AVERAGE (RECOMMENDED) HALF-LIFE VALUES FOR TWO NEUTRINO DOUBLE BETA DECAY: UPGRADE'2019

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HISTORY

- First time I’ve presented average (recommended) half-life values at MEDEX’01 in 2001

  [Czech. J. Phys. 52 (2002) 567]

- Then I’ve made upgrade for MEDEX’05 in 2005

  [Czech. J. Phys. 56 (2006) 437]

- New upgrade in 2009 at MEDEX’09

  [AIP Conf. Proc. 1180 (2009) 6; PRC 81 (2010) 035501]

- Latest upgrade in 2013-2014 at MEDEX’13

  [AIP Conf. Proc. 1572 (2013) 11; NPA 935 (2015) 52)

New results since last review

- ^{48}Ca (NEMO-3)
- ^{76}Ge (GERDA)
- ^{82}Se (NEMO-3, CUORE-0)
- ^{100}Mo (NEMO-3, LUMINEU/CUPID-Mo)
- ^{116}Cd (NEMO-3, AURORA)
- ^{130}Te (CUORE0, CUORE)
- ^{136}Xe (KanLAND)
- ^{150}Nd (NEMO-3)
- ^{150}Nd-^{150}Sm(0^+; 740.4 keV) (Gran Sasso)
- ^{78}Kr (Baksan)
- ^{124}Xe (XENON1T)

New 15 results for 10 nuclei

WHY DO WE NEED THE PRECISE VALUES OF HILF-LIVES?

1. Nuclear spectroscopy.

2. Nuclear Matrix Elements (NME).
   ⇒ *to improve the quality of NME(2ν) and NME(0ν) calculations.*

3. To fix g_A.

4. To check "bosonic" neutrino hypothesis, LV and SSD mechanism.

WAITED AVERAGE PROCEDURE (recommended by Particle Data Group)

- $x \pm \delta x = \Sigma\, w_i x_i / \Sigma w_i \pm (\Sigma w_i)^{-1/2}$,   (1)

  $w_i = 1/(\delta x_i)^2$.

- Here x_i and δx_i are the value and error reported by the i-th experiment, and the sums run over N experiments.
- We then calculate $\chi^2 = \Sigma w_i (x - x_i)^2$ and compare it with **N-1**.

- If $\chi^2/(N-1) \le 1$ - no problem

- If $\chi^2/(N-1) >> 1$ - we may choose not to use the average at all
- If $\chi^2/(N-1) > 1$, but not greatly so, we increase our error by a scale factor

  $$S = [\chi^2/(N-1)]^{1/2} \qquad (2)$$

- For average we add the statistical and systematic errors quadratically and use this combined error for **δx**.

1. ^{48}Ca.

1) $[4.3^{+2.4}_{-1.1}(\text{stat}) \pm 1.4(\text{syst})] \cdot 10^{19}$ yr — Moe et al., 1996

(S/B ≈ 1/5; N ≈ 100 events)

2) $4.2^{+3.3}_{-1.3} \cdot 10^{19}$ yr — TGV, 2000

(S/B ≈ 5/0; N = 5)

3) $[6.4^{+0.7}_{-0.6}(\text{stat})\ ^{+1.2}_{-0.9}(\text{syst})] \cdot 10^{19}$ yr — NEMO-3, 2016

(S/B ≈ 3.9; N = 153 events)

{ $[4.4^{+0.5}_{-0.4}(\text{stat}) \pm 0.4(\text{syst})] \cdot 10^{19}$ yr — NEMO-3, 2008}

- **Average value:** $5.3^{+1.2}_{-0.8} \cdot 10^{19}$ yr

(2015: $4.4^{+0.6}_{-0.5} \cdot 10^{19}$ yr)

[Shell Model: (2-4.5) $\cdot 10^{19}$ yr]

2. ^{76}Ge

1. **$(0.9 \pm 0.1) \cdot 10^{21}$ yr** ITEP-ErPI, 1990
   (S/B ≈ 1/8, N ≈ 4000)

2. **$1.1^{+0.6}_{-0.3} \cdot 10^{21}$ yr** F. Avignone et al., 1991
   (S/B ≈ 1/6, N = 758)

