Review of Dark Matter Searches with Noble Liquid Detectors and Recent Results from XMASS

Hiroyuki Sekiya
ICRR & Kavli-IPMU, University of Tokyo
for the XMASS collaboration

Feb. 7 2014
Kavli IPMU Seminar
Contents

• Principle of direct detection
  – Direction insensitive searches

• Detection technologies with liquid noble gasses = noble liquids
  – Review of double phase detectors
  – Review of single phase detectors
    • XMASS
    • Liquid Xe TPC

• Future noble liquid detectors
Principle of WIMP Direct Detection

- Particle physics $\times$ Astrophysics
  
  (cross section) (flux)

$$R = \sigma_{X-N} \times n\langle v \rangle$$

$$= \sigma_{X-N} \times \rho \int \bar{v} f(\bar{v}) d\bar{v}$$

- $\sigma_{X-N}$: WIMP-nucleus cross section
- $\rho$: WIMP density
- $f(\bar{v})$: WIMP velocity distribution

Both the WIMP cross section and flux must be studied, but…
Astrophysics -The model-

Dark Halo
\[ \rho(r) \propto \frac{1}{r^2} \]

\[ \rho(r_{\text{Sun}}) = 0.3 \text{GeV/cm}^3 \]

Collision-less Boltzmann equation

Maxwell distribution
\[ f(\vec{v}) = \frac{1}{\pi^{3/2}\sigma^3} e^{-|\vec{v}|^2/\sigma^2} \]

\[ \sigma = \sqrt{3/2}v_{\text{ROT}} \]

\[ v_{\text{ROT}} = 220 \text{ km/s} \]

\[ v_{\text{esc}} = 544 \text{ km/s} \]

“Standard halo model”
Astrophysics - Recent N-body simulations -

- Density
  \[ \rho = 0.39 \text{GeV/cm}^3 \]  
  [arXiv:0907.0018]
  \[ \rho = 0.37 \text{GeV/cm}^3 \]  
  [JCAP 02(2010) 012]

- Velocity distribution
  Indications of deviations from Maxwell distribution, particularly at high velocities.
  \[ \rightarrow \text{Impact on Light WIMPs} \]
  \[ \text{Direction sensitive search} \]  
  [JCAP 02(2010) 030]

Halo density profile in the galactic plane

8.5 kpc

3 GeV/cm$^3$
1 GeV/cm$^3$
0.3 GeV/cm$^3$
0.1 GeV/cm$^3$

Maxwellian simulation

1$\sigma$
Recent Halo models

• Tidal streams

• Debris flow

• Extra galactic components

• Dark disk

• etc,…..
  – …
Particle physics after LHC

- SUSY $\tilde{\chi}^1_0$ is still attractive, but it goes far...
  - Nucleon scattering cross section, $\sigma_{\chi\cdot n}$, is now down to $\sim 10^{-48} \text{ cm}^2$

H. Sekiya


arXiv:1311.0678
WIMP-Nucleus elastic scattering

- **Recoil energy**

\[
E_R = \frac{M_N M_X^2}{(M_N + M_X)^2} v^2 (1 - \cos \eta)
\]

\(\eta\): scattering angle in CM

- **Cross section**

\[
\sigma_{\chi-N} = 4G_F^2 \left( \frac{M_X M_N}{M_X + M_N} \right)^2 \left( C_N^{SI} + C_N^{SD} \right)
\]

\[
C_N^{SI} \propto A^2 \sigma_{\chi-n} \quad C_N^{SD} \propto \left( a_p \langle S_p \rangle_N + a_n \langle S_n \rangle_N \right)^2 \frac{J + 1}{J}
\]

In this talk I will focus on only SI (but I love Fluorine!)
Digression: $^{19}\text{F}$

\[
\sigma_{\chi-N} = 4G_F^2 \mu_{\chi-N}^2 C_N
\]

Enhancement factor
\[
C_N = C_{N}^{SD} + C_{N}^{SI} \quad (C_{N}^{SI} \propto A^2)
\]
\[
C_{N}^{SD} \propto \left( a_p \langle S_p \rangle_N + a_n \langle S_n \rangle_N \right)^2 \frac{J+1}{J}
\]

\[
\mu_{\chi-N} = \frac{M_{\chi}M_N}{M_{\chi} + M_N}
\]

