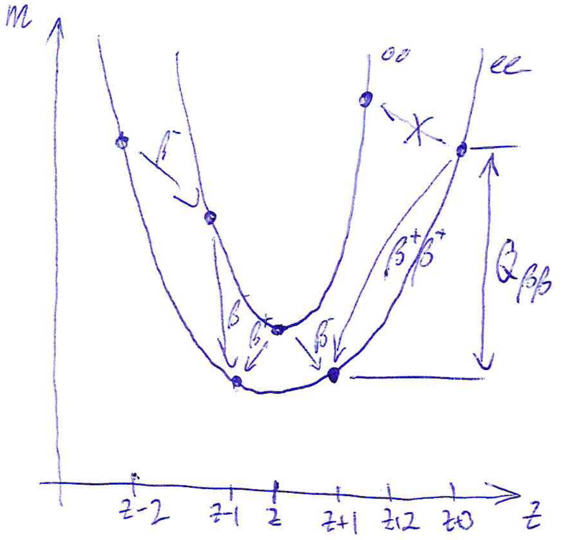
Neutrinoless double-beta decay (0νββ) experiments

Candidate nuclei



→ β decay to next isobar forbidden, but ββ decay energetically allowed

isotope	$Q_{\beta\beta}$	a
* 76 ge	2.04 MeV	7.8%
^{82}Se	3.00 MeV	8.7%
^{100}Mo	3.04 MeV	9.6%
^{96}Zr	3.35 MeV	2.8%
^{150}Nd	3.37 MeV	5.6%
^{128}Te	0.87 MeV	31.7%
* ^{130}Te	2.53 MeV	34%
* ^{136}Xe	2.46 MeV	8.9%
^{116}Cd	2.81 MeV	7.5%
^{48}Ca	4.27 MeV	0.2%

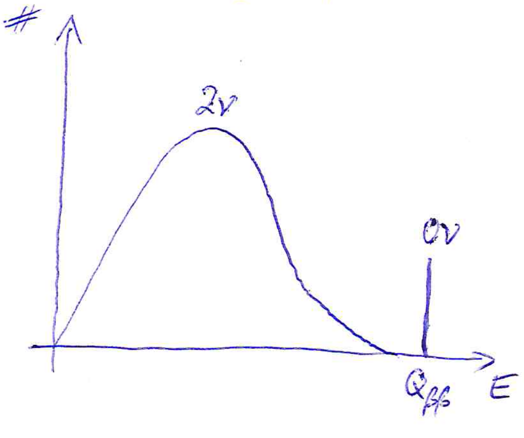
2νββ: allowed in SM, $T_{1/2} \sim 10^{20}$ yrs, observed for many isotopes

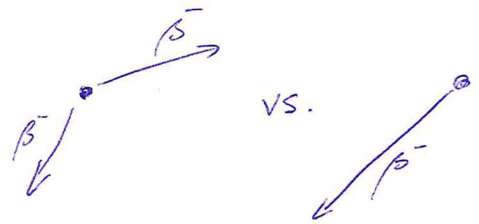
0νββ: $\Delta L = 2$, Majorana neutrinos → new physics!

Experimental signature

Sum energy spectrum (in calorimetric measurement)

source ≡ detector





→ event topology (tracking detectors)

Expected number of ββ-events:

$$N = \log 2 \cdot \frac{N_A}{W} \cdot \varepsilon \cdot a \cdot \frac{M \cdot t}{T_{1/2}^{0\nu}}$$

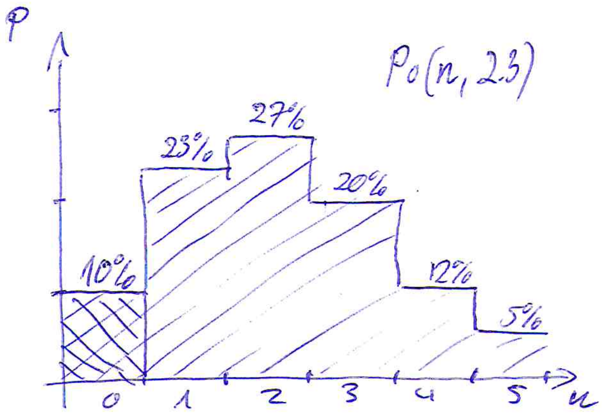
N_A	Avogadro constant
W	atomic weight of isotope
ε	detection efficiency
a	abundance of isotope
M	detector mass
t	time of measuring
$T_{1/2}^{0\nu}$	0νββ half life

