Beyond the CDMS-II Dark Matter Search: SuperCDMS

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Presently the CDMS-II collaboration's Weakly Interacting Massive Particle (WIMP) search at the Soudan Underground Laboratory sets the most stringent exclusion limits of any WIMP cold dark matter direct-detection experiment. To extend our reach further, to WIMP-nucleon cross sections in the range $10^{-46} - 10^{-44}\text{cm}^2$, we propose SuperCDMS, which would take advantage of a very deep site. One promising site is the recently approved SNOLab facility in Canada. In this paper we will present our overall plan, identify primary issues, and set the goals that need to be met prior to embarking upon each phase of SuperCDMS.

I. INTRODUCTION

The identification of dark matter is of fundamental importance to cosmology, astrophysics and high-energy particle physics [1]. Over the last decade a variety of cosmological observations, from the primordial abundance of light elements to the study of large-scale structure, in combination with high-redshift supernovae findings, weak-lensing observations, and detailed mapping of the anisotropy of the cosmic microwave background, have led to the construction of a concordance model of cosmology. In this very successful model, the universe is made of ∼ 4% baryons which constitute the ordinary matter, ∼ 23% non-baryonic dark matter which dominates structure formation, and ∼ 73 % dark energy [2].

A leading hypothesis is that the dark matter is comprised of Weakly Interacting Massive Particles, or

WIMPs, a hypothetical elementary particle that was produced moments after the Big Bang. Supersymmetry extensions to the standard model of particle physics predict a stable particle with the appropriate properties, the Lightest Supersymmetric Particle (LSP) [3].

If WIMPs are indeed the dark matter they can be detected via elastic scattering from nuclei in a suitable target [4]. The predicted energy depositions and event rate of these expected nuclear recoils are low. The direct WIMP-search experiments, in particular CDMS II [5], EDELWEISS [6], and ZEPLIN I [7] are beginning to set significant upper limits on the WIMP-nucleon scattering cross-section. The CDMS ZIP (Z-dependent Ionization and Phonon) detectors, which are sensitive to both ionization and athermal phonon signals, have demonstrated extraordinary selectivity for the nuclear recoils expected from WIMP interactions and are currently the most sensitive detectors in the search for WIMPs [5].

While the present direct WIMP-search experiments, with target masses of a few kgs, already provide interesting constraints on the hypothetical WIMP particle properties (and thus constraints on models of supersymmetry), there is a strong demand to perform more sensitive direct WIMP searches with larger detector mass.

Figure 1 shows the present CDMS II WIMP-exclusion limit and the allowed regions of mass and cross-section that arise from a number of favoured supersymmetry models. Also shown is the SuperCDMS program which is proposed to increase the ultimate WIMP-search reach by a factor of a few hundred past that of CDMS-II. This would allow a sensitivity in the WIMP-nucleon scalar cross-section to complement that of upcoming supersymmetry searches, notably at the Large Hadron Collider (LHC).

Figure 2 shows the overall time-line, including the commissioning and data-taking for each proposed SuperCDMS phase. Note that the detector deployment is phased, commensurate with the fabrication and testing schedule required for the new ZIP-style detectors.

Funding approval for SuperCDMS would enable a new generation of direct detection experiments utilizing ZIP-style detectors with target masses starting at 27 kg (Phase A), growing to 145 kg (Phase B), and up to 1100 kg (Phase C) to study a potential WIMP signal.

II. SUPERCDMS

The goal of each phase of SuperCDMS is to operate with a nuclear-recoil event background close to zero. The resultant WIMP-search sensitivity would then scale linearly with exposure and allow each phase of SuperCDMS to be conducted within a few years.

