
Double beta decay transitions and the light neutrino mass

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Summary of the presentation

- The light neutrino mass problem:
Majorana or Dirac?
- Current experimental limits and
sensitivities.
- The half-life for nuclear double-beta
decay processes.
- Nuclear matrix elements and their
sensitivity.
- Concluding remarks

The light neutrino mass problem

- The standard model of electroweak interactions sees light neutrinos as members of the left-handed doublet and without mass.
- The neutrinoless double-beta decay, if it is observed will demonstrate the need to go beyond the standard model to accommodate massive neutrinos in right and left doublets.
- Massive neutrinos will then be Majorana particles (thus identical to their antiparticles).
- If it is so then right handed currents (and bosons) should be added.

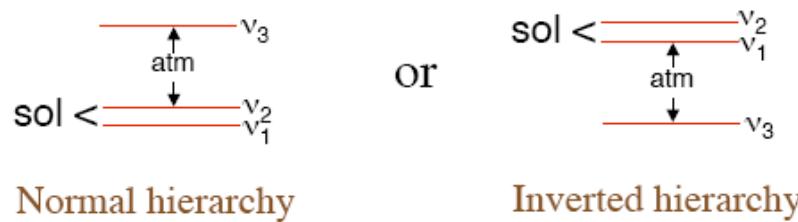
Neutrino mass eigenstates and hierarchies

How Large is $m_{\beta\beta}$?

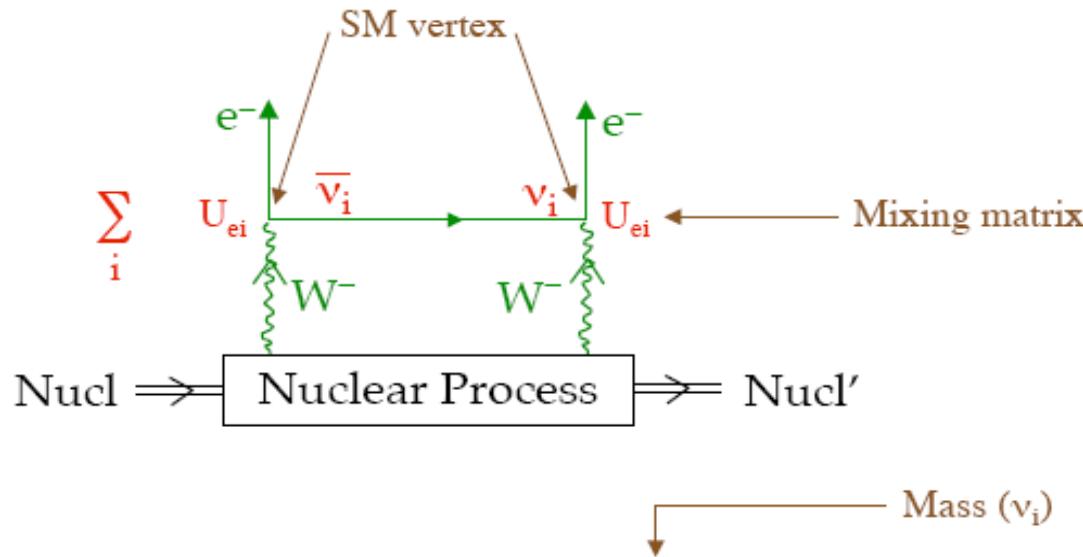
How sensitive need an experiment be?

Suppose there are only 3 neutrino mass eigenstates. (More might help.)

