NEXT International Collaboration

Coimbra-LIP research team

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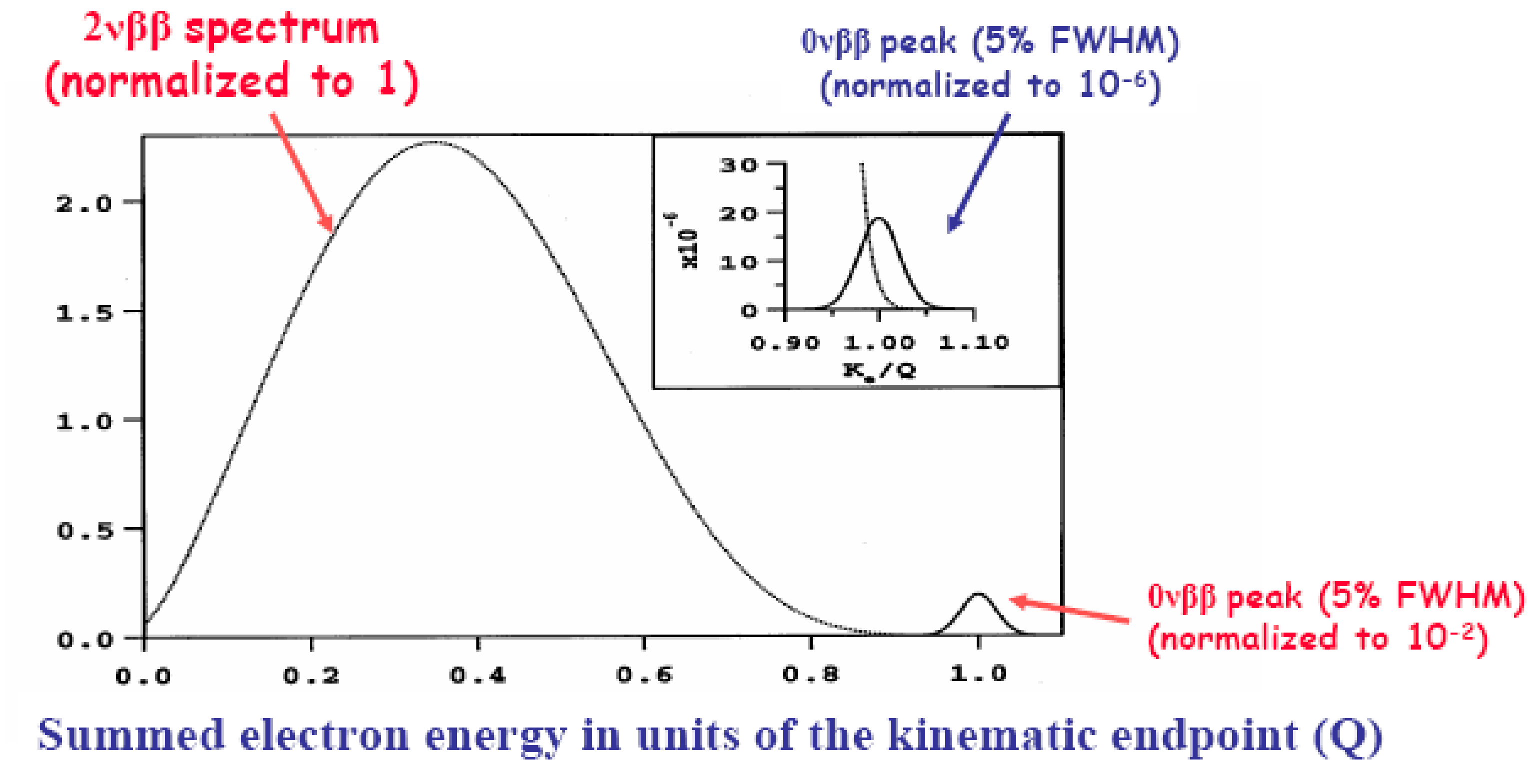
Purpose

Search for neutrinoless double beta decay ($\beta\beta 0\nu$):

- Tests Majorana nature of neutrino
- Helps determine absolute neutrino mass
- If observed, lepton number NOT conserved

How to look for neutrino-less decay

- Measure the spectrum of the electrons



Where to look for neutrino-less decay

- In a number of even-even nuclei, β-decay is energetically forbidden, while double-beta decay is energetically allowed

$$(A,Z) \rightarrow (A,Z+2)$$

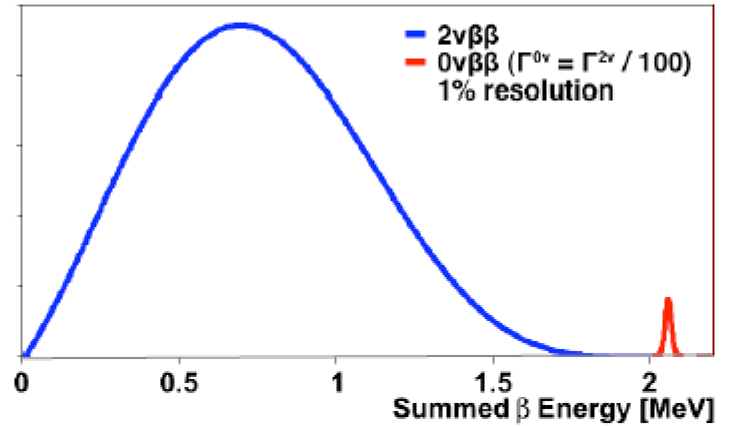
$(A,Z) \rightarrow (A,Z+2) + e^-_1 + \underline{\nu}_1 + e^-_2 + \underline{\nu}_2$ ββ2γ

$(A,Z) \rightarrow (A,Z+2) + e^-_1 + e^-_2$ ββ0γ

Candidates are

^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{136}Xe, ^{150}Nd

Experimental considerations



Extremely slow decay rates

- Large (> 100kg) and very efficient source mass
    - detector active medium as source?
- Best possible energy resolution
    - separate both peaks
- Extremely low backgrounds in the 0γββ peak region
    - must have:
        - Ultra clean radiopure materials
        - Hability to discriminate signal from background

Ideal detector

- Source serves as detector (enough active material)
- Elemental enriched source
- Large Q-value eliminates most potential backgrounds
- Slow $\beta\beta2\nu$ rate would help control irreducible background
- Eliminate background:
  - Direct identification of the decay to (except $\beta\beta2\nu$)
  - Event reconstruction/ spatial resolution and timing to eliminate background
- Some isotope might work better than others (are better understood)

Why use Xe for $\beta\beta0\nu$ search

- Only inert gas with a $\beta\beta0\nu$ candidate (isotope 136)
- Long $\beta\beta2\nu$ lifetime ~10^{22}-10^{23} y (not seen yet)
- No need to grow crystals
- Can be re-purified in place (recirculation)
- No long lived Xe isotopes
- Noble gas:
    - easier to purify
    - no chemistry involved
- ^{136}Xe enrichment easy (natural 8.9%)

LXe or HPXe?

With high-pressure xenon (HPXe)
A measurement of ionization alone
is sufficient to obtain
good energy resolution…

Xenon: Strong dependence of energy resolution on density!

