The XENON100 Dark Matter Experiment at LNGS: Status and Sensitivity
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The XENON program for Dark Matter Detection

**past**
(2005 - 2007)

**current**
(2008-2012)

**the future**
(2013-2015)

**XENON10**
Achieved (2007) $\sigma_{SI}=8.8 \times 10^{-44}$ cm$^2$

**XENON100 & 100+**
Projected (2010) $\sigma_{SI} \sim 2 \times 10^{-45}$ cm$^2$
Projected (2012) $\sigma_{SI} \sim 2 \times 10^{-46}$ cm$^2$

**XENON1T**
Projected (2015) $\sigma_{SI} < 10^{-47}$ cm$^2$
XENON10 Results

**Spin-independent**

**Spin-dependent**

(NO BKG SUBTRACTION)

<table>
<thead>
<tr>
<th>Mass</th>
<th>Cross-section [cm$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 GeV</td>
<td>$8.8 \times 10^{-44}$</td>
</tr>
<tr>
<td>30 GeV</td>
<td>$4.5 \times 10^{-44}$</td>
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Constrained Minimal Supersymmetric Model

(NO BKG SUBTRACTION)

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<th>Mass</th>
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<td>30 GeV</td>
<td>$6 \times 10^{-39}$</td>
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Liquid Xenon for Dark Matter

- **scalability**: relatively inexpensive for very large detector (today ~$1300/kg)
- **Xe nucleus (A~131)**: good for SI plus SD sensitivity (~50% odd isotopes)
- **“easy” cryogenics**: 170 K (LXe)
- **Charge & Light**: highest yield among noble liquids and best self-shielding
- **low energy threshold**: photosensors within liquid for efficient light detection
- **background reduction**: by charge-to-light ratio and 3D-event localization
- **Intrinsically pure**: no long-lived radioactive isotopes; Kr/Xe reduction to ppt level with established methods

\[ R \sim \frac{M_{det}}{M_\chi} \rho \sigma \langle \nu \rangle \]

WIMP Scattering

\[ M_\chi = 100 \text{ GeV}, \sigma_{\chi-p} = 10^{-45} \text{ cm}^2 \]

- 18 evts/100-kg/year
  
  \( (E_{th}=5 \text{ keVr}) \)
- 8 evts/100-kg/year
  
  \( (E_{th}=15 \text{ keVr}) \)
The XENON two-phase TPC

- Single electron and single photon measurement sensitivity
- > 99.5% ER rejection via Ionization/Scintillation ratio ($S_2/S_1$)
- 3D event-by-event imaging with millimeter spatial resolution
The XENON100 Experiment

- ~100 more sensitive than XENON10
- ~100 x less background and ~10 x more fiducial target than XENON10
- Target: 30 cm drift x 30 cm diameter TPC
- Cryocooler and FTs outside shield
- Materials screened for low radioactivity
- ~1 mBq (U/Th) and ~30% QE PMTs
- LXe veto around target on all sides
- 170 kg ultra pure LXe (target + veto)
- Improved passive shield (Cu, Poly, Pb)
XENON100: The TPC Assembly

170 kg LXe (70 kg target)
XENON100: New Cryogenics System Design

LXe behaves like most other liquids. We can use this for detector design.
1. Odd shaped detectors
2. Transporting heat (cold)
3. Efficient conversion gas - liquid

But, it also might freeze.

In equilibrium state direct relation between pressure and temperature. Therefore, two ways to control the liquid.

