Progress of CDMS-II at the Soudan Mine

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The Cryogenic Dark Matter Search (CDMS) has recently completed its first year of running in the deep site at the Soudan Underground Laboratory (2090 mwe). This year produced two distinct data sets: the first, Run 118, used the same four germanium and two silicon detectors as previous CDMS runs from the shallower Stanford site; while the second, Run 119, included two additional Ge detectors and four new Si detectors. The Run 118 data set, with 52.6 kg-days of Ge exposure before cuts, currently gives the world's best exclusion limit for spin-independent WIMP interactions: 4×10^{-43} cm^2 for a WIMP mass of 60 GeV/c^2 (90% confidence level). Run 119 provides 110 kg-days of Ge exposure before cuts. The blinded analysis of this data set is in progress, with an expected improvement in combined sensitivity of a factor of three.

1. Introduction

The Cryogenic Dark Matter Search (CDMS) seeks to directly detect the Weakly Interacting Massive Particles (WIMPs) that may make up the majority of the matter in the universe [1]. The present concordance picture of cosmology, supported by a wide variety of observations, suggests that 23% of the energy in the universe is in non-baryonic dark matter of unknown composition [2]. This dark matter governs the formation of structure and the dynamics of galaxy clusters. The even more mysterious dark energy contributes another 73%, and only 4% is in the form of familiar baryonic matter. More locally, the rotation curves of spiral galaxies such as our own strongly confirm that the visible galactic disk is surrounded by a larger and more massive dark halo [3]. Inert WIMPs left as relics of the early universe are a strong candidate for the composition of this halo. They are also naturally present as the lightest new particle in many supersymmetric models, specifically those that conserve R-parity [4].

If the galaxy's dark matter halo is indeed composed of WIMPs, they should interact occasionally with the target nuclei in dark matter detectors on the Earth, depositing energies on a scale of 10 keV at a rate $\lesssim$ 1/kg/d [5]. The CDMS-II detectors are designed to have a low energy threshold and a low background event rate in the signal region in order to make them sensitive to these expected rare, low-energy elastic scatters. Because WIMPs are expected to interact primarily with the target nuclei, while most of the background scatters are electromagnetic, discriminating sensors can be used to achieve a very low effective background. The CDMS Z-sensitive Ionization and Phonon (ZIP) detectors distinguish nuclear recoils from electron recoils and also distinguish events caused by surface contaminants from bulk recoils in the detector crystals.

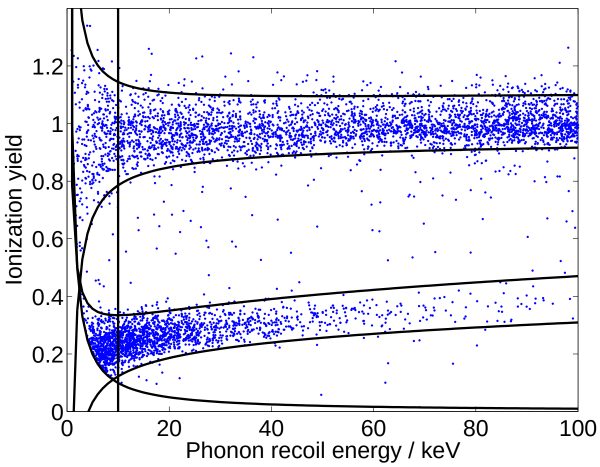

Figure 1: Ionization yield vs. recoil energy for Run 119 calibration data with a ^{252}Cf source for the third detector of tower 2 (Ge). The two-sigma electron- and nuclear-recoil bands are shown, along with the analysis threshold in the ionization channel (hyperbola) and phonon channel (vertical line).

2. Experimental Apparatus

2.1. CDMS Detectors

Each CDMS-II ZIP detector is a 250-g (100-g) crystal of germanium (silicon), 76 mm in diameter and 10 mm thick. One face of the crystal is patterned with superconducting Transition Edge Sensors (TESs), which collect athermal phonons as a measure of the total energy of each particle interaction. The detector substrates are kept below 50 mK, and the TESs self-heat to the transition temperature of their tungsten thin films, 70-100 mK. The energy of the phonons is transmitted into the tungsten films via aluminum collector fins on the crystal surface, and this energy is measured as a heating and consequent change in resistance of the tungsten TESs. The phonon sensors of each detector are divided into four independent quadrants, and the relative pulse height and delay in these four channels gives substantial information about the position of each event within the crystal.

