Neutrinos : désintégration double-béta

Neutrinos: double-beta decay

Federico Ferri

CEA-Saclay Irfu-DPhP

Journée prospectives DPhP 2017-2027, October 16, 2017

- Some starting points and inputs for discussion
- **!!NOT!!** a comprehensive review talk

$0\nu\beta\beta : (A, Z) \rightarrow (A, Z + 2) + 2e^-$

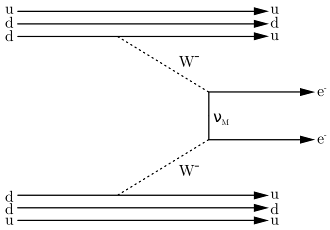
Equivalent decay modes with lower experimental sensitivity:

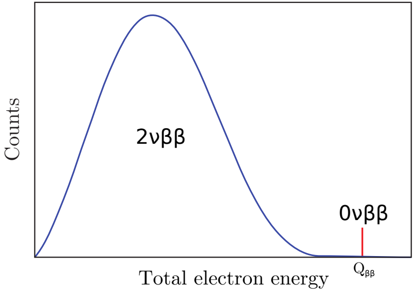
$(A, Z) \rightarrow (A, Z + 2) + 2e^+$ $\quad$ $(A, Z) + 2e^- \rightarrow (A, Z - 2)$ $\quad$ $(A, Z) + e^- \rightarrow (A, Z - 2) + e^+$

Proposed about 80 years ago.

- Violates lepton number by two units
  $\rightarrow$ did νs played an important role in the creation of the matter-antimatter asymmetry in the universe?
- Can only happen if neutrinos are Majorana fermions, i.e. $\nu \equiv \bar{\nu}$
- Neutrinos would have a Majorana mass
  - and $0\nu\beta\beta$ would allow to set constraints on their mass scale, complementary to direct and cosmological ones
- Can help shed light onto the mass hierarchy problem
- Unique possibility to measure the neutrino Majorana phases

$0\nu\beta\beta : (A, Z) \rightarrow (A, Z + 2) + 2e^-$





- Forbidden in the Standard Model (SM)
- Most appealing mechanism: exchange of light Majorana neutrinos.
- Runners up:
  - exchange of heavy right-handed (RH) neutrino of mass of $\mathcal{O}(10\,\text{GeV})$
  - RH currents and (heavy) intermediate bosons
  - → direct searches possible (e.g. LHC)
- Allowed in the SM: $2\nu\beta\beta$. **Irreducible background** for the $0\nu\beta\beta$ search.

(Almost) one slide of theoretical framework

Process half-life for exchange of light neutrino:

$$\left(t_{1/2}^{0\nu}\right)^{-1} = G_{0\nu}\, \left|g_A^{\,2}\, M_{0\nu}\right|^2 \frac{|m_{\beta\beta}|^2}{m_e^2}$$

$G_{0\nu}$ phase space integral: nowadays considered "accurate"

g_A axial coupling: not fully understood yet

- vacuum value $g_A = 1.269$; is it quenched in the nuclear medium?
- no clear arguments, no well defined "control samples" (e.g. unclear if the same in $0\nu\beta\beta$ and $2\nu\beta\beta$ transitions)

10% variation in $g_A \rightarrow$ same measurement in $\approx \times 2$ time

- auxiliary experimental efforts ongoing to shed light on this

$$M_{0\nu} = \left(M_{0\nu}^{\mathrm{GT}} - \left(\frac{g_V}{g_A}\right)^2 M_{0\nu}^{\mathrm{F}} + M_{0\nu}^{\mathrm{T}}\right), \qquad m_{\beta\beta} = \sum_{k=1}^{3} |U_{ek}^{L}|^2\, m_k\, e^{i\varphi k}$$

