Xenon TPC with High-Purity Germanium like Energy Resolution

Counting Electrons in a TPC using Negative Ion Drift

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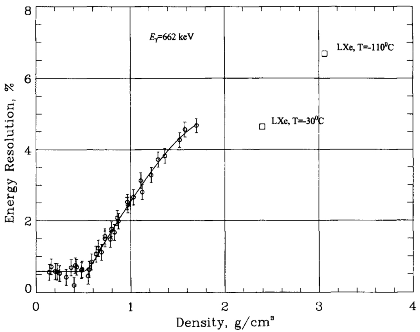
Intensity Frontier Neutrino Subgroup Workshop 2013

Intrinsic Energy Resolution of Gaseous Xenon is Excellent, Significantly Better than Liquid Xenon

A. Bolotnikov, B. Ramsey / Nucl. Instr. and Meth. in Phys. Res. A 396 (1997) 360–370



- Energy resolution improves separation of $0\nu2\beta$ from $2\nu2\beta$ and other bkgs.
- $\frac{\delta E}{E} = 2.35\sqrt{\frac{F}{N_e}}$
- Energy resolution xenon gas: **0.27% FWHM, 0.11%σ**

  (W=21.9eV, Q=2.48MeV, F=0.15)
- Current state of the art for liquid: $\approx$ 3.9% FWHM or 1.67%σ at the Q value.

- Ion chamber results with amplifier noise subtracted
- At 662keV intrinsic energy resolution is 0.52% FWHM

Avalanche Gain Degrades Energy Resolution

- Gas gain(Townsend avalanches) reduces preamp noise contribution , but...
- Avalanche fluctuations are large in a low fano factor gas. $\frac{\delta E}{E} = 2.35\sqrt{\frac{F+f}{N_e}}$
- Typical F = 0.15, f=0.7
- Even with all electrons available, fluctuations degrade resolution
- Better calibration or construction does not help!

NUCLEAR INSTRUMENTS AND METHODS 89 (1970) 155–165; © NORTH-HOLLAND PUBLISHING CO.

STATISTICS OF ELECTRON AVALANCHES AND ULTIMATE RESOLUTION OF PROPORTIONAL COUNTERS

G. D. ALKHAZOV

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Received 27 July 1970

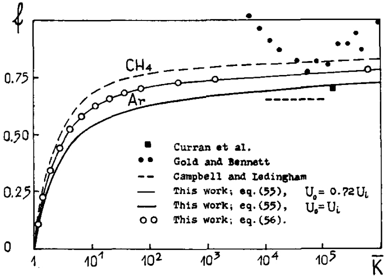

Fig. 6. The relative variance of gas amplification as a function of $\bar{K}$ in argon and methane filled proportional counters for $pr_a = 1.9$ torr·cm. Experimental data are taken from works of Curran et al.[5] (50% Ar + 50% CH_4, $pr_a = 3.8$ torr·cm); Gold and Bennet[16] (95% CH_4 + 5% N_2, $pr_a = 0.51$ torr·cm) and Campbell and Ledingham[17] (75% Ar + 25% C_3H_8, $pr_a = 0.95$ torr·cm).

Negative Ions...that's for Controlling Diffusion.

What does that have to do with Energy Resolution?

ELSEVIER Nuclear Instruments and Methods in Physics Research A 440 (2000) 355–359

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

www.elsevier.nl/locate/nima

Suppressing drift chamber diffusion without magnetic field

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- Introduces negative ion drift and focuses on lower diffusion
- *"will allow a negative ion drift chamber to function as a time expansion chamber"*

3rd Symposium on Large TPCs for Low Energy Rare Event Detection IOP Publishing
Journal of Physics: Conference Series **65** (2007) 012003 doi:10.1088/1742-6596/65/1/012003

A negative-ion TPC with ultra-high energy resolution for 0-ν double beta decay search in ^{136}Xe

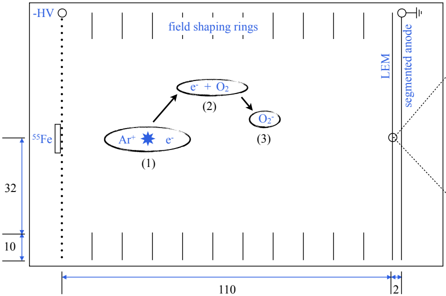
David R Nygren
Lawrence Berkeley National laboratory, 1 Cyclotron Road, Berkeley, CA 94720

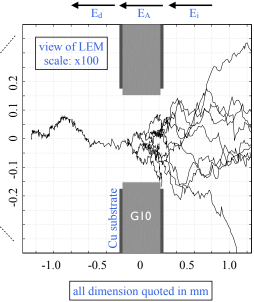
- Expands on the notion of better energy resolution and lays the ground work for the topic of this talk.

