Excited State Transitions in Double Beta Decay: A brief Review

Fifteenth International Symposium on Capture Gamma-Ray Spectroscopy and Related Topics (CGS15)

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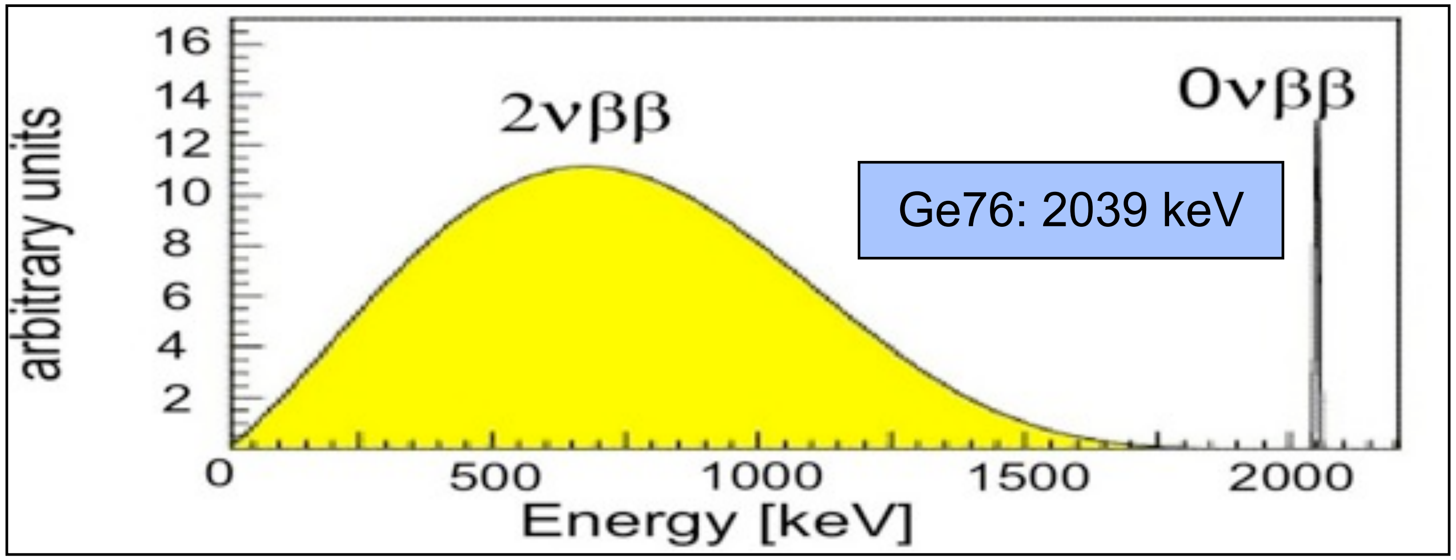
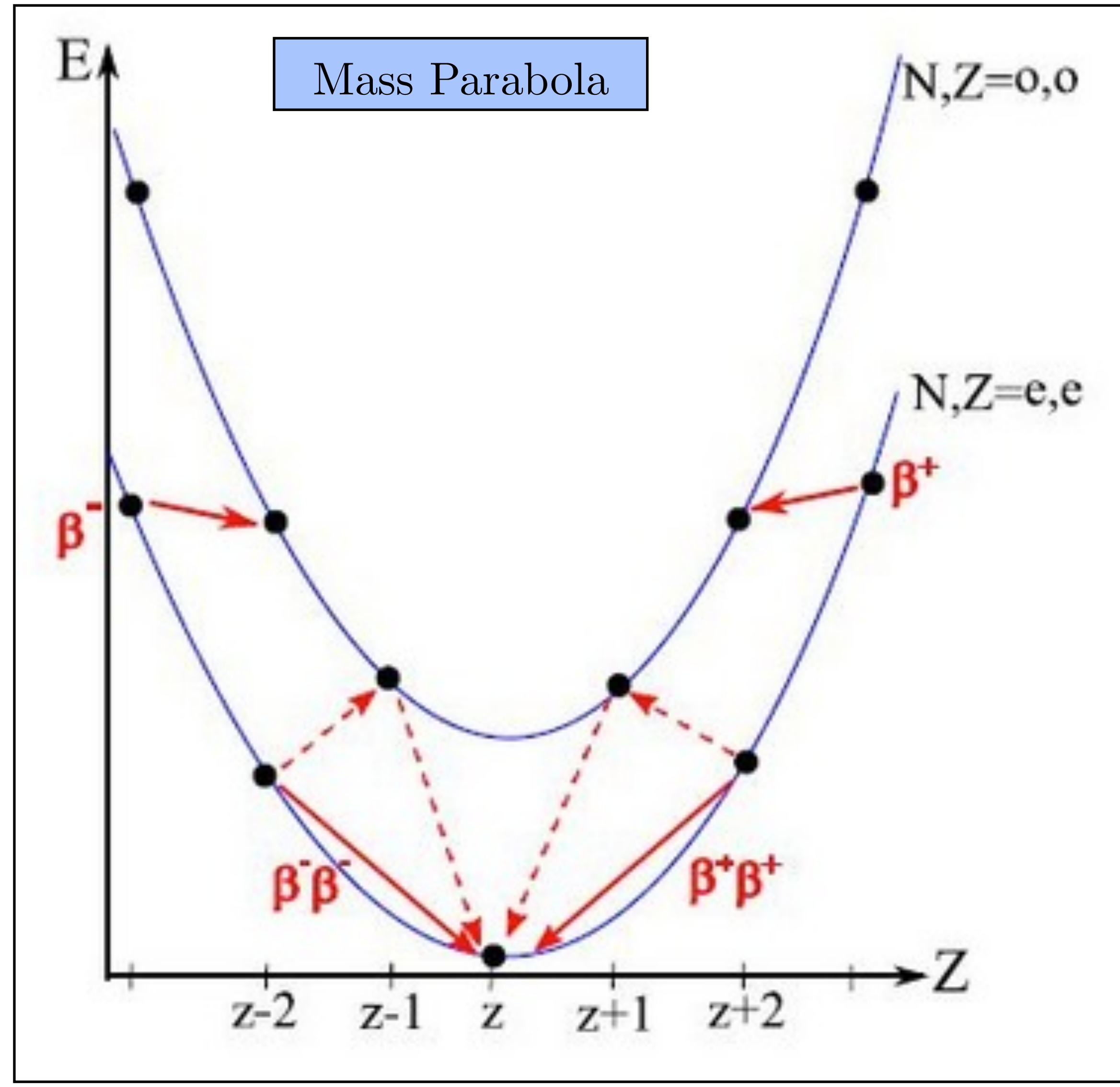
TECHNISCHE UNIVERSITÄT DRESDEN

Double Beta Decay

$$2\nu\beta\beta : (Z, A) \rightarrow (Z+2, A) + 2e^- + 2\bar{\nu}_e$$

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





Effective neutrino mass:

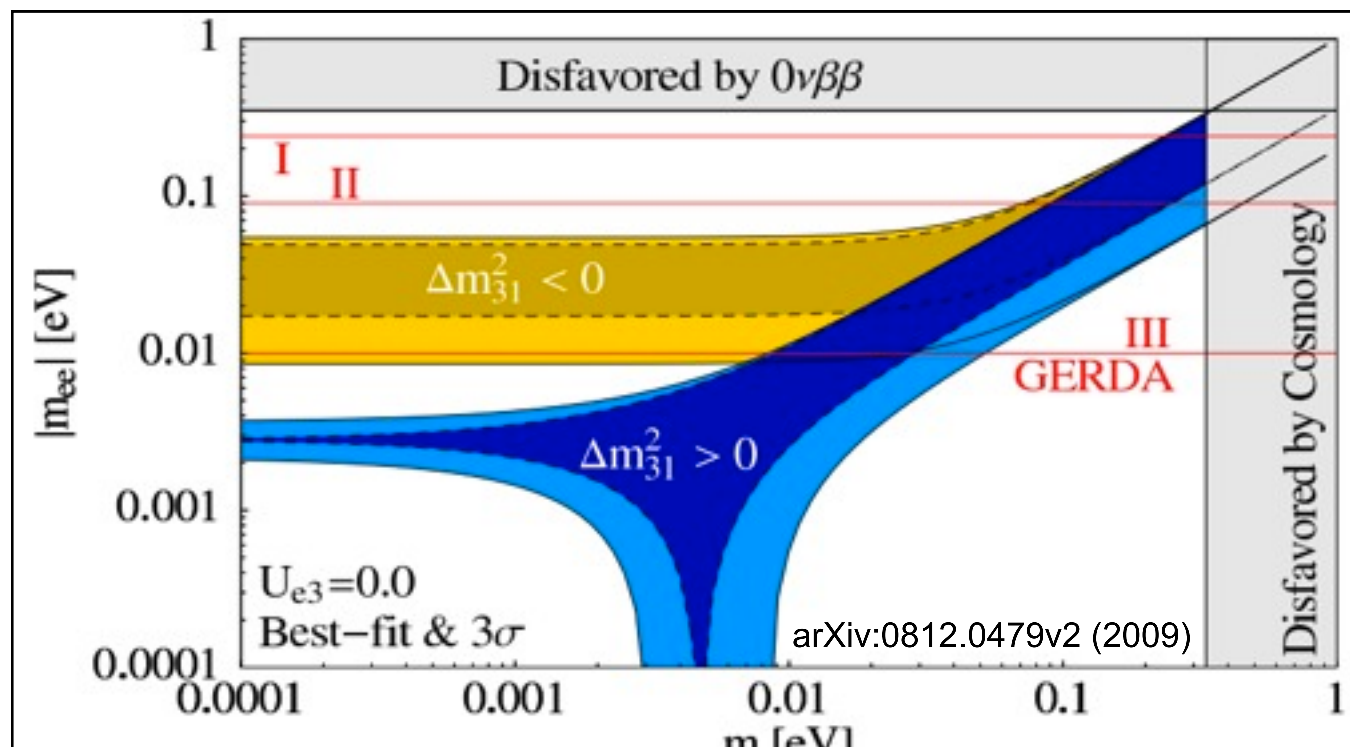
(only for dominant light Majorana neutrino exchange)

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu} \cdot |\mathcal{M}^{0\nu}|^2 \cdot |m_{ee}|^2$$

