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Limits on WIMP–nucleon interactions from the Cryogenic Dark Matter Search at the Soudan Underground Laboratory

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Abstract

We present the results of the first two data runs of the Cryogenic Dark Matter Search at Soudan Underground Laboratory. These data exclude substantial new parameter space for both spin-independent and spin-dependent WIMP–nucleon interactions within the standard halo model.

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Keywords: Dark matter; Direct detection; CDMS

1. Introduction: the move to Soudan

The Cryogenic Dark Matter Search (CDMS) seeks to detect dark matter WIMPs (weakly interacting massive particles) via their interaction with nuclei in crystals of Ge or Si at millikelvin temperatures. CDMS uses ZIP (*Z*-sensitive ionization and phonon) detectors to discriminate

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between electron-recoils (most backgrounds) and nuclear-recoils (WIMPs and neutrons) on an event-by-event basis via a simultaneous measurement of ionization and athermal phonons. Bulk and surface electron-recoils are rejected using the relative amplitudes and timings of these signals.

After initial runs at a shallow site at Stanford University [1], CDMS moved to Soudan Underground Laboratory in northern Minnesota, USA. The new installation is at a depth of 2090 m water equivalent, reducing the expected neutron rate below 1 event/kg/year. An Oxford 400-S dilution refrigerator is used to cool an external cold volume (‘‘icebox’’) housing the detectors to temperatures near 50 mK. The icebox is constructed of low-activity materials and contained within layers of passive shielding and an active scintillator veto, and the entire installation resides in an RF-shielded room. This work describes results from runs with the first two ‘‘towers’’ of 6 ZIPs each, installed in 2003 and operated during 2003–2004.

2. WIMP-search data runs

2.1. First Soudan run: 6 ZIPs

The first tower (4×250 g Ge $+2 \times 100$ g Si), previously run at Stanford, was operated at Soudan from October 11, 2003–January 11, 2004. Detector response to electron- and nuclear-recoils was calibrated in situ using radioactive gamma (^{133}Ba) and neutron (^{252}Cf) sources [2]. After subtracting out periods of known bad data, cryogenic fills, and poor detector neutralization, 52.6 live days of WIMP-search data were acquired. One Si ZIP was excluded due to contamination, leaving 52.6 (5.26) kg-days of Ge (Si) exposure before cuts.

A blind analysis was performed in which the nuclear-recoil region of each WIMP-search data set was masked while the various analysis cuts (in particular, the phonon timing cuts) were finalized. This initial analysis showed no WIMP-candidate events from 10 to 100 keV in recoil energy. Soon after, it was determined that a sub-optimal algorithm had mistakenly been used to determine charge amplitudes in this analysis. When the superior algorithm was used as intended, with its more effective cuts, the additional efficiency resulted in one candidate at 64 keV in Ge, consistent with the expectation of 0.7 ± 0.3 misidentified surface electron recoils. Further details may be found in Ref. [3].

2.2. Second Soudan run: 12 ZIPs

The second tower of ZIPs (4 Si + 2 Ge) was run alongside the first between March 25th and August 8th, 2004. A total of 74.5 live days were accumulated, yielding (after excluding three of the detectors on the ends of the tower stacks) a total of 96.8 (31.0) kg-days Ge (Si) exposure before cuts.

Numerous improvements were made in the analysis of this run, including reduced noise, larger and more evenly distributed calibration data sets, and new phonon timing/shape analyses [2]. One event at 10.5 keV in Ge was seen in the blind analysis of these data, consistent with the expected $0.4 \pm 0.2 \pm 0.2$ ($1.2 \pm 0.6 \pm 0.2$) misidentified betas in Ge (Si). This event was later found to occur in a period of very poor detector neutralization. Further details may be found in Ref. [12]

3. Limits on WIMP–nucleon interactions

These results, with one event found in each of the two runs, may be interpreted in terms of limits on the WIMP–nucleon elastic scattering cross-section. We assume that the local WIMP distribution is described by the ‘‘standard halo model’’ (0.3 GeV/cm^3, Maxwellian, $v_0 = 220$ km/s, $v_{esc} = 650$ km/s) and consider scalar (spin-independent) interactions in which the WIMP-nucleus cross-section scales as A^2. Under these assumptions, CDMS sets the most stringent upper limits on WIMP interactions to date (Fig. 1). These limits have begun to cut into parameter space favored by the minimal supersymmetric extension to the standard model (MSSM), and even into that of more constrained models (CMSSM).

