XENON and Other Cryogenic Noble Liquid Dark Matter Experiments

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http://www.astro.columbia.edu/~lxel/XENON/
Plan for Talk

Cryogenic Noble Liquids: a brief review

LXe Based Detectors
XENON, ZEPLIN

LAr Based Detectors
WARP

Other LXe/LAr Detectors
Direct Detection Methods/Experiments

XENON, XMASS-II, ZEPLIN2, ZEPLIN3, WARP, ArDM

Double Phase (Xe, Ar)

Ge

Ge, Si

Al2O3, LiF, ...

CaWO4, BGO, ...

NaI, CaF2, LXe, LAr, ...

EDELWEISS

CDMS

CRESST

ZEPLIN1

XMASS

Mini-CLEAN

DAMA/LIBRA
**Cryogenic Noble Liquids: Basic properties**

- Suitable materials for detection of ionizing tracks:
  - Dense, homogeneous, target and also detector (ionization and scintillation)
  - Do not attach electrons
  - High electron mobility (except neon in some conditions)
  - Commercially easy to obtain and to purify (in particular, liquid Argon)
  - Inert, not flammable, very good dielectrics

<table>
<thead>
<tr>
<th>Element</th>
<th>Liquid Density ($\rho$/cm$^3$)</th>
<th>Energy loss $dE/dx$ (MeV/cm)</th>
<th>Radiation length $X_0$ (cm)</th>
<th>Collision length $\lambda$ (cm)</th>
<th>Boiling point @ 1 bar (K)</th>
<th>Electron mobility (cm$^2$/Vs)</th>
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Cost:
- $\epsilon$
- $\epsilon\epsilon$
- $\epsilon\epsilon\epsilon$
Cryogenic Noble Liquids: Basic challenges

- **Cryogenics**: Efficient, Reliable and Cost Effective Cooling systems
- **Safety**: hazard of large volumes of cold liquids in confined space underground
- **Detector Materials**: compatible with low radioactivity and high purity requirements
- **Intrinsic Radioactivity**: Ar-39 and Ar-42 for LAr and Kr-85 for LXe
- **Light Detection**:
  - Efficient, cost effective VUV PMTs, directly coupled to the liquid → low T and high P capability + high purity compatibility; effective VUV reflector materials
  - Wavelength shifters → visible PMTs (high QE) but worry about mixing of shifter with liquid with different effect on singlet and triplet states decay time
  - Light can be absorbed by H2O and O → especially for LXe, absorption cross section of water largest around Xe wavelength → continuous purification
- **Charge Detection**:
  - requires <<1ppb (O2 equivalent) for electron lifetime > 1 ms → commercial purifiers and continuous circulation → easier to achieve in colder LAr → for E~1kV/cm residual presence of CO, N2O can reduce yield as attachment cross section increases w/ field
  - Electric fields >1kV/cm required for max yield from mip (for alphas and nuclear recoils, field dependence much weaker) → detecting a small charge signal in presence of HV → a challenge even when using charge extraction from liquid-to-gas (2-phase)
Ionization/Scintillation Mechanism in Noble Liquids

Kubota et al. 1979, Phys. Rev.B

\[ Xe \rightarrow Xe^+ + e^- \]

\[ Xe + Xe^* \rightarrow 2Xe + h\nu \]

\[ Xe^+ + Xe \rightarrow Xe_2^+ \]

\[ Xe_2^+ + e \rightarrow Xe^{**} + Xe \]

\[ Xe^{**} \rightarrow Xe^* + \text{heat} \]

\[ Xe + Xe^* \rightarrow Xe_2^* \rightarrow 2Xe + h\nu \]

\[ \lambda \sim 128_{\text{LAr}} \]

\[ \lambda \sim 175_{\text{LXe}} \]

\[ \lambda \sim 77.5_{\text{LNe}} \]
Figure 3.9: Scintillation decay curves in liquid argon are plotted. The experimental results show for both excitation (obtained at 6 kV/cm) and recombination components the presence of two different contributions, one characterized by a $\tau_s \approx 6$ ns decay time and one by a $\tau_t \approx 1500$ ns decay time [63].
Particle ID by Pulse Shape Discrimination

A. Hitachi PRB 27 (1983) 5279
PMTs for Cryogenic Liquids

- Initial studies of LA/LXe scintillation done with visible PMTs coupled to transparent windows coated with appropriate wavelength shifters (POPOP, sodium salicylate, etc.)

