Non-accelerator Experiments: Physics Goals and Challenges

Carter Hall,
University of Maryland
Detecting galactic WIMP dark matter

Dark matter “Halo” surrounds all galaxies, including ours.

Density at Earth:

\[ \rho \sim 300 \ \frac{m_{\text{proton}}}{\text{liter}} \]

\[ m_{\text{wimp}} \sim 100 \ m_{\text{proton}}. \]

3 WIMPS/liter!

Typical orbital velocity:

\[ v \approx 230 \ \text{km/s} \]

\[ \sim 1/1000 \ \text{speed of light} \]

Coherent scalar interactions: \( A^2 \)

Rate: < 1 event/kg/100 day, or much lower
Nuclear Recoil Spectra from WIMP scattering

\[ m_{\text{WIMP}} = 100 \text{ GeV}, \sigma_{\text{W-N}} = 4.0 \times 10^{-43} \text{ cm}^2 \]

Diagram showing the rate of nuclear recoil events versus recoil energy for different isotopes: Xe (A=131), Ge (A=73), and Ar (A=40). The rate is given in units of [kg/day] for recoil energies [keVr].
Dark matter search results

- Sensitivity to low mass WIMPS determined by detector threshold
- Overall scale determined by detector size, run time, and background rates.
Neutrinoless Double Beta Decay ($\beta\beta 0\nu$)
Forbidden if neutrino mass is Dirac only

$N(Z,A) \rightarrow N(Z+2,A)e^-e^-$

Severe chiral suppression: $T_{1/2} > \sim 10^{25}$ years
What nuclei are $\beta\beta$ candidates?

- Decay energy ~ few MeV

Diagram showing the atomic mass, number of protons, and decay pathways for nuclei such as $^{136}_{53}$I, $^{136}_{54}$Xe, $^{136}_{56}$Ba, $^{136}_{57}$La, $^{136}_{58}$Ce, and $^{136}_{59}$Pr.
The most sensitive double beta decay experiments to date are based on 76-Germanium.

Heidelberg-Moscow (76Ge) energy spectrum

Half-life limit: $1.9 \times 10^{25}$ years (H-M and IGEX)
Majorana neutrinos ruled out for masses greater than $\sim 0.35$-$1.0$ eV
Ordinary radioactive decay

**Alpha decay**

**Beta decay**

**Gamma decay**

\[
\begin{align*}
\text{Co}^{60} & \rightarrow \text{Ni}^{60} \\
& \quad \text{5.26 a} \\
& \quad 0.31 \text{ MeV } \beta \\
& \quad 1.17 \text{ MeV } \gamma \\
& \quad 1.33 \text{ MeV } \gamma
\end{align*}
\]
Nuclide half lives

“Peninsula of stability”
Peninsula of Stability

Thorium-232
Uranium-238
Uranium-235
Plutonium-244
Curium-247
Thorium-232
Uranium-238
Ordinary radioactive decay here on earth

Q values:

ββ0ν Q values:

WIMP dark matter
Shielding gammas is difficult!

Gammas travel about 2 cm before scattering in lead.

Q values
Uranium-238 decay chain

\[ \text{T(1/2) \approx 10^9 \text{ years: the worst half-life in physics!}} \]

Too long to decay away, but still \( 10^{16} \) times faster than \( \beta \beta 0 \nu \)!

Need ultra-high detector materials + extremely sensitive screening methods

Thorium-232 decay chain

gamma sources
Dark matter: shielding is not so difficult @ 10 keV

Gamma interaction cross section

(b) Lead ($Z = 82$)

- experimental $\sigma_{\text{tot}}$

Only MeV $\gamma$'s can penetrate, but only keV $\gamma$'s can fake a WIMP

Cross section (barns/atom)

$\sigma_{\text{p.e.}}$

$\sigma_{\text{Rayleigh}}$

$\sigma_{\text{Compton}}$

$\kappa_{\text{nuc}}$

$\kappa_{e}$

Typical WIMP recoil energies

1 Mb

1 kb

1 b

10 mb

10 eV

1 keV

1 MeV

1 GeV

100 GeV

Photon Energy
Shielding Gamma Rays

Water, 2.6 MeV gammas

Water

Liquid Xe, 2.6 MeV gammas

Liquid Xenon

1 m water shielding

1 m liquid Xe
Self-shielding effect
Sensitivity improves quickly as target mass increases due to geometry!