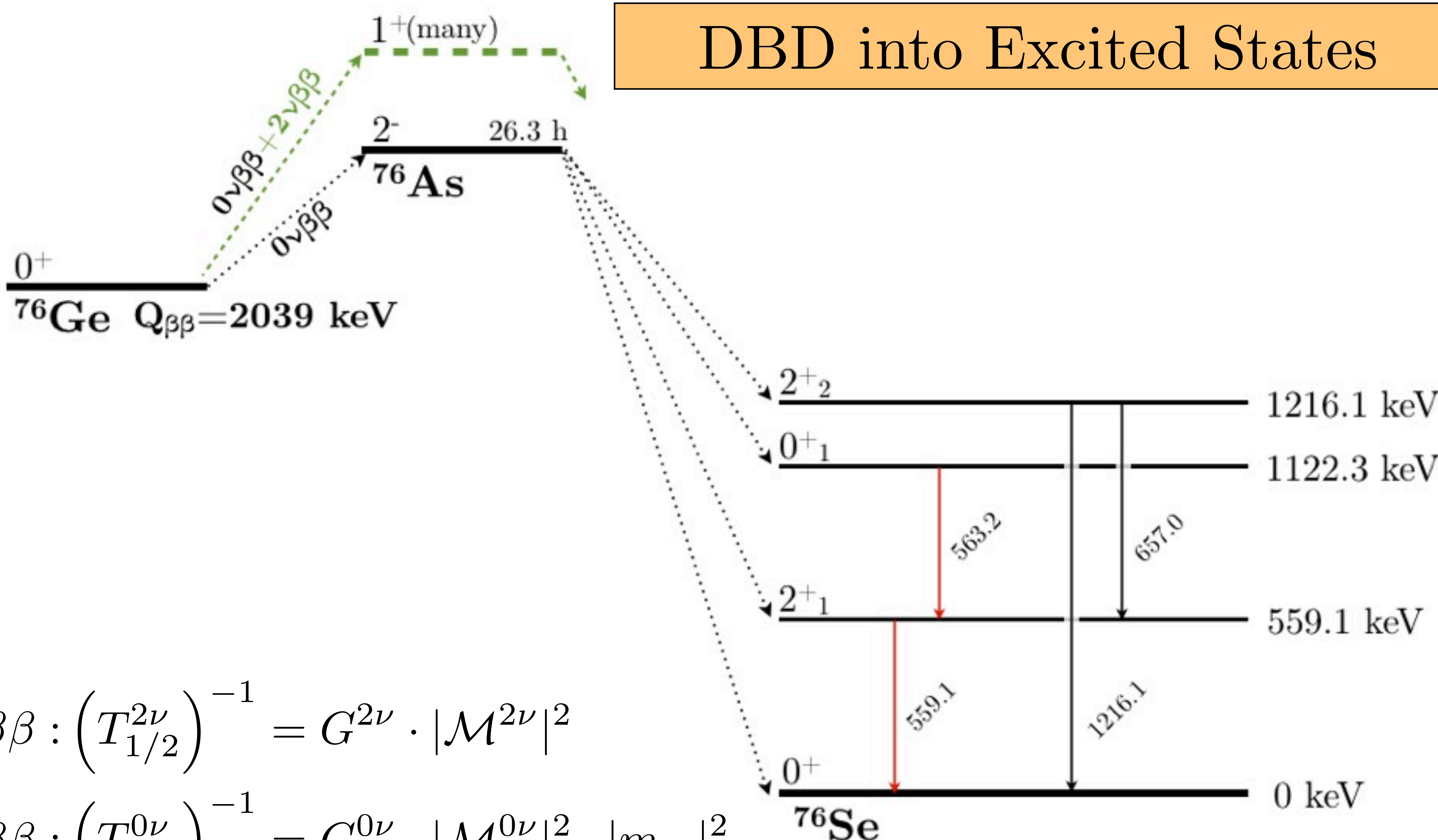
$G^{0\nu}$: phase space factor

$\mathcal{M}^{0\nu}$: nuclear matrix element

m_{ee} : effective neutrino mass



DBD into Excited States



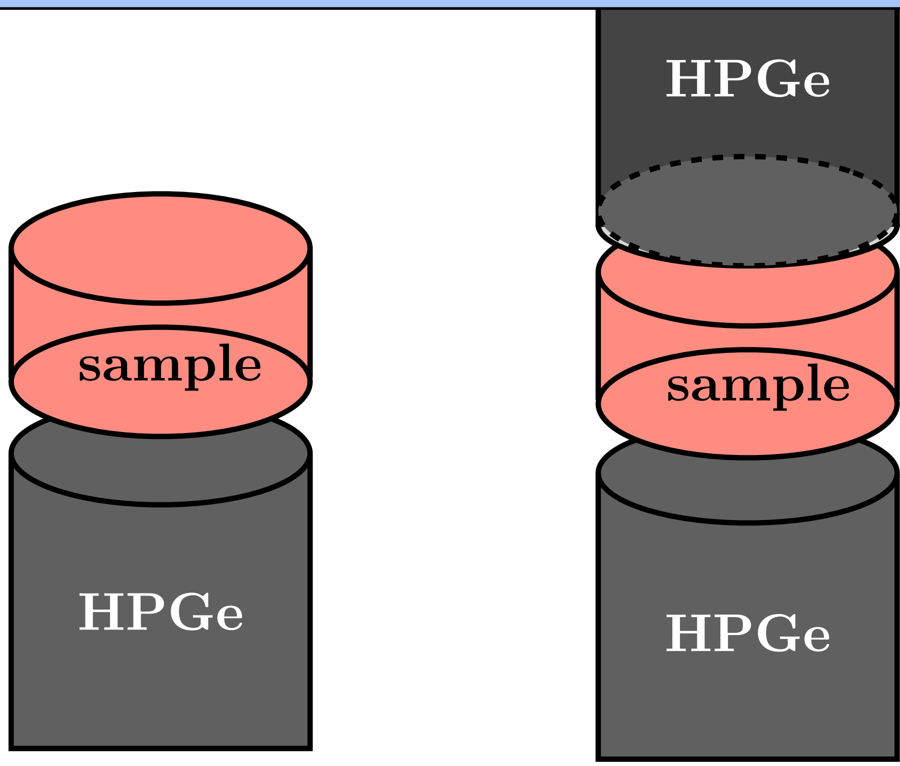
$$2\nu\beta\beta : \left(T^{2\nu}_{1/2}\right)^{-1} = G^{2\nu} \cdot |\mathcal{M}^{2\nu}|^2$$

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

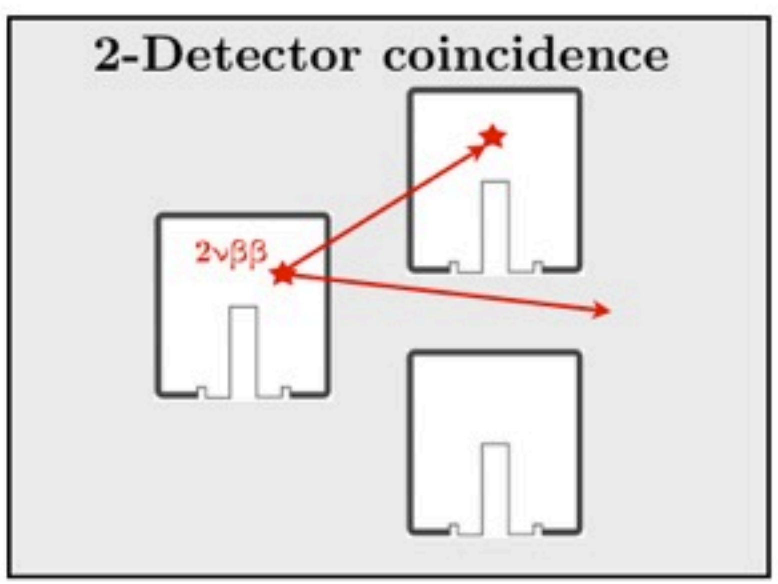
- Experimental information for 2νββ helps matrix element calculations for 0νββ
- 0^+_1 expected to have highest excited state rate ($\propto E^{11}$ (for 2ν), 2^+_1 spin suppressed)
- Effective parameters can be constrained: (e.g. g_A quenching)

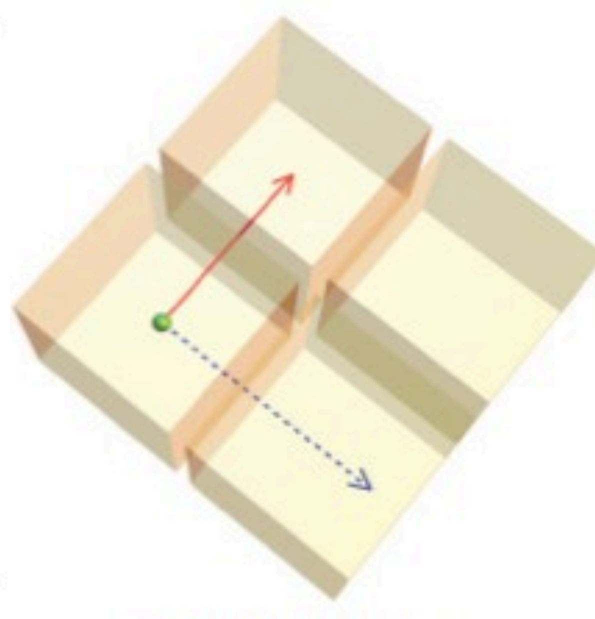
Experimental Approaches

Gamma spectroscopy



$0\nu\beta\beta$ experiments





Theoretical Approaches

Direct calculation

$$\left(T_{1/2}^{2\nu}\right)^{-1} = G^{2\nu} \cdot \left|M^{2\nu}\right|^2$$

- Direct calculation with various nuclear models (QRPA, SM, HFB, IBM...)
- Often very inconsistent

Scaling to ground state $T_{1/2}$

$$\mathcal{R} = \frac{T_{1/2}^{0_1^+}}{T_{1/2}^{0_{g.s.}^+}} = \frac{G^{0_{g.s.}^+} \cdot \left(\mathcal{M}^{0_{g.s.}^+}\right)^2}{G^{0_1^+} \cdot \left(\mathcal{M}^{0_1^+}\right)^2}$$

- Use ratio of NME and PSF which cancels some uncertainties (e.g. g_A)
- Then scale with measured g.s. $T_{1/2}$

Excited States Experimental Overview

- So far $2\nu\beta\beta\ 0^+_1$ transition discovered in ^{100}Mo (1995) and ^{150}Nd (2004)
- 2002 full collection of DBD information:

  Tretyak and Zdesenko, Atom. Data Nucl. Data Tabl., vol. 80, pp. 83–116
- 2007 excited states:

  Barabash, arXiv:0710.2194v1 [nucl-ex]
- 2010 combination of DBD results:

  Barabash, Phys. Rev. C, vol. 81, p. 035501

Scaling with g.s. $T_{1/2}$ and full set of PSF and NME
Phys. Rev. C85, 034316 (2012)
Phys. Rev. C87, 014315 (2013)

Transition $2\nu\beta\beta$	$0^+_{g.s.}$ exp $T_{1/2}$ [yr]	0^+_1 exp $T_{1/2}$ [yr]	0^+_1 QRPA [61] [62] $T_{1/2}$ [yr]	0^+_1 QRPA [63] $T_{1/2}$ [yr]	0^+_1 IBM-2 $T_{1/2}$ [yr]
$^{48}_{20}$Ca → $^{48}_{20}$Ti	$4.4^{+0.6}_{-0.5}\cdot 10^{19}$ [57][a]	$> 1.5\cdot 10^{20}$ [64]	—	—	$1.5\cdot 10^{23}$
$^{76}_{32}$Ge → $^{76}_{34}$Se	$1.84^{+0.14}_{-0.10}\cdot 10^{21}$ [58]	$> 6.2\cdot 10^{21}$ [65]	$(7.5-310)\cdot 10^{21}$	$4.5\cdot 10^{21}$	$5.7\cdot 10^{24}$
$^{82}_{34}$Se → $^{82}_{36}$Kr	$9.2\pm 0.7\cdot 10^{19}$ [57][a]	$> 3.0\cdot 10^{21}$ [66]	$(1.5-3.3)\cdot 10^{21}$	—	—
$^{96}_{40}$Zr → $^{96}_{42}$Mo	$2.3\pm 0.2\cdot 10^{19}$ [57][a]	$> 6.8\cdot 10^{19}$ [67]	$(2.4-2.7)\cdot 10^{21}$	$3.8\cdot 10^{21}$	$2.7\cdot 10^{24}$
$^{100}_{42}$Mo → $^{100}_{44}$Ru	$7.1\pm 0.4\cdot 10^{18}$ [57][a]	$= 5.9^{+0.8}_{-0.6}\cdot 10^{20}$ [57][a]	$1.6\cdot 10^{21}$ [68]	$2.1\cdot 10^{21}$	$2.2\cdot 10^{22}$
$^{110}_{46}$Pd → $^{110}_{48}$Cd	$> 1\cdot 10^{17}$ [30]	$> 2.0\cdot 10^{20}$ [40]	$(4.2-9.1)\cdot 10^{23}$ [38]	—	$> 1.1\cdot 10^{22}$
$^{116}_{48}$Cd → $^{116}_{50}$Sn	$2.8\pm 0.2\cdot 10^{19}$ [57][a]	$> 2.0\cdot 10^{21}$ [69]	$1.1\cdot 10^{22}$	$1.1\cdot 10^{21}$	$6.4\cdot 10^{23}$
$^{124}_{50}$Sn → $^{124}_{52}$Te	—	—	$2.7\cdot 10^{21}$	—	—
$^{130}_{52}$Te → $^{130}_{54}$Xe	$6.8^{+1.2}_{-1.1}\cdot 10^{20}$ [57][a]	$> 1.3\cdot 10^{23}$ [70]	$(5.1-14)\cdot 10^{22}$ [b]	—	$2.2\cdot 10^{25}$
$^{136}_{54}$Xe → $^{136}_{56}$Ba	$2.29\pm 0.08\cdot 10^{21}$ [b]	$> 1.2\cdot 10^{23}$ [71]	$2.5\cdot 10^{21}$	$6.3\cdot 10^{21}$	$2.6\cdot 10^{25}$
$^{150}_{60}$Nd → $^{150}_{62}$Sm	$8.2\pm 0.9\cdot 10^{18}$ [57][a]	$= 1.33^{+0.45}_{-0.26}\cdot 10^{20}$ [57][a]	—	—	$1.9\cdot 10^{21}$