Ideal experiment: no background!
If no event is observed, upper limit:

Poisson distribution: $Po(n,\mu) = \frac{\mu^n}{n!} e^{-\mu}$ μ: mean value

$$\rightarrow Po(0,\mu) = e^{-\mu}$$

$$\rightarrow \mu_{up} = -\log(1-C.L.) = 2.3 \quad \text{for CL } 90\%$$
$$3 \quad \text{for } 95\% \text{ etc.}$$



→ for $\mu > 2.3$, the probability to observe 0 events is less than 10%

→ half-life limit in case of $n=0$

constant depending on element

$$T_{1/2}^{0\nu} \geq \frac{K \cdot \varepsilon \cdot a \cdot M \cdot t}{2.3} \quad \boxed{a \cdot (M \cdot t) \equiv \text{exposure}}$$

depends on confidence level

Experiment including background (= real)

b: background expectation

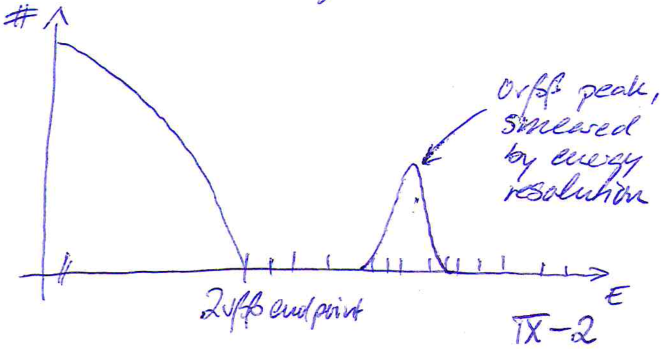
$$Po(n; \mu+b) = \frac{(\mu+b)^n}{n!} e^{-(\mu+b)}$$

Simplified approach: large b; n=b observed

$$\rightarrow \text{uncertainty: } \Delta n = \sqrt{b}$$

$$\rightarrow T_{1/2}^{0\nu} \geq \frac{K \cdot \varepsilon \cdot a \cdot M t}{\sqrt{b}}$$

amount of background to be considered:



$$b = c \cdot Mt \cdot \Delta E$$

background rate [cts/(keV·kg·yr)]

width of region of interest (ROI) ← energy resolution

$$\rightarrow \boxed{T^{0\nu}_{1/2} \geq K \cdot \varepsilon \cdot a \sqrt{\frac{Mt}{C\Delta E}}}$$

figure of merit for experiments

rises with ∝ $\sqrt{Mt}$ of exposure

Can be related to effective $0\nu\beta\beta$-mass $m_{\beta\beta}$ via

$$\frac{1}{T^{0\nu}_{1/2}} = |\mathcal{M}_{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2 \cdot G(Q_{\beta\beta})$$

adds uncertainty → nuclear matrix element

probability of helicity flip

phase space factor

$$\rightarrow m_{\beta\beta} \simeq K_2 \sqrt{\frac{1}{\varepsilon a}} \left(\frac{C\Delta E}{Mt}\right)^{1/4}$$

What isotope to use?

- Q-value: $Q_{\beta\beta}$ should be high! (Se) (Nd)
  - → large phase space factor → higher decay rate
  - → radioactive background: for $Q_{\beta\beta} > 2.6$ MeV above end of U/Th chain γ-spectrum
- Elemental abundance: signal ∝ aMt, while background uncertainty ∝ $\sqrt{cMt}$
  - → the more of the $\beta\beta$-isotope per detector mass, the better (Te)
  - → easy possibility for enrichment? (Xe) (Ge)

What detection technique to use?

