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WIMP hunting with the Cryogenic Dark Matter Search

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Summary. — The Cryogenic Dark Matter Search (CDMS) seeks to directly detect the scattering of weakly interacting massive particle (WIMP) dark matter in an array of cryogenic particle detectors at Soudan Underground Laboratory. CDMS uses simultaneous measurements of ionization and phonons to discriminate between nuclear and electron recoils on an event-by-event basis. The most recent run of CDMS at Soudan accumulated 397.8 (53.5) kg-days of Ge (Si) exposure and observed no candidate events, setting the strongest limit to date on spin-independent WIMP-nucleon interactions at WIMP masses $\gtrsim 44\,\text{GeV}/c^2$. CDMS also sets competitive upper limits on various axion-like models. A data set $\sim 2.5\times$ larger is currently under analysis, and prototype detectors for the larger-scale SuperCDMS experiment are currently acquiring data at Soudan.

PACS 95.35.+d – Dark matter (stellar, interstellar, galactic, and cosmological).
PACS 14.80.Ly – Supersymmetric partners of known particles.

1. – Dark matter and its detection

In the decades since Fritz Zwicky's observations of anomalous galaxy cluster motions in the 1930s [1], astronomers and physicists have accumulated a vast array of evidence that the bulk of the universe's matter is in some "dark" form, thus far detected only through its gravitational influence. The visible objects we see through our telescopes are now thought to be imbedded within far more massive dark matter formations, and it is these which dominate the evolution of large-scale structure in our universe.

Though there is now broad consensus on the amount of dark matter present in the universe, very little is known about its composition. There is now overwhelming evidence that it is primarily non-baryonic in nature, however, as supported by observations of light element abundances [2] and the microwave background [3]. Whatever the constituent particles of dark matter are, they must be stable (or at least have a lifetime long compared to the present age of the universe), non-relativistic during the epoch of structure formation, and have limited interactions with other matter. Determining the nature of this dark matter remains one of the most pressing questions of modern cosmology.

Among the innumerable dark matter candidates proposed over the years, weakly interacting massive particles (WIMPs) are among the most promising. A WIMP is a hypothetical stable particle with mass $1\,\mathrm{GeV} \lesssim M_\chi c^2 \lesssim 10\,\mathrm{TeV}$ and coupling strengths characteristic of the weak interactions. The strength of the WIMP hypothesis comes from a confluence between cosmology and particle physics: the thermal relic density of such a particle can naturally match the observed dark matter abundance, and many extensions to the Standard Model of particle physics independently predict new stable particles at the weak scale. Examples of WIMPs include the lightest neutralino in many supersymmetric models, the lightest Kaluza-Klein particle in models with additional spatial dimensions, and the lightest T-odd particle in some Little Higgs theories.

If WIMPs constitute the universe's dark matter, they should occasionally scatter elastically upon atomic nuclei as the Earth passes through the Milky Way's dark matter halo. Such scattering events may be observable in sufficiently sensitive particle detectors, a strategy known as "direct detection" [4]. For $60\,\mathrm{GeV}/c^2$ WIMPs incident on a Ge target at galactic velocities ($\sim 0.001c$), we expect an exponential spectrum of nuclear recoils with energy depositions of $\sim 30\,\mathrm{keV}$. Even in clean, heavily shielded environments, however, the rate of background events far exceeds that expected from WIMP interactions (no more than a few scattering events per year in each kilogram of target material). Detecting these events thus presents an enormous experimental challenge, demanding very low energy thresholds and exquisite control over cosmogenic and radiogenic backgrounds.

