Neutrinoless Double Beta Decay
$0\nu\beta\beta$

Prof Jeanne Wilson

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Introducing myself

Professor in Particle Physics

How did I get here?

- PhD on SNO experiment, University of Oxford
- 5 years of post-doctoral work: COBRA, SNO+
- 1st Lectureship @ Queen Mary, University of London
- Moved to Kings College London in 2019
- Plus lots of support and encouragement along the way!

Outline

Lecture 1

- What is double beta decay?
  - SEMF splitting
  - Known isotopes
- 2 neutrino double beta decay
- Neutrino-less double beta decay
  - Theory
  - Dirac and Majorana neutrinos
  - See-saw mechanism

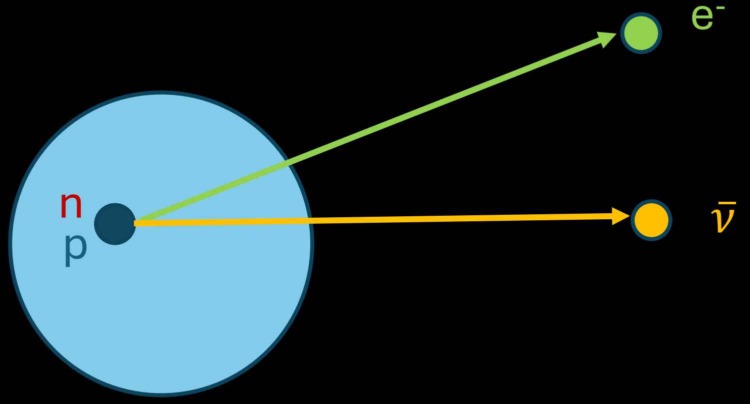
Lecture 2

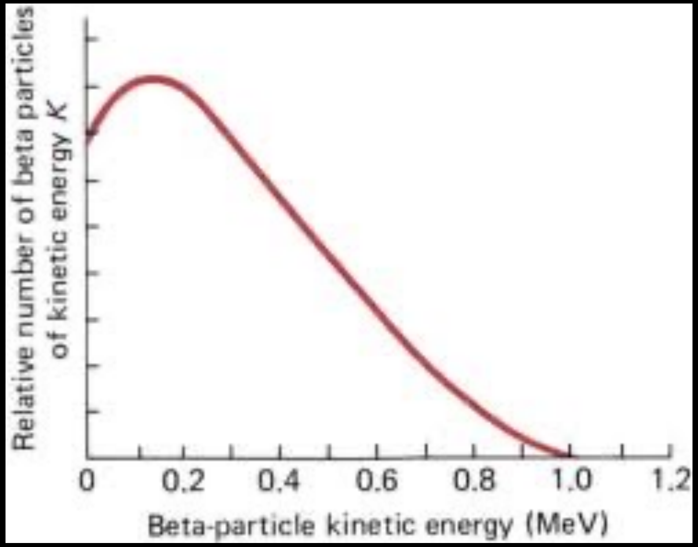
- Half-life / rate
  - Phase space
  - Matrix elements
- Experimental considerations
  - Challenges
  - Backgrounds
- Experiment examples

Lecture 3

- Neutrino mass
- Lobster plots
- Limits vs Discovery
- Alternative mechanisms and probing new physics
- $\beta^+\beta^+$ decays
- Future prospects

Beta Decay



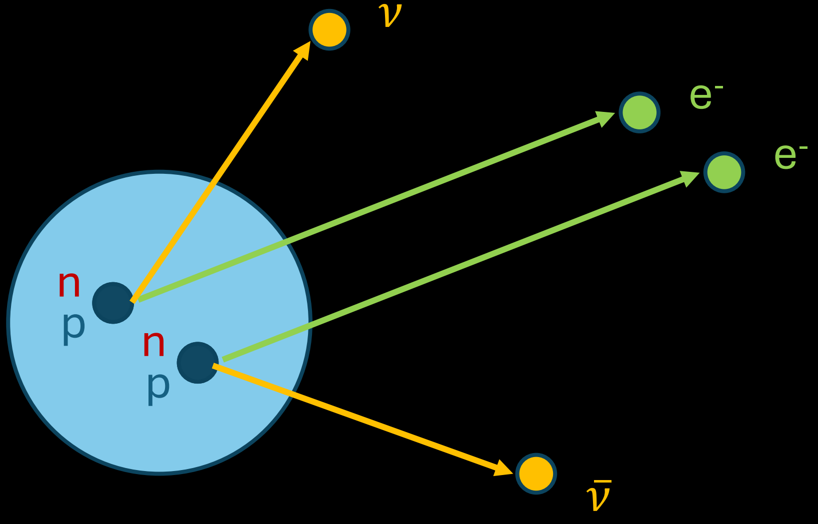


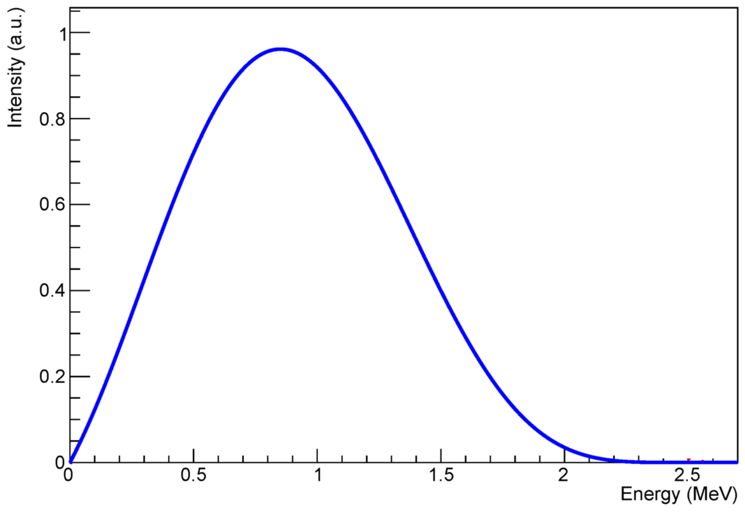
$$n \rightarrow p + e^{-} + \bar{\nu}_e$$

- Beta decay is only possible if parent nucleus has greater atomic mass than final nucleus

$$M(A, Z) > M(A, Z + 1)$$

Double Beta Decay ($2\nu\beta\beta$)





Sum energy of 2 betas

$$2n \rightarrow 2p + 2e^{-} + 2\bar{\nu}_e$$

Semi-Empirical Mass Formula (SEMF)

- Semi-empirical mass:

$$m = Zm_p + (A - Z)m_n - E_B$$

- Binding energy

$$E_B = a_V - a_S A^{\frac{2}{3}} - a_C \frac{Z(Z-1)}{A^{\frac{1}{3}}} - a_A \frac{(A-2Z)^2}{A} + \delta(A,Z)$$

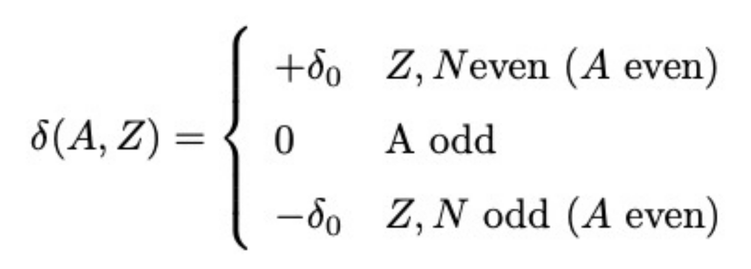
Volume term
Related to inter-nucleon
strong force so ∝ A

Surface term
Corrects for strong force at
nucleon's surface where
therer are less nearest
neighbours ∝ $A^{2/3}$

Coulomb electrostatic term
Related to repulsion
between protons in nucleus

Asymmetry term
∝ relative number of n and p
in nucleus
Pauli Exclusion Principle

Pairing term
Effect of spin-coupling
Even number of n(p) means
equal ↑↓

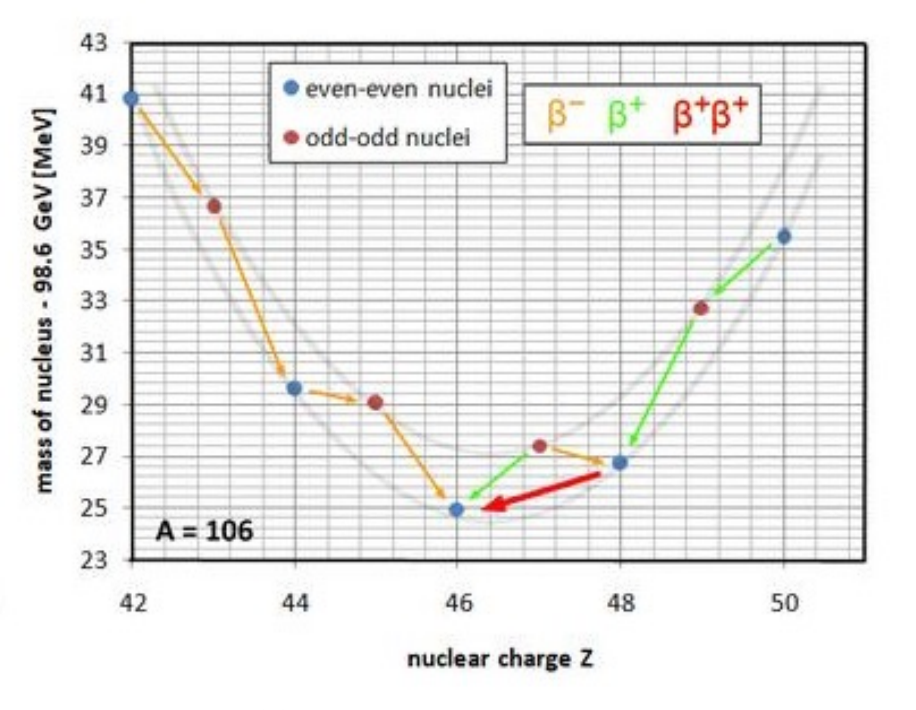


$$\delta(A,Z) = \begin{cases} +\delta_0 & Z, N \text{even } (A \text{ even}) \\ 0 & \text{A odd} \\ -\delta_0 & Z, N \text{ odd } (A \text{ even}) \end{cases}$$

