Dark Matter Searches: Technology and Backgrounds

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Abstract

The current status of direct dark matter searches is reviewed, with special emphasis on the effect of various backgrounds to the sensitivity attainable by that technology. The current leader in sensitivity is the Cryogenic Dark Matter Search, now operating at the Soudan Underground Lab in Minnesota. The next generation of larger and more sensitive detectors will require ever more radiopure materials and access to screening facilities to ensure rapid turn-around in decisions based on material selection and fabrication modification. Recent surveys collected from the DUSEL working groups point to a tripling in screening needs, many of which require an overburden. Low background counting facilities should be established at existing underground sites and integration of their complementary strengths would ensure that new techniques in dark matter, solar neutrino, and neutrinoless double beta decay have the resources they need to build ton scale detectors.

Dark matter; WIMP;CDMS;Soudan; low background counting; LBCF;screening;SUSY;supersymmetry;Cryogenic Dark Matter Search

1. Dark Matter Direct Detection

Studies of the microwave background, supernova, and elemental abundances indicate that the mass-energy density of the Universe is 73% dark energy, 23% dark matter, and only 4% normal, baryonic components. Dark matter is also indirectly observed via its effect on stellar motion in galaxies and clusters of galaxies. A direct detection would confirm its existence (ruling out arguments based solely on the modification of gravity), as well as define its properties.

Excellent candidates for dark matter are weakly-interacting relic particles from the Big Bang, the so-called WIMPs. If supersymmetry is the correct extension of the Standard Model, one would interpret the nonbaryonic dark matter as its lightest stable neutral particle, the neutralino. Supersymmetric models yield a wide range of neutralino mass and cross section predictions, much of which is accessible through direct detection. What is actually detected is the recoil energy of a nucleus (few tens of keV) elastically scattered by a WIMP passing through the detector as the earth moves through the dark matter cloud.

2. Target Material

In the zero-momentum transfer limit, the elastic scattering cross section of neutralinos on nuclei can be generally written [1,2] as $\sigma_{\chi A}=4G_F^2\mu^2C_A$ where μ is the reduced mass of the χA system. C_A depends on the form of the interaction. If the underlying interaction is scalar (spin-independent), then $C_A = 1/4\pi[Zf_p+(A-Z)f_n]^2$ and the cross section is proportional to A^2 (assuming equal proton and neutron coupling strengths: $f_p=f_n$). If the coupling is axial, then $C_A = 8/\pi[a_p<S_p>+a_n<S_n>]^2(J+1)/J$ where $<S>$ is the nuclear spin and a is the coupling strength. The A^2 enhancement favors high Z materials. However, loss of coherence at higher masses (form factor suppression) can moderate this advantage. For example, the rate of WIMP detection (evts/kg/keV/day) in liquid xenon (A=131) starts out an order of magnitude higher than liquid argon (A=40) at recoil energies of 10 keV, but falls rapidly as the recoil energy increases, eventually dropping below argon by 50 keV. Thus liquid xenon must realize its potential by keeping its energy threshold low.

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The axial, or spin-dependent cross section requires a net nuclear spin, constraining the isotopic choice. Many experiments have some sensitivity to this, due to natural abundances. For example, the unpaired neutron in the 7.73% of ^{73}Ge (spin=9/2) and the 4.68% of ^{29}Si (spin=1/2) in the CDMS crystals gives them competitive limits in n-coupling. Superheated bubble experiments COUPP [3], Picasso [4], and SIMPLE [5] have explored various fluorocarbons compounds for the best combination of bubble formation and spin-dependent sensitivity. Since both the n and p couplings need to be explored, different isotopic targets create complementary exclusion ellipses, cutting through the a_p vs. a_n plane along different axes. Xenon has an interesting advantage in that 6 different isotopes can be separated, making it possible to test both n and p couplings in the same apparatus.

