WIMP Searches with Liquid Xenon: the XENON10 Experiment

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Why Liquid Xenon?

High atomic mass \( (A \sim 131) \): favorable for SI case \( (\sigma \sim A^2) \)

Odd isotope with large SD enhancement factors \((^{129}\text{Xe, }^{131}\text{Xe})\)

High atomic number \((Z=54)\) and density \((3\text{g/cm}^3)\)
=> compact, self-shielding geometry

‘Easy’ cryogenics at -100 C

No long-lived radioisotopes

High photon yield \((\sim \text{with NaI(Tl)) and high charge yield})\)

Scintillation + ionization => background discrimination
Liquid Xenon

Ionization: recombination 15 ns

Electron recoils: good charge collection
Nuclear recoils: strong recombination

Scintillation: 175 nm
singlet: 3 ns, triplet: 27 ns
WIMP Recoil Spectrum in Xe

Xe $E_{\text{th}} = 16$ keVr gives 0.1 event/kg/day (30% of zero thresh. sig.)

Xe rate enhanced by high A, but low threshold necessary to avoid Form Factor suppression.
Modular design: 1t active Xe target distributed in an array of 10 3D position sensitive dual-phase (liquid/gas) XeTPCs, actively shielded by 5 cm LXe veto.

R&D for XENON funded by NSF. Testing concept feasibility/capabilities with various prototypes. Construction and underground deployment of a 10 kg detector (XENON10) within 2005, recently approved.

1st 100 kg module (XENON100) to be ready for data taking by end of 2007. After 3 months at a background < 1x10^-4 cts/keV/kg/day after rejection, the sensitivity of XENON-100 would be $\sigma \sim 2 \times 10^{-45}$ cm^2.
The XENON Collaboration

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XENON: Event Discrimination

n, WIMPs: slow nuclear recoils
⇒ Strong columnar recombination
⇒ Primary scintillation (S1) preserved, but
  ionization (S2) strongly suppressed

e-, γ: fast electron recoils
⇒ Weaker S1, stronger S2 signal

Ionization signal from nuclear recoils too small to be detected directly
⇒ Extract charges from liquid to gas
⇒ Detect proportional signal
⇒ Dual-phase detector

(S2/S1)electron >> (S2/S1)nuclear
⇒ event-by-event discrimination

Challenge: ultra-pure liquid and high drift field to preserve small electron signal (~20 electrons); efficient extraction into gas phase, efficient detection of small primary light signal (~200 photons) associated with 16 keV nuclear recoil energy
- PTR used to maintain stable temperature at LXe at $-95.1 \pm 0.05 \, ^\circ C$
- Array of 7 PMTs (Hamamatsu R9288) directly coupled to the Xe 5 cm long active volume
- Fast and slow digitizers for direct and proportional waveforms
- Diaphragm pump is used to circulate Xe gas at 5 l/min.
- Calibration with gamma, alpha and neutron sources
R&D Milestone: > 1m Electron Attenuation Length

XENON goal of 30 cm drift and high E-field to detect small charge signal from 16 keV Xe recoil requires extreme purity of the LXe target, with contaminants concentrations < 1 ppb O₂ equivalent.

=> Continuous circulation of xenon gas through high purification system

\[ Q(t) = Q(0) \exp\left(-t/\tau\right) \]
\[ \lambda = \nu \tau \]

![Diagram of purification system with electron lifetime graph showing ~1.2 kV/cm](Image)
Measurement of the Scintillation Yield

Efficiency = \frac{\text{Nuclear recoil scintillation}}{\text{Electron recoil scintillation}}

Measured at p-beam at Nevis/Columbia (together with Yale) with single-phase LiXe chamber \((p(t,^3\text{He})n)\) down to 10 keV \(E_{\text{recoil}}\)
\(E_n = 2.4 \text{ MeV} (<10\% \text{ spread})\)

Borated Polyethylene (30 cm)

Pb

\(L_1 = 60 \text{ cm}\)

LXe

\(L_2 = 50 \text{ cm}\)

\(\theta\)

BC501 A

7.5 cm x 7.5 cm
Measurement of the Scintillation Yield

- Light waveforms from LXe and BC501A were digitized for TOF and PSD.
- Time of flight between LXe and BC501A counters to resolve $\gamma$ and n ($2\text{ ns/cm}$) events.

