DOUBLE BETA DECAY EXPERIMENTS: PAST AND PRESENT ACHIVEMENTS

A.S. BARABASH

ITEP, MOSCOW

Plan:

- Historical Introduction
- Best achievements:
  - **2**ν decay
  - **0**ν decay
  - **0**$\nu\chi^0$ decay
  - methods
- Conclusion

Historical Introduction

THEORY:

- 1930 – neutrino (W. Pauli)
- 1933 – theory of β decay (E. Fermi)
- 1935 - $2\beta2\nu$ decay (M. Goeppert-Mayer)
- 1937 – Majorana neutrino (E. Majorana)
- 1939 - $2\beta0\nu$ decay (W. Farry)
- 1981 - $2\beta\chi^0$ decay (H. Georgi, S.L. Glashow, S. Nussinov, C.B. Gelmini, M. Rocandelli)

he potential contribution of double β decay to particle physics and cosmolog
s correspond to the masses of the right-handed neutrinos in the see-saw mecha

ethe in 1935 (left), Enrico Fermi together with Maria Goeppert-Mayer i
Volfgang Pauli in 1958 (right).

EXPERIMENT

- **1948** – first counter experiment (Geiger counters, $T_{1/2}(0\nu) > $ **$3 \cdot 10^{15}$ y**)
- **1950** – **first evidence** for **$2\beta2\nu$** decay of **^{130}Te** in first geochemical experiment:

  $T_{1/2} \approx 1.4 \cdot 10^{21}$ y
- **1950-1965** – a few tens experiments with sensitivity **$\sim 10^{16}$-10^{19} y**
- **1966-1975** – in 3 experiments sensitivity to **0**ν decay reached **$\sim 10^{21}$ y**!!!

Best results in 1966-1975

- $T_{1/2}(0\nu;{}^{76}\mathbf{Ge}) >$ **$5\cdot10^{21}$ y**; Ge(Li) detector, **1973** (E. Fiorini et al.)
- $T_{1/2}(0\nu;{}^{48}\mathbf{Ca})$ **$> 2\cdot10^{21}$ y**; streamer chamber + magnetic field + plastic scint., **1970** (C. Wu et al.)
- $T_{1/2}(0\nu;{}^{82}\mathbf{Se})$ **$> 3.1\cdot10^{21}$ y**; streamer chamber + magnetic field + plastic scint., **1975** (C. Wu et al.)
- Geochemical experiments with **^{130}Te, ^{128}Te, ^{82}Se ("positive" results)**

Main achievements in 1976-1987

- **2β2ν** decay was first time detected in direct (counting) experiment ⇒

  $$T(^{82}Se)_{1/2} = 1.1^{+0.8}_{-0.3} \cdot 10^{20}\ y$$

  (35 events; TPC, **1987**, S. Elliott, A. Hahn, M. Moe))
- First time **enriched Ge** detector was used in experiment (ITEP-ErFI; **1987**)