A 3-V bias (4 V for Si ZIPs) across the crystal drifts electrons and holes produced in the interaction to electrodes on the surfaces. This measurement of ionization provides a second estimate of the energy deposited in the crystal. Moreover, the ionization signal is quenched for nuclear recoils relative to electron recoils by a factor of $\sim$3, so that the simultaneous measurement of charge and phonons allows event-by-event nuclear recoil discrimination. The ratio of ionization to phonons, normalized to 1 for bulk electron recoils, is known as "yield" and forms the primary discrimination parameter for CDMS (See Fig. 1). Each detector has two electrodes: a central disk defining a fiducial volume (85% of the detector) and an outer guard ring (15% of the detector) where edge effects become significant.

The detectors are installed in close (2mm separation) vertical stacks (or "towers") of six ZIPs. This configuration allows important information to be extracted from events that deposit energy in more than one detector, as described below.

Particle interactions in the crystal generate a population of prompt athermal phonons, but the charges drifting through the electric field also produce a second, much faster, population of Neganov-Luke phonons [6]. At a 3-V bias (3.8V for Si), these two populations have approximately equal energies for electron recoils. Nuclear recoils, with ionization suppressed by a factor of three, also have a smaller Luke phonon population. Electron recoils, therefore, cause phonon pulses with faster rising edges than nuclear recoils. In addition, events near the surfaces of the detectors have faster rising edges than bulk electron recoils because of phonon interactions with the metallized surfaces. The risetime of phonon pulses, and the delay of phonon pulses relative to phonons, therefore present a second way of rejecting electron recoil backgrounds.

The ionization yield alone is very effective for rejecting bulk electron backgrounds such as gamma-emitting contaminants. Very near the surfaces of the crystals, however, is a thin "dead layer" in which the ionization signal is suppressed because the electrons and holes may travel to the wrong electrodes. This allows surface events, caused for instance by beta-emitting surface contaminants, to be mistaken for nuclear recoils. These are also the events for which the ZIP detectors' timing-based discrimination is most effective, so the combination of ionization yield and phonon pulse timing together gives a very small leakage of electromagnetic backgrounds into the WIMP signal region. The distribution of timing parameters for bulk electromagnetic recoils, low-yield events near the detector surface, and neutrons is shown in Fig. 2.

Neutrons passing through the ZIP detectors appear identical to WIMPs, both in ionization yield and phonon timing. Therefore, neutrons can only be rejected statistically. A neutron has a significant (but less than 10%) chance of interacting in several detectors [10], while a WIMP has a scattering length of light years and will never multiply scatter. Neutrons are almost equally likely to scatter in silicon and germanium ZIPs, and have a harder spectrum in silicon. Given a 10-keV energy threshold, this leads to an expectation of about twice as many neutron scatters in silicon as in germanium. WIMPs, on the other hand, are expected to scatter much more often in germanium because of the A-squared dependence of the WIMP scattering cross section on the nuclear mass of the target. Therefore, multiply scattering nuclear recoil events and nuclear recoils in silicon can be used to