~MeV $\gamma$

~keV scattering event – forward scattering

must cross full volume without scattering again
but it’s defeated by Kr-85 dissolved in the bulk. Self-shielding works....
New screening technique to detect krypton at the part-per-trillion level

arXiv:1103.2714v1

open leak valve
Detect electronegative impurities at less than a part-per-billion

- Open leak valve, bypass gas purifier
- Flow through gas purifier
- Close leak valve to measure backgrounds

Xe is constant due to cold trap

18 ppb N₂
5 ppb O₂
0.25 ppb CH₄

~few ppm Ar

NIM 621 678 (2010)
Massive detectors for solar neutrinos

BOREXINO
First $< \text{MeV}$ measurement of solar neutrinos (PRL 101, 091302, 2008)
1000 tons of ultra-pure ($10^{-17}$ g/g U, Th) scintillator, 2000 PMTs.
Borexino Solar Neutrino Spectrum – 192 days of exposure

\[ \chi^2 / \text{NDF} = 185/174 \]

- $^7\text{Be}$: $49 \pm 3$ cpd/100 tons
- $^{210}\text{Bi} + \text{CNO}$: $23 \pm 2$ cpd/100 tons
- $^{85}\text{Kr}$: $25 \pm 3$ cpd/100 tons
- $^{11}\text{C}$: $25 \pm 1$ cpd/100 tons
- $^{14}\text{C}$
- $^{10}\text{C}$

$^{14}\text{C}$ overwhelms dark matter in organic scintillator
WIMPs and Neutrons scatter from the Atomic Nucleus

Photons and Electrons scatter from the Atomic Electrons
The Signal ... and Backgrounds

WIMPs

Nucleus Recoils

$\nu/c \approx 7 \times 10^{-4}$

$E_r \approx 10$'s KeV

Neutrons also interact with nuclei, but mean free path a few cm

WIMP

gammas and betas

Electron Recoils

$\nu/c \approx 0.3$

$\gamma$
Background rejection through Particle ID

- Nuclear recoils vs. electron recoils
  - Division of energy
  - Timing
  - Stopping power

- Division of energy
- Timing
- Stopping power

Two-phase noble liquids (ZEPLIN, WARP, XENON, LUX)

Cryogenic semiconductors (CDMS)

Light

Ionization

WIMP

Phonons/heat

100% energy slowest cryogenics

scintillating bolometers (CRESST)

Single-Phase noble liquids (XMASS, DEAP/CLEAN)
Scintillation pulse shape as particle ID

Excimer Molecules – (Ar)(Ar)* molecule has triplet and singlet states.
Scintillation pulse-shape-discrimination (PSD) in Liquid Argon

Singlet decay (~7 ns)

Triplet decay (~1.6 μs)
Scintillation pulse shape discrimination (PSD) in Argon

Data: Mini-Clean (McKinsey/Yale)

Discrimination is very powerful....... >10^6
CLEAN proposal: Liquid Argon and Neon dark matter search

- No $^{14}\text{C}$ background (Borexino)
- Exquisite pulse shape rejection of common b & g backgrounds
- BUT.....natural argon has its own problem – 39Ar (use depleted Argon instead)

artist rendition courtesy of LANL
CDMS - 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.

380 μm Al fins

60 μm wide

380 μm Al fins

Si or Ge surface

2 μm wide

W transition edge sensor

W - Al overlap
Ionization yield $Y$ = ratio of ionization to phonon.

The black lines demonstrate the +/- $2\sigma$ bounds of the electron/nuclear recoil band.