3. **$1.27^{+0.21}_{-0.16} \cdot 10^{21}$ yr** $(0.93^{+0.2}_{-0.1} \cdot 10^{21}$ yr) F. Avignone et al., 1994
   (S/B ≈ 4, N = 138)

(Problem with internal background- F. Avignone and S. Elliott, Front. In Phys. 7 (2019) 6)

4. **$(1.45 \pm 0.15) \cdot 10^{21}$ yr** IGEX, 1999
   (S/B ≈ 1.5, N ≈ 3000; not published)

5. **$[1.74 \pm 0.01(\text{stat})\ ^{+0.18}_{-0.16}(\text{syst})] \cdot 10^{21}$ yr** H-M, 2003
   (S/B ≈ 1.5, N ≈ 64000)

6. **$[1.84^{+0.09}_{-0.08}\ (\text{fit})\ ^{+0.11}_{-0.06}\ (\text{syst})] \cdot 10^{21}$ yr** GERDA-I, 2012
   (S/B ≈ 4, N ≈ 7030)

7. **$[1.925 \pm 0.094] \cdot 10^{21}$ yr** GERDA-I, 2015
   (S/B ≈ 3 (4), N ≈ 30000)

Average value: $(1.88 \pm 0.08) \cdot 10^{21}$ yr

[2015: $(1.65^{+0.14}_{-0.12}) \cdot 10^{21}$ yr]

3. ^{82}Se

- **$1.08^{+0.26}_{-0.06} \cdot 10^{20}$ yr** **M. Moe, 1992**
  (S/B ≈ 7.8, N = 89.6)

- **[0.83 ± 0.10(stat) ± 0.07(syst)] $\cdot 10^{20}$ yr** **NEMO-2, 1998**
  (S/B ≈ 2, N = 149)

- **[0.96 ± 0.03(stat) ± 0.1(syst)] $\cdot 10^{20}$ yr** **NEMO-3, 2005**
  (S/B ≈ 4, N = 2750)
  [0.939 ± 0.017(stat) ± 0.054(syst)] $\cdot 10^{20}$ yr **NEMO-3, 2018**
  (S/B ≈ 4, N = 3472)

  (1.3 ± 0.05)$\cdot 10^{20}$ y (geochemistry, 1986)

Average value: (0.93 ± 0.05) $\cdot 10^{20}$ yr

[2015: (0.92 ± 0.07) $\cdot 10^{20}$ yr]

4. ^{96}Zr

1) **$[2.1^{+0.8}_{-0.4}(stat) \pm 0.2(syst)] \cdot 10^{19}$ yr** **NEMO-2, 1999**
(S/B ≈ 2, N = 26.7)

2) **$[2.35 \pm 0.14(stat) \pm 0.16(syst)] \cdot 10^{19}$ yr** **NEMO-3, 2009**
(S/B ≈ 1, N = 453)

- $(3.9 \pm 0.9) \cdot 10^{19}$ y (geochemistry) **A. Kawashima et al., 1993**
  $(0.94 \pm 0.32) \cdot 10^{19}$ y (geochemistry) **M. Wieser, 2001**

- **Average value: $(2.3 \pm 0.2) \cdot 10^{19}$ yr**

[2015: $(2.3 \pm 0.2) \cdot 10^{19}$ yr]

5. ^{100}Mo

1. $11.6^{+3.0}_{-2.0}$ x 10^{18} (S/B ~ 1/7, N ~ 500) ELEGANT-V, 1991

2. [9.5 ± 0.4(stat) ± 0.9 (syst)]x10^{18} yr (S/B ~ 3, N = 1433) NEMO-2, 1995
   [8.1 ± 0.35(stat) ± 0.8 (syst)]x10^{18} yr ; HSD
   [7.3 ± 0.35(stat)± 0.8 (syst)]x10^{18} yr ; SSD

3. $7.6^{+2.2}_{-1.4}$ x10^{18} yr (S/B ~ 1/2, N = 175) Si-detectors, 1997

4. [$6.82^{+0.38}_{-0.53}$(stat) ± 0.68(syst)] x10^{18} yr (S/B ~ 10, N = 377) M. Moe et al., 1997