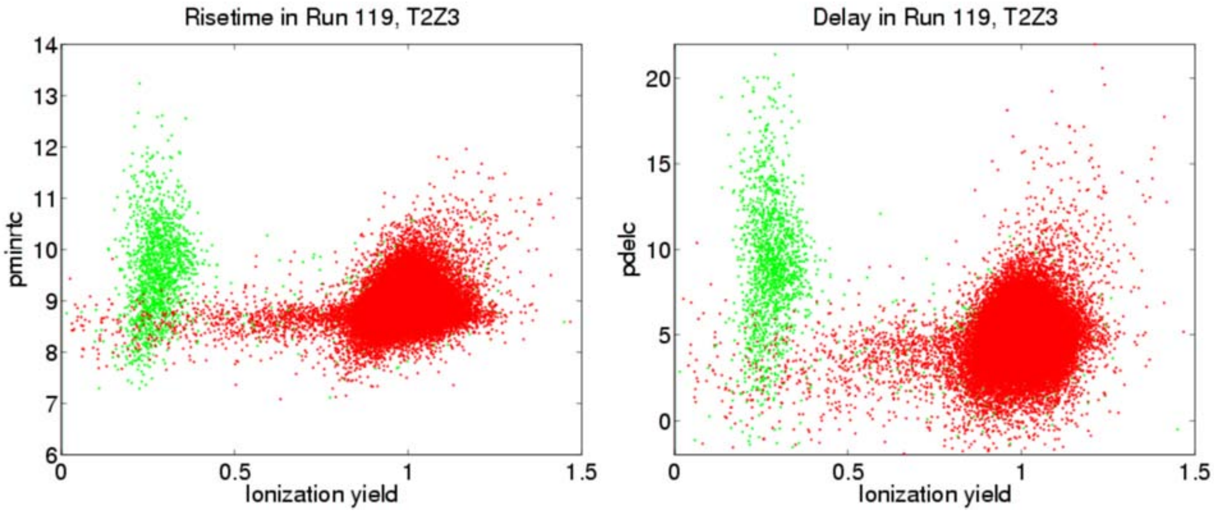

Figure 2: Discrimination power in phonon pulse risetime (left) and delay (right) for Run 119 calibration data. The points shown are from ^{133}Ba (dark) and ^{252}Cf (light) calibration data. The behavior of neutrons, bulk gammas, and low-yield electromagnetic recoils is similar in the two quantities. The neutrons at left extend to longer risetime and delay. The bulk electron recoils on the right have somewhat shorter risetime and delay, and the low-yield electron recoils (detector surface events) in between have much faster timing. In these plots, all data quality cuts and the fiducial volume cut have been imposed. The recoil energy range shown is 20-100 keV.

characterize any signal events as statistically consistent with or inconsistent with a neutron background.

2.2. Experimental Site and Shielding

The first six ZIP detectors were operated in a shallow underground site at Stanford University until July of 2002. The WIMP sensitivity of the experiment was limited by the background of neutrons produced by cosmic ray muons interacting in the concrete walls of the chamber, outside the experiment's shielding [10]. Reducing this background required moving the experiment to a deeper site.

The CDMS-II deep experimental site is the Soudan Underground Laboratory in northern Minnesota. This site provides half a mile (2090 meters water equivalent) of rock overburden, reducing the cosmic ray muon flux by a factor of 5×10^4. The outermost layer of shielding is an active muon veto constructed of scintillator panels and photomultiplier tubes, which can reject muons passing near the detector volume. The efficiency of the muon veto is >99.9% for muons passing through the apparatus, and >99.4% for muons stopping within the shielding. Inside the active veto are (from outside in) 45 cm of polyethylene neutron moderator, 9 cm of lead, 4.5 cm of ancient lead (for low ^{210}Pb content), and another 10 cm of polyethylene. The cryogenic volume or "icebox" is a series of six nested copper cans cooled by an Oxford 400S dilution refrigerator outside the shielding. A set of six copper tubes connects the refrigerator to the detector volume, allowing the detectors to operate at < 50 mK in the innermost icebox can without being physically near the refrigerator and its cryogens. It is desirable for the refrigerator to be outside the shield because the refrigerator itself does not have as low a level of radioactive contamination as the specially screened copper of the icebox. The icebox is immediately surrounded by a thin mu-metal shield for isolation from external magnetic fields.

Beginning in November of 2003, the shield has been purged with a constant flow of old air to remove radon from the air near the detector volume. This purge has reduced the radon decay rate in the air around the icebox from 500 Bq/m^3 to 35 Bq/m^3, and the background of electromagnetic recoil events with low ionization yield in the detectors by a factor of two.

3. Data Sets

The first WIMP-search data set from Soudan was Run 118, lasting from October 2003 through February 2004. Run 118 used the same four Ge and two Si detectors (1 kg Ge, 200 g Si) as the Run 21 data set from the shallow underground site at Stanford [10]. During this period the detectors accumulated 52.6 kg-days of Ge raw exposure (before cuts). The main causes of dead time were cryogen transfers (3 hours/day), and periods of elevated base temperature. After all data quality and background-rejection cuts, this yielded 22 kg-days of WIMP-search exposure. The hardware trigger threshold was below 2 keVin most detectors, with a background trigger rate of 0.1 Hz during Run 118.

The second data set was Run 119, lasting from

March through August of 2004. During this run, the same six detectors plus an additional two Ge and four Si (for a total of 1.5 kg Ge and 600 g Si) collected 110 kg-days of raw Ge exposure. The final WIMP-search cuts and exposure for Run 119 are still in preparation.

During both Run 118 and Run 119, the low-background data sets of the WIMP search were interspersed with calibration data for which a radioactive source was placed near the detectors. A ^{133}Ba gamma source produced gamma-ray energies of 276, 303, 356, and 384 keV for energy calibration and studies of detector stability, as well as providing a sample of electromagnetic recoils against which background rejection techniques were developed and tested. A ^{252}Cf neutron-emitting source was used to develop the nuclear-recoil selection cuts and to calculate the efficiencies of the data cuts for nuclear recoil events. A comparison of the observed californium neutron spectrum with Monte Carlo predictions also allows a check of the recoil energy calibration for nuclear recoil events.