2. – The Cryogenic Dark Matter Search

The Cryogenic Dark Matter Search (CDMS) is currently the world's most sensitive experiment for the direct detection of WIMP dark matter. CDMS operates an array of cryogenic particle detectors at the Soudan Underground Laboratory in northern Minnesota, USA. These detectors use a simultaneous measurement of ionization and athermal (out-of-equilibrium) phonons to distinguish nuclear recoils (WIMPs and neutrons) from electron recoils (most backgrounds) on an event-by-event basis. CDMS uses this immense discrimination power to operate in a "zero-background" regime: we seek to maintain an expected background of $\lesssim 1$ event, so that no background subtraction is necessary and even a handful WIMP-candidate events would constitute a significant signal.

2·1. *ZIP detectors.* – The central component of the CDMS experiment is an array of thirty Z-sensitive Ionization and Phonon (ZIP) detectors [5]. Each ZIP is a disk of high-purity crystalline Ge or Si, 7.6 cm in diameter and 1 cm thick. The thirty ZIPs at Soudan are arranged into five stacks of six detectors, maintained at 40 mK to reduce thermal noise. Figure 1 illustrates a representative ZIP detector and a view of the five detector stacks installed at Soudan.

The top flat face of each detector is photolithographically patterned with four phonon sensors, each composed of 1036 tungsten transition-edge sensors (TESs) [6] wired in parallel. Energetic phonons reaching the crystal surface break Cooper pairs in superconducting aluminum fins surrounding each TES. The resulting quasiparticles diffuse across the fins and heat the TES, producing a change in resistance which is detected by a SQUID ammeter. Due to rapid response time of the TESs ($\tau_{\mathrm{rise}} \sim 5\mu\mathrm{s}$), the shapes and amplitudes of the four phonon pulses record the characteristics of the initial wave of phonons, which carries information about the event's position and total deposited energy.

Each detector's bottom face is patterned with an aluminum grid to form two ionization electrodes: an inner primary electrode and a surrounding guard ring. These electrodes

Fig. 1. – Left: a CDMS II ZIP detector in its Cu housing. The phonon sensor photolithography is visible on the top detector surface. Right: the CDMS icebox configuration in this data run, showing the tops of the five detector stacks and associated cold hardware.

are biased to $-3\,\mathrm{V}$ (for Ge; $-4\,\mathrm{V}$ for Si) with respect to the phonon sensor array to produce an electric field within the crystal. Electrons and holes generated by particle interactions drift to the surfaces under the influence of this field, producing image currents in the electrodes which are detected by a JFET charge amplifier. The inner electrode defines the detector's fiducial volume; any event depositing significant energy in the outer electrode is rejected from WIMP-search analysis.

CDMS's primary background rejection comes from ionization yield, defined as the ratio of an event's ionization signal to its total deposited energy. Fast, lightweight projectiles (*e.g.*, recoiling electrons from electromagnetic backgrounds) passing through a crystal lattice transfer a larger fraction of their energy into the production of electron-hole pairs than do slow, heavy projectiles (*e.g.*, recoiling nuclei from WIMP or neutron interactions). The left panel of fig. 2 illustrates the power of this discrimination technique