Reduced mass

\[
G_F \quad \text{Fermi coupling constant}
\]

\[
\langle S_p \rangle_N \quad \text{nucleon spin in the nucleus}
\]
\[
\langle S_n \rangle_N
\]

\[a_p, a_n: \chi\text{-nucleon coupling}\]

Since the signs of $\langle S_p \rangle_N$ and $\langle S_n \rangle_N$ are opposite.

$^{19}\text{F}$ can play a unique role in

setting limits on $a_p$ & $a_n$

Materials used so far;

<table>
<thead>
<tr>
<th>Isotope</th>
<th>J</th>
<th>$\langle S_p \rangle_N$</th>
<th>$\langle S_n \rangle_N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{19}\text{F}$</td>
<td>1/2</td>
<td>0.441</td>
<td>-0.109</td>
</tr>
<tr>
<td>$^7\text{Li}$</td>
<td>3/2</td>
<td>0.497</td>
<td>0.004</td>
</tr>
<tr>
<td>$^{23}\text{Na}$</td>
<td>3/2</td>
<td>0.248</td>
<td>0.020</td>
</tr>
<tr>
<td>$^{73}\text{Ge}$</td>
<td>9/2</td>
<td>0.009</td>
<td>0.372</td>
</tr>
<tr>
<td>$^{127}\text{I}$</td>
<td>5/2</td>
<td>0.309</td>
<td>0.075</td>
</tr>
<tr>
<td>$^{129}\text{Xe}$</td>
<td>1/2</td>
<td>0.028</td>
<td>0.359</td>
</tr>
<tr>
<td>$^{131}\text{Xe}$</td>
<td>3/2</td>
<td>-0.009</td>
<td>-0.227</td>
</tr>
</tbody>
</table>

Solid: LiF/NaF
Liquid: CF$_3$I, C$_4$F$_{10}$
Gas: CF$_4$
Expected detection rate

- Integrated over the velocity distribution (SI)

For different Nuclei

- Ton scale experiments are necessary.
- Heavy nuclei and Light WIMPs are easier for experimentalists

\[ \sigma_{\chi-n} = 10^{-48} \text{cm}^2 \]

\[ M_\chi = 100 \text{GeV} \]
Direct Search Experimental Challenge

As we have seen

• WIMP nuclear recoil signal is:
  – Low rate (<1 events/ton/year)
  – Low energy (<10keV, actual visible energy is even lower)
  – Expected exponential spectrum is similar to many background signals

• Detection technique must be:
  – Extremely low background
  – Low threshold
  – Large mass

• It’s better to be
  – Position sensitive to allow fiducialization
  – Discriminating between WIMPs/n and $\gamma/\beta$
  – Directional
Technologies in 2003

Y. Ramachers

Technologies in 2013

CDMS, EDELWEISS, SuperCDMS, EURECA

IGEX, GENIUS, CoGENT, CDEX, DAMIC, TEXONO

ZEPLIN, XENON, LUX, DarkSide, WARP, ArDM

DAMA, LIBRA, NAIAD, XMASS, DEAP, CLEAN, DM-ICE

CRESST, CUORE, ROSEBUD

Tracking
DRIFT, NEWAGE, DMTPC, MIMAC, emulsion

Superheated liquid
COUPP, PICASSO, SIMPLE
Direct searches on Earth
Current Status

- SI WIMP-nucleon cross section limits as of Nov 2013
  - The best is LUX, reaches $10^{-46}$ cm$^2$.
  - Top 3 limits are all from double-phase Xe detectors

arXiv:1310.8214

Noble liquid detector

- scintillation detector / ionization detector
Why are noble liquids good for WIMP searches?

- Large mass/scalability especially Ar ← cost
- Large mass number especially Xe
  → Passive BG rejection: self shielding by fiducialization
- Large light yields → low threshold
- Purification → low BG

- Both scintillation and ionization signals are detectable.
- Excitation/ionization ratio provides electron/nuclear recoil separation
  → Active BG rejection
How to use noble liquids

3 concepts has been considered.