[a] world average values
[b] corrected in [72]

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Scaling with g.s. $T_{1/2}$ and full set of PSF and NME
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${}^{124}_{50}\mathrm{Sn} \to {}^{124}_{52}\mathrm{Te}$	—	—	$2.7 \cdot 10^{21}$	—	—
${}^{130}_{52}\mathrm{Te} \to {}^{130}_{54}\mathrm{Xe}$	$6.8^{+1.2}_{-1.1} \cdot 10^{20}$ [57]^a	$> 1.3 \cdot 10^{23}$ [70]	$(5.1 - 14) \cdot 10^{22}$ ^{b}	—	$2.2 \cdot 10^{25}$
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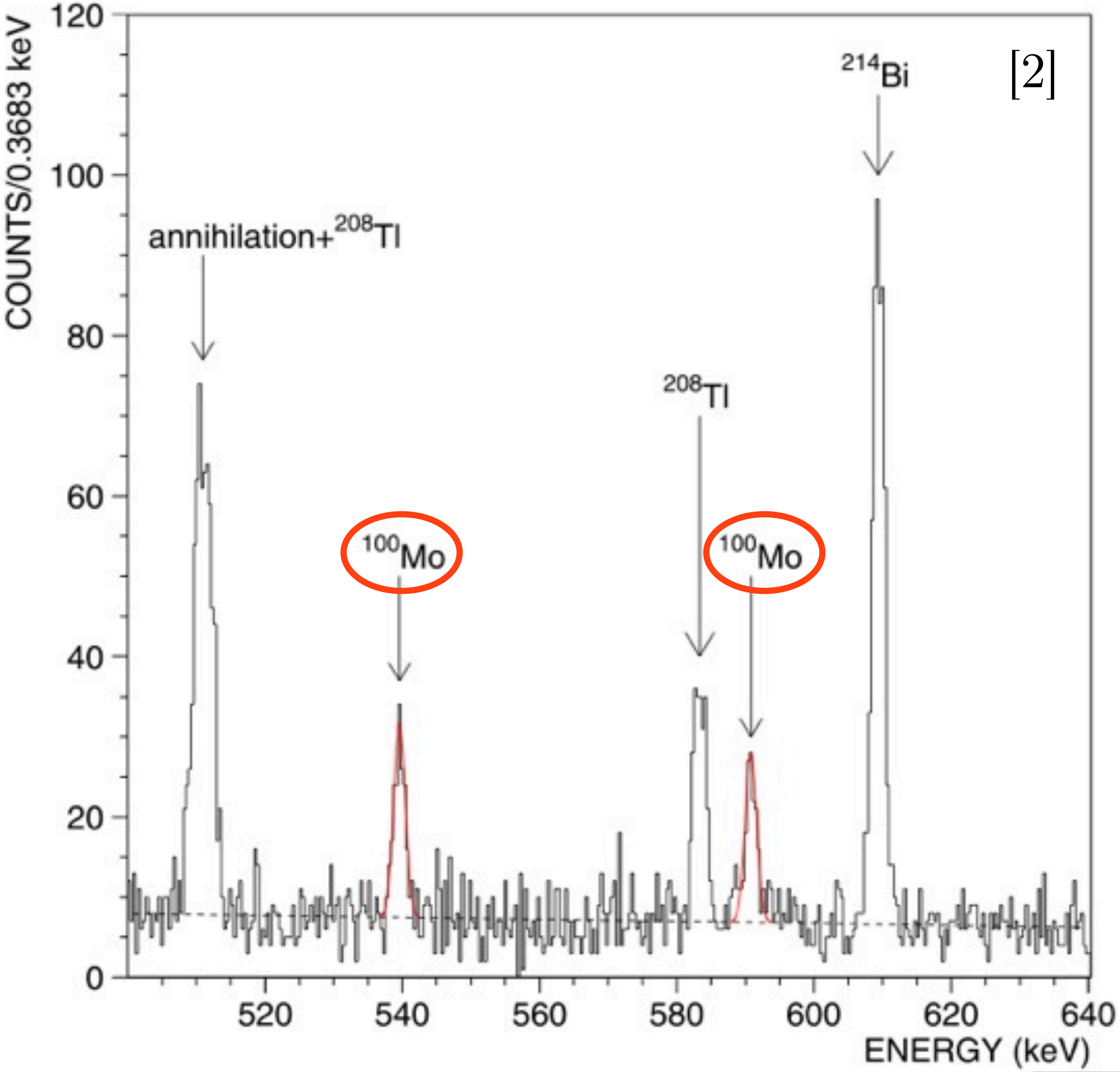
^{a} world average values
^{b} corrected in [72]

^{100}Mo $0^+{}_1$

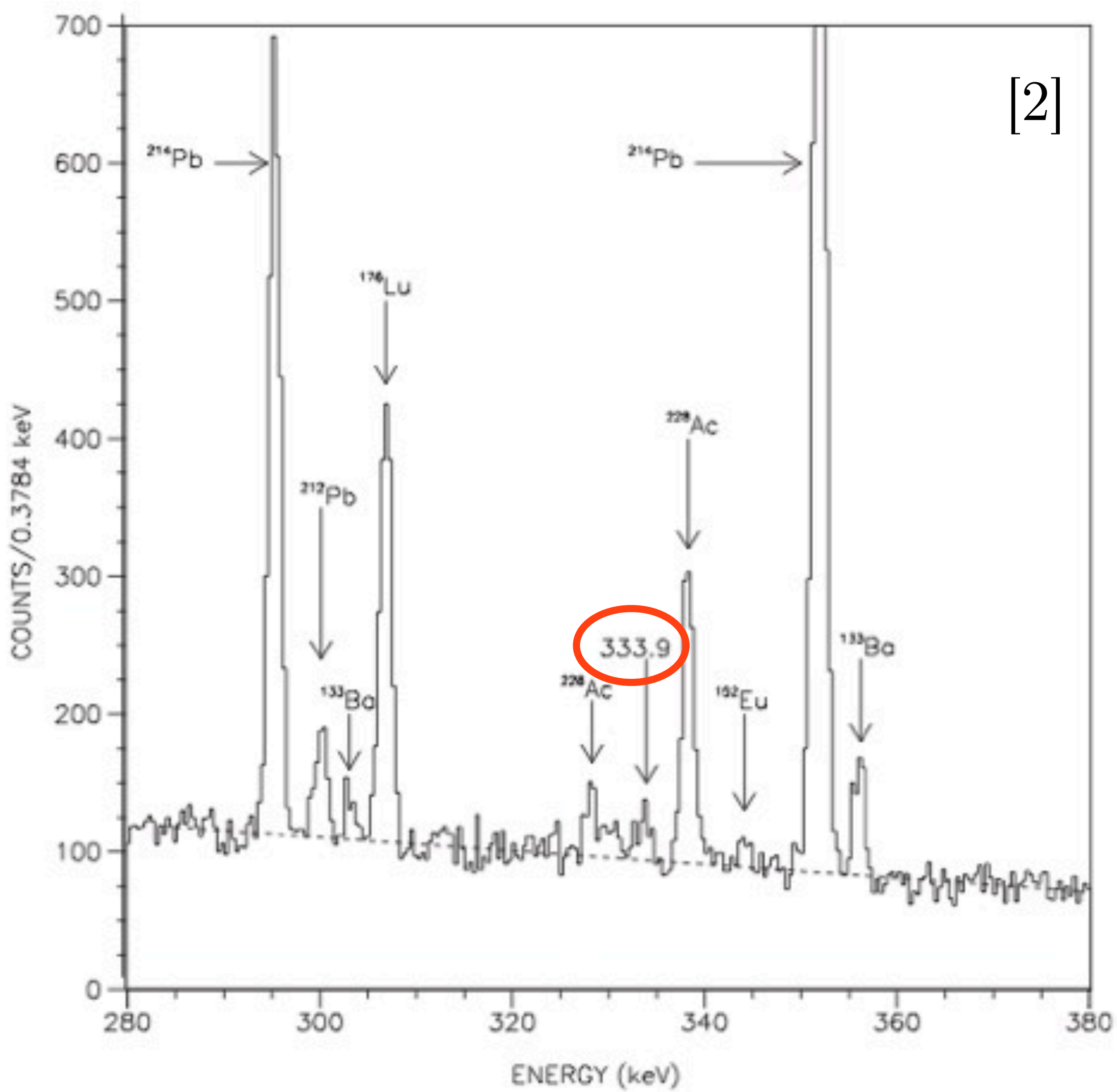
- Gammas: 539.5 keV and 590.8 keV
- [1] First discovered in 1995 by Barabash et al.: Phys. Lett. B, vol. 345, pp. 408–413 (1995)
- [2] Latest measurement by NEMO-3 Collaboration: Nucl. Phys. A, vol. 925, pp. 25–36 (2014)



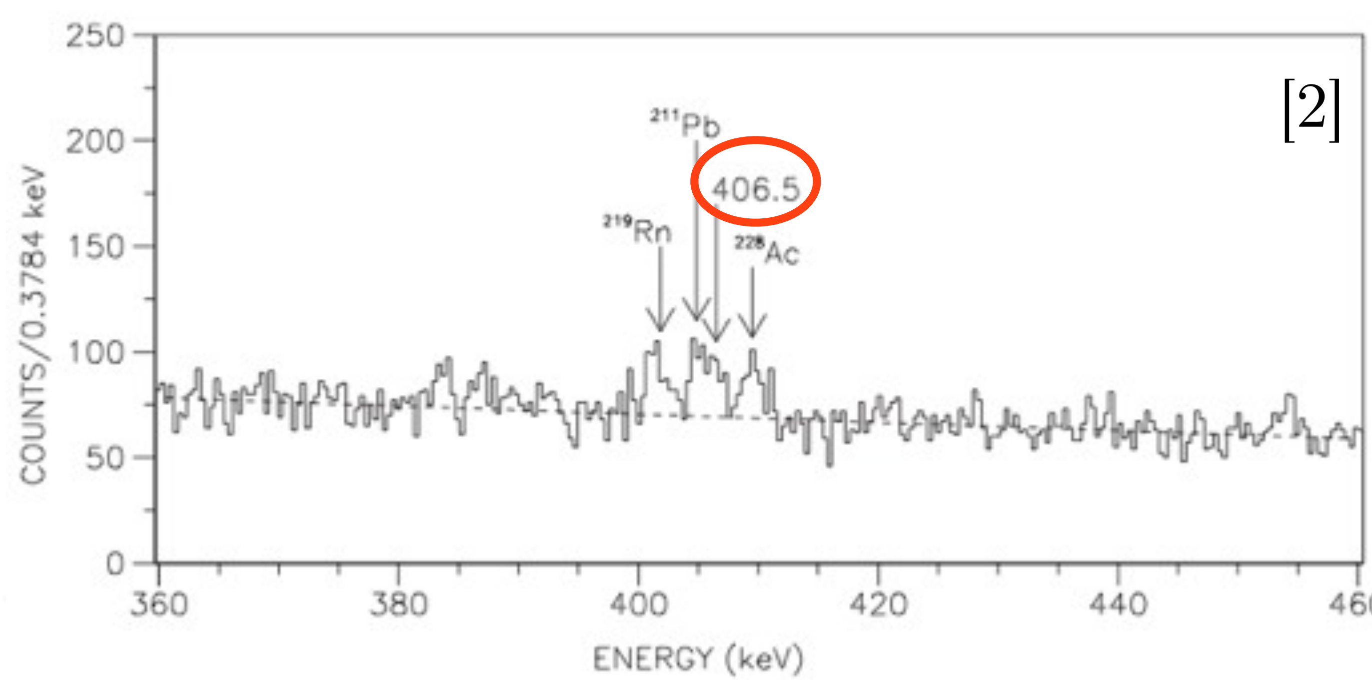
- 2.6 kg of enriched metallic ^{100}Mo
- 600 cm^3 HPGe detector
- 3.3% efficiency @ 540 keV
- Exp [2]: $T_{1/2} = 7.5 \pm 1.2 \cdot 10^{20}$ yr
- QRPA: $T_{1/2} = (1.6 - 2.2) \cdot 10^{21}$ yr
- IBM-2: $T_{1/2} = 2.2 \cdot 10^{22}$ yr