During Run 118, the barium calibration data were taken mainly in several very large data sets in early December of 2003, and the californium calibration data were taken at three discrete points during the run. The Run 119 barium data sets, totaling 8 million events, were taken more uniformly throughout the run, giving a calibration sample that has both high statistics and a similar distribution in time to the WIMP-search data. Because exposure to the californium source activates the Ge substrate of ZIP detectors, the neutron calibration sample was kept small (215,000 events) and was not interspersed uniformly with WIMP-search data.

In order to ensure an unbiased treatment, both Run 118 and Run 119 have been analyzed under formal blinding schemes. A preliminary, wide WIMP-search cut was defined, and all events passing this cut were hidden from users until unblinding. This cut allowed analysis of low-background data clearly outside of the WIMP signal region, such as multiple scatters, electron recoils, and events coincident with muons in the veto. The ionization yield cut used in the blinding scheme is deliberately made wider than any of the possible final cuts, so that the final signal region will reliably be blinded. The pulse timing cut is not used in the blinding, except for one problematic Ge detector (ZIP 1) in which the ionization yield is subject to an unusually large variation with position in the detector. Once all of the WIMP-search cuts were defined, the full data set was unblinded for a counting of WIMP candidate events.

For some data sets in Run 118 the cuts of the blind analysis were defined on a different charge energy estimator than intended. This energy quantity is quite similar to the intended ionization quantity, but is slightly more sensitive to certain types of noise for the charge channels. The problem was discovered immediately after unblinding, so R118 has both a formally blind analysis, and a second "intended" analysis. This uses the same cuts, but applies them to the intended, slightly better, charge energy quantities for all data sets.

In Run 119, a similar blinding scheme has been imposed on the background data. This blinding remains in place pending final studies of the WIMP-search cuts.

With the very large calibration data sets now available, the Run 119 analysis has divided the barium source data into two halves, interleaved throughout the run. One half is used for developing cuts, especially the timing cuts for rejecting surface events. Once the cuts are frozen, the second half of the barium data is used for estimating the leakage of electromagnetic backgrounds into the signal region. This additional form of blinding allows the estimated background leakages - especially for the pulse timing cut – to be calculated in a simple way from an independent electron recoil data sample. This procedure was not used in Run 118, which had a smaller sample of barium calibration data. Instead, the timing cut was defined to pass exactly one low-ionization electron recoil event in each detector from the entire barium calibration data set. This was then scaled to the smaller number of electron recoils in the background data set to give an expected WIMP-search leakage of 0.1 event.

, and the expected leakages for the background data set followed from this definition.

4. Analysis

The CDMS analysis applies a number of data quality cuts to the WIMP-search data, followed by WIMP-candidate selection cuts. The data quality cuts remove periods of known poor detector performance and elevated base temperature; events with abnormally shaped phonon pulses; events with energy below the analysis threshold in recoil (ordinarily 10 keV, but as low as 5 keV in analyses tailored to low-mass WIMPs) or ionization energy (1-3 keV); and events with unusually high baseline noise before the trigger. These data quality cuts remove 5% of the events. A fiducial volume cut rejects the annular region near the outer edge of the crystal (15% of the detector volume), where the ionization signal may be incomplete. WIMP candidate events must also pass several background rejection cuts: they must be single scatters interacting in only one detector, not coincide with a muon in the veto, and have ionization yield and pulse timing consistent with a nuclear recoil.

The ionization yield cuts are defined as two-sigma band cuts, calculated for each detector from the californium calibration neutrons. The band cut is a function of energy. This is the primary gamma background rejection cut of the ZIP detectors.

The phonon pulse timing cuts are an area of active development. The cuts used in Run 118 achieved 80% nuclear recoil acceptance for 20% electron-recoil acceptance by using independent cuts on the rise time of the phonon pulses and their delay relative to the ionization signal. The effectiveness of these cuts at rejecting low-yield events such as surface betas is substantially higher. Further analyses under study in Run 119 define new pulse-timing parameters with richer information, and combining the available parameters together in more sophisticated ways to achieve better performance. The rich timing and position information provided by the ZIP detectors are expected to allow substantial improvements in the pulse timing cuts.

5. Results

The Run 118 blind analysis produced zero signal events with 22 kg-days of exposure after all cuts [7]. The subsequent, "intended" analysis contained one candidate event, which marginally passed the fiducial volume cut in this analysis but was rejected in the blinded analysis. This event, with a recoil energy of 64 keV, appears likely to be caused by surface contamination. Its high energy makes it a poor match for WIMPs with mass below about 50 GeV, so it has little effect on the final WIMP exclusion limits below this mass.