• **Single-phase (liquid)**
  – Just as scintillators
  – **TPC** to measure ionization directly

• **double-phase (liquid+gas)**
  – **TPC** same as single-phase, but this is easier.

---

How to use *noble solids* (R&D@ UCLA, Fermilab, …)

• **Single-phase (solid)**
  – Just as scintillators
  – **TPC** to measure ionization directly

• **double-phase (solid+gas)**
  – **TPC** same as single-phase, but this is easier.

---

*Xenon phase diagram*
Single-phase scintillator

- This concept has been realized recently
  - Also sensitive to ionization, in a sense, through the recombination process
  - Singlet/triplet ratio differs between nuclear/electron recoil events

← possibility of PSD
Single-phase TPC

• The original concept, but has not been realized yet.
  – By applying an electric field, electrons produced by ionization can be collected. These can be observed via charge amplification or proportional scintillation with a strong electric field.
double-phase TPC

- Realized first. Now well-established with several successful implementations

  - Same as single phase TPC, but if electrons are extracted from liquid phase to gas phase, charge amplification / proportional scintillation become easier with a strong electric field
Liquid Xe/Ar TPCs

**LUX@SURF**
- 350kg total
- 118kg FV
- 122 2” PMTs
- Data taking will continue until 2015

**XENON100@LNGS**
- 161kg total
- 50kg FV
- 242 1” PMTs
- Data taking on-going

**PANDA-X @CJPL**
- 125kg total
- 25kg FV
- 143 1” PMTs
- 37 3” PMTs
- Started data taking

**ArDM @Canfranc**
- 850kg total
- 100kg FV
- 28 3” PMTs
- Commissioning will start taking data in 2014

**Darkside @LNGS**
- 50kg total
- 33kg FV
- 38 3” PMTs
- Started data taking

---

Based on
N.J.T. Smith ICRC2013
L. Baudis SUSY2013

IPMU ACP seminar 7/2/2014
H. Sekiya
Example events in double-phase detectors

- 1.5keV gamma in LUX
- 9keV recoil in XENON100


L. Baudis SUSY 2013
Electron/nuclear recoil separation power

- XENON100’s performance

- ER calibration: $^{60}\text{Co}$ and $^{232}\text{Th}$, NR Calibration: AmBe
- 99.75% ER rejection for 50% efficiency loss on NRs

N. Priel SUSY2013
DM search results

- LUX 85 days
  - Profile-Likelihood Ratio used to determine nWIMP 90% CL upper limit
  - Value ranges from 2.4 events at low mass to 5.3 events at highest masses
  - p-value of 35% consistent with ER background and no WIMP signal

- XENON100 225 days
  - Expected background of 1 +/- 0.2 events
  - 2 events observed
  - Compatible with the background hypothesis


N. Priel SUSY2013
Liquid Xe/Ar scintillators

**XMASS-1@Kamioka**
- 835kg total
- 100kg FV
- 642 2” PMTs
- Refurbished
- Restarted data taking

**miniCLEAN@SNOLab**
- 500kg total
- 180kg FV
- LNe for solar neutrino
- Under construction
- Will start taking data in 2014

**DEAP3600@SNOLab**
- 3.6 ton total
- 1 ton FV
- 255 8” PMTs
- Under construction
- Will start data taking in 2014
XMASS
Where?