- Development of PMTs for cryogenic operation starts in 1996 for LXe (MEG, LXeGRIT, XMASS, XENON) with Hamamatsu and later for LAr (ICARUS, WARP) and LXe (ZEPLÍN) with EMI

- Challenge: Choice of Photocathode a) Bialkali :K-Cs-Sb, Rb-Cs-Sb show steep increase in sheet resistance at low temperature b) Multialkali +Na show less dependence on T..but more difficult to make

- Development of Metal Channel Dynode Structure by Hamamatsu → evolution of compact (4 cm long) PMTs with improved response at 178 nm, working at −100 C and 5 bar (used by MEG and XENON early prototypes)

- XENON has now adopted a square geometry Metal Channel PMT (R5900-Mod) with higher QE (>20%) and lower activity

2” - 3” Glass or Quartz windows

New WARP PMTs (EMI Type D749-D750)

Bialkali photocathode

2” - 1” Quartz window
LXe & LAr for Dark Matter Direct Detection

- **Liquid Xenon**
  - Large A (~131): good SI case (\(\sigma \sim A^2\)) but low threshold a must
  - Presence of \(^{129}\text{Xe} (26.4\%)\) and \(^{131}\text{Xe} (21.2.4\%)\) good for SD
  - No long-lived radioisotopes. Kr85 fraction to ppt level proven
  - Excellent stopping power for compact, self-shielding geometry
  - ‘Easy’ cryogenics at -100 C
  - Efficient scintillator (80% of NaI) with fast time response
  - Excellent charge and light yields (\(W_p = 22.4\) eV; \(W_e = 15.6\) eV for mip; For NR, QF ~0.2 but large and field independent charge yield
  - Background Discrimination Methods: Charge and Light ratio plus 3D event localization

- **Liquid Argon**
  - A=40 good for higher mass WIMPs
  - No odd isotopes for SD
  - \(^{39}\text{Ar}\) at ~1 Bq/kg require rejection > 10^7
  - Not so “Easy” Cryogenics at ~186 C but easier to purify
  - Larger volumes required to compensate low Z and density \(\rightarrow\) larger cryostat (cost) and LAr mass but cost of raw Ar is cheap
  - ‘Less light and charge than LXe for mip but much larger scintillation efficiency’ for NR, QF~0.8.
  - Background Discrimination Methods: Charge and Light ratio plus 3D event localization plus Light PSD
The XENON Experiment: Overview

- **Modular design:** 1 ton LXe (XENON1T) in ten modules (XENON100). Module is a 3D position sensitive dual-phase (liquid/gas) XeTPC with 100kg active Xe target.

- **Event-by-event discrimination** of nuclear recoils from electron recoils (>99.5%) down to 16 keVr from:
  - a) simultaneous detection of scintillation (S1) and ionization (via proportional scintillation S2)
  - b) 3D event localization

- **XENON10 Phase:** TPC with 15 kg active target at Gran Sasso Lab as of March, 2006. Shield under construction. Integrate detector with shield by end May. **Physics run June, 2006 →**

- **XENON100 Phase:** design/construction in FY07 and FY08. Commission underground and start physics run within 2008.

XENON funded by NSF and DOE
XENON Dark Matter Goals

**XENON10 (2006-2007):**
10 kg target ~2 events/10kg/month

Equivalent to CDMSII Goal for mass >100 GeV
(Current CDMS limit is 10 x above this level)

XENON10 underground to establish performance of dual phase TPC and to guideto design optimization for XENON100

**XENON100 (2007-2009):**
100 kg target ~2 events/100kg/month
(similar projection for WARP-140 kg)

**XENON-1T (2009-2012?):**
1 ton (10 x 100 kg? larger modules?)
$10^{-46}$ cm² or ~1 event/1 tonne/month

Dark Matter Data Plotter
http://dmtools.brown.edu
Extraction of electrons from liquid to gas

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

Diagram:
- PMT Array
- Proportional Gas Xe
- Liquid Xe
- Direct
- Gamma
- Bottom PMT Array

Mathematical equation:
\[(S_2/S_1)_{\text{wimp}} \ll (S_2/S_1)_{\text{gamma}}\]
Recent Highlights from XENON R&D

LXe Scintillation Efficiency for Nuclear Recoils
- The most important parameter for DM search
- No prior measurement at low energies

LXe Ionization Efficiency for Nuclear Recoils
- XENON concept based on simultaneous detection of recoil ionization and scintillation
- No prior information on the ionization yield as a function of energy and applied E-field

Development of XENON10 Experiment for Underground Deployment
- Validated Cryogenics, HV, DAQ systems with 6kg prototype (XENON3)
- Demonstrated low energy threshold and 3D position reconstruction
- Installed/tested larger (15 kg) detector in same cryostat (Dec 05- Feb06)
- XENON10 equipment shipped to Italy on March 2, 2006
Scintillation Efficiency of Nuclear Recoils

