The Search for Dark Matter in the form of WIMPs: CDMS (Cryogenic Dark Matter Search)

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for
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Dark Matter WIMPs

- The Science
  - Scientific case compelling for dark matter WIMPs
  - Galaxy formed in dark matter gravitational potential
    - Our solar system rotates through swarm of WIMPs
  - If hypothesis correct, billions of WIMPS per $m^2$ per sec
    - These would only interact with nuclei not electrons
    - Nearly all background electrons produced by gammas
- CDMS II SUF (Stanford site) results
  - Tower 1 (4 Ge and 2 Si detectors) at SUF (neutron limited)
- CDMS II Soudan (northern Minnesota) results
  - Same Tower 1 at Soudan - new result submitted to PRL
  - Best sensitivity by a factor of four over EDELWEISS
- Conclusions
Concordance Model of Cosmology

- Supernovae + Cosmic Microwave Background + Large Scale Structure

\[ \Omega_m = 0.27 \pm 0.04 \]
\[ \Omega_\Lambda = 0.73 \pm 0.04 \]

- Great overall success!
- However raises even more questions about origin of dark energy

WMAP + flat:

\[ \Omega_m = 0.27 \pm 0.04 \]
\[ \Omega_\Lambda = 0.73 \pm 0.04 \]
Numerical simulations

- The phase-space structure of a dark-matter halo: Implications for dark-matter direct detection experiments, A. Helmi, S. White, and V. Springel
  PRD 66, 063502 (2002)

- Solar system moves with respect to zero mean velocity halo at 220 km/s
Rotation Curves and Galactic Dark Matter

- Solar System obeys Kepler laws

\[
\vec{F} = -\frac{GMm}{r^2} \hat{r}
\]
\[
= -m \frac{v^2}{r} \hat{r}
\]
\[
v = \sqrt{\frac{GM}{r}}
\]

- Galaxies have constant rotation curves

For:
\[ v \approx \text{constant} \]
then:
\[ M(r) \propto r \]
\[ M_{\text{dark}} \geq 10M_{\text{lum}} \]
The Signal and Main Background

**Signal**
(or neutrons)
- Nucleus Recoils
- $E_r \approx 7 \times 10^{-4}$
- $E_r \approx 10$'s KeV
- phonons

**Background**
(gammas)
- Electron Recoils
- $E_r$ v/c $\approx 0.3$
- ionization
Direct Detection of Neutralinos

- [e. g., Lewin & Smith; and Jungman, Kamionkowski & Griest]
- The observed differential rate of events is given by

$$\frac{dR}{dQ} = \frac{\sigma_0 \rho_0}{\sqrt{\pi} v_0 m_\chi m_r^2} F^2(Q) T(Q) \eta(Q)$$

$R$ in evts/kg - d, typically $\sigma_{0, scalar} >> \sigma_{0, spin}$; $\rho_0$ WIMP ($\chi$) at earth, $\sim 0.3$ GeV/cm$^3$
$v_0$ velocity of sun around galaxy, $\sim 220$ km/s
$m_\chi, m_N$ mass of neutralino & nucleus, $m_r = \frac{m_\chi m_N}{m_\chi + m_N}$; recoil energy $Q = \frac{m_r^2 v^2}{m_N^2} (1 - \cos \theta^*)$

- For a Maxwell distribution of incident velocities

$$T(Q) = \exp\left[-\left(\frac{v_{\text{min}}}{v_0}\right)^2\right] \text{ where } v_{\text{min}} = \sqrt{Q m_N / m_r}$$

$\eta(Q)$ is the detector efficiency as a function of $Q$
Spin independent scalar cross section

- To compare the coherent rates of different materials

\[ \sigma_{0,\text{scalar}} = \frac{4m^2 m^4}{\pi \left( m_x + m_N \right)^2 \left( \frac{f_n}{m_n} \right)^2}, \]  
where \( f_n \approx f_p \) is the WIMP - nucleon coupling.

