Optimal Detectors for both WIMP & 0-ν $\beta\beta$ decay searches:

High-pressure ^{136}Xe Gas TPC

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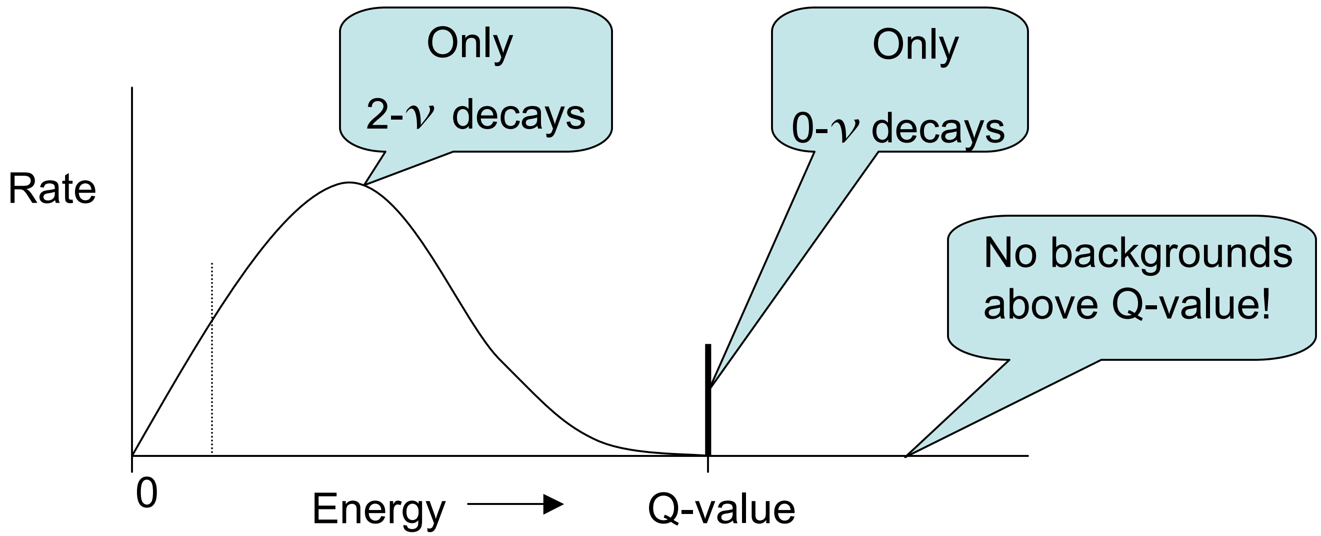
Double beta decay

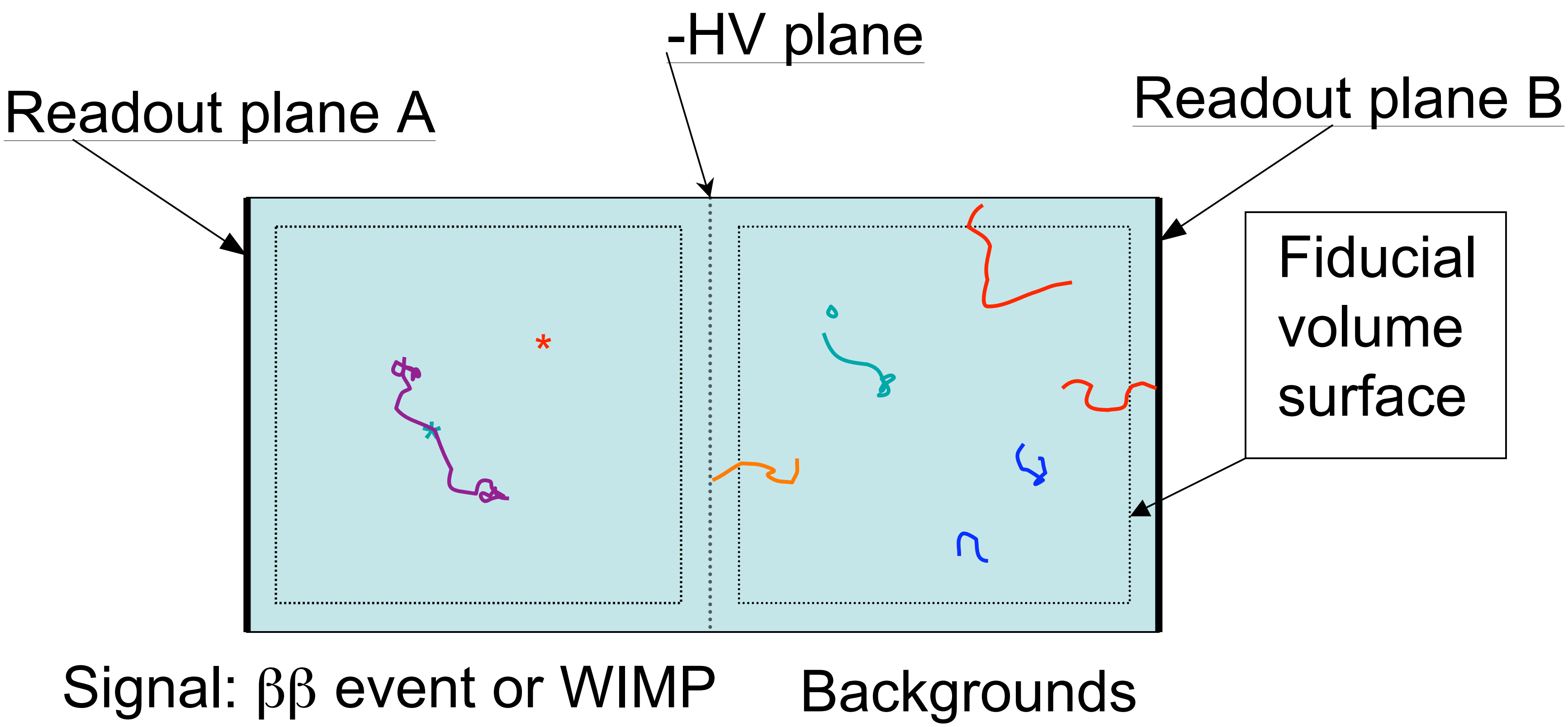


The ideal result we seek is a spectrum of all $\beta\beta$ events, with negligible or very small backgrounds.

TPC: Basic Advantages...

- Fiducial volume surface:
  - Single, continuous, fully active, variable,...
  - 100% rejection of charged particles (surfaces)
  - but: TPC needs a t_0 to place event in z
- Tracking:
  - Available in gas phase only
  - Topological rejection of single electron events

TPC Signal & Backgrounds



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Energy resolution ??