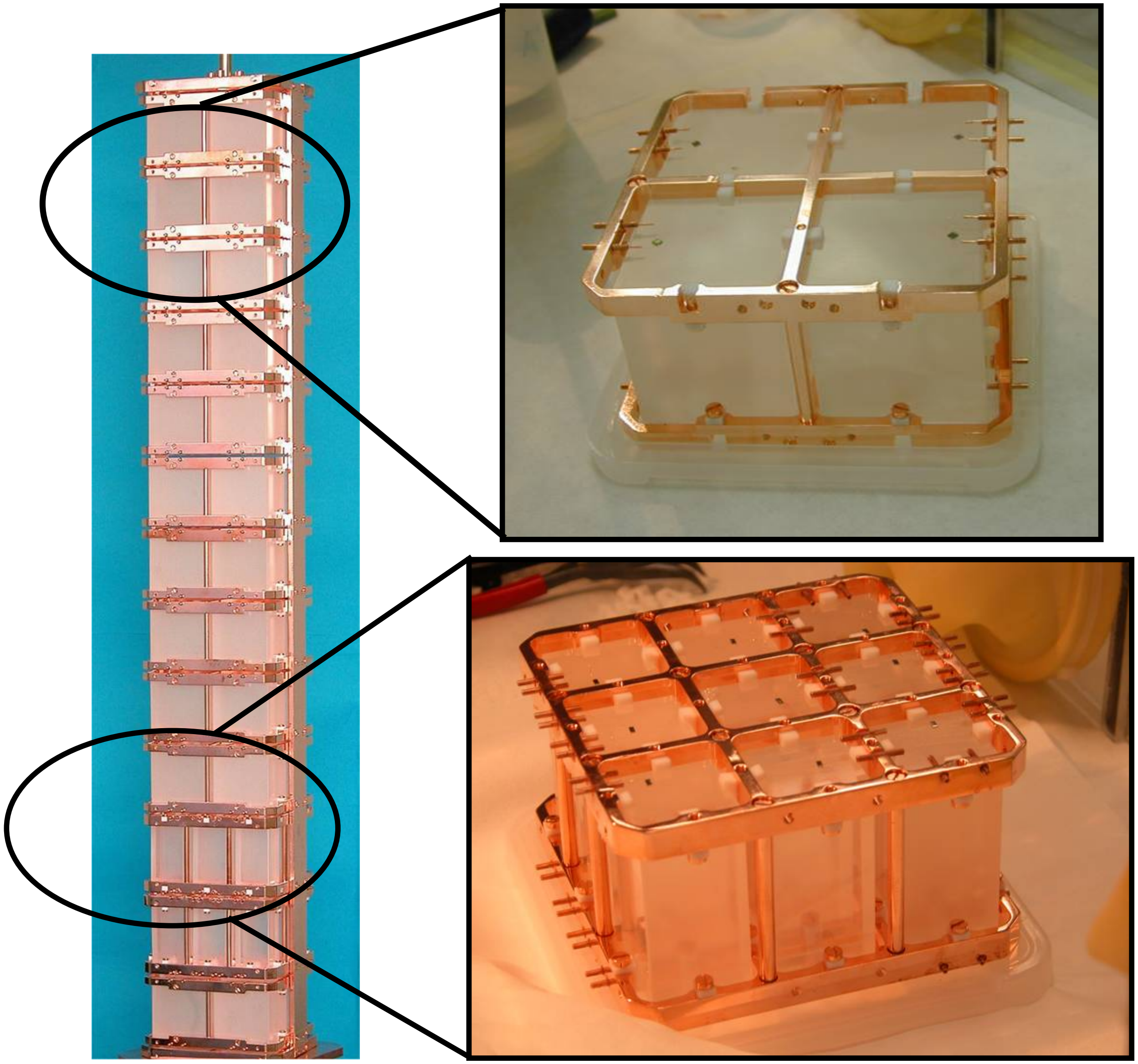
Main achievements in 1988-2001

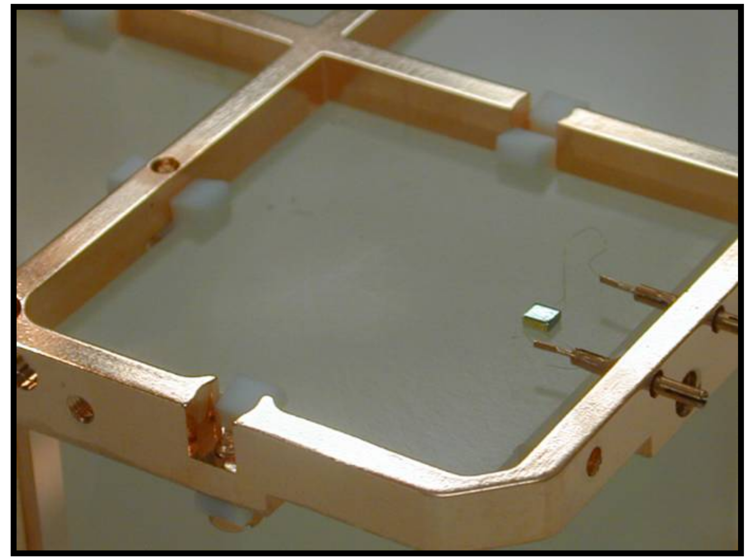
- $T_{1/2}(0\nu;{}^{76}\mathrm{Ge})$ **> (1.6-1.9)·10^{25} y**; (HM and IGEX; enriched HPGe detectors)
- $T_{1/2}(0\nu)$ **> 10^{22}-10^{23}** y for **^{136}Xe, ^{82}Se, ^{116}Cd, ^{100}Mo**
- **2ν**-decay was detected for many nuclei (TPC, ELEGANT-V, NEMO-2, HM, IGEX, Solotvino….)

