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Liquid Xenon TPCs

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"LXe TPCs":

Are they really time projection chambers?Do they really project a track?Are they tracking devices at all?Can we really *see* tracks in liquid xenon??

Ranges of particles in liquid xenon:

1 MeV electron	$\sim 1 \text{mm}$
0.5 MeV electron	~0.5 mm
100 keV electron	\sim 50 μ m
10 keV electron	~0.5 μ m
10 keV nuclear recoil	\sim 0.5 μ m

Tracks of relativistic protons in liquid krypton



LKr emission streamer chamber with optical readout (ITEP)

Bolozdynya et al.,1980

Initial part of 1 MeV electron track in LXe (Monte Carlo)



Figure 2.6 The initial part of 1 MeV electron track in LXe with energy depositions shown as bubbles. The area of each bubble is proportional to local energy deposition; the scale (100 eV) is shown as a separated bubble on the left. The electron propagates from left to right. Simulated with the PENELOPE code.

Chepel and Araújo, JINST 8(2013)R04001

Low energy electron tracks in LXe (MC)



Figure 2.7 Examples of low energy electron tracks in LXe. A circle of 4.5 μ m radius corresponds to the mean thermalization distance according to Mozumder, 1995b. The tracks are simulated with PENELOPE. At the right, an example of energy deposition pattern is shown. The area of each bubble is proportional to local energy deposition; the scale (100 eV) is shown as a separated bubble.

Chepel and Araújo, JINST 8(2013)R0400

Low energy nuclear recoil tracks in LXe (MC)

1 keV

10 keV



Figure 2.8 Examples of xenon recoil tracks in LXe for 1 keV (left) and 10 keV (right) initial energy. Each dot represents an energy exchange location due to either the primary or secondary recoils. An arrow indicates the initial position and direction on the primary recoil. Simulated with the SRIM code.

Chepel and Araújo, JINST 8(2013)R04001

Gas vs Liquid

Concerns in GAS

Drift velocity

Diffusion

Electron trapping by impuritties

Stable amplification at the readout

plane



Concerns in LIQUID

Drift velocity



ELECTRON TRAPPING BY IMPURITIES

Stable amplification – NOT POSSIBLE IN LIQUID

Can fill up the chamber only partially

- → two-phase liquid/gas
- \rightarrow try amplification in the gas phase

New issues:

-- electron transfer through the liquid surface

(electron emission)

- -- recombination
 - (e.g., α -particles: ~100% extraction in gas ~ few % in liquid)



LXeGRIT – Liquid xenon Compton imaging telescope (TPC)



SAMPLE

SAMPLE

LXePET – another example of LXe ionization drift chamber (~TPC)

Q(t)

Е

⊕i⊕→

γ



Chepel, Nucl. Tracks. Rad. Meas. 21 (1993) 47





Solovov e.a., NIMA 477 (2002) 184

Fun – drift chamber with full 3D time encoding



V. Chepel, PhD Thesis, 1988

LXe drift chamber with electroluminescence in liquid



Gushchin e.a., Instr. Exp. Tech. 3 (1982) 49

First prototype of LXe WIMP detector – single phase, electroluminescence in the liquid

S. Suzuki et al., NIMA327 (1993) 203



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. 3. Variations of the scintillation intensity as a function of V_{a-c} for (a) 122 keV gamma rays and (b) 5.5 MeV alpha particles. The scintillation intensities are normalized to the value of primary scintillation at 0 V for each source.



Fig. 4. A typical energy spectrum for 122 keV gamma rays from primary scintillation and secondary scintillation at V_{a-c} = 3.5 kV using 4.5 µm wires.



Fig. 2. Scinillation signals for 3 μ m wires at $V_{a-c} = 3.0$ kV; (a) 5.5 MeV alpha from ²⁴¹Am, (b) 122 keV gamma rays from ⁵⁷Co.

