Radon Induced Backgrounds in Search for Dark Matter WIMPs with Ge & Si Detectors

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Outline

• After many years the field of direct detection has entered most interesting sensitivity region.

• CDMS has lead field for most of past decade and is continuing with SuperCDMS Soudan and SNOLAB

• Exciting new technologies based on noble liquids making significant advances with XENON100 now leading the field.

• Recent new analysis of Si detectors in CDMS-II show hint of signal from light mass WIMPs (about 8 GeV/c^2)

• Major background from radon contamination producing ^{210}Pb surface betas and ^{206}Pb surface nuclear recoils.

• Advance iZIP interleaved detector design dramatically improves rejection of surface backgrounds and enables ton scale cryogenic experiments in the future.
Expanding universe - simulations and data
Composition of the Cosmos

New Planck best fit

WIMPs
Dark Matter - clumps 23%
Free H & He - cold 3%
Stars + gas 0.5%
Ghostly neutrinos 0.3%
Heavy elements - us 0.03%

Dark Energy - expands 73%

Older WMAP best fit

WIMPs
Dark Matter 26.8%
Ordinary Matter 4.9%

Dark Energy 68.3%
Concordance Model of Cosmology
Bullet Cluster demonstrates reality of DM

- Stars 4% of cluster mass - optical image from Hubble and Magellan telescopes (D. Clowe, et al)
- Gas 16% of cluster mass - x-ray image in red from Chandra satellite (M. Markevitch, et al)
- Dark matter 80% of cluster mass - weak lensing of background galaxies (M. Bradac, et al)
What is the dark matter?

- neutrino $\nu$ – hot DM
- neutralino $\chi$
- "generic" WIMP
- axion $a$
- axino $\tilde{a}$
- gravitino $\tilde{G}$
- wimpzilla, …

L. Roszkowski

Alpha Workshop - October 24, 2013

Blas Cabrera - Stanford University
Complementarity mSugra/CMSSM

LHC most sensitive to Co-annihilation and Bulk

Indirect Detection e.g. Fermi/GLAST most sensitive to Co-annihilation and Higgs funnel regions

Direct Detection: most sensitive to Bulk and Focus point regions

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<th>Detector</th>
<th>Region</th>
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- LHC: 1 fb$^{-1}$, 100 pb$^{-1}$
- Fermi/GLAST: Focus Point
- Focus Point: $10^3$ GeV
- Higgs Funnel: $10^4$ GeV

Graphs showing the parameter regions for different detectors and their sensitivities.
The Signal and Main Background

Signal

(or neutrons)
Nucleus Recoils

\[ E_r \approx 10\text{'s KeV} \]

\[ v/c \approx 7 \times 10^{-4} \]

phonons

\[ \chi^0 \]

Background

(gammas)
Electron Recoils

\[ E_r \]

\[ v/c \approx 0.3 \]

ionization

\[ \gamma \]
Direct Detection Techniques

Ge, CS$_2$, C$_3$F$_8$

DRIFT
IGEX
COUPP

ZEPLIN II, III XENON
WARP
ArDM
LUX
SIGN

Ionization

~20% of Energy

ZEPLIN II, III XENON
WARP
ArDM
LUX
SIGN

ZEPLIN II, III XENON
WARP
ArDM
LUX
SIGN

DM SAG at P5

Cd, Si

Al$_2$O$_3$, LiF

Nal, Xe, Ar, Ne

Nal, Xe, Ar, Ne

Nal, Xe, Ar, Ne

Nal, Xe, Ar, Ne
WIMP Search Sensitivity

courtesy of Vuk Mandic

from Mandic
XENON100 (Double phase Xenon)

161 kg (48 kg)
XENON1T (G2)

10 m x 10 m water shield
active muon veto

ICARUS

XENON1T

LNGS Hall B

2.5 t Active LXe

3” QUPID
(121 top, 121 bottom)

Titanium Vessels
(5 mm x 2, 400 kg)

WARP
CDMS II Experiment

- 30 detectors - 4.75 kg of Ge, 1.1 kg of Si

Data Run History:
- Data in PRL Jan 2009
- Data in Science Feb 2010
CDMS-II at Soudan (2090 mwe)
CDMS-II Soudan facility

[Diagram of CDMS-II Soudan facility with labels for lead, plastic scintillators, outer polyethylene, ancient lead, and inner polyethylene.]
CDMS II Active Background Rejection

- Radioactive source data defines the signal (NR – neutrons from $^{252}$Cf) and background (ER – gammas from $^{133}$Ba) regions.