Main recent achievements (2002-2006)

- **NEMO-3** and **CUORICINO** start to collect data and produce results

CUORICINO (Gran Sasso)





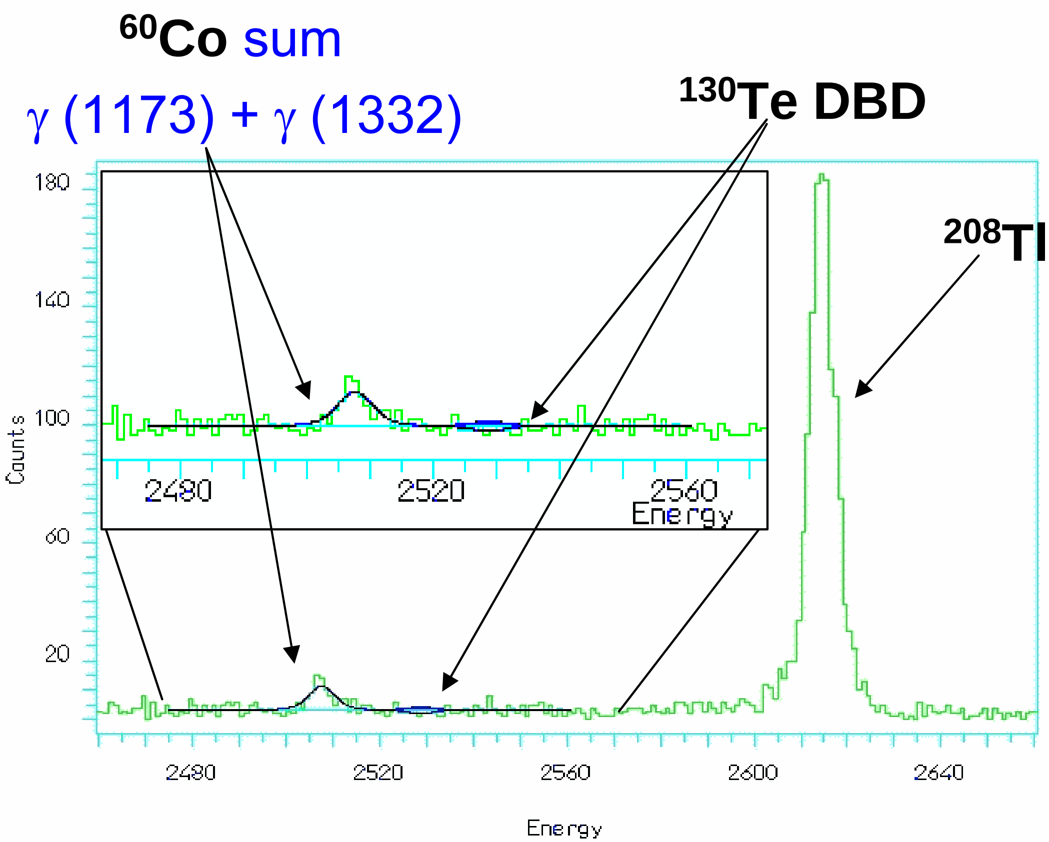
Active mass during first runs:

42 x 0.790 kg = 33.2 kg

17 x 0.330 kg = 5.6 kg

~ 11 kg ^{130}Te

Cuoricino results



STATISTICS:

•anticoincidence spectrum detector efficiencies: 86.4% (790g) and 84.5% (330g)

•run I + run II = 7.09 kg (^{130}Te) x year

•No peak is observed at the 0νDBD transition energy (2528.8 keV)

