Search for Dark matter with ZEPLIN II
Liquid Xenon Detector and LUX
xenon two phase dark matter direct detection

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1. Brief Introduction
2. Direct Detection
3. The ZEPLIN II Detector
4. Performance and Results
5. The LUX Detector
Evidence for dark matter

Rotation curves of spiral galaxies

\[ v = \sqrt{\frac{GM}{r}} \]

DISTRIBUTION OF DARK MATTER IN NGC 3198
Gravitational lenses:
The blue arcs are light from a distant galaxy whose light has been deflected by the galaxy cluster in the foreground.
Dark matter - gravitational lenses
Reconstruction of the mass distribution in the galaxy cluster

The luminous mass is not enough, the reconstructed mass is much larger!
⇒ Dark Matter!
Big Bang Nucleosynthesis

- Light elements up to $^7$Li are produced in the Big bang
- Nuclear reactions are known
- The amount of light elements can be calculated
- Compare with observations
- The baryons can only make up a small fraction of the dark matter

From Turner et al.

M. Signore, New Astro. Rev. 1999
The discovery, using NASA’s Chandra X-ray Observatory and other telescopes, gives direct evidence for the existence of dark matter.

*Pink: Hot gas, Blue: Dark Matter*
Wilson Microwave Anisotropy Probe (WMAP)

\[ \Omega_m h^2 = 0.127^{+0.007}_{-0.013} \]

\[ \Omega_b h^2 = 0.0223^{+0.0007}_{-0.0009} \]

\[ h = 0.73^{+0.03}_{-0.03} \]
Dark Matter: Everything here is only <1% of the whole story

THE BIG BANG THEORY

1. The cosmos goes through a superfast "inflation," expanding from the size of an atom to that of a grapefruit in a tiny fraction of a second.

2. Post-inflation, the universe is a seething hot soup of quarks and other particles.

3. A rapidly cooling cosmos permits quarks to clump into protons and neutrons.

4. Still too hot to form into atoms, charged electrons and protons prevent light from shining; the universe is a superhot fog.

5. Electrons combine with protons and neutrons to form atoms, mostly hydrogen and helium. Light can finally shine.

6. Gravity makes hydrogen and helium gas coalesce to form the giant clouds that will become galaxies; smaller clumps of gas collapse to form the first stars.

7. As galaxies cluster together under gravity, the first stars die and spew heavy elements into space; these will eventually form into new stars and planets.

NOTE: The numbers in cosmology are so great the numbers in subatomic physics are so small that it is often necessary to express them in exponential form. Ten multiplied by itself 100 is written as 10^100.
A WIMP $\chi$ (Weakly Interacting Massive Particle)  
Created in the Big Bang:  
Is predicted in Supersymmetric theory of particle physics:  
Lightest particle, neutralino, with a mass 
$\sim 100 \times$ proton mass and stable  
Has exactly the right properties to be the dark matter!

We see only SM particles Today Symmetry break at higher M scale
Relative size of luminous galaxy and the dark matter halo

\[ \nu = \sqrt{\frac{GM}{r}} \]

Cored spherical isothermal halo

\[ \rho(r) = \rho_0 \frac{a^2 + r_0^2}{a^2 + r^2} \]

With Maxwelian local distribution

\[ f(\nu)d^3\nu = \frac{e^{-\nu^2/\nu_0^2}}{\pi^{3/2}\nu_0^3} d^3\nu \]
Indirect searches: CDF & D0 at Fermilab (TeV-tron)
CMS & Atlas at CERN (LHC)
Direct Detection Strategy

\[ f(\nu) d^3\nu = \frac{e^{-\nu^2/\nu_0^2}}{\pi^{3/2} \nu_0^3} d^3\nu \]

\[ \nu_{\text{max}} = 650 \text{ km} / \text{s} \]

\[ \rho = 0.3 \text{ GeV/cm}^{-3} \]

\[ \nu \approx 220 \text{ km} / \text{s} \]

\[ \text{flux} \approx 10^5 \text{ s}^{-1} \text{ cm}^{-2} \]
form factor effect with various targets