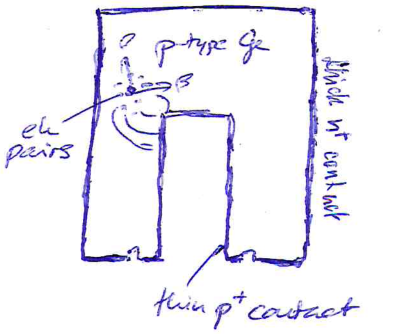
- Energy resolution: defines width of ROI (Ge)
  - → avoid overlapp with $2\nu\beta\beta$ spectrum!
- Source ≡ detector concept: (Ge, Xe, Te ...)
  - → optimal use of mass
  - → no effects from absorption/scattering in source etc.
- Low-background material/surroundings: low b (Ge)

  ↕
- Possibilities for particle discrimination: b suppression

  ↕ → α/β/γ separation
- study of event kinematics: identify exact decay process → Right-handed currents etc.
- scalability

Experiments:

- ## ^{76}Ge-diodes



(+) energy resolution: FWHM ~0.2%

(+) clean: crystal growing

(+) enrichment to 80% possible

(+) pulse shape discrimination / segmentation → BG reduction

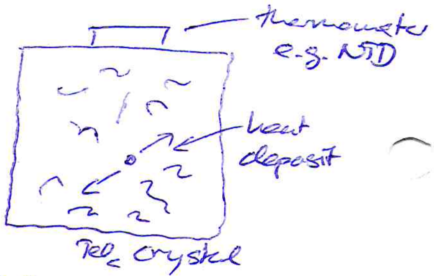
(+) high detection effiziency

(−) low Q value

- Heidelberg-Moscow exp (LNGS)
  - 11 kg of 86% enriched Ge
  - 55 kg yrs exposure: limit $T_{1/2} > 1.9 \cdot 10^{25}$ yrs or signal?
- Gerda
  - phase I: 15 kg, better shielding, $T_{1/2} > 2.1 \cdot 10^{25}$ yrs, HdM excluded
  - phase II: 24 kg, $c = 10^{-3}$ $(\text{keV} \cdot \text{kg} \cdot \text{yr})^{-1}$ starting this year

- ## Cryogenic bolometers

e.g. CUORE TeO_2



(+) good energy resolution: FWHM ~ 0.3%

(+) no enrichment necessary, a = 34% for ^{132}Te

(+) large mass can be realized: ~ 1t

(−) CUORE-0 results: high background levels (α's)
→ additional event discrimination (LUCIFER...)?

- ## XENON-TPCs

e.g. EXO, 175 kg of LXe (80% enriched)

(+) large mass + enrichment

(+) good event discrimination

(+) easy to scale up

(−) moderate energy resolution: ~4%

Current limit: $T_{1/2} > 1.6 \cdot 10^{25}$ yrs

- Loaded liquid scintillators

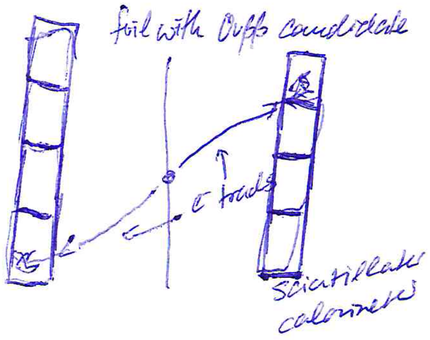
e.g. KamLAND-Zen, SNO+
(Xe) (Te)
↳ balloon filled with Xe-loaded LS

⊕ huge detectors → masses

⊕ self-shielding of LS, clean materials

⊖ poor energy resolution: ~10% → $2\nu\beta\beta$ leaking in ROI

- Tracking calorimeters



Super-NEMO

⊕ energy, charge, momentum resolved
→ excellent BG suppression

⊕ multiple isotopes

⊖ relatively poor energy resolution: ~8%

⊖ low efficiency: 8%

⊖ low mass-to-size/cost ratio
→ not easy to scale