Columbia and Yale

2.4 MeV neutrons

Use pulse shape discrimination and ToF to identify n-recoils

\[ E_r \approx E_n \frac{2M_n M_{Xe}}{M_n + M_{Xe}} (1 - \cos \theta) \]

Nuclear Recoils Ionization Yield and Field Dependence

Columbia +Brown and Case (2 independent measurements)

Aprile et al., astro-ph/0601552, submitted to PRL
LXe Response to Nuclear and Electron Recoils

5 keVee energy threshold = 10 keV nuclear recoil
event waveforms

3.8 kV/cm, AmBe

20050328T2209_00011#4142
S1: 21 pe (11.8 keVee)
S2/S1: 72.4
Event type: neutron

3.8 kV/cm, Cs-137

20050329T0007_00002#2641
S1: 42 pe (23.6 keVee)
S2/S1: 155
Event type: gamma

20050328T2209_00011#341
S1: 60 pe (33.7 keVee)
S2/S1: 41.1
Event type: neutron

20050329T0007_00002#1789
S1: 90 pe (50.6 keVee)
S2/S1: 263.1
Event type: gamma
Neutron/Gamma Discrimination

Electron recoils rejection efficiency 98.5% down to 20keVr, at 2kV/cm with 50% nuclear recoils acceptance.

Efficiency limited by charge loss at edge of detector due to field non uniformity

\[ \gamma \text{ leakage mainly from edge events} \]

improvement expected with XY event localization in a 3D TPC with optimized electric field shaping

\[ \text{Teflon (PTFE)} \]

\[ \text{Neutron Inelastic }^{19}\text{F } 110 \text{ keV} \gamma \]

\[ 40 \text{ keV} \]

\[ \text{ELASTIC Nuclear Recoil} \]

\[ \text{Gas Xenon} \]

\[ \text{Liquid Xenon} \]

\[ \text{P. Majewski} \]

\[ \text{L. Viveiros/ R. Gaitskell} \]
XY Position Reconstruction and Sensitivity: XENON3 TPC

\[ \chi^2(x, y) = \sum_{i=1}^{21} \frac{[S_i - s_i(x, y)]^2}{\sigma_i^2} \]

dge event with long drift time

S1

S2

\( \sigma \approx 2 \text{ mm} \)
XENON3 Data: Edge events can be well identified

5 mm radial cut clearly reduces gamma events leaking into the nuclear recoils region (DD- 2.5 MeV neutrons irradiation)

XY position reconstruction of 122 keV Co-57 gammas from side
XENON10: Cryostat Assembly

- Pulse tube cryocooler
- Re-condenser
- LXe Active
- Gas Region
- PMTs (top)
- PMTs (bottom)
- Vacuum Cryostat
**XENON10 Cryogenic System**

**“Built-in” cryocooler**

**Pulse Tube Cryocooler:**

**Advantages:** Just switch on!
- Precise temperature and pressure control
- $\text{L}_2\text{N}_2$-Free operation
- Quiet, maintenance free for long time operation
- XENON10 machine in use since 2003
- Stability within $\pm 0.025\, \text{K}$

**Can afford:**
- up to $\sim 200\, \text{W} @ 165-170\, \text{K}$
**XENON10: Detector Assembly**

- 89 Hamamatsu R5900 (1” square)
- 20 cm diameter, 15 cm drift length
- 22 kg LXe total; 15 kg LXe active

Top PMT Array, Liquid Level Meters, HV-FT

Bottom PMT Array, meshes, PTFE Vessel

LN Emergency Cooling Loop

PMT Base (Cirlex)
XENON10: Underground at LNGS

Occupancy

XENON
HALL A
HALL B
HALL C
MI R&D
Borexino
ICARUS
LVD
DAMA
WARP
OPERa
HDMS
GENIUS-TF
CRESST2
Cobra
CUORE
CUORICINO
LUNA2
XENON10: Underground at LNGS
Summary: XENON10 Backgrounds

Monte Carlo studies of Radioactivity (Background Events) from:

- Gamma / Electron
  - Gammas inside Pb Shield
  - PMT (K/U/Th/Co)
  - Vessel: Stainless Steel (Co)
  - Contributions from Other Components
- Xe Intrinsic Backgrounds (incl. $^{85}$Kr)
- External Gammas - Pb Shield
- Rn exclusion
- Detector Performance/Design
  - Gamma Discrimination Requirements
  - Use of $xyz$ cuts instead of LXe Outer Veto
- Neutron Backgrounds
  - Internal Sources: PMT ($\alpha,n$)
  - External: Rock ($\alpha,n$): Muons in Shield
  - Punch-through neutrons: Generated by muons in rock