Coherent enhancement on event rate

\[ \sigma_c = \frac{\mu_{X,N}^2}{\mu_{X,n}^2} \sigma_{X,n} A^2 \]
Recoil Spectra of different Targets

\[
\frac{dR}{dE_R} = \frac{\sigma_0 \rho_x}{4 \nu_e m_x \mu_{x,N}^2} F^2(E_R) \left[ \text{erf}\left(\frac{\nu_{\text{min}} + \nu_e}{\nu_0}\right) - \text{erf}\left(\frac{\nu_{\text{min}} - \nu_e}{\nu_0}\right) \right]
\]

\[
\sigma_0 = \frac{\mu_{X,N}^2}{\mu_{X,n}^2} \sigma_{X,n} A^2
\]

- Red: Xenon 100 GeV Summer
- Purple: Argon 100 GeV Summer
- Blue: Germanium 100 GeV Summer

Nuclear Recoil Energy (keV)
Annual Modulation

\[
\frac{dR}{dE_R} = \frac{\sigma_0 \rho_x}{4\nu_e m_x m_r^2} F^2(E_R) \left[ \text{erf}\left( \frac{\nu_{\text{min}} + \nu_e}{\nu_0} \right) - \text{erf}\left( \frac{\nu_{\text{min}} - \nu_e}{\nu_0} \right) \right]
\]
Sources of Background

$^{40}$K: $4 \times 10^7 \gamma$/day ($\sim 1.5$MeV)

Detector Target

$10^3$/(kg-day)

all materials used for detector construction are contaminated by Uranium and Thorium

Cosmic rays produce large rate in detector too

Current limit $\sim 0.1$ event/kg/day
High Mountain
Or Deep Underground

To reduce
Background
events

U, Th

Veto

Shield

target

U, Th
Detector response to WIMPs and Background

- WIMP or Neutron
- Nuclear Recoil
- Electron Recoil
- Ionization
- Scintillation
- Phonon
- Background Discrimination

Radioactive background

Target Nuclei
Principle Tests Setup & Results

1. Ceramic.
2. Quartz Window,
4. Source.
5. Grounded Grid.
6. Anode wire frame

NIM A327 (1993) 203
A simple purification process developed to achieve 5 ms electron lifetime in liquid xenon

\[ \tau = \frac{T_d}{\ln\left(\frac{Q_c}{Q_a}\right)} > 5\text{ms} \]

Purification system

single phase studies using a 2kg liquid xenon detector

1995-1996

H Wang UCLA thesis 1998
2kg single phase detector @ Mt. Blanc LAB

Aug. 1996
Scintillation Efficiency (quenching factor) measurement

7MeV Proton on Li target (1-4mg/cm²)
Van de Graaff accelerator
Legnaro (Padova Italy)

NIM A 449 (2000) 147-157
$N_{ph/e} \approx 70 \left( \frac{E}{P} - 1.3 \right) \cdot X \cdot P$

E: Electric field (kV/cm),
P: Gas Pressure (Bar),
X: electron Drift Distance (cm)
Why Xenon

- Available in Large Quantities
- Large abundance for both $s_{1/2}$ ($^{129}\text{Xe} \sim 26\%$) and $s_0$ ($^{132}\text{Xe} \sim 27\%$)
- High Atomic Number ($\sigma_{\text{WIMP-Nucleon}} \propto A^2$, $Z_{\text{Xe}}=54$, $A=131$)
- High Density ($\sim 3\text{g/cm}^3$ liquid) (compact detector design)
- High Scintillation Light (175nm) & Ionization Yield
- Small fano factor ($F=0.041$ Energy Resolution $\frac{\Delta E}{E} = 2.35\sqrt{\frac{FW}{E}}$)
- Scintillation decay profile difference (primary) (PSD)
- Large quenching factor (observed energy/e.e.Energy)
- Can be Highly Purified
  - long light attenuation length ($\sim \text{m}$)
  - long free electron life time ($\sim \text{5ms}$)
- Gamma & Recoil signal Discrimination
- Capable of Scale up to Large Volume (ton)
- No Long Lived Radioactive Isotopes (low background)
Liquid Xenon Scintillation Mechanism