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

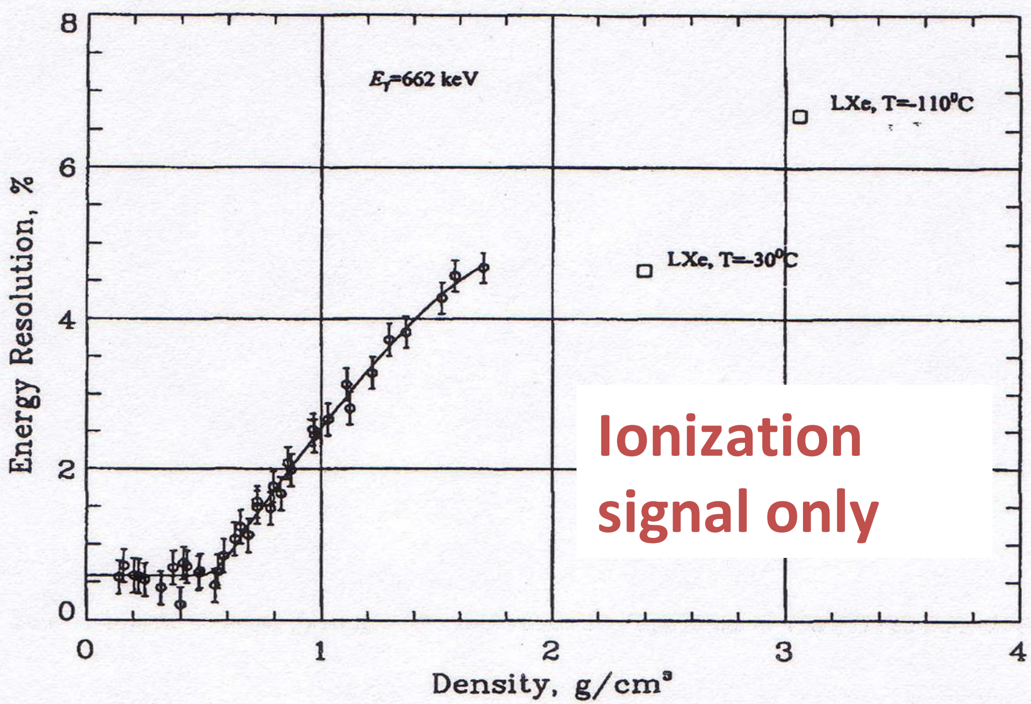


Fig. 5. Density dependencies of the intrinsic energy resolution (%FWHM) measured for 662 keV gamma-rays.

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

Detector Concept

- Use enriched High Pressure Xenon
  - Guarantees the large source mass
- TPC to provide image of the decay particles
- Design to <u>also</u> get an energy measurement as close to the intrinsic resolution as possible

In fact it all comes down to **energy resolution** and **background rejection**!!

“Intrinsic” Energy Resolution for Ionization at ^{136}Xe Q-Value

Q-value ($^{136}Xe \rightarrow {}^{136}Ba$) = 2480 keV

W = energy per ion/electron pair in xenon gas = 21.9 eV,

N = number of ion pairs = Q/W

F = Fano factor. Measured in Xe gas: F = 0.13 – 0.17 (assume 0.15)

$$\frac{\Delta E}{Q} = 2.35 \cdot \frac{\sqrt{FN}}{Q} = \sqrt{\frac{FW}{Q}} \approx 2.8 \cdot 10^{-3} \text{ FWHM}$$

Comparison:

Germanium diodes @ 2.5 MeV — $\Delta E/E \sim$ 1-2 10^{-3} FWHM

Fano Factor of Liquid Xe ~20 $\Rightarrow$ $\Delta E/E \sim$ 35 10^{-3} FWHM

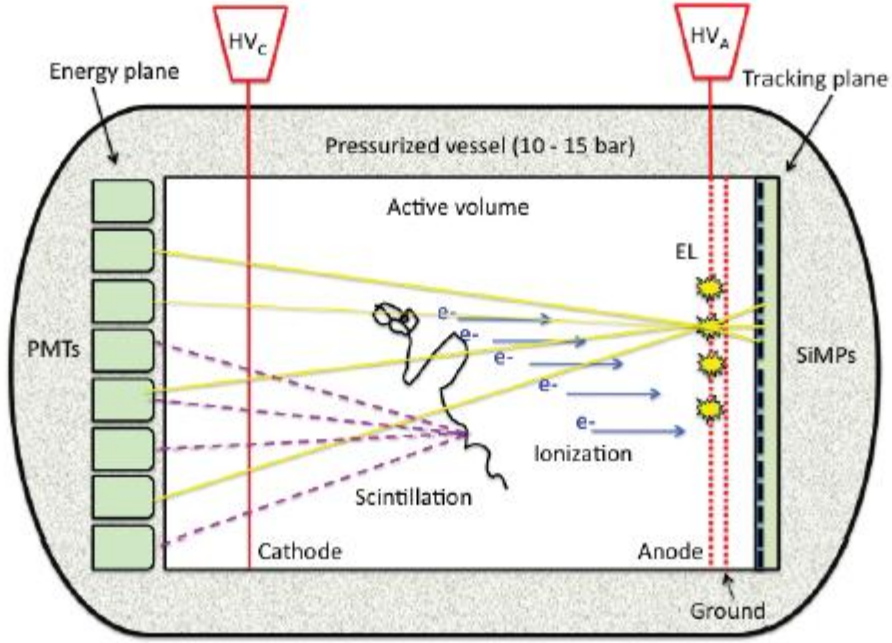
Electro-Luminescence (EL)

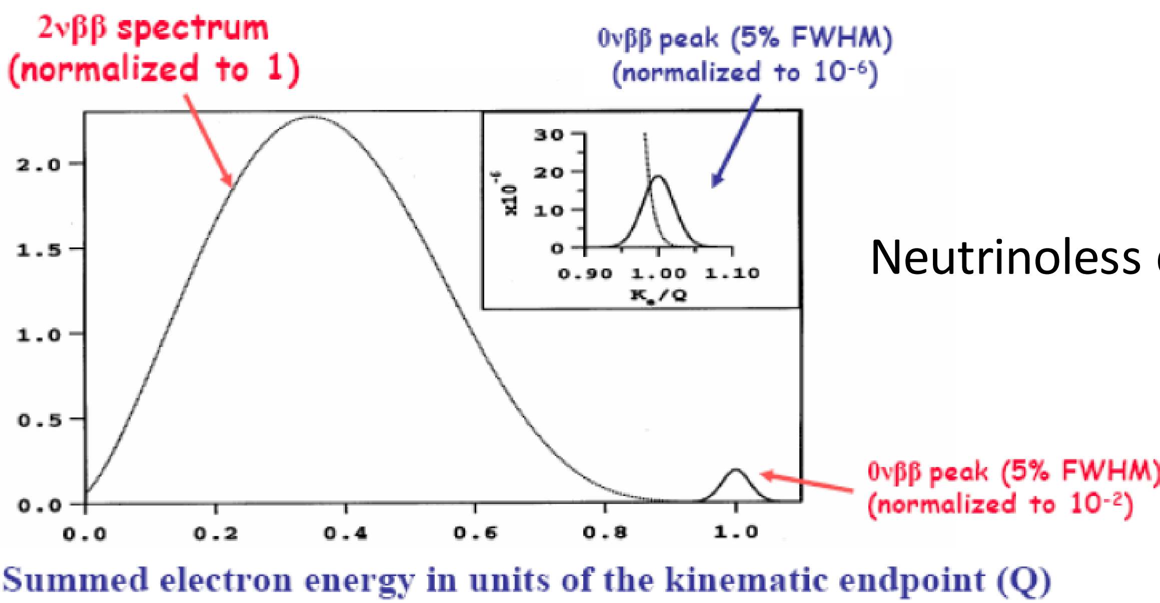
(Gas Proportional Scintillation)

- Electrons drift in low electric field region
- Electrons then enter a high electric field region
- Electrons gain energy, excite xenon, lose energy
- Xenon generates UV
- Electron starts over, gaining energy again
- Linear growth of signal with voltage
- Photon generation up to ~1000/e, but no ionization
- Early history irrelevant, $\Rightarrow$ **fluctuations are small**
- Maybe… G ~ F?