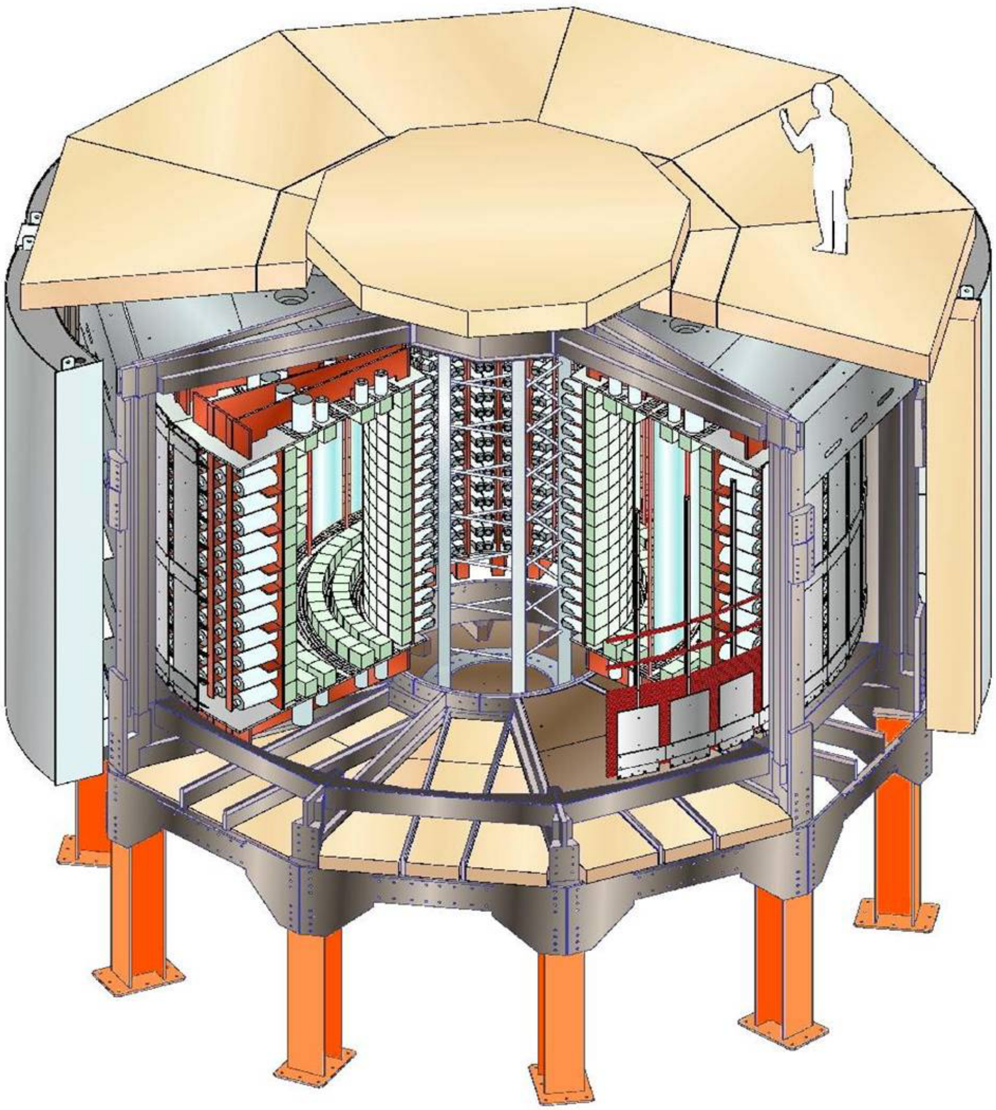
•Bkg counting rate in the 0νDBD region = 0.18 ± 0.02 c/keV/kg/y

$t^{1/2}$ > 2.2 10^{24} y at 90% C.L. **$<m_\nu>$ < [0.19÷0.98] eV**

➢ **~5% variation of the limit when changing the energy region, the bkg shape (linear or flat) and when including/excluding the 2615 keV peak**

The NEMO3 detector

Fréjus Underground Laboratory : 4800 m.w.e.