- NOTE: Active Muon Shield Not Required for XENON10 @ LNGS
  - Neutron flux from muon interaction in Pb shield $\ll$ Target Level

[Background Modeling U. FLORIDA / BROWN/COLUMBIA]
XENON10 - Fiducial Volume

- Stainless Steel Cryostat & PMTs (background in 5-25 keVee) [Dominant BGs]
  - Stainless: MC using value of 100 mBq/kg 60Co
    - Based on stainless samples screened to date - 4x higher than originally assumed = but faster assembly
  - PMTs - 17.2/<3.5/12.7/<3.9 mBq/kg (U/Th/K/Co) - 89 Low activity 1” Hamamatsu tubes
    - Increased Bg from Increased Number of PMTs / trade off with increased position info. = Bg diagnostic

Radius (10 cm) - Depth (15 cm) Event Rates (log(/keV/kg/day)) In XENON10

Application of 1 cm surface cut
15 kg -> 10 kg LXe

Original XENON10 Goal
Electron Recoils <0.14 /keVee/kg/day
(assumes 99.5% electron recoil rejection)

Currently estimate that we will be above original goal by ~2-3x
XENON10 Shield Construction - LNGS

Red-Shield Dimension Blue-Ex-LUNA Box Dimension

Clearance to Crane Hook (after moving crane upwards) 20 mm

Brown Design / LNGS Engineering
40 Tonne Pb / 3.5 Tonne Poly
Low-Activity (\(^{210}\)Pb 30 Bq/kg) inner Pb &
Normal Activity (\(^{210}\)Pb 500 Bq/kg) Outer Pb

Construction Underway: Contractor
COMASUD – Mid May Expect
Completion of Installation

LNGS (Ex-LUNA) Box Dimensions are critical constraints for shield - expansion of shield to accommodate much larger detector difficult

Inner Space for XENON10 detector
900 x 900 x 1075(h) mm

P5 - Fermilab - 19 April 2006

Elena Aprile, Columbia University
The XENON10 Collaboration

Columbia University
Elena Aprile (PI), Karl-Ludwig Giboni, Sharmila Kamat, Maria Elena Monzani, Guillaume Plante*, and Masaki Yamashita

Brown University
Richard Gaitskell, Simon Fiorucci, Peter Sorensen*, Luiz DeViveiros*

University of Florida
Laura Baudis, Jesse Angle*, Joerg Orboeck, Aaron Manalaysay*

Lawrence Livermore National Laboratory
Adam Bernstein, Norm Madden and Celeste Winant

Case Western Reserve University
Tom Shutt, Eric Dahl*, John Kwong* and Alexander Bolozdynya

Rice University
Uwe Oberlack, Roman Gomez* and Peter Shagin

Yale University
Daniel McKinsey, Richard Hasty, Angel Manzur*, Kaixuan Ni

LNGS
Francesco Arneodo, Alfredo Ferella*

Coimbra University
Jose Matias Lopes, Luis Coelho*, Joaquim Sai
The US ZEPLIN Group: U. Rochester, SMU, TA&MU, UCLA

**ZEPLIN II Design Principle**

- PM
- PM
- PMT
- LHe
- e
- e
- γ
- n-
- r
- (S2)
- (S1)
- gas
- liquid
- PTFE

**Data shown 3-D Event Distribution**

45kg Xenon (Fiducial 32kg)
ZEPLIN II Electron Lifetime and Light Collection in Liquid Xenon

- Liquid purification well understood
- Greater than 1-ms electron lifetime typical
- 1.6 photoelectron/keV at zero field

103pe/122keV

$^{57}\text{Co}$

Light yield v Purity

1000

Light yield, pe/keV (zero field)

Purity (µs)

5 day

1000

e-lifetime (µs)

Pump switched on

- Active Recirculation
- Passive Recirculation

Elena Aprile, Columbia University
- **89% signal**
- **4-sigma cut** $3.2 \times 10^{-5}$
- **Very clean waveform**
- **Excellent recoil discrimination from S2/S1**
- **Possible neutron double scatter overlap S2**
- **AmBe Run & Dark Matter run**
- **S2/S1 vs S1 Plot**
- **Background Discrimination**

Elena Aprile, Columbia University
ZEPLIN II Operation Underground at Boulby Mine, UK

- Detector fully operational
- Physics data taking in progress (expect 300kg-day mid May)
- Data analysis in progress
After the completion of the first Physics run we will continue with R&D to push the limits of performance of ZEPLIN II to optimize the technology for the one-ton detector ZEPLIN IV.