• The response of the detectors is best demonstrated with in-situ calibration photon and neutron sources.
• Complete charge collection (after crystal neutralization) at 3V/cm.

Photon and Neutron Calibration

- Bulk Electron Recoils (Gammas, X-rays and high-energy electrons)
- Bulk nuclear recoils (neutrons and WIMPS)
LUX Design – Active Volume

- 350 kg of liquid Xe
- Active volume: h=59cm, d=49cm
- Light collection ~2.0 phe/keVr
- 2x better than Xe10
- Analysis threshold down to < 3 keVr

- 122 PMT R8778
  - 2” diameter
  - 175 nm, QE > ~30%
  - U/Th ~9/3 mBq/PMT

- Dodecagonal field cage + PTFE reflectors

- Cu PMT holding plate

Design by J. White
Photons vs neutrons with liquid xenon

Allows discrimination between common radioactivity and WIMP events. Background rejection factor of ~180

Ionization to Scintillation ratio
Detector self-shielding —
absorption of naturally occurring radioactivity

LUX300v4_R8778H - TopPMTs, BotPMTs
(U 18.00, Th 17.00, K 30.00, Co 8.00 mBq/PMT )
(All Events) (5-25keVee)(RFR=5cm)

PMT radioactivity dominates
Comparison of Low-radioactive Photon Detectors from Hamamatsu

R8520
1 inch

R8778
2 inch

QUPID
3 inch

XENON10
XENON100

LUX
(XMASS)

XENON100+
DarkSide
MAX, XAX
QUPID (QUartz Photon Intensifying Detector)

Made by Synthetic Silica only.
US Patent (No. 5374826) pending.
New 3” QUPID (Production Version)
Electron Bombardment Gain (QHA26)

QHA26 Bombardment Gain Test, Various Temperatures

Photocathode High Voltage (-kV)

Gain

25 °C

-100 °C

G = 800
The first scintillating lights detected by QUPID from $^{57}\text{Co}$ in liquid xenon

1, 2, and 3 photoelectron peaks

<table>
<thead>
<tr>
<th>Photoelectron Peaks</th>
<th>Mean (μ)</th>
<th>Standard Deviation (σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 PE</td>
<td>31.7316</td>
<td>4.42699</td>
</tr>
<tr>
<td>2 PE</td>
<td>55.0522</td>
<td>13.1332</td>
</tr>
<tr>
<td>3 PE</td>
<td>85.9126</td>
<td>9.52833</td>
</tr>
<tr>
<td>Sum of 1, 2, and 3 PE</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
PMTs (LZS and LZD 20 tonne LXe)

- Current LUX 350 Experiment: Using 122 x 2” R8778 Hamamatsu
  - Production yields high/very stable - long track record with technology
  - U/Th 10/2 mBq/PMT
    - There has been tremendous progress in reducing PMT backgrounds
    - The level of radioactivity already achieved in these PMTs would be an acceptable baseline for the LZS and LZD experiments
  - Demonstrated QE: average=33%, max 39% at 175 nm
    - Permits factor 3 better phe/keV response in LUX than in XENON100
PMTs (LZS and LZD 20 tonne LXe)

- Under LZ S4 development program: DUSEL R&D
  - Larger diameter - twice collection area. Radioactivity further reduced.
  - In 2009 initially fab of and tested Hamamatsu 3” R11065 in LXe
    - Tested QE/LXe operation - all PMTs performed identically to those of same as R8778
    - High gains >5x10^6 mean that no additional amplifiers required. Electronics within cryostat are limited to passive components with very low/well understood radioactive backgrounds
  - Developed new ultra low background 3” PMTs for LXe: R11410mod
    - Background measured U/Th <1/1 mBq/PMT (90% CL) - No U/Th signal seen
    - This comfortably exceeds background requirements for LZD detector
    - Upgraded Hamamatsu Super bialkali photocathodes will also be available to move QE above 40%