3. Background Shielding

Interleaved layers of hydrogenous and high-Z material are required to shield underground experiments from natural radiation due to U/Th in the rock walls, as well as lower energy cosmogenic neutrons. The CDMS shield [6] typifies this method with 40 cm of polyurethane surrounding 18 cm of lead. An inner layer of 4.5 cm of ancient lead reduces radiation from the ^{210}Bi in the normal lead and a further 10 cm inner poly ring blocks γs and moderates lower energy n's created in the Pb. If there is space, a tank of purified water > 4 m thick provides an inexpensive multi-purpose neutron shield which will also reduce cavern background to acceptable levels. Siting the experiment deep underground reduces the muon flux and thus the induced neutron flux, but it hardens the spectrum making those neutrons that are left extremely hard to shield. Thus there is still interest in understanding the expected flux of these punch-through neutrons.

This rate must be estimated using Monte Carlo simulations. Both FLUKA and GEANT4 can provide guidance in the specific design of the shielding, but there is still considerable uncertainty in the normalization of the cosmogenic neutrons and their multiplicities. Although many studies have been done [7,8] there is still controversy [9]. Since the low flux of muon-induced neutrons at deep sites prevents easy benchmarking of simulations, the normalization uncertainty is not likely to improve beyond ~50 % for a while.

Active veto shields, such as the 5 cm thick scintillator surrounding the CDMS passive shield, tag virtually all the neutrons produced by muons striking the interior passive shielding. However, it also does a better job than expected at reducing neutrons produced by muons in the rock, since the veto is sensitive to accompanying shower fragments and parent muons. For CDMS, >93% of the neutrons energetic enough to make a nuclear recoil in our detectors are vetoed, up from 80% if only intersecting muons are counted. An efficient active veto, combined with the higher multiplicity of deep muon-induced hadronic showers thus makes shallower sites, such as Soudan and Boulby, more competitive for dark matter searches.

Although radon is relatively easy to remove in small installations where the active area can be maintained in a nitrogen atmosphere, it is important to guard against plate-out (and dust-borne) contamination by radon daughters on components or shielding during manufacture, shipping and storage. Large radon-mitigated zones, such as those provided by surface air ventilation (e.g. Kamiokande) or radon scrubbing [10], ensure success with these precautionary measures.

4. Background Discrimination

Most new direct detection experiments distinguish electron recoils caused by gamma and beta background, from nuclear recoils caused by the heavier WIMPs and neutrons. This is done by comparing two complementary signals: scintillation vs. ionization for noble liquids, ionization vs. phonon (both athermal and thermal) for cryogenic solid state, and scintillation vs. thermal phonon for cryogenic inorganic scintillators.

Experiment	Technology	β,γ rejection	Comments
CDMS Edelweiss CRESST, Rosebud	Cryo Ge/Si Cryo Ge Cryo $CaWO_4$	ionization/phonon ionization/thermal scintillation/thermal	surface β's, timing helps surface β's, NbSi helps low light for WIMP on W
Zeplin, XENON, WArP, ArDM, XMASS CLEAN	LXe 2-phase LAr 2-phase LXe LAr/LNe	charge/scintillation charge/scintillation scint,self-shielding, scint,pulse shape disc.	low light, PMT radioactivity purification (^{39}Ar,^{42}Ar,^{85}Kr) No E-field, good scaling also solar ν, no E-field
Majorana, Gerda Genius, GEDEON Cuoricino	HPGe counting HPGe counting Cryo TeO_2	energy resolution extreme purity stat. subtraction	primarily ββ-decay large mass, ann mod.
DAMA,LIBRA, ANAIS	NaI scint.	pulse shape disc. extreme purity	large mass, ann mod. also ββ-decay
Picasso, COUPP	bubble chambers	nucleation thresh	large mass, alpha bkgd
DRIFT	drift chmbr (gas)	track length	directionality/low density

Figure 1. Summary of background rejection and/or discrimination techniques for dark matter experiments, sorted by technology.

In general, there is a trade-off between good discrimination using dual technology readout and ease of scaling to the larger masses required for the next generation of dark matter searches. The wealth of information available to the cryogenic solid state detectors yields excellent background rejections, yet also makes them intrinsically difficult to manufacture and run at the tens of mK level required. The simplicity of self-shielded noble liquids makes them more scalable. This is especially true for CLEAN [11] and XMASS [12] which do not require E-fields to drift the electron-hole pairs, whereas dual-phase TPC's lie somewhere in between. LAr has the advantage that nuclear recoils have a larger ratio of fast: slow scintillation components, giving electron recoil rejection via pulse shape discrimination, without the complication of charge readout.

