First Result from XENON10 Dark Matter Experiment at Gran Sasso Laboratory

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http://xenon.astro.columbia.edu
Existence of dark matter is required by a host of observational data:
galactic halos, 
clusters of galaxies, 
large scale structures, 
CMB, 
high-redshift SN\textsubscript{e} Ia.

Baryonic Matter - Mostly known
Visible Matter (stars) only \(\sim\)1% of the total.
Non-Baryonic Dark Matter
New Particle - SUSY
Observations (gravitational lensing)

Bullet Cluster
merger of two galaxy

A titanic collision between two massive galaxy clusters

encourage Direct Dark Matter Detection.
Weakly Interacting Massive Particle

Dark Matter is required to be
- Neutral
- Non-baryon
- Cold (non-relativistic)

SUSY
⇒ good candidate is the **lightest SUSY particle is stable** and likely becomes a dark matter candidate

**Linear combination of SUSY particles**

\[
\chi_1^0 = \alpha_1 \tilde{B} + \alpha_2 \tilde{W} + \alpha_3 \tilde{H}_u^0 + \alpha_4 \tilde{H}_d^0
\]

Rare Event

\(10^{15}\) through a human body each day: only < 1 will interact, the rest is passing through unaffected!
**Direct Detection Principle**

WIMPs elastically scatter off nuclei in targets, producing nuclear recoils.

\[
\frac{dR}{dE_R} = \frac{R_0 F^2(E_R) k_0}{E_0 r} \frac{1}{2\pi v_0} \int_{v_{\text{min}}}^{v_{\text{max}}} \frac{1}{v} f(v, V_E) d^3v
\]

- **R0**: Event rate
- **F**: Form Factor
  - should be calculated
- Maxwellian distribution for DM velocity is assumed.
  - \( V \): velocity onto target,
  - \( V_E \): Earth’s motion around the Sun

### Spin independent case:

\[
\sigma_0 = A^2 \frac{\mu_T^2}{\mu_p^2} \sigma_{\chi-p} \quad \text{Large } A
\]

### Spin dependent case:

\[
\sigma_0 = \frac{(\lambda^2_{N,Z} J(J+1))^{\text{Nuclear}}}{(\lambda^2_{p,Z} J(J+1))^{\text{proton}}} \frac{\mu_T^2}{\mu_p^2} \sigma_{\chi-p}
\]

**Graph**

- **Green Line**: Ar \( A=40 \)
- **Red Line**: Ge \( A=73 \)
- **Blue Line**: Xe \( A=131 \)

**Parameter Values**

- \( M_{\text{WIMP}} = 100 \text{ GeV} \)
- \( \sigma_{WN} = 4 \times 10^{-43} \text{ cm}^2 \)
Direct Detection Principle

WIMPs elastically scatter off nuclei in targets, producing nuclear recoils.

\[ \frac{dR}{dE_R} = \frac{R_0 F^2(E_R)}{E_0 r} k \frac{k}{2\pi v_0} \int_{v_{\min}}^{v_{\max}} \frac{1}{v} f(v, v_E) d^3v \]

**R0**: Event rate  
**F**: Form Factor  
should be calculated

Maxwellian distribution for DM velocity is assumed.  
V: velocity onto target,  
VE: Earth’s motion around the Sun

Spin independent case:

\[ \sigma_0 = A^2 \frac{\mu_T^2}{\mu_p^2} \sigma_{\chi-p} \quad \text{Large A} \]

Spin dependent case:

\[ \sigma_0 = \frac{(\lambda_{N,Z}^2 J(J+1))_{\text{Nuclear}}}{(\lambda_{p,Z}^2 J(J+1))_{\text{proton}}} \frac{\mu_T^2}{\mu_p^2} \sigma_{\chi-p} \]

\[ M_{\text{WIMP}} = 100 \text{ GeV} \]
\[ \sigma_{WN} = 4 \times 10^{-43} \text{ cm}^2 \]

Xe (A=131) is one of the best target
Direct Detection Experiments (background rejection)

- CDMS
- EDELWEISS
- LIGHT
- ZEPLIN
- XENON
- XMASS
- WARP
- ArDM

E_R

Phonons

Charge

Light
The XENON Collaboration

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XENON consists of US and European institutes.
Why Liquid Xenon?