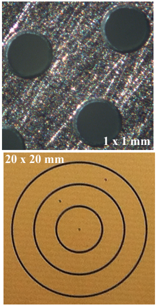
Demonstration of Electron Counting with Ion Drift

Capture and drift of electrons on oxygen ions

Stripping and amplification of each electron with a LEM

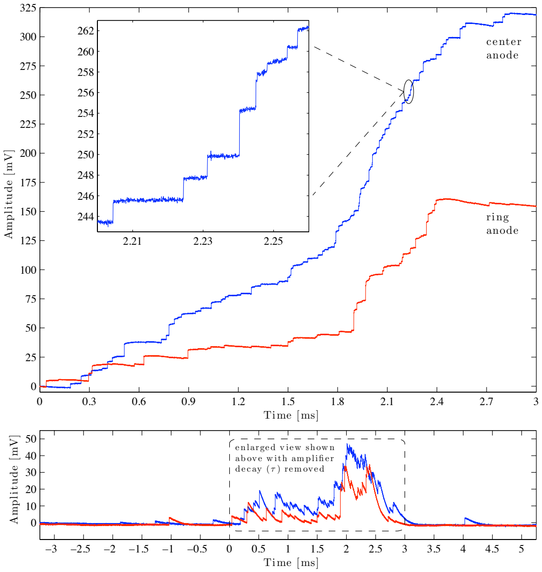






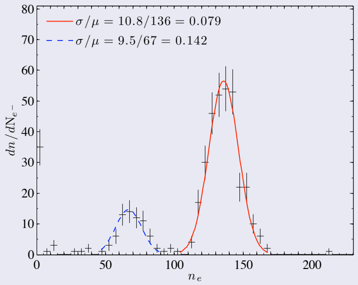
Argon bulk gas with oxygen capture agent
Published: NIM A 686 (2012) 106-111

Example Event from Experiment

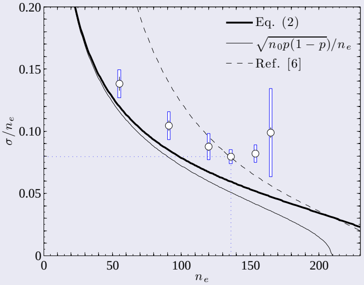


Results so far...

^{55}Fe spectrum from **counting** electrons



Energy Resolution vs. Collected Electrons



- First demonstration using neg. ions to improve energy resolution
- Results are in rough agreement with expectations

Final Thoughts

Negative Ions appear to be a promising path forward if a appropriate capture agent can be identified, need to demonstrate higher pressure

- There are a number of possibilities for capture agents
- Simulations indicate that MicroMegas might work better, still to be tested
- A ton of gaseous xenon at at 10atm is only a few meters in size
- Negative ion readout would be a low mass, low cost, radioactively pure structure such as a LEM or MicroMegas (no PMTs)
- Readout electronics are just scalers counting ions per channel
- Event topology preserved by low diffusion
- This method should be considered when thinking about the multi-ton scale $0\nu2\beta$ experiments

Backup

$0\nu2\beta$ in a High-Pressure Xenon TPC

- The gas phase TPC provides tracking and energy resolution
- The tracking is useful in background rejection as demonstrated with the Gotthard TPC
- $1.6x10^{25}\ {}^{136}Xe \approx 3.6kg$
- 207liter 5bar
- Energy resolution was not optimal, $\approx$8%FWHM (extrapolated to 2.48MeV)

VOLUME 67, NUMBER 10 PHYSICAL REVIEW LETTERS 2 SEPTEMBER 1991

New Limit on Neutrinoless Double β Decay in ^{136}Xe with a Time Projection Chamber

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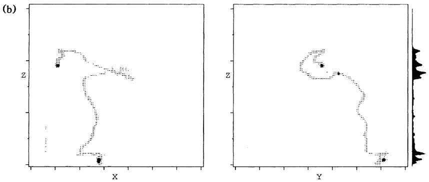
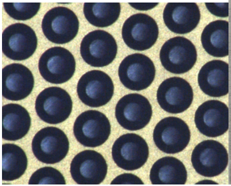
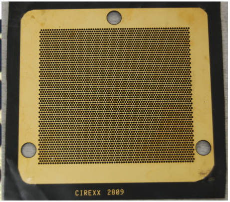


FIG. 2. Typical tracks recorded by the TPC with 5 atm of xenon. (a) Single electron; (b) two-electron candidate event; and (c) β decay followed by emission of an α particle. In (a)–(c) the full range is 60 cm for both X and Y, while the Z calibration is 10.9 cm per unit.