Neutrinoless double beta decay experiments require excellent energy resolution and large mass, and have traditionally done gamma spectroscopy with high purity germanium detectors. As dark matter detectors, they rely on statistical subtraction of their (very well characterized) background in the energy region below 50 keV. Larger segmented arrays [13] (e.g. Majorana, GERDA, GEDEON) will use coincidence and active LAr shields to reduce Compton background and also reject more neutrons based on multiple scatters. Arrays of NaI counters have a similar approach [14], although they also have some pulse shape discrimination to reduce the number of electron recoils in their sample.

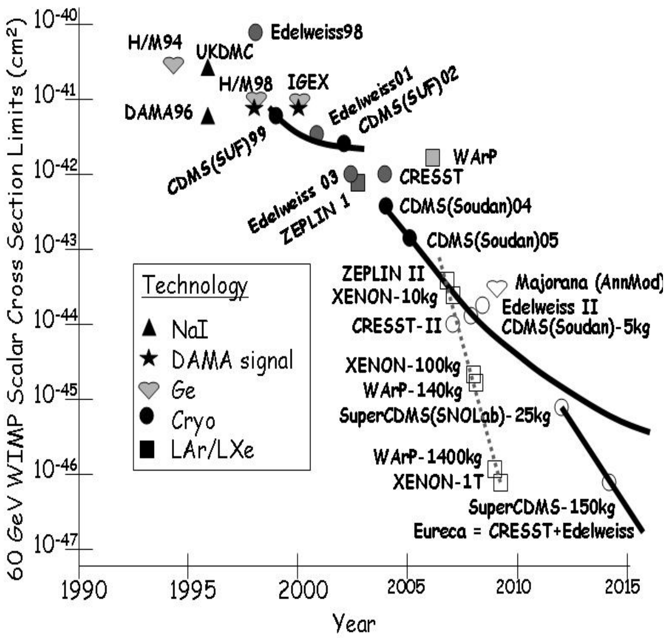

Figure 2. Recent spin-independent limits from dark matter searches, sorted by technology. These limits are for 60 GeV WIMPs using the standard dark-matter halo and nuclear physics WIMP model. The dark symbols (inlcuding grey-scale to distinguish between experiments) represent published limits and the clear symbols represent the expected reach for proposed experiments as projected by the experiments themselves. The DAMA annual modulation , interpreted as a standard WIMP signal, is represented by stars. The dark lines connect the CDMS published results at SUF and Soudan, as well as the projected SuperCDMS at SNOLab, clearly showing how depth limits the sensitivity reach, when neutron background needs to be statistically subtracted. The dotted line represents an aggressive timeline for noble liquids, assuming that they surmount problems with ionization drift at high E-field and can operate at low enough energy thresholds. A similar plot and a multitude of references can be found in a review of dark matter direct detection [25]

A timeline of dark matter spin-independent cross section limits, sorted by technology, is shown in figure 2. The field was dominated in the early 90's by high-purity germanium detectors, such IGEX, UKDM, and Heidelberg-Moscow (H/M) [15]. DAMA [16] entered the scene in 1996 with the best limit, using NaI crystals. After longer exposure, they found an annual modulation signal compatible to that expected from WIMPs (shown as stars) [17]. In the couple years following, neutrons could be found in the CDMS [18] sample due to insufficient overburden (SUF = shallow site at Stanford). Edelweiss [19] (deep enough at Frejus) was limited by poor electron to nuclear recoil discrimination. Statistical subtraction of backgrounds made it impossible to convincingly challenge the DAMA signal, though gradual progress was made by Edelweiss and CRESST [20], a cryogenic technique using sapphire instead of germanium. However, when CDMS moved to the deeper Soudan site and Edelweiss improved their detectors, event-by-event discrimination allowed them to demonstrate that the DAMA modulation could not be caused by WIMP scalar interactions in standard galactic halos [21]. Noble liquid detectors, ZEPLIN I [22] and WARP [23] have recently published results which also confirm this.

