Dark Matter Detection with Cryogenic Detectors

Dr. Daniel A. Bauer
Fermilab, MS209, PO Box 500, Batavia, IL 60510
bauer@fnal.gov

Abstract. Direct detection of dark matter in the form of Weakly-Interacting Massive Particles (WIMPS) is an active field of research. Cryogenic detectors have been in the forefront of the field, due to their exquisite ability to reject backgrounds from interactions of normal matter. In this paper, I describe the current status and future prospects for such experiments.

1. The landscape of dark matter direct detection
Observations of galaxies, superclusters, distant supernovae and the cosmic microwave background radiation, tell us that ~85% of the matter in the universe is not made of particles that emit or absorb electromagnetic radiation. A leading hypothesis is that it is comprised of Weakly Interacting Massive Particles [1], or WIMPs, that were produced moments after the Big Bang. Particle physics theories provide possible WIMP candidates with masses ~10-1000 GeV/c^2. For example, supersymmetry contains a lightest supersymmetric partner (LSP) that is stable and interacts at roughly the weak-interaction rate, allowing it to decouple from ordinary matter in the early universe with a relic density comparable to the dark matter density [2]. Similarly, many models involving extra dimensions predict the lightest Kaluza Klein excitation is stable, with weak-scale mass and interaction cross sections [3].

If WIMPs are indeed the dark matter, their density in the galactic halo may allow them to be detected via elastic scattering from atomic nuclei in a suitable terrestrial target. The energy depositions and interaction rates are low, requiring that this type of experiment be located deep underground for protection from cosmic rays and requiring the use of radio-pure materials to shield against radioactivity in the environment. The current generation of direct detection experiments is now reaching the level of sensitivity needed to probe theoretical predictions in a way that is quite complementary to accelerator searches. The combination of LHC and WIMP-nucleus elastic-scattering experiments would check the consistency of the models and provide powerful constraints on the parameters. More generally, the low mass of the Higgs inferred from electroweak measurements point to a WIMP-nucleon cross section in the range 10^{-45} to 10^{-44} cm^2 [4].

The WIMP detection field has grown over the last several years, with the introduction of new technologies. There are now approximately fourteen operating experiments (DAMA/LIBRA, KIMS, CaF2-Kamioka, WARP, XENON-10, ZEPLIN-II, DEAP-I, XMASS, CDMS, CRESST, EDELWEISS, COUPP, PICASSO, DRIFT) and at least another three active R&D programs (ArDM, LUX and DEAP/CLEAN). In this paper, I will focus on the status and prospects for cryogenic direct-detection experiments. A separate contribution to these proceedings will survey non-cryogenic techniques [5].
1.1. WIMP detection
When considering the scattering of WIMPs on nuclei, two types of coupling between the WIMP and a nucleon must be considered: spin-dependent and spin-independent [6]. The balance between the two types of coupling in supersymmetry depends on the flavor composition of the lightest particle and can strongly favor one or the other coupling. However, in the case of spin-dependent couplings, there is a cancellation between opposite-aligned spins in the target nucleus, while in the spin-independent case, all nucleons add coherently. This amplifies the sensitivity of experiments using large-A nuclei to search for spin-independent scattering by a factor \( A^2 \). For this reason, the experimental community has focused most attention and resources on attempts to discover WIMPs via spin-independent interactions. Note that this coherence is lost if the WIMP mass becomes much heavier than the mass of the target nucleus. Use of several different target materials can help to distinguish whether any nuclear recoil events seen are due to WIMP interactions, or backgrounds. If no events are seen, upper limits on the cross section are presented as WIMP-nucleon cross sections versus WIMP mass. Even a signal of a few events would constrain the cross section and WIMP mass to within about an order of magnitude.

1.2. Backgrounds
Direct detection dark matter experiments have currently reached a level of sensitivity corresponding to a few events per kilogram of target mass per year. This has already required a large effort to shield the detectors against gammas, electrons and neutrons from radioactivity. In addition, the experiments must be located deep underground to avoid neutrons produced in cosmic ray interactions. Finally, the experiments must have either significant event-by-event discrimination between electron recoils (from electromagnetic background sources) and nuclear recoils (from either WIMP or neutron interactions), or exploit some other expected characteristic of WIMPS such as annual modulation or directionality.

It is crucial that direct detection experiments strive for zero background. This clearly maximizes discovery potential, and allows WIMP sensitivity to improve linearly with increase in target mass and running time. If a background arises, the sensitivity improvement will initially degrade as the square root of exposure (the product of target mass and running time) and then plateau at an irreducible level until the background can be removed or rejected.