(G is a measure of the precision with which a **single** electron from an ionizing track can be counted).

NEXT TPC scheme





Neutrinoless double beta decay spectrum

However…

So, the use of pure gaseous xenon with EL technique guarantees a very good intrinsic energy resolution,

BUT electron drift velocity in Xe is low and diffusion coefficients are high, blurring the identification of the ionization track hindering the necessary background rejection.

The use of xenon doped with a molecular additive has been a suggested solution to increase electron drift velocity and decrease diffusion coefficients.

Coimbra-Lip Team GOALS

Find molecular additives to be mixed to xenon to

- increase electron drift velocity
- decrease electron diffusion coefficients

without compromising detector energy resolution

HOW

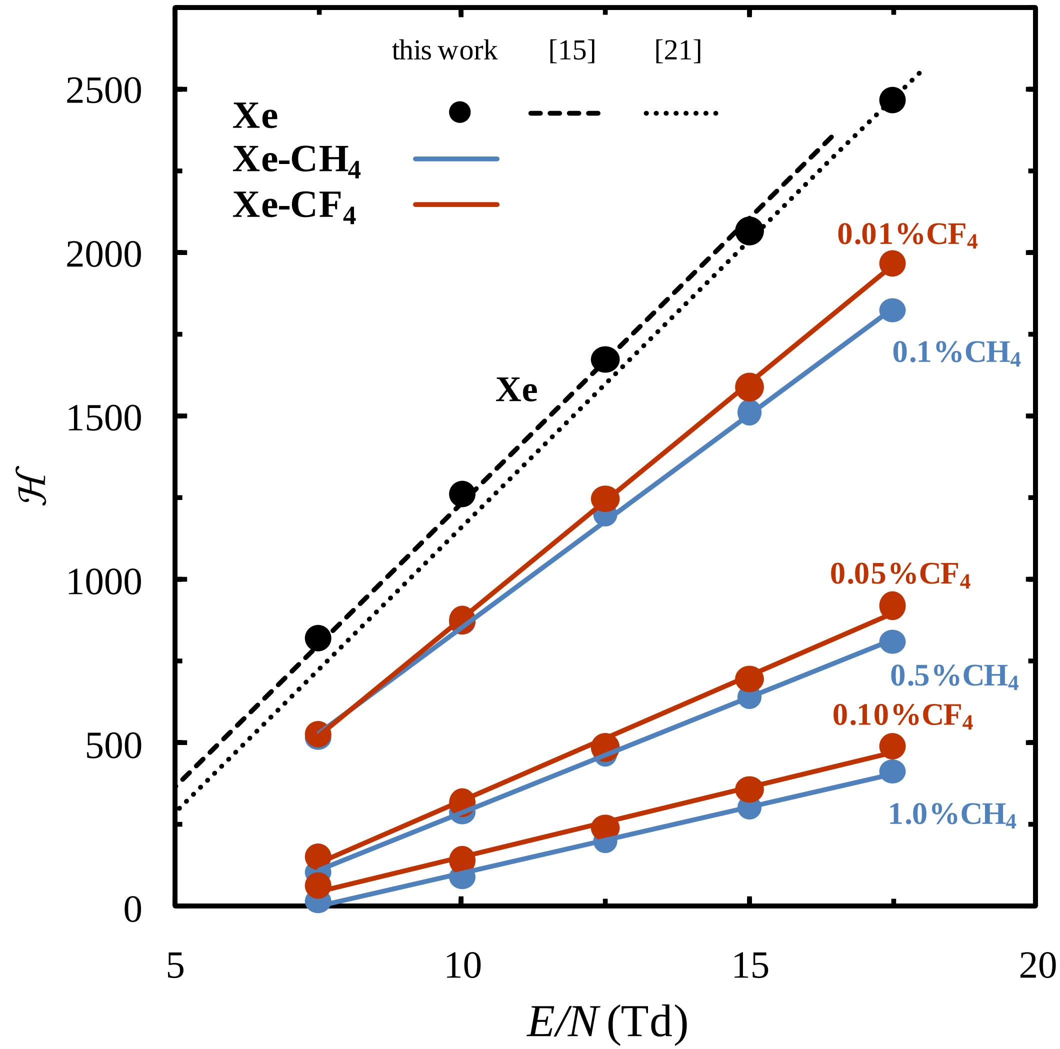
- Monte Carlo simulation
- experimental measurements

of GPSC elecroluminescence (EL) yield & energy resolution

ADDITIVE Candidates

N_2, CH_4, CF_4, TMA.