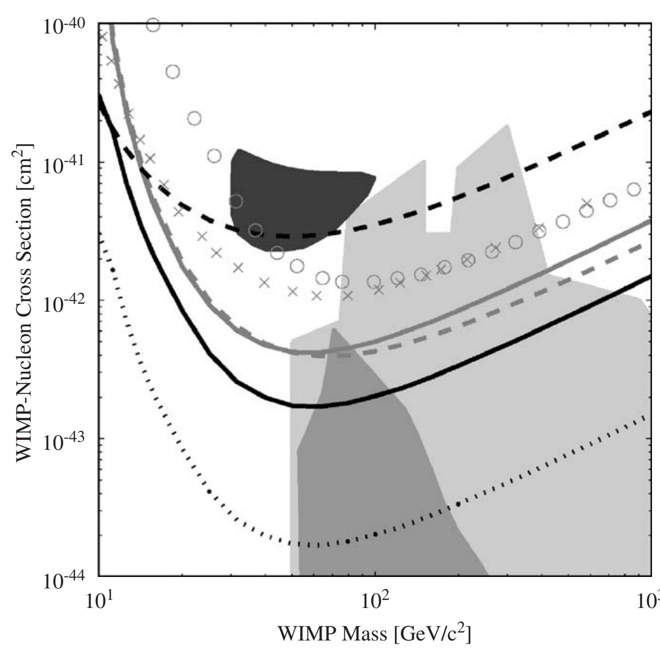

Fig. 1. Spin-independent WIMP limits from the first (intended analysis: gray solid; initial analysis: gray dash) and combined first and second (Ge: black solid; Si: black dash) Soudan runs. Also shown are current limits from other leading experiments (Edelweiss [6]: circles; ZEPLIN [7]: crosses) and CDMSs expected reach by 2007(dot). Filled regions indicate MSSM [4] (light gray) and CMSSM [5] (medium gray) models, as well as an interpretation of the DAMA/NaI annual modulation signal [8] (dark gray).

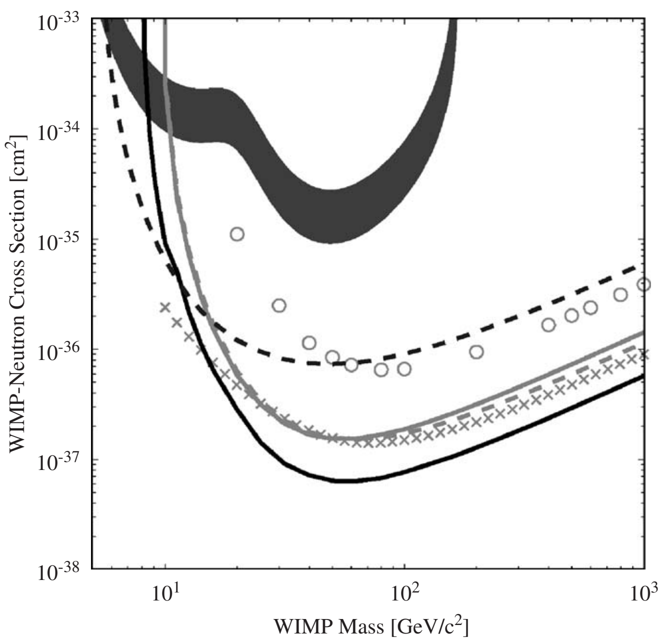

Fig. 2. Spin-dependent WIMP limits from CDMS and other experiments in the case of axial couplings to neutrons alone. Experimental results are labeled as in Fig. 1.

Since the CDMS detectors contain two significant isotopes of non-vanishing spin (^{73}Ge and ^{29}Si), we may also interpret these limits in terms of axial (spin-dependent) WIMP–nucleon interactions. CDMS sets world-leading limits in the case of axial couplings to neutrons alone (Fig. 2), and is competitive in more generic cases, as well [9,10].

4. The future: 30 ZIPs and beyond

CDMS has installed three additional towers at Soudan for a total of 30 ZIPs (4.75 kg Ge, 1.1 kg Si). Data-taking with this arrangement is expected to run until 2007, improving our experimental reach by another factor of 10. Proposals have also been submitted for SuperCDMS [11], an extension of our technology to the 25 kg scale and beyond.

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