1.2.1. Sources of backgrounds
The primary sources of radioactivity in the natural environment are long-lived isotopes of Uranium and Thorium, which yield alpha, beta and gamma particles from their decay chains. Also troublesome are the long-lived isotopes \(^{40}\text{K}\) and \(^{210}\text{Pb}\), the latter resulting from decays of ubiquitous Radon gas. It is possible to screen materials for radioactive contamination by detecting either the gamma or alpha particles emitted from surfaces. However, the sensitivity required for direct detection experiments is beginning to challenge the best screening technologies.

A limiting background for all direct detection experiments is the presence of neutrons, since they produce the same nuclear recoil signature as WIMPS. Mounting the experiments far enough underground is sufficient to reduce neutrons from cosmic ray showers. However, neutrons also come from (alpha,n) reactions and fission decays, both resulting from the presence of small residues of radioactivity surrounding the detectors. This background will likely begin to dominate in the next generation of experiments without extreme efforts to further reduce contamination. Use of multiple target materials with different atomic weights can exploit the likelihood that WIMP scattering scales as \( A^2 \), whereas neutron cross sections are relatively insensitive to \( A \), to allow statistical rejection of a neutron background. Similarly, the ability to recognize multiple scattering of neutrons, extremely unlikely for WIMPS, can also allow an experiment to recognize a neutron background. However, the presence of a neutron background would still limit discovery potential, since it would require a much larger sample of events to measure and subtract a neutron background, so as to extract a WIMP signal.
1.2.2. Background reduction
Copper, germanium, xenon, neon are among the cleanest materials available to direct detection experiments, with no naturally occurring long-lived isotopes. Argon suffers from the presence of $^{39}$Ar, produced by cosmic rays in the atmosphere and having a half-life of 239 years, although it is possible that underground sources of Argon may have much less $^{39}$Ar. Lead is one of the best shielding materials against gamma radiation, especially ancient lead which tends to be free of $^{210}$Pb ($T_{1/2} = 22$ years). High-density polyethylene and purified water make excellent neutron moderators with which to surround dark matter detectors. It is also important to reduce the presence of Radon gas in the vicinity of detectors, since it tends to plate out on surfaces and leave radioactive decay daughters. There is a substantial literature on these topics [7].

1.2.3. Active background rejection
The most sensitive direct detection experiments have now achieved extremely good active (event by event) discrimination against electromagnetic backgrounds, in some cases exceeding one part in a million. This is most often accomplished by measuring at least two types of signals (e.g. ionization and phonons, ionization and light, or even light and phonons) that differ for nuclear recoil events as compared with electron recoil events. Space does not allow a complete survey of these techniques here, but they have been summarized in recent review articles [8].

2. Cryogenic dark matter detectors
For the purposes of this article, a cryogenic direct detection experiment is defined as one in which the active detector material is maintained at temperatures <77K. In practice, all such experiments use dilution refrigerators and maintain their solid-state detectors at temperatures < 100 mK. This allows the detection of phonons from the interaction of a single particle in a crystal lattice. Comparison to either the collected ionization or scintillation light from the interaction allows excellent discrimination between nuclear recoils and electron recoils. The drawback of the technique is primarily the need for a cryogenic infrastructure, but also the relatively small target mass achieved by placing phonon sensors on solid-state crystals. Nevertheless, cryogenic detectors have been in the forefront of WIMP direct detection experiments for the last decade.

3. Status and prospects for cryogenic experiments
There are three cryogenic direct detection experiments in various stages of operation at present. CDMS II has been operating in the Soudan Underground Laboratory since 2003. EDELWEISS II is commissioning their new apparatus at the Modane Underground Laboratory and CRESST II is at a similar phase in the Gran Sasso Underground Laboratory. There are also a few smaller R&D efforts, as well as plans for future, large cryogenic experiments. I summarize briefly the status and prospects for these experiments in this section.

3.1. CDMS
The Cryogenic Dark Matter Search (CDMS) Collaboration has pioneered the use of low temperature phonon-mediated detectors to search for the rare scattering of WIMPs on nuclei and distinguish them from backgrounds. The CDMS II experiment was constructed over several years (1998-2002) in the Soudan Underground Laboratory (2000 mwe) and has operated successfully since 2003.