Then the spectrum looks like —



Basic notions on the decay

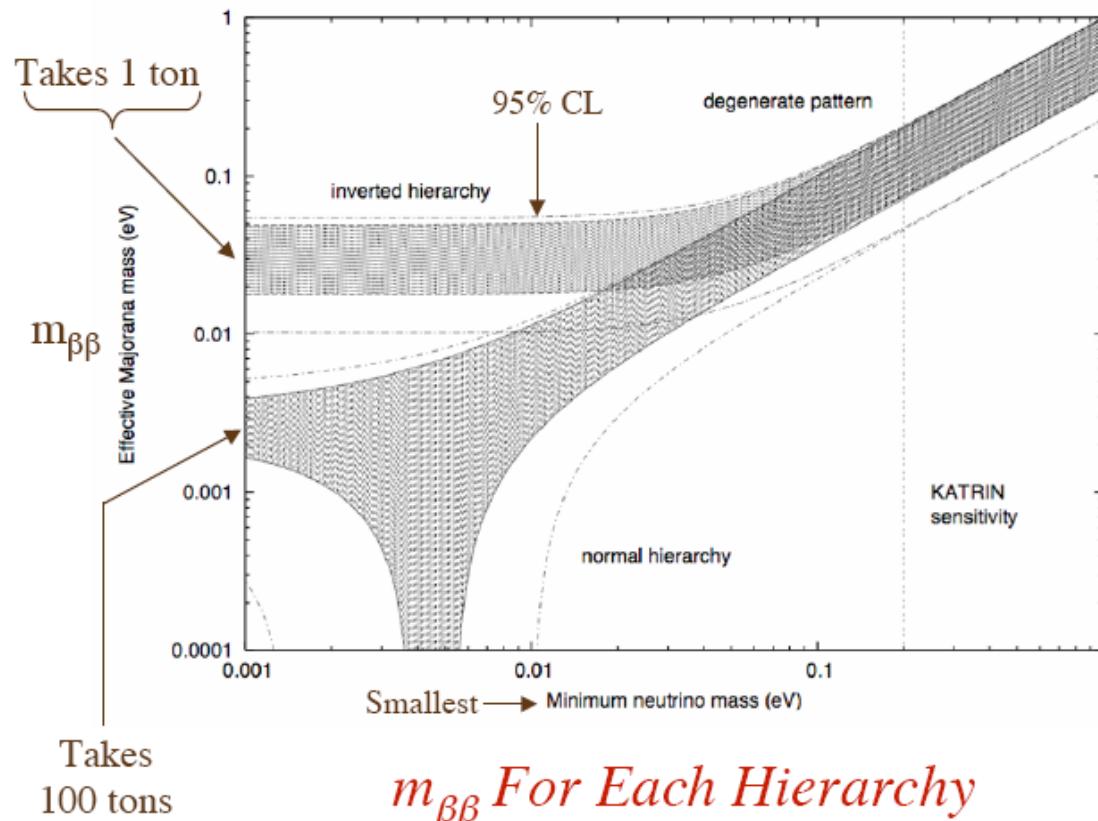


the $\bar{\nu}_i$ is emitted [RH + O{ m_i/E }LH].

Thus, Amp [ν_i contribution] $\propto m_i$

$$\text{Amp}[0\nu\beta\beta] \propto \left| \sum_i m_i U_{ei}^2 \right| \equiv m_{\beta\beta}$$

Allowed values for each hierarchy



Mass hierachies

There is no clear theoretical preference for either hierarchy.

Suppose the hierarchy is found, via accelerator neutrino experiments, to be **inverted**.

Then $0\nu\beta\beta$ searches with sensitivity to $m_{\beta\beta} = 0.01$ eV have a very good chance to see a signal.

If these $0\nu\beta\beta$ searches establish that $m_{\beta\beta} < 0.01$ eV, then, barring unlikely cancellations from exotic mechanisms, we can say that neutrinos are Dirac particles: $\bar{\nu} \neq \nu$.

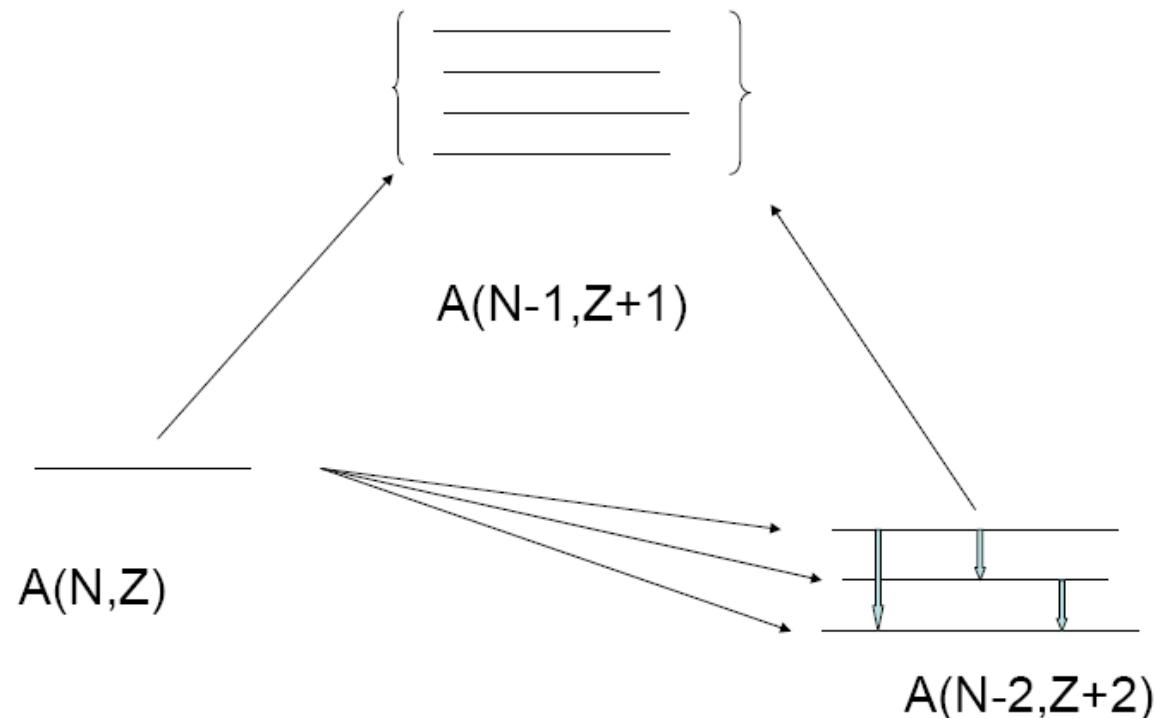
Experiments (R&D)