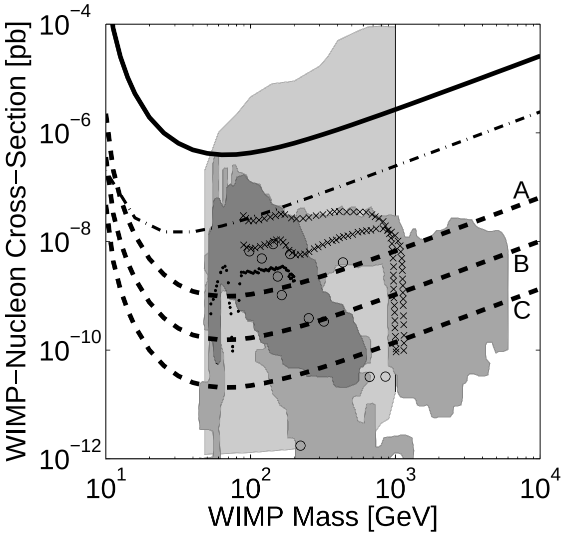

FIG. 1: Present CDMS II (solid curve) [5] WIMP exclusion limit (90% C.L. above curve); projected sensitivity goal of CDMS II (dot-dashed curve), and projected SuperCDMS phases A, B & C (labelled dashed curves). The lightest grey region is the allowed WIMP-nucleon cross-section under standard model assumptions for the Minimal SuperSymmetric Model (MSSM) parameter space [8]. SuperCDMS will probe nearly all split-supersymmetry models (×'s [9] and dots [10]) and much of the mSUGRA region [11] (medium grey), including most post-LEP benchmark points (circles) [12] and nearly all the subset (dark grey) consistent with a supersymmetric interpretation of the muon $g-2$ measurement.

Scaling from the recent CDMS Soudan results [5], the sensitivity goal of $2 \times 10^{-45}\text{cm}^2$ for SuperCDMS Phase A (for a 60 GeV mass WIMP, see Fig. 1) corresponds to an event rate of 4×10^{-4}/kg/day, integrated over the nuclear recoil energy range of interest: 15-45 keV. However, this sensitivity goal is for setting a 90% confidence WIMP-exclusion upper limit. The desired "zero-background" contamination level required is $\sim 1 \times 10^{-4}$/kg/day for 15-45 keV. Experience with the ZIP detectors of CDMS suggests an integrated exposure of one to two years with 27 kg of Ge ZIP-style detectors would be required to reach the SuperCDMS Phase A goal, assuming zero background events.

A. Site Selection: Neutron Background

The CDMS II WIMP-search experiment is operated at the Soudan Mine with an overburden of 2090 meter-water-equivalent (m.w.e.) and an active muon-veto shield and substantial polyethylene, all to mitigate neutron backgrounds [5]. The neutron background at Soudan that could mimic WIMP events in the CDMS II experiment is estimated to be 4×10^{-4}/kg/day (with an uncertainty of a factor of two) for the Ge nuclear recoil energy range of interest, 15-45 keV [13]. Thus, the SuperCDMS Phase A zero-background goal cannot be accomplished at the Soudan site with our present shielding configuration. Although further shielding measures at Soudan could accomplish the Phase A goal, later SuperCDMS phases would still remain out of reach.

During the last year a significant development occurred with the approval in Canada of the SNOLab deep-site facility at the Sudbury Mine. The ~ 6000 m.w.e. overburden at this site results in over two orders of magnitude suppression in the neutron background compared to Soudan and would even allow SuperCDMS Phase C (with 1100 kg of Ge detectors running for several years) to be accomplished. The SuperCDMS proposal has generated strong interest at SNOLab and further discussions are in progress.

With the possibility of SNOLab occupancy in 2007, Fig. 2 shows a possible timeline for the execution of the SuperCDMS program. The Phase A WIMP-search would commence at the new deep site in a new cryogenic system, which would also be used for the following Phases B & C.

B. Detector Performance: Gamma and Beta Backgrounds

Recent results from the CDMS II detectors at Soudan [5, 13] confirm the excellent discrimination ability of the ZIP detectors against the most common source of background events, photons from external sources of radioactivity interacting in the bulk of the detector. Thus, the expected gamma background of SuperCDMS (~ 1/keV/kg/day) is not an immediate source of concern for SuperCDMS Phases A & B. However, a more problematic source of backgrounds that does need to be addressed prior to SuperCDMS Phase A is that due to electromagnetic events near the detector surfaces.