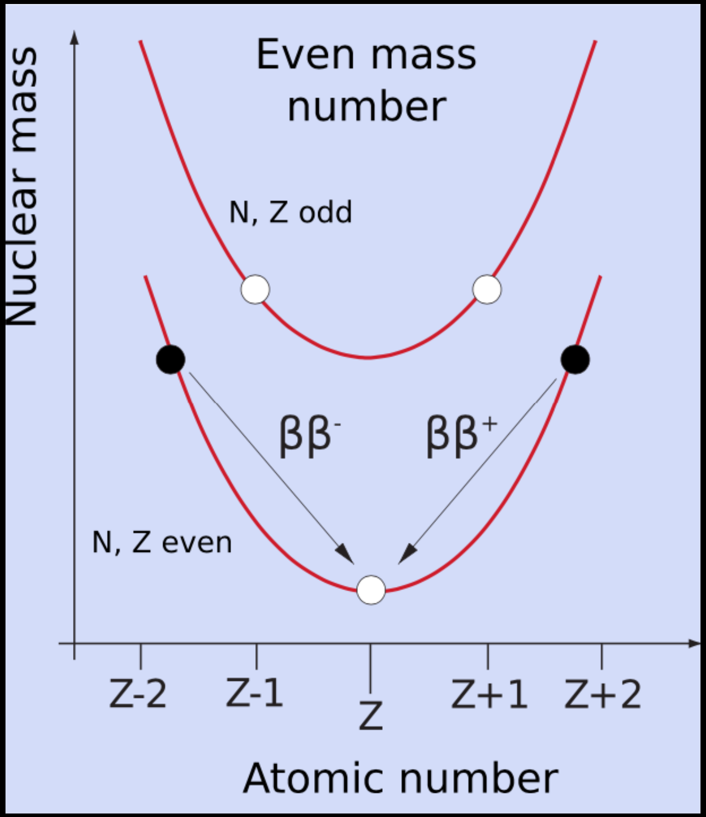
Semi-Empirical Mass Formula (SEMF)

- Gives rise to parabolic curves for fixed mass number (A) and different proton number (Z).
- Odd A = one curve
- Even A = 2 curves due to pairing term

$$\delta(A,Z) = \begin{cases} +\delta_0 & Z, N\text{even } (A \text{ even}) \\ 0 & \text{A odd} \\ -\delta_0 & Z, N \text{ odd } (A \text{ even}) \end{cases}$$



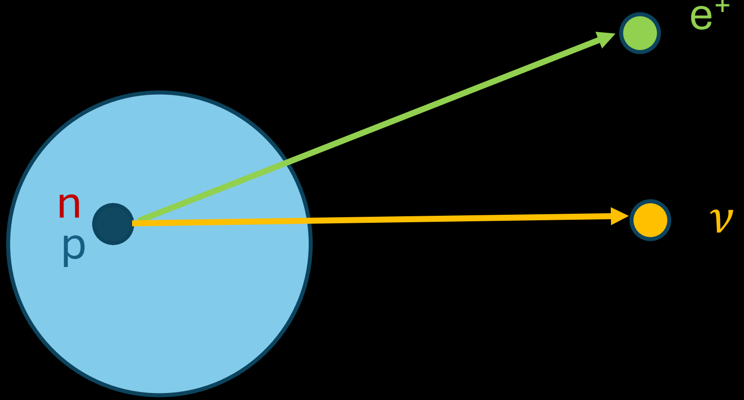
Which isotopes?

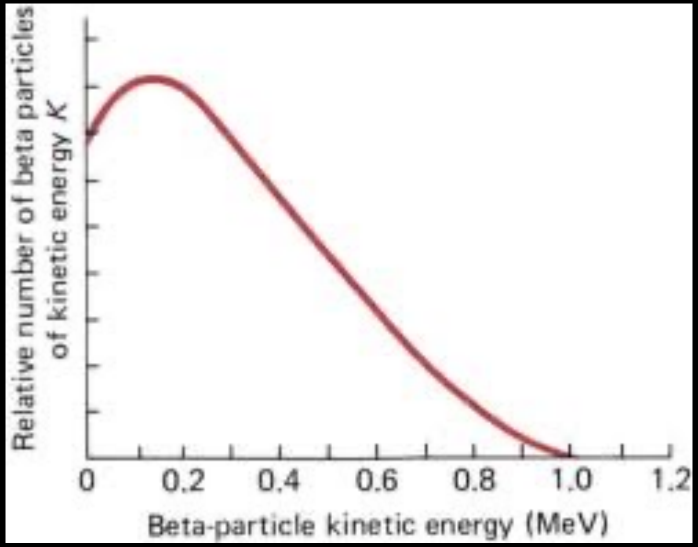


- A single beta decay that requires energy input is forbidden (or at least strongly suppressed)

- There are 35 possible isotopes where single beta decay is forbidden but two consecutive β^- decays result in a net energy decrease
- These are all even-even nuclei

Beta$^+$ Decay





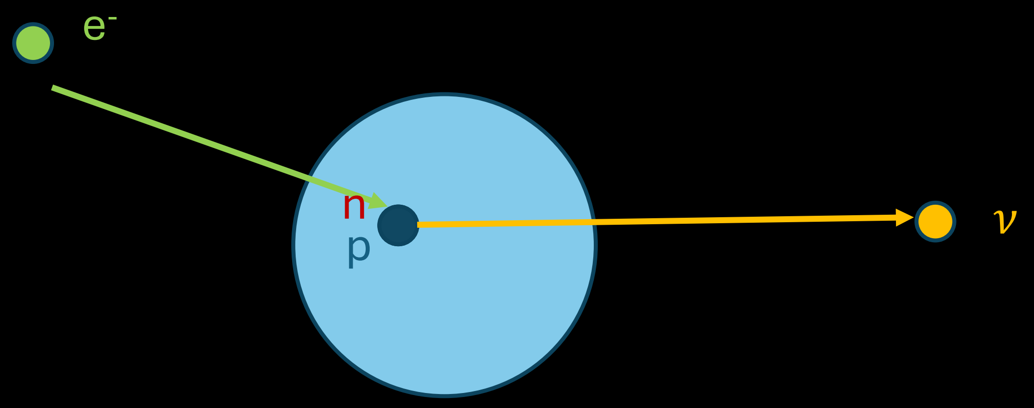
$$\mathrm{p} \rightarrow n + e^+ + \nu_e$$

Slide 4: Beta decay requirement

$$M(A,Z) > M(A,Z+1)$$

$$M(A,Z) > M(A,Z-1) + 2m_e$$

Electron Capture

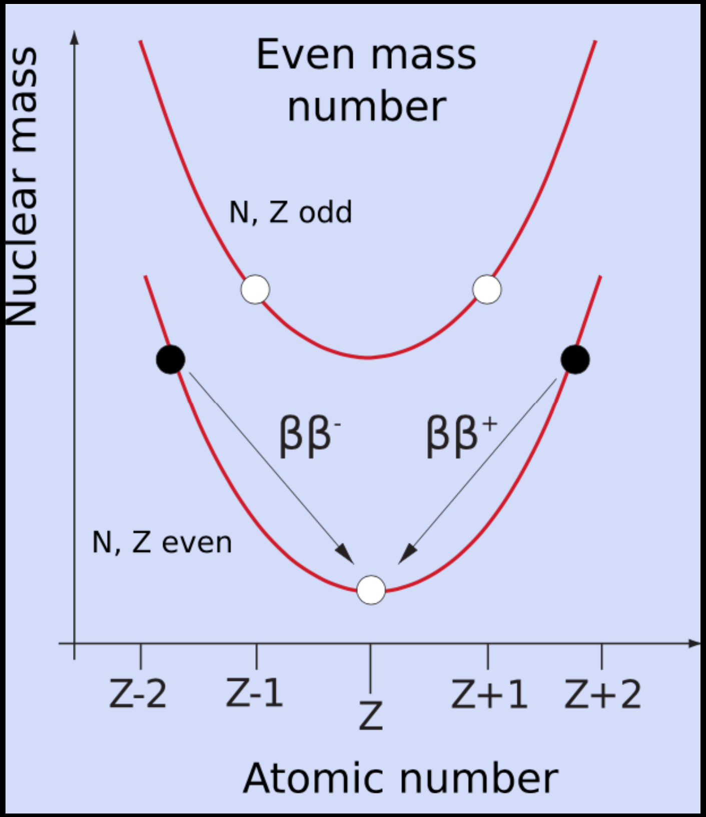


$$e^- + p \rightarrow n + \nu_e$$

No final state electron
Only visible signal is de-excitation energy release from nucleus:
cascade transition giving X-rays and/or Auger electrons.

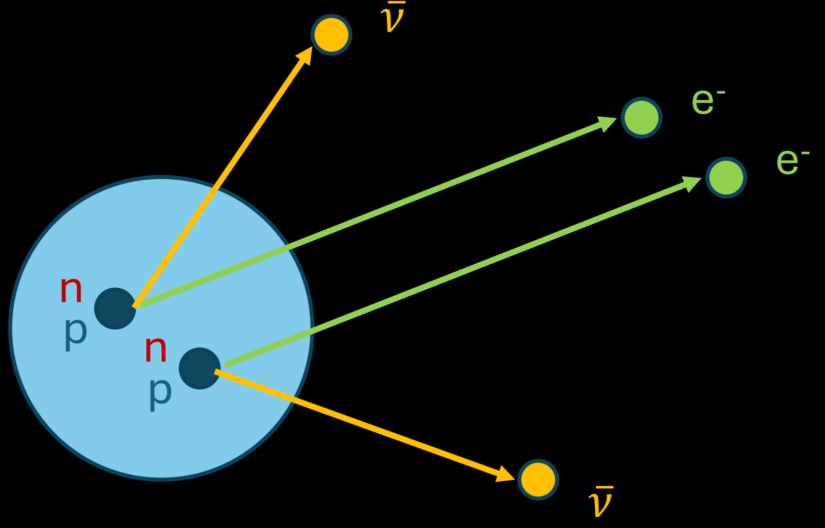
- Electron capture (EC) occurs when a nucleus does not have enough energy to create and emit a positron
  - Captures an electron from a low orbital leaving a hole to be filled by a higher orbital electron

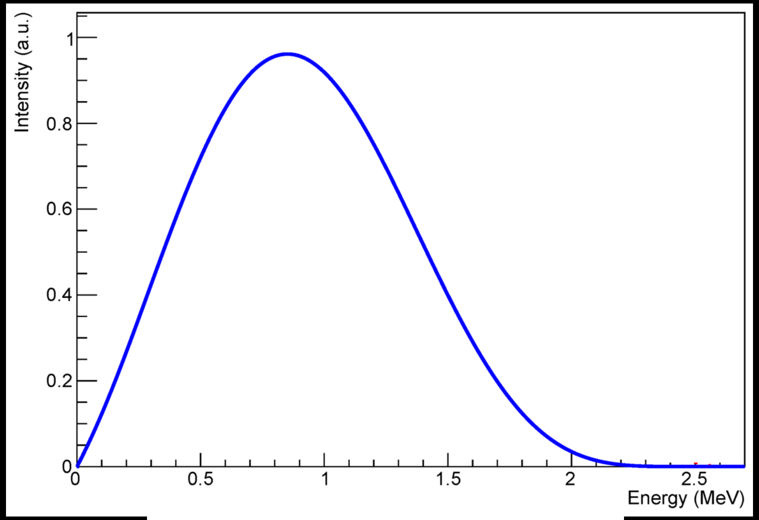
Which isotopes?