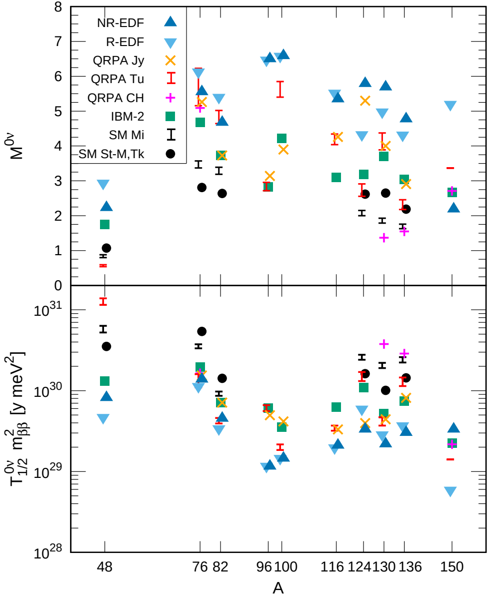
Nuclear Matrix Elements (NMEs)

$$\left(t_{1/2}^{0\nu}\right)^{-1} = G_{0\nu}\,|g_A^2 M_{0\nu}|^2\,\frac{|m_{\beta\beta}|^2}{m_e^2}$$

- NMEs improving results (especially their errors)
- Still a factor of 2 discrepancy among methods
- No agreement with “standard candles” either
  - single β decay, electron capture, $2\nu\beta\beta$

However, bottom line:

- No isotope significantly preferred when comparing decay rate per mass
- Choice mainly driven by experimental considerations

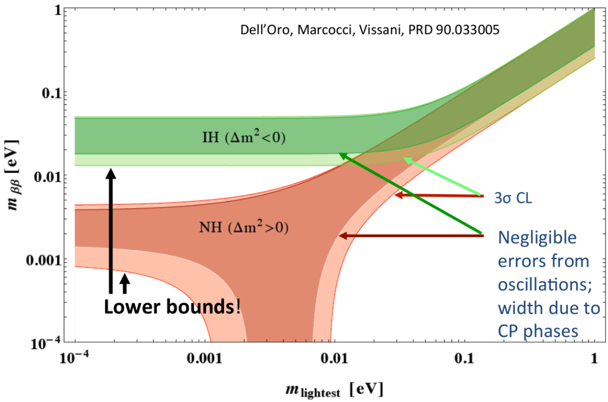


Range of $m_{\beta\beta}$ from oscillation experiments

$$\left(t_{1/2}^{0\nu}\right)^{-1} = G_{0\nu}\,|g_A^2 M_{0\nu}|^2\,\frac{|m_{\beta\beta}|^2}{m_e^2}$$

$$m_{ee} = f(m_1, \underbrace{\Delta m^2_{sol}, \Delta m^2_{atm}, \theta_{12}, \theta_{13}}_{\text{from oscillation experiments}}, \alpha\text{-}\beta)$$

Goal of next generation experiments:



Experiments: mainstreams

- Arrays of calorimeters with excellent energy resolution and improved background suppression methods (e.g. GERDA, MAJORANA) or based on unconventional techniques (e.g. CUORE, CUPID)

- Detectors with generally poor energy resolution but with topology reconstruction (e.g. EXO, SuperNEMO)

- Experiments based on suitable modifications of an existing setup aiming at a different search (e.g. SNO+, KAMLAND)

Vivid community with intense R&D activities on experimental isotopes, signal discrimination techniques, analysis techniques, ...

- @TAUP2017: first results from Cuore, new results from GERDA, new results from EXO

Experiments: next generation

Current best limits:

KamLAND-Zen	^{136}Xe	$10.7\cdot10^{25}$ y
GERDA	^{76}Ge	$5.3\cdot10^{25}$ y

$$N_{0\nu\beta\beta} = \frac{\ln 2 \cdot N_A \cdot \text{Sensitive exposure}}{m_a \cdot t_{1/2}}$$

(approx. for zero bkg exp.)

Sensitive exposure = Isotope Mass · live time · corrections

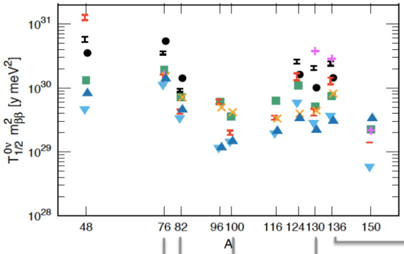
(efficiency, acceptance, prob. $0\nu\beta\beta$ event in ROI)

Sensitive background = $N_{\text{bkg}}(\text{ROI})$/Sensitive exposure

- The best possible energy resolution and excellent time resolution, giving the maximum information on the deposited energy and event topology;
- A reliable and easy to operate detector technology, suitable for long time underground data taking with minimum maintenance;
- A mass of not less than $\mathcal{O}(1\,\text{t})$, possibly isotopically enriched
  - $\approx$ one order of magnitude larger than current experiments