Why LEMs

- Easy to build and work with
- Cheap to scale up
- Can match holes to pads to prevent charge sharing





0.3mm holes, 0.16mm isolate

C. Shalem et al. / Nuclear Instruments and Methods in Physics Research A 558 (2006) 475–489

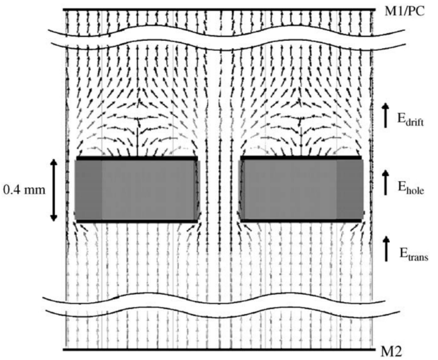


Fig. 3. Electric field map in THGEM#9 (Table 1) calculated by MAXWELL for $\Delta V_{THGEM} = 2\,kV$, $E_{drift} = 0.1\,kV/cm$ and $E_{trans} = 3\,kV/cm$; the latter are set by the potentials on meshes M1 (or photocathode) and M2. The calculated field E_{hole} within the holes varies between 10–40 kV/cm.

What's Wrong with Proportional Avalanche

Detector Performance Issues

- Space charge and pile up
- Gain variation across detector
- Amplifier noise
- Recombination and electronegative contaminates

Intrinsic Avalanche Fluctuations

- Avalanche fluctuations are large in a low fano factor gas.

$$\frac{\delta E}{E} = 2.35\sqrt{\frac{F+f}{N_e}}$$

- Typical F = 0.15, f=0.7
- Better calibration or construction does not help!

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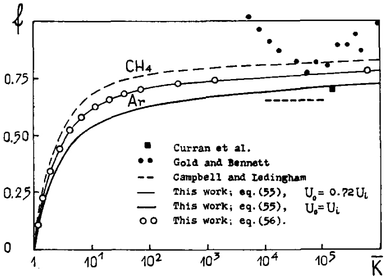

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Why not an Ion Chamber TPC

Single Pad Ion Chamber

- No gain and therefore no avalanche fluctuations.
- Very good amplifiers can get to of order 40e rms noise.
- Close to intrinsic energy resolution is possible (e.g. Bolotnikov)

Multi-Pad Ion Chamber (TPC with no gain)

- A segmented ion chamber with one amplifier per pad.
- Large system of 1000's of amplifiers, generously assume 60e rms.
- For good tracking and collecting all of the charge assume 150(50) voxels for each track.
- The resulting amplifier noise would be about 1040(600)e rms which corresponds to about 2.1(1.2)% FWHM
- This solution is 8(4.5) times worse than the intrinsic fluctuations.

Counting Avalanches Initiated by Individual Charges is an Alternative (still electron drift)

Time Expansion Chamber

- Purpose: to improve resolution of particle in relativistic rise
- Count clusters of charge along the track
- Works by reducing the drift field to slow the charge drift
- Avalanche effects are thresholded away.
- Free electron lifetimes are probably too short for a large, slow drift xenon TPC.

IEEE Transactions on Nuclear Science, Vol. NS-26, No. 1, February 1979

THE TIME EXPANSION CHAMBER AND
SINGLE IONIZATION CLUSTER MEASUREMENT*

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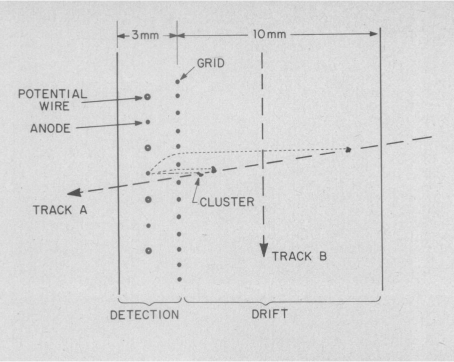
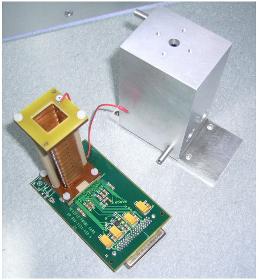
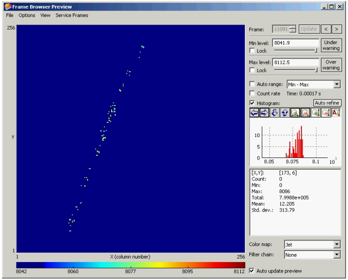