- Ionization Yield $>10^4$ Rejection of $\gamma$

- Ionization collection incomplete on surface. Yield can be sufficiently low to pollute the signal region $ER$ and $NR$.

- Faster down conversion of athermal phonons at surface provides faster phonon signal for $\beta$'s.

Net result: Yield + timing $>10^6$ discrimination.
The cosmologists’ widely accepted “concordance model” asserts that only about 15% of the mass of matter in the cosmos is baryonic—made of protons and neutrons. Most of the predominating nonbaryonic mass is presumed to consist of still unknown “dark-matter” particles without electromagnetic or strong nuclear interactions, but heavy enough to have been nonrelativistic in the early epochs of galaxy formation.

Just such weakly interacting massive particles (WIMPs) are predicted by most proposed extensions of particle theory’s standard model. The leading WIMP candidate is the lightest of the many new species anticipated by the supersymmetry theories. Presumably created in the Big Bang, it could be stable and, with a mass something like 100 times that of the proton, abundant enough to account for the gravitational effects on the clustering and rotation of galaxies whose observation raised the dark-matter issue long ago.

In interactions with nucleons, WIMPs would have very small but nonvanishing elastic-scattering and production cross sections, comparable to those of the ordinary weak interactions. So particle-physics experimenters have been looking for the production of WIMP pairs in high-energy colliders. And on a more modest scale, they

Figure 1. Ionization-yield and timing parameters for candidate WIMP-collision events that survived all prior event-selection cuts in the final year’s exposure of the CDMS II dark-matter detector. The two parameters, described in the test, serve to weed out imposter events. Ionization yield is plotted in standard deviations from the mean for nuclear recoils, as measured with neutron collisions (green dots) in calibration exposures. The zero point of the timing parameter is shifted to its final cutoff value. In the signal region defined by the final cuts (red box), only two WIMP candidates survive. (Courtesy of CDMS.)
Dark Matter Search Results from the CDMS II Experiment

The CDMS II Collaboration*†

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†All authors and their affiliations appear at the end of this paper.

Astrophysical observations indicate that dark matter constitutes most of the mass in our universe, but its nature remains unknown. Over the past decade, the Cryogenic Dark Matter Search (CDMS II) experiment has provided world-leading sensitivity for the direct detection of Weakly Interacting Massive Particle (WIMP) dark matter. The final exposure of our low-temperature Ge particle detectors at the Soudan Underground Laboratory yielded two candidate events, with an expected background of 0.9 ± 0.2 events. This is not statistically significant evidence for a WIMP signal. The combined CDMS II data place the strongest constraints on the WIMP-nucleon spin-independent scattering cross section for a wide range of WIMP masses and exclude new parameter space in inelastic dark matter models.

![Graph showing WIMP mass vs. WIMP-nucleon scattering cross section]
Recent Silicon Results after Unblinding

- Surface Event Distribution
- Neutron Distribution

Normalized Yield vs. Normalized Timing

Normalized Yield

Normalized Timing
Analysis favors a WIMP region of interest \( \approx 3\sigma \)

- Most likely value at 8.6 GeV WIMP mass with 1.9x10^{-41} cm^2 cross section
- Consistent with earlier CDMS Ge and Si limits
- Also consistent with a WIMP interpretation of the COGENT experiment
- In tension with limits from Xenon 10, Xenon 100 experiments

Data are insufficient to claim discovery of a WIMP signal, but does warrant further investigation
SuperCDMS Soudan iZIP Detectors

- Cool to within 0.05 degrees of absolute zero (-459.6 F)
- For each event simultaneously measure the charge produced and the heat produced.
- Allows us to tell if recoiling particle was an electron (backgrounds) or nucleus (WIMP and neutrons)
- Deep underground to avoid neutrons from cosmic ray activity
iZIP interleaved charge & phonon design

- Interleaved electrodes and phonon sensors on both sides of the detector.
- Alternating +2V/ground on one side and -2V/ground on the opposite side with phonon sensors at ground potential on both sides.
iZIP interleaved charge & phonon design

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Phonon thermalization process

- Diffusive phonons are localized -> ballistic phonons distribute uniformly
- Two separate events on left and right hand side
- Top is top side and bottom is the bottom side
- Note that after 500 µs all channels identical
- Position information in leading part
soon GEANT4 framework
Advanced iZIP removes surface e background