Experiments: attendance call

from S. Schoenert https://cern.ch/go/h8Lk



LXe TPC:	EXO-200 / nEXO
gas-Xe TPC:	NEXT, PandaX-III
Xe-loaded LS:	KamLAND-Zen

Te-loaded LS:	SNO+
Te-bolometers:	CUORE / CUPID-Te

Mo-bolometers:	CUPID-Mo (ex Lumineu)
	AMoRE

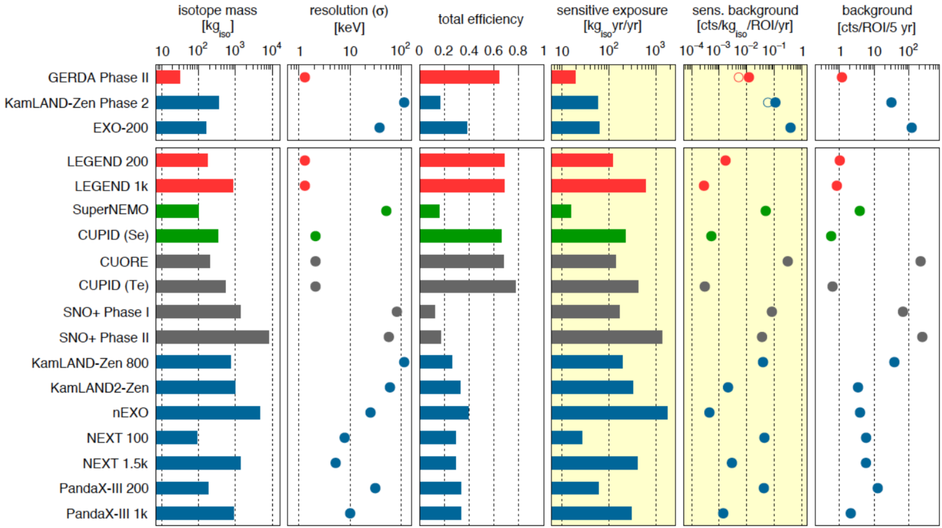
Se-bolometers:	CUPID-0 (ex Lucifer)
Se-calo-tracko:	SuperNEMO

Ge-semiconductor: GERDA, MJD, LEGEND

& other interesting, but less advanced R&D; ^{48}Ca, ^{150}Nd not available in large quantities