45 wires, 4 μ m diameter

Charge amplification in liquid xenon – exists but not good enough



M.Miyajima *e.a.*, NIM 143(1976)403

Muller e.a., PRL 27(1971)532

Amplification in liquid xenon – how it looks like?





LXe:

Minimum ionization energy – **9.2 eV** Minimum excitation energy – **8.15 eV**

Electron emission from LXe -- experiment

Relative extraction efficiency



High fields are required at the liquid surface in LXe for effective emission

What happens at the surface?



Shape of the potential barrier at the liquid-vapour interface in argon (solid line). Dotted line shows the effect of the electric field of $E_l = 4 \text{ kV/cm}$ perpendicular to the liquid surface; dashed line – the effect of the image potential.

→ $V_0 = -0.165 \text{ eV}$ in LAr ($\approx 23 \times k_B T$) $V_0 = -0.64 \text{ eV}$ in LXe ($\approx 46 \times k_B T$) (potential energy of electron in the liquid with respect to vacuum)

Delayed emission from LAr but not from LXe



Undersurface trapping time versus

field in the liquid

Signal waveform with GEM in gas



Borghesani et al., PLA 149(1990)481

Bondar et al., JINST 4(2009)P09013

Two-phase emission electroluminescence detector

The first two-phase emission detector operated on the principles of modern LXe WIMP detectors – gamma-camera for medical radioisotope imaging







V.Egorov e.a., NIM 205 (1983) 373

General concept of a two-phase LXe detector for WIMP search



ZEPLIN-II – the first two-phase emission detector for WIMPs operated in the world





Deep PTFE chamber containing 31 kg of LXe Read by 7 photomultiplier (13 cm diameter) Completed data taking in 2007.

Alner et al., 2007

ZEPLIN-III – betting on strong field







Copper chamber containing 12 kg of LXe (active) Strong field configuration (3.9 kV/cm in liquid) Read by 31 photomultiplier (2") Completed data taking in 2008 (first run); 2010/11 (scond run after upgrade)

Akimov et al., 2007

Single electron signal and event position reconstruction

S2 from single electrons emitted from the liquid in ZEPLIN-III



Santos et al., JHEP 2011(2011)1

Important step in position reconstruction – adjustment of light response function of each PMT (unknown) – ZEPLIN-III



Solovov et al., 2012

XENON-10 – low drift but strong emission fields

2006-2007



Redrawn from Aprile et al., AP 34(2011)679.



14 kg of LXe 15 cm drift Extraction field >> drift field PMTs on top and bottom (89 square 1"x1") Electron lifetime 2.2 ms Diving bell

XENON-100 – increasing the mass

2010-2014



62 kg of LXe inside the active volume

LXe scintillation veto aroung the active volume

Drift field + strong extraction field

178 PMTs total (64 for veto)



LUX350 (Large Undeground Xenon experiment)



2014-2016



Т

[244] LUX collaboration, D.S. Akerib, X. Bai, S. Bedikian, E. Bernard, A. Bernstein, A. Bolozdynya et al., The large underground xenon (LUX) experiment, arXiv:1211.3788.

300 kg active LXe Titanium double wall cryostat 61 x 2 PMTs Thermosyphon for Xe condensing Severe charging of PTFE was observed

XENON-1T and XENONnT to come



From Aprile et al., Eur. Phys. J. C, 77(2017)881

The same cryostat can be used for XENONnT



Just decommisionned It is currently the largest operated LXe detector 2 tons of active LXe, (3.2t total) (4t and 8t for XENONnT) 240 3" PMTs

The first observation of 2ν double electron capture in ¹²⁴Xe (~ 10^{22} years)

Aprile et al., Nature 568 (2019) 532

LZ (LUX + ZEPLIN) under construction



neutron calibration (6). From Akerib *et al.*, NIMA953(2020)163047 **Direct supply of HV to the cathode (up to 100kV)** Drift field of ~300 V/cm is planned ~500 PMTs

LXe skin veto (+93 PMTs)

PandaX-I and PandaX-II detectors

Chinese project, operates in the world deepest underground laboratory in Jinping CJPL (6500 mwe)



PandaX-I -- demo
120 kg of active LXe
Drift field ~1 kV/cm
Extraction field 4.2 kV/cm (~0.9 efficiency)
Short data taking run with 37kg of fiducial LXe
in 2014

Cao et al., Sci. China Phys. Mech. Astron. 27(2014)1476.