- A single beta decay that requires energy input is forbidden (or at least strongly suppressed)
- There are 35 possible isotopes where single beta decay is forbidden but two consecutive β^- decays result in a net energy decrease
- There are 34 more that can undergo double electron capture (ECEC)
  - Some of these have Q>1.022MeV so β^+EC allowed
  - 6 of these have Q>2.044MeV so $\beta^+\beta^+$ decay allowed
- These are all even-even nuclei

Double Beta Decay ($2\nu\beta\beta$)





Sum energy of 2 betas

Standard model double Weak process

- Long half life $T_{1/2} \sim 10^{20}$years
- Observed for several isotopes

A Little History

- Maria Goeppert-Mayer
  - Proposed double beta decay in 1935
  - Nobel prize 1963 (shell model)
- Ettore Majorana
  - Proposed 2 component neutrino in 1937
  - ‘Majorana neutrino’
- Wendell Furry
  - If neutrinos are majorana, double beta decay could proceed without the emission of any neutrinos (1939)

$2\nu\beta\beta$ Observations - indirect

- Double beta decay of ^{130}Te was first detected in 1950 geochemically
- Detection of excess of ^{130}Xe was proof of $\beta\beta$ decay of the initial nucleus, allowed first determination of $2\nu\beta\beta$ halflife $T_{1/2} = 1.4 \times 10^{21}\, \boldsymbol{yr}$

Inghram M G and Reynolds J H 1950 Phys. Rev. 78 822–3

- $T_{1/2}^{2\nu}$ for ^{238}U → ^{238}Pu measured to be $(2.0 \pm 0.6)\times 10^{21}$years by chemically isolating plutonium accumulated over 35 years from 8.4kg of purified Uranyl nitrate Turkevich, Economou, and Cowan, Phys. Rev. Lett. **67**, 3211 (1991)

$2\nu\beta\beta$ Observations - direct

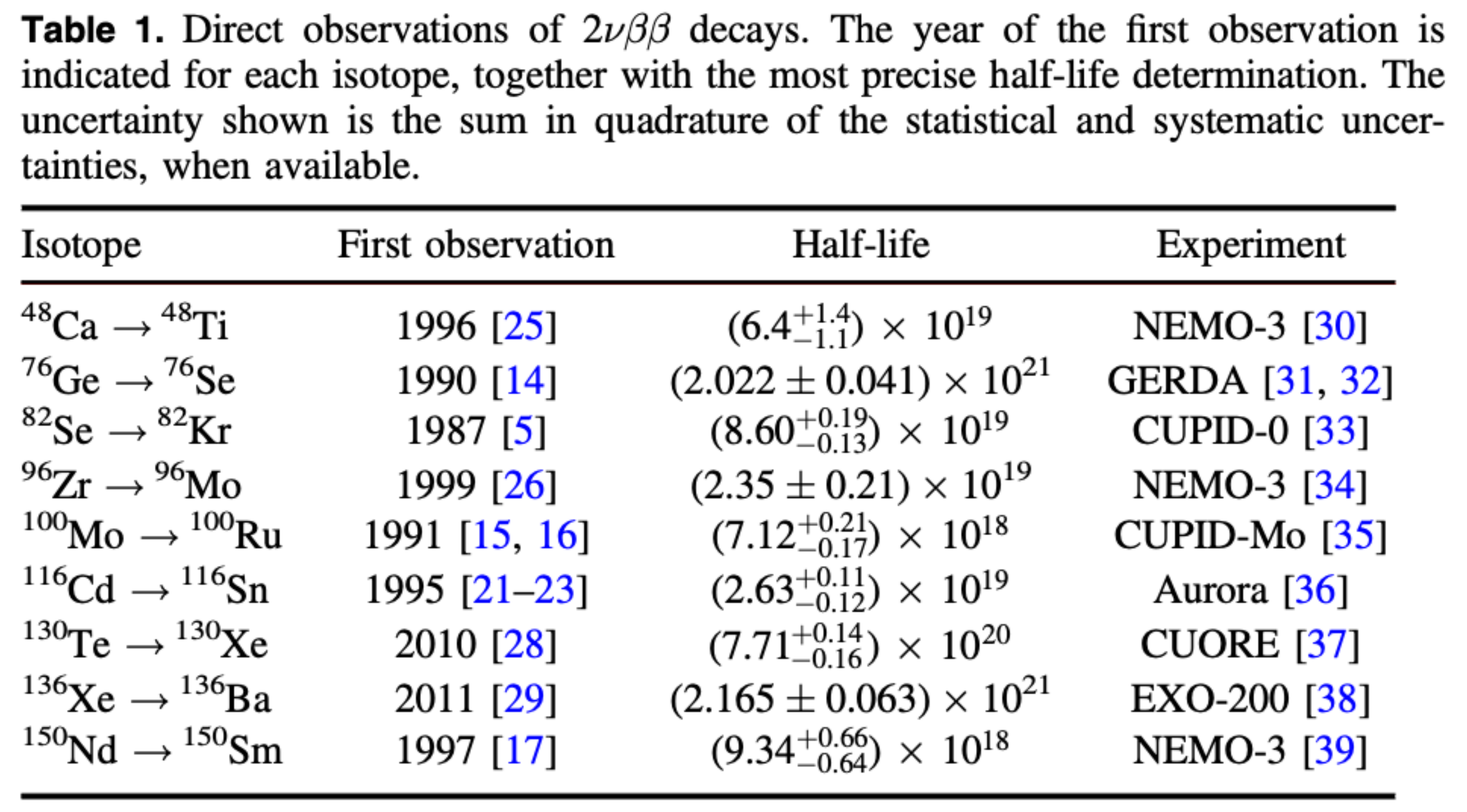


Table 1. Direct observations of $2\nu\beta\beta$ decays. The year of the first observation is indicated for each isotope, together with the most precise half-life determination. The uncertainty shown is the sum in quadrature of the statistical and systematic uncertainties, when available.

Isotope	First observation	Half-life	Experiment
$^{48}\mathrm{Ca} \rightarrow {}^{48}\mathrm{Ti}$	1996 [25]	$(6.4^{+1.4}_{-1.1}) \times 10^{19}$	NEMO-3 [30]
$^{76}\mathrm{Ge} \rightarrow {}^{76}\mathrm{Se}$	1990 [14]	$(2.022 \pm 0.041) \times 10^{21}$	GERDA [31, 32]
$^{82}\mathrm{Se} \rightarrow {}^{82}\mathrm{Kr}$	1987 [5]	$(8.60^{+0.19}_{-0.13}) \times 10^{19}$	CUPID-0 [33]
$^{96}\mathrm{Zr} \rightarrow {}^{96}\mathrm{Mo}$	1999 [26]	$(2.35 \pm 0.21) \times 10^{19}$	NEMO-3 [34]
$^{100}\mathrm{Mo} \rightarrow {}^{100}\mathrm{Ru}$	1991 [15, 16]	$(7.12^{+0.21}_{-0.17}) \times 10^{18}$	CUPID-Mo [35]
$^{116}\mathrm{Cd} \rightarrow {}^{116}\mathrm{Sn}$	1995 [21–23]	$(2.63^{+0.11}_{-0.12}) \times 10^{19}$	Aurora [36]
$^{130}\mathrm{Te} \rightarrow {}^{130}\mathrm{Xe}$	2010 [28]	$(7.71^{+0.14}_{-0.16}) \times 10^{20}$	CUORE [37]
$^{136}\mathrm{Xe} \rightarrow {}^{136}\mathrm{Ba}$	2011 [29]	$(2.165 \pm 0.063) \times 10^{21}$	EXO-200 [38]
$^{150}\mathrm{Nd} \rightarrow {}^{150}\mathrm{Sm}$	1997 [17]	$(9.34^{+0.66}_{-0.64}) \times 10^{18}$	NEMO-3 [39]