Two questions

What is the best energy resolution that can be obtained with a

high-pressure xenon gas TPC

- in principle?
- in **practice?**

"Intrinsic" Energy Resolution for Ionization at ^{136}Xe Q-value

Q-value of ^{136}Xe = 2480 KeV

W = ΔE per ion/electron pair = 21.9 eV (depends on E-field)

N = number of ion pairs = Q/W = 2.48 x 10^6 eV/22 eV = **~113,000**

σ_N **= (FN)$^{1/2}$** **~130** electrons rms @ 2480 keV

F = 0.13 - 0.17 for xenon gas; take **F = 0.15**

$\delta E/E = 2.35 \times (FW/Q)^{1/2}$

Answer to question #1:

$\delta E/E$ **~2.8 x 10^{-3}** FWHM @ 2480 keV

(xenon gas - intrinsic ionization fluctuations only)

Xenon: Strong dependence of energy partitioning on density!

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

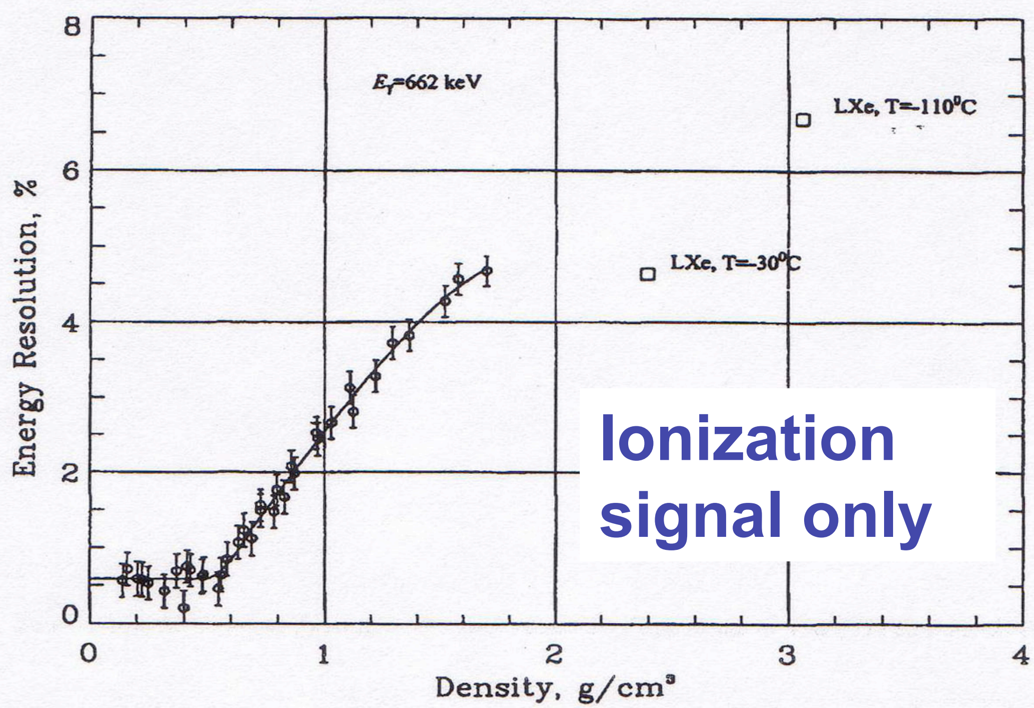


Fig. 5. Density dependencies of the intrinsic energy resolution (%FWHM) measured for 662 keV gamma-rays.

For ρ >0.55 g/cm^3, energy resolution deteriorates rapidly

What's happening at densities $\rho > 0.55\ g/cm^3$?

Two phases of xenon coexist (fog, lace,...)

- High atomic density+ ionization density

  $\Rightarrow$ sites of complete recombination,

  energy is returned as scintillation & heat
- Landau: $\Rightarrow$ large dE/dx fluctuations

  $\Rightarrow$ non-Gaussian partition of energy

{Scintillation $\Leftrightarrow$ Ionization} *(+ HEAT...)*

Impact for WIMP Search

Scintillation (S_1) & Ionization (S_2) are signals that can be used to reject electron recoils

But:

LXe: S_2/S_1 fluctuations anomalously large

Strong anti-correlations observed for e-recoils

HPXe: S_2/S_1 fluctuations are normal

Maybe,... HPXe is better (...much better) ??

But: S_2/S_1 ratio in HPXe is not yet well-measured

Energy Resolution (β particles) in Xenon Gas Detectors

- Intrinsic fluctuations
  - Fano factor (partition of energy): small for $\rho < 0.55$ g/cm^3
- Loss of signal (primary):
  - Recombination, quenching by molecular additives (heat)
- Loss of signal (secondary):
  - Capture by grids or electronegative impurities
- Gain process fluctuations:
  - Avalanche charge gain fluctuations are large
- Gain process stability:
  - Positive ion effects, density and mix sensitivity,...
- Long tracks $\Rightarrow$ extended signals
  - Baseline shifts, electronic non-linearities, wall effect,...

Generalization

- If fluctuations are uncorrelated, then*

  $\sigma_N = ((F + L + G)N)^{1/2}$

  F = Fano factor = 0.15

  L = loss of primary ionization

  G = fluctuations & noise in gain process

  Goal: Keep L and G smaller than F

  Is this possible ??

*D. Nygren, *Nucl. Inst. & Meth.* **A 581** (2007) 632

Loss of signal

As long as L << F, losses without correlations* to F & G, *e.g.,* capture on grids, are forgiving:

- For L = 0.05 $\delta E/E$ ~3 x 10^{-3} FWHM @ 2480 keV
- For TPC, I expect that L < 1%, insignificant loss

Set L = 0

*Losses to electronegative impurities are highly correlated to drift distance and each event must receive a specific correction

Avalanche Charge Gain

Early fluctuations determine outcome

- for wire ($E \sim 1/r$) $0.6 < G < 0.9$ *
- $\sigma_N = ((0.15 + 0.8)N)^{1/2} = 328$
- **$\delta E/E$ = ~7.0 x 10^{-3}** FWHM

  Lost all benefit from the small Fano factor

Micromegas, GEM, LEM,... may do better, but

Serious challenges to maintain gain calibration

*Alkhazov G D *Nucl. Inst. & Meth.* **89** (1970) 155 (for cylindrical proportional counters)

What is this factor “G”?

- In a very real sense:

  G is a measure of the precision with which a **single** electron can be counted.
- Consider next:
  - Ionization Imaging TPC - no gas gain!
  - Negative Ion TPC - count each electron!
  - Electro-Luminescent TPC ?