Electromagnetic interactions within the first $35\,\mu$m of the present ZIP detector surface give a suppressed ionization signal, and for events within the first $1\,\mu$m of the surface the suppression is sufficiently severe that the ionization yield measured mimics nuclear recoils. The great advantage of the ZIP detectors of CDMS is that the athermal phonon signal for such surface events have measurably faster risetimes. Thus software analysis cuts can be established to remove them.

The CDMS II data analysis approach for each WIMP-search run at Soudan has been to use the *in-situ* photon and neutron calibrations, laboratory calibrations with beta sources, and their Monte-Carlo simulations to establish event identification cuts, which are estimated to leave less than one "beta-leakage" event in the (blinded) nuclear-recoil WIMP-search data [5, 13]. Clearly, the more aggressive the cuts need to be to reduce the beta-leakage estimate, the lower the net efficiency for true nuclear recoil identification and the less sensitive the WIMP-search becomes. No statistical subtraction of beta events in the WIMP-search data is presently attempted, nor assumed for SuperCDMS.

Studies [13] of the detector stacking configuration used by CDMS show that single-scatter events caused by electrons ejected from nearby material by an incident photon have a depth distribution in the detector that is deeper, and thus less problematic, than electrons of similar deposited energy emitted from beta sources on the detector surfaces. With the expected gamma background of SuperCDMS, the ejected-electrons due to photon-induced events are not a source of concern. Instead, the source of background that needs to be reduced is electrons due to beta contamination. Here we take beta contamination to include beta-emitters, internal-conversion sources, Auger electrons and soft X-ray sources as well, although the source is most likely to be a beta-emitter.

The present ZIP detectors' discrimination performance and data analysis results in an inferred "mis-identified beta" background due to beta-emitter contaminants of $\sim 1 \times 10^{-2}$/kg/day for the 15-45 keV nuclear recoil energy range of interest [5, 13]. This is a factor of one hundred too high for Phase A.

C. Detector Advances Required

In order to achieve the sensitivity goals of the proposed SuperCDMS Phases A & B (with zero background events), a number of improvements are required to the present CDMS II ZIP detector technology to reduce the inferred mis-identified beta background. We have identified three approaches, all of which we believe will contribute at a similar level: improved ZIP-style detector performance, advances in analysis techniques, and actual reduction of the source of beta-contamination itself. Table I summarizes our expectations for the target improvement factors that will contribute to both Phases A & B.

Referring to Table I and focussing on the requirements for Phase A, the primary ZIP detector development requirement for SuperCDMS is to increase the detector thickness from the present 10 mm to 25 mm. This will both give an effective increase of a factor 2.5 in detector rejection capability for beta-like surface events, and increase the throughput in detector fabrication, testing, and calibration.

The remaining factor of two in detector background rejection capability we believe will come from optimizing the hydrogenation of the amorphous-Si electrodes used for the ionization signal measurement. For technical reasons hydrogenation of the amorphous Si for the ZIP detectors deployed in CDMS II at Soudan was not possible. However, earlier detectors used by CDMS had higher ionization-only based rejection ca-