5. [7.5 ± 1.1(stat) ± 1.5(syst)] x10^{18} yr (S/B ~ 1/9, N ~ 800) Liq. Ar, 2001

6. [7.11 ± 0.02(stat) ± 0.54 (syst)]x10^{18} yr (S/B ~ 40, N = 219000); SSD NEMO-3, 2005

7. [7.15 ± 0.37(stat) ± 0.66(syst)] · 10^{18} yr (S/B ~ 5, N ~ 350) $ZnMoO_4$, 2014

8. [6.90 ± 0.15(stat.) ± 0.37(syst.)] × 10^{18} yr (S/B ~ 10, N ~ 9000) $Li_2{}^{100}MoO_4$, LUMINEU, 2017

9. [6.81 ± 0.01 (stat) +0.38−0.40 (syst)] ×10^{18} yr (S/B ~ 80, N ~ 500000) NEMO-3, 2019

(2.1 ± 0.3)x10^{18} yr (geochemistry; 1-3 billion years minerals) 2004

Average value: (6.88 ± 0.25) · 10^{18} yr; SSD

[2015: (7.1 ± 0.4) · 10^{19} yr]

6. ^{100}Mo- ^{100}Ru (0^+; 1130.29 keV).

1. $6.1^{+1.8}_{-1.1}$ x 10^{20} yr (S/B ~ 1/6, N = 66); SOUDAN, 1995

2. [$9.3^{+2.8}_{-1.7}$(stat) ± 1.4(syst)] x 10^{20} yr (S/B ~ 1/3, N = 76)
MODANE, 1999

3. [$5.9^{+1.7}_{-1.1}$(stat) ± 0.6(syst)] x 10^{20} yr (S/B ~ 8, N = 19.5)
TUNL-ITEP, 2001

4. [$5.5^{+1.2}_{-0.8}$(stat) ± 0.3(syst)] x 10^{20} yr (S/B ~ 8, N = 35.5)
TUNL-ITEP, 2009

5. [$5.7^{+1.3}_{-0.9}$(stat) ± 0.8(syst)] x 10^{20} yr (S/B ~ 3, N = 37.5)
NEMO-3, 2007

6. [$6.9^{+1.0}_{-0.8}$(stat) ± 0.7(syst)] x 10^{20} yr (S/B ~ 1/10, N = 299)
ARMONIA, 2010

7. [7.5 ± 0.6(stat) ± 0.6(syst)] x 10^{20} yr (S/B ~ 1/10, N = 299)
NEMO-3, 2014

Average value: $(6.7^{+0.5}_{-0.4}) \cdot 10^{20}$ yr

[2015: $(6.7^{+0.5}_{-0.4}) \cdot 10^{20}$ yr]

7. ^{116}Cd

1. $2.6^{+0.9}_{-0.5} \cdot 10^{19}$ yr (S/B ≈ 1/4, N ≈ 180); ELEGANT-V, 1995

2. [2.9 ± 0.06(stat) $^{+0.4}_{-0.3}$(syst)] $\cdot 10^{19}$ yr (S/B ≈ 3/1, N ≈ 9850); KIEV, 2003

3. [3.75 ± 0.35(stat) ± 0.21(syst)] $\cdot 10^{19}$ yr (S/B ≈ 4/1, N = 174.6); NEMO-2, 1996

   [2.9 ± 0.3(stat) ± 0.2(syst)] $\cdot 10^{19}$ yr (after correction)

4. [2.74 ± 0.04(stat) ± 0.18(syst)] $\cdot 10^{19}$ yr (S/B ≈ 12 , N = 4968); NEMO-3, 2017

   [2.88 ± 0.04(stat) ± 0.16(syst)] $\cdot 10^{19}$ yr (NEMO-3, 2011)

5. $(2.63^{+0.11}_{-0.12}) \cdot 10^{19}$ yr (S/B ≈ 5 , N ≈4000) (S/B ≈ 1.5 , N ≈ 93000); AURORA, 2018

Average value: (2.69 ± 0.09) $\cdot 10^{19}$ yr

[2015: (2.87 ± 0.13)$\cdot 10^{19}$ yr]

