

CDMS, Supersymmetry and Extra Dimensions

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The CDMS experiment aims to directly detect massive, cold dark matter particles originating from the Milky Way halo. Charge and lattice excitations are detected after a particle scatters in a Ge or Si crystal kept at ~ 30 mK, allowing to separate nuclear recoils from the dominating electromagnetic background. The operation of 12 detectors in the Soudan mine for 75 live days in 2004 delivered no evidence for a signal, yielding stringent limits on dark matter candidates from supersymmetry and universal extra dimensions. Thirty Ge and Si detectors are presently installed in the Soudan cryostat, and operating at base temperature. The run scheduled to start in 2006 is expected to yield a one order of magnitude increase in dark matter sensitivity.

1. The CDMS Experiment at Soudan

The Cryogenic Dark Matter Search (CDMS) experiment is designed to search for cold dark

matter in form of weakly interacting massive particles (WIMPs). These hypothetical thermal relics of the big bang are expected to have masses and annihilation cross sections at the weak scale if their relic density is around $\Omega=0.2$.

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Examples are the lightest supersymmetric particle (LSP, or neutralino) and the lightest Kaluza-Klein particle (LKP) in theories with large universal extra dimensions.

In CDMS, WIMPs can be detected via their elastic scattering with Ge or Si nuclei. Events with nuclear recoil energies of a few tens of keV and rates below $1 \text{ event kg}^{-1}\text{d}^{-1}$ are expected. The experiment is operated at the Soudan Underground Laboratory in Minnesota (at 2080 m.w.e.), in a dedicated low-background facility. At its core are thirty z-dependent ionization- and phonon-mediated (ZIP) detectors, arranged in 5 towers. Within one tower the ZIPs are stacked 2 mm apart, with no intervening material. Such close packing shields the crystals against surface low-energy electrons, and allows to identify multiply scattered events. A particle interaction in a ZIP detector deposits energy into the crystal via lattice vibrations, or phonons, and via charge excitations, or electron-hole pairs. The simultaneous measurement of both phonon and ionization signals allows to accurately measure the recoil energy, and to distinguish between nuclear- and electron recoil events. This distinction becomes possible since nuclear recoils produce fewer charge pairs than electron recoils of the same energy. The ionization yield, defined as the ratio of ionization to full recoil energy, is unity for electron recoils with complete charge collection, and ~ 0.3 (~ 0.25) for nuclear recoils in Ge (Si) with recoil energies above 20 keV.

ZIP detectors measure the athermal phonons created in a particle interaction using quasiparticle-assisted electrothermal-feedback transition-edge sensors (QETs) photolithographically patterned onto one of the crystal surfaces. The QETs, which are made of $1 \mu\text{m}$ wide strips of tungsten connected to eight superconducting aluminum fins are divided into four independent channels, each consisting of 1036 QETs operated in parallel. The narrow tungsten strips form the transition-edge sensors (TESs), which are voltage biased and kept stably within their superconducting to normal transition by electrothermal feedback based on Joule self-heating. Energy deposited in the tungsten electron system raises the temperature of the film, increasing its

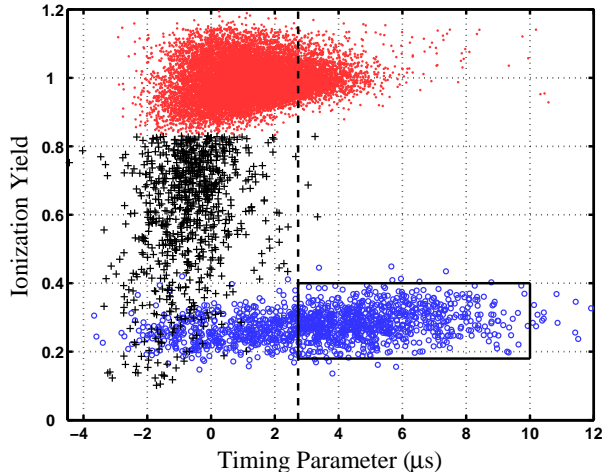


Figure 1. Ionization yield versus phonon timing parameter for ^{133}Ba gamma calibration events (dots and crosses) and ^{252}Cf neutron calibration events (circles). Low-yield ^{133}Ba events (crosses) have small values of the timing parameter, a typical cut is indicated by the dashed vertical line.

resistance. The corresponding change in current is detected by a high-bandwidth SQUID array. The phonon pulse rise times are sensitive to the phonon arrival times at each of the four quadrants and allow to localize an event in the x-y plane. In addition, events occurring near the detector's surface display faster rise times than bulk events, allowing for a fiducial volume cut. For the ionization measurement, a drift field of a few V/cm is applied across the crystal using electrodes deposited on the two faces of each detector. The electrodes are segmented radially, in an outer annular guard ring and a central disk-shaped volume, a design optimized to veto events near the edge of the crystals. A detailed description of the CDMS apparatus and shield is given in [1].