"Ionization Imaging" TPC

No avalanche gain

- dn/dx ~ 1 fC/cm: ⇒ ~6,000 (electron/ion pairs)/cm
- gridless "naked" pixel plane (~5 mm pads)
- **very high operational stability**

But, electronic noise must be added!

- σ = 50 e^- rms/pixel
- $G = \sigma^2/n_e = 50^2/3000 = \sim 0.8$
- $\delta E/E$ ~ **7×10^{-3} FWHM**
- **But: complex signals, many channels, waveform capture, new,... R&D + E needed**

“Negative Ion” TPC

“Counting mode” = digital readout, (F + L)

- Electron capture on electronegative molecule
- Very slow drift to readout plane;
- Strip electron in high field (?), generate avalanche
- Count each “ion” as a separate pulse:
  - Ion diffusion much smaller than electron diffusion
  - Avalanche fluctuations and noise enter only as L
  - Pileup and other losses: L~ 0.04 ? uncorrelated?
  - **$\delta E/E$ = ~3 x 10^{-3} FWHM ?**
- Appealing, but will it work in HPXe?...

Electro-Luminescence (EL)

(aka Proportional Scintillation)

- Electrons drift to high field region
- Electrons gain energy, excite xenon, lose energy
- Xenon generates UV, process starts over again
- Linear, not exponential growth of signal
- Photon generation up to ~1000/e, but no ionization
- Sensitivity to density much smaller than avalanche
- Early history irrelevant, so $\Rightarrow$ **Fluctuations small**?
- **Maybe… G ~ F?**

H. E. Palmer & L. A. Braby

Nucl. Inst. & Meth. **116** (1974) 587-589

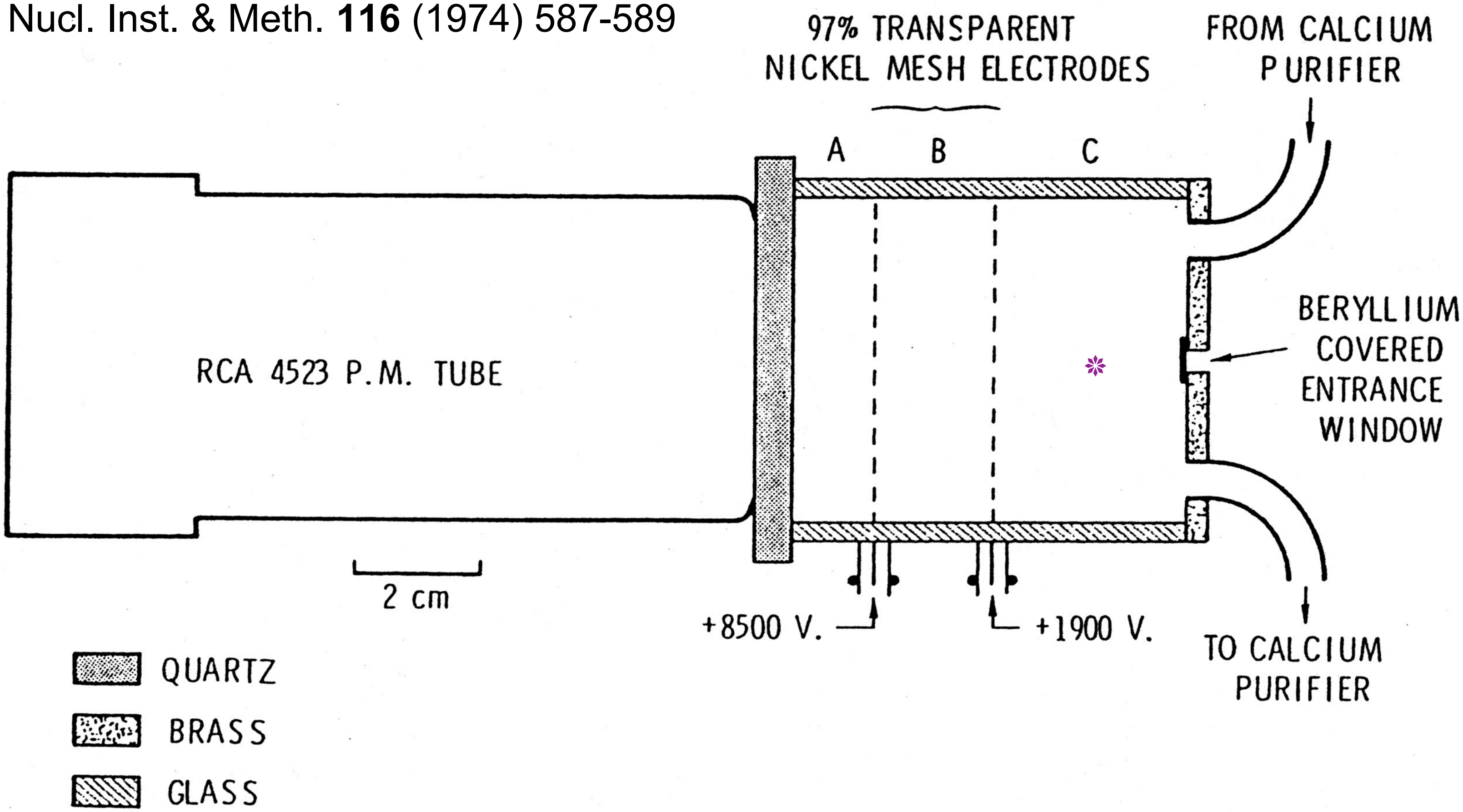


Fig. 1. Sketch of 5 cm diameter parallel plate gas scintillation proportional counter.