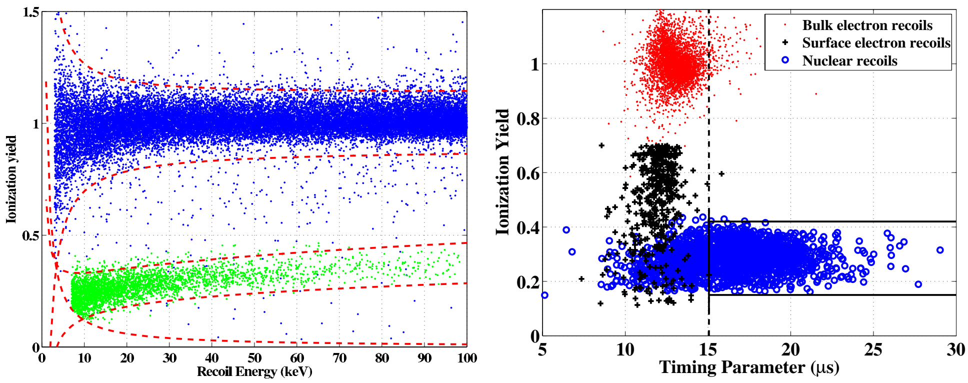

Fig. 2. – (Colour on-line) Left: ionization yield *vs.* recoil energy for particle events from *in situ* calibrations with radioactive sources. Blue (dark) points indicate electron recoils from a ^{133}Ba source, green (light) points indicate neutrons from a ^{252}Cf source. Dashed lines delineate approximate boundaries of the electron and nuclear recoil populations, as well as the ionization energy threshold. Right: ionization yield *vs.* a composite phonon pulse timing parameter, plotted for calibration data from a Ge ZIP. The solid line indicates the approximate signal region.

using data from *in situ* calibrations with radioactive sources. A cut in ionization yield alone reduces the electron recoil background by a factor of $> 10^4$ while maintaining $> 90\%$ acceptance of nuclear recoils.

Interactions within $\sim 10\,\mu$m of a detector surface (*e.g.*, from electrons or low-energy photons) may exhibit incomplete charge collection and reduced ionization yield. These surface events are identified by the faster arrival of their phonons, an effect thought to arise from changes in the phonon spectrum from phonon interactions at the metal electrodes. In this analysis we place cuts on a composite timing parameter, the sum of the rise time of the largest phonon pulse and the difference in start times between that pulse and the ionization signal. The right panel of fig. 2 illustrates the combined scheme for background rejection. Phonon pulse timing cuts reduce the surface event background by a factor of ~ 200, for overall discrimination of $> 10^6$ against electron recoil events.

2·2. *The Soudan installation.* – CDMS is currently located at Soudan Underground Laboratory, on the 27th level of a historic iron mine in northern Minnesota, USA. The laboratory is protected by a rock overburden equivalent to 2090 meters of water, which reduces the flux of cosmic ray muons by a factor of $\sim 5 \times 10^4$ from that at the surface. The detectors are housed within the "icebox," a $\sim 1\,\text{m}^3$ cold volume maintained at 40 mK by an Oxford dilution refrigerator. Further cooling power at 4 K is provided by a Gifford-McMahon cryocooler. The icebox is composed of several layers of low-activity OFHC copper; other materials near the detectors are similarly chosen to be low in radioactivity. The area surrounding these cans is purged with low-activity aged air to reduce radon plateout near the copper. The icebox is surrounded by a passive shield consisting of 50 cm of polyethylene and 22.5 cm of lead, the inner 4.5 cm of which is ancient, low-activity lead. This passive shield is encased within an active shield of forty scintillator panels to tag cosmic ray muons and their associated particle showers. The entire arrangement is located within an RF-shielded room for protection from electromagnetic interference.

3. – WIMP-search analysis

3·1. *Data set.* – CDMS's most recent result [7] is based upon the first two exposures of CDMS at Soudan with its full complement of thirty ZIP detectors (19 Ge and 11 Si). The first run acquired data from October 21, 2006, through March 20, 2007. After a brief period of cryogenic maintenance, the second data run proceeded from April 20 through July 16, 2007. WIMP-search acquisitions were interspersed with regular calibration runs with ^{133}Ba and ^{252}Cf sources; the former yielded 28 million electron-recoil events between 10–100 keV (30× the number of comparable events in the WIMP-search background), the latter more than 10^5 nuclear recoils with which to calibrate response to nuclear recoils. Data quality and uniformity was monitored continuously through a series of automated consistency checks and visual inspections. After excluding periods of inconsistent data quality and poor detector performance, these data sets yielded a total of 397.8 (53.5) kg-days of Ge (Si) exposure.

3·2. *WIMP candidate selection.* – In order to limit bias in the cut-setting process, the analysis of this data set was carried out blindly. A region of parameter space in the WIMP-search data covering the signal region was masked until all WIMP-selection cuts were defined. All criteria for WIMP identification were set and characterized using calibration data and the unmasked portion of the WIMP-search data. Only when all criteria were finalized did we unmask the signal region and observe the number of candidate events.