- High Atomic mass Xe (A~131) good for SI case (cross section $\propto A^2$)
- Odd Isotope (Nat. abun: 48%, 129,131) with large SD enhancement factors
- High atomic number (Z~54) and density ($\rho$=3g/cc):
  - compact, flexible and large mass detector.
- High photon yield (~ 42000 UV photons/MeV at zero field) and high charge yield
- Easy to purify for both electro-negative and radioactive purity
- by recirculating Xe with getter for electro-negative
- Charcoal filter or distillation for Kr removal
Event Discrimination: Electron or Nuclear Recoil

- **WIMP** or **Neutron**
- Nuclear recoil or Electron recoil

4 keVee event

Hit Pattern of Top PMTs

- 8 p.e.
- 3k p.e.
XENON10 at LNGS

Corno Grande
The Gran Sasso underground Lab

- 3 experimental halls: 100 m long, 20 m wide, 18 m high (total underground area: 18,000 m²)
- Natural temperature: 6° C
- Relative humidity: 100%
- Location: 963 m over sea level

Main research lines:
- Neutrino physics
- Dark matter
- Nuclear astrophysics
- Gravitational waves
- Geophysics
- Biology
March, 2006 From Columbia Univ. in NY to LNGS
Muon flux ~ 24 \( \mu \)m\(^2\)/day (10\(^6\) reduction from sea level)
Neutron Flux ~ 10\(^{-6}\) n/cm\(^2\)/sec
Shield
20 cm Lead (15cm-700Bq/kg \(^{210}\)Pb, 5cm-15Bq/kg)
20 cm Polyethylene

Full checkout of cryogenics with Pulse Tube Refrigerator
10 months operation with stable condition
48 PMTs on top, 41 on bottom,
Hamamatsu R8520 PMT: Compact metal channel:
1 inch square x 3.5 cm
Quantum Efficiency: >20% @ 178 nm
20 cm diameter, 15 cm drift length
22 kg needed to fill the TPC. Active volume 15 kg.
3D position sensitive TPC

Z-position: Drift Time, X-Y position: Top array of PMTs (neural network)
• Position dependency correction by looking at activated line.
  • Uniform source in the whole detector
  • Activated Xe (5x10^6 n/s Cf, ~ 2 weeks)
  • 164 keV Xe131-m, 236 keV Xe129-m (half life ~ 10 days)
  • Injected ~ 400 g activated Xe gas into detector
XENON10 nuclear and electron recoil band calibration

AmBe Neutron Calibration (NR-band)
In-situ Dec 1, 2006 (12 hours)
Source (~3.7MBq) in the shield

Cs-137 Gamma Calibration (ER-band)
In-situ Weekly calibration
Source (~1kBq) in the shield
XENON10 Background Rejection Power

Flattened band

~50% NR Acceptance

~99.5% rejection power
For 50% Nuclear Recoil Acceptance
XENON10 Blind Analysis

- Basic Quality Cuts (QC0): remove noisy and uninteresting events
- Fiducial Volume Cuts (QC1): capitalize on LXe self-shielding
- High Level Cuts (QC2): remove anomalous events (S1 light pattern)
- In addition to those cuts Energy Window was decided before opening data.

Fiducial Volume chosen by both Analyses:
$15 < dt < 65$ us, $r < 80$ mm

Fiducial Mass = 5.4 kg (reconstructed radius is algorithm dependent)

Overall Background in Fiducial Volume ~0.6 event/(kg d keVee)
More XENON10 Events

Multiple scattering $\gamma$

Drift time (peak1): 32 us
Drift time (peak2): 68 us
S1 energy: 142 keVee
charge 1: 3,600 electrons
charge 2: 12,790 electrons
$\log_{10}(S2/S1) = 2.87$
$\Rightarrow$ multiple gamma event

6 scatters
QC2 Cut

\[ \frac{S2}{S1} > \frac{S2}{S1 + S1x} \]
filled with PTFE, Now data taking started
5 “non-Gaussian” events remain after all QC2 cuts on the WIMP search data.

• The sigma of delta log10(S2/S1) shows higher number (+0.09, 2-12 keVee) → the “gaussian leakage” events estimated from 137Cs data appear to be too conservative before opening the box.