^{55}Fe Resolution: **8.4%** FWHM

From this spectrum: **G ~0.19**

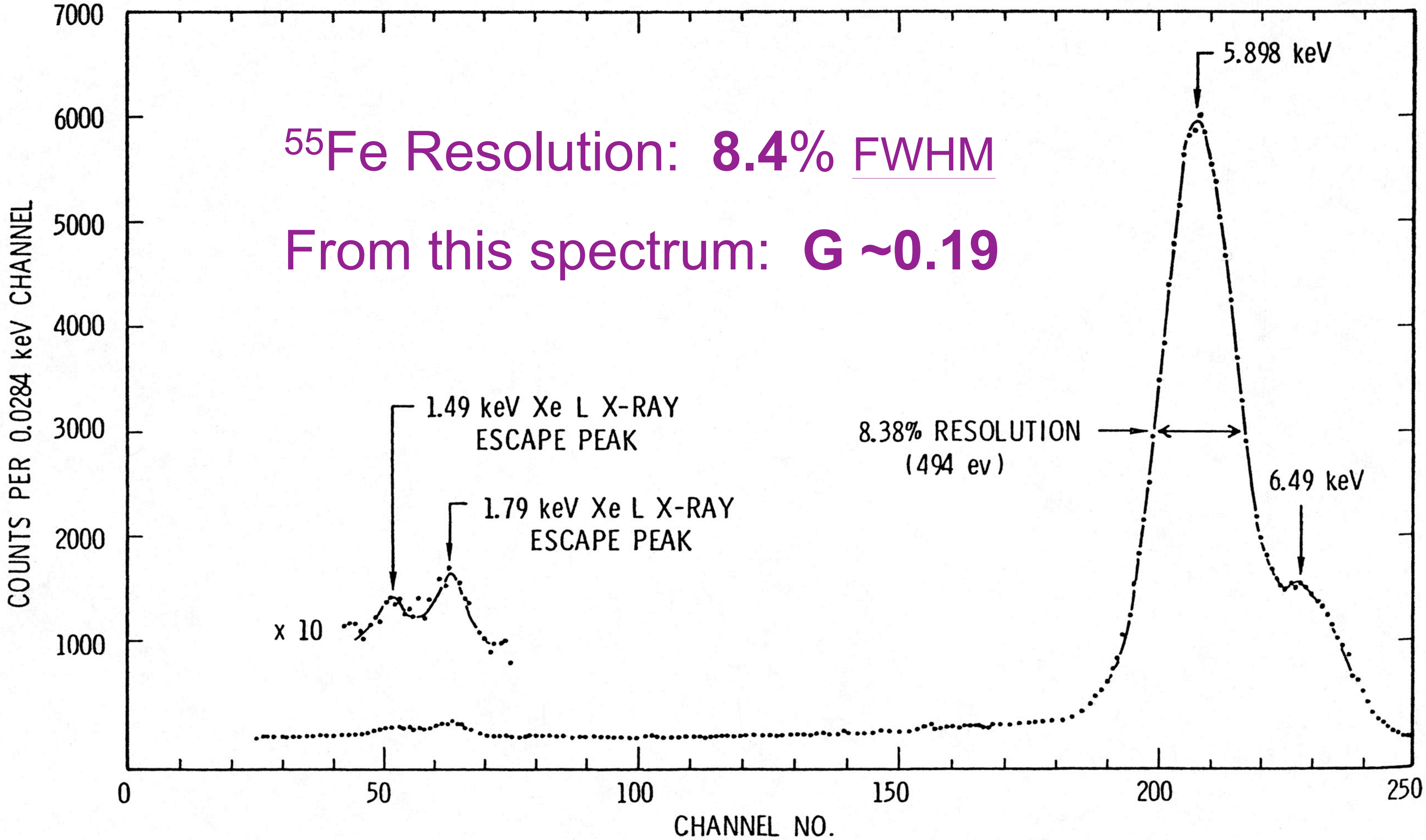


Fig. 2. Pulse-height spectra of an ^{55}Fe source from a parallel plate gas scintillation proportional counter.

Fluctuations in EL

G for EL contains three terms:

1. Fluctuations in n_{uv} (UV photons per e): $\sigma_{uv} = K/\sqrt{n_{uv}}$
   - $n_{uv} \sim HV/E_\gamma = 6600/10$ eV **~ 660** **K < 1**
2. Fluctuations in n_{pe} (detected photons/e): $\sigma_{pe} = 1/\sqrt{n_{pe}}$
   - n_{pe} ~ solid angle x QE x n_{uv} x 0.5 **= 0.1 x 0.25 x 660 x 0.5 ~ 8**
3. Fluctuations in PMT single PE response: $\sigma_{pmt} \sim 0.6$

$$G = \sigma^2 = K/(n_{uv}) + (1 + \sigma^2_{pmt})/n_{pe}) \sim 0.17$$

Assume F + G **=** 0.3

Ideal energy resolution (σ^2 = **0.3** x E/W):

δE/E ~4 x 10^{-3} FWHM @ 2480keV

Electro-Luminescent Readout

- To keep $G < F = 0.15$, then:

$$n_{pe} > 10\text{/electron}$$

$$\Rightarrow \Sigma n_{pe} > \mathbf{1{,}000{,}000} \text{ @ 2480 keV !}$$

More would be better!