8. ^{150}Nd

- $[1.88^{+0.69}_{-0.39}(\text{stat}) \pm 0.19(\text{syst})] \cdot 10^{19}$ yr (S/B ≈ 1.8, N = 23);
  ITEP-TPC, 1995
- $[6.75^{+0.37}_{-0.42}(\text{stat}) \pm 0.68(\text{syst})] \cdot 10^{18}$ yr (S/B ≈ 6, N = 414);
  M.Moe-TPC, 1997
- $[9.11^{+0.25}_{-0.22}(\text{stat}) \pm 0.63(\text{syst})] \cdot 10^{18}$ yr (S/B ≈ 2.8, N = 2043);
  NEMO-3, 2009

  $[9.34 \pm 0.22(\text{stat})\ ^{+0.62}_{-0.60}(\text{syst})] \cdot 10^{18}$ yr (S/B ≈ 4, N = 2214);
  NEMO-3, 2016

$\chi^2/(N-1) = 5$ S = 2.23

Average value: $(8.4 \pm 1.1) \cdot 10^{18}$ yr

Recommended value : $9.34^{+0.67}_{-0.64} \cdot 10^{18}$ yr

[2015: $(8.2 \pm 0.9) \cdot 10^{18}$ yr]

9. ^{150}Nd- ^{150}Sm (0^+; 740.4 keV).

1. [$1.33^{+0.36}_{-0.23}$ (stat) $^{+0.27}_{-0.13}$(syst)] $\cdot 10^{20}$ yr (S/B ≈ 1/5, N = 177.5)
   MODANE, 2009

2. [$1.07^{+0.45}_{-0.25}$ (stat) ± 0.07(syst)] $\cdot 10^{20}$ yr (S/B ≈ 1.2, N = 21.6)
   TUNL, 2014

3. [$0.47^{+0.41}_{-0.19}$ (stat) ± 0.05(syst)] $\cdot 10^{20}$ yr (S/B ≈ 2.5, N = $5.7^{+3.8}_{-2.6}$)
   (coincidence regime; preliminary results) Gran Sasso, 2018
   Recent value is $0.7^{+0.58}_{-0.26}$ x10^{20} yr Gran Sasso, 2019
   (presented at MEDEX'2019)

- **Average value: $1.2^{+0.3}_{-0.2} \cdot 10^{20}$ yr**

[2015: $1.2^{+0.3}_{-0.2} \cdot 10^{20}$ yr]

10. ^{238}U

A.Turkevich et al., 1991

- $(2.0 \pm 0.6) \cdot 10^{21}$ yr (radiochemistry)
  $^{238}U \rightarrow {}^{238}Pu$ (α decay, 87.7 yr)
- This is the only measurement!
  Confirmation is needed!

[2015: $(2.0 \pm 0.6) \cdot 10^{21}$ yr]

11. ^{128}Te and ^{130}Te

- $T_{1/2}(130)/T_{1/2}(128) = (3.52 \pm 0.11) \cdot 10^{-4}$ (no gas retention age problem!)
- There are two groups of results:
- I.

  ^{130}Te $\Rightarrow$ $(2.55 \pm 0.2) \cdot 10^{21}$ yr (T.Kirsten'83; internally dated ores)

  $(2.7 \pm 0.1) \cdot 10^{21}$ yr (T.Bernatowicz'93)

  ^{128}Te $\Rightarrow$ $> 5 \cdot 10^{24}$ yr (T.Kirsten'86; internally dated ores)

  $(7.7 \pm 0.4) \cdot 10^{24}$ yr (T.Bernatowicz'93)
- II.

  ^{130}Te $\Rightarrow$ $(7.9 \pm 1.0) \cdot 10^{20}$ yr (N.Takaoka'96; "young" ores)

  $8 \cdot 10^{20}$ yr (O.Manuel'91)

  ^{128}Te $\Rightarrow$ $(1.8 \pm 0.7) \cdot 10^{24}$ yr (W.Lin'88)

  $2 \cdot 10^{24}$ yr (O.Manuel'91)

  $(2.2 \pm 0.3) \cdot 10^{24}$ yr (N.Takaoka'96; "young" ores)
- <u>WE HAD A BIG PROBLEM HERE</u>

Recent geochemical measurements (only young minerals were used)