Monte Carlo simulation results: EL Yield

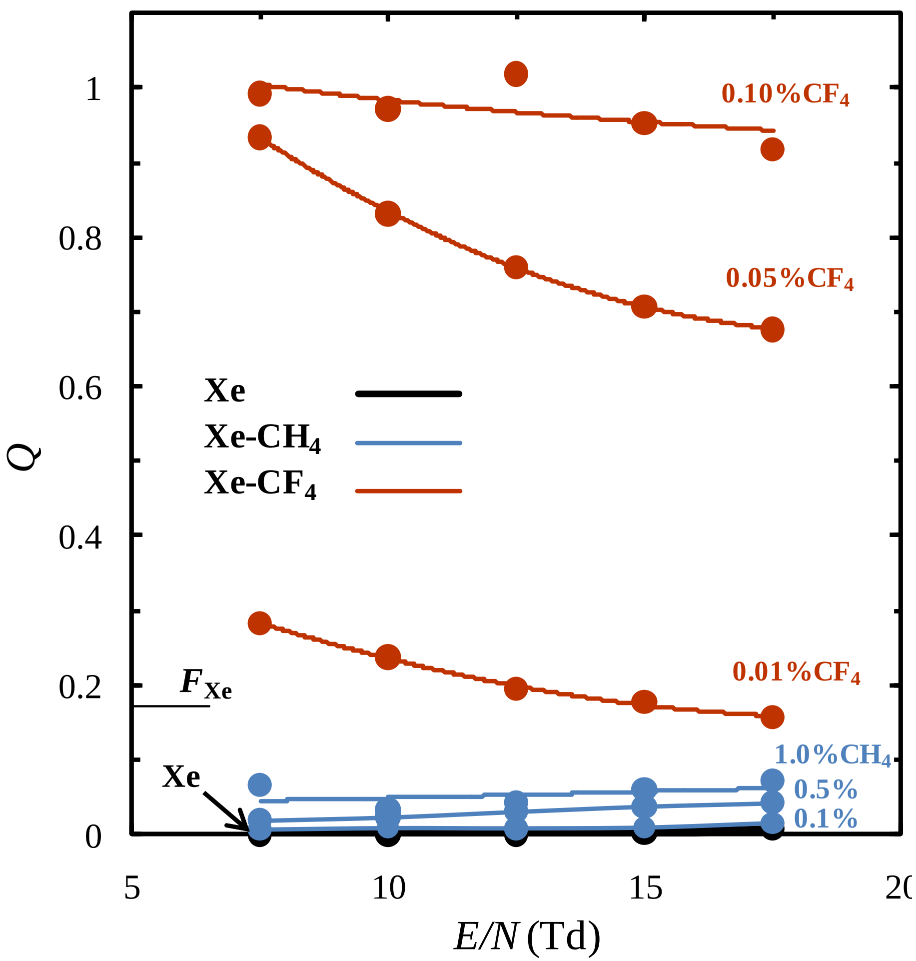


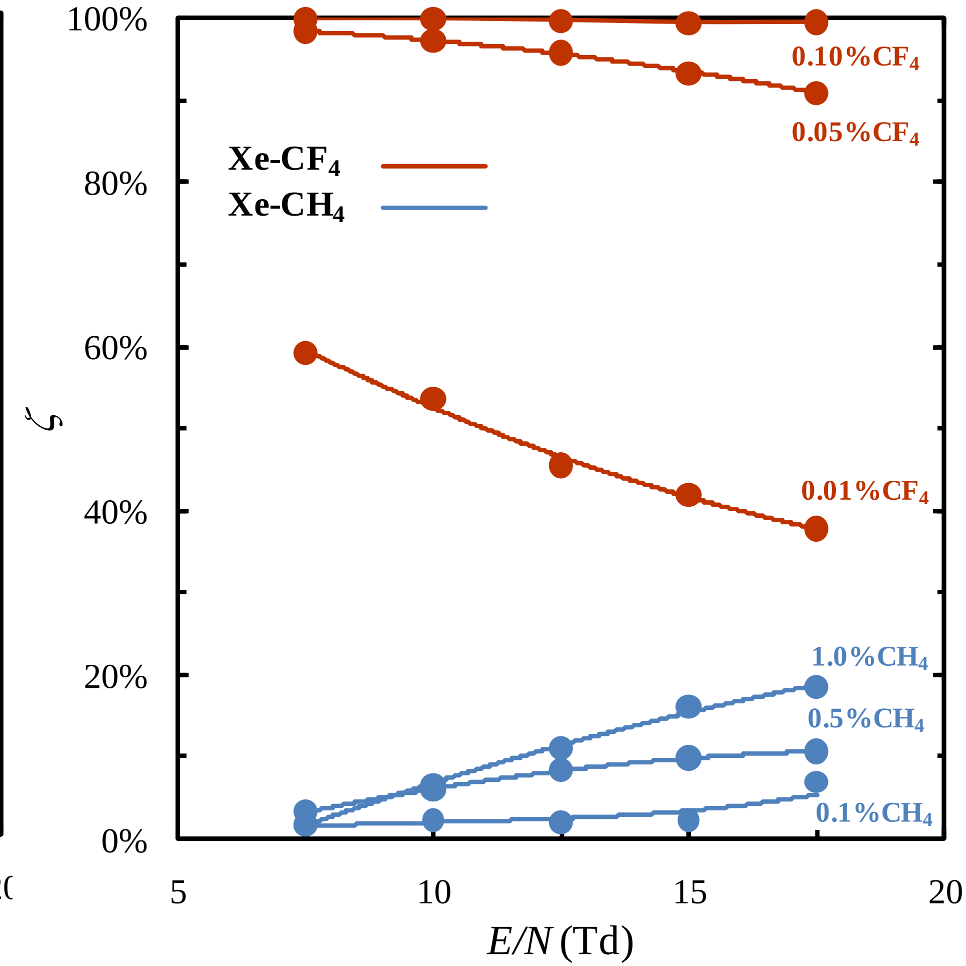
$$R_{int}^2 \propto (1/n)\,(F + Q)$$

$$\begin{cases} F = \sigma_n{}^2/n \\ Q = J/\mathcal{H} \\ \quad J = \sigma_{\mathcal{H}}{}^2/\mathcal{H} \end{cases}$$

EL yield $\mathcal{H}$ (UV photons per electron), produced under applied reduced electric fields *E/N*, when **one electron** drifts across a ***D*=0.5 cm** long **EL region** in **Xe** or in the **Xe-CH_4** and **Xe-CF_4** mixtures with the indicated **η_{CH4} and η_{CF4} molecular concentrations** [*p* = **7600 Torr**, T=293 K].

Monte Carlo simulation results: EL Fluctuations





Fluctuations parameter $Q=J/\mathcal{H}$ of the EL yield $\mathcal{H}$, where $J=\sigma_{\mathcal{H}}^2/\mathcal{H}$ is the relative variance of $\mathcal{H}$. The bar F_{Xe} marks the Xe Fano factor.

Fraction ζ of electrons that become attached to CH_4 or CF_4 molecules in the EL region.

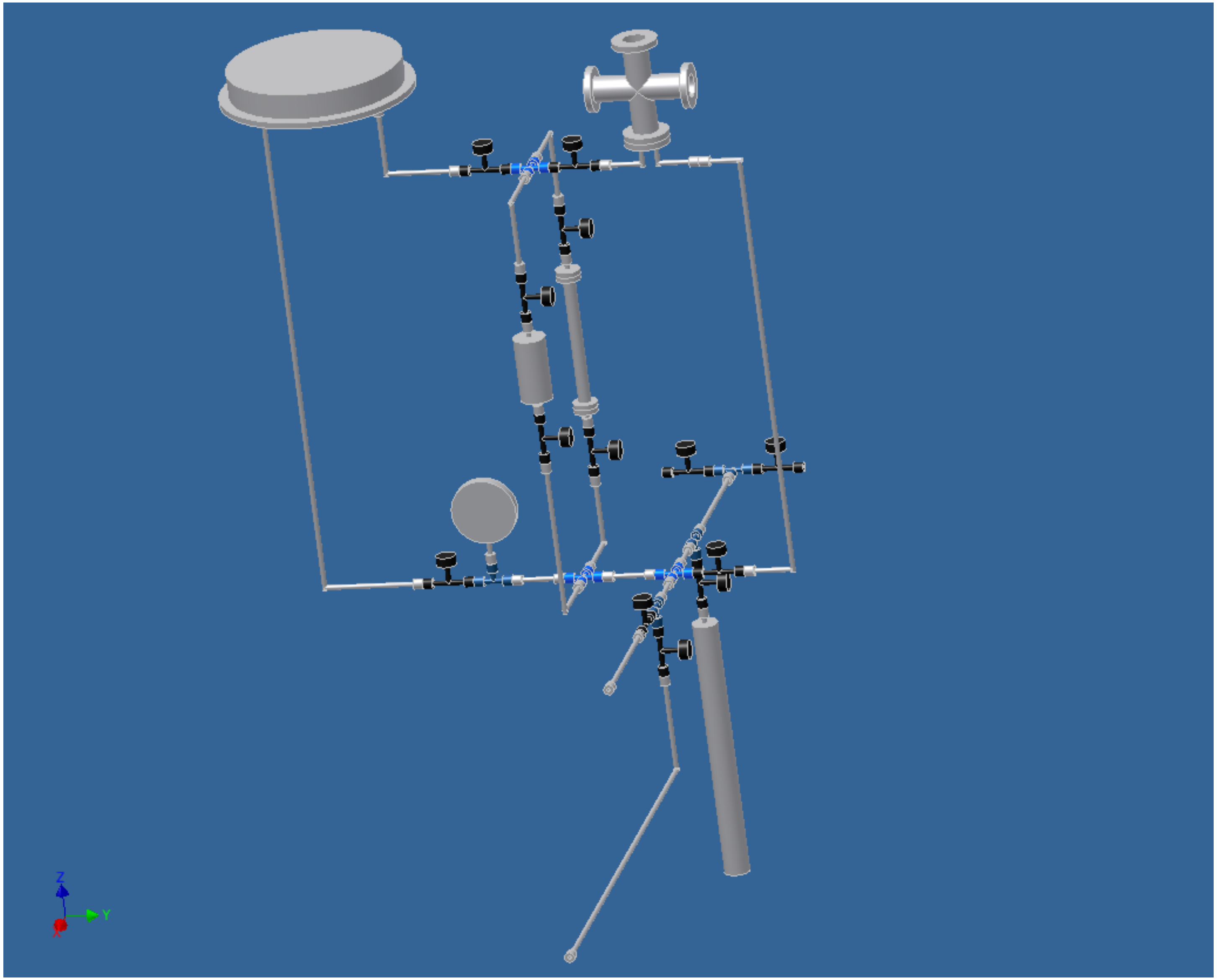
$$R_{int}^2 \propto (1/n)\,(F+Q)$$

Conclusions from EL simulation results:

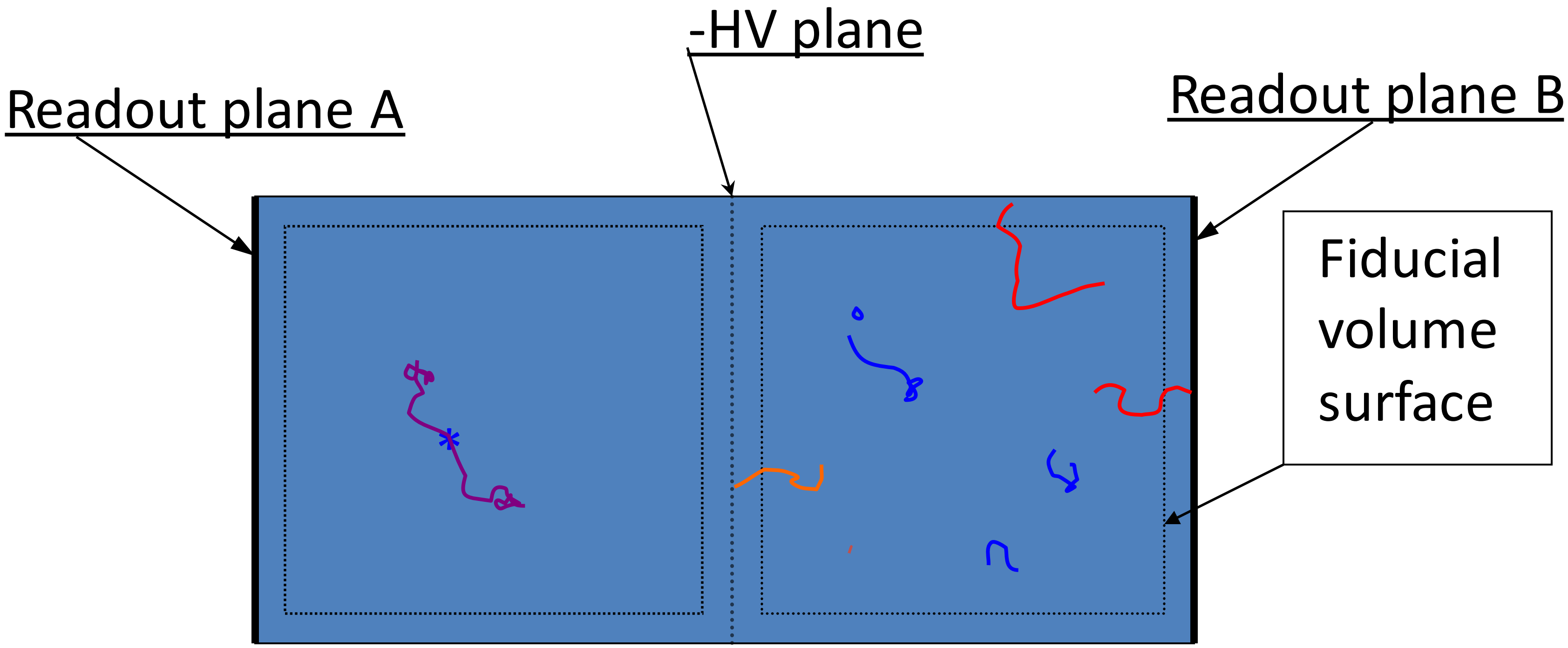
- CH_4 may be a good candidate below ~ 1% concentrations
- CF_4 apparently is not, even at much lower concentrations (<0.01%).

However, $\mathcal{R}_{int}$ ($\mathcal{R}_{int}^2 \propto (1/n)(\boldsymbol{F} + \boldsymbol{Q})$) is also determined by other factors, namely n (recombination), the Fano factor, etc

And not all candidates have enough and credible data to implement a reliable simulation scheme so…


Z
Y
X

TPC: ββ Signal & Backgrounds



Signal: **ββ event**

Backgrounds

Fluctuations in Electroluminescence (EL)

EL is a linear gain process

G for EL contains three terms:

1. Fluctuations in n_{uv} (UV photons per e):
2. Fluctuations in n_{pe} (detected photons/e):
3. Fluctuations in photo-detector single PE response:

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

For G = F = 0.15 $\Rightarrow$ $n_{pe} \geq 10$

The more photo-electrons, the better!

Equivalent noise: <u>much</u> <u>less</u> than 1 electron rms!