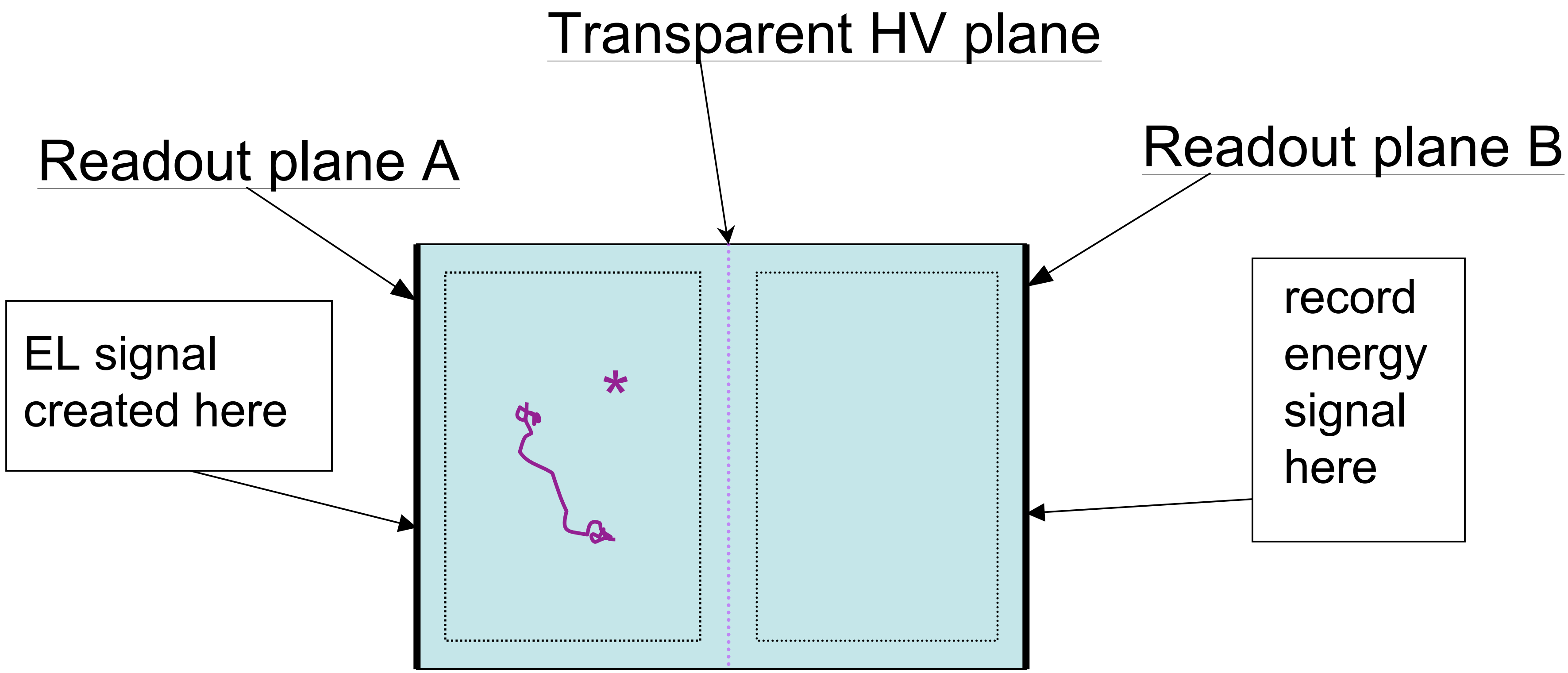
Electro-Luminescent Readout

How to detect this much signal?

Answer: Use both TPC readout planes

- If EL signal is generated in plane “A”
- do “tracking” in Plane “A”
- but: record “energy” in plane “B”

TPC Signal



Signal: ββ event or WIMP

Pure xenon + EL: energy

- Drift velocity: ~ 1 mm/μs (slow!)
- ββ events occur over 10's of μs
- Hundreds of PMTs contribute to Σn_{pe}
- n_{pe} per PMT in plane B: ~10 per μs
  - no dynamic range problem in plane B
  - gentle cosine effect with solid angle

Energy measurement in plane B: OK

Pure xenon + EL: tracking

n_{pe} per μs per PMT in plane A: ~2000

- no saturation problem in plane A
- Track-finding by center-of-gravity
- Track resolution: σ <1 mm
- Track-pair resolution ~ 10 mm ?

Tracking in plane A: OK

EL: How much light?

- Boundary condition: n_{pe}/electron ≥ 10
- Let photon detection efficiency = η

  η = solid angle x transparency x QE_{PMT}

  Assume reflective TPC field cages

  $\eta = \pi/(4 \times 4\pi) \times 2 \times 0.9 \times 0.3 = 0.03$
- n_{pe}/electron ~ $N_{photons} \times \eta = 10$

$\Rightarrow N_{photons} \geq 300$/electron

Can this be done?

Generation of EL in xenon

$dN/dx = 140(E/p - 0.83)p$ UV photons/cm

- $E/p = 8$ kV/cm-bar is maximum for EL only
- $E/p = 0.83$ kV/cm-bar is minimum for any EL
- best resolution obtained from $E/p \sim 3 - 8$

- Parallel meshes:

gap for 20 bars: < 1 mm

difficult,... so what about using...

Wires!

Wire: $E(r) = E_0 r_0/r$ (fix $E_0 = 8p$)

$N_{photons} = 140\ p\ r_0\{(\mathbf{E_0}/p)\ \ln(9) - 5.8\}$

$N_{photons} = 1650\ p\ r_0\ \equiv 300$

$\Rightarrow$ **$p\ r_0 \geq 0.2$ (bar-cm)**

$\Rightarrow$ $r_0 = 0.01$ cm for $p = 20$ bars **Easy!**

Let's set $r_0 = 0.15$ cm, then: $n_{pe} = 15$, $G = 0.08$

$\delta E/E = 3.4 \times 10^{-3}$ FWHM @ 2480keV

A Wire Plane for EL

- A single "MWPC" readout plane works
  - radius of wire: r_0 = 0.015 cm (150 μm)
  - wire spacing: ~ 5 mm
  - field wires needed to obtain $E_0 = 8p$
  - most light generated on "top" of wire
  - high transparency obtained automatically
  - gap between MWPC and PMT: ~2 $\varnothing_{PMT}$

Answer to Question #2

- Best practical energy resolution:

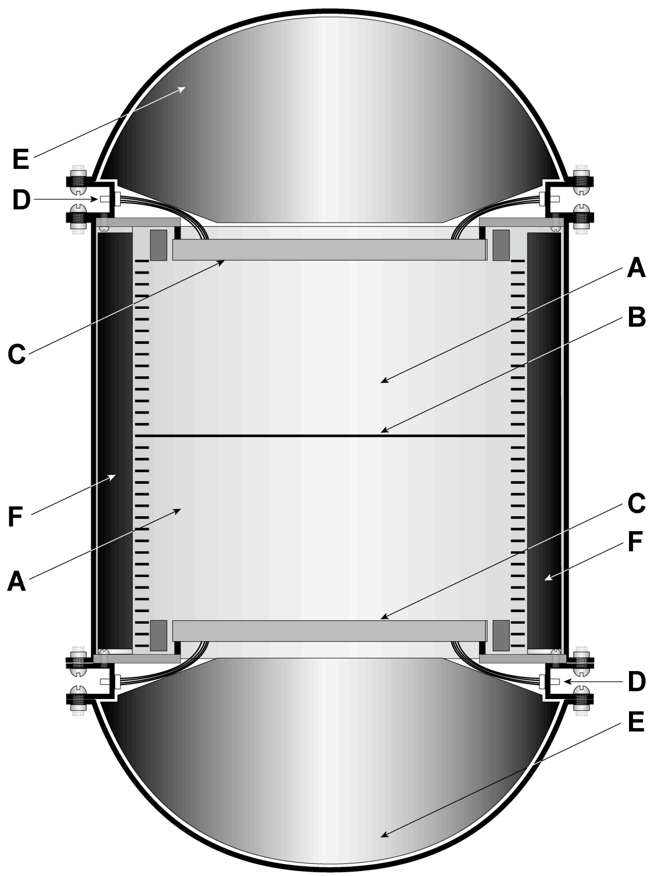
  TPC with MWPC EL readout planes

  - separated function: tracking (A) ↔ energy (B)
  - planes A & B symmetric and equivalent

  $\delta E/E = 3.4 \times 10^{-3}$ FWHM @ 2480keV

  - Can radio-purity be good enough?
  - What is S_2/S_1 for HPXe (nuclear, electron)?

1000 kg Xe: ∅ = 225 cm, 2 x L =225 cm
ρ ~ 0.1 g/cm^3 (~20 bars)



A. Sensitive volume

B. HV cathode plane

C. GPSC readout planes, optical gain gap is ~1-2 mm

D. Flange for gas & electrical services to readout plane

E. Filler and neutron absorber, polyethylene, or liquid scintillator, or …

F. Field cages and HV insulator, (rings are exaggerated here) possible site for scintillators

Some Issues...

