-section of 1.3×10^{-45} cm^2. Figure 3 shows projected WIMP search potential for each phase of detector operation. The SuperCDMS experiment can scan most of the region of WIMP-nucleon cross-section and mass parameter spaces.

Acknowledgments

This work is supported by the National Science Foundation under Grant No. PHY-9722414, by the Department of Energy under contracts DE-AC03-76SF00098, DE-FG03-90ER40569, DE-FG03-91ER40618, DE-FG02-94ER40823, and by Fermilab, managed by the Fermi Research Alliance, LLC, under Contract No. DE-AC02-07CH11359 with the Department of Energy. The ZIP detectors were fabricated in the Stanford Nanofabrication Facility operated under NSF.

References

1. D. N. Spergel *et al.*, (WMAP Collab.), Astrophys. J. Suppl. **148**, 175 (2003); M. Tegmark *et al.*, (SDSS Collab.), Phys. Rev. D **69**, 103501 (2004).
2. G. Steigman and M.S. Turner, Nucl. Phys. **B253**, 375 (1985).
3. G. Jungman, M. Kamionkowski, and K. Griest, Phys. Rep. **267**, 195 (1996);
4. P. Salucci and A. Borriello, Lect. Notes Phys. **616**, 66 (2003); T. Broadhurst *et al.*, Astrophys. J. **621**, 53 (2005).
5. J. D. Lewin and P. F. Smith, Astropart. Phys. **6**, 87, 1996.
6. K.D. Irwin *et al.*, Rev. Sci. Instr. **66**, 5322 (1995); T. Saab *et al.*, *AIP Proc.* **605**, 497, 2002.
7. Y. G. Kim *et al.*, JHEP **12**, 034 2002.
8. J. Ellis *et al.*, Phys. Rev. D **71**, 095007 (2005).
9. E. A. Baltz and P. Gondolo, JHEP **10**, 052, 2004.

10. R. Bernabei *et al.*, Phys. Lett, **B389**, 757, 1996.
11. D. S. Akerib *et al.*, (CDMS Collab.) Phys. Rev. D **68**, 082002 (2003).
12. D. S. Akerib *et al.*, (CDMS Collab.) Phys. Rev. Lett. **93**, 211301 (2004).
13. D. S. Akerib *et al.*, (CDMS Collab.), submitted to PRD. arXiv:astro-ph/0507190.
14. D. S. Akerib *et al.*, (CDMS Collab.), submitted to PRL. arXiv:astro-ph/0509259.
15. R. W. Schnee *et al.*, (SuperCDMS Collab.), astro-ph/0502435; P. L. Brink *et al.*, (SuperCDMS Collab.), astro-ph/0503583.