^{150}Nd 0^+_1

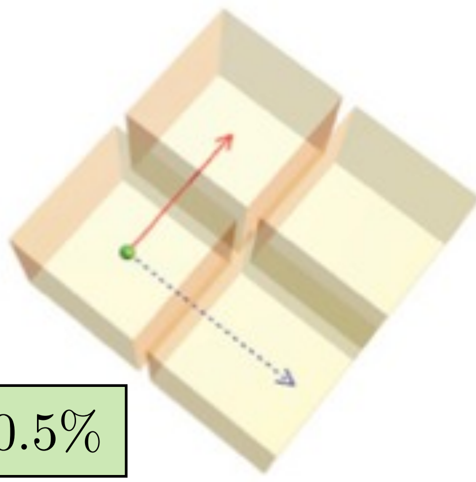
- Gammas: 333.9 keV and 406.5 keV
- [1] First discovered in 2004 by Barabash et al.: JETP Lett., vol. 79, pp. 10–12 (2004)
- [2] Latest measurement by Barabash et al.: Phys. Rev. C, vol. 79, no. 4, p. 045501 (2009)



- 3 kg of natural Nd_2O_3 (153 g ^{150}Nd)
- HPGe: 2.3% efficiency @ 334 keV
- [2]: $T_{1/2} = 1.33^{+0.63}_{-0.36} \cdot 10^{20}$ yr
- IBM-2: $T_{1/2} = 1.9 \cdot 10^{21}$ yr

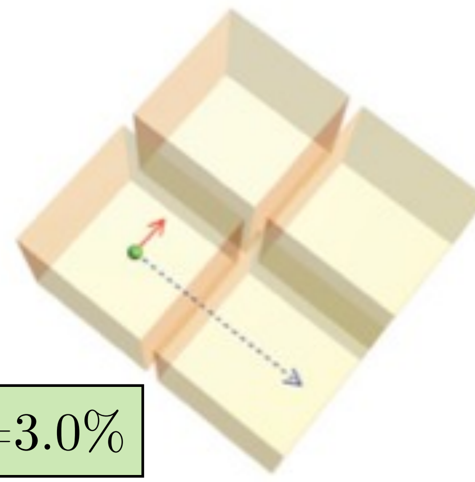


CUORICINO: ^{130}Te



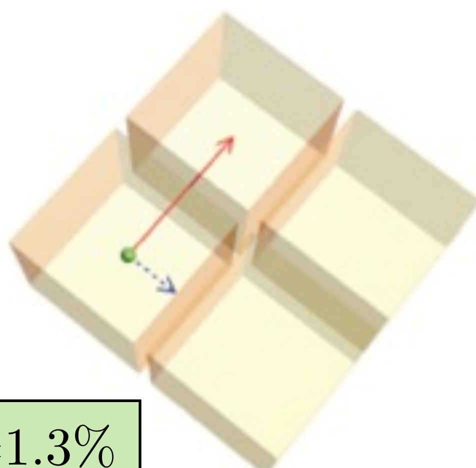
ϵ=0.5%

(a) Scenario 1



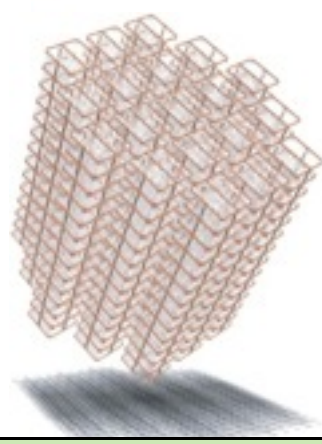
ϵ=3.0%

(b) Scenario 2



ϵ=1.3%

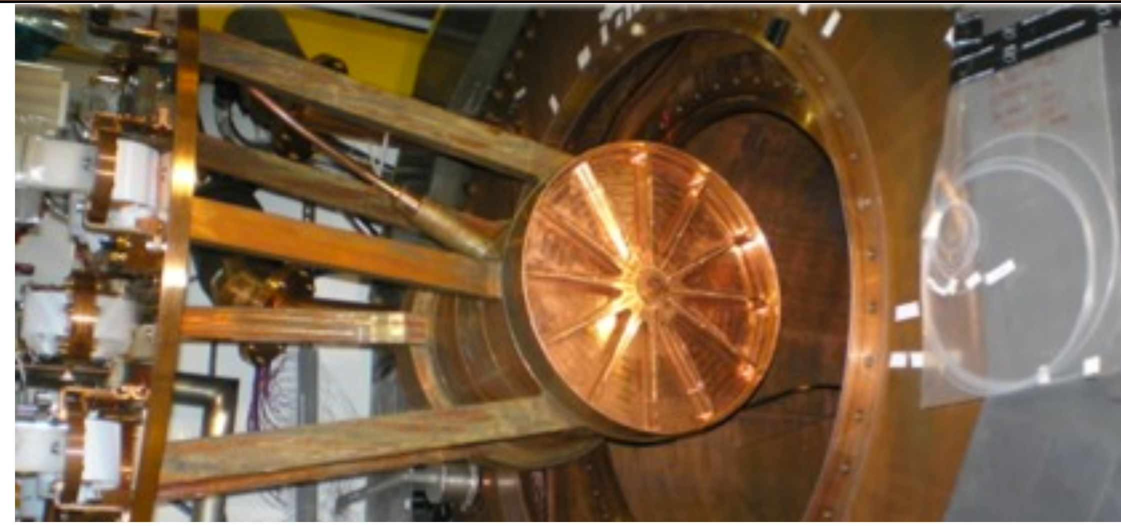
(c) Scenario 3

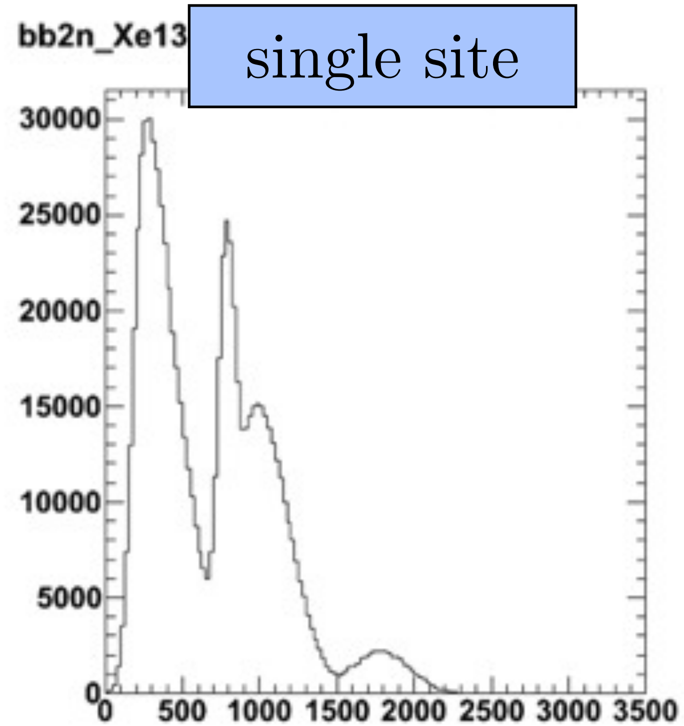


Future CUORE
19 towers x 13 floors

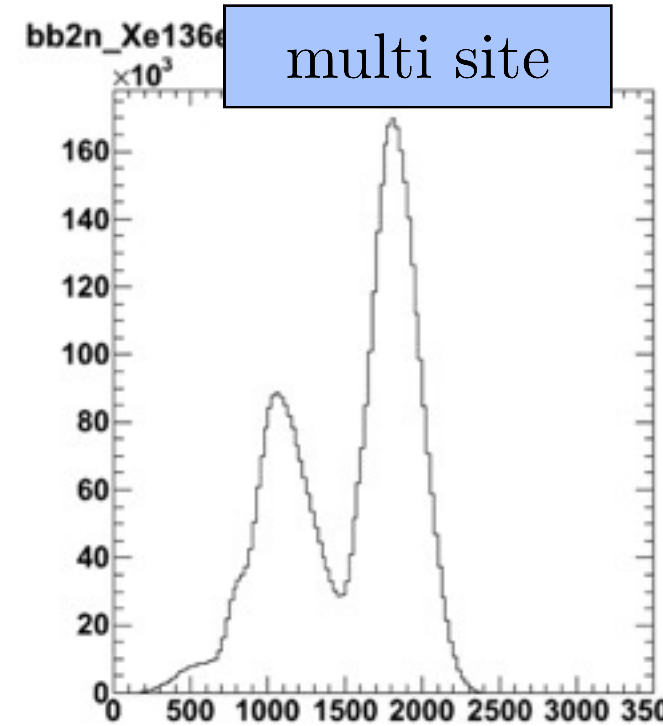
- 11.3 kg of TeO_2 bolometers
- ɣ: 536 keV and 1257 keV; β <734 keV
- $T_{1/2} > 1.3 \cdot 10^{23}$ yr [Phys. Rev. C 85 045503 (2012)]
- QRPA: $T_{1/2} = (0.5 - 1.4) \cdot 10^{23}$ yr
- IBM-2: $T_{1/2} = 2.2 \cdot 10^{25}$ yr