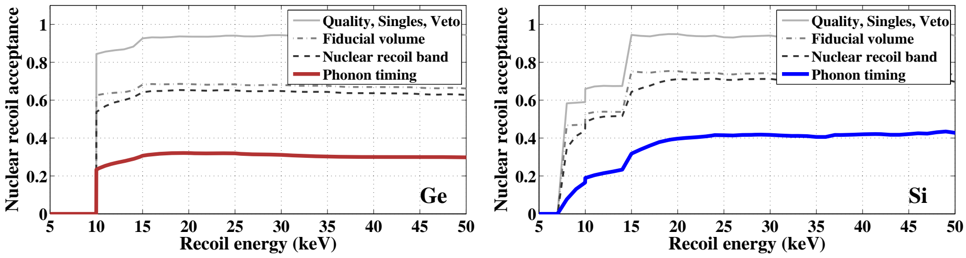

Fig. 3. – Combined nuclear recoil acceptances as functions of energy for Ge (left) and Si (right) ZIPs. Curves represent total acceptances after applying the indicated cut and all those preceding it in the caption.

After removing periods of poor data quality and poorly reconstructed events, we demand that a WIMP candidate satisfy the following major conditions:

1) *Multiplicity*: Significant energy deposited in one and only one detector, and none in the surrounding scintillator panels.
2) *Fiducial volume*: No significant ionization energy deposited in the outer electrode.
3) *Ionization yield*: Each event's ionization yield must be consistent with that of neutrons at the 95% level.
4) *Phonon timing*: Each event's phonon timing parameter must exceed a detector-dependent threshold, chosen to exclude surface events.

Figure 3 illustrates the efficiency (fractional signal acceptance) of these cuts as a function of energy. In this analysis we only consider events with recoil energy between 10–100 keV for the Ge detectors (7–100 keV for Si), with slightly higher thresholds imposed on some detectors with poorer noise performance.

4. – Expected backgrounds

4·1. *Nuclear recoils.* – The rate of neutrons from cosmogenic muons has been calculated using the GEANT4 and FLUKA Monte Carlo packages, accounting for the effects of the shielding and analysis cuts and calibrated against the rate of muons observed in the scintillator panels. Based upon these simulations, the cosmogenic neutron background for this analysis is expected to be < 0.1 events. This prediction is lower than some previous estimates (*e.g.* [8]), primarily due to an improved estimate of the scintillator shield's ability to tag particle showers even when the initial muon is not detected.

Neutrons may also be produced by (α, n) and spontaneous fission processes caused by uranium and thorium contaminants in the surrounding shielding materials. Similar processes also occur in the surrounding rock, but the polyethylene shield renders their contributions negligible. Based upon current estimates and upper limits on these contaminants, we expect < 0.1 background events in this analysis from radiogenic neutrons. Improved upper limits on contamination are expected to reduce this estimate.

4·2. *Electron recoils.* – The expected background from surface electron recoils (predominantly from the radon chain) was estimated based upon the performance of the phonon timing cut on WIMP-search events just outside of the signal region.