Source: 10 kg of ββ isotopes
cylindrical, S = 20 m^2, 60 mg/cm^2

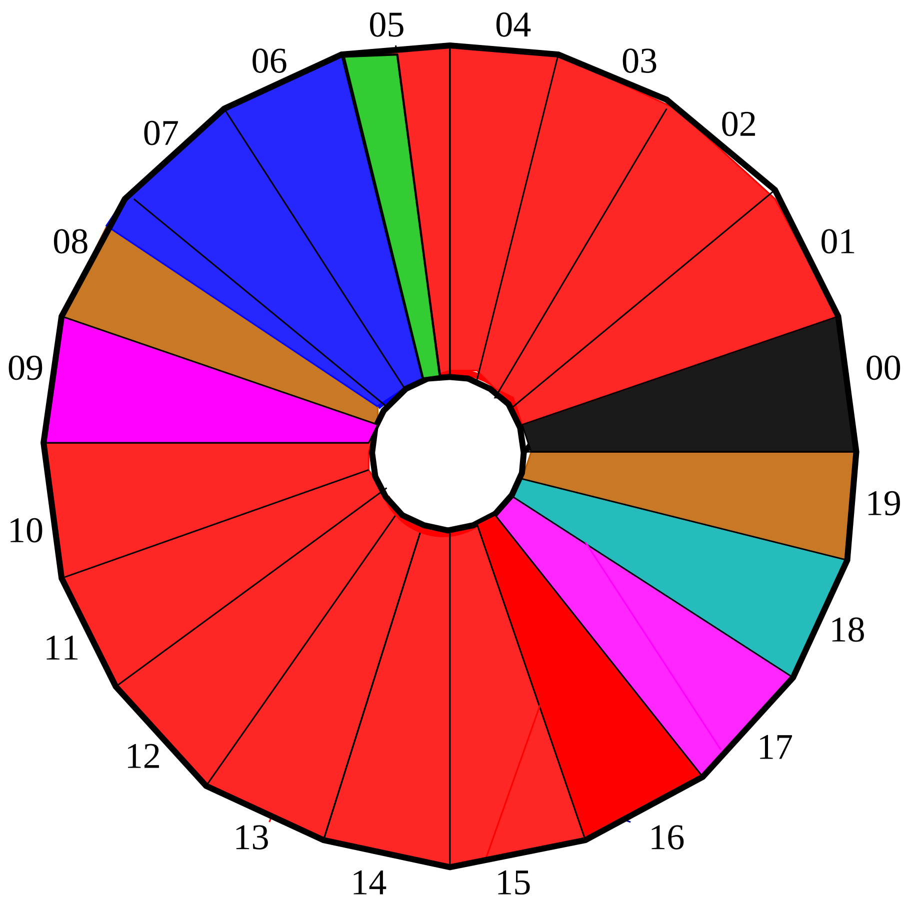
Tracking detector:
drift wire chamber operating
in Geiger mode (6180 cells)
Gas: He + 4% ethyl alcohol + 1% Ar + 0.1% H_2O

Calorimeter:
1940 plastic scintillators
coupled to low radioactivity PMTs

Magnetic field: 25 Gauss
Gamma shield: Pure Iron (18 cm)
Neutron shield: borated water (~30 cm) + **Wood (Top/Bottom/Gapes between water tanks)**