- We define the fundamental WIMP-nucleon cross section

\[ \frac{\sigma_{0,Wn}}{m^2_{r\chi n}} = \frac{4}{\pi} f_n^2 = \frac{\sigma_{0,\text{scalar}}}{A^2 m^2_{r\chi n}}, \]  
which gives \( \sigma_{0,Wn} \) in terms of \( \sigma_{0,\text{scalar}} \) with \( A \equiv m_N / m_n \).

- Two target materials such as Si and Ge very powerful

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**Graphs:**

- Left graph: Recoil energy vs. \( dR/dQ \) for Si and Ge targets at different energies.
  - Si(30 keV) 0.09 cts/kg/d
  - Si(3 keV) 0.42 cts/kg/d
  - Ge(15 keV) 0.97 cts/kg/d
  - Ge(2 keV) 2.44 cts/kg/d

- Right graph: Recoil energy vs. \( dR/dQ \) for Si and Ge targets at different energies.
  - Si(30 keV) 1.00 cts/kg/d
  - Si(3 keV) 2.03 cts/kg/d
  - Ge(15 keV) 0.57 cts/kg/d
  - Ge(2 keV) 1.08 cts/kg/d

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**Parameters:**

- \( m_x = 40 \text{ GeV} \)
- \( \sigma_{0,\text{scalar}} = 5 \times 10^{-42} \text{ cm}^2 \)

**Note:**

- Neutron background

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Nuclear form factor suppression

- For spin-independent or coherent interactions the form factor $F^2(Q)$ suppression is shown below and results in suppressed rates for heavy

$$F(Q) = 3 \frac{j_1 \left( \frac{Q r_n}{\hbar c} \right)}{Q r_n / \hbar c} \exp \left[ - \left( \frac{Q s}{\hbar c} \right)^2 / 2 \right],$$

where $r_n \approx \left( 0.89 A^{1/3} + 0.3 \right)$ fm and $s \sim 1$ fm

50 keV true nuclear recoil threshold is equivalent to about 5 keVee recoil
Search for Dark Matter WIMPs

- DAMA 100 kg of NaI has claimed a WIMP signal
- CDMS earlier results at shallow site largely ruled out DAMA
- Best published result from EDELWEISS Ge detectors
- CDMS-II new result submitted to PRL
- New limit \(\sim\)x4 better than EDELWEISS
CDMS ZIP Detectors (Ge/Si)

Phonon sensors (4) (TES)
Ionization Electrodes (2)

x-y-z imaging:
from timing, sharing

WIMPs: \%(Ge) \gg \%(Si)
Neutrons: \%(Ge) \& \%(Si)
Fabricated in CIS/SNF

- Pallette can hold four 1 cm thick Ge or Si substrates.
- First part of fabrication cycle is to deposit a trilayer of amorphous Si, followed by Al, and then W.
ZIP detector phonon sensor technology

- TES’s patterned on the surface measure the full recoil energy of the interaction
- Phonon pulse shape allows for rejection of surface recoils (with suppressed charge)
- 4 phonon channels allow for event position reconstruction

~25% QP collection eff.
Transition Edge Sensors (TES)

- Steep Resistive Superconducting Transition
  - $W T_c \sim 70 \text{ mK}$
  - $T_c$ width (10%-90%) $< 1 \text{ mK}$

- Voltage bias is intrinsically stable

  The Joule heating produced by bias
  
  $P_J = \frac{V_B^2}{R} \Rightarrow P_J \downarrow \text{ when } R \uparrow$
  
  is stable whereas for current bias
  
  $P_J = I_B^2 R \Rightarrow P_J \uparrow \text{ when } R \uparrow$
  
  which is intrinsically unstable

}\]
The shallow Stanford Underground Facility (SUF)

- Tower 1 operated at SUF during calendar 2002 at a depth of 17 mwe sufficient to eliminate the hadronic component of cosmic rays.
The ZIP Detector Signal

- Charge & Phonon signals occur on a similar timescale
- Phonon pulse time of arrival allows for event position reconstruction
- 20 keV event in a Si & Ge ZIP