EXO-200: ^{136}Xe





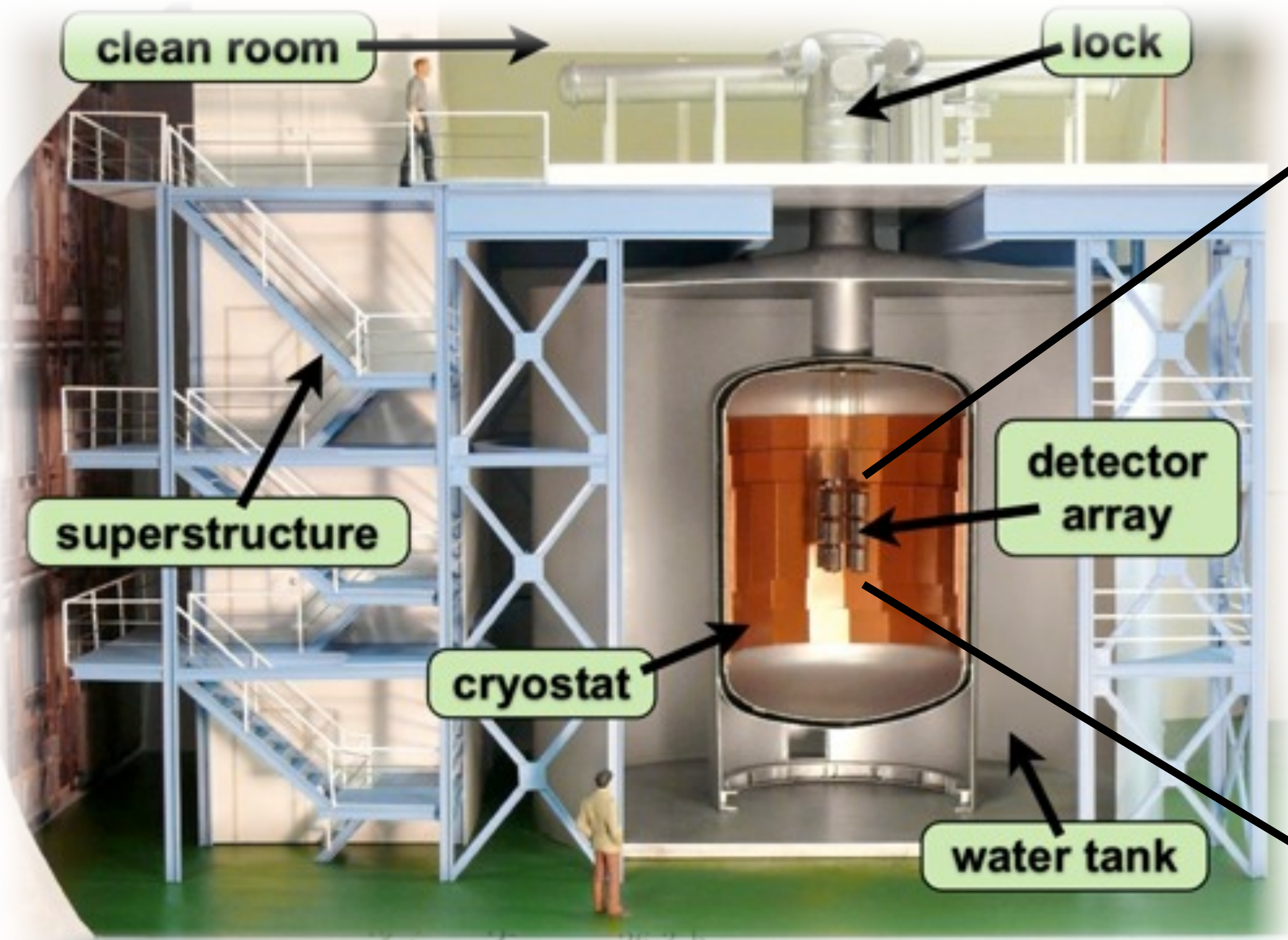
single site

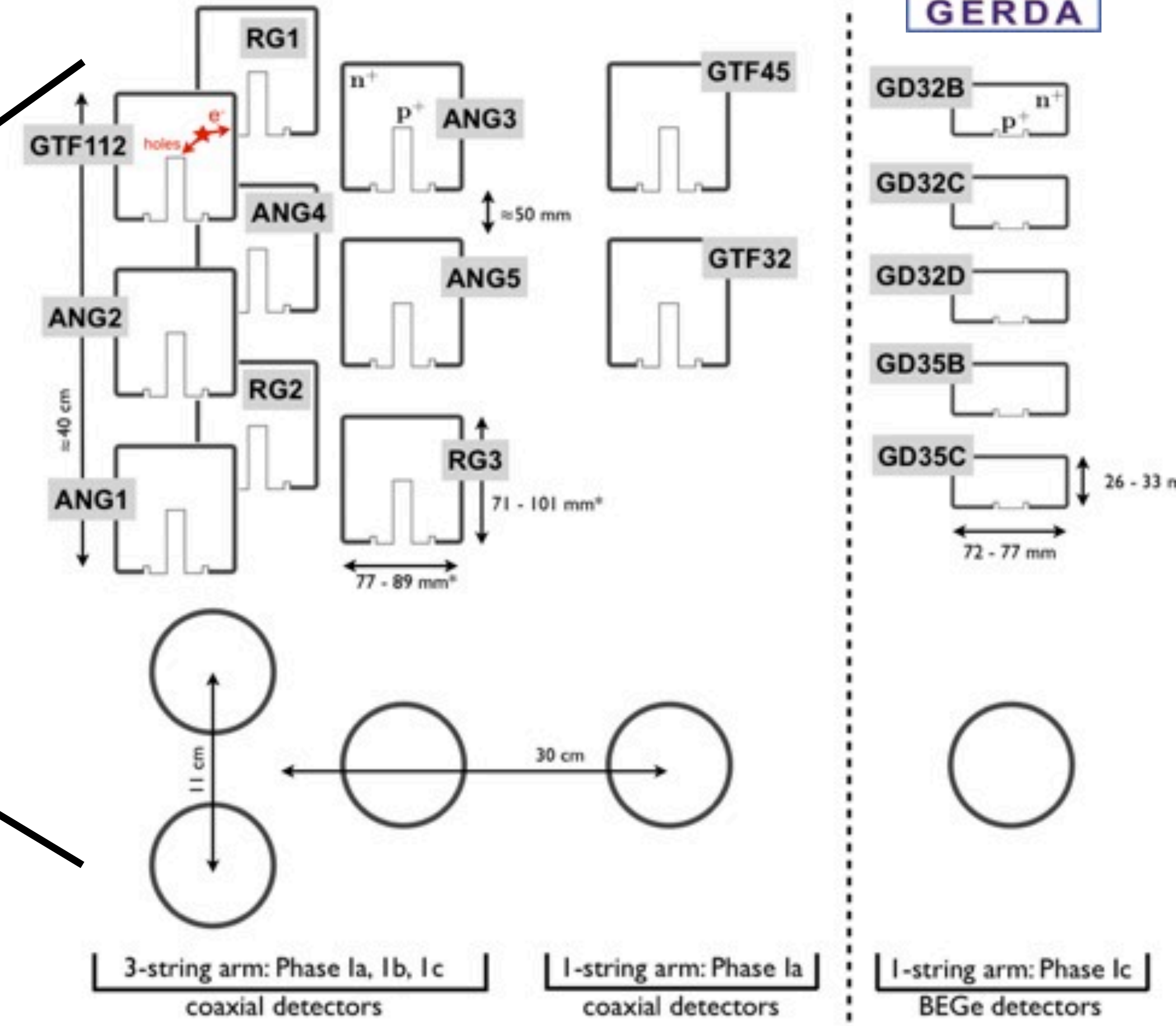


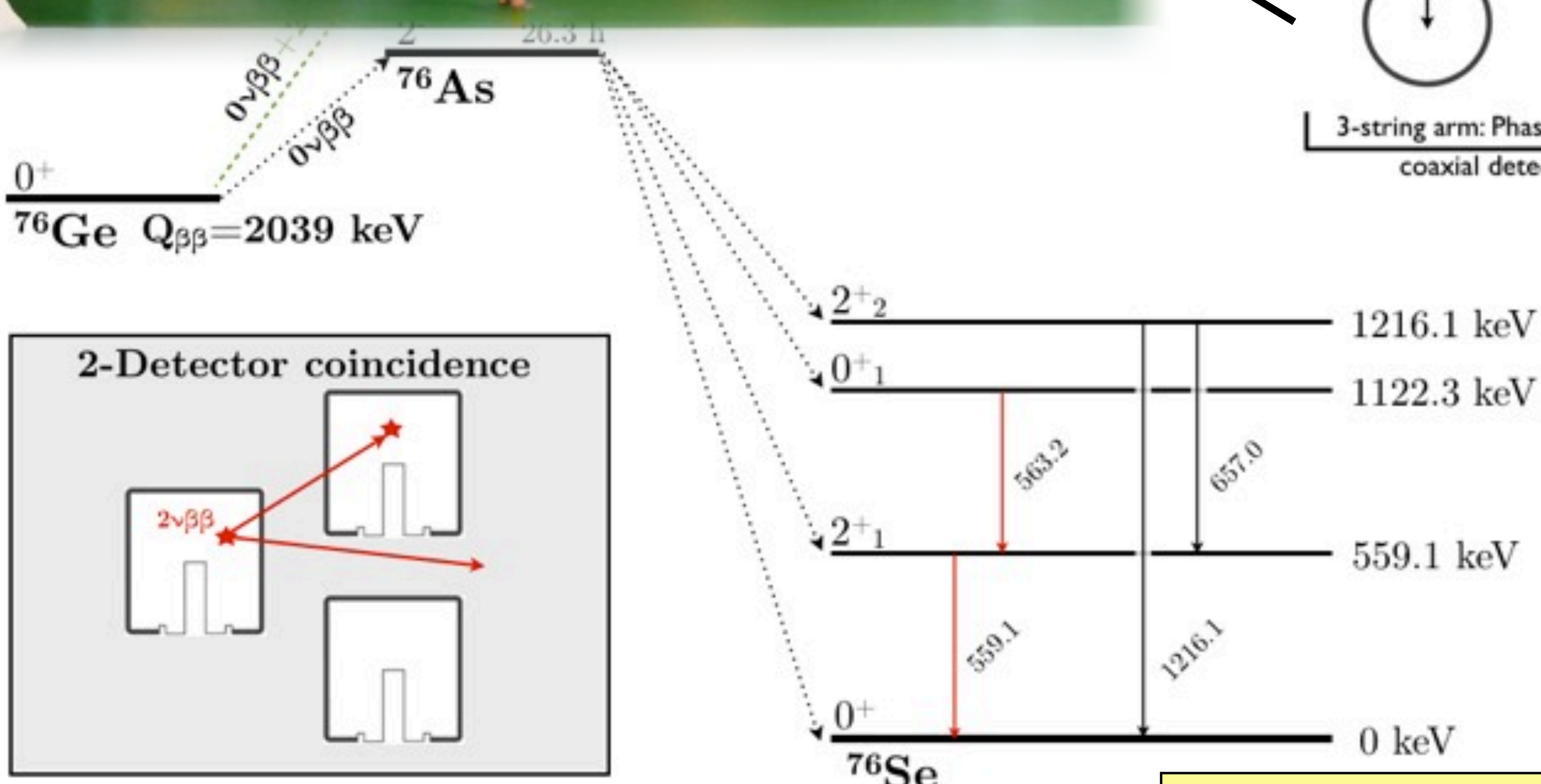
multi site

- 80 kg liquid enriched Xe TPC
- Complicated analysis without segmentation
- ɣ: 761 keV and 819 keV; β: <879 keV
- $T_{1/2} > 1.2 \cdot 10^{23}$ yr [PhD Thesis Yung-Ruey Yen (2013)]
- IBM-2: $T_{1/2} = 2.5 \cdot 10^{25}$ yr