Future limits, as anticipated by the collaborations themselves are shown using clear symbols. How fast an experiment can approach a new limit depends on their exposure (mass x time), which itself depends on funding and the ease by which the chosen technology can be scaled to larger masses. This is the great advantage of noble liquids and superheated droplet technology and explains why the dotted line connecting the WARP and XENON [24] projections is so steep, but there are still problems to be worked out before taking these projections at face value. Dual-phase LXe experiments have not yet demonstrated sufficient ionization drift in the high field regime (>kV/cm) and struggles with low light yield, whereas LAr has to worry about removing long-lived radioactive isotopes. However, the inherent risetime difference between fast and slow scintillation components in LAr may allow WARP and simpler, non dual-phase LAr experiments, such as DEAP and CLEAN, to overtake the LXe TPC.

The sub-Kelvin cryogenic experiments' projections are more reliable, since the technology is well-established and only minor improvements are envisioned. CDMS becomes SuperCDMS and moves to SNOLab in 2009, with results several years later, while CRESST and Edelweiss join forces to become Eureca, with a hybrid detector combining the best of both technologies. The solid line connecting the CDMS limits demonstrates the way in which sensitivity limits scale linearly with mass x time (assuming a constant rate of detector production and no unexpected delays in commissioning) while the experiment remains background-free. Once statistical subtraction of a background is required, the limits go as the square root of exposure. For CDMS, this has been due to the appearance of neutrons in the nuclear recoil band at shallow sites and which may resurface at Soudan for SuperCDMS, assuming the most conservative estimates from systematics-limited Monte Carlo projections (see Section 3).

5. CDMS Background Rejection

The Cryogenic Dark Matter Search is currently the most sensitive direct detection experiment. Five towers of 6 detectors each are currently being operated in the Soudan Underground Lab in northeastern Minnesota. Each detector is 1 cm thick and 7.6 cm in diameter, and made of either high-purity germanium (250g) or silicon (100g). Four quadrants of phonon readout cover the top surface. Each quadrant consists of 1,036 quasiparticle-assisted transition edge sensors (TES) operated in parallel. Each TES is a 1 micron wide strip of tungsten connected to eight superconducting aluminum collection fins. Its current is monitored by SQUIDs and maintained within the superconducting transition region by electrothermal feedback.

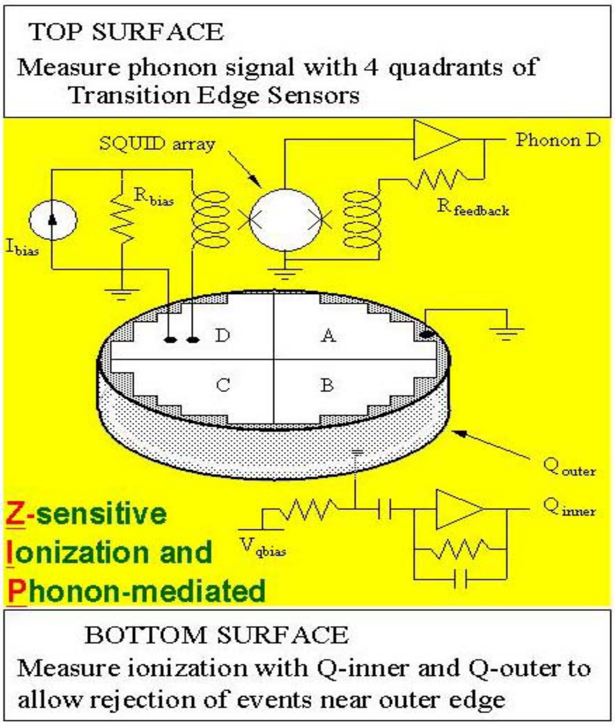

Figure 3. A diagram of the dual readout which gives CDMS such good electroin recoil rejection. The athermal phonon signal is read out by TES and ionization is collected on the opposite face of the crystal.