Because Run 119 remains blinded, the count of candidate events is unknown. However, some information from the unblinded portion of the background data is available and informative. There is one event in which a throughgoing muon (tagged by the veto both when entering and exiting) produced a neutron within the shielding, and this neutron was seen in the detectors. This neutron deposited 42 keV in the bottom (Si) detector of the first tower, and 6 keV in the (Ge) detector above it. Its ionization yield is consistent with a nuclear recoil in both detectors. This is the only muon-coincident nuclear recoil event in the background data set.

If a neutron is produced by a muon interacting in the cavern wall, it may pass through the veto and the passive shielding without being stopped or tagged. Although such events came to limit the WIMP-search sensitivity of CDMS at the shallow site, the low muon flux in the Soudan Mine leads to an estimate of one unvetoed neutron in several years of WIMP-search running. If any such events scattered in several detectors, they would not be subject to blinding; no veto-anticoincident neutron double scatters are seen in the Run 119 low-background data with 110 kg-days before cuts.

The WIMP exclusion limits in the cross-section - mass plane are shown in Fig. 3. The Run 118 limits are shown both for the zero-event blinded result, and for the one-event intended analysis. The Run 119 curves are an expected sensitivity, since the number of candidate events remains blinded at this time. The Run 120 curves assume that the full complement of thirty ZIP detectors will be run at Soudan for one year. In all cases, a standard isothermal, spherical WIMP halo is assumed, with a mean WIMP velocity of 230 km/s. All cross-sections are normalized to a single nucleon, and only the spin-independent case is shown.

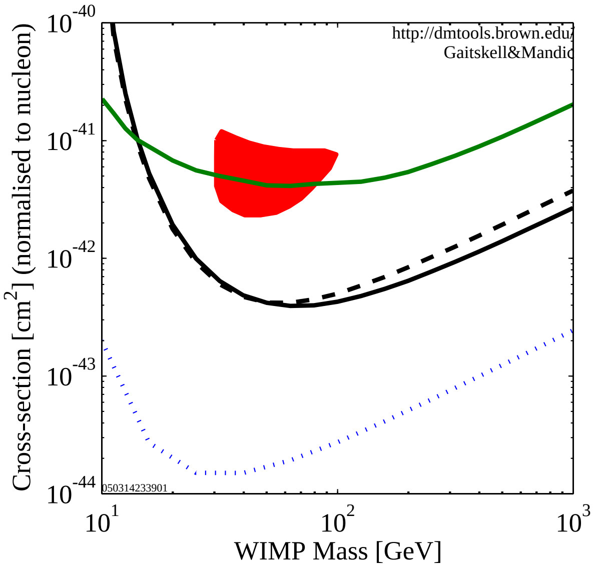

Figure 3: Current and projected WIMP exclusion limits from CDMS-II at Soudan. Parameter space above each curve is excluded at 90% confidence level. The upper dotted line is the result from CDMS at Stanford, with no background subtraction [10]. The solid line is the limit from the Run 118 blind analysis, and the dashed line is from the Run 118 intended analysis [7]. The lower dotted line is the projected final sensitivity of CDMS-II at Soudan. The solid region is the DAMA (1-4) 3σ allowed region [11] under the same standard model assumptions.

Although its primary analysis focuses on WIMPs with spin-independent couplings, for which coherent scattering from the entire nucleus enhances its sensitivity, CDMS also sets competitive limits on WIMPS with spin-dependent couplings [8].

6. Current Status

After the end of Run 119 in August 2004, an additional eighteen detectors were installed in the Soudan icebox. These give a total of 4.75 kg Ge and 1.10 kg Si target mass, and the three newly-added ZIPs are expected to be cleaner than the earlier ones from the point of view of surface contamination. Preparations are underway for the beginning of the next run with all thirty detectors. This completes the full complement of detectors for CDMS-II, although more may be added as part of the SuperCDMS development project [9].

7. Conclusion

Run 118 has established the current leading WIMP exclusion limits for a wide range of WIMP masses under standard halo assumptions. The Run 119 data in hand will improve this sensitivity by a factor of two. Continued running with thirty detectors is expected to reach the CDMS-II projected sensitivity shown in Fig. 3. The already successful ZIP detectors form the basis of the SuperCDMS development project described in these proceedings [9]. CDMS-II has already begun to probe the ranges of parameter space predicted by theoretically interesting supersymmetric models. The experimental setup already in place will continue to extend this reach, and the ZIP detector technology provides a clear path forward for large-mass experiments.

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