Excited States in GERDA Phase I







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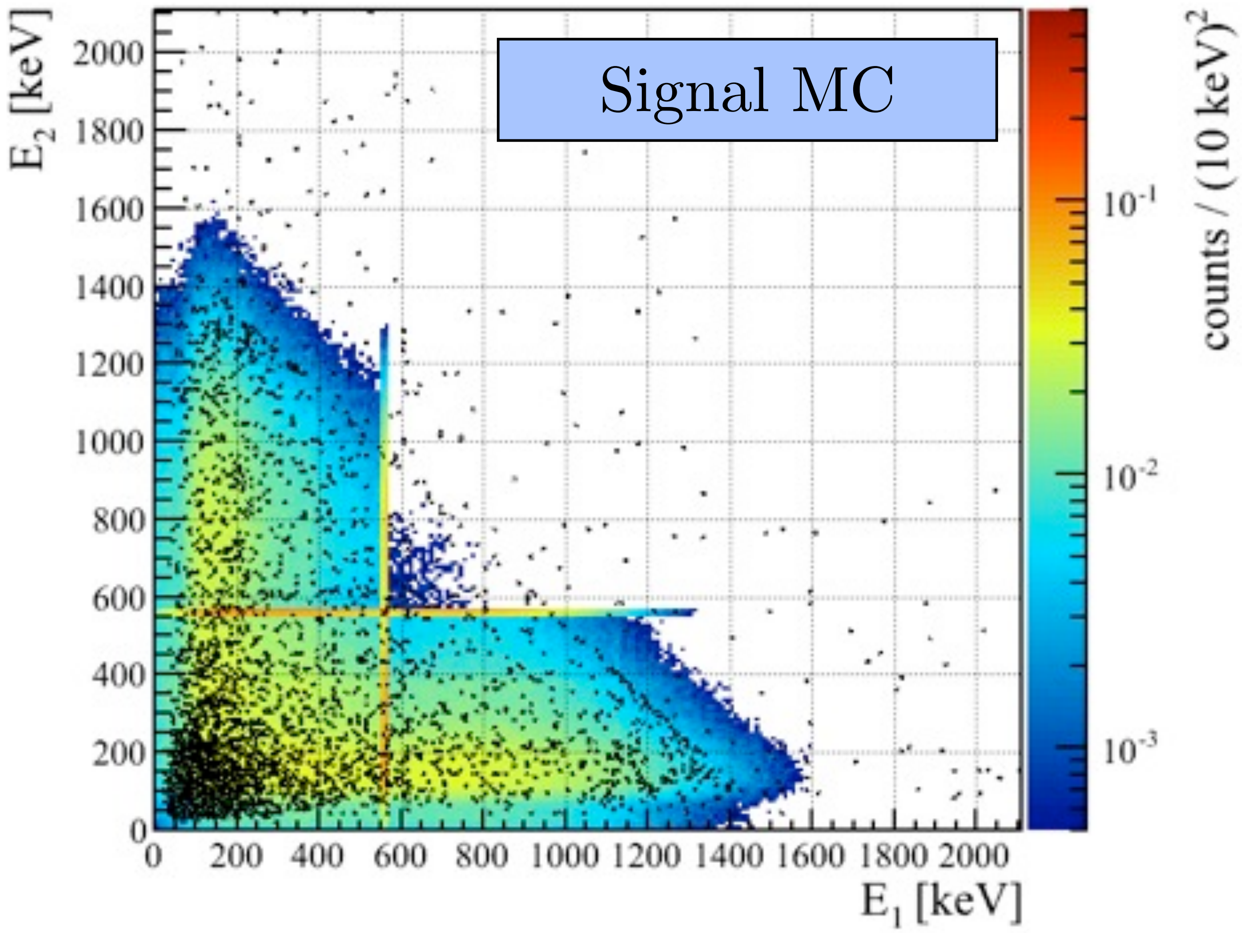
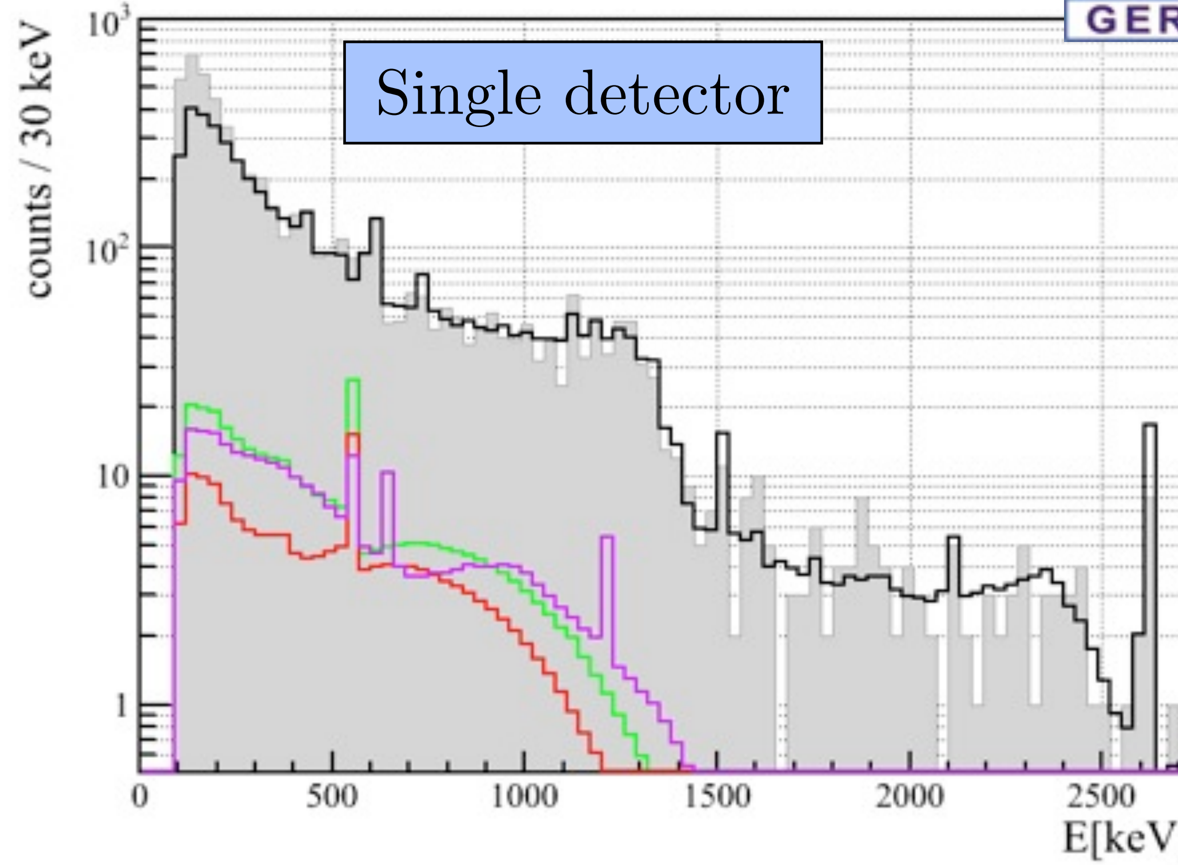
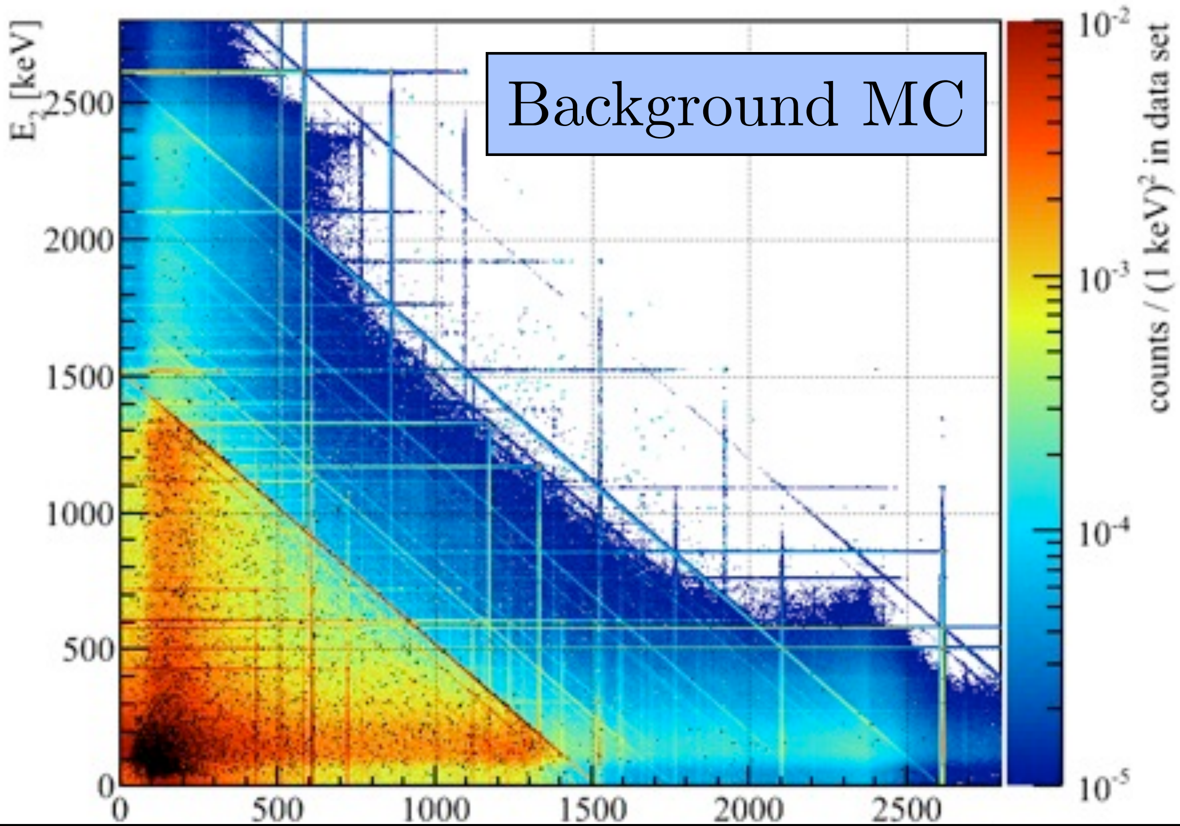
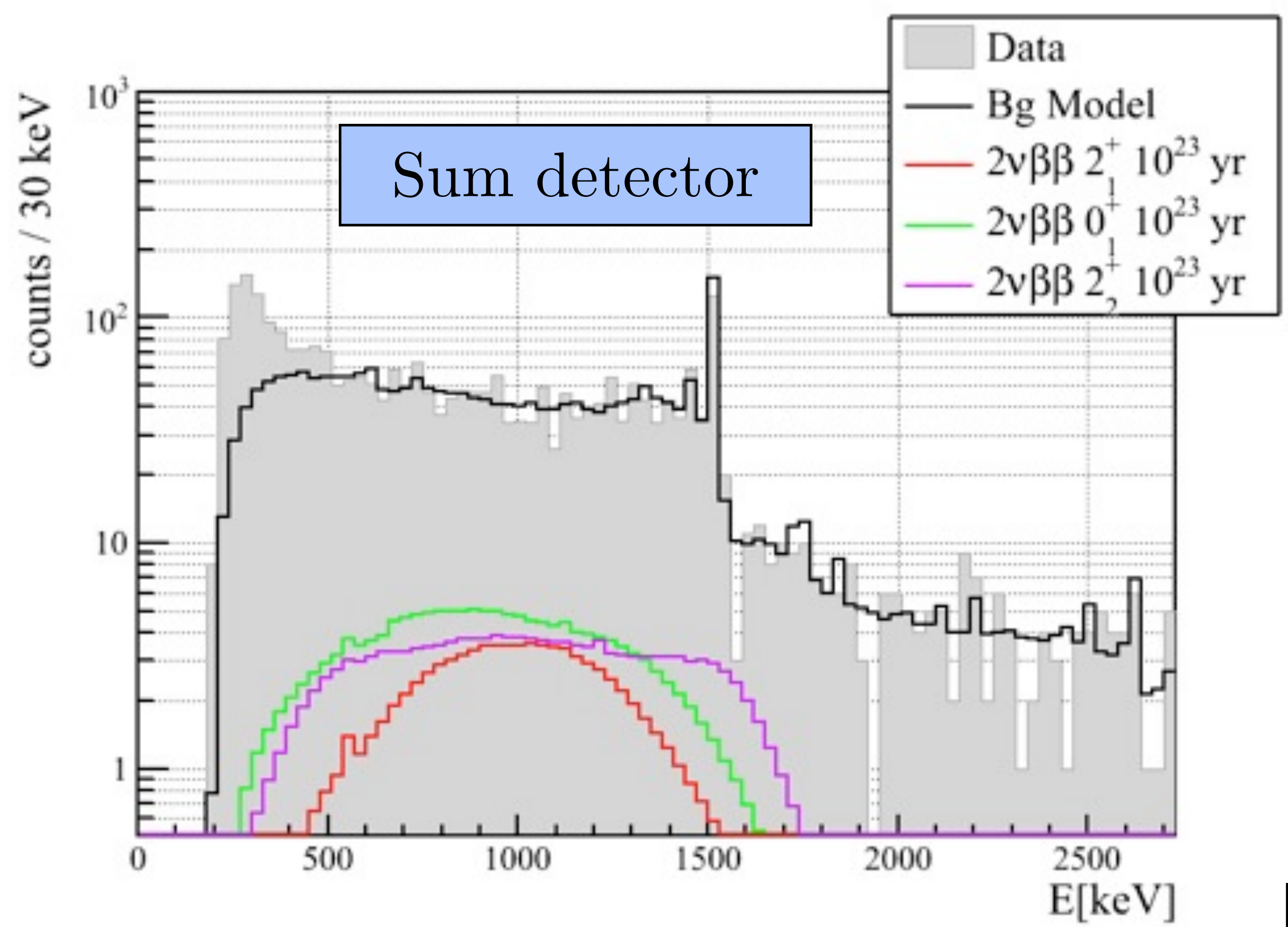