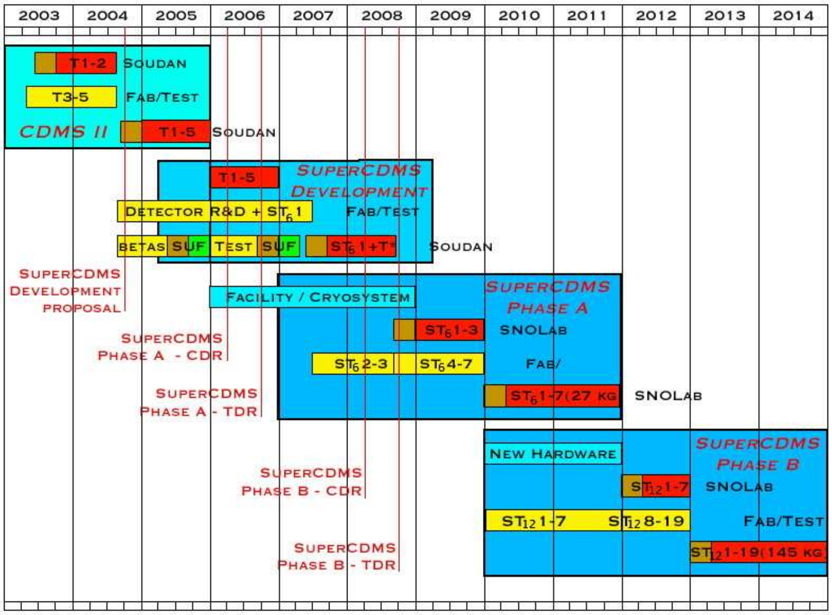

FIG. 2: Proposed timeline for the SuperCDMS Development program and SuperCDMS Phases A & B. Note the phased deployment of detectors to allow early science returns, even in the Development program. The WIMP-search running of the 27 kg of Ge of Phase A and the 145 kg of Ge of Phase B are proposed to occur at SNOLab.

TABLE I: Target improvement factors to achieve the SuperCDMS Phase A and Phase B WIMP-search sensitivities. The first and third columns are relative to the present CDMS II ZIP detector performance at Soudan [5].

Improve	**Phase A**	**Phase B**	**Combined**
Detector rejection	×5	×2	×10
Analysis discrimination	×4	×2	×8
Contamination reduction	×5	×2	×10
Total improvement	= ×100	= ×8	= ×800

pability, thus our interest in developing this option further.

Further improvements in software analysis of the athermal phonon pulse shapes will also increase our background rejection ability. Most of the desired improvement (factor of four) for SuperCDMS Phase A (relative to the first analysis of CDMS II Soudan data [5]) is already close at hand.

Finally, we are also investigating the possible sources of beta contamination present in the first CDMS II detectors run at Soudan. The dominant radioactive background appears to be Pb-210, most likely from Radon plate-out. Studies[13] of the Soudan data, Monte-Carlo simulations of possible sources, and surface-analysis of test samples appear to indicate that the other likely candidates, K-40 and C-14, are not significant ($<$ 20% of the present total) so no remedial actions are required for those sources prior to SuperCDMS Phase A. During the course of CDMS II more rigorous procedures were put in place to mitigate radon plate-out. The impact of these efforts will only be known as later detector towers of CDMS II come into operation at Soudan over the next year. Of course it is possible that a significant fraction of the present beta contamination is due to a source not yet identified. Inductively-coupled plasma mass spectroscopy (ICP-MS) is a quick method for identifying most of the potential exotics. Alpha, beta and gamma screeners are able to identify the others.

Note that it is only the combined affect of these three approaches to the misidentified beta-contamination background that matters: some approaches will be more or less successful than originally anticipated, but they will all be pursued under the SuperCDMS program to ensure that the overall risk is minimized.

D. SuperCDMS Development Project

The first part of SuperCDMS, proposed jointly to the DOE & NSF in late 2004, is the Development Project that will demonstrate that all the detector advances required for Phase A (outlined above) have been met.

An additional goal of the Development Project indicated in Fig. 2 is to continue our present operations at Soudan to extend our WIMP-search reach beyond the CDMS II goals. The first new ZIP-style Ge detectors of SuperCDMS would also first be tested at Soudan (designated "ST_6 1" in Fig. 2), in the present Soudan ice-box along-with the incumbent five towers of CDMS II detectors (designated as T* in Fig. 2) and thus allow further science returns prior to a deeper site, such as SNOLab, becoming operational.

The SuperCDMS Development Project would also allow development of additional longer lead-time items that would be required to achieve the SuperCDMS Phases B & C goals. These include both the increased zero-background goals, and accelerated detector manufacturing rates.

E. SuperCDMS Apparatus Concepts

Here we will outline the longer-term infrastructure needs of SuperCDMS and highlight some of the elements we consider necessary for the later Phases.

1. *Cryogenics*

In order to deploy the larger mass of Ge detectors for SuperCDMS a new, larger cryogenic facility at a new, deeper site is required. To accommodate 1000 kg-worth of Ge detectors requires a cold volume of $\simeq 1\,\mathrm{m}^3$. Figure 3 shows a possible arrangement of the 25 mm thick ZIP-style detectors of SuperCDMS for each phase of the program within the new cold volume.