Able to identify e^-, e^+, γ and α

$\beta\beta$ decay isotopes in NEMO-3 detector



^{100}Mo 6.914 kg
$Q_{\beta\beta}$ = 3034 keV

^{82}Se 0.932 kg
$Q_{\beta\beta}$ = 2995 keV

$\beta\beta0\nu$ search

$\beta\beta2\nu$ measurement

^{116}Cd 405 g
$Q_{\beta\beta}$ = 2805 keV

^{96}Zr 9.4 g
$Q_{\beta\beta}$ = 3350 keV

^{150}Nd 37.0 g
$Q_{\beta\beta}$ = 3367 keV

^{48}Ca 7.0 g
$Q_{\beta\beta}$ = 4272 keV

^{130}Te 454 g
$Q_{\beta\beta}$ = 2529 keV

^{nat}Te 491 g

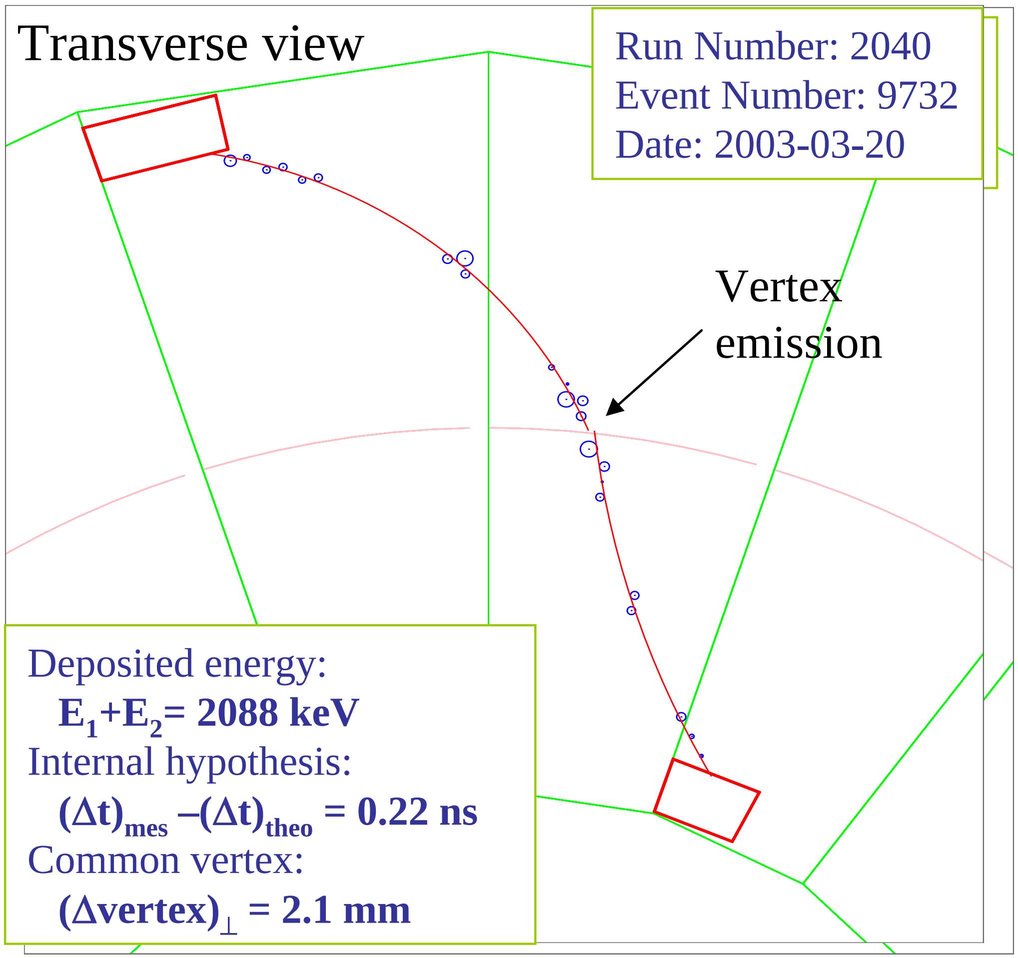
Cu 621 g

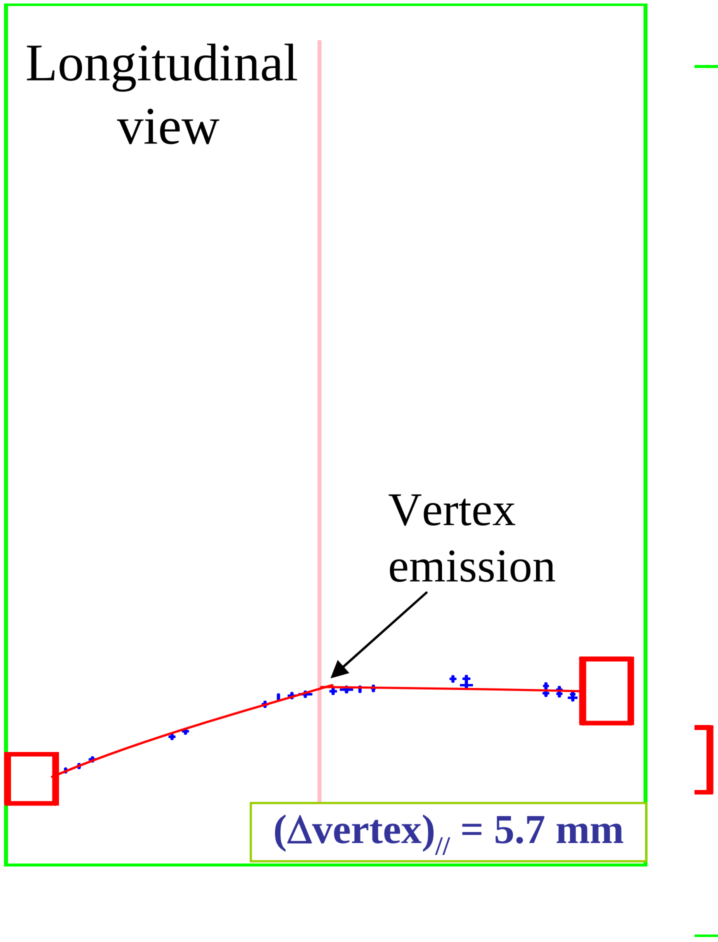
External bkg measurement

(All enriched isotopes produced in Russia)