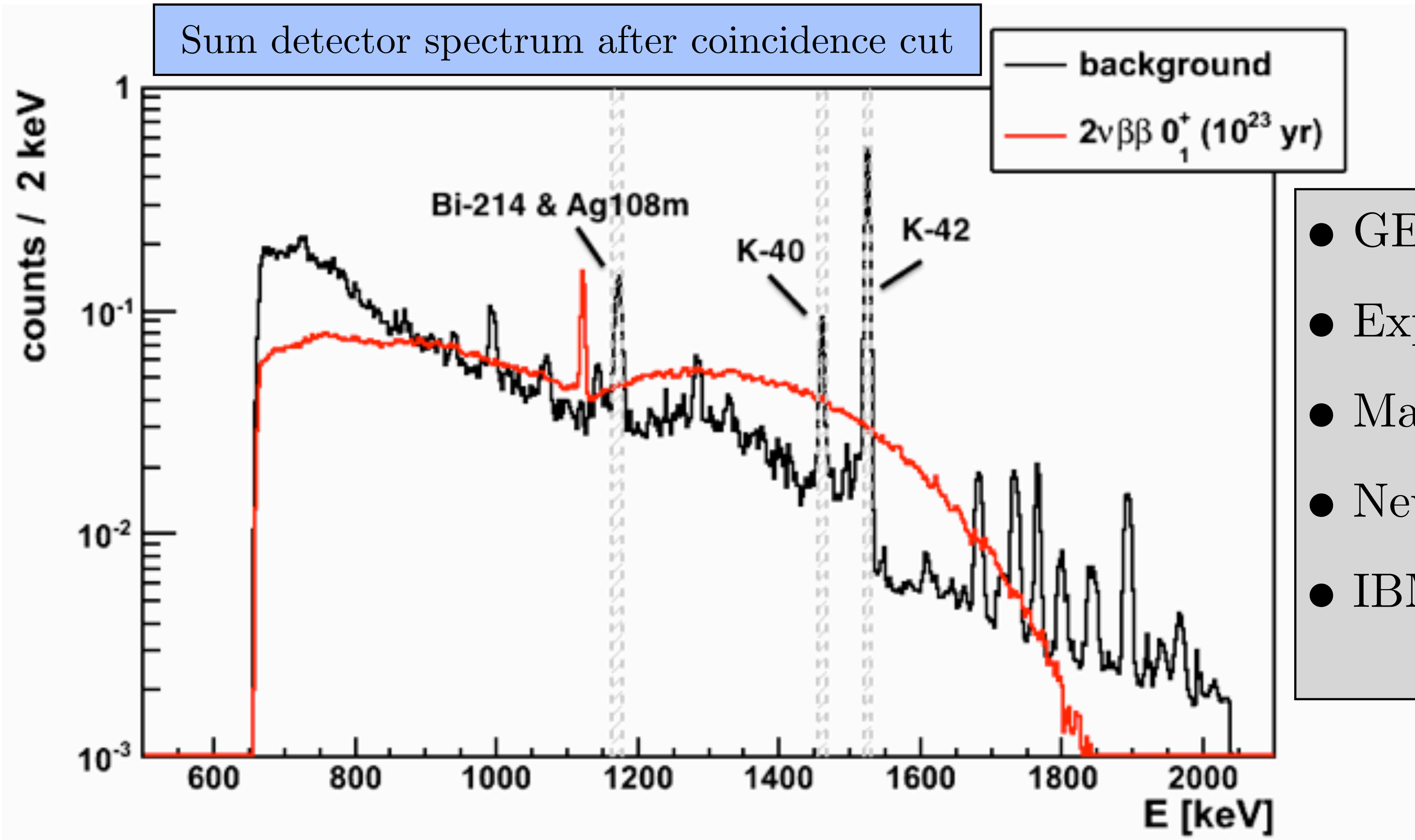




Excited States in GERDA Phase I

- Single detector spectra used for analysis
- Cut flow in 4 levels:
  0. Standard cuts: Quality cuts and muon-veto
  1. Coincidence cuts: Any of the 2 detectors has any de-excitation gamma energy +-2 sigma
  2. Background cuts: Exclusion of background gamma lines
  3. Pair cuts: Choose detector pairs that maximize sensitivity

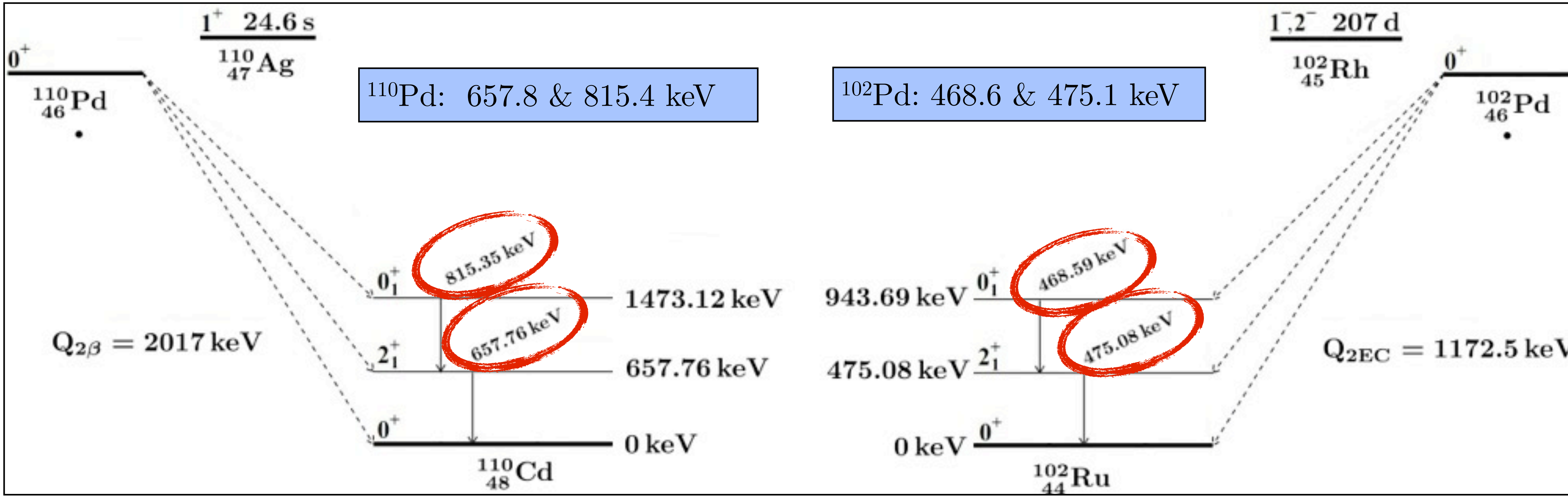
Sum detector spectrum after coincidence cut



- GERDA sensitivity $> 1 \cdot 10^{23}$ yr
- Exp $(0^+{}_1)$: $T_{1/2} > 6.2 \cdot 10^{21}$ yr
- Many old predictions $< 1 \cdot 10^{23}$ yr
- New (RQRPA): $T_{1/2} = 1.2 - 5.8 \cdot 10^{23}$ yr
- IBM-2: $T_{1/2} = 5.7 \cdot 10^{24}$ yr

Work in progress ...

Palladium: ^{110}Pd and ^{102}Pd



- ^{110}Pd: $2\nu\beta^-\beta^-$
- nat abundance: 11.72 %
- Q-value 2017.9 keV PRL 108, 062502 (2012)
- Only measurement for g.s. (1952)

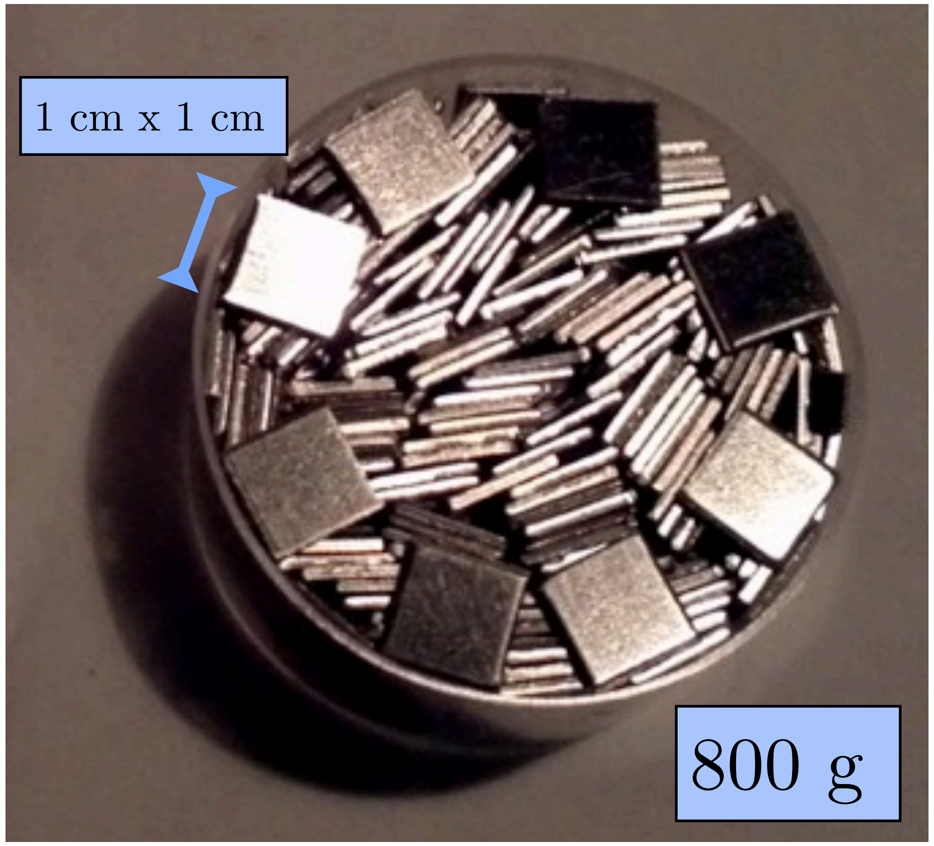
- ^{102}Pd: 2νECEC, $2\nu EC\beta^+$
- nat abundance: 1.02 %
- Q-value: 1172 keV
- No previous measurement

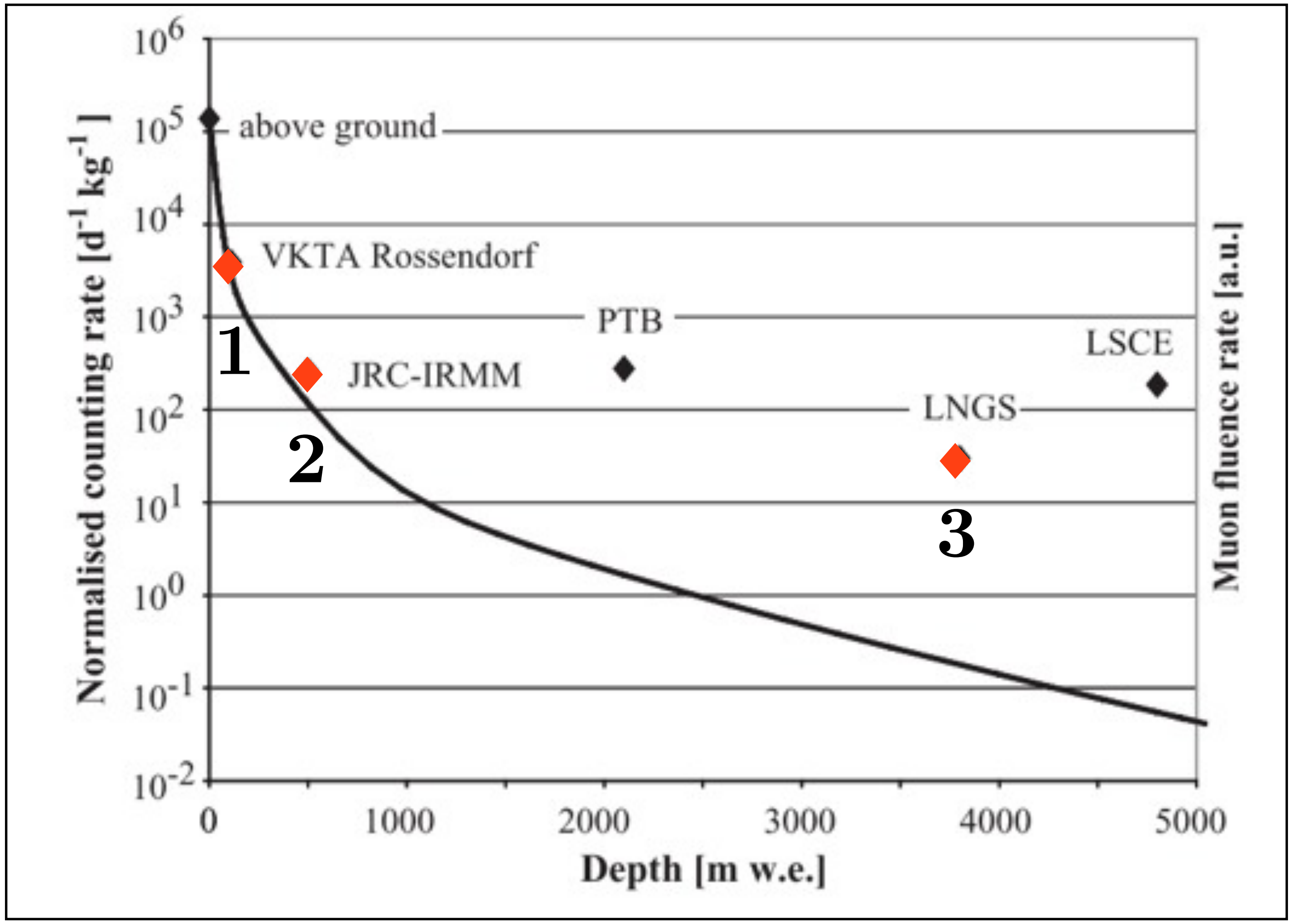
- Idea: Measure sample with HPGe γ-spectroscopy in low background env.
- Use only γ-lines from excited state transitions as experimental signatures
- Not sensitive to g.s. transitions; No separation between 2νββ and 0νββ