Temperature regulated: PTR cooling
Pressure regulated: Emergency LN2 cooling

Feedthroughs and Cooling Tower outside Shield

Detector Vessel

Simulated Shield Door
Cooling Tower

The cooling tower supports all instrumentation:
1. Refrigerator Head (incl. Motor Valve and Buffer Tank)
2. LN2 Emergency Cooling Coil
3. Vacuum Pumps for Chamber and Cryostat
4. Vacuum Gauges, Pressure Gauges, Rupture Disk
5. Feedthroughs for Control Circuits

Iwatani PTR PC150, Cooling power 200 W with 6.5 kVA compressor

Sufficient to fill or re-circulate with 10 SLPM

PID Temperature Controller, Stability < 0.1 C

Emergency cooling with LN2 coil.
Regulated with pressure.
Two completely independent systems.
**XENON100: The PMTs**

- 242 PMTs (Hamamatsu R8520-06-Al)
- 1" square metal channel developed for XENON
- Low radioactivity (<1 mBq U/Th per PMT)
- 80 PMTs for bottom array (33% QE)
- 98 PMTs for top array (23% QE)
- 64 PMTs for top/bottom/side Veto (23% QE)
XENON100: Data Acquisition System

Requirements:
- digitize full waveform (320μs) of 242 PMTs
- no deadtime
- high rate capability for calibration

CAEN V1724 Flash ADC: 14bit, 100MHz
- circular buffer → no deadtime
- on board FPGA: Zero Length Encoding

⇒ calibration rates >50 Hz possible
XENON100 TPC: Electric Fields

- cathode: $-30kV \rightarrow$ drift field $1kV/cm$
- anode: extraction field $\sim 5kV$
- field inside TPC was optimized in simulations for field homogeneity $\rightarrow$ 40 double field shaping rings
- anode stack optimized for
  - optical transparency
  - S2 energy resolution (+4%)
- hexagonal mesh structures,
  pitch cathode 5mm, anode 2.5mm
XENON100: Purification System

- Gas purification with continuous re-circulation of the 170 kg of Xe gas through hot getter (SAES)
- Re-circulation speed 10 slpm (5 slpm in XENON10)
- Impurities in LXe affect both charge and light
- Source of Impurities: 1) leaks, 2) materials outgassing and 3) Xe gas contamination.
- Light is strongly absorbed by H2O. Charge is strongly reduced by electronegative substances
- We have succeeded to reduce the H2O level to < 1ppb as measured with dedicated IR detector
- We have succeeded in drifting electrons through entire 30 cm gap as measured directly with S2
XENON100: Kr Removal System

Xe has no long lived isotopes BUT has traces of radioactive Kr85

Kr85 (Emax = 687 keV, t ~11 yr) is present in natural Kr at ~ 10^{-11}

The Kr level in the XENON100 fill gas is currently at ~1 ppb level as measured with delayed coincidence events

A dedicated Cryogenic Distillation Tower designed for Kr reduction by 10^3 has been commissioned and installed next to XENON100: purification run scheduled for July 2009

XENON100 science goal requires ~ 50 ppt of Kr (<1 ev / 0.5 yr)
A new facility for XENON: an Atom Trap Trace Analysis System

- Major Research Infrastructure proposal by Columbia University to the National Science Foundation
- Proposal submitted January 2009 and now approved for funding - 3 Years Development Effort
- System based on laser cooling, slowing and trapping of single Kr atoms from Xe purified sample
- Single atoms counted by detection of their fluorescence with high S/N photodetector
Radioactivity of all materials used in XENON100 measured with a dedicated 2.2 kg HPGe counter at LNGS.
XENON100 Operating Underground @ LNGS
XENON100 Collaboration

USA, Switzerland, Portugal, Italy, Germany, France, Japan, China

45 people: 15 GRA, 10 postdocs

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XENON100 Status and Preliminary Results

- Detector fully functional and taking gamma calibration data underground at LNGS
- Both Charge and Light signals detected
- Optimizing trigger level, threshold, overall response
- Light Yield is maximum and Electron Lifetime currently 225 microsec and keeps increasing
- Initial background run shows a background level consistent with level predicted by MC simulations
- Following Neutron Calibration with AmBe in Fall 09 the 1st DM search run will start before end of the year
• In April 09 we replaced a vacuum seal and reduced further detector outgas with bake-out and hot gas re-circulation

• In May 09 we filled TPC again (current run-06): Light Yield 3.2 pe/keV for 662keV