Best present limits on $\langle m_\nu \rangle$

Nuclei	$T_{1/2}$, y	$\langle m_\nu \rangle$, eV QRPA + others	$\langle m_\nu \rangle$, eV [SM]	Experiment
^{76}Ge	$>1.9 \cdot 10^{25}$	$< 0.22\text{-}0.41$	< 0.69	HM
	$\approx 1.2 \cdot 10^{25} (?)$	$\approx 0.28\text{-}0.52 (?)$	$\approx 0.87 (?)$	Part of HM'04
	$\approx 2.2 \cdot 10^{25} (?)$	$\approx 0.21\text{-}0.38 (?)$	$\approx 0.64 (?)$	Part of HM'06
	$>1.6 \cdot 10^{25}$	$< 0.24\text{-}0.44$	< 0.75	IGEX
^{130}Te	$>2.8 \cdot 10^{24}$	$< 0.29\text{-}0.59$	< 0.77	CUORICINO
^{100}Mo	$>1.1 \cdot 10^{24}$	$< 0.29\text{-}0.93$	-	NEMO
^{136}Xe	$>4.5 \cdot 10^{23}$	$< 1.41\text{-}2.67$	< 2.2	DAMA
^{82}Se	$>3.6 \cdot 10^{23}$	$< 0.89\text{-}1.61$	< 2.3	NEMO
^{116}Cd	$>1.7 \cdot 10^{23}$	$< 1.45\text{-}2.76$	< 1.8	SOLOTVINO

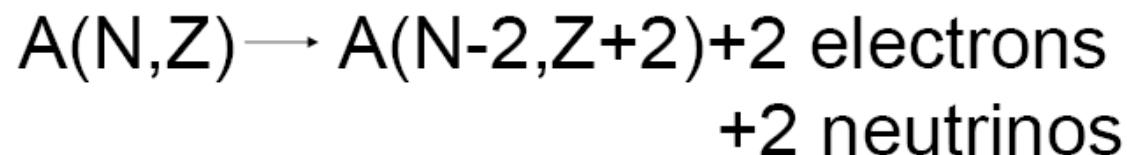
Nuclear matrix elements

Schematic view



Nuclear matrix elements

2-neutrino mode



$$\left[t_{1/2}^{(2\nu)} (0_I^+ \rightarrow 0_F^+) \right]^{-1} = G^{(2\nu)} \left| M_{\text{GT}}^{(2\nu)} \right|^2$$

- a) Lepton number is conserved
- b) Suppressed by kinematics (four leptons in the final state)
- c) Independent of neutrino properties

Nuclear matrix elements

0-neutrino mode



$$\left[t_{1/2}^{0\nu}(J_f) \right]^{-1} = C_{mm}^{(0\nu)} \frac{\langle m_\nu \rangle^2}{m_e^2}$$

$$C_{mm}^{(0\nu)} = G_1^{(0\nu)} \left[(M_{GT}^{(0\nu)}) (1 - \chi_F) \right]^2$$

- a) lepton number is not conserved
- b) not suppressed by kinematics (two leptons in the final state)

Nuclear matrix elements (corrected for Jastrow short range correlations)

Table 1. Calculated ground-state-to-ground-state NMEs for $g_A = 1.25$ using the Jastrow short-range correlations. The last line summarizes the overall magnitude and the associated dispersion of the NMEs of the cited nuclear model (without ^{48}Ca included).