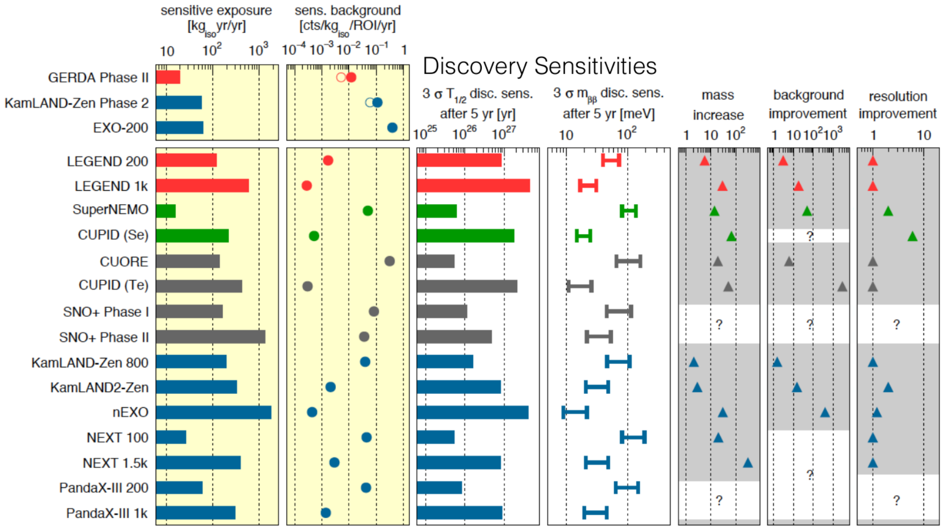
Experiments: comparisons

from S. Schoenert https://cern.ch/go/h8Lk



Experiments: comparisons

from S. Schoenert https://cern.ch/go/h8Lk

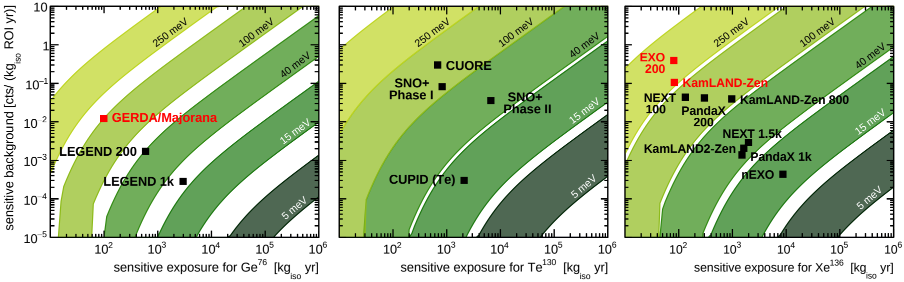


Discovery sensitivity (5 y lifetime)

from M. Agostini, G. Benato, J.A. Detwiler https://cern.ch/go/9bdz

Bayesian discovery probability as a function of sensitive exposure and sensitive background

- Non zero mass both for the lightest neutrino and for $m_{\beta\beta}$
- NMEs uncertainties included in the fit
- Cosmological constraints also considered

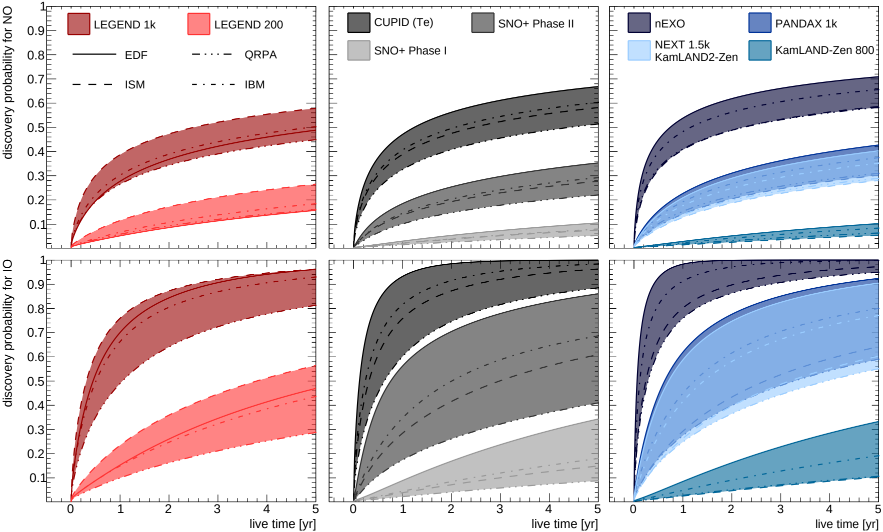


N.B. g_A quenching studied: while it degrades the sensitivity (low $m_{\beta\beta}$ inaccessible) it relaxes constraints on high $m_{\beta\beta}$ by current experiments

$\Longrightarrow$ impact on discovery potential much reduced w.r.t. sensitivity

Discovery probability

from M. Agostini, G. Benato, J.A. Detwiler https://cern.ch/go/9bdz



Neutrinos @ Irfu

Disclaimer: surely not an exhaustive list of activities

- Long baseline experiments (T2K) — DPhP
- Short baseline experiments (DoubleChooz, CeSOX) — DPhP + DPhN
- Cosmological analyses (BOSS/SDSS *et al.*) — DPhP
- Direct searches of heavy RH neutrinos at LHC — DPhP

- $0\nu\beta\beta$ **@DPhP**: impact on a next generation experiment
  - based on existing expertise on bolometers
  - current R&D on ^{130}Te, ^{100}Mo, ^{116}Cd, ^{82}Se
  - target of building a demonstrator

- $0\nu\beta\beta$ not @DPhP: PandaX (DPhN), spherical Xe gas TPC (DEDIP)

- Support from DEDIP across all of these items!
- Collaborations with theorists at Irfu also common!

Instead of conclusions

- Approximate timescales ($\approx$ common to all experiments):
  - 2020 choice of the next generation technology (e.g. isotope)
  - 2030 ultimate setup
    - most likely with an intermediate step at $\approx$ 1/5 of the full scale detector around 2025

- Pouvons-nous identifier des expériences dans notre périmètre scientifique auxquelles nous devrions participer ?

- Avons-nous de nouveaux concepts d'expérience à proposer ?