A possible ton scale ZEPLIN IV design
Tentative approval by SNOLAB (or US DUSEL)

Current and Future
ZEPLIN Goals
WARP: The Motivation

- **TARGET**: Atomic number 40
  - No loss of coherence at high energies
  - Complete retention of gold plated events (60-120 keV)

- **WIMP CANDIDATES IDENTIFICATION**: highest discrimination between nuclear recoils and $\beta/\gamma$-like background
  - $^{39}$Ar, 0.8 Bq/kg $\rightarrow$ need $10^7$ rejection against betas (for 140 kg detector)
  - Projected discrimination exceeds $10^8$ at 30 keV

- **LOTS OF SIGNAL**: Highest Light Yield for Nuclear Recoils!
  - 32 photons/keV
  - Ar quenching 0.8
  - Xe quenching 0.2
WARP - WIMP Dark Matter Search with LAr

Two simultaneous criteria to discriminate potential WIMP recoils from backgrounds:

1. Simultaneous detection of prompt scintillation (S1) and drift time-delayed ionization (S2) in LAr, after electron extraction in gas and local multiplication:
   - Pulse height ratio S2/S1 is strongly dependent from columnar recombination of ionizing tracks.
   - 3D reconstruction of the event from drift time and PMT localization of centroid of S2 within 1 cm³.

2. Pulse shape discrimination of primary scintillation:
   - Wide separation in rise times between fast ($\approx 10$ ns) and slow ($\approx 1.6$ µs) components of the emitted UV light. This is a unique feature of Argon.

- Scintillation yield is $\approx 2$ phel. / keV$_{\text{ion}}$
- Trigger Threshold is 5 keV$_{\text{ion}}$
- WIMP Analysis threshold is $\approx 15 \div 20$ keV$_{\text{ion}}$

- Technique established with operation of 3.8-kg prototype in LNGS since 2004
Double Discrimination in WARP

- $S_1$ = primary (prompt) liquid scintillation signal
- $S_2$ = secondary (delayed) gas scintillation signal (proportional to ionization)

- **Minimum ionising particles:** high $S_2/S_1$ ratio (~100) + slow $S_1$ signal
- **α particles and nuclear recoils (R-like events):** low (<30) $S_2/S_1$ + fast
Neutron-Induced Recoils

50-100 keV

Combination of two discrimination methods

Pulse Shape Discrimination

Counts

10^3

10^5

WIMP Search 40 kg*day

50-100 keV >10^6 events
3.8-kg Prototype: Physics Results

- 3.8-kg prototype equipped with seven 2” PMs designed to work at LAr temperature
- Scaled version of the 100 liters detector, with field-shaping electrodes and gas to liquid extraction and acceleration grids
- Equipment contained in a high-vacuum tight container immersed into an external, refrigerating, liquid argon bath
- LAr Purity kept stable by means of argon recirculation: continuous and stable operation during several months
- No selection of materials: background left intentionally high to study ID and rejection power with high statistics

Galbiati promised to give plot on Tuesday

Preliminary Results from xx kg-day exposure (y weeks long data taking Feb-Mar 2006) Full discussion of data next week IFAE 2006
WARP 140-kg detector

- Sensitive mass 140 kg (100 liters LAr)
  - Adds third discrimination: 3-D event localization (within 1 cm³) by means of
    - Drift time recording (vertical axis)
    - Centroid of PM’s secondary signal amplitudes (horizontal plane)

- Unique feature: 4pi active VETO system, 9 tons active LAr
  - tags and measures the neutron-induced background with an ID-factor ≈ 99.99%

- In construction, commissioned within the end of 2006

- Designed also to host a 1 ton detector

- 140-kg stage funded INFN+NSF
  - INFN 2.0 M€ (plus personnel)
  - NSF 650 k$

- Funds cover inner detector, 200 of 400 veto tags and measures the neutron-induced background with an ID-factor ≈ 99.99%
WARFP 140-kg Final Considerations

- Argon excellent candidate for WIMP Dark Matter Search

- Achieved the most advanced and best performing technology for a (WIMP-induced) recoil identification. Identification power of Ar recoils vs. $\gamma/\beta$ events at 30 keV $E_{\text{ion}}$ threshold:
  - 1 in $10^3$ events from S2/S1
  - 1 in $10^5$ events from Pulse Shape Discrimination

- 140-kg detector commissioned within 2006
  - Will bring further upgrade on light yield. Background minimized
  - Big jump (x100) in sensitivity for WIMP Dark Matter Searches in 2007
  - Active neutron coincidence will...
Other Cryogenic Liquid Detectors for DM

- **XMASS** (Scintillating LXe Calorimeter - 800 kg) → Solar Neutrino/Dark Matter → Kamioka
  See Y. Koshio talk at http://cryodet.lngs.infn.it/agenda/agenda.htm