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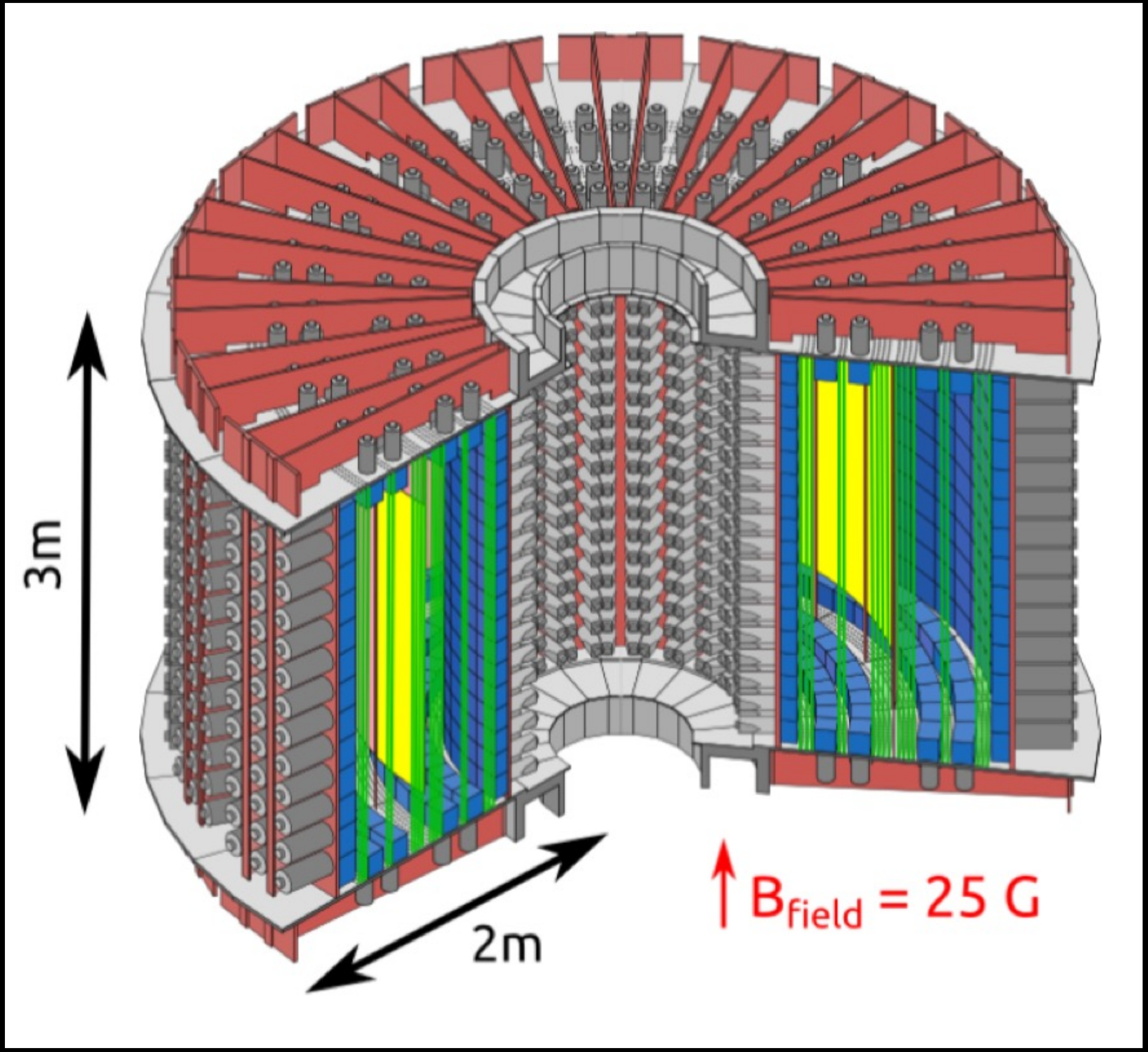
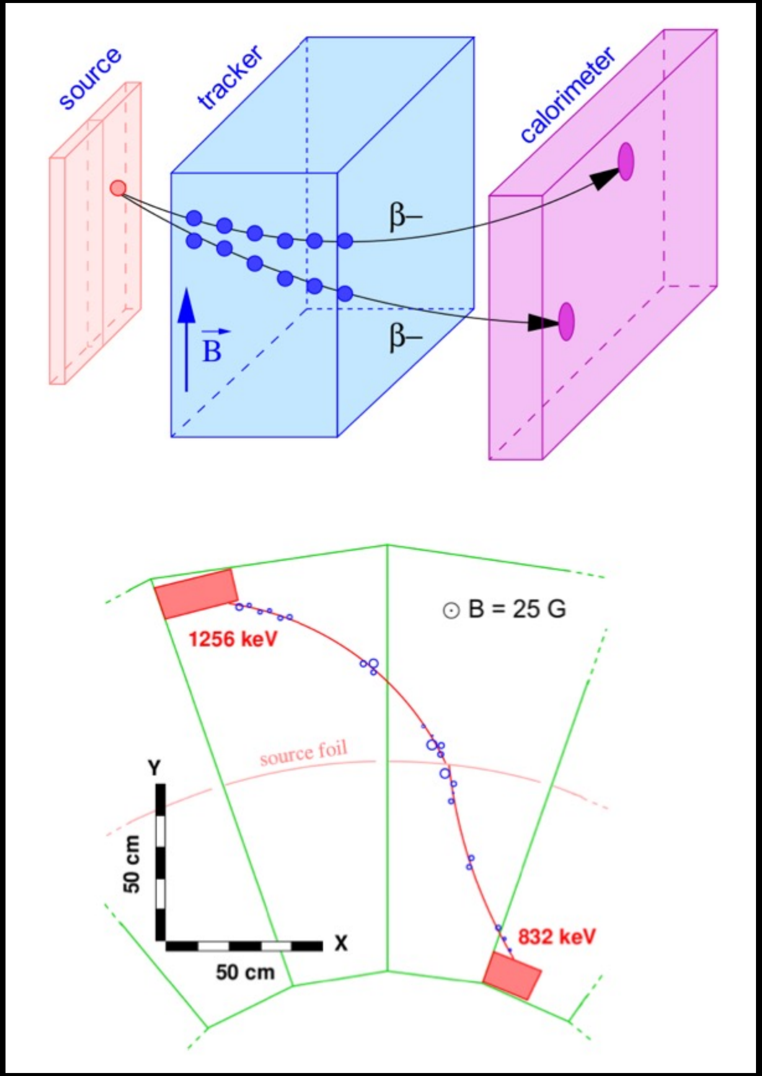
Example – NEMO3

- $\beta\beta$ experiment combining tracker and calorimetric measurements.
- @Modane (LSM) 4800mwe, 2003-11





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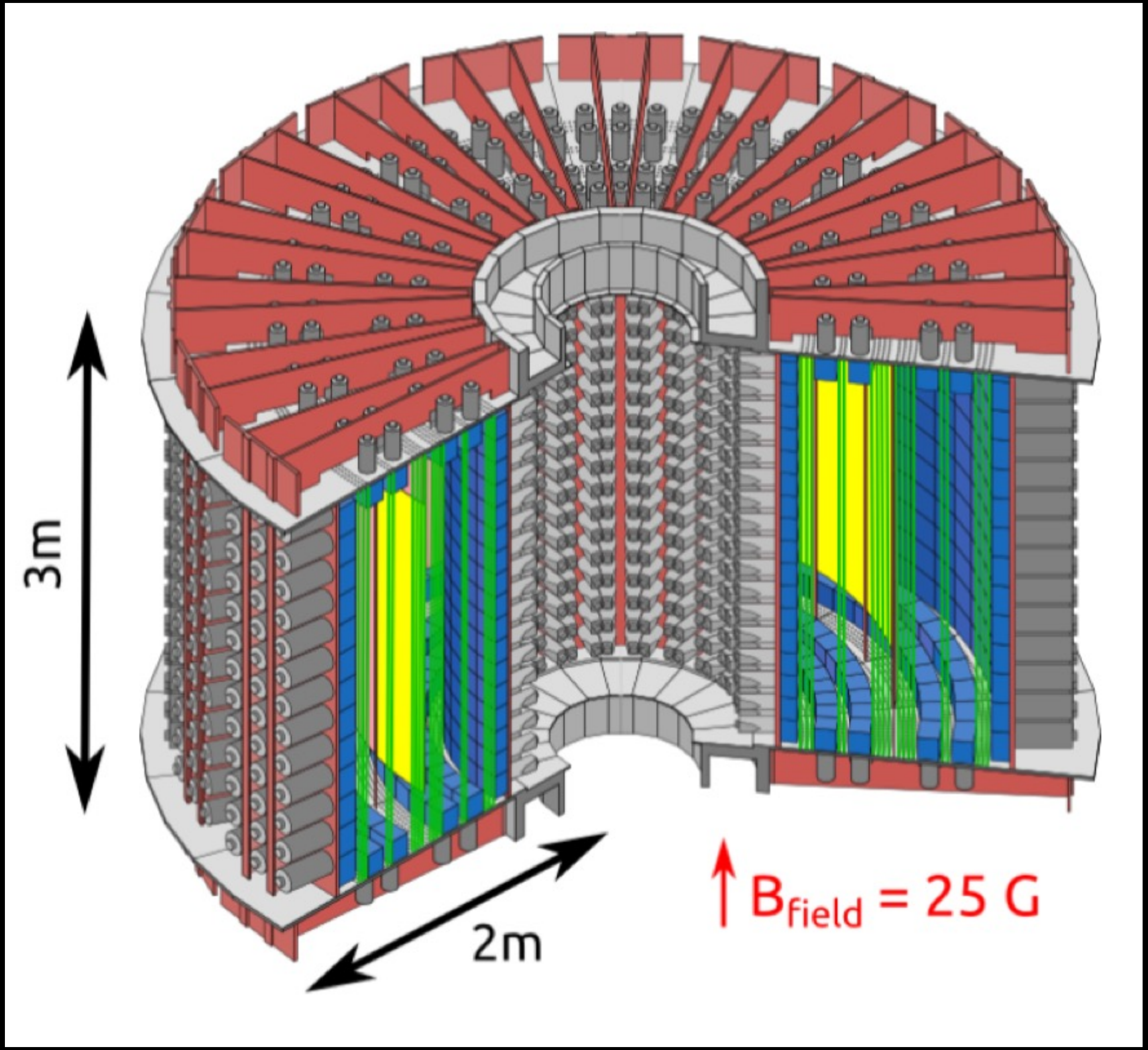
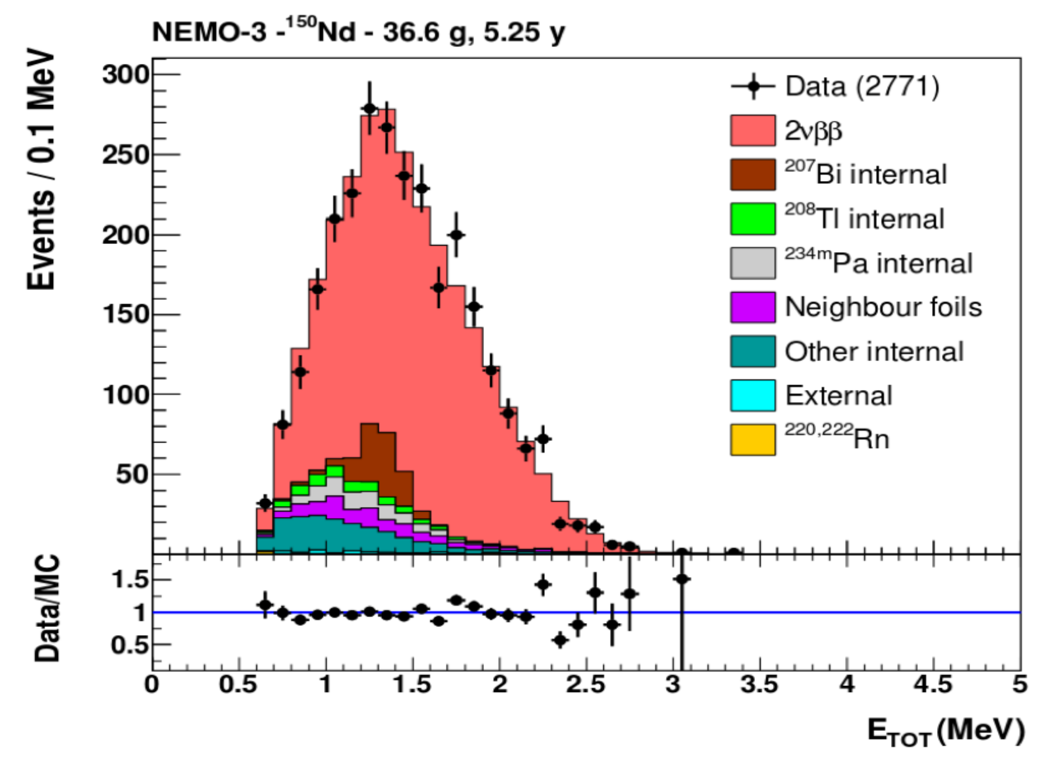
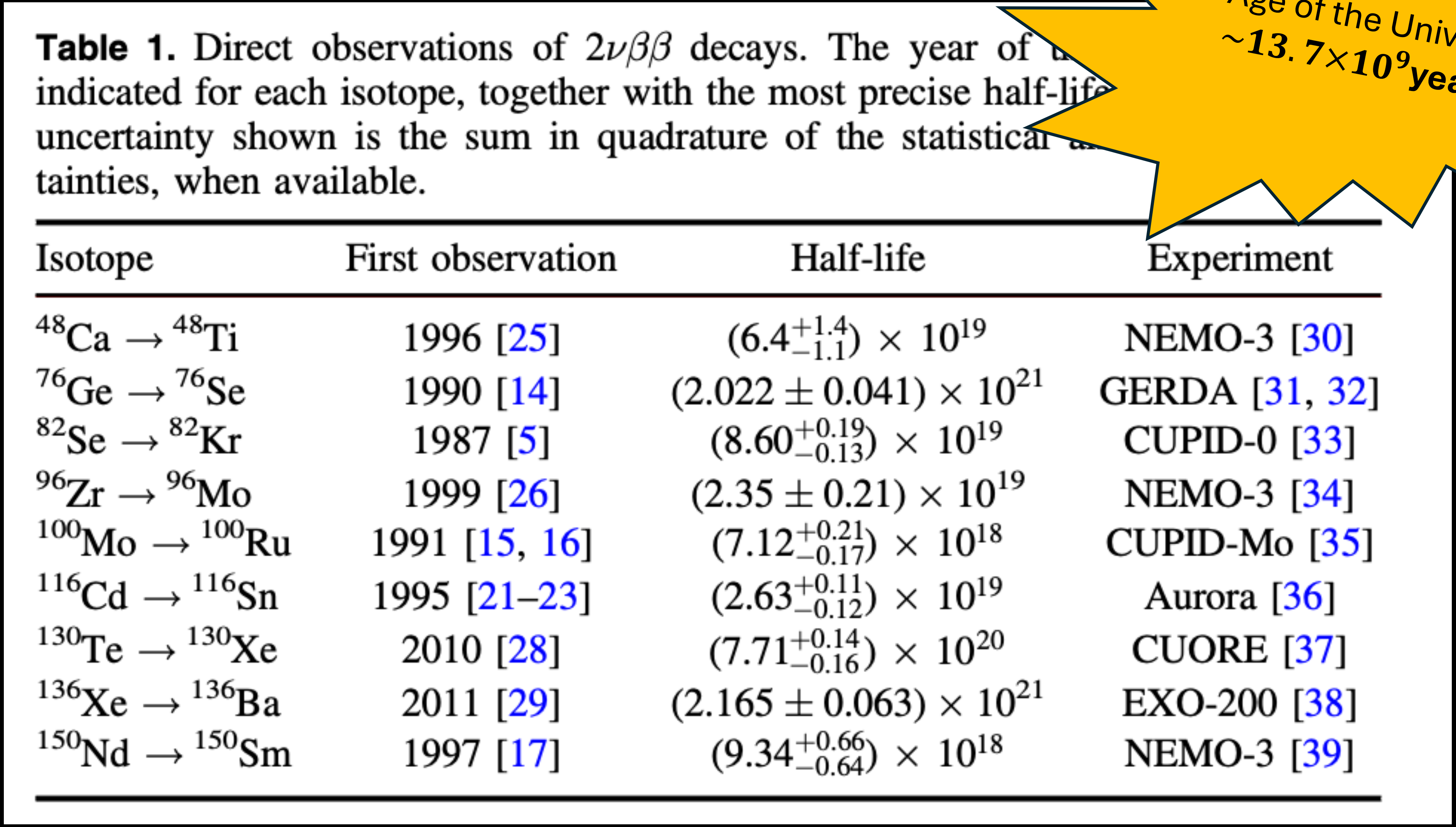