Double Beta Decay Spectra

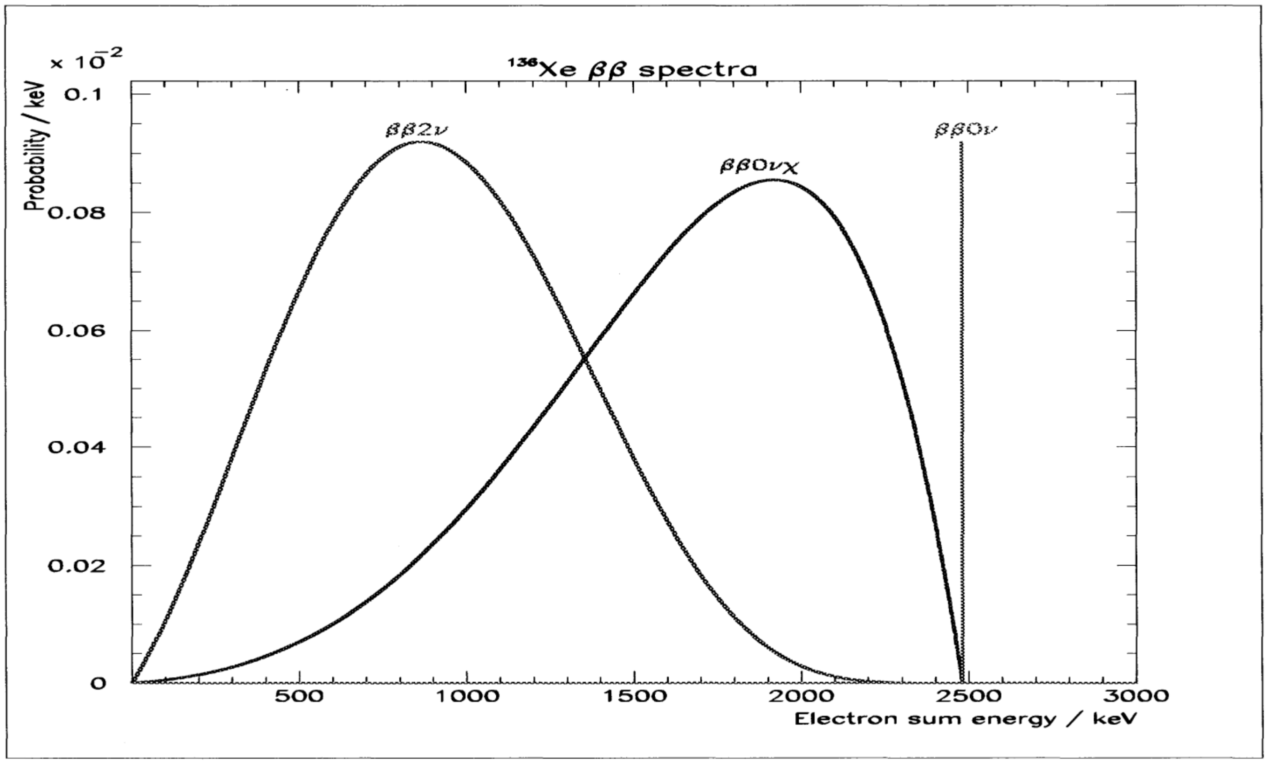
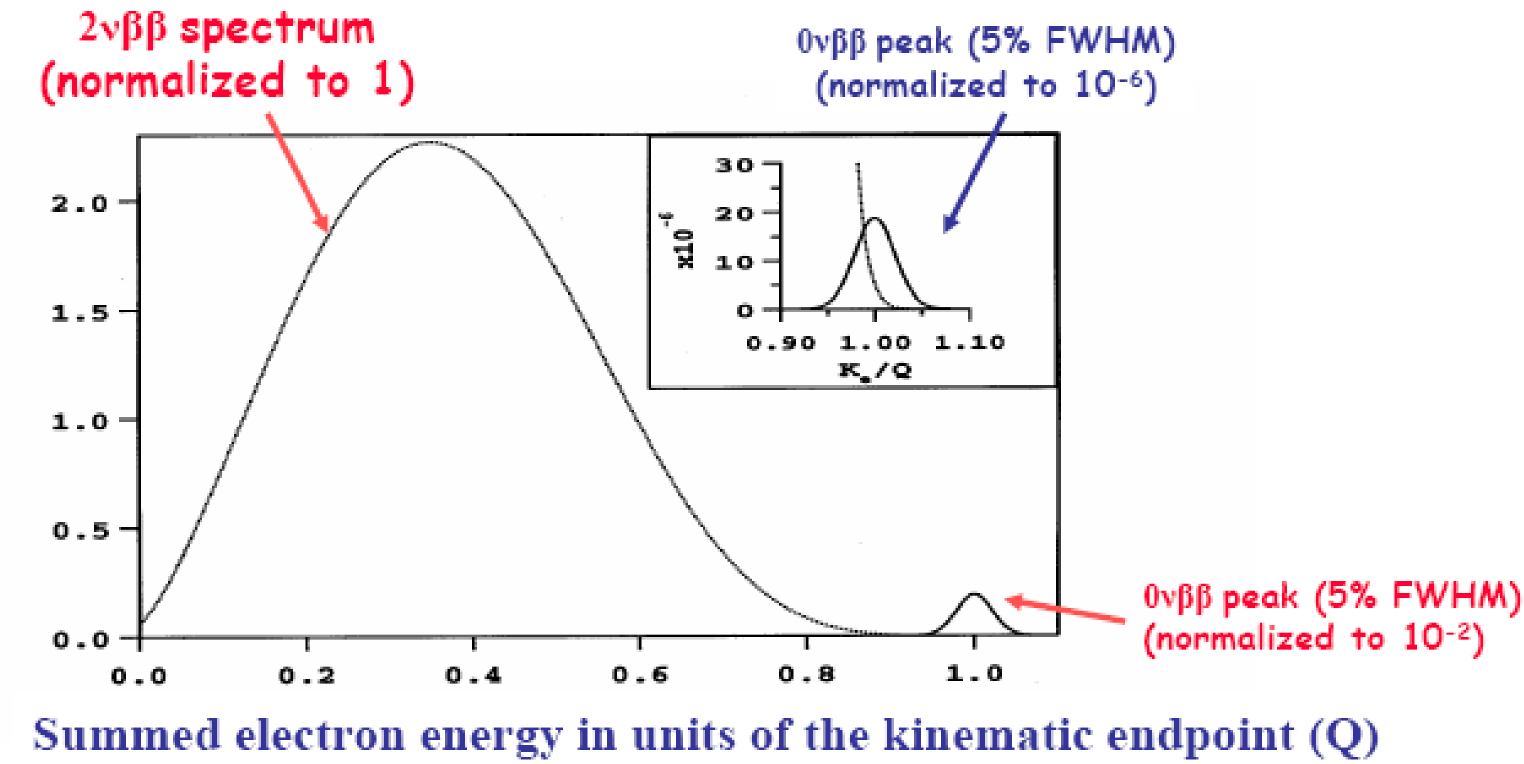


Figure 2.4: The two neutrino, zero neutrino, and Majoran double beta decay modes. The only method to distinguish the modes is via kinematic measurement.

How to look for neutrino-less decay

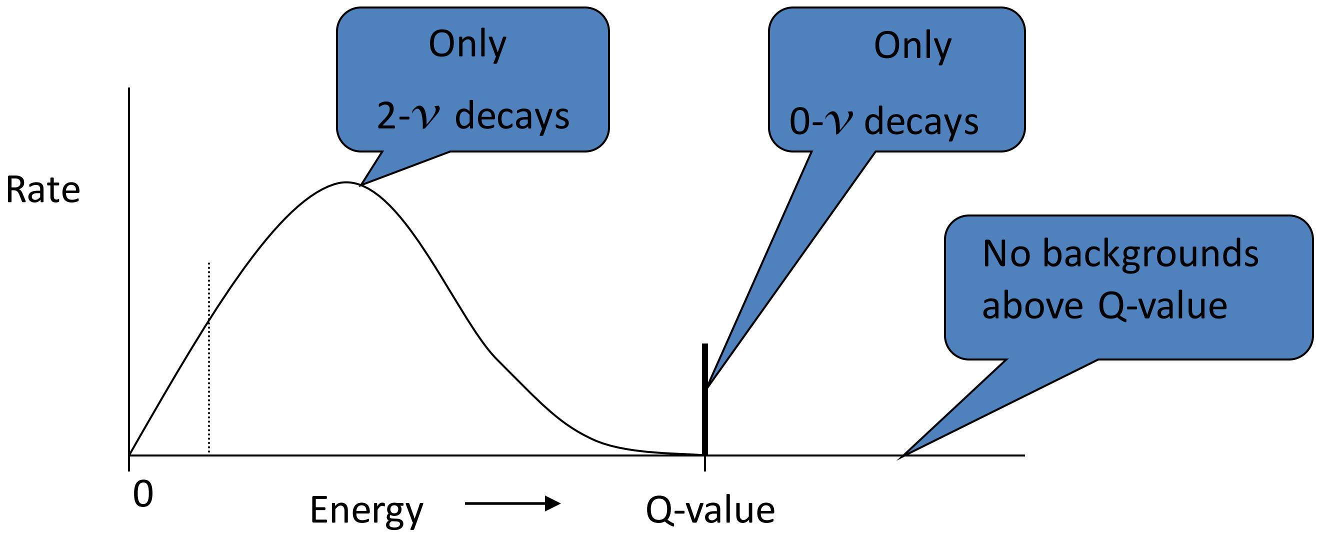
- Measure the spectrum of the electrons



What's needed…

- Long lifetimes (>10^{25} years) require:
  - Large Mass of relevant isotope (>100 kg)
  - Small or No background:
    - Clean materials
    - Underground, away from cosmic rays
    - Background rejection methods:
      - Energy resolution
      - Event topology
      - Particle identification
      - Identification of daughter nucleus
  - Years of data-taking

Double beta decay



The ideal result is a spectrum of all ββ events, with a 0-ν signal present as a narrow peak, well-separated from 2-ν

Renewed Impetus for $0\nu\beta\beta$

The discovery that neutrinos are not massless particles, provides compelling arguments for performing neutrinoless double-beta decay ($0\nu\beta\beta$) experiments with increasing sensitivity.