- $^{57}\text{Co} - 122\text{keV}$
- LXe Light

- $\sigma = 8.7\%$
- 6 p.e./keV

- Xe Recoils 15 keV
- Xe Recoils 55 keV
Measurement of the Scintillation Yield

Measurement consistent with ICARUS and ZEPLIN
At 10 keV recoil energy the efficiency drops to ~ 0.13
Light yield does not change much with comparing to gamma, the field dependency is similar to

astro-ph/0503621
Measurement of the Ionization Yield

100 g Fiducial (ø4 cm x 2 cm thick) 2xø5 cm PMT (at Nevis Labs, together with Brown)

Number of electrons was measured with strong AmBe source

Light response: similar to previous measurements

1x10 n/sec AmBe source

Lead source

Liquid Xe

130 degrees

60 cm

BC501A (dia. 4inch x 4inch)
Measurement of the Ionization Yield

AmBe source: n-spectrum peaked at 4 MeV (+4.43 MeV gammas suppressed by 10 cm of Pb)  
\[ V_C = 4 \text{ kV/cm (max field probed), } V_A = 3.5 \text{ kV/cm} \]

Inelastic events: 40 keV (129-Xe*), 80 keV (131-Xe*)
Features in Energy Spectrum

**In AmBe spectrum:**
- Elastic NR in Xe
- Inelastic NR in Xe (129-Xe*, 131-Xe*), 40 keV, 80 keV
- Gammas from inelastic NR in Teflon ($^{19}$F), 110 keV, 200 keV
Features in Energy Spectrum

In calibration spectrum:
- 57-Co: 122 keV
- Xe activation lines: 236 keV ($^{129m}\text{Xe}$), 164 keV ($^{131m}\text{Xe}$)
  (the liquid Xe has been activated by exposure to AmBe for 10 days)
Ionization Yield of Xe Nuclear Recoils

Number of electrons does not depend much on electric field. Ionization density decreases as recoil energy is increasing.
Rejection Power by S2/S1

Rejection power

(84% acceptance window)
~95 % (with flat component)
>99% (by gaussian fit)

Flat component due to edge events
Non-uniform E-field
Charge trapped on Teflon

=> Improve with 3D detector
Measurement of the Charge/Light Yield at UF

3kg dual-phase detector at the University of Florida
- confirmation of Columbia results with larger chamber and R8520 (square) PMTs
- study field dependency at different recoils energies
- study yield as a function of Xe purity
Inner Chamber

**Teflon structure:** bottom plate, grid spacers, top plate, filler ring and mountings rods

**SS cathode, anode + gate grids:** 29 || 120 µ wires

**Al mounting spool** connected to the SS UHV can top plate

**4 R8520 Hamamatsu PMTs**
Gas Purification and Re-circulation System

Recirculation: diaphragm pump (5l/min)
Purification: high T SAES getter
n-experiment at UF Tandem

Measure the ionization + scintillation yield down to 10 keV nuclear recoils (+ study field dependence at various $E_R$)

Demonstrate $>95\%$ discrimination at 16 keV recoil energy
Material Screening at UF

New low-background, high-purity Ge detector (GATOR) at Soudan lab (in SOLO facility, operated together with Brown)
- 2 kg (100% efficient)
- FWHM = 1.14 keV at 122 keV,
- 2.06 keV at 1332 keV
- screen detector, shield components
- for U/Th, K, Co
- now background measurement

![Graph showing energy levels: 1173 keV, 1332 keV, 511 keV, 2506 keV]
Monte Carlo simulations of gamma calibrations ($^{133}$Ba, etc) and expected backgrounds of XENON10 at Gran Sasso (together with Brown, Columbia):

- Outer SS cryostat
- XENON10 MC geometry
- $^{133}$Ba calibration GEANT4 spectrum
Now testing XENON prototype at Nevis for underground operation