1. A.P. Meshik et al., Nucl. Phys. A 809 (2008) 275:

$T_{1/2}$ (^{130}Te) = (9.0 ± 1.4) · 10^{20} yr

$T_{1/2}$ (^{128}Te) = (2.4 ± 0.4) · 10^{24} yr

2. H.V. Thomas et al., Phys. Rev. C 78 (2008) 054606:

$T_{1/2}$ (^{130}Te) = (8.0 ± 1.1) · 10^{20} yr

$T_{1/2}$ (^{128}Te) = (2.3 ± 0.3) · 10^{24} yr

Average value (geoch):

(8.4 ± 0.9) · 10^{20} yr for ^{130}Te

(2.3 ± 0.3) · 10^{24} yr for ^{128}Te

^{130}Te direct experiments

1) C. Arnaboldi et al., Phys. Lett. B 557 (2003) 167:

$T_{1/2} = [6.1 \pm 1.4(stat)\ ^{+2.9}_{-3.5}(syst)] \cdot 10^{20}$ y (S/B ~ 1/8, 260 events)

2) NEMO-3 (2011):

$T_{1/2} = [7.0 \pm 0.9(stat) \pm 1.1\ (syst)] \cdot 10^{20}$ y (S/B ~ 1/2, 178 events)

3) CUORE-0 (2017)

$T_{1/2} = [8.2 \pm 0.2(stat) \pm 0.6\ (syst)] \cdot 10^{20}$ y (S/B ~ 0.1-0.3, ~ 33000 events)

4) CUORE (2019)

$T_{1/2} = [7.9 \pm 0.1(stat) \pm 0.2\ (syst)] \cdot 10^{20}$ y (S/B > 1, ~ 20000 events)

- **Average value: $(7.91 \pm 0.21) \cdot 10^{20}$ yr**

[and **$(2.25 \pm 0.09) \cdot 10^{24}$ yr** for **^{128}Te** using well known **^{130}Te/^{128}Te** ratio]

[2015: $(6.9 \pm 1.3) \cdot 10^{20}$ yr for ^{130}Te
and $(2.0 \pm 0.3) \cdot 10^{24}$ yr for ^{128}Te]

12. ^{130}Ba; ECEC(2ν)

Geochemistry:

1. A. Barabash and R. Saakyan, 1996:

$T_{1/2} > 4 \cdot 10^{21}$ yr

[and $T_{1/2} = 2.1^{+3.0}_{-0.8}) \cdot 10^{21}$ yr]

2. A. Meshik et al., 2001

$T_{1/2} = (2.2 \pm 0.5) \cdot 10^{21}$ yr

3. M. Pujol et al., 2009:

$T_{1/2} = (0.60 \pm 0.11) \cdot 10^{21}$ yr

In 2017 it was demonstrated that main part of ^{130}Xe is connected with spallation reactions.
(A. Meshik, O. Pravdivtseva, JPS Conf. Proc. 14 (2017) 020702)

- Recommended value: $(2.2 \pm 0.5) \cdot 10^{21}$ yr

[2015: ~ 10^{21} yr]
[2010: $(2.2 \pm 0.5) \cdot 10^{21}$ yr]

Direct experiments will be very useful

13. ^{136}Xe

- **EXO, 2014:**

  $T_{1/2}$ = [2.165 ± 0.016(stat) ± 0.059(syst)] · 10^{21} yr

  (S/B ~ 10; ~ 19000 events)

- **KamLAND-Zen, 2016:**

  $T_{1/2}$ = [2.21 ± 0.02(stat) ± 0.07(syst)] · 10^{21} yr

  (S/B ~ 10; ~ 100000 events)

Average value: (2.18 ± 0.05) · 10^{21} yr
(accuracy ~ 2.3%)

[2015: (2.19 ± 0.06) · 10^{21} yr]

14. ^{78}Kr; 2K(2v)

1. $[0.92^{+0.55}_{-0.26}\text{(stat)} \pm 0.13\text{(syst)}] \cdot 10^{22}$ yr

(~ 2.5σ effect or $T_{1/2} > 5.5 \cdot 10^{21}$ yr; 12.8 events)

Baksan, 2013

2. $[1.9^{+1.3}_{-0.7}\text{(stat)} \pm 0.3\text{(syst)}] \cdot 10^{22}$ yr

(~ 4σ effect; 15 events, errors at 90% C.L.)

Baksan, 2017

Very complicated analysis, confirmation is needed!

This is indication to the «positive» result.