$0\nu\beta\beta$ decay probes fundamental questions:

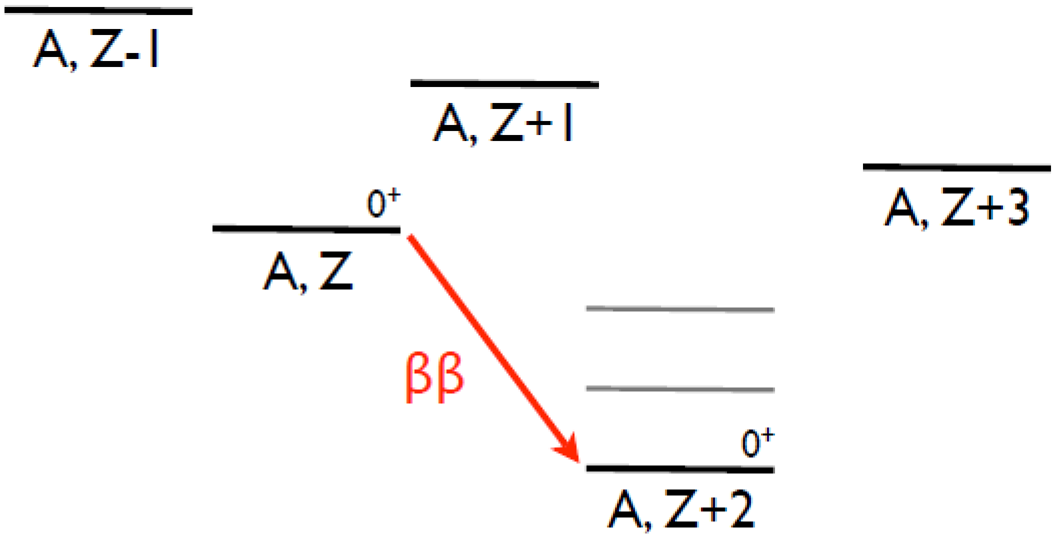
- Lepton number conservation — might Leptogenesis be the explanation for the observed matter - antimatter asymmetry?
- Neutrino properties — the only practical technique to determine if neutrinos are their own anti-particles — Majorana particles.

If $0\nu\beta\beta$ is observed:

- Provides a promising laboratory method for determining the absolute neutrino mass scale that is complementary to other measurement techniques.
- Measurements in a series of different isotopes potentially can reveal the underlying interaction process(es).

Double-Beta Decay

In a number of even-even nuclei, β-decay is energetically forbidden, while double-beta decay, from a nucleus of (A,Z) to (A,Z+2), is energetically allowed.



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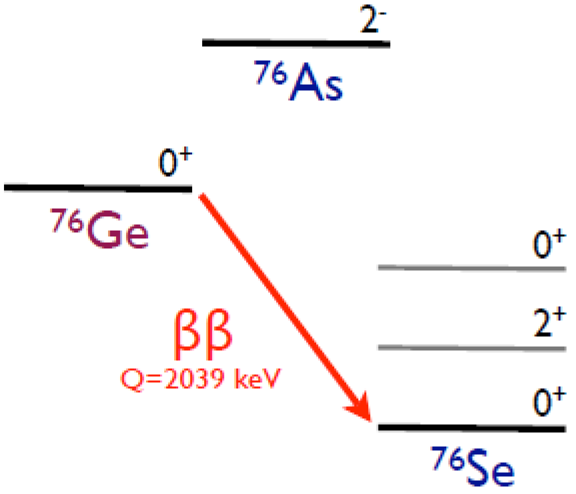


^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr ^{100}Mo, ^{116}Cd ^{128}Te, ^{130}Te, ^{136}Xe, ^{150}Nd

Double-Beta Decay Modes

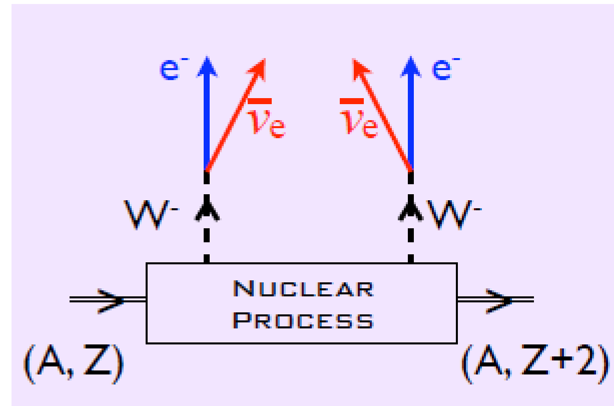
2ν double-beta decay (2νββ): Nucleus (A, Z) → Nucleus (A, Z+2) + e^- + $\bar{\nu}_e$ + e^- + $\bar{\nu}_e$

Allowed second-order weak process

Maria Goeppert-Mayer (1935)

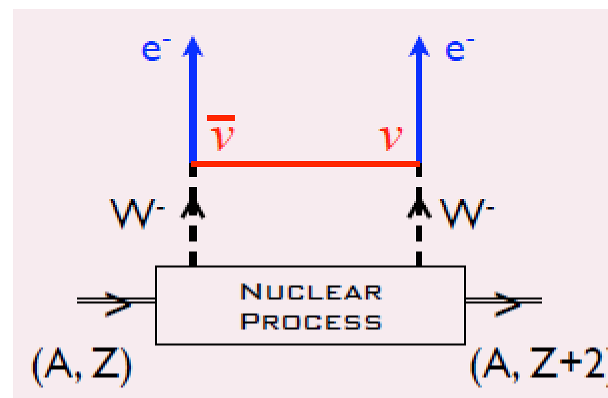
2νββ observed for

^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr ^{100}Mo, ^{116}Cd ^{128}Te, ^{130}Te, ^{150}Nd



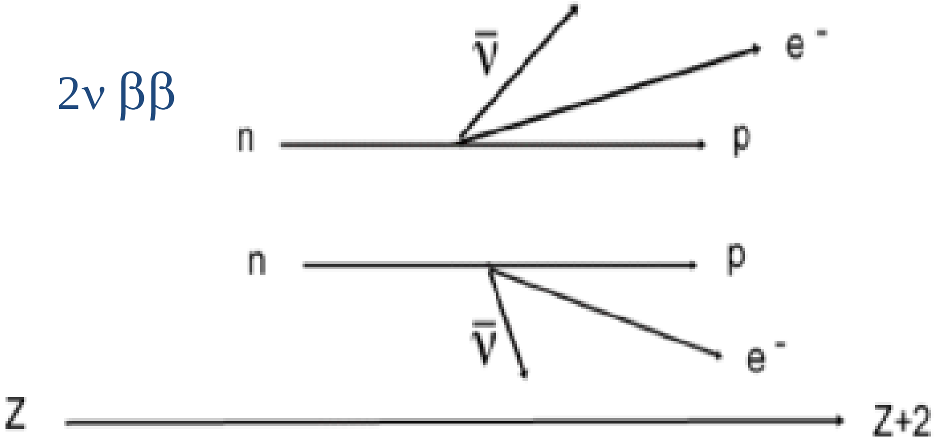
0ν double-beta decay (0νββ): Nucleus (A, Z) → Nucleus (A, Z+2) + e^- + e^-

Ettore Majorana (1937) realized symmetry properties of Dirac's theory allowed the possibility for electrically neutral spin-1/2 fermions to be their own anti-particle