**Si ZIP**

*20 keV Event in a Si ZIP*

**Ge ZIP**

*20 keV Event in a Ge ZIP*

(EXCELLENT S/N FOR 20 KeV TRUE RECOIL ENERGY)
ZIP Phonon Position Sensitivity

Am$^{241}$:
g 14, 18, 20, 26, 60 keV

Cd$^{109}$ + Al foil:
g 22 keV
Recoil [keV] vs Charge [keVee]

Yellow
$^{252}\text{Cf}$

Blue
$\mu$ coin

Red
$\mu$ anti
Tower 1 (4 Ge and 2 Si detectors) at SUF

- SUF Run 21
  - Calendar 2002
  - 52.6 kg-d of Ge after cuts
- Saw 19 nuclear recoils
  - Clean separation of gamma & beta events
  - See 10 keV and 67 keV lines for energy calibration
- All consistent with neutrons
  - Consistent ratio of Ge singles to Ge multiples
  - Consistent ratio of Ge events to Si events
  - Only gain as sqrt(MT)
- TO DO BETTER NEED TO GO DEEPER
Soudan, Minnesota:
The CDMS II Deep Site
CDMS II Soudan Experimental Enclosure

MINOS connecting tunnel

HVAC
Mezzanine

Mechanical
Pumps, Cryogenics

RF-shielded Clean room

Front-end Electronics

Detector Prep
Clean Benches

DAQ/Electronics
Mezzanine

Shield
Fridge
Icebox

Soudan II
Outside of the Experiment

- Lead
- Plastic scintillators
- Outer polyethylene
- Inner polyethylene
- Ancient lead
Tower 1 and Tower 2 now cold in Soudan
Energy calibration of Ge ZIP with $^{133}$Ba source

Excellent agreement between data and Monte Carlo
Nuclear recoil calibration of Ge & Si ZIPs with $^{252}$Cf

Nuclear recoils in Ge ZIP

Nuclear recoils in Si ZIP

Excellent agreement between data and Monte Carlo
252Cf Neutron & Gamma calibration data

- Upper red dashed line are +/- 2 s gamma band
- Lower red dashed line are +/- 2 s nuclear recoil band
- Separate high statistics calibrations with 133Ba gamma source
- Determined with calibration data as was the analysis threshold energy
133Ba gamma & 252Cf neutron calibrations

- Use phonon risetime and charge to phonon delay for discrimination of surface electrons “betas”
- Cuts and analysis thresholds determined entirely from calibration data with WIMP search data blinded until after the cuts and thresholds were set.
In 92 days between October 11, 2003 and January 11, 2004, we collected 52.6 live days - a net exposure of 22 kg-d after cuts. Below data are shown before (left) and after (right) timing cuts.

(yellow points are from neutron calibration)
New CDMS limit from Soudan Lab

- Exposure after cuts of 52.6 kg-d raw exposure with Ge ≈ 20 kg-days for 60 GeV/c^2 WIMP
- NO EVENTS in nuclear recoil band (one leakage event second analysis)
- Expect 0.7 +/- 0.35 expected leakage betas
- Expect 0.07 unvetoed neutrons (0.7 muon coincident neutron)
- New limit ~x4 better than EDELWEISS at a WIMP mass of 60 GeV/c^2
CDMS II should reach its goal!

Simulation of limits based on our extended Cousin-Feldman likelihood ratio test

Currently 45% Z 2,3,5 > 10keV
90% CL upper limit 0.005

Blue points illustrate random fluctuation from experiment to experiment

CDMS II Goal 1998

Zero background 58% efficiency

Expected Tower 1+2
Summer 04

Expected CDMSII end 2005

Tower 1: Fall 03

WIMP mass = 60 GeV/c²
No signal
Efficiency 58 percent above 10 keV
Contamination 0.003/kg/day

04/04/14
Summary and future

- Now and for next several years will explore ‘natural’ cross section range of MSSM
- DAMA ruled out for spin independent scalar interactions
- Light mass region suggested by Bottino largely ruled out
- Plan another factor of five improvement with CDMS III at Soudan
- THEN MUST GO DEEPER possibly SNOLAB in Canada

Chattopadhyay et. al Theory results - post WMAP