3.1.1. Current and pending results
The first year of CDMS II running at Soudan, with a target mass of about 1(0.5) kg Ge(Si) and a raw Ge exposure of 75 kg-days, produced limits on WIMP-nucleus cross sections that were substantially better than achieved by any other experiment at the time. Figure 1 shows the published [9] spin-
independent limits, with a minimum cross section of $1.6 \times 10^{-43}$ cm$^2$ at 60 GeV/c$^2$. Spin-dependent limits were also derived for both Ge and Si [10]. Recently, the Xenon 10 experiment [5] has shown improved limits (also shown in Fig 1) based on a raw exposure of 316 kg-days, albeit with a significant background of 10 events in the signal region that limits their discovery potential. Meanwhile, CDMS II has continued to run, now with increased target mass of 4 kg Ge and 1.5 kg Si, and has accumulated a total exposure of ~1200 kg-days as of the end of 2007. The expected sensitivity corresponding to that exposure, assuming no background, is also shown in Fig 1, indicating that CDMS II limits will again be the world’s best, reaching cross sections $\sim 2 \times 10^{-44}$ cm$^2$. Blind analysis of the first 400 kg-days of data is underway and results are expected in early 2008. Analysis of the full data set should follow by summer 2008.

The most difficult background source for CDMS II, as for most solid-state detectors, is due to residual surface contamination, particularly from beta-emitting radioactive isotopes. There is a very thin ‘dead layer’ on the surface of the crystals, where ionization is not collected efficiently, leading to a potential event signature that mimics that of WIMPs. Fortunately, the phonon signal carries timing information that can distinguish surface events from bulk events, resulting in a 99.9% rejection of surface events in CDMS II. This discrimination can be improved further, with only a gradual loss of nuclear recoil acceptance, allowing the experiment to remain ‘background free’.

CDMS II will continue to operate at Soudan at least through 2008, with another data set of ~1200 kg-days expected, and a final cross section goal of $\sim 10^{-44}$ cm$^2$ at 60 GeV/c$^2$. It is important to emphasize that CDMS II is the only direct detection experiment currently running with less than one background event in the signal region. This is crucial for spotting the first few events of a WIMP signal. Indeed, CDMS II may have the reach to discover WIMPs in the coming year or two, before the Tevatron or the LHC see evidence for supersymmetry. Conversely, should supersymmetry be discovered at the Tevatron or LHC, CDMS II may clarify whether the lightest supersymmetric particle constitutes the dark matter.

3.1.2. SuperCDMS 25 kg

The CDMS collaboration has proposed a new SuperCDMS experiment, with 25 kg of Ge target mass. Combined with improved background rejection and location at the very deep (6000 mwe) site at SNOLAB, this experiment would represent another order of magnitude improvement in dark matter sensitivity. Preparation for the SNOLAB phase of the experiment will overlap with continued running of CDMS II detectors at Soudan in 2009, and the full detector payload would operate at SNOLAB in 2011-13.

The SuperCDMS detectors are each 2.5 times more massive than the CDMS II detectors and have both improved rejection capability and decreased surface backgrounds. The projected exposure of 18,000 kg-days should reach a WIMP-nucleon cross-section of $\sim 10^{-45}$ cm$^2$ for a WIMP mass around 60 GeV/c$^2$ as shown in Fig 1.
Figure 1. WIMP-nucleon cross section versus WIMP mass for several recent direct detection experiments. In solid blue are the published results of CDMS II, while the recently reported Xenon 10 results are in solid red. The blue dotted curve shows the current CDMS II sensitivity, whereas the black dashed curve shows the expected final sensitivity of CDMS II assuming no background. The black dotted curve is the sensitivity goal for SuperCDMS 25 kg.

3.2. Edelweiss

Edelweiss I operated three, 320 g Ge detectors at the Modane Underground Laboratory (4800 mwe) until 2002, and achieved significant limits on WIMP interactions based on a raw exposure of 62 kg-days [11]. The experiment became limited by backgrounds due to Radon contamination on copper covers surrounding the detectors at the level of ~5 events/kg-day. The Edelweiss I detectors used thermal readout of the phonon signal, which cannot exploit phonon timing to reject surface events. The collaboration is now pursuing Edelweiss II, with a rebuilt apparatus and improved detectors.