The Saclay “Digital TPC”

- Uses MediPix (2D) or TimePix(3D) chip
- 65,536 pixes, 55μm on a side, 16x14 mm overall dimensions
- 150ns peaking time preamp/shaper, 90e rms noise
- 3000 electron threshold, digital noise feedback
- Images individual electrons – Delta rays can be resolved
- Simple threshold readout, detector effects minimized
- Better energy resolution?
- Too small?

Pictures from http://irfu.cea.fr/





The Effect of Losing Some of the Charges

From Nygren's Paper...

"All loss mechanisms such as columnar recombination, unreleased electrons, finite electronic threshold, pulse pile -up, gain fluctuations, failure of ions to enter the amplification channels, charge sharing between pixels2, etc, can then be included in one loss parameter η."
And the effect on resolution is mild.

Assuming the primary fluctuations are independent of subsequent loss (η), one can derive :

$$\frac{\delta E}{E} = 2.35\sqrt{\frac{F+\eta}{N_e}}/(1-\eta)$$

Example

If $F = \eta = 0.15$ this only increases the resolution by $\frac{\sqrt{2}}{.85} \approx 1.66$
That is, the 0.27% FWHM would increase to 0.45% FWHM

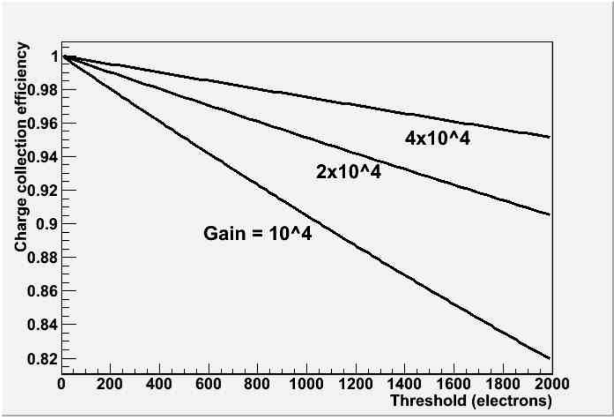
Loss of Charges in Pile-up

The concentration of capture agent would be tuned to provide a "ribbon" of charge extended in the drift direction. The width would be selected to provide reasonable tracking and maintain low pile up.

- Assume
  - 1mm ribbon thickness
  - 3.2m/s drift speed
  - All 115,300 electrons fall on 20 pads
  - Poisson arrival statistics with mean from above assumptions (18.4 ions/μs)
- 10ns time resolution $->$ 1.5% loss
- 20ns time resolution $->$ 5.4% loss

Loss of Charges in Amplification

Assume simple case of f=1 for the electron avalanche.
At reasonable gain and threshold the loss is small.



The probability for charge release from the ions to start the avalanche is an unknown right now

Capture Agents

- CS2 and Nitromethane have been shown to work at low pressure
- The have capture length of order 100μm to maintain spacial resolution
- For this effort we can allow capture lengths of order mm
- At higher pressure the obtainable E/p is more constrained and the mean free path is smaller
- Perhaps electron affinity is the place to start in screening candidates
- Just above thermal is probably what we need. (0.1-.4eV)

NIST web site, about 100 compounds (0.1 to .5 eV)

Electron Affinity	Compound
0.024,0.22	N2O
0.2, 0.11	CH3I
0.334	Acetophenone
0.4	Trichloroethylene
0.4	R-12
0.44	O2
0.46	SF6
0.47	C2H2
0.486	Nitromethane
0.6, 0.9	CS2

The Negative Ion TPC

The TPC would have..

- High pressure (20-50 atm) gas
- Dimensions of order few meters
- Use negative ion drift as a means to slow the charge drift.

Advantages

- Large scale structures can be built.
- Cheap construction compared to PMTs
- Far less mass at the edge of the sensitive volume.
- Amplifier noise and avalanche statistics only enter 2nd order
- Full ADC resolution is not needed. Simple low-cost low-power electronics
- Low diffusion maintains good tracking