- Located underground in Mozumi zinc mine at a 2700 m.w.e. depth.
- 2km horizontal access by cars
LAB-C

- Water tank
- LXe tank for Distillation
- LXe Circulation system
- Gas Xe tank for emergency collection
- Emergency LN
- Distillation Tower
- Gas Xe compressor for emergency collection
XMASS Projects

Multipurpose low BG experiment with single phase (liquid) Xe

- Xenon MASSive detector for Solar neutrino ($\text{pp}/^7\text{Be}$)
- Xenon neutrino MASS detector (double beta decay)
- Xenon detector for Weakly Interacting MASSive Particles (DM)

The ultimate XMASS

Y. Suzuki, hep-ph/0008296

24t
(10t fiducial)
Ø 2.5m
XMASS-1

- 835kg LXe detector for Dark Matter search
XMASS must be extremely clean

- 10m x ∅10m water shield for external BG
- Made of pure materials
  - Development of low BG PMTs
- Xe purification technologies
  - Distillation system
### Radiopure PMT

<table>
<thead>
<tr>
<th>YEAR</th>
<th>2000</th>
<th>2002</th>
<th>2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>Prototype</td>
<td>R8778</td>
<td>R10789</td>
</tr>
<tr>
<td>Material:Body</td>
<td>glass</td>
<td>Kovar</td>
<td>Kovar</td>
</tr>
<tr>
<td>QE</td>
<td>25%</td>
<td>25%</td>
<td><strong>27-39%</strong></td>
</tr>
<tr>
<td>RI:</td>
<td>w/ PMT base</td>
<td></td>
<td></td>
</tr>
<tr>
<td>U [mBq/PMT]</td>
<td>50</td>
<td>18±2</td>
<td>0.70±0.28</td>
</tr>
<tr>
<td>Th [mBq/PMT]</td>
<td>13</td>
<td>6.9±1.3</td>
<td>1.51±0.31</td>
</tr>
<tr>
<td>$^{40}$K [mBq/PMT]</td>
<td>610</td>
<td>140±20</td>
<td>9.10±2.15</td>
</tr>
<tr>
<td>$^{60}$Co [mBq/PMT]</td>
<td>&lt;1.8</td>
<td>5.5±0.9</td>
<td>2.92±1.61</td>
</tr>
</tbody>
</table>

- A radiopure PMT Base has also been developed
Xe Distillation System

- Commercial “pure Xe” contains $\sim 0.1$ppm Kr
  - $^{85}$Kr / K = $1.2 \times 10^{-11}$, $\tau = 10.8$ year, $Q_\beta = 687$keV
  - 5 order reduction was essential.

<table>
<thead>
<tr>
<th></th>
<th>Boiling point (@0.2MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xe</td>
<td>178K</td>
</tr>
<tr>
<td>Kr</td>
<td>140K~150K</td>
</tr>
</tbody>
</table>

We established Xe purification using distillation

- 1 ton LXe = 170 m$^3$ gas Xe
- Process speed: 4.7kg/hr $\rightarrow$ 10 days
- Confirmed Kr < 2.7ppt by API-MS

→ XENON
Detector Response

- Highest LXe scintillation yields: 14.7 p.e./keVee
- Lowest threshold: 4 hits $\rightarrow$ 0.3 keVee

$^{57}$Co 

Calibration spectrum 

59.3 keV of W 

122 keV 

136 keV 

real data 
simulation 

Reconstructed vertex 

Simulation 

- 1.4 cm r.m.s. @ $z = 0$
- 1.0 cm r.m.s. @ $z = \pm 20$ cm

Top PMT manipulator

IPMU ACP seminar 7/2/2014

H. Sekiya

NIM A 716 (2013) 78
(extremely tiny) Calibration sources

Rod

source

adopter (SUS304)

OFHC (C1020) rod

<table>
<thead>
<tr>
<th>Isotopes</th>
<th>Energy [keV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{55}\text{Fe}$</td>
<td>5.9</td>
</tr>
<tr>
<td>$^{109}\text{Cd}$</td>
<td>8(*1), 22, 58, 88</td>
</tr>
<tr>
<td>$^{241}\text{Am}$</td>
<td>17.8, 59.5</td>
</tr>
<tr>
<td>$^{57}\text{Co}$</td>
<td>59.3(*2), 122</td>
</tr>
<tr>
<td>$^{137}\text{Cs}$</td>
<td>662</td>
</tr>
</tbody>
</table>
Unexpected BG

- BG is 2 orders of magnitude higher than expected.