3.2.1. Preparations and prospects for Edelweiss II

Edelweiss II has significant improvements compared with the earlier experiment. Much more attention has been devoted to materials screening and the experiment is enclosed in a clean room supplied with air that has reduced Radon concentration. Both gamma (Pb) and neutron (polyethylene) shielding have been made thicker, with more complete coverage, and a muon veto surrounds the experiment. The new cryostat can accommodate up to 40 kg of detectors. Currently available are twenty-one, 320 kg Ge detectors with thermal readout and seven, 400 kg Ge detectors with NbSi thin-film phonon sensors that may ultimately provide surface event rejection similar to that achieved with CDMS II.

The new experiment is currently being commissioned. An engineering run resulted in ~19 kg-days of data with eight detectors, a recoil energy threshold ~30 keV and no events in the nuclear recoil region. Judging from the alpha counting rate, there is still a background from $^{210}\text{Pb}$, but at a level 2-3 times lower than in the previous experiment. Prototypes of the new NbSi sensor readout indicate 90(99)% surface event rejection, with signal acceptance of 70(50)%. It is expected that physics running will start soon, with a sensitivity goal of $1 \times 10^{-43}$ cm$^2$ by spring 2008. Thereafter, detectors will be added
every few months until the full payload is achieved. Sensitivity of $\sim 10^{-44}$ cm$^2$ should be possible by 2009-2010 [12].

3.3. CRESST
The CRESST experiment operates CaWO$_4$ detectors with sensors that give simultaneous measurement of phonons and scintillation light for discrimination of nuclear recoils from electromagnetic backgrounds. Oxygen recoils will come mainly from neutrons while W recoils will be preferentially from WIMP interactions. The experiment is located in the Gran Sasso Underground Laboratory (3500 mwe). Results from the earlier CRESST 1 experiment came from a short exposure in 2004 [13], in which it was realized that the shielding surrounding the experiment was not adequate to reject neutron backgrounds.

3.3.1. Preparations and prospects for CRESST II
CRESST II has a substantially improved shield and SQUID-based readout of the phonon signal, as well as a new cryostat and data acquisition system. There is space in the new cryostat for thirty-three, 300 g detectors. A first physics run with three detectors accumulated ~60 kg-days and reached a sensitivity of about $7 \times 10^{-43}$ cm$^2$. Backgrounds seem to be understood, and the experiment currently has 3 kg of detector mass deployed and is working on electronic noise and calibration issues [14]. It is expected that a physics run will commence in early 2008. The ultimate goal of CRESST II is to reach a sensitivity $\sim 10^{-44}$ cm$^2$.

3.4. Eureca
The groups pursuing EDELWEISS and CRESST have tentatively agreed to join forces after their current experiments are complete and pursue a new European facility called EURECA. The goal is to host up to 1000 kg of various cryogenics detector targets, in order to reach spin-independent WIMP-nucleon cross section sensitivity $\sim 10^{-46}$ cm$^2$. The likely location for the experiment would be Modane and the time scale is probably 2013 or later.

3.5. 3He experiments (Mimac, Ultima)
There has been some R&D work on developing bolometric detection of nuclear recoils from WIMPS in 3He. The technique would employ mechanical wire resonators installed in a 100 µK superfluid 3He cell and driven at resonance via the Lorentz force in a 100 mT uniform B field. Energy depositions would produce quasiparticles that damp the resonator motion and thus shift the resonant frequency. One would also have to sense either ionization or scintillation to provide discrimination against electron recoils.

4. Comparison with collider searches for WIMPs
Collider searches and direct detection are reaching similar WIMP sensitivities at about the same time. The two approaches are complementary. In most models of supersymmetry, if the LHC detects a neutralino, it will also have a sufficiently large elastic scattering cross section with nuclei to be visible in direct detection. Collider experiments are needed to establish WIMP properties, although direct detection can help determine the WIMP mass accurately and indeed have a larger mass reach than at the LHC! Only direct detection can establish convincingly that a WIMP signal detected in collider experiments is a significant part of the dark matter halo of our galaxy.

5. Summary
Cryogenic detectors will continue to be at the forefront of dark matter direct detection over the next few years, with new results expected from CDMS, EDELWEISS and CRESST. Figure 2 shows some sample projections for the next decade, although these should always be treated with caution since history shows they are usually optimistic. The field will benefit greatly from the multiplicity of techniques used if a WIMP signal is detected by one of the experiments. The key to increased
sensitivity will be increasing target mass while continuing to reduce and reject backgrounds. Only a background-free experiment has real discovery potential for WIMPs!

Figure 2. WIMP-nucleon cross section versus WIMP mass projections for upcoming experiments, compared with current limits. Note that as the target mass increases, the background levels must decrease to achieve the sensitivity goals.

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