(A) Pulse Shape discrimination: due to decay profile difference between nuclear recoil & electron recoil

(B) When $E_{\text{drift}}$ applied, and measure $E_i$ & $E_s$,
Very good background rejection due to $(E_i/E_s)_{\text{M.I.P.}} >> (E_i/E_s)_{\text{H.I.P.}}$

ZEPLIN I (A)
ZEPLIN II (A&B)

Pulse shapes:
- Nuclear recoil: 27 ns
- Electron recoil: 2 ns

Excitation processes:
- Singlet 3 ns --- 175 nm
- Triplet 27 ns --- 175 nm

Ratio: Nuclear = 10 x electron
ZEPLIN II Design Principle

\[ N_{ph/e} = 70 \left( \frac{E}{P} - 1.3 \right) X \cdot P \]

\(~9\text{p.e./e}\)
Drift and Luminescence
Field Modeling

Mesh Structure

Main Drift Volume
Typical ER and NR event

Electron Recoil

Nuclear Recoil
Single Electron Detection

A single electron leaving liquid surface can be detected using S2! (~9p.e./e)
The first piece being made at UCLA Physics Machine shop in 2001!

PTFE cone and field ring holder
Stainless Steel cast Vacuum Vessel

Top

Bottom

On CNC machine at UCLA physics machine shop
ZEPLIN II
PMT Assembly
7 UV sensitive low temperature PMTs (by Electron Tubes Inc.)
PTFE
Heater
gas extraction
field shaping rings
wire mesh
Zep II Charge Extraction & Luminescence Field Grid

88% transparency

Cold deflection test

Width of secondary pulses As a function of distance
Home Made HV feedthrough & internal cable
PTFE Baffle
Wire mesh
Detector Shielding Set up

A: Xenon Target
B: Veto
C: Neutron Shield
D: Lead
First science run:
- 5 months continuous operation
- 1.0t*day of raw DM data
- Results submitted to Astropart. Phys.
Location of ZEPLIN II Detector

Boulby Site
1,100-m deep underground
Depth (m.w.e.)

- WIPP: 1600-2300
- Soudan: 2200
- Boulby: 3300
- Gran Sasso: 3800
- Sudbury: 6200 (SNOLAB)
- Homestake: 7200 (deep opt.)
- San Jacinto: 5400-6300
Recoil Event
A high energy gamma event

Optical feedback

Cathode

A high energy gamma event
Optical feedback: A detailed look with wider window
Neutron multi-scatter In ZEPLIN II

ZII Neutron data - multiple scatters

Frequency vs. Number Of Scatters

$y = 1.76 \times 10^4 \times e^{-1.25x}$  $R = 1.000$

Signal (V) vs. Time (ns)

Events S1, S2a, S2b, S2c, S2d
Using S2 from each PMT to Determine the X-Y location

$^{57}$Co source data from bottom

0.55 p.e./keV @ 1kV/cm

122 (&136) keV

S1

S2

0.55 p.e./keV @ 1kV/cm
Discrimination and acceptance box determination

- Upper bound set at 50% n.r. acceptance
- Fixed S2/S1 lower bound
- Energy range from 5 to 20keVee
- 98.5% $\gamma$ discrimination
Science Run Results

Blue star: Even in coincident with veto

Lower band due to Radon daughters on side walls
Background expectations

Gamma from Co-60

Radon Daughters
Cross-Section results, first run
In review: submitted to Astropart. Phys.