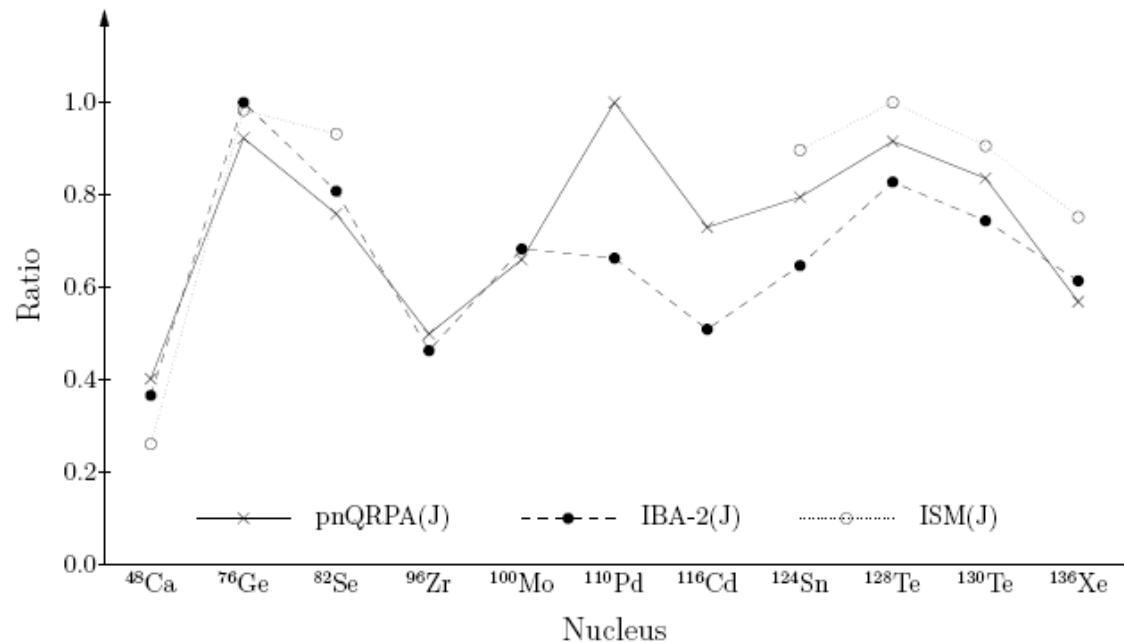
Transition	pnQRPA(J)	IBA-2(J) [52]	ISM(J) [12]	PHFB(J) [7]
$^{48}\text{Ca} \rightarrow {}^{48}\text{Ti}$	1.67 ± 0.09 [53]	2.00	0.61	-
$^{76}\text{Ge} \rightarrow {}^{76}\text{Se}$	3.83 ± 0.53 [46]	5.46	2.30	-
$^{82}\text{Se} \rightarrow {}^{82}\text{Kr}$	3.15 ± 0.30 [46]	4.41	2.18	-
$^{96}\text{Zr} \rightarrow {}^{96}\text{Mo}$	2.07 [35]	2.53	-	2.80 ± 0.10
$^{100}\text{Mo} \rightarrow {}^{100}\text{Ru}$	2.74 [35]	3.73	-	6.19 ± 0.46
$^{110}\text{Pd} \rightarrow {}^{110}\text{Cd}$	4.15 ± 0.41 [27]	3.62	-	7.07 ± 0.58
$^{116}\text{Cd} \rightarrow {}^{116}\text{Sn}$	3.03 [35]	2.78	-	-
$^{124}\text{Sn} \rightarrow {}^{124}\text{Te}$	3.30 ± 0.92 [27]	3.53	2.10	-
$^{128}\text{Te} \rightarrow {}^{128}\text{Xe}$	3.80 ± 0.37 [46]	4.52	2.34	3.59 ± 0.28
$^{130}\text{Te} \rightarrow {}^{130}\text{Xe}$	3.47 ± 0.37 [46]	4.06	2.12	4.01 ± 0.45
$^{136}\text{Xe} \rightarrow {}^{136}\text{Ba}$	2.36 ± 0.22 [46]	3.35	1.76	-
Overall NME	3.19 ± 0.66	3.80 ± 0.86	2.13 ± 0.21	4.73 ± 1.81

Nuclear matrix elements (corrected for nucleon-nucleon correlations)

Table 2. Calculated ground-state-to-ground-state NMEs for $g_A = 1.25$ using the UCOM short-range correlations. The last line summarizes the overall magnitude and the associated dispersion of the NMEs of the cited nuclear model (without ^{48}Ca included).