ββ events selection in NEMO-3

Typical ββ2ν event observed from ^{100}Mo





Trigger: at least 1 PMT > 150 keV

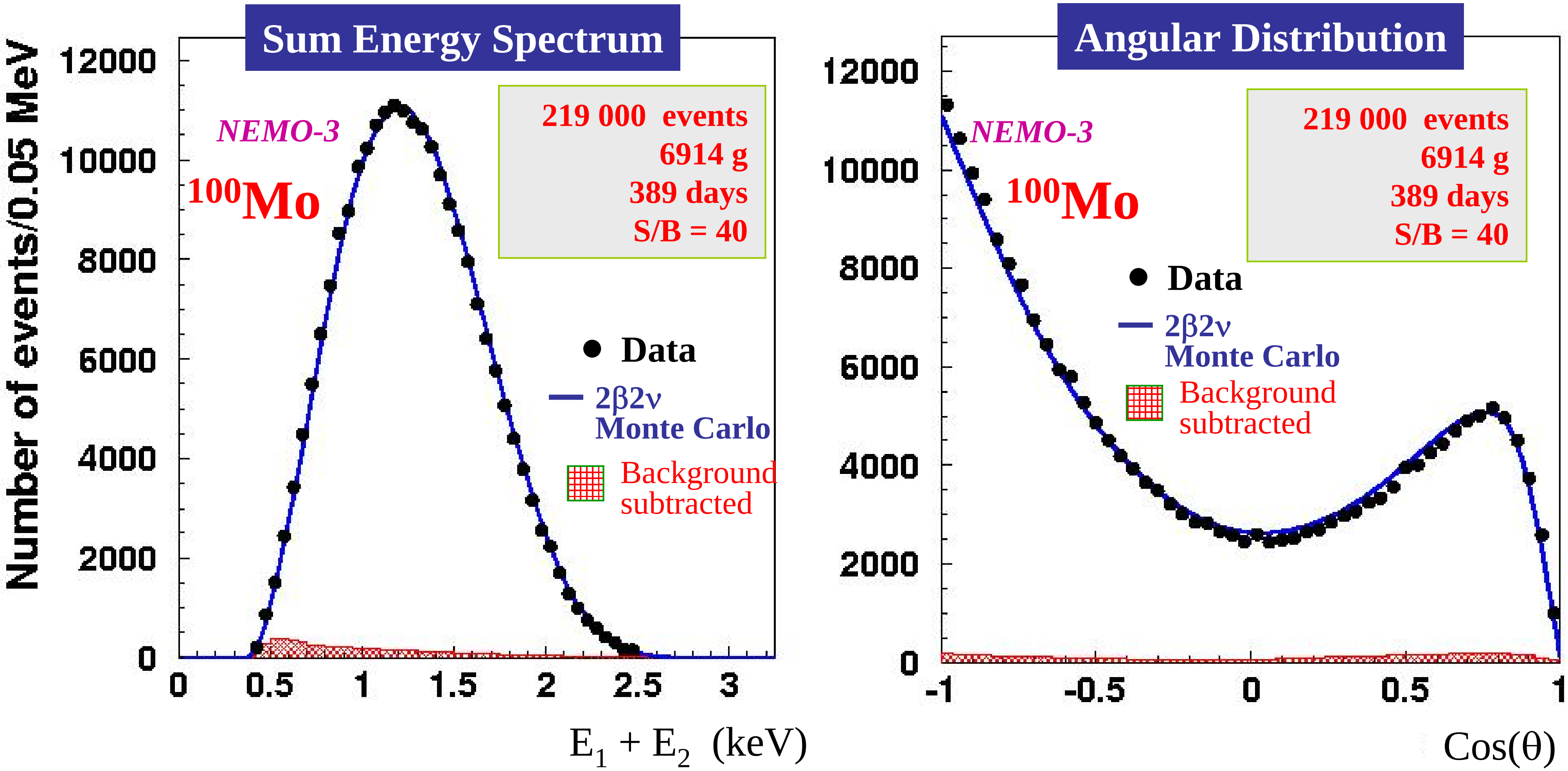
≥ 3 Geiger hits (2 neighbour layers + 1)

Trigger rate = 7 Hz

ββ events: 1 event every 2.5 minutes

^{100}Mo 2β2ν results

(Data Feb. 2003 – Dec. 2004)