- Requirement is for 1000x3” PMT for LZD (20 tonne)
  - Production yields and cost well understood
Only directional detection can correlate with Cygnus: unambiguous positive observation of Dark Matter in presence of backgrounds.
DMTPC: detector concept

Low-pressure CF$_4$ TPC
- 50 torr: 40 keV F recoil ~2mm

Optical readout (CCD)
- Image scintillation photons in amplification region
- 2D, $\$\$, proven technology, clean

PMT and charge readout
- Trigger and E measurement

Amplification region
- Woven mesh 250 $\mu$m pitch

CF$_4$ is ideal gas
- F: spin-dependent interactions
- Good scintillation efficiency
- Low transverse diffusion
- Non flammable, non toxic
Calibration with low-energy neutrons:

$^{252}$Cf run with mesh detector

- Mesh-based detector: 1D $\rightarrow$ 2D projection of recoil
- Stable data-taking at 75 torr
  - “Head-tail” effect demonstrated down $\sim$ 100 keV
- Excellent data-MC agreement
- Angular resolution: $15^\circ$ at 100 keV
10-liter DMTPC detector

Second generation - DMTPC 10-l
- Mesh-based amplification planes
- 23 cm O and 20 cm drift/TPC
- 3.3g @75 torr
- 2 CCD cameras (top and bottom)
P-type Point Contact High Purity Germanium

CoGeNT:
neutrino &
astroparticle physics
using large-mass,
ultra-low noise
germanium detectors
(CANBERRA, PNNL, ORNL, UC, UNC, UW)

PPC HPGe
JCAP 09(2007)009

Applications:
• Light Dark Matter
• Coherent $\nu$ detection
• $\beta\beta$ decay (MAJORANA)

Conventional HPGe coaxial detector

PPC HPGe
$\sim 400$ eV threshold, working on further reduction

Counts / keV kg day

$\sigma_{SI} (cm^2)$

$E_x (GeV/c^2)$

Extensive constraints on DAMA's claim:
• Light WIMPs
• Dark scalars
• Dark pseudoscalars

J. Collar, U. Chicago
P-type Point Contact High Purity Germanium

What is happening?

Standard coaxial HPGe

P-type modified electrode

241Am collimated 59.5 keV gammas

amplitude of averaged preamplifier traces (a.u.)

time (ns)

amplitude of averaged preamplifier traces (a.u.)

time (ns)
P-type Point Contact High Purity Germanium

Other nice features brought by the point contact:

That was then...

TOP: preamp trace
BOTTOM: 10ns int.+ diff. TFA
(follows charge arrival)

Limited ability to distinguish singles from multiples
(one bump or two?)

J. Collar, U. Chicago
P-type Point Contact High Purity Germanium

This is now.

Different hits get clearly stretched in time.

All this with optimal energy resolution and charge collection (and one channel)

J. Collar, U. Chicago
Double beta decay: get smarter with single Ba\(^+\) ion detection

\[ ^{136}\text{Xe} \rightarrow ^{136}\text{Ba}^{++} \ e^- e^- \]

Daughter identified by optical spectroscopy of Ba\(^+\), well studied in ion traps for more than 25 years

\[ \text{Ba}^+ \]

\[ ^2\text{P}_{1/2} : \sim 7.9\text{ns} \]

\[ ^2\text{S}_{1/2} \]

\[ ^2\text{D}_{3/2} : \text{metastable} \sim 83\text{s} \]

- very specific signature ("Λ" shelving)

- cycling 493/650 nm transitions gives a fluorescence rate of \(~10^8\) Hz (in vacuum)

plenty of light!