Transition	pnQRPA(U)	EDF(U) [6]	ISM(U) [12]	PHFB(U) [7]
$^{48}\text{Ca} \rightarrow {}^{48}\text{Ti}$	-	2.37	0.85	-
$^{76}\text{Ge} \rightarrow {}^{76}\text{Se}$	5.18 ± 0.54 [46]	4.60	2.81	-
$^{82}\text{Se} \rightarrow {}^{82}\text{Kr}$	4.20 ± 0.35 [46]	4.22	2.64	-
$^{96}\text{Zr} \rightarrow {}^{96}\text{Mo}$	3.12 [35]	5.65	-	3.32 ± 0.12
$^{100}\text{Mo} \rightarrow {}^{100}\text{Ru}$	3.93 [35]	5.08	-	7.22 ± 0.50
$^{110}\text{Pd} \rightarrow {}^{110}\text{Cd}$	5.63 ± 0.49 [27]	-	-	8.23 ± 0.62
$^{116}\text{Cd} \rightarrow {}^{116}\text{Sn}$	3.93 [35]	4.72	-	-
$^{124}\text{Sn} \rightarrow {}^{124}\text{Te}$	4.57 ± 1.33 [27]	4.81	2.62	-
$^{128}\text{Te} \rightarrow {}^{128}\text{Xe}$	5.26 ± 0.40 [46]	4.11	2.88	4.22 ± 0.31
$^{130}\text{Te} \rightarrow {}^{130}\text{Xe}$	4.76 ± 0.41 [46]	5.13	2.65	4.66 ± 0.43
$^{136}\text{Xe} \rightarrow {}^{136}\text{Ba}$	3.16 ± 0.25 [46]	4.20	2.19	-
Overall NME	4.37 ± 0.86	4.72 ± 0.51	2.63 ± 0.24	5.53 ± 2.09

Nuclear matrix elements: ratios between model predictions



Nuclear matrix elements: transitions to excited states.

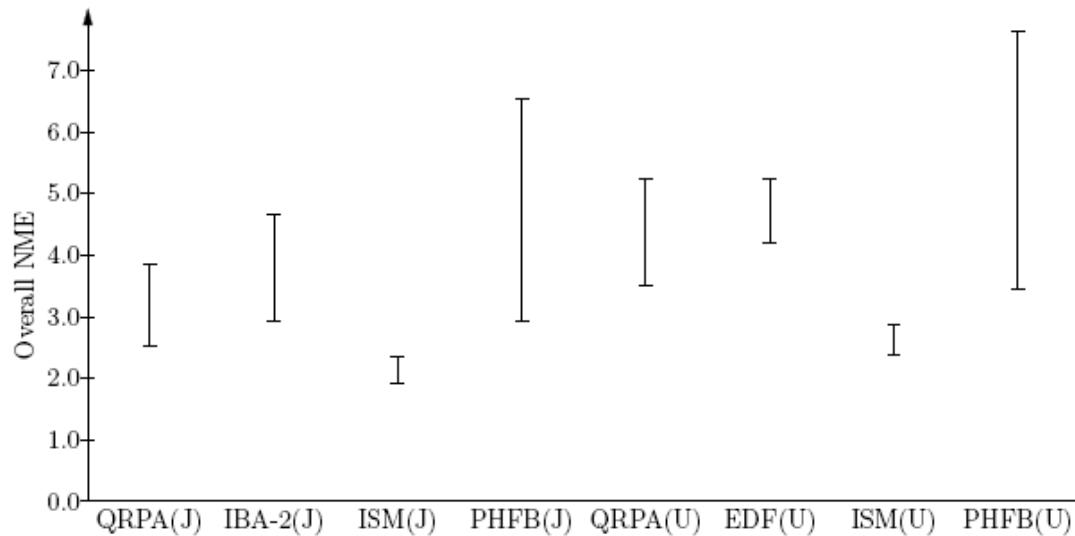
Table 4. Calculated ground-state-to-excited-state NMEs for $g_A = 1.25$ using the Jastrow (J) and UCOM (U) short-range correlations. The last line summarizes the overall magnitude and the associated dispersion of the NMEs of the cited nuclear model (without ^{48}Ca included).