PandaX-II -- scaled in height by x2 580 kg of active LXe Drift field ~400 V/cm Extraction field 3 kV/cm (~0.5 efficiency) LXe skin veto Electron life time ~0.8 ms Short data taking runs in 2015-2017

PandaX-4T (in progress)



Zhang et al., Sci. China Phys. Mech. Astron. 62(2019)31011



Scaled up version of PandaX-II Design similar to XENONnT and LZ 4t active mass (6t total) Drift field ~400 V/cm Extraction field ~3 kV/cm (in liquid)

RED-100 (Russian Emission Detector)

Aim – observation of coherent elastic scattering of neutrinos off nucleus (CNS)



2. Electron shutter (G2) to prevent S2 from muons

Akimov *et al.*, Instrum. Exp. Tech. 60(2017)175 Akimov *et al.*, JINST 15(2020)P02020

Dreams...

Electron multiplication with microstructures in LXe

Microstrip plate



Microgap chamber



Fig. 1. Schematic drawing of the microgap plate: $P = 200 \ \mu m$, $W(anode) = 9 \ \mu m$ and $S(insulator) = 17 \ \mu m$.

We attempted, too

Unstable, discharges, no gain could be measured

Lopes and Chepel, in Electronic Exciitations in Liquefied Rare Gases, Am. Sci. Publ., Eds. W.F.Schmidt and E.Illenberger, 2005, p.331

We used in LXe μm anode strip width μm cathode strips μm pitch

Gain of 10-15 has been obtained

Policarpo et al., NIMA365(1995)568

Electron multiplication in two-phase Xe

GEMs and THGEMs



Mcromegas, 50 μm

Lightfoot et al., NIMA 554(2005)266

Gain of ~500 in Xe+2%CH₄ Disappeared after 10-30 min of operation

Probably, Xe condensation in the structure. Condensation is favoured in a strong field (~140 kV/cm in that experiment) by the high polarizability of Xe atoms.

from Buzulutskov, JINST 7(2012)C02025

3GEM – tripple GEM (Bondar et al., NIMA556(2006)273) SGEM – single GEM (Balau et al., NIMA598(2009)126) 2THGEM – double THGEM (Bondar et al., JINST 6(2011)P07008)

> Maximum gain with 3GEM was only ~200 in Xe but ~3000 in Ar

Electron multiplication with microstructures GEM





Xenon condensation in the holes, a small

Electron multiplication with microstructures in LXe

Microtips

LXe – tested in our group



E ~10⁷ V/cm Multiplication region $\leq 1 \mu$ m

Unstable, no gain could be measured

(unpublished)

Lopes and Chepel, in Electronic Exciitations in Liquefied Rare Gases, Am. Sci. Publ., Eds. W.F.Schmidt and E.Illenberger, 2005, p.331

LAr dopped with Xe

Kim et al., IEEE TNS-50(2003)1073; NIMA535(2004)

Negative result, too Unstable, discharges

Hypothetically, bubble formation near the tips

Electron multiplication with microstructures

P. Majewski, 2006

H. Wang, 2006



A microstructure

Revisiting electroluminescence on thin wires in LXe

Proportional EL gain vs applied voltage to a 10 μ m anode wire between two cathode grids



Aprile et al., JINST 9(2014)P11012



662 keV γ -rays



Electroluminescence in GEM holes in two-phase Xe





Local dual-phase TPC – Liquid Hole Multiplier (LHM)

Electroluminescence in bubbles



LHM (Liquid Hole Multiplier) – "local dual-phase TPC" – the concept

from Erdal *et al.*, JINST 15(2020)C04002