- Interleaved charge and phonon lines provide extremely high rejection of surface electrons - so these no longer contribute to background only neutrons are significant.
Configuration for up to 3 yr run to Mar 2015

\[ ^{210}\text{Pb source} \]

\[ ^{210}\text{Pb source} \]
Pb210 source produced with Rn exposure

- 5,000 Bq $^{226}$Ra source - 12 days in 1 liter box
- equivalent to 7 d exposure in 5 MBq/m$^3$ of $^{222}$Rn
- $\sim$400 $^{210}$Pb decays per day per wafer face in average volume of 0.05 liter
- about same plate out rate as seen for our detectors with $\sim$ 5 Bq/m$^3$ exposure for $\sim$100 d
- $^{210}$Po in 95% equilibrium with $^{210}$Pb after 2 yrs
Ultra low background XIA alpha counter

- Ar drift chamber identifies alpha decays with background below 0.005 alphas per day per cm$^2$
- tray area 1,800 cm$^2$ and drift height 10 cm in 1 kV
**Pb210 Source Data from SuperCDMS Soudan**

- Two detectors with one Pb210 decay every min operated for 20 live days corresponds to more than total Pb210 events for SuperCDMS Soudan and even for future 200 kg SuperCDMS SNOLAB

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**Figure 4:** Response of iZIPs to betas and neutrons. Left: Nuclear recoils from $^{252}$Cf (green) and bulk electron recoils (blue) have symmetric ionization response between the two sides of the iZIP. Surface events from the $^{210}$Pb source (red), installed on side 1 of the detector, have an asymmetric response. Right: Ionization yield versus phonon recoil energy for the same data, with 2 sigma ionization yield selection of neutrons indicated by the green lines. The sloping black line is the ionization threshold (2 keV) and the vertical black line is the recoil energy threshold (8 keV$_{nr}$). The $^{210}$Pb source produces electrons in the 10–100 keV range at a rate of 70 events/hour. These populate the region between the electron recoil and nuclear recoil bands at an ionization yield of ~0.6. In addition to the electrons, the recoiling $^{206}$Pb nucleus from the $^{210}$Po alpha decay is also seen with an ionization yield of ~0.2, clearly ending at the 103 keV$_{nr}$ endpoint energy of the decay and confirming that we understand our nuclear energy scale.

Studies performed at the Berkeley test facility have shown that partitioning of energy between phonon sensors on the two faces of the detector can also be used to achieve surface/bulk discrimination down to 2 keV$_{nr}$. In cases where charge information is degraded, the outer phonon guard channels can also be used to identify events that take place at larger radius in the detector. Finally, phonon signal pulse shapes exhibit significant differences between surface events and bulk events. As the analysis of the Soudan data is refined, we will explore the use of phonon information to further improve rejection of surface events at low energies and diagnose systematic effects in the ionization-defined fiducial volume.

**3.2 Cryogenics**

The cryogenics system at Soudan, originally designed for the CDMS II experiment, consists of a commercial dilution refrigerator with cooling power of 400 uW at 0.1 K, ultra-pure copper cans to house the detectors, copper stems to carry heat from the detectors and bring their signals to room temperature, a cryocooler to remove excess heat at 4 K and 77 K, reliquifiers to maintain liquid helium and liquid nitrogen levels in the dilution refrigerator and all of the associated plumbing, instrumentation, controls and pumps to service the system.
Status of Direction Detection Search

- Several have the potential to reach $10^{-45}$ cm$^2$ soon and $10^{-47}$ cm$^2$ in future

$^8$B solar $\nu$'s

$^3$H background important
Community should promote $^8$B signal

- from Louis Strigari

- for 0.3 $t$-$y$ Ge have 46, 12 & 3 evts above 1, 2 & 3 keVnr
Conclusion

• Experiments now in most exciting region for neutralino as dark matter in many models of supersymmetry (mSUGRA)
• XENON100 now leads field by x3 at high mass with 3 events in signal region. Plans progressing for XENON1T.
• LUX, DarkSide, DEAP, CLEAN and COUPP progressing as well.
• SuperCDMS Soudan is now operating 9 kg of Ge and will run for two years improving sensitivity by x5. SuperCDMS SNOLAB with iZIP detectors totaling 200 kg is in R&D phase with plans to start operations in SNOLAB by 2015 will improve sensitivity by an additional x10.
• We have a great horse race for discovering WIMPs. Strong science case for ton scale direct detection major projects.