Transition	pnQRPA (U)	pnQRPA (J)	IBA-2 (J) [52]	ISM (J) [12]
$^{48}\text{Ca} \rightarrow {}^{48}\text{Ti}$	-	-	5.90	0.68
$^{76}\text{Ge} \rightarrow {}^{76}\text{Se}$	4.87 ± 0.73 [9]	4.67 ± 0.70 [9]	2.48	1.49
$^{82}\text{Se} \rightarrow {}^{82}\text{Kr}$	1.53 ± 0.31 [9]	1.46 ± 0.29 [9]	1.25	0.28
$^{96}\text{Zr} \rightarrow {}^{96}\text{Mo}$	-	1.96 [61]	0.04	-
$^{100}\text{Mo} \rightarrow {}^{100}\text{Ru}$	-	0.31 [62]	0.42	-
$^{110}\text{Pd} \rightarrow {}^{110}\text{Cd}$	1.63 ± 0.21 [27]	1.59 ± 0.21 [27]	1.60	-
$^{116}\text{Cd} \rightarrow {}^{116}\text{Sn}$	-	0.25 [61]	1.05	-
$^{124}\text{Sn} \rightarrow {}^{124}\text{Te}$	6.00 ± 0.18 [27]	5.74 ± 0.19 [27]	2.72	0.80
$^{128}\text{Te} \rightarrow {}^{128}\text{Xe}$	-	-	3.24 [†]	-
$^{130}\text{Te} \rightarrow {}^{130}\text{Xe}$	$6.31 \pm 0.58^*$	$6.06 \pm 0.57^*$	3.09	0.19
$^{136}\text{Xe} \rightarrow {}^{136}\text{Ba}$	5.34 ± 0.94 [9]	5.11 ± 0.92 [9]	1.84	0.49
Overall NME	4.28 ± 2.15	3.02 ± 2.35	1.77 ± 1.10	0.65 ± 0.52

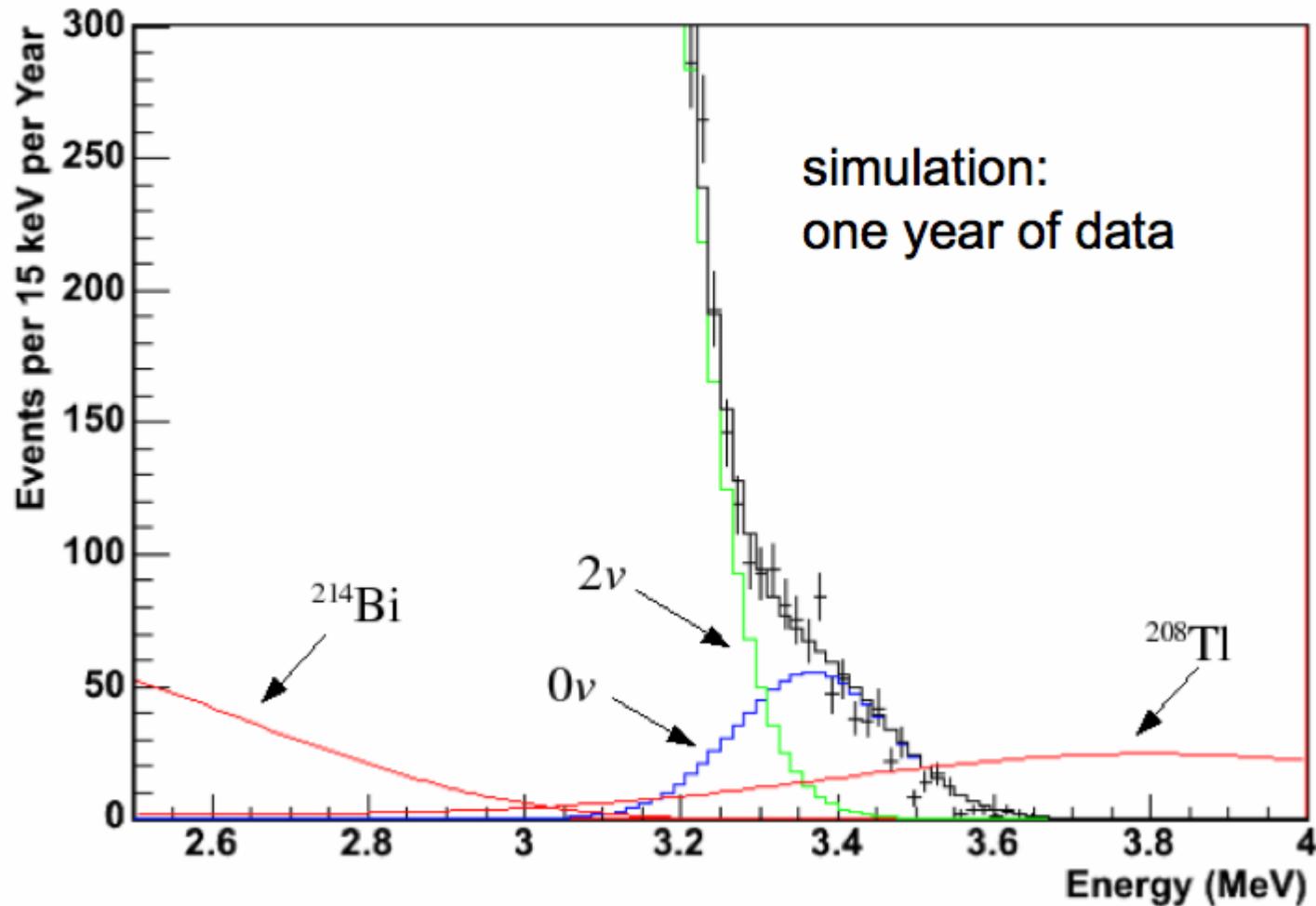
* This work.