- HPXE TPC has ~9x surface area of LXe

  "Rejection of single-e events >>30 x LXe"

  "S_2/S_1 rejection of e-recoils is much better"

- HPXe: use <1% N_2, shift UV to ~340 nm
  - Better for PMT QE, no penalty in yield

Perspective

- ✓ Near-intrinsic energy resolution in HPXe EL TPC
- ✓ Ionization signal alone is sufficient to achieve this
- ✓ WIMP + $\beta\beta$ search: dual-purpose, no compromise
- ✓ keV - MeV energy range: dynamic range OK
- ✓ Both primary signals recorded by photo-detectors
- ✓ Scintillation UV for S_1 & t_0 automatically available
- ✓ EL offers stable, robust operation - no sparks
- ✓ Simple MWPC readout plane appears optimal
- ✓ No cryogenics, easier gas purification,storage,...
- ✓ Separated function TPC novel, but well-motivated

EL GRANDE

Electro-**L**uminescence:

Great **R**ewards **A**wait **N**EXT **D**ouble-β **E**xperiment

Backup Slides

R&D Summary

- Measure S_1/S_2 ratios and resolutions
  - for both neutrons and gammas in HPXe
  - versus ρ, N_2 admixtures
- Determine radio-purity requirements
  - Simulations, for neutron & gamma rejection
  - PMTs
  - Pressure containment, TPC HV, etc,...

Germanium Diodes

Fano factor: similar to xenon gas: ~0.13 ±0.02

Energy per electron-ion pair: 2.96 eV

More carriers $\Rightarrow$ Ge diodes better by $(22/3)^{1/2} = 2.7$?

$\delta E/E$ ~1 x 10^{-3} FWHM @ 2480 keV, **germanium, ideal**

$\delta E/E$ ~2.4 x 10^{-3} FWHM @ 2480 keV **germanium, real**

Why aren't Ge diodes as good as Ge (ideal)?

Factors: electronic noise, edge effects, trapping, complex interactions: Compton, photo-conversion…

ΔE: Three Pathways

- When a particle loses energy in xenon, where does the energy go?
  - Ionization
  - Scintillation: VUV ~170 nm (τ_1, τ_2 …)
  - Heat!
- How is the energy partitioned?
  - Responses differ for α, β, nuclei
  - Dependence on xenon density ρ, E-field
  - Processes still not completely understood

High-pressure Xenon Gas (HPXe) Ionization Chambers

- Positive ions cause a pulse defect - very low mobility
  - Screen grids help, but screening is imperfect
- Microphonic noise is a serious problem
  - absent in germanium diodes
- Electronic noise is significant.
  - Signals are much smaller than germanium: 3/22 = 1/7
- Electronegative impurities may capture electrons.
  - Ratio of electron lifetime to drift length must be ~1000
- Extended track length at MeV energies?
  - Edge effects, pulse shape variations
- Geminate recombination depends on ***E*** field
  - Substantial effect in cylindrical ionization chambers (1/r)

Liquid xenon

EXO: LXe TPC

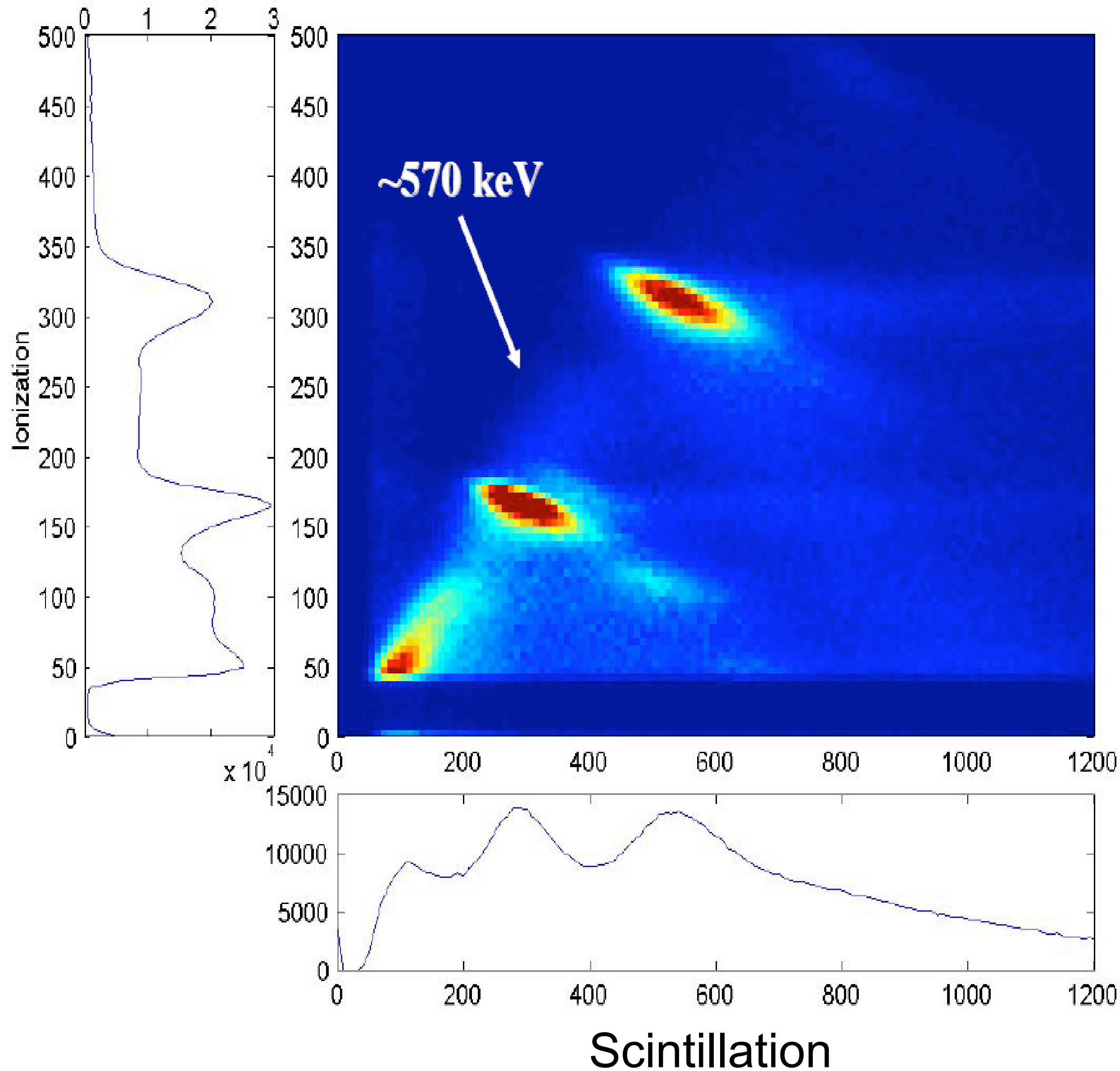
• A **strong anti-correlation** is observed between scintillation and ionization signals