^{78}Kr; 2K(2v)

$T_{1/2}^{-1} = g_A^4 \cdot G \cdot |M_{2v}|^2$

$|M^{eff}_{2v}| = g_A^2 \cdot |M_{2v}|$

2β-decay: 0.018 — 0.185

^{130}Ba: 0.175

^{124}Xe: 0.061

^{78}Kr: 0.39

If result for ^{78}Kr is correct → we have a deal with abnormally large NME !!!

15. ^{124}Xe; 2K(2ν)

XENON1T:

$T_{1/2}$ = [1.8 ± 0.5(stat) ± 0.1(syst)]·10^{22} yr

(126± 29 events; ~ 4.4 σ ; S/B ~ 0.2)

Gran Sasso, 2019

XMASS-I: $T_{1/2}$ > 2.1·10^{22} yr (90% C.L.)

Kamioka, 2018

This is the only measurement!

Confirmation is needed!

Recommended values for half-lives:

- ^{48}Ca - $(5.3^{+1.2}_{-0.8}) \cdot 10^{19}$ yr
- ^{76}Ge – $(1.88 \pm 0.08) \cdot 10^{21}$ yr
- ^{82}Se – $(0.93 \pm 0.05) \cdot 10^{20}$ yr
- ^{96}Zr – $(2.3 \pm 0.2) \cdot 10^{19}$ yr
- ^{100}Mo – $(6.88 \pm 0.25) \cdot 10^{18}$ yr
- ^{100}Mo – ^{100}Ru (0^+_1) – $(6.7^{+0.5}_{-0.4}) \cdot 10^{20}$ yr
- ^{116}Cd – $(2.69 \pm 0.09) \cdot 10^{19}$ yr
- ^{128}Te – $(2.25 \pm 0.09) \cdot 10^{24}$ yr
- ^{130}Te – $(7.91 \pm 0.21) \cdot 10^{20}$ yr
- ^{136}Xe – $(2.18 \pm 0.05) \cdot 10^{21}$ yr
- ^{150}Nd - $9.34^{+0.67}_{-0.64} \cdot 10^{18}$ yr
- ^{150}Nd – ^{150}Sm (0^+_1) – $(1.2^{+0.3}_{-0.2}) \cdot 10^{20}$ yr
- ^{238}U(rad) - $(2.0 \pm 0.6) \cdot 10^{21}$ yr
- ^{130}Ba(geo) - $(2.2 \pm 0.5) \cdot 10^{21}$ yr
- ^{78}Kr(2K2v) - $1.9^{+1.3}_{-0.8} \cdot 10^{22}$ yr (?)
- ^{124}Xe(2K2v) – $(1.8 \pm 0.5) \cdot 10^{22}$ yr

PRESENT STATUS FOR HALF-LIVES

1. **^{76}Ge, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{136}Xe** — accuracy is **~ 2-5%**

2. **^{82}Se, ^{96}Zr, ^{100}Mo – ^{100}Ru (0^+_1)** – **accuracy is ~ 5-10 %**

3. **^{48}Ca, ^{150}Nd** — **accuracy is ~ 10-12%**

4. **^{150}Nd – ^{150}Sm (0^+_1), ^{130}Ba, ^{124}Xe, ^{238}U** – accuracy is **~ 25-30%**

5. **^{78}Kr – accuracy is ~ 50-60% (confirmation is needed!)**

Future improvements

1. ^{76}Ge – MAJORANA-DEMONSTRATOR (this year !?)
   accuracy ~ 4-5%

2. ^{82}Se – CUPID-0/Se (this year !?)
   accuracy ~ 2-3%

3. ^{100}Mo – CUPID-0/Mo (this year !?)
   accuracy ~ 2-3%

4. ^{150}Nd–^{150}Sm(0^+_1) – Gran Sasso (final result) (~ 2020 ?)

5. ^{78}Kr (?) - new measurements are needed

6. ^{124}Xe – XENON1T, XENONnT, XMASS, PandaX-4T, BAKSAN, LZ (in a few years?)

7. ^{124}Sn (Q = 2287.7 keV, 5.79%; $T_{1/2}$ ~ 10^{20}-10^{21} yr)
   (this decay can be first time registered!)

THANKS FOR YOUR ATTENTION!!!