[†] The $0\nu\beta^-\beta^-$ transition is Q -forbidden.

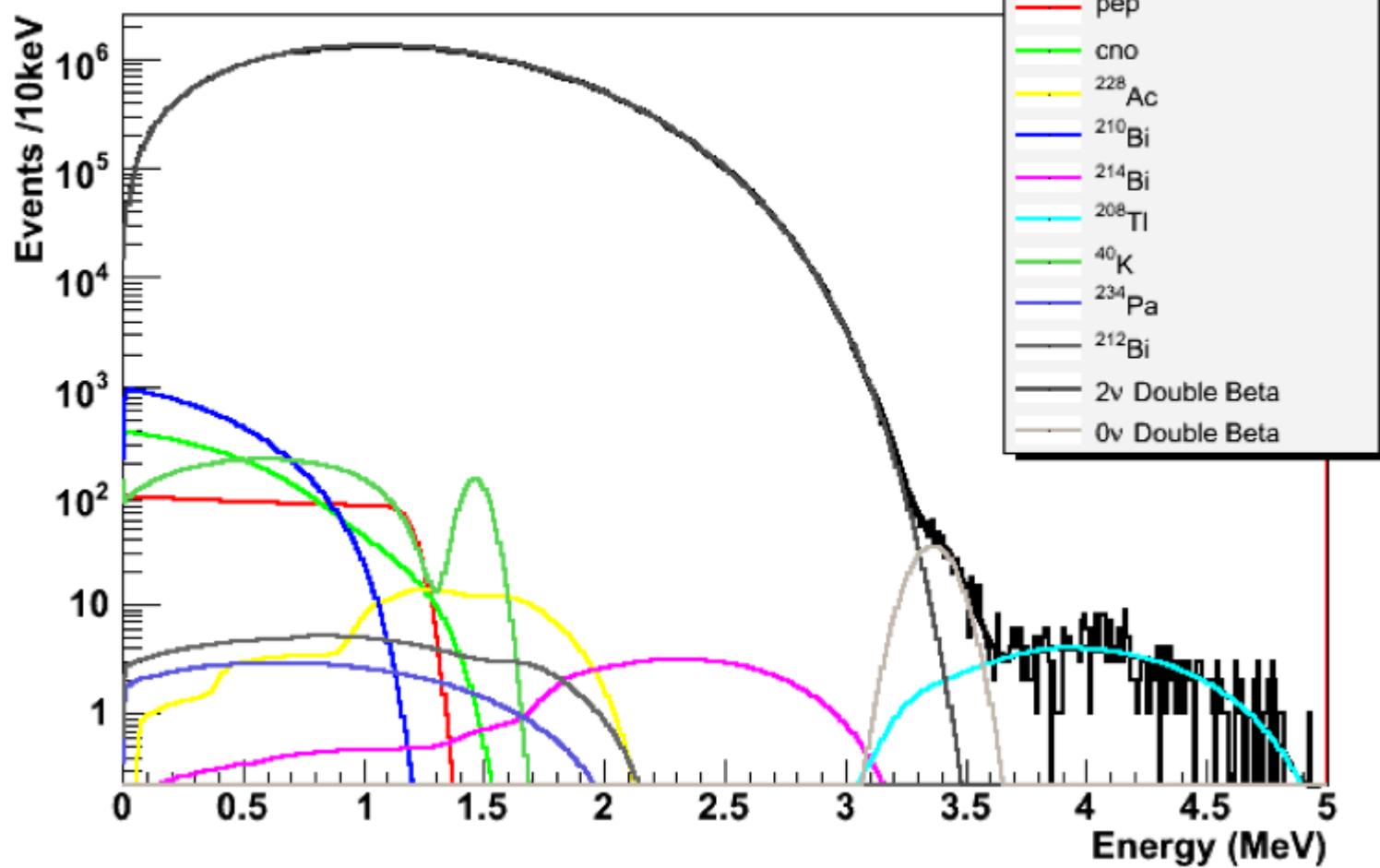
Nuclear matrix elements (range of theoretical overall values)