2. CDMS data, results and current status

The most recent CDMS data were collected between March and August 2004 with two towers

(6 Ge and 6 Si ZIPs) for a total of 74.5 live days yielding an exposure of 34 kg d in Ge and 12 kg d in Si in the 10-100 keV nuclear recoil energy range [2]. To avoid bias, the analysis was performed blind, whereby events in and near the signal region were masked in the WIMP search data sets. The cuts defining a signal were determined using calibration data from ^{133}Ba and ^{252}Cf sources and from non-masked WIMP search data. The calibrations were also used to monitor detector stability and to characterize detector performance. One Si detector had a known ^{14}C contamination, while one Si and one Ge detector showed a poor phonon sensor performance. The reported results are thus from 5 Ge and 4 Si ZIPs, chosen before unmasking the WIMP signal region [2].

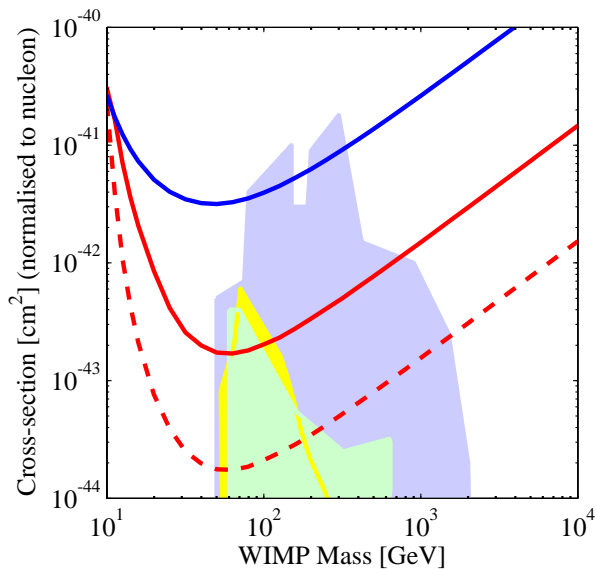


Figure 2. CDMS results for spin-independent WIMP nucleon cross sections versus WIMP mass. Shown are the Si (blue solid) and Ge (red solid) data [2], as well as the prediction for the 5 towers run at Soudan (red dashed). The predicted (filled) regions from supersymmetry are taken from [4]. Plot generated with [5].

The selection criteria for signal events are based on quantities from the phonon and ionization pulses, and are described in detail in [1]. To identify surface electron recoils, 5 different analyses were performed, the rejection criteria being developed by using events with low ionization yield in the ^{133}Ba data sets. The surface event analysis methods are described in detail in [3]. In the simplest analysis technique, the risetime of the largest phonon pulse, along with its time delay with respect to the ionization signal are used to form a timing parameter (shown in Fig. 1). Since surface events show a smaller timing parameter than most nuclear recoils from the ^{252}Cf source, WIMP-induced nuclear recoils are required to exceed a minimum value for this parameter.

After un-masking the data, one candidate nuclear recoil event at 10.5 keV was observed in Ge, while no events were seen in the Si data [2]. Although the candidate event occurred in a Ge detector during a period of inefficient ionization collection, the result is consistent with the expected background from surface events. The derived upper limit on spin-independent WIMP-nucleon cross sections is $1.6 \times 10^{-43} \text{cm}^2$ from Ge, and $3.4 \times 10^{-42} \text{cm}^2$ from Si, both at the 90%CL and at a WIMP mass of $60 \text{ GeV}/c^2$ [2]. Figure 2 shows the spin-independent limits as a function of the WIMP mass, along with theoretical expectations from supersymmetric models.

In theories with flat universal extra dimensions (UED) [6], the best studied dark matter candidate is $\gamma_{(1)}$, the first Kaluza-Klein (KK) mode of the hypercharge gauge boson. Its thermal relic density has been calculated in [7] and [8], including all the relevant coannihilation processes. It is compatible with WMAP results for a wide range of LPK masses, and depends for instance on the masses of the first level KK quarks [8]. In considering the direct detection of $\gamma_{(1)}$ through elastic scattering off nuclei, one starts, as in the case of the neutralino, at the quark level. The interaction takes place through KK-quark and Higgs exchange, and in the extreme non relativistic limit divides into a spin-independent and a spin-dependent part. While $q_{(1)}$ exchange contributes to both scalar and spin-dependent couplings, Higgs exchange contributes only to the for-