- Major BG source was thought to be $\gamma$ from PMTs, but the observed data seemed to indicate additional surface contamination.
  - Aluminum sealing parts for the PMT (btw metal body and quartz glass) contains $^{238}$U and $^{210}$Pb (>5keV)
  - GORE-TEX between PMT and holder is suspicious below 5keV.
To make matters worse

• Those backgrounds deposit energy on “dead zones” and make position reconstruction difficult
  – Could not conduct a FV analysis.
XMASS Full Volume: Low BG w/o PID

- Although extra BG sources were found, XMASS BG level is still competitive.
  - w/o rejecting electron recoil events.
- XMASS has a competitive sensitivity to Light WIMPs

---

E. Aprile, 2010
Princeton

XMASS full volume 5591.4kg days

---

CoGeNT arXiv:1002.4703
XENON10 (before fv)

CRESST arXiv:0809.1829

CDMS arXiv:0912.3592
DAMA arXiv:1002.1028

XENON100 (before fv)
XENON100 (after fv)
Light WIMPs

- XMASS set an upper limit on the WIMP-nucleon cross section for WIMPs with masses below 20GeV w/o PID and excluded part of the parameter space allowed by DAMA

**Search via inelastic scattering**

- XMASS can probe WIMP energy deposition through inelastic scattering using electronic events
- $^{129}\text{Xe}$ (NA 26.4%) has an excited state at 39.578 keV

**Simulated signal in XMASS**

- Excitation by WIMP
- WIMP $\rightarrow$ Xe129 $\rightarrow$ Nuclear recoil
- WIMP $\rightarrow$ Xe129 $\rightarrow$ Nuclear recoil
- deexcitation $\rightarrow$ $\tau = 0.97$ ns
- 40 keV gamma

**Graphical Data**

- $M_{\text{WIMP}} = 20\text{ GeV}$, $50\text{ GeV}$, $100\text{ GeV}$, $1000\text{ GeV}$

---

IPMU ACP seminar 7/2/2014

H. Sekiya 41
Limits on $^{129}\text{Xe}$ inelastic scattering cross section

arXiv:1401.4737, submitted to PTEP

- Asymptotic means ...

\[
\sigma_I(v) = \frac{\mu^2}{\pi M_N} |\langle N^* | M | N \rangle|^2 \left(1 - \frac{v_{\text{thr}}^2}{v^2} \right)^{1/2}
\]

\[= \sigma_{\text{as}} \left(1 - \frac{v_{\text{thr}}^2}{v^2} \right)^{1/2} \quad v_{\text{thr}}^2 = 2 \Delta E c^2 / \mu, \]

The threshold velocity needed to excite $^{129}\text{Xe}$
Solar Axions

- Through the axio-electric effect in Xe, XMASS also has sensitivity to solar axions, which may be produced by Bremsstrahlung and Compton effects ($g_{aee}$) in the Sun
  - N.B. Not $g_{a\gamma\gamma}$ through Primakoff effect

Expected flux $g_{aee} = 10^{-10}$.
Solar Axions

- Same data set as Light WIMP search
- No indication of signals. Bound in $g_{aee}$ vs. mass.
- Better than any other constraint in 10-40keV.
- Better than any other experimental constraint
XMASS-1 **Refurbishment for Background reduction**

- **Countermeasures**
  - PMT+Cu surfaces were cleaned and GORE-TEX was removed.
  - High purity Al was deposited on the side of PMT window to prevent light leakage from dead zone.
  - PMT Aluminum seal was covered
    - Cu ring around aluminum seal
    - Electro-polished Cu plate above Cu rings
XMASS-1 *Refurbishment* for Background reduction

- Countermeasures
Refurbishment

• Resumed data taking in November 2013
  – First data looks… improved!
Quick look at the data after RFB

- \( \text{maxPE/totalPE} = \frac{\text{Maximum photoelectrons in one PMT}}{\text{Total photoelectrons}} \)

PMT array

Large maxPE/totalPE

Small maxPE/totalPE

The larger R, the larger maxPE/totalPE

EXCEPT events in the dead zone

Could not discriminate FV events from surface events
Quick look at the data after RFB

Normalized by live time

- At least 1/10 BG reduction
  - Another 1/10 reduction is expected through the position reconstruction (PE,timing)

New results coming soon!