Ba\(^+\) Tagging: Ion Trap + fluorescence

~9\(\sigma\) discrimination in 5s integration

M. Green et al., *Phys Rev A* 76 (2007) 023404

Ba\(^+\) Tagging: RIS

- Resonant Ionization Spectroscopy uses lasers tuned to atomic resonances to first *excite* and then *ionize* specific atoms.
- We use pulsed dye lasers at 553.5 nm and 389.7 nm.
- Autoionization: The 5d8d \(^{1}P\_1\) state decays to a lower energy ionized state, allowing use of the high cross section of the resonance to achieve ionization.
Ba\(^+\) Tagging: RIS

Efficiency of \(~10^{-3}\) in “bulk mode” setup. New “single ion mode” setup about to start taking data.
SNO+: $^{150}$Nd Double Beta Decay Concept

- Energy resolution in a liquid scintillator is relatively poor.
- Search for endpoint shape distortion at high Q-value above the gamma lines from natural radioactivity.
- $^{150}$Nd has highest phase space factor and NME, thus highest predicted rate.

Simulation:
- One year of data
- 1% NdLS
- $m_{\text{eff}} = 0.15$ eV
Nd Liquid Scintillator Synthesis

- the organometallic form is a carboxylate
- similar to Gd-loaded scintillator for Daya Bay
- solvent-solvent extraction method to transfer to the organic phase
- this method was used to make NdLS at both BNL and Queen’s University

\[
\text{linear alkylbenzene (LAB)} \quad \text{Nd(RCOO)}_3
\]

\[
\begin{align*}
\text{(organic phase)} & \quad \text{(aqueous phase)} \\
\text{Nd}^3+(\text{Cl}^-)_3 + 3\text{RCOO}^- & \rightarrow \text{Nd(RCOO)}_3 \\
\text{NH}_3 + \text{RCOOH} & \rightarrow \text{NH}_4^+ + \text{RCOO}^-
\end{align*}
\]

photo depicts NdLS in two different solvents and unloaded scintillator
Nd in Various Scintillation Solvents
Measuring the complete Solar neutrino spectrum

- $E_{th}=114$ keV (95% of pp spectrum)
- Measure pp-$\nu$ flux @ 3%
- Determine CNO-fraction
- Measure $T_{\text{sun}}$ by change in mean energy of $^7\text{Be}$ line – maybe (hep-ph/9309292)
- needs separate calibration experiment –”LENS Sterile”

**LENS**

complementary use: sterile neutrinos

$$\nu_e + ^{115}\text{In} \rightarrow e^- + \gamma + (\gamma/e^-) + ^{115}\text{Sn}$$

**The Indium Low Energy Neutrino Tag**

- $B(GT) = 0.17; Q_v = 114$
- $B(GT) = 0.17; Q_v = 114$
- $\beta_{\text{max}} = 498.8$
- $115\text{Sn}$
LENS proposal: real-time solar neutrino spectral measurement
# Indium Loaded Pseudocumene (PC) Scintillator Performance

<table>
<thead>
<tr>
<th>Metal loaded LS status</th>
<th>InPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Indium concentration</td>
<td>8%</td>
</tr>
<tr>
<td>2. Scintillation signal efficiency</td>
<td>~7000 hν/MeV</td>
</tr>
<tr>
<td>3. Transparency at 430 nm: L(1/e) (working value):</td>
<td>8m (long term)</td>
</tr>
<tr>
<td>4. Light yield (Y%pc) (working value):</td>
<td>55–60%</td>
</tr>
<tr>
<td>5. Chemical and Optical Stability:</td>
<td>Stable &gt;1.5 yr with L(1/e)&gt;8m</td>
</tr>
<tr>
<td>6. InLS Chemistry</td>
<td>Robust</td>
</tr>
</tbody>
</table>

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![Graph showing transparency of InPC](image)

Transparency of InPC

- 8.6 m after 8 months

UV/Vis absorbance of zVt45 (pH 6.88) with time
Linear Alkyl Benzene as a alternative to Pseudocumene: Promising Absorbance Results for in InLAB
LENS: optical lattice for improved pattern recognition and background rejection
Lattice Structure

Single Foil

Solid teflon segmentation

Double Foil

Double-layer (air-gap) lattice
Thanks to: Paul Brink, Derek Roundtree, Mark Chen, Katsushi Arisaka, Rick Gaitskell, Gabriella Sciolla, Juan Collar