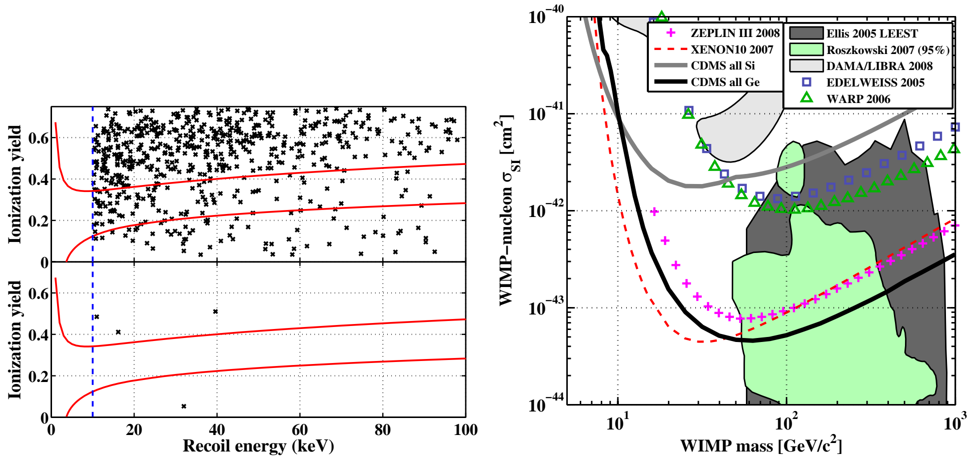

Fig. 4. – Left: distribution of low-yield events in the Ge detectors before (top) and after (bottom) application of the phonon timing cut. Solid lines indicate the ionization yield acceptance region, while the dashed line is the energy threshold of this analysis. Right: limits on spin-independent WIMP-nucleon interactions from CDMS at Soudan, alongside other recent experimental results [10-13]. Also shown for comparison are regions from representative predictions from constrained supersymmetric models [14,15] and one interpretation [16] of the DAMA/LIBRA signal claim [17].

Details of the low-statistics Bayesian estimator used are described in [9]. We expect $0.6^{+0.5}_{-0.3}$(stat.)$^{+0.3}_{-0.2}$(syst.) electron recoil background events in Ge in this analysis, $1.1^{+0.9}_{-0.6}$(stat.) $\pm$ 0.1(syst.) in Si.

5. – WIMP-search results

The WIMP-search data from the Ge detectors were unmasked on February 4, 2008; no WIMP candidate events were observed. The left panel of fig. 4 illustrates the low-yield events observed in the Ge detectors before (top) and after (bottom) application of the phonon timing cut. The Si detectors were unmasked on December 3, 2008; again, no candidate events were observed.

The right panel of fig. 4 illustrates the combined results from this analysis and all previous CDMS data from Soudan, interpreted as upper limits on the spin-independent (scalar) WIMP-nucleon scattering cross-section (σ_{SI}). Also shown for comparison are results from several other leading experiments, as well as predictions from recent studies of supersymmetric parameter space. The combined CDMS Ge data set requires $\sigma_{SI} < 4.6 \times 10^{-44}\,\mathrm{cm}^2$ (46 zeptobarns) at 90% confidence for a WIMP of mass $60\,\mathrm{GeV}/c^2$. This limit is 3.4$\times$ stronger than that from the previous CDMS data sets [18, 19], and the strongest upper limit yet set above $\sim 44\,\mathrm{GeV}/c^2$. These data can also be interpreted as limits on spin-dependent (axial) WIMP-neutron interactions (not shown), but no new parameter space is excluded.

6. – Searches for axion-like particles

In addition to the WIMP-search analysis described above, other rare-event searches can benefit from the low background rate and excellent energy resolution of the CDMS data set (left panel of fig. 5). We have recently completed two analyses of these data