• Equivalent to 4.5 pe/keV for 122 keV

• With event position reconstruction we can now measure the S1 position dependence
Calibration Sources for XENON100

1) **External Sources:** Cs-137 (662 keV), Co-57 (122 keV), Co-60 (1173, 1332 keV), Th-228 (2600 keV), AmBe (~ MeV)

2) **Internal Sources:**
   - Xe-131m (164 keV, 11.84 d), Xe-129m (236 keV, 8.88 d) from neutron activation of Xe
   - Kr-83m (32 keV, 9 keV) from Rb-83, studied as calibration tool for the KATRIN neutrino mass experiment (Applied Radiation and Isotopes 63 (2005) 323-327)
Initial Results from Cs-137 Gamma Calibration

S1 Spectrum

S2 Spectrum

corrected for the Z dependence of the LY

corrected for drift time dependence of charge

s1c_hist
Entries 33822
Mean 946.8
RMS 304.4
\( \chi^2 / \text{ndf} \) 39.63 / 21
Constant 1462 ± 12.8
Mean 1034 ± 1.7
Sigma 182.1 ± 1.8

s2c_hist
Entries 11245
Mean 1.741e+05
RMS 4.346e+04
\( \chi^2 / \text{ndf} \) 14.57 / 14
Constant 595.5 ± 9.1
Mean 1.937e+05 ± 602
Sigma 2.157e+04 ± 423
XENON100 Data: Background Reduction by LXe Veto

Left plot: the right band is the 662 keV full absorption peak and the left band is the energy deposited by gammas that backscatter in the sensitive volume.

Right plot: when we apply a cut for events with a 2 fold coincidence in the veto the left band disappears (and the overall rate is also lower) --> Gammas that backscatter (depositing 478 keV) in the LXe of target, interact in the veto and are removed by cut.
XENON100 MonteCarlo: Background Reduction by LXe Veto

- The LXe Veto (embedding the target on all sides) decreases the background rate in the target by more than 50% even with a 200 keV veto threshold.

Figure 5: Background rate reduction with fiducial volume cuts and active veto cuts. Dashed Lines show the background rate with the passive veto.
XENON100 Background: Monte Carlo Prediction

GEANT4 Simulations of full experiment: detector + shield + cavern

50 kg: $<1 \times 10^{-2}$ evts/kg/keV/day
(2000 kg-day, background free)

30 kg: $<3 \times 10^{-3}$ evts/kg/keV/day
(6000 kg-day, background free)

rate before S2/S1 discrimination!
XENON100 Background: preliminary data

- we are very pleased at what we see in this first peek!
XENON100 Sensitivity

50 kg target, 40 days: \( \sigma = 6 \times 10^{-45} \text{ cm}^2 \) (at \( M_W = 100 \text{ GeV} \))
30 kg target, 200 days: \( \sigma = 2 \times 10^{-45} \text{ cm}^2 \) (at \( M_W = 100 \text{ GeV} \))
XENON100+ (2010-12)

- increase fiducial target to >100 kg
- decrease background by factor 10
- increase sensitivity by factor 10
- pathfinder for XENON1T
- funded in the US by the NSF
- strong non-US support

Extremely low radioactivity: << 1mBq
Large area: ~3 inch
Single photon detection capability
High QE: > 30%
Low temperature operation
  - Liquid Xenon: -108 °C
  - Liquid Argon: -186 °C
Summary

- XENON100: 1st 100 kg scale LXe dark matter experiment operating underground
- Two-phase TPC works as designed: currently optimizing response with sources
- Neutron Calibration by Fall 09 and 1st dark matter search before end of 2009
- XENON100+: funded and moving ahead with design and tests of key technologies
Discovery Potential of XENON100 Program

XENON Sensitivity Projection - 100 GeV WIMPs

Current Best Sensitivity

Expected # of WIMP Events (σ_{χp} = 10^{-44} cm^2)

σ_{χp} (90% C.L. upper limit) [cm^2]

Exposure Time with Zero Bkg [month]

- 2009
- 2011-2012