- **XMASSII** (Double Phase LXe-15 kg) → Dark Matter → Kamioka
  See S. Suzuki talk at http://cryodet.lngs.infn.it/agenda/agenda.htm

- **ArDM** (Double Phase LAr- 1Ton) → Dark Matter → Canfranc
  See L. Kaufmann talk at http://www.physics.ucla.edu/hep/dm06/talks.html

- **Mini-CLEAN** (Scintillating LNe/LAr? Calorimeter - 100Kg) → Solar Neutrino/Dark Matter → SNOLAB/Homestake?
Additional Material
# XENON Budget Profile

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## XENON10 LNGS Schedule

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<th>2005</th>
<th>2006</th>
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<td>November</td>
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<td>2005 12 01</td>
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<td>Upgrade 0-&gt;10</td>
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<td>Data Taking (A)</td>
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<td>Data Taking (B)</td>
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<td>Packing</td>
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<td>Detector Installation (w/o shield, Box 2)</td>
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<td>Detector Testing</td>
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<td>Installation ex-LUNA Box</td>
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<td>Design/Fabrication</td>
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<td>Reassemble/Test XENON10 Detector</td>
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<td>PHYSICS RUN-2</td>
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<td>ex-LUNA BOX</td>
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<td>LOW BACKGROUND SHIELD</td>
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<td>Shield Engineering Design</td>
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<td>Shield Construction (COMASUD)</td>
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<td>Shield Installation</td>
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<td>2006 06 09</td>
<td></td>
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<td>XENON100+</td>
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<td>Design Studies</td>
<td>2006 07 01</td>
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<td>Proposal Submission Funding for FY Aug 07:08 - 09:10</td>
<td>2006 09 29</td>
<td>2006 09 29</td>
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</table>
MonteCarlo Simulation of XENON10 Position Sensitivity
Columbia

48 PMTs on top, 41 on bottom
8 inch diameter, 6 inch drift length
about 15 kg liquid xenon

Assumptions for GEANT4 Simulation

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
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<tbody>
<tr>
<td>PTFE reflectivity</td>
<td>92%</td>
</tr>
<tr>
<td>Stainless steel reflectivity</td>
<td>20%</td>
</tr>
<tr>
<td>Light absorption length</td>
<td>100 cm</td>
</tr>
<tr>
<td>Rayleigh scattering length</td>
<td>30 cm</td>
</tr>
<tr>
<td>Liquid xenon index of refraction</td>
<td>1.61</td>
</tr>
<tr>
<td>W value of light for electron recoil</td>
<td>21.6 eV</td>
</tr>
<tr>
<td>Gas gain for proportional light</td>
<td>200</td>
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<tr>
<td>Nuclear recoil scintillation efficiency</td>
<td>$0.06 E_n^{0.34}$</td>
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<tr>
<td>Quenching of $S1$ at 1 kV/cm for nuclear recoil</td>
<td>95%</td>
</tr>
<tr>
<td>Quenching of $S1$ at 1 kV/cm for electron recoil</td>
<td>50%</td>
</tr>
<tr>
<td>Nuclear recoil ionization yield at 1 kV/cm [e-]</td>
<td>$15.4 E_n^{0.643}$</td>
</tr>
<tr>
<td>Charge collection for electron recoils at 1 kV/cm</td>
<td>65%</td>
</tr>
<tr>
<td>PMT quantum efficiency</td>
<td>20%</td>
</tr>
<tr>
<td>PMT collection efficiency</td>
<td>70%</td>
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</table>

Fitting from measurements by Columbia and XENON Collaborators ($E_n$ in keVr), see:
- Aprile et al., astro-ph/0601552
XENON10: Expected Position Resolution

S2 signal for each PMT from simulation, convoluted by S2 resolution and statistical fluctuation of photoelectrons in PMTs

10 keV nuclear recoils

Position resolution ($\sigma$) is less than 3 mm for 10 keV nuclear recoil events

Reconstructed positions obtained by the minimum chisq method (same as for XENON3)

Position reconstruction for XENON10: a 122 keV gamma event from side (data)
XENON10: Identify Multiple-step Events

Most of the multiple scattering events can be easily identified by drift time separation ($\Delta Z > 2$ mm).

Events with $\Delta Z < 2$ mm can be identified by the chisq value from XY position reconstruction.

One neutron event with two steps (5 keVr each) separated by $\Delta L$.

Events with two steps separated by more than 3 cm in XY can be efficiently identified.
**Kr removal - Case**

- $^{85}$Kr - beta decay, 687 keV endpoint.
  - Goals for 10, 100, 1000 kg detectors: Kr/Xe < 1000, 100, 10 ppt.
  - Commercial Xe (SpectraGas, NJ): ~ 5 ppb (XMASS)
- Chromatographic separation on charcoal column
  - Different adsorption of Kr and Xe -> separation in time for steady flow through column.