•Anti-correlation also observed in all other LXe data

$\delta E/E$ = **33**•10^{-3} FWHM

$0\nu-\beta\beta$, Q = 2480 keV

♦*What about the tails?*



“Effective Fano Factor” for LXe

Conti *et al:* “F” ~ 20 to match their LXe data

Compare: LXe/HPXe Fano factors: $(\text{“20”}/0.15)^{1/2}$ = **11.5**

$\delta E/E = 2.35 \times (FW/Q)^{1/2} \Rightarrow 31 \times 10^{-3}$ FWHM

Anti-correlation (use it!):

Using **both** the scintillation and ionization signals together allows recovery of the total signal (except for heat).

But: in practice, only a fraction of the light can be detected; the energy resolution in LXe cannot be as good as intrinsic.

The impact of energy lost to heat on resolution is unknown.

Molecular physics of xenon

- **Macroscopic**:
  - Critical temperature of xenon: **room temperature**
  - **Gas & liquid phases** can **coexist** together at normal temp
  - Strong departures from ideal gas law: **high compressibility**
- **Microscopic**:
  - For densities above ~0.5 g/cm^3, **fog** or lacework forms
  - Aggregates form a localized quasi-**conduction** band
  - Ionization process $\Rightarrow$ very non-uniform **dE/dx**
  - Recombination is ~ **complete** in the regions of high **q/v**
  - Recombination increases **scintillation,** reduces ionization

$\Rightarrow$ **A non-gaussian partition of energy between ionization & scintillation occurs for ρ >0.5 g/cm^3**

"Gotthard TPC"

Pioneer TPC detector for 0-ν $\beta\beta$ decay search

- 5 bars, enriched ^{136}Xe (3.3 kg) + 4% CH_4
- MWPC readout plane, wires ganged for energy
- No scintillation detection $\Rightarrow$
  - no TPC start signal!
  - No measurement of drift distance!
- $\delta E/E \sim 80 \times 10^{-3}$ FWHM (1592 keV)

  $\Rightarrow$ 66×10^{-3} FWHM (2480 keV)

Reasons for this less-than-optimum resolution are not clear…

Likely: uncorrectable losses to electronegative impurities

Possible: Undetectable losses to **quenching** (4% CH_4)

α particles

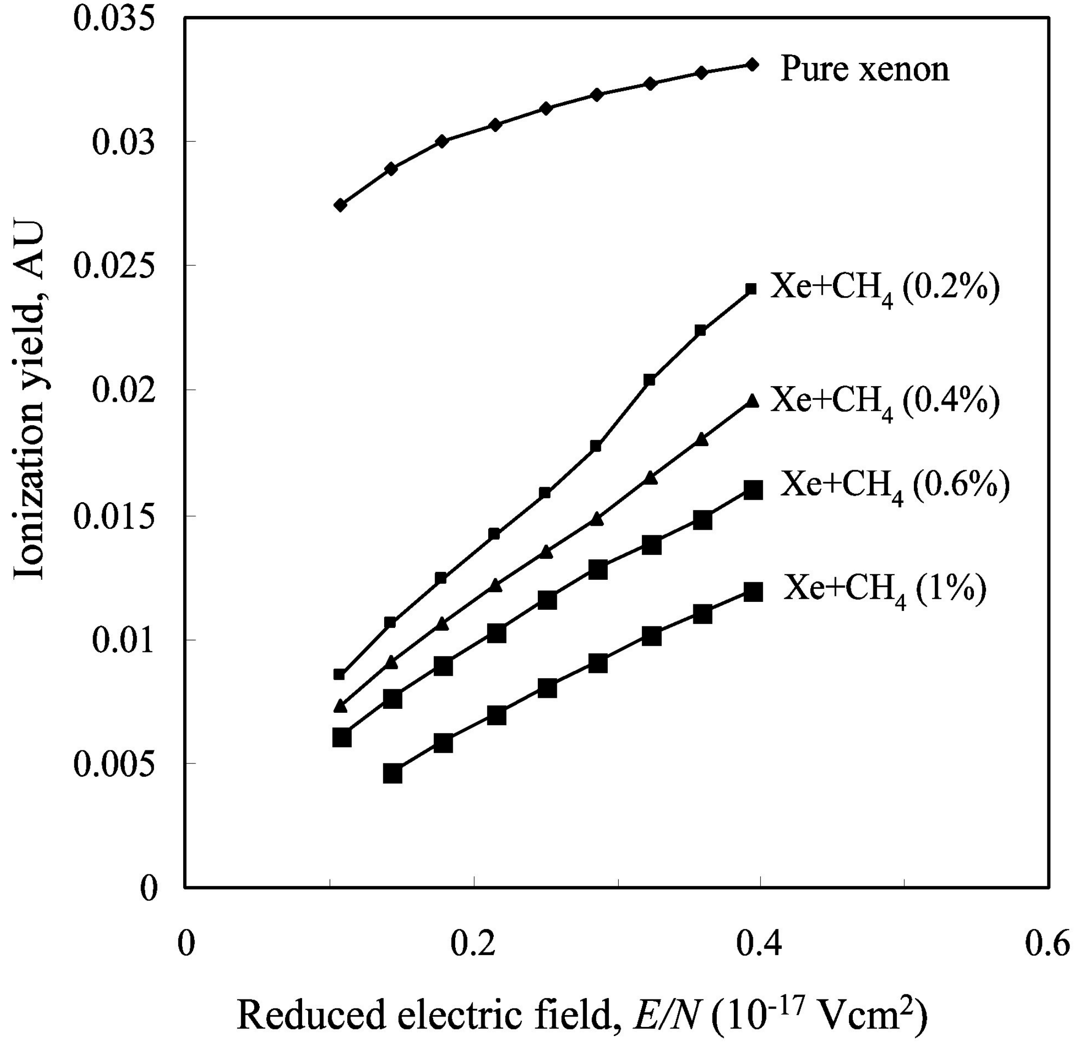


Fig.7. Dependence of ionization yield on reduced electric field (E/N) at a pressure of 2.6 MPa. **(~25 bars)**

K. N. Pushkin *et al,* 2004

IEEE Nuclear Science Symposium proceedings

A scary result: adding a tiny amount of simple molecules (CH_4, N_2, H_2) to HPXe quenches both ionization **and** scintillation for α's

α particle: dE/dx is very high

Gotthard TPC: 4% CH_4
Loss(α): factor of 6

For β particles, what was effect on energy resolution?