An applied electric field of a few volts/cm drifts the electron-hole pairs to the faces of the crystal. The ionization signal is then collected on the opposite face of the crystal by a disk-shaped inner electrode 69 mm in diameter. An outer guard ring is used to reject events occurring near the edge of the crystal where the electric field is non-uniform.

The normalized ratio of ionization to phonon recoil energy is called the "yield", with electron recoils giving an average yield of 1 and nuclear recoils giving yields around 1/3. Calibration data is used to determine the electron-recoil and nuclear-recoil yield bands. Any WIMP should show up inside the nuclear-recoil band. None have yet been seen for 34 kg-days of germanium exposure and 12 kg-days of silicon exposure. CDMS expects to reach a sensitivity of 10^{-44} cm^2 for a 60 GeV WIMP by 2008, using the standard dark-matter halo and nuclear physics WIMP model. An even deeper experiment with thicker crystals is proposed for SNOLab by 2009.

Electron recoils near the surface of the crystal suffer incomplete ionization (thus lower yield), and can begin to be confused with nuclear recoils. Luckily, electron recoils in general have a faster risetime and shorter delay (relative to the charge pulse) than nuclear recoils, due to the production of higher velocity ballistic phonons as the electron-hole pairs drift through the crystal. Phonon signals from electron recoils near a surface are even faster, due to prompt ballistic down-conversion of the high frequency phonons at the metal-crystal interface [26]. This discrimination, along with the xy position gleaned from charge sharing and relative timing between the 4 quadrants, enables CDMS to perform a background-free WIMP search to 10^{-44} cm^2 at the 2100 mwe depth of Soudan.

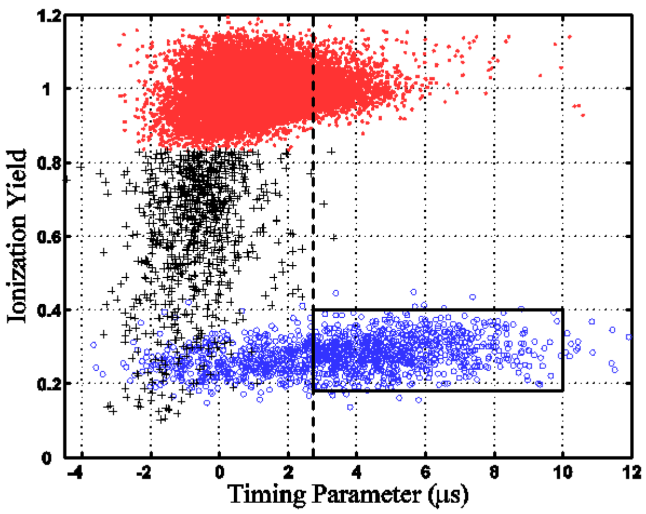

Figure 4. CDMS calibration source data (^{133}Ba produces gammas and surface electrons via gamma-induced beta scatters from one detector surface onto the neighboring face; ^{252}Cf produces neutrons). The electon recoils can be distinguished from nuclear recoils by both yield (normalized ratio of ionization to phonon) and by risetime and delay parameters. The surface betas are less well-separated in yield, but removed by timing cuts. The WIMP serach region is the black box. If neutrons are shielded, the box can be chosen to be background free.

In order to maintain a background-free experiment for the next stage, a 25 kg installation at SNOLab (6060 mwe), the following improvements are being made: thicker detectors, interleaved electrode design for better E-field uniformity, better handling methods to avoid radon-related ^{210}Pb plate-out, more sophisticated maximum likelihood methods to separate the electron and nuclear recoil populations, and a dedicated beta screener. The minimized surface area and the screening will address directly the issue of beta-emitting contamination on the detector surface. The beta screener is a neon-filled multiwire proportional chamber into which entire CDMS detectors or test wafers can be introduced and the beta decays directly counted. This data provides feedback on fabrication, as well as quantifying the expected surface beta flux. Currently CDMS uses surface analysis (SIMS, RBS, PIXE), which is only applicable to beta emitters with natural abundances, such as ^{14}C or ^{40}K , which can then be identified via their more abundant isotopes.