- 29 events seen in box
- 28.6±4.3 expected (total)
- 10.4 upper limit to n.r.
- 225 kg*days
- 7.2kg fiducial

Standard Halo
Scalar Interaction

WIMP-nucleon cross-section limits for 31 days (225 kg-days): $6.6 \times 10^{-7}$ pb (@65GeV)
ZEPLIN II/III

My Dream Detector

0.5-ton

1-ton

ZEPLIN IV?

1.6-ton

5.8-ton total

1.6-ton

5.8-ton total

My Dream Detector
ZEPLIN long term strategy II

Towards ton-scale PMT-less detector

1-ton

5-ton

Nano-Tip Charge Readout

CsI
Future Multi-Ton detector

Central ball 4pi covered with charge collecting and amplifying micro-structure

Nano-Tip Structure for Charge Readout

Requirements:

• Sensitivity to single electron
• High readout segmentation for position information
The LUX Detector

One Possible System for Installation
LUX Dark Matter Experiment - Summary

- Brown, Case, LLNL, LBNL, Rochester, Texas A&M, UC Davis, UCLA
  - XENON10, ZEPLIN II (US) and CDMS; ν Detectors (Kamland/SuperK/SNO/Borexino); HEP/γ-ray astro
  - (Also ZEPLIN III Groups after their current program completed)

- 300 kg Dual Phase liquid Xe TPC with 100 kg fiducial
  - >99% ER background rejection for 50% NR acceptance, E>10 keVr
    (Case+Columbia/Brown Prototypes + XENON10 + ZEPLIN II)
  - 3D-imaging TPC eliminates surface activity, defines fiducial

- Backgrounds:
  - Internal: strong self-shielding of PMT activity
    - γ/β < 7x10^{-4} /keVee/kg/day, from PMTs (Hamamatsu R8778 or R8520).
    - Neutrons (α,n) & fission subdominant
  - External: large water shield with muon veto.
    - Very effective for cavern γ+n, and HE n from muons
    - Very low gamma backgrounds with readily achievable <10^{-11} g/g purity.

- DM reach: 2x10^{-45} cm^{2} in 4 months
  - Possible ~5x10^{-46} cm^{2} reach with recent PMT activity reductions, longer running.
LUX program: exploit scalability

- LUXcore: Final engineering for large-scale detector
  - Cryostat, >100 kV feedthrough, charge drift, light collection over large distance
  - Full system integration, including ~1m water shield
  - 40 kg narrow “core”, 14 PMTs, 20 cm Ø x 40 cm tall.
    - Radial scale-up requires full-funding.

- LUX in ~ 6m Ø water shield
- Very good match to early-implementation DUSEL (e.g., Homestake “Davis” cavern)
  - SNOLAB LOI
- System scalable to very large mass.
Cryostat arrived at Case (Feb. 12 2007)
LUX Dark Matter Goal

- **Dark Matter Goals**
  - **LUX - Sensitivity curve at 2x10^{-45} cm^2 (100 GeV)**
    - Exposure: Gross Xe Mass 300 kg
      - Limit set with 120 days running x 100 kg fiducial mass x 50% NR acceptance
        - If candidate dm signal is observed, run time can be extended to improve stats
      - ~1 background event during exposure assuming most conservative assumptions of
        - ER 7x10^{-4} /keVee/kg/day and 99% ER rejection
        - ER bg assumed is dominated by guaranteed Hamamatsu PMT background (R8778 or R8520) - recent PMTs from Hamamatsu achieving lower backgrounds, but not guaranteed
        - Improvements in PMT bg (and rejection power) will extend background free running period, and DM sensitivity
  - **Comparison**
    - SuperCDMS Goal @ SNOLab: Gross Ge Mass 25 kg
      - (x 50% fid mass+cut acceptance)
      - Limit set for 1000 days running x 7 SuperTowers

XENON10 Results will be announced at APS April Meeting