Surely small but not known, and needs investigation

Molecular Chemistry of Xenon

- Scintillation:
  - Excimer formation: $Xe^* + Xe \rightarrow Xe_2^* \rightarrow h\nu + Xe$
  - Recombination: $Xe^+ + e^- \rightarrow Xe^* \rightarrow$
- Density-dependent processes also exist:

$$Xe^* + Xe^* \rightarrow Xe^{**} \rightarrow Xe^+ + e^- + \text{heat}$$

  - Two excimers are consumed to make one photon!
  - More likely for both high ρ **+** high ionization density

– Quenching of both ionization and scintillation can occur!

$Xe^* + M \rightarrow Xe + M^* \rightarrow Xe + M + \text{heat}$ (similarly for Xe_2^*, Xe^{**}, Xe_2^{*+}…)

$Xe^+ + e^-(\text{hot}) + M \rightarrow Xe^+ + e^-(\text{cold}) + M^* \rightarrow$

$Xe^+ + e^-(\text{cold}) + M + \text{heat} \rightarrow e^-(\text{cold}) + Xe^+ \rightarrow Xe^*$

Barium daughter tagging and ion mobilities…

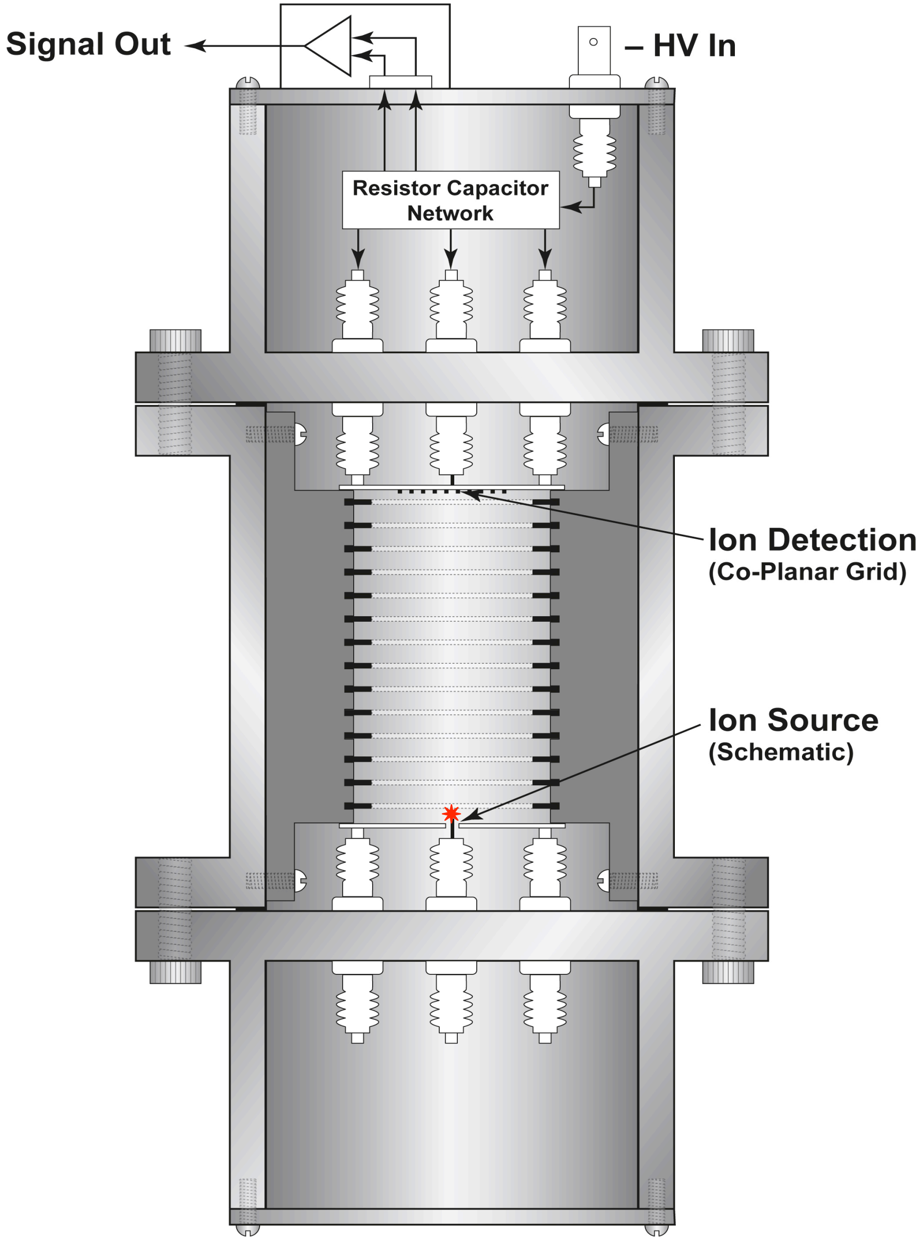
- Ba^{+} and Xe^{+} mobilities are quite different!
  - The cause is **resonant charge exchange**
  - RCE is macroscopic quantum mechanics
    - occurs only for ions in their parent gases
    - no energy barrier exists for Xe^{+} in xenon
    - energy barrier exists for Ba ions in xenon
    - RCE is a long-range process: $R >> r_{atom}$
    - glancing collisions = back-scatter

RCE increases viscosity of majority ions

Barium daughter tagging and ion mobilities…

- Ba^{++} ion survives drift: IP = 10.05 eV
  - IP of xenon is 12.14 eV
- Ba^{++} ion arrives at HV plane, well ahead of all other Xe^{+} ions
  - Mobility difference, ~50%, is known to be true at low density
- Ba^{++} ion liberates at least one electron at cathode surface
  - May be an unrealistic fantasy
- Electrons drift back to anode plane, make detectable signal
  - Arriving electron signal serves as “echo” of the Ba^{++} ion,
- A very strong constraint on event validity is obtained:
  - Process is automatic!

- Clustering effects are likely to alter this picture!



A small test chamber can show whether ion mobility differences persist at higher gas density (no data now).

This could offer an automatic method to tag the "birth" of barium in the decay, by sensing an echo pulse if the barium ion causes a secondary emission of one or more electrons at the cathode.