Photo yeild is almost same as before: ~13keV/pe

ADCs are saturated

BG from dead zone

~13 keV/pe

Before RFB

After RFB

Improved!
Next step: XMASS-1.5

- Inner Ø: 1.5 m
  - contains 5 tons of LXe
  - fiducial mass 1 ton

- Lessons from XMASS-1

- Flat photocathode cannot see photons from dead zone

- Plano-concave photocathode can!
XMASS-1.5

- Actively being developed w/ Hamamatsu

- Effectiveness is verified with MC
Single-phase TPC

- The original concept, but has not realized yet.
Single-phase TPC

Before the realization of two-phase detectors, there were many studies focused on charge amplification and proportional scintillation in single-phase LXe.

Charge gain ~400

Miyajima NIM 134 (1976) 403
Charge gain ~100
S2 in LXe

Masuda NIM 160 (1979) 247

Charge gain & proportional scintillation

Benetti NIMA 327 (1993) 203

$^{109}\text{Cd}$ 22keV was observed

---

Fig. 1. Schematic drawing of the test chamber (1) HV insulator (Macor), (2) UV quartz window, (3) Cathode (stainless steel), (4) Source, (5) Grid (grounded), (6) Anode.

Fig. 5. Charge avalanche signal from preamplifier of 22 keV gamma rays from $^{109}\text{Cd}$ together with the nonintegrated scintillation signal.

---

Fig. 5. Energy spectra of $^{207}\text{Bi}$ for the center wire of 11 μm in diameter at $V = 4.0\text{ kV}$ which is the optimum voltage for this wire. The upper spectrum is for the charge and the lower for the proportional scintillation. The peak positions in both spectra are laid at the same channel.
Single-phase TPC

- Spherical LXe TPC
  - High electric field in XMASS
  - 20kV at the center

Will be tested with single wire in this chamber
Single-phase TPC

• Thick GEM in LXe

Thick GEM

Thickness 0.4mm

Breskin
ParisTPC conf (2012)

RD51  Aug 2013

THGEM 70 kV/cm

$E_{\text{top}} = 0, E_{\text{drift}} = 1 \text{ kV/cm}$
**Single-Phase TPC**

- **Panda-X**

  Double phase TPC has Leveling problem!

---

**Comparison of Methods**

- **Baseline Design**
  - Dual Phase TPC
  - Upper PMT
  - Liquid Level
  - Anode
  - Cathode
  - Lower PMT

- **New Design**
  - Single Phase TPC
  - Upper PMT
  - Anode wires
  - Liquid Level
  - LXe
  - Cathode
  - PTFE
  - Lower PMT
Future Projects
How much noble liquid do we need?

- To reach $\sim 10^{-48}$ cm$^2$

arXiv:1306.3244
Future Projects (all in water)

- **XENON1t**
  - 3.5t total
  - 248 3” PMTs
  - In 2015?

- **XENON nt**
  - 5t total
  - New 3” PMTs
  - $x \pi$?

- **XMASS1.5**
  - 5t total

- **LZ = LUX+ZEPLIN**
  - 7t total
  - 500 3” PMTs

- **XMASS 2**
  - 24t total
  - 20t LAr
  - 10t LXe

- **DarkSide G2**
  - 5t total

- **DARWIN**
  - 20t LAr
  - 10t LXe

**IPMU ACP seminar 7/2/2014**

H. Sekiya
Evolution of Direct Dark Matter Search

- Can we push to such low BG levels?

L. Baudis Phys Dark Univ. 1(2012) 94

1 events/kg/yr

1 events/ton/yr
Conclusion

• Direct detection experiments have reached sensitivity to WIMP cross sections down to $\sim 10^{-46}\text{cm}^2$ with noble liquid technologies.

• Detectors coming online in the next 5 years will aim for $< 10^{-47}\text{cm}^2$ and all will use noble liquids.
  – Can noble liquids catch Dark Matter?
  – Beyond noble liquids, completely new technology will be required?
  – SUSY? After LHC upgrade, we may have to go further...or...