Moved from R9288 (Ø 2'') to R8520 (1'' square) to improve backgrounds and maximize x-y position information

Hamamatsu R8520
QE>20% at 178 nm
U/Th = 13/3 mBq
Rb-Cs-Sb photocathode
New Detector Construction/Testing Schedule

**XENON3**: running chamber with top PMTs (array of 21)
  - 21 top PMTs, 14 bottom PMTs: \( \varnothing 19 \text{ cm} + 11 \text{ cm} \) drift (9 kg total, 3 kg fiducial)
  - install bottom PMTs when next Hamamatsu batch arrives
  - radioactivity of tubes: \(< 3 \text{ mBq/tube U/Th/K}\)

**XENON10**: increase number of tubes
  - 46 top PMTs, 32 bottom PMTs: \( \varnothing 25 \text{ cm} + 15 \text{ cm} \) drift (21 kg total, 10 kg fiducial)

**Light collection**:
  - expect \( \sim 1 \text{ phe/keVee} \) (0.5 phe/keVr)
  - for XENON3/10

Array of 46 R8520 PMTs for x-y position
XENON10 at Gran Sasso

Install/commission by end of 2005
Start physics run in January 2006

Poly, 23 cm, 31 t
Poly, 30 cm, 2.2 t
Teflon
Low activity PMTs
Liquid xenon, ø18 cm
LiXe veto, 5 cm
Dark Matter Goals

XENON10:
- Sensitivity curve corresponds to $\sim 2$ dm events/10kg/month

XENON100:
- First 100 kg module, in GS in 2007/2008
- Sensitivity curve corresponds to $\sim 20$ dm events/100kg/year

XENON1t:
- 1 ton (10 x 100 kg modules), in GS in 2010-2015

Test a large part of the predicted parameter space

Discover WIMPs!
Conclusions

**XENON** - demonstration milestones achieved (various prototypes)
- measurement of scintillation yield down to 10 keVr with n-beam
- measurement of ionization yield of nuclear recoils with AmBe source
- confirm with larger chamber at n-beam

**XENON10**
- commissioning at LNGS end 2005
- start physics run in January 2006
- funding from NSF/DoE secured

**XENON10 design:**
- Top + bottom PMTs
- 15 cm drift at 3kV/cm => 50 kV HV system
- Conventional shield design (Pb/Poly), no muon veto for first phase

**GOALS:**
- 10kg: 5-10 x better limit than current CDMS after few months of running
- Demonstrate operation in low background environment
- Establish electron/nuclear recoil discrimination
- Refine understanding of backgrounds (in conjunction with MCs)
- Design XENON100
More slides
S2/S1 Ratio for Electrons and Alpha Recoils

Clear separation of two recoils
Scintillation Yield at Low Energies

Efficiency = \frac{\text{Nuclear recoil scintillation}}{\text{Electron recoil scintillation}}

- First measurements down to 10 keV recoil energies
- Measurements (> 40 keV) consistent with ICARUS and ZEPLIN

**XENON data**

supressed by electronic quenching
Distribution of S2/S1 in Each Energy Bin

Ratio of S2/S1:

\sim \text{factor 10 different between electron and nuclear recoil}

To establish rejection power:

84\% acceptance window
Event position reconstruction

GEANT4 MC simulation

Edge events can be rejected based on reconstructed position

Reconstructed event positions

10 keV nuclear recoil events near the detector edge
Sample Events from Xenon Detector (XeBaby)

XeBaby: 2-phase chamber response to neutrons (AmBe) and gammas (137Cs)
- 2 PMTs (bottom one in liquid, top one in gas)
- EC = 2.5 kV/cm, EA = 8.0 kV/cm
- ~ 30ns decay time of Xe excitation
- Max drift time: ~ 7.5 µs for 15 mm (~ 1µs shaping on slow digitizer)

Gamma event

Nuclear recoil event

Fast ADC
1ns/sample
500ns across plot

Slow ADC
200 ns/sample
1µs shaping
30µs across plot