A conceptual sketch of the envisioned overall cryogenic design is shown in Fig. 4 and is similar to the present CDMS II arrangement at Soudan [14]. An MRI proposal to the NSF for both the design and construction of the desired system was submitted in early 2005. One of the design philosophies is that the mounting and electrical readout of detectors is modular, so that some flexibility is possible in the utilization of the cryogenic facility.

2. *Electronics*

The readout of the ionization signals in CDMS presently requires FETs self-heated to 140 K relatively close to the detectors. As we increase the number of detectors for the later phases of SuperCDMS, the heat-load will necessitate the replacement of the FET readout with the lower power dissipation of SQUID-based charge readout [15]. Such concepts require further development under the SuperCDMS program and related long-term R & D proposals.

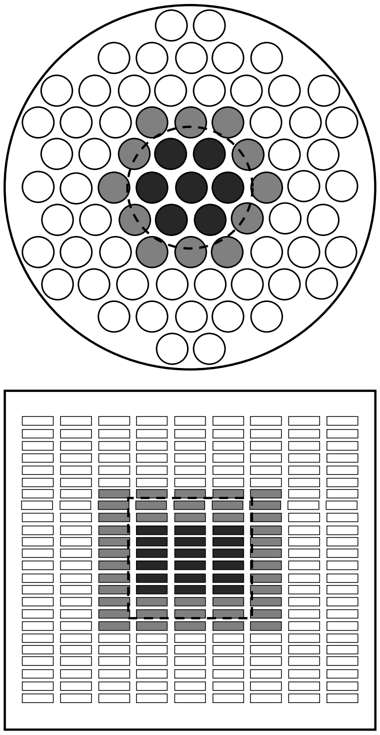

FIG. 3: Plan and elevation views of the SuperCDMS cold-volume showing deployment of 7 towers of 6 detectors each for SuperCDMS Phase A (darkest circles), 19 towers of 12 detectors each in the 145 kg Phase B (grey circles), and 73 towers of 24 detectors each in the 1.1 tonne Phase C (open circles). The required cold-volume will be three times larger in each dimension (dashes) than that of CDMS.

As the number of phonon-signal readout channels is increased there is additional motivation to move from the present CDMS single-stage SQUID readout to two-stage configurations. Apart from ease in manufacture and demonstrated multiplexing schemes [16], opportunities are present for improving the detector phonon sensor design. Larger phonon collection area designs would be possible and substitution of the present W Transition-Edge-Sensor (TES) elements with Al-Mn TESs [17] would also be possible. These avenues are of interest both for improving the phonon sensor performance and easing the manufacture of future ZIP-style detectors.

3. *Detectors*

An alternative configuration of the ionization and phonon channels to that of CDMS II had been suggested by Luke [18] where the ionization bias electrodes are interdigitated with the phonon sensors such that electric fields are now present tangentially to the detector surface in addition to the usual bulk drift field through the detector. This would allow vetoing of ion-