- $\beta\beta$ experiment combining tracker and calorimetric measurements.
- @Modane (LSM) 4800mwe, 2003-11
- 20 identical sectors, investigated 7 different isotopes



Phys.Rev. D94 (2016), 072003

$2\nu\beta\beta$ Observations - direct



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Age of the Universe
$\sim 13.7 \times 10^9$ years

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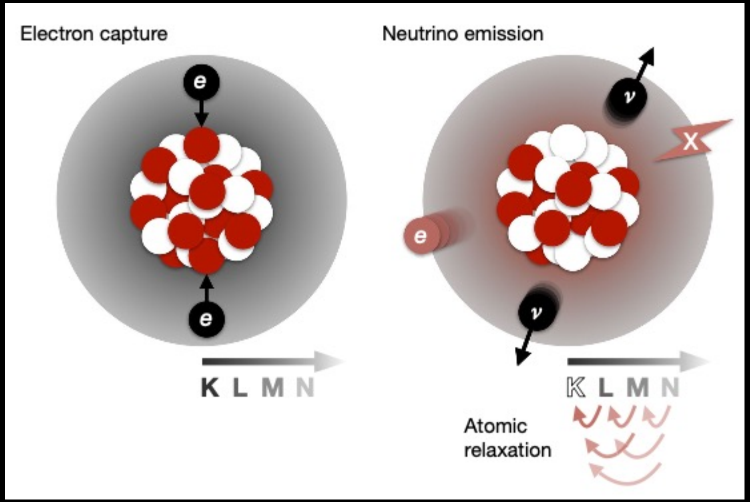
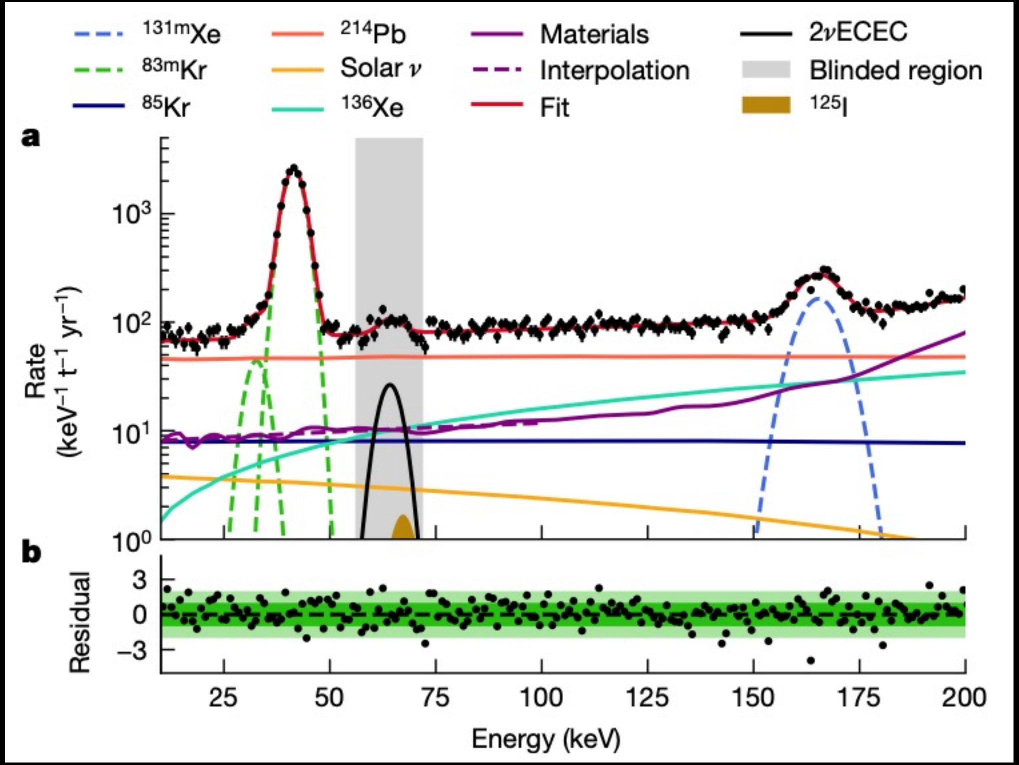
$2\nu ECEC$ measurement

- $2\nu ECEC$ in ^{124}Xe measured in the XENON1T dark matter detector
- Q = 2857keV but most of E carried by neutrinos.
- We only observe X-rays and Auger electrons → $E_{tot}^{obs} = 64.3keV$