---

10 Kg- charcoal column system at Case

---

ili, Columbia University
Production for XENON10

- Purification better $> 10^3$. Adequate for XENON10.
- System throughput now at 1.8 kg/day with $\sim 50\%$ up-time. Project: 26 kg purified end April.

Checked in Case detector: Purity for charge drift not affected by Kr removal

Production cycling

- Post-production purity check
- Anticipate $\sim$ ppt sensitivity
• Processing speed: 0.6 kg/hour
• Design factor: 1/1000 Kr/1 pass
• Purified Xe: Off gas = 99:1

<table>
<thead>
<tr>
<th></th>
<th>Boiling point (@2 atm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xe</td>
<td>178.1K</td>
</tr>
<tr>
<td>Kr</td>
<td>129.4K</td>
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</table>

Raw Xe: ~3 ppb Kr

Operation @ 2 atm

Lower (178K)

~3m

~1%

Off gas Xe: 330 ± 100 ppb Kr (measured)

Higher (180K)

~99%

Purified Xe: 3.3 ± 1.1 ppt Kr (measured)
Low Backgrounds / DAQ

- Rick Gaitskell
- Particle Astrophysics Group, Brown University, Department of Physics
- (Supported by US DOE HEP)
- see information at
  http://www.astro.columbia.edu/~lxe/XENON/
  http://xenon.brown.edu/
89 channel DAQ System – Implementation (Brown)

Sample Pulse – Drift Distance: 15cm = 75µs

Cluster Being Installed in LNGS Computer Center

Tape Archive

Digitizers/DAQ

Brown

Cluster Data Analysis

Remote Backup

100 MHz VME

10 ns/sample

Front End Analogue Electronics

XENON10: 48 Top PMTs + 41 Bottom PMTs

Fast ADC

8ch

Fast ADC

8ch

Fiber

Channel

G5 XRaid

5.6 TB Storage

PC#1

Data Acquisition

Event Compression

Gbit Ethernet

Single phe threshold triggering

n≥2 coincidence demonstrated

(necessary for best threshold goal >16 keVr, S1~0.8 phe/keVrecoil)

Event Compression

Case Western
XENON10 Neutron Backgrounds

- Main Neutron Backgrounds
  - (alpha,N)/Fission Neutron from Rock
    - (alpha,N) Neutron Flux: $10^{-6}$ N/(sec·cm$^2$)
  - Muon Induced Neutrons from Pb Shielding
    - Neutron Yield in Pb: $4 \times 10^{-3}$ N/(muon g cm$^{-2}$)
    - Muon Flux at Gran Sasso: 1 muon / (hour m$^2$)
  - Event rates for above types of Neutron sources are reduced below XENON10 goal by ~1/10x.
    - Low Energy Neutrons are currently moderated by 20cm internal poly. (XENON100 would require muon veto for Pb events + external poly)

- High Energy Neutrons from Muons in Rock (see table)
  - Depth necessary to reduce flux
  - LNGS achieves XENON10/100 goal
  - Traditional Poly shield is not efficient in moderating High Energy Muon-Induced Neutrons

<table>
<thead>
<tr>
<th>Goal (Rates for Current Shield Design)</th>
<th>DM NR Signal Rate Xe @ 16 keVr</th>
<th>Soudan 2.0 kmwe</th>
<th>Gran Sasso 3.0 kmwe</th>
<th>Home-stake 4.3 kmwe</th>
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<tbody>
<tr>
<td>High Energy Neutron Relative Flux (from muons)</td>
<td>x1</td>
<td>X1/6</td>
<td>x1/30</td>
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<tr>
<td>XENON10 ($\sigma \sim 2 \times 10^{-44}$ cm$^2$)</td>
<td>400 $\mu$dru</td>
<td>x 20</td>
<td>x 120</td>
<td>x 600</td>
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<tr>
<td>XENON100 ($\sigma \sim 2 \times 10^{-45}$ cm$^2$)</td>
<td>40 $\mu$dru</td>
<td>x 2</td>
<td>x 12</td>
<td>x 60</td>
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<tr>
<td>XENON1T ($\sigma \sim 2 \times 10^{-46}$ cm$^2$)</td>
<td>4 $\mu$dru</td>
<td>x 0.2</td>
<td>x 1</td>
<td>x 6</td>
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</table>

TABLE: Integ. WIMP Signal ($m_w=100$ GeV) / HE Neutron BG evt
[~1/2–2x uncertainty in actual HE neutron BG]