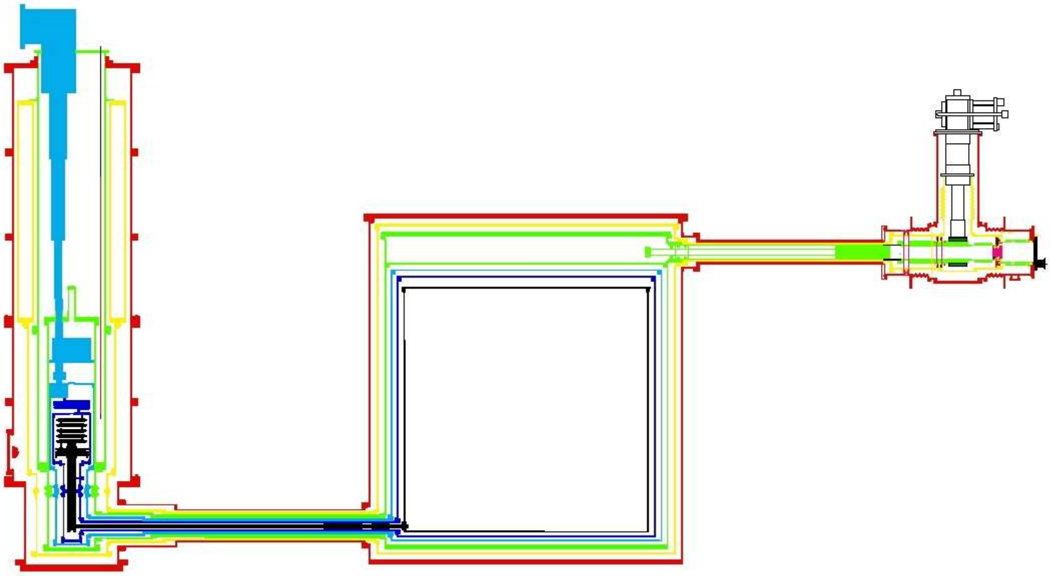

FIG. 4: Design concept for cryogenic facility showing (left to right) a commercial dilution refrigerator connected to the radio-pure copper vessel containing the Ge detectors, with electrical readout through the stem to the right cooled by a closed-cycle cryocooler.

izing surface events. We suspect that such a scheme may be required to achieve the detector performance goals of SuperCDMS Phase B.

Alternative double-sided phonon sensor readout schemes would also improve our utilization of athermal phonon signal pulse-shape analysis and event reconstruction. The biasing of the CDMS II-style ionization electrodes would be more complicated for these schemes but is being studied under long-term R & D base programs.

III. CONCLUSION

The potential of the CDMS ZIP detectors has become readily apparent over the last few years, with CDMS II presently the world-leading WIMP-search direction-detection experiment [5]. The measurement of *both* ionization and phonon signals for each event avoids possible ambiguities at the low recoil of energies of interest. A positive signal identification from *any* WIMP-search experiment must be compelling - with no other alternative sources of events, detector pathologies, or systematic affects clouding the issue. We believe SuperCDMS will satisfy these demands.

SuperCDMS is by no means the only way forward, but we believe that it will be a strong contender with other large-mass detector concepts [19]. Indeed, comparison of any WIMP discovery by complementary detector technologies is a scientific necessity and will also aid in refining properties of the WIMPs, for example their mass, velocity distribution and coupling strengths to nucleonic matter. The age of WIMP astronomy is approaching.

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[1] L. Bergstrom, Rep. Prog. Phys. **63**, 793 (2000)

[2] D.N. Spergel *et al.*, Astrophys. J. Suppl. **148**, 175

(2003)

[3] G. Jungman *et al.*, Phys. Rep., **267**, 195 (1996)

[4] J.R. Primack *et al.*, Annu. Rev. Nucl. Part. Sci. **38**, 751 (1988)

[5] D.S. Akerib *et al.* (CDMS Collaboration), Phys. Rev. Lett. **93**, 211301 (2004)

[6] A. Benoit *et al.* (EDELWEISS Collaboration), Phys. Lett. **B545**, 43 (2002)

[7] J. Alner *et al.* (U.K. Dark Matter Collaboration), *To be published in Astropart. Phys.*

[8] Y.G. Kim *et al.*, J. High Energy Phys. **0212**, 034 (2002)

[9] G.F. Guidice and A. Romanino, Nucl. Phys. B **699** 65 (2004)

[10] A. Pierce, Phys. Rev. **D70**, 075006 (2004)

[11] E.A. Baltz and P. Gondolo, J. High Energy Phys. **0410**, 052 (2004)

[12] M. Battaglia *et al.*, Eur. Phys. J. **C33**, 273 (2004)

[13] D.S. Akerib *et al.*, *in preparation*

[14] R.W. Ogburn *et al.*, *these Proceedings*

[15] K.D. Irwin *et al.*, *in preparation*

[16] K.D. Irwin *et al.*, Nucl. Instr. and Meth. A. **444**, 184 (2000)

[17] B.A. Young *et al.*, Nucl. Instr. and Meth. A. **520**, 307 (2004)

[18] P. Luke, Appl. Phys. Lett. **65**, 2884 (1994)

[19] K. Ni *et al.* (XENON Collaboration), *these Proceedings*; A. Sonnenschein *et al.* (COUPP Collaboration), *these Proceedings*