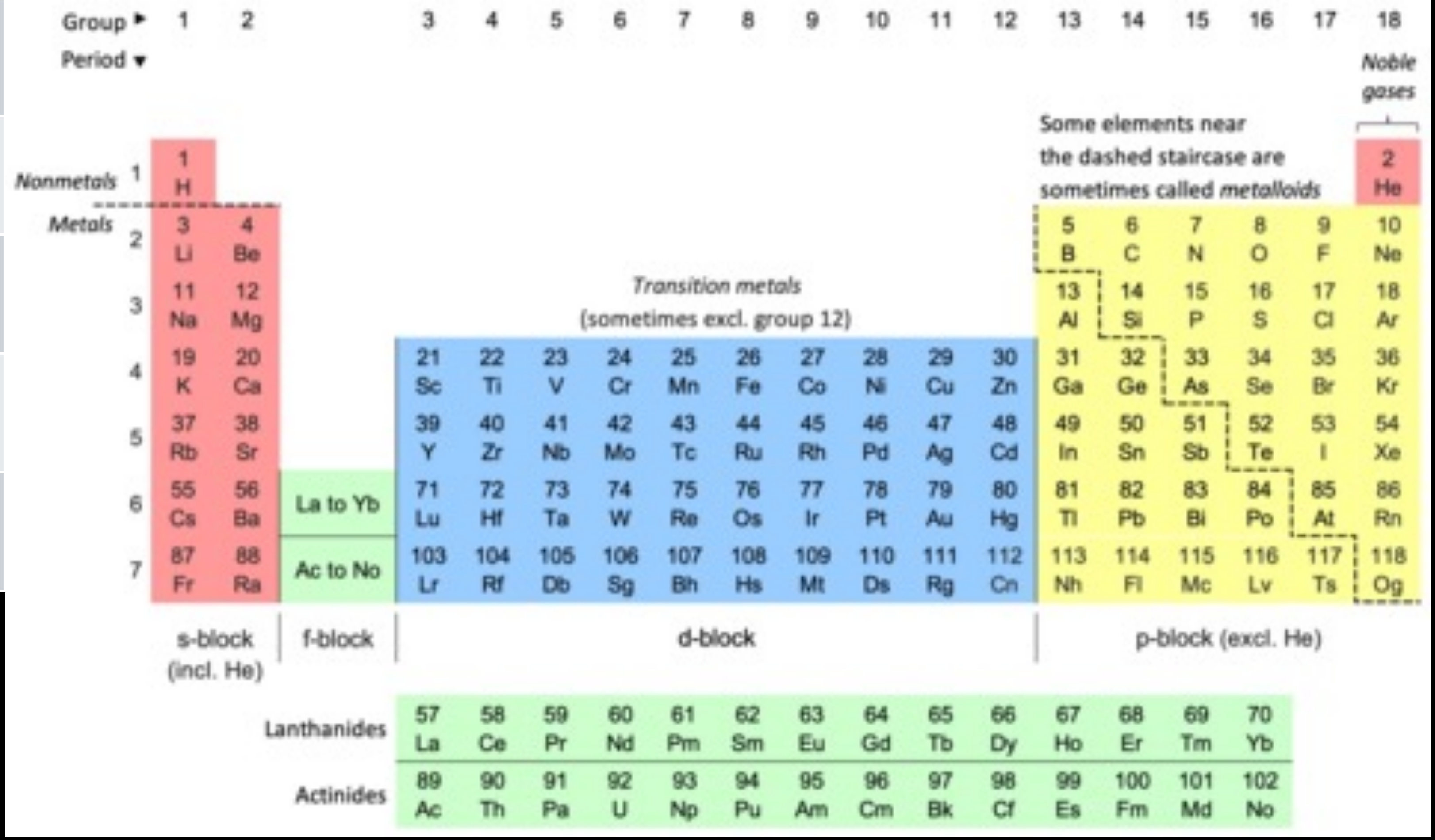


- $T_{1/2} = 1.8 \times 10^{22}$ years
- Longest directly measured half-life so far!

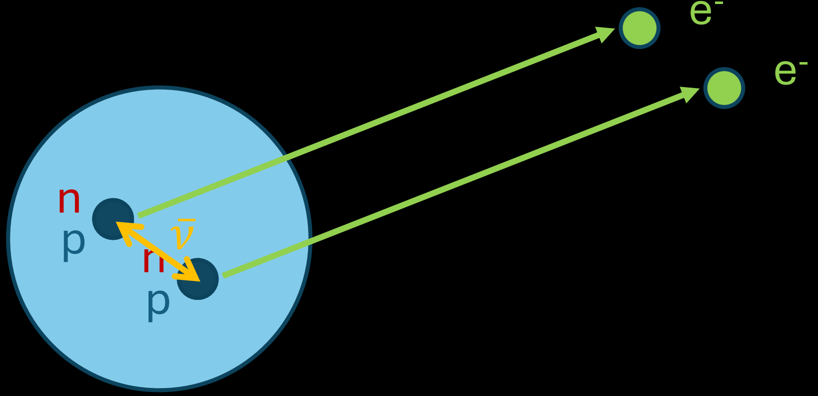
https://www.nature.com/articles/s41586-019-1124-4

Quiz: How does it decay?

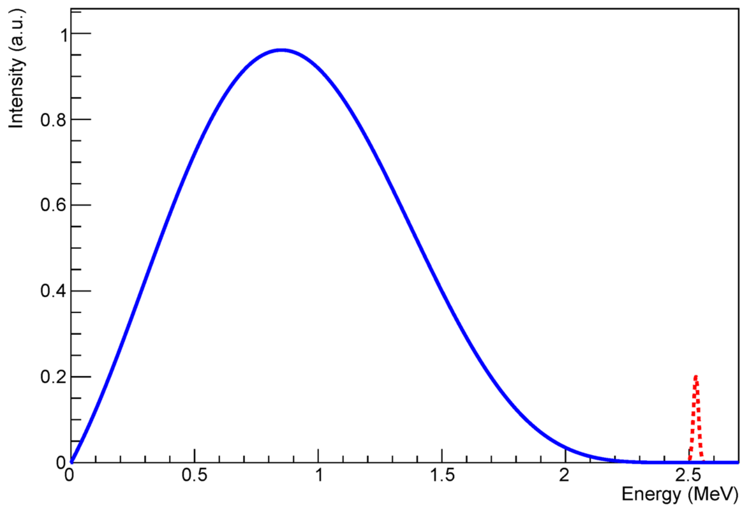
Decay	Q-value (MeV)	Decay Type	Event Signature
$^{116}Cd \rightarrow ^{116}Sn$	2.813		
$^{130}Ba \rightarrow ^{130}Xe$	2.6237		
$^{64}Zn \rightarrow ^{64}Ni$	1.096		
$^{108}Cd \rightarrow ^{108}Pd$	0.2718		
78Kr→78Se	2.881		



Neutrino-less Double Beta Decay $(0\nu\beta\beta)$

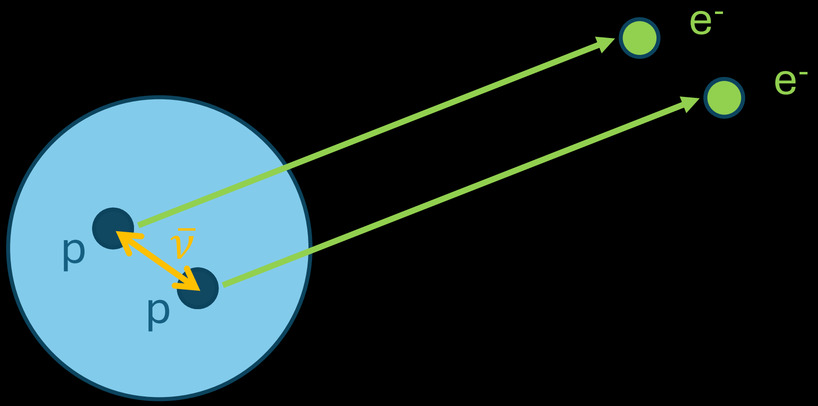


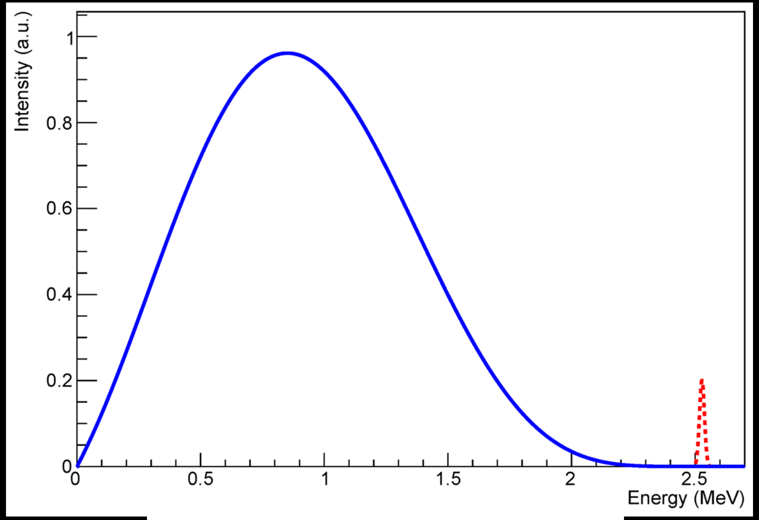
$$2n \rightarrow 2p + 2e^-$$



Sum energy of 2 betas

Neutrino-less Double Beta Decay ($0\nu\beta\beta$)