The Simulated Spectrum of Double Beta Decay Events



Simulated SNO+ Energy Spectrum



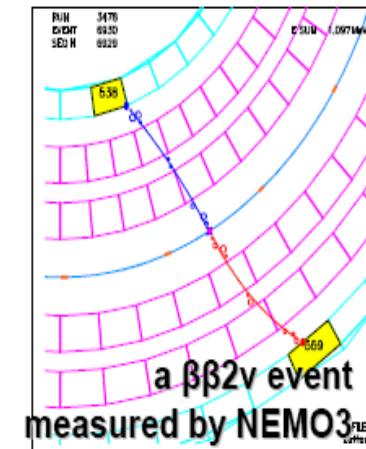
CTA-LINK november 20, 2012

From NEMO3 to SuperNEMO

— SuperNEMO is the proposed successor to the running NEMO3 experiment

GOAL : Reach a sensitivity of ~ 50 meV on the effective neutrino mass.

HOW : With extending and improving the tracko-calorimeter technique using knowledge from NEMO3 (purification of $\beta\beta$ isotopes, identification and measurement of all sources of background, ...)



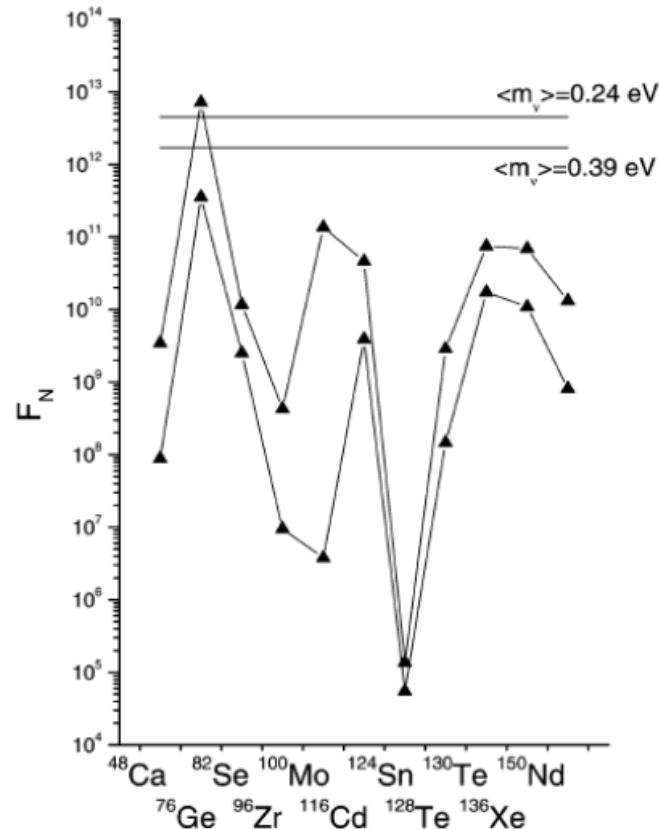
From NEMO3 to SuperNEMO

$$T_{1/2} > \frac{\ln 2 \ N_A \ \epsilon}{k_{CL} \ A} \sqrt{\frac{m \ t}{N_{bdf} \ R}}$$

N_A Avogadro number
 ϵ detection efficiency
 $m \ t$ exposure (kg.y)
 k_{CL} confidence level
 A isotope atomic mass
 N_{bdf} background events (/keV/kg/y)
 R energy resolution (keV)

NEMO3		SuperNEMO
$T_{1/2} > 1.4 \times 10^{24} \text{ y}$ $\langle m \rangle < 390 - 810 \text{ meV}$	EXPECTED SENSITIVITY	$T_{1/2} > 1 - 1.5 \times 10^{26} \text{ y}$ $\langle m \rangle < 43 - 145 \text{ meV}^*$
7 kg	Mass of Isotopes	100 – 200 kg
8 % FWHM @ 3 MeV	Calorimeter Resolution	4 % FWHM @ 3 MeV
18 %	Efficiency	30 %
$^{208}\text{TI} < 20 \mu\text{Bq} / \text{kg}$ $^{214}\text{Bi} < 300 \mu\text{Bq} / \text{kg}$	Foils Radiopurity	$^{208}\text{TI} < 2 \mu\text{Bq} / \text{kg}$ $^{214}\text{Bi} < 10 \mu\text{Bq} / \text{kg}$

Extracted electron-neutrino mass



Conclusions

- Current experiments may soon reach sensitivities in the range needed to check the claims of positive signals of neutrinoless double beta decay.
- Best limits for are of the order of $\langle m \rangle < 0.4 \text{ eV}$
- The dispersion of the values of the nuclear matrix elements have been strongly reduced.
- Next generation of experiments (today in R&D) may found the answer to the neutrino mass problem (hopefully).