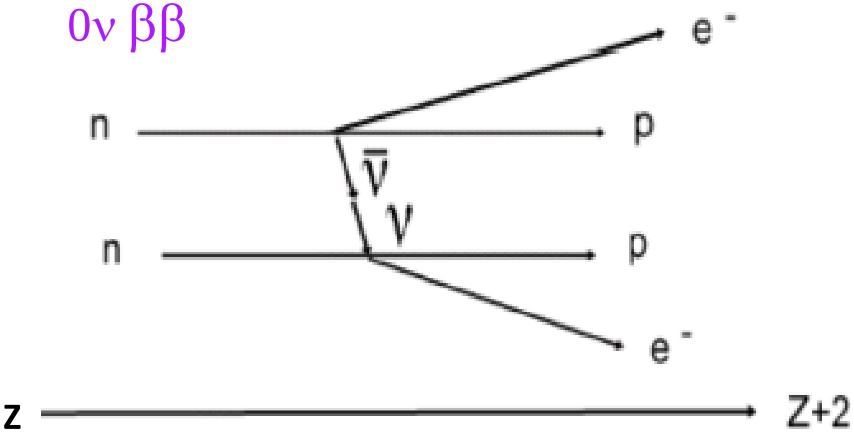


Two Types of Double Beta Decay

2ν ββ



0ν ββ



Neutrinoless double beta decay.

A known standard model process and an important calibration tool

$$T_{\frac{1}{2}} \approx 10^{19} \, yrs.$$

If this process is observed:

Neutrino mass ≠ 0

Neutrino = Anti-neutrino!

Lepton number is not conserved!

$$\frac{1}{T_{\frac{1}{2}}} = G \times \|\mathbf{M}\|^2 \times m_{\bar{\nu}}{}^2$$

Neutrinoless double beta decay lifetime

Neutrino effective mass

Early Estimates of ββ Decay Rates

2ν double-beta decay ($2\nu\beta\beta$)

Maria Goeppert-Mayer (1935)
using Fermi Theory

$$\left[T_{1/2}^{2\nu\beta\beta}\right]^{-1} \propto \text{Phase Space (4-body)} \propto Q^{10-12}$$

$$T_{1/2}^{2\nu\beta\beta} \approx 10^{25} \text{ years}$$

0ν double-beta decay ($0\nu\beta\beta$)

Furry (1939), assuming Parity
conserved, so no preferential handedness

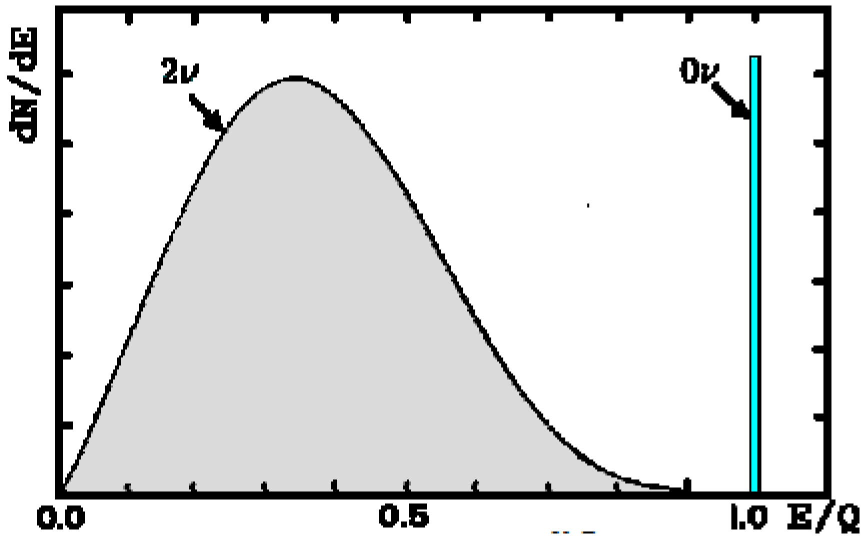
$$\left[T_{1/2}^{0\nu\beta\beta}\right]^{-1} \propto \text{Phase Space (2-body)} \propto Q^{5}$$

$$T_{1/2}^{0\nu\beta\beta} \approx 10^{19} \text{ years}$$

$0\nu\beta\beta$ mode highly favored over $2\nu\beta\beta$

If observe
$2\nu\beta\beta \Rightarrow$

neutrinos are
Dirac



If observe
$0\nu\beta\beta \Rightarrow$

neutrinos are
Majorana

- **Rare nuclear transition between same mass nuclei**
  - **Energetically allowed for even-even nuclei**

- $(Z,A) \rightarrow (Z+2,A) + e^-_1 + \underline{\nu}_1 + e^-_2 + \underline{\nu}_2$
- $(Z,A) \rightarrow (Z+2,A) + e^-_1 + e^-_2$
- $(Z,A) \rightarrow (Z+2,A) + e^-_1 + e^-_2 + \chi$

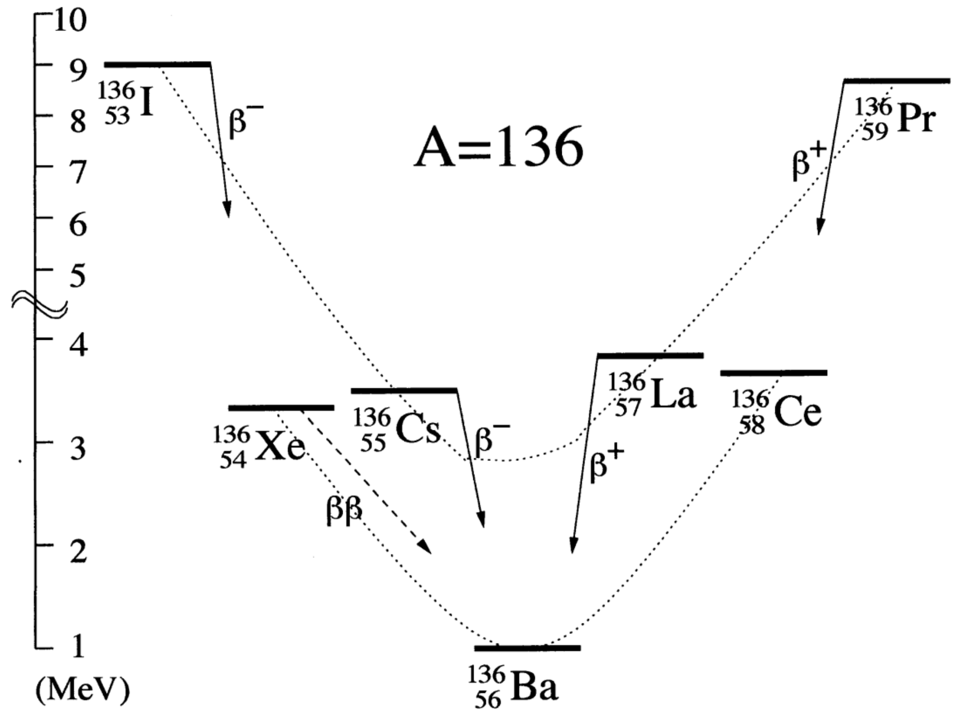


Figure 2.1: Simplified atomic mass scheme for nuclei with A=136. The parabolae connecting the odd-odd and even-even nuclei are shown. While ^{136}Xe is stable to ordinary beta decay, it can decay into ^{136}Ba by double-beta decay.

What is this factor “G”?

- In in practice:

  G is a measure of the precision with which a **single** electron (from an ionizing track) can be counted.