DM Signal/HE Neutron BG needs to be >>10 to ensure WIMP differential signal spectrum can be observed in adequate recoil energy range (compared to flatter differential neutron bg spectrum)
1T Detector can use “thicker” shield (e.g. water/active) to reduce HE neutrons for even greater reach
Comparison of High Energy (HE) Neutron Shielding

- Additional reduction in HE Neutron BG possible using thick water shield…
  - Also consider active shields
- But Maintain Adequate Safety Margins since
  - High Energy Neutron Flux still being studied - x2 (at least?) uncertainties
  - Shield Introduces extra BG systematic to worry about / Shield under-performance quite possible if too large a reduction factor aimed for.

**CONCLUSION:**
- Depth is Important
- Shield upgrade can provide some reduction in HE neutron BG, but don’t over-depend on shield performance (and give up on depth)
- Change in shield type may also be attractive for other reasons. E.g. water - lower cost for large shield geometries with low gamma bg. E.g. active - additional veto for (a,n) neutrons.

![Energy Histogram for Xe detector (63kg) inside different Shields](chart)

Dark Matter Differential Spectra for 100 GeV WIMP with $\sigma \sim 10^{-46}$ cm$^2$ in Xe, Ge, Ar & Ne targets

Nuclear Recoil Spectrum in Xe due to events caused by high energy neutrons penetrating shield of
(i) 40 cm poly/20 cm Pb / (ii) 2 m thick water / (iii) 4 m thick water
Dark Matter Sensitivity

- **CDMSII @ Soudan**
  - (Run ’04) 1.5 kg Ge before cuts
  - Exposure: Net after cuts:
    - 20 kg-day (Run ’03) + 34 kg-day (Run ’04)
    - WIMP <0.05/kg/day >10 keVr
    - 1 Neutron from 23 cm Pb shield due to muons - vetoed in shield - 8 cm poly inside Pb reduces neutrons by ~7x
    - (Effective depth 6.5x shallower that of LNGS - so would not expect 5 muon generated neutron events in WARP data)

- **WARP (Latest Data)**
  - (Run ’05) 3.2 kg Ar before cuts
  - Exposure: 35 kg-days
    - 5 evts 20-40 keVr: 0.15/kg/day
    - 0.53/kg/day equiv in Ge >10 keVr
    - Factor 10 above CDMSII current

- **XENON10 (90% CL limit)**
  - assuming zero evts >16 keVr, eq. Ge>10keVr
  - LXe 14 kg inner -> 10 kg fiducial (1 cm surface cut)
    - Match current WARP: 11 hours live
    - Match current CDMS II: 4.6 days live
    - XENON10 Goal: 46 days live
### Noble Liquids

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<th>Property</th>
<th>He</th>
<th>Ne</th>
<th>Ar</th>
<th>Kr</th>
<th>Xe</th>
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<td>Boiling Point $T_b$ at 1 atm [K]</td>
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<td>87.3</td>
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<td>Melting Point $T_m$ at 1 atm [K]</td>
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<td>Gas Density at 1 atm &amp; 298 K [g/l]</td>
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<td>3.43</td>
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<td>Gas Density at 1 atm &amp; $T_b$ [g/l]</td>
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<td>Liquid Density at 1 atm &amp; $T_b$ [g/cm³]</td>
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<td>Critical Temperature $T_c$ [K]</td>
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<td>44.4</td>
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<td>Critical Pressure $P_c$ [atm]</td>
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<td>Critical Density [g/cm³]</td>
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<td>0.91</td>
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<td>Dielectric Constant of Liquid</td>
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<td>–</td>
<td>1.51</td>
<td>1.66</td>
<td>1.95</td>
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</table>
ZEPLIN III
(Coimbra, Edinburgh, ICL, ITEP, RAL, Rochester, Texas, UCLA)

- 8kg fiducial mass
- 31 PMTs in liquid
- 3.5 cm drift depth
- 0.5 cm electroluminescent gap
- reverse field region
- position sensitivity
- open plan – no surfaces
Summary
by T. Sumner (Imperial College) @ CryoDet Conf., March 06

- **ZEPLIN II is operating in Boulby mine.**
  - Full depth operation
  - Final in-situ calibrations ongoing

- **ZEPLIN III is up and running.**
  - Performance so far is as expected.
  - Some indication of higher photon yield than expected in xenon.
  - Further surface evaluation and optimisation in progress – another 3 months

- **FP 7 Design Study proposal for ton scale – ELIXIR – Loi submitted to ILIAS/ApPEC**

- **FP7 Single Project proposal for ZEPLIN III deployment - LoI submitted to ILIAS/ApPEC**