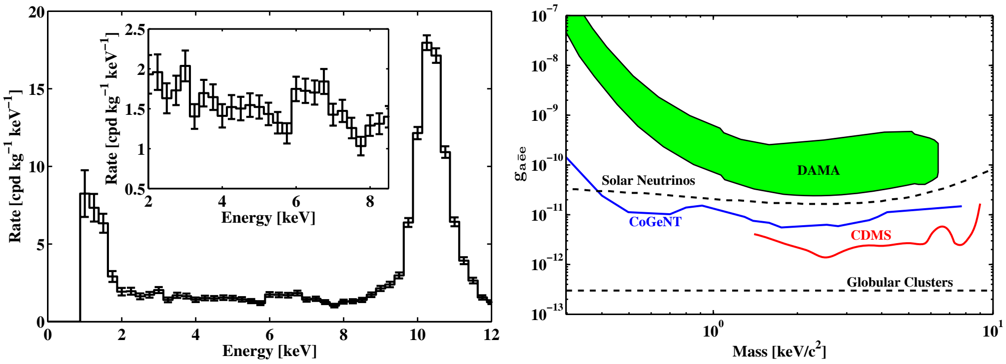

Fig. 5. – Left: rate of low-energy electron-recoils in all CDMS Ge detectors, after correcting for detection efficiency. The prominent spectral lines at left and right are known X-rays from neutron activation of Ge. The inset shows a closer view of the region from 2–8.5 keV. Right: upper limits on the axio-electric coupling of a galactic dark matter particle from CDMS, CoGeNT, and various astrophysical searches. Also shown is one interpretation of the DAMA annual modulation signal.

to search for axion-like particles [20] which deposit electromagnetic energy through conversion to photons or electron-positron pairs. CDMS sets an upper limit on an axion-like component of the galactic halo that is comparable to interpretations of the DAMA/LIBRA annual modulation signal (right panel of fig. 5). CDMS also sets interesting limits on axion-like particles produced in the Sun, based upon a novel analysis incorporating our knowledge of the absolute orientations of each detector's crystal axes.

7. – The future of CDMS

The CDMS Collaboration is currently analyzing further data from this detector array, acquired at Soudan between July 2007 and September 2008. This new data set is expected to represent an increase in sensitivity of $\sim 2.5\times$ over current limits. New results with these data are expected in summer 2009.

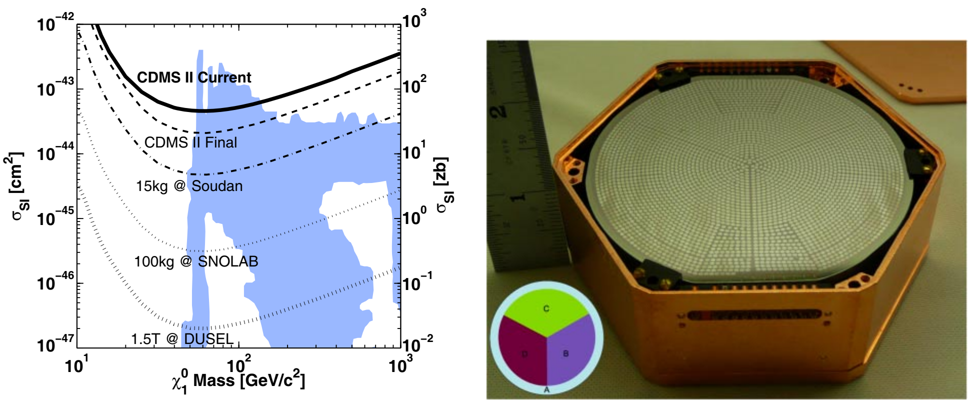

Fig. 6. – Left: projected sensitivities of proposed extensions to CDMS, assuming continued "zero-background" operation. Shaded region represents a scan of CMSSM models [22]. Right: prototype SuperCDMS ZIP. The new phonon sensor patterning is visible on the top surface and shown schematically in the inset.

Development is also underway toward larger-scale WIMP-search experiments using CDMS technology (left panel of fig. 6). The right panel of fig. 6 illustrates a next-generation ZIP detector for SuperCDMS, an upgrade of the Soudan installation to 15 kg of Ge target mass. These detectors are 2.5× thicker than current ZIPs, a change that limits the costs of fabrication and the rate of surface events in each unit of target mass. These ZIPs also incorporate improvements in phonon sensor design to increase sensitivity and simplify event position reconstruction. We are also developing technology for a 1 ton Ge experiment at the upcoming Deep Underground Science and Engineering Laboratory (DUSEL) at Homestake. Technologies under consideration include large-diameter substrates made from dislocation-free Ge, interleaved ionization electrodes [21], and multiplexed phonon sensors based upon kinetic inductance.

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