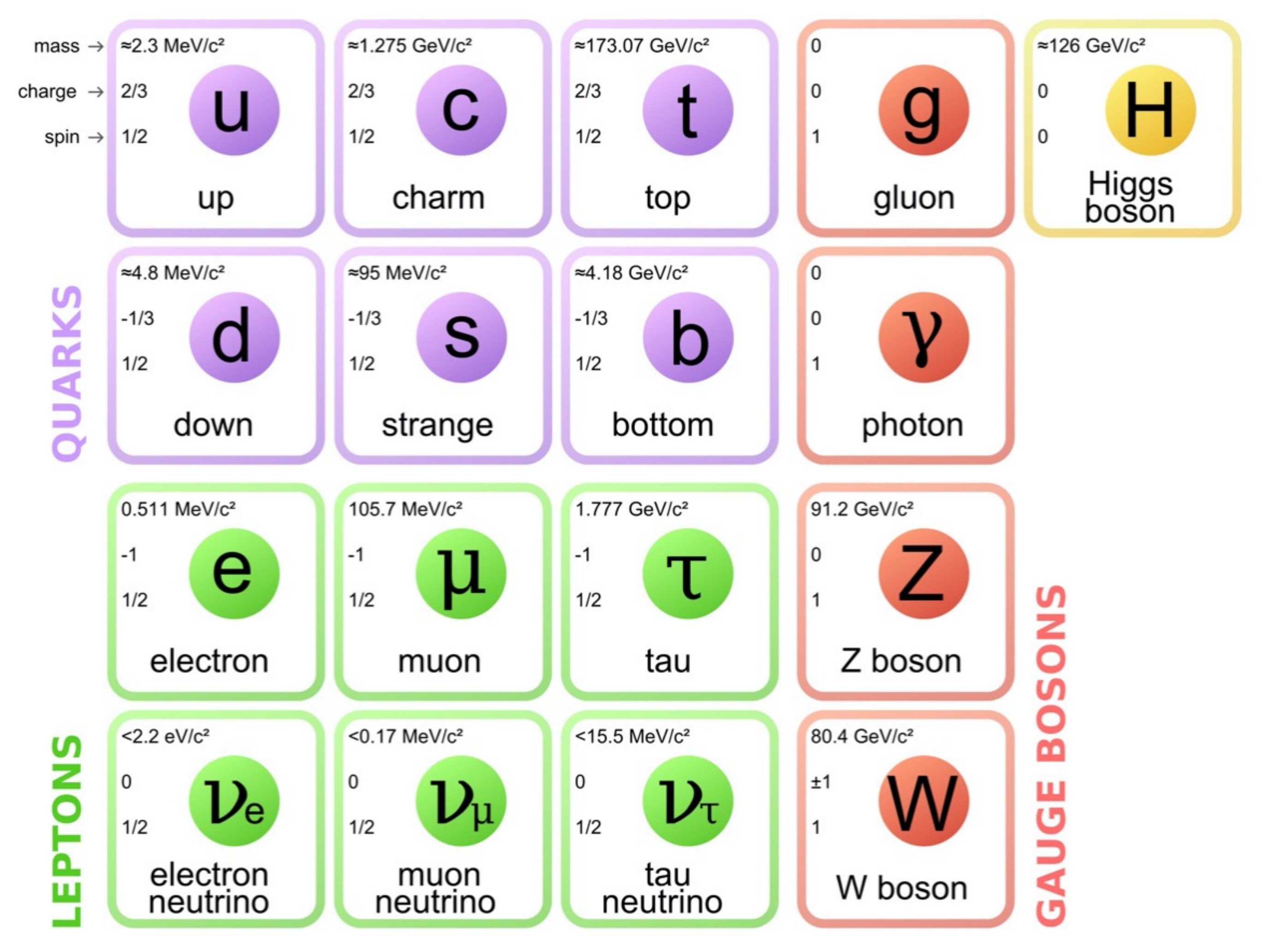


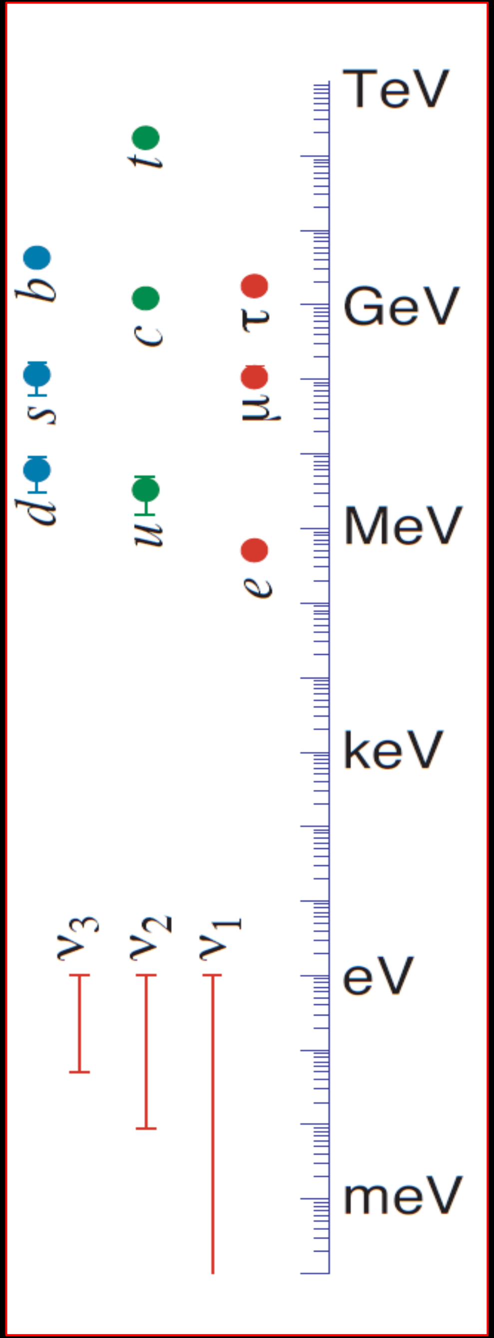
Sum energy of 2 betas

$$2n \rightarrow 2p + 2e^-$$

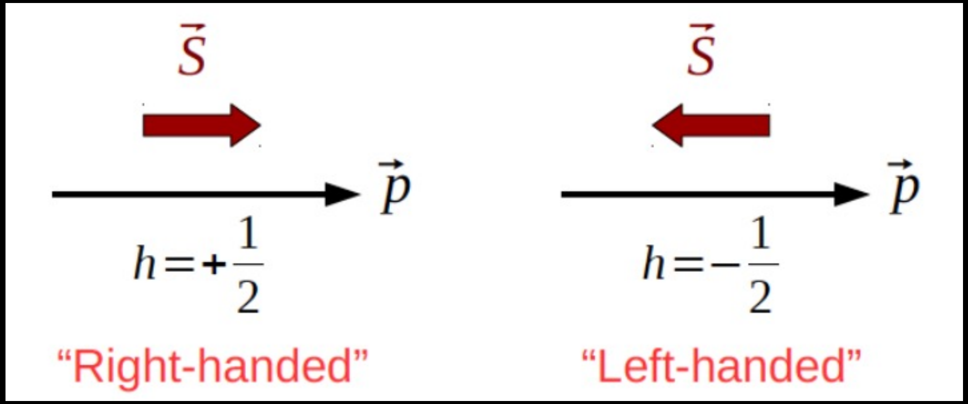
- No neutrinos in final state, $2e^-$ carry full Q-value of decay
    - Lepton number violated $\Delta L = 2$
    - Matter created without anti-matter
- Not yet observed but predicted for all $2\nu\beta\beta$ isotopes

Current Standard Model





Helicity



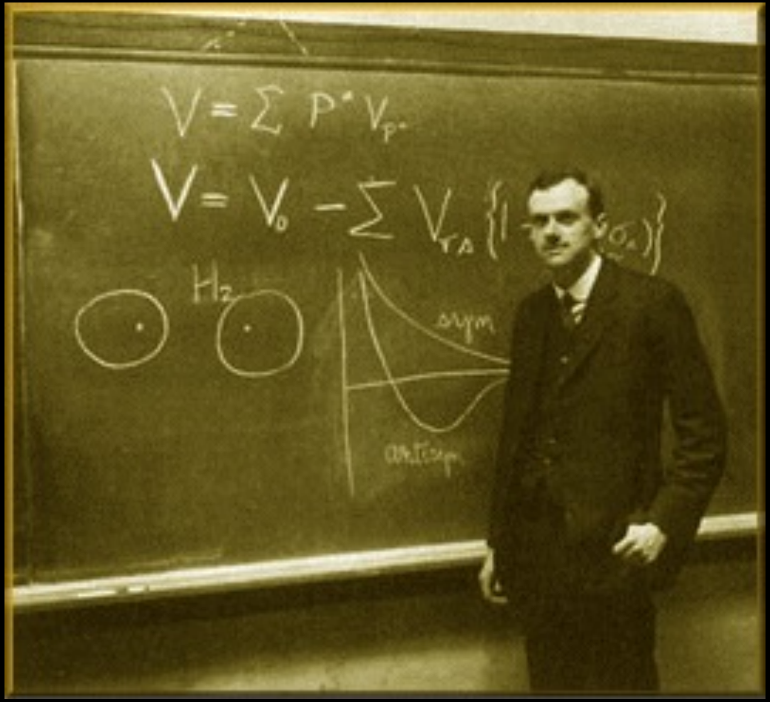
- If a particle has mass it travels less than the speed of light so can be over-taken. Then you would observe it in the opposite helicity state
- Helicity is not a fundamental property (not a good quantum number)

Chirality

- For massless particles chirality = helicity
- A massive particle has a specific chirality : left-chiral or right-chiral
  - But a left-chiral particle could be observed as right-helicity
  - ie. helicity depends on your reference frame

- Left-chiral and right-chiral particles behave differently in the standard model
  - Weak force only couples to left-chiral particles (and right-chiral anti-particles)
  - Hence no right-handed neutrinos in standard model

Dirac Neutrinos



- Could add a mass term like all other fundamental fermions,
- Need 4 states: $\begin{pmatrix}\nu_L \\ \bar{\nu}_R\end{pmatrix} \longleftrightarrow \begin{pmatrix}\nu_R \\ \bar{\nu}_L\end{pmatrix}$

New
No weak
interactions

- $L_D \sim m_D(\bar{\nu}_L \nu_R + \bar{\nu}_R \nu_L)$
- Right handed neutrinos not observed $\nu_{sterile}$?
- Requires unnaturally small coupling to Higgs field to explain small neutrino masses

How are these different?

- Charge?	- Same (0)
- Mass?	- Same
- Chirality?	- Same
- Lepton number	$\Delta L = 2$

But Lepton Number is just an observed symmetry

Chirality

- For massless particles chirality = helicity
- A massive particle has a specific chirality : left-chiral or right-chiral
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- Left-chiral and right-chiral particles behave differently in the standard model
  - Weak force only couples to left-chiral particles (and right-chiral anti-particles)
  - Hence no right-handed neutrinos in standard model

For $m_\nu \neq 0$, either there must be a right-handed neutrino which only shows up in the standard model to give the neutrino mass, but otherwise cannot be observed as the weak interaction doesn't couple to it, or there is some other sort of mass term out there.

Charge Conjugation

- The charge conjugation operator, $\hat{C}$ turns a particle state $|\psi\rangle$ into its anti-particle state $|\bar{\psi}\rangle$. Where C is the charge conjugation eigenvalue

$$\hat{C}|\psi\rangle = C|\bar{\psi}\rangle$$

- The neutrino is the left-handed state created by $W^+ \to l^+\nu$
- The anti-neutrino is the right-handed state created by $W^- \to l^-\bar{\nu}$

but we never actually 'see' the ν or $\bar{\nu}$ themselves!

Majorana Neutrinos

- Perhaps the neutrino is a single Majorana particle with two independent chiral components - a left- and right–handed component $\nu = \nu_L + \nu_R$
- Left- and right-handed fields are linked via:

$$\nu_R = C\bar{\nu}_L^T = \nu_L^C$$

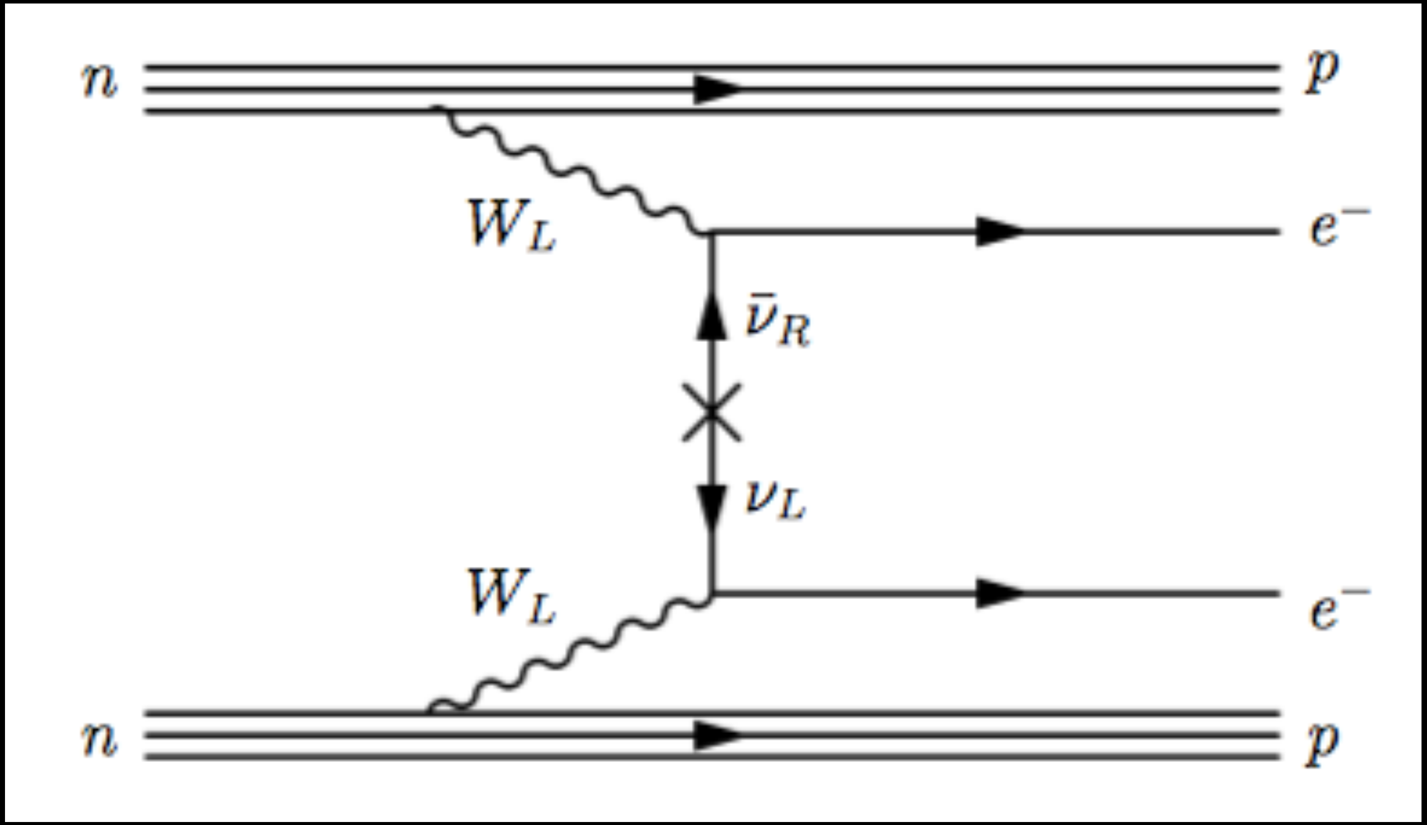
Majorana field is $\nu = \nu_L + \nu_R = \nu_L + \nu_L^C$ and the charge conjugate of this is $\left(\nu_L + \nu_L^C\right)^C = \left(\nu_L^C + \nu_L\right)$

→ The charge conjugate of the Majorana field is the field itself.

→ A Majorana particle is its own antiparticle

- The Majorana lagrangian $L_M \sim m_M \bar{\nu}_L^c \nu_L$ can be built out of only the left-handed field (though evidence that right handed part also exists)
- Only works for neutral particles and allows breaking of lepton number $\Delta L = \pm 2$

Majorana Neutrino in $0\nu\beta\beta$



The See-saw Mechanism

- Tries to explain the relatively small mass (small Higgs coupling) by combining Dirac and Majorana terms into a single Lagrangian

$$L_{see-saw} = L_D + L_M = -\frac{1}{2}\left(\bar{\nu}_L \bar{\nu}_R^C\right)\begin{bmatrix} m_M^L & m_D \\ m_D & m_M^R \end{bmatrix}\begin{pmatrix} \nu_L^C \\ \nu_R \end{pmatrix} + \text{h.c.}$$

- Assume ν_L and ν_R which now result from mixing of Majorana and Dirac terms are linear combinations of mass eigenstates ν and N that couple directly to the Higgs field via a purely Majorana Mass term
  - ie Higgs or GUT symmetry breaking only gave Majorana mass to neutrinos, but not dirac mass

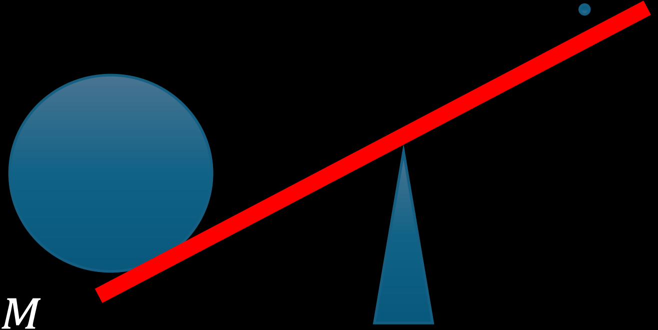
$$L_{mass\ terms} = -\frac{1}{2}(\bar{\nu}, \bar{N})\begin{bmatrix} m_\nu & 0 \\ 0 & M \end{bmatrix}\begin{pmatrix} \nu \\ N \end{pmatrix} + \text{h.c.}$$

The See-saw Mechanism

$$\tilde{\mathcal{M}} = \begin{bmatrix} m_\nu & 0 \\ 0 & M \end{bmatrix}$$

$$\mathcal{M} = \begin{bmatrix} m_M^L & m_D \\ m_D & m_M^R \end{bmatrix}$$

$m_\nu \sim \frac{m_D^2}{m_M}$



$M \sim m_M$

- The weak eigenstates that we detect, ν_L and ν_R are linear super-positions of ν and N, the mass eigenstates

Diagonalising, using eigenvalue equations...

$$m_M^R m_M^L = m_D^2$$

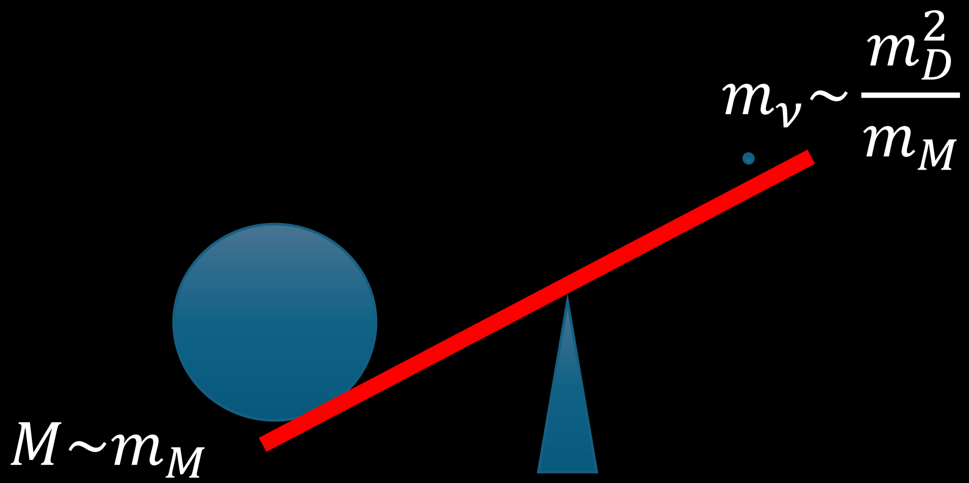
- For fixed m_D, as you increase m_M^R you decrease m_M^L

Small mixing leads to one small mass state and one large one

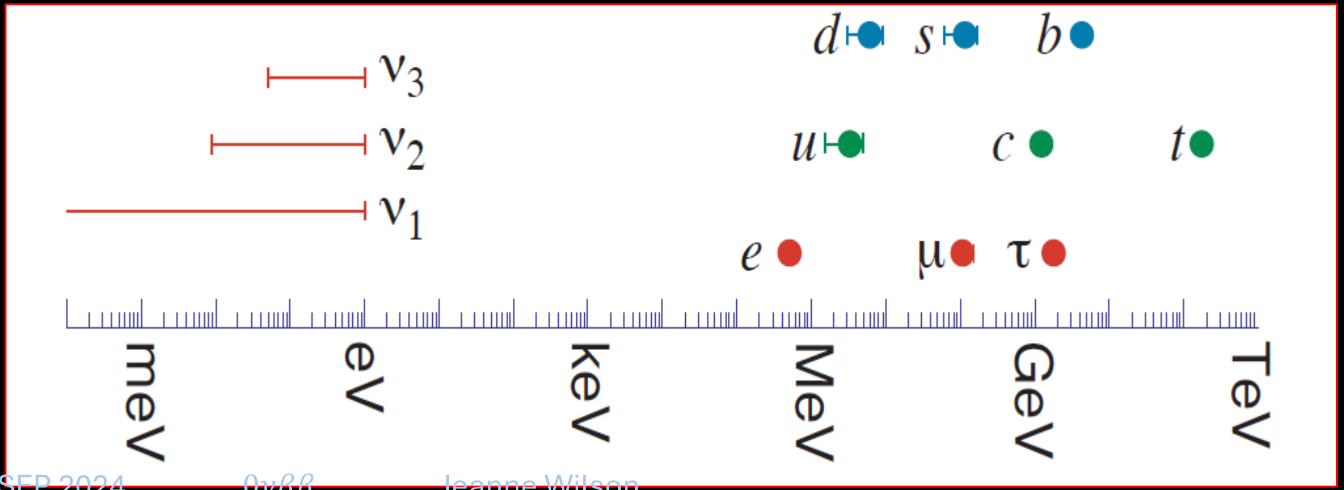
$$M \approx m_M^R \gg m_D > m_M^L \approx 0$$

The See-saw Mechanism

Using $m_M^R m_M^L = m_D^2$ how heavy would the heavy partner have to be to generate neutrino masses of order meV?



Hint – what should we assume for m_D?



Recap

- Natural explanation for the tiny neutrino mass:
  - Neutrino is a Majorana particle
  - There exists an extremely heavy partner to the neutrino which is too large for us to be able to create

  - Such particles would have been created in very early universe
  - No longer exist as stable particles
    - Decayed to lighter states as the Universe cooled
  - But due to the uncertainty principle they could exist for the short time necessary to generate mass

Leptogenesis and the matter-antimatter imbalance

- These very heavy neutrinos, the Majorana particles, decayed as the universe cooled into lighter left-handed neutrinos or right-handed antineutrinos, along with Higgs bosons, which themselves decayed to quarks
- If the probability of one of these heavy neutrinos to decay to a left-handed neutrino was slightly different than the probability to decay to a right-handed anti-neutrino, then there would be a greater probability to create quarks than anti-quarks and the universe would be matter dominated
- Formally thought that $B - L$ is conserved
  - Violation in L conservation would manifest as a violation in B
  - The missing anti-matter problem could arise from CP violation in neutrinos
- No direct connection between CP violation of heavy and light neutrinos but still motivation for long-baseline CP violation measurements

Summary – lecture 1

- What is double beta decay ?
- Which isotopes can double-beta decay ?
    - SEMF
- $2\nu\beta\beta$ observed
- Motivation for Majorana neutrinos
    - theoretical description
    - See-saw mechanism
    - Leptogenesis
- Why search for $0\nu\beta\beta$?