mer one. Since the contributions to the scalar interaction interfere constructively, there is a lower bound on both cross sections [9]. Following [9] and [10], the masses of the first level quarks (all degenerate), $q_{(1)}$ are taken as a free parameter, and the ratio $\Delta_{q_{(1)}} = (m_{q_{(1)}} - m_{\gamma_{(1)}}) / m_{\gamma_{(1)}}$, which quantifies the mass splitting between $\gamma_{(1)}$ and the KK-quarks, is varied from 10^{-3} to 0.5. The reach of CDMS is then calculated and shown in the 2-dimensional plane of $\Delta_{q_{(1)}}$ versus the LKP mass in Figure 3 [11]. The region excluded by the CDMS Ge (Si) data is at the left of the curve labeled 'Ge' ('Si'). The expected sensitivity of future experiments such as SuperCDMS [12] and XENON1t [13] are also shown. The region above the red curve labeled 100% is excluded by WMAP data, 100% corresponding to $\Omega_{LKP} = 0.27$ [11].

At present, 5 ZIP towers are installed in the Soudan cryostat, for a total of 4.5 kg of Ge and 1 kg of Si. The 30 detectors have successfully been cooled down to base temperature and their performance is being checked with gamma calibration events. The WIMP search run scheduled to start in fall 2006 is expected to yield a factor of ~ 10 increase in sensitivity (dashed curve Fig. 2). The proposed SuperCDMS program [12] is based on 640 g ZIP detectors with total masses of 25 kg, 150 kg and 1 ton. With a target sensitivity of $\sim 1 \times 10^{-45} \text{cm}^2$, already the 25 kg phase would be complementary to LHC/ILC in the search for new physics at the weak scale. As shown in Fig. 3, SuperCDMS-1t could test the entire region allowed by the WMAP data for Kaluza-Klein dark matter in UED [11].

REFERENCES

1. D. Akerib *et al.* (CDMS Collaboration), *Phys.Rev. D* **72** (2005) 052009.
2. D. Akerib *et al.* (CDMS Collaboration), *Phys. Rev. Lett.* **96** (2006) 011302.
3. G. Wang *et al.*, these proceedings.
4. H. Baer *et al.*, *JCAP* **0309** (2003) 007, E. Baltz and P. Gondolo, *Phys. Rev. D* **67** (2003) 063503, J. Ellis *et al.*, *Phys.Rev. D* **71** (2005) 095007.
5. R. Gaitskell, V. Mandic, J. Fillipini, <http://dmtools.berkeley.edu/limitplots/>

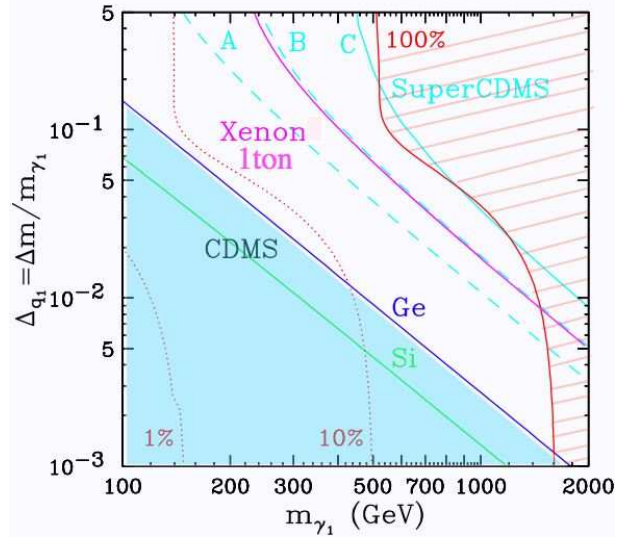


Figure 3. $\Delta_{q_{(1)}}$ (see text) versus the LKP mass. The CDMS Ge (Si) data excludes the region at the left of the line labeled 'Ge' ('Si'). SuperCDMS can probe the parameter space at the left of the curves labeled 'A' (25 kg), 'B' (150 kg) and 'C' (1 ton), while XENON-1t will probe the space below the solid magenta curve. Also shown are the curves where 1%, 10% and 100% of the dark matter is made of LKPs. The hashed region above the 100% curve is excluded by WMAP results [11].

6. T. Appelquist, H.-C. Cheng and B.A. Dobrescu, *Phys. Rev. D* **64** (2001) 035002.
7. G. Servant and T. Tait, *Nucl.Phys. B* **650** (2003) 391-419.
8. K. Kong and K.T. Matchev, *JHEP* **0601** (2006) 038.
9. H.-C. Cheng, J.L. Feng and K.T. Matchev, *Phys.Rev.Lett.* **89** (2002) 211301.
10. G. Servant and T.M.P. Tait, *New J.Phys.* **4** (2002) 99.
11. L. Baudis, K.C. Kong and K. Matchev, in preparation.
12. R.W. Schnee *et al.*, astro-ph/0502435, P.L. Brink *et al.*, astro-ph/0503583.
13. E. Aprile *et al.* (XENON) *New Astr. Rev.* **49** (2005) 289.