Three Palladium Measurements

The Palladium world tour:

1. Felsenkeller (Dresden, Germany)
2. HADES (Mol, Belgium)
3. LNGS (L'Aquila, Italy)





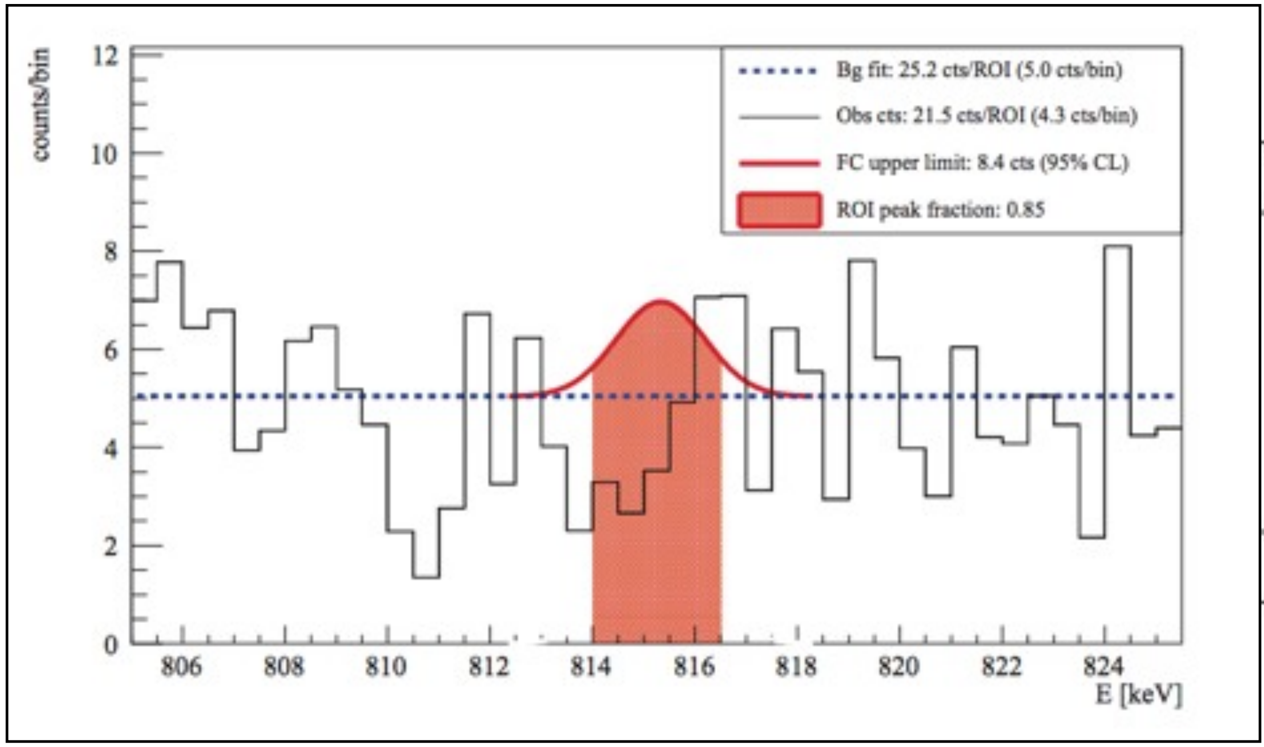
Applied Radiation and Isotopes 61 (2004) 167–172

First ^{110}Pd and ^{102}Pd Limits

Felsenkeller: Phys. Lett. B 705 47–51 (2011)

HADES: Phys. Rev. C 87, 034312 (2013)

LNGS: in preparation



- First excited state limits for ^{110}Pd
- (0^+_1): $T_{1/2} > 2 \cdot 10^{20}$ yr
- QRPA: $T_{1/2} = (4 - 9) \cdot 10^{23}$ yr
- IBM-2: $T_{1/2} > 1.1 \cdot 10^{22}$ yr

(no ground state measured)

Th model	Lower Limit $T_{1/2}$ [yr]	Reference	Year of Publication
^{110}Pd Ground State Transition			
Exp	$1 \cdot 10^{17}$ (68 % CL)	[30]	1952
PHFM	$1.41 \cdot 10^{20}$ and $3.44 \cdot 10^{20}$ [1]	[31]	2005
SSDH	$1.75 \cdot 10^{20}$	[32]	2000
SSDH	$1.2 - 1.8 \cdot 10^{20}$ [2]	[33]	1998
SRPA	$1.6 \cdot 10^{20}$	[34]	1994
OEM	$1.24 \cdot 10^{21}$	[35]	1994
QRPA	$1.16 \cdot 10^{19}$	[36]	1990
SSD	$1.2 \cdot 10^{20}$	[37]	2005
pnQRPA	$1.1 \cdot 10^{20}$ and $0.91 \cdot 10^{20}$ [3]	[38]	2011
^{110}Pd 2^+_1 Excited State Transition @ 657.76 keV			
Exp	$4.40 \cdot 10^{19}$ (95 % CL)	[39]	2011
Exp	$1.72 \cdot 10^{20}$ (95 % CL)	[40]	2013
SSD	$4.4 \cdot 10^{25}$	[37]	2005
SRPA	$8.37 \cdot 10^{25}$	[34]	1994
pnQRPA	$1.48 \cdot 10^{25}$	[41]	2007
pnQRPA	$0.62 \cdot 10^{25}$ and $1.3 \cdot 10^{25}$ [3]	[38]	2011
^{110}Pd 0^+_1 Excited State Transition @ 1473.12 keV			
Exp	$5.89 \cdot 10^{19}$ (95 % CL)	[39]	2011
Exp	$1.98 \cdot 10^{20}$ (95 % CL)	[40]	2013
SSD	$2.4 \cdot 10^{26}$	[37]	2005
pnQRPA	$4.2 \cdot 10^{23}$ and $9.1 \cdot 10^{23}$ [3]	[38]	2011
^{110}Pd 2^+_2 Excited State Transition @ 1475.80 keV			
Exp	$9.26 \cdot 10^{19}$ (95 % CL)	[40]	2013
SSD	$3.8 \cdot 10^{31}$	[37]	2005
pnQRPA	$11 \cdot 10^{30}$ and $7.4 \cdot 10^{30}$ [3]	[38]	2011
^{110}Pd 0^+_2 Excited State Transition @ 1731.33 keV			
Exp	$1.38 \cdot 10^{20}$ (95 % CL)	[40]	2013
SSD	$5.3 \cdot 10^{29}$	[37]	2005
^{110}Pd 2^+_3 Excited State Transition @ 1783.48 keV			
Exp	$1.09 \cdot 10^{20}$ (95 % CL)	[40]	2013
SSD	$1.3 \cdot 10^{35}$	[37]	2005

Conclusions

- Excited states in 2νββ DBD helps 0νββ NME calculations
- New generation 0νββ DBD will soon discover more 2νββ $0^+{}_1$ transitions
- New result in ^{136}Xe (EXO-200) and ^{130}Te (CUORICINO)
- Analysis with ^{76}Ge (GERDA Phase I) in preparation
- New first limits for ^{110}Pd and ^{102}Pd

Transition $2\nu\beta\beta$	$0^+_{g.s.}$ exp $T_{1/2}$ [yr]	0^+_1 exp $T_{1/2}$ [yr]	0^+_1 QRPA [61] [62] $T_{1/2}$ [yr]	0^+_1 QRPA [63] $T_{1/2}$ [yr]	0^+_1 IBM-2 $T_{1/2}$ [yr]
$^{48}_{20}Ca \rightarrow ^{48}_{20}Ti$	$4.4^{+0.6}_{-0.5} \cdot 10^{19}$ [57][a]	$> 1.5 \cdot 10^{20}$ [64]	—	—	$1.5 \cdot 10^{23}$
$^{76}_{32}Ge \rightarrow ^{76}_{34}Se$	$1.84^{+0.14}_{-0.10} \cdot 10^{21}$ [58]	$> 6.2 \cdot 10^{21}$ [65]	$(7.5 - 310) \cdot 10^{21}$	$4.5 \cdot 10^{21}$	$5.7 \cdot 10^{24}$
$^{82}_{34}Se \rightarrow ^{82}_{36}Kr$	$9.2 \pm 0.7 \cdot 10^{19}$ [57][a]	$> 3.0 \cdot 10^{21}$ [66]	$(1.5 - 3.3) \cdot 10^{21}$	—	—
$^{96}_{40}Zr \rightarrow ^{96}_{42}Mo$	$2.3 \pm 0.2 \cdot 10^{19}$ [57][a]	$> 6.8 \cdot 10^{19}$ [67]	$(2.4 - 2.7) \cdot 10^{21}$	$3.8 \cdot 10^{21}$	$2.7 \cdot 10^{24}$
$^{100}_{42}Mo \rightarrow ^{100}_{44}Ru$	$7.1 \pm 0.4 \cdot 10^{18}$ [57][a]	$= 5.9^{+0.8}_{-0.6} \cdot 10^{20}$ [57][a]	$1.6 \cdot 10^{21}$ [68]	$2.1 \cdot 10^{21}$	$2.2 \cdot 10^{22}$
$^{110}_{46}Pd \rightarrow ^{110}_{48}Cd$	$> 1 \cdot 10^{17}$ [30]	$> 2.0 \cdot 10^{20}$ [40]	$(4.2 - 9.1) \cdot 10^{23}$ [38]	—	$> 1.1 \cdot 10^{22}$
$^{116}_{48}Cd \rightarrow ^{116}_{50}Sn$	$2.8 \pm 0.2 \cdot 10^{19}$ [57][a]	$> 2.0 \cdot 10^{21}$ [69]	$1.1 \cdot 10^{22}$	$1.1 \cdot 10^{21}$	$6.4 \cdot 10^{23}$
$^{124}_{50}Sn \rightarrow ^{124}_{52}Te$	—	—	$2.7 \cdot 10^{21}$	—	—
$^{130}_{52}Te \rightarrow ^{130}_{54}Xe$	$6.8^{+1.2}_{-1.1} \cdot 10^{20}$ [57][a]	$> 1.3 \cdot 10^{23}$ [70]	$(5.1 - 14) \cdot 10^{22}$ [b]	—	$2.2 \cdot 10^{25}$
$^{136}_{54}Xe \rightarrow ^{136}_{56}Ba$	$2.29 \pm 0.08 \cdot 10^{21}$ [b]	$> 1.2 \cdot 10^{23}$ [71]	$2.5 \cdot 10^{21}$	$6.3 \cdot 10^{21}$	$2.6 \cdot 10^{25}$
$^{150}_{60}Nd \rightarrow ^{150}_{62}Sm$	$8.2 \pm 0.9 \cdot 10^{18}$ [57][a]	$= 1.33^{+0.45}_{-0.26} \cdot 10^{20}$ [57][a]	—	—	$1.9 \cdot 10^{21}$

[a] world average values
[b] corrected in [72]

BACKUP

Angular Correlations