6. Screening Facilities

As the sensitivity requirements become more stringent and experiments move to larger mass and longer timescales, the radiopurity of every component that goes into the detector must also meet higher standards, usually established by screening samples of each type of material. A variety of techniques can be used: high purity germanium detectors, scintillator counters and gas proportional counters. However, an ever larger percentage of the components require ultra-sensitive screening that exceeds the capability of even the best screening facilities available in shielded sites at the earth's surface. Yet there are no underground sites in the US with user-oriented low background counting facilities [27]. Surveys of experimental needs completed over the last year by the NSF-sponsored Deep Underground Science and Engineering Lab (DUSEL) working groups indicate that the total number of samples requiring some sort of screening for current and next generation dark matter, solar neutrino, and double beta decay experiments far exceed any realistic single-site underground facility. The chart below includes data from experiments expecting to run in the next few years (EXO, MEGA, SuperCDMS, XENON), as well as estimates from DUSEL experimental modules. It sorts the screening by year and sensitivity limits. The jump in demand in 2010 corresponds to the overlap of near term future experiments and the start of screening for DUSEL experiments.

Thus there is renewed interest in developing a number of underground sites as screening facilities that can serve the physics community, but recoup operating costs by serving a wider user community. These ultra-sensitive screening detectors can also be used by geology, microbiology, archaeology, environmental science, and national security applications to identify radioisotopes, date samples, and measure tracers introduced into hydrological or biological systems. In particular, the Soudan Underground Lab, which hosts MINOS and CDMS, now has two high-purity germanium detectors in a shielded enclosure [28] which are in constant use as gamma screeners by XENON, CDMS, and Majorana. The kiloton Soudan2 proton decay calorimeter was removed, and its proportional tube veto upgraded with a modern data acquisition system. This created a 4300 m^3 experimental hall lined with an active muon veto shield. A third gamma screener, the CDMS beta screener, commercial α, β counters, and a BF neutron detector are being commissioned in a new clean room under this shield. A proposal to install a 10 meter diameter water tank with multiple top-loading ports for additional screeners, including a high pressure xenon gas detector, is pending.

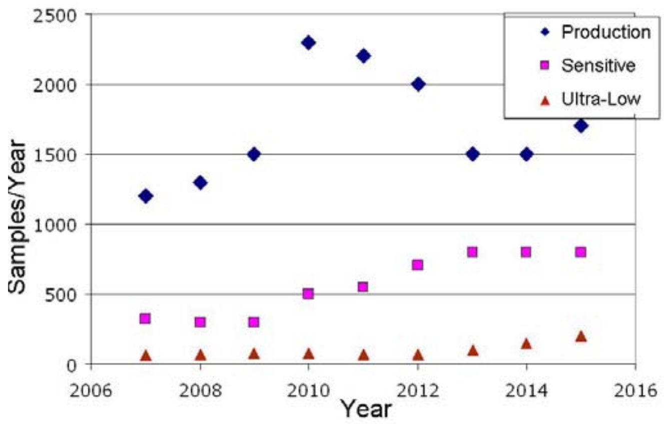

Figure 5. Future creening needs for underground physics experiments, as compiled by the NSF DUSEL S1 Working Group (Low Level Counting)

7. Conclusion

The next generation of detectors will approach ton scale installations. At these sensitivities, large regions of supersymmetric theories will be probed. This comes at the same time that the Large Hadron Collider is turning on at CERN, hoping to directly produce these supersymmetric particles. While accelerator searches are limited by the 2 TeV center of mass energy (resulting in a < 300 GeV limit for neutralinos), dark matter searches are limited by cross section, which is overcome by increased exposure. Noble liquids and bubble chamber technologies are inherently easier (cheaper) to scale up, and will eventually overtake cryogenic solid state detectors. At what stage this happens will crucially depend on the development of ultrapure materials and screening technology for ever smaller amounts of trace radioisotopes. Until this is solved, experiments with excellent electron recoil discrimination, such as CDMS, will remain the most sensitive.

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