• These non-Gaussian events will be studied by modifying the detector to remove a large fraction of dead LXe layers. We note that these events appear mostly at higher energies. 4 of these have been cut by the Secondary Analysis QC2 cuts.

• “Blind” analysis has provided a good sample to study these events since the origin is different from 137Cs.
- Sum of S2 signal from Top PMTs was used for trigger.
- The threshold for S2 is 300 photoelectron (~ 10 ionization electrons).
- A gas gain of a few hundred allows 100% S2 trigger efficiency.
- The S1 signal associated with an S2 signal was searched for in the off-line analysis.
- The coincidence of 2 PMT Hits is used in the analysis and the S1 energy threshold is set to 4.4 photoelectrons. Its efficiency is ~ 100%. (2keVee)
- The QC2 cuts efficiency varies between 95% and 80% in the 2-12 keVee energy window.
Scintillation Efficiency = \frac{\text{nuclear recoil}}{\text{electron recoil}}

- Very low threshold achieved
- Very good agreement with MC in over all range
- It is true that some uncertainty at low energy (20-35% error in sensitivity curve)
- We take average 19% but new measurement is planned for <5 keVr.
XENON10 WIMP Search Data with Blind Cuts

136 kg-days Exposure = 58.6 live days x 5.4 kg x 0.86 ($\varepsilon$) x 0.50 (50% NR)

- WIMP “Box” defined at ~50% acceptance of Nuclear Recoils (blue lines): [Mean, $-3\sigma$]
- 10 events (●) in the “box” after all cuts in Primary Analysis
- 6.9 events expected from $\gamma$ Calibration
- 5 of them not consistent with Gaussian distribution of ER Background
- 4 of the 5 non-Gaussian events (1 of lowest energy and 3 near upper energy band) are removed by cuts developed in the Secondary Analysis
- Only 1 non-Gaussian event survives both Primary and Secondary cuts (>15keVr, S2/S1 = 2.7$\sigma$ away from NR centroid)

NR Energy scale: use a constant 19% Quenching Factor

\[
Er = \frac{Ee}{Leff} \cdot \frac{Se}{Sr} = S1tot (pe)/3.0 \text{ pe/keV/0.19*0.54*0.93}
\]

2 – 12 KeVee → 4.5 – 27 KeVr
The events in the WIMP search box

- We think the 5 non-gaussian events are not likely WIMP events
  - No 1 coincidence requirement is met because of noise glitch
  - No 2, 6, 8, 10
    - clustered in lower part
    - The expected nuclear recoil spectrum for both neutron and WIMP falls exponentially where as not in this case.
XENON10 Experimental Upper Limits
Spin Independent case

- Upper limits on the WIMP-nucleon cross section derived with Yellin Method (PRD 66 (2002))
- No bg subtraction
- \(8.8 \times 10^{-44} \text{ cm}^2\) Max Gap (4.5-15.5keVr)
  for a WIMP of mass 100 GeV/c^2
  Factor of 2 below best previous limit (CDMSII)

For lower WIMP mass (35 GeV) \(\rightarrow 4.5 \times 10^{-44} \text{ cm}^2\) Factor of 10 lower than best limit
XENON10 WIMP Search Results for SD Interactions

- natural Xe: $^{129}$Xe, 26.4 %, spin 1/2, $^{131}$Xe, 21.2%, spin 3/2
- use shell-model calculations by Ressel and Dean [PRC 56, 1997] for $<S_n>$, $<S_p>$
- upper limits: Yellin Maximal Gap method, no background subtraction
Summary


- upper limit to Spin Independent WIMP-nucleus cross section
  - $4.5 \times 10^{-44}$ cm$^2$ at 35 GeV
- upper limit to Spin Dependent WIMP-n cross section
  - $5.2 \times 10^{-39}$ cm$^2$ at 35 GeV

Roszkowski, Ruiz & Trotta (2007)

| CDMS-II, XENON10+, COUPP, CRESST-II, EDELWEISS-II, ZEPLIN-III,... |
| 1 event/kg/ |
| SuperCDMS1t, WARP1t, ArDM XENON1t, EURECA, ELIXIR, |
| 1 event/t/ |