7.37 kg.y

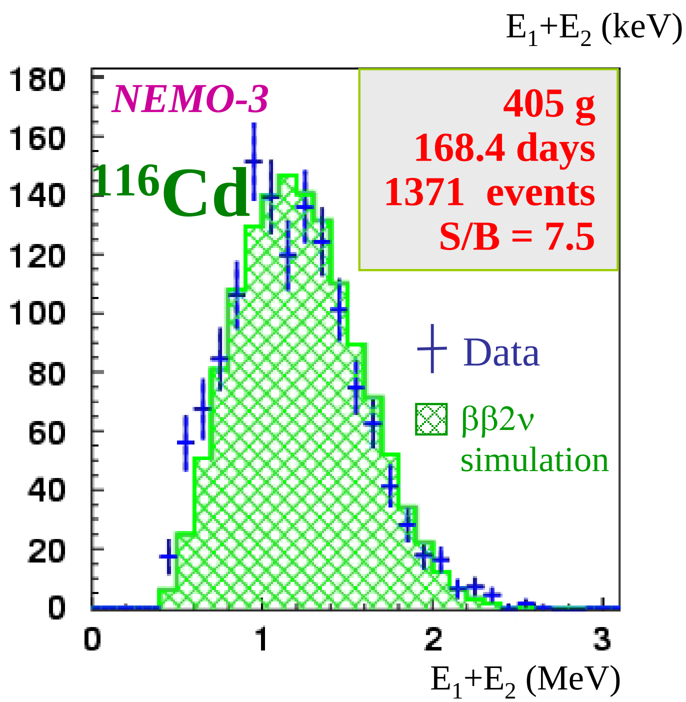
$T_{1/2} = 7.11 \pm 0.02\ (\text{stat}) \pm 0.54\ (\text{syst}) \times 10^{18}$ y

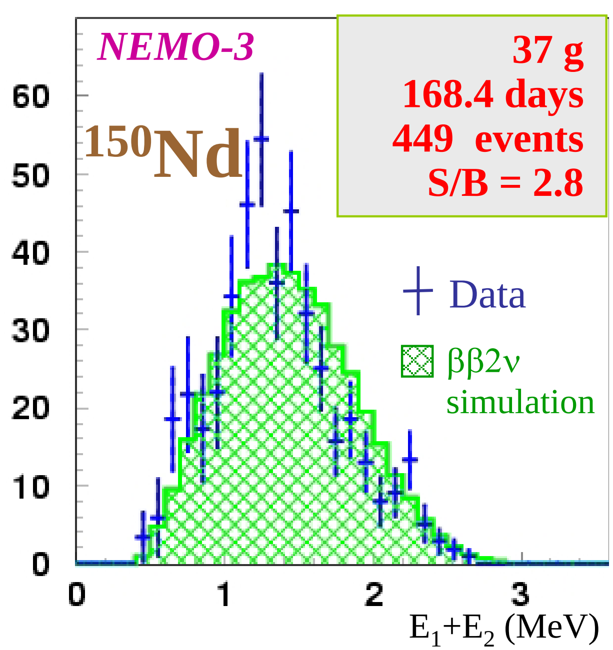
Phys Rev Lett 95, 182302 (2005)

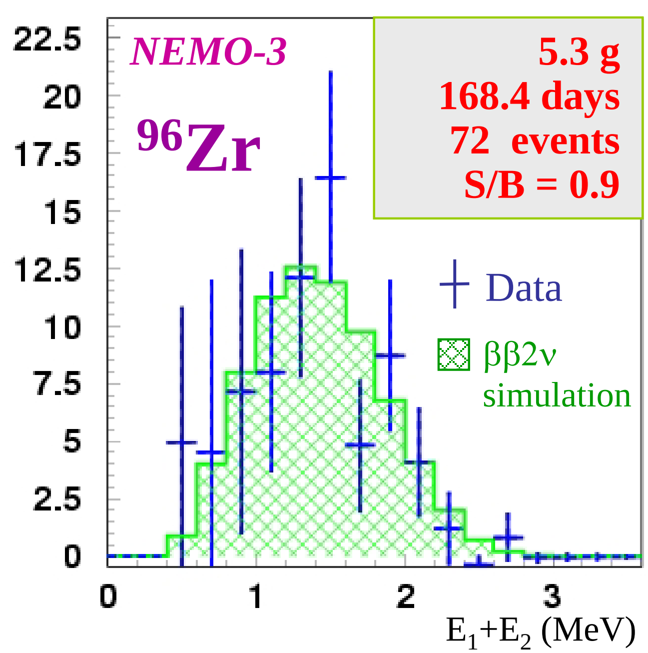
2β2ν preliminary results for other nuclei

^{116}Cd	$T_{1/2}$ = 2.8 ± 0.1 (stat) ± 0.3 (syst) × 10^{19} y (SSD)
^{150}Nd	$T_{1/2}$ = 9.7 ± 0.7 (stat) ± 1.0 (syst) × 10^{18} y
^{96}Zr	$T_{1/2}$ = 2.0 ± 0.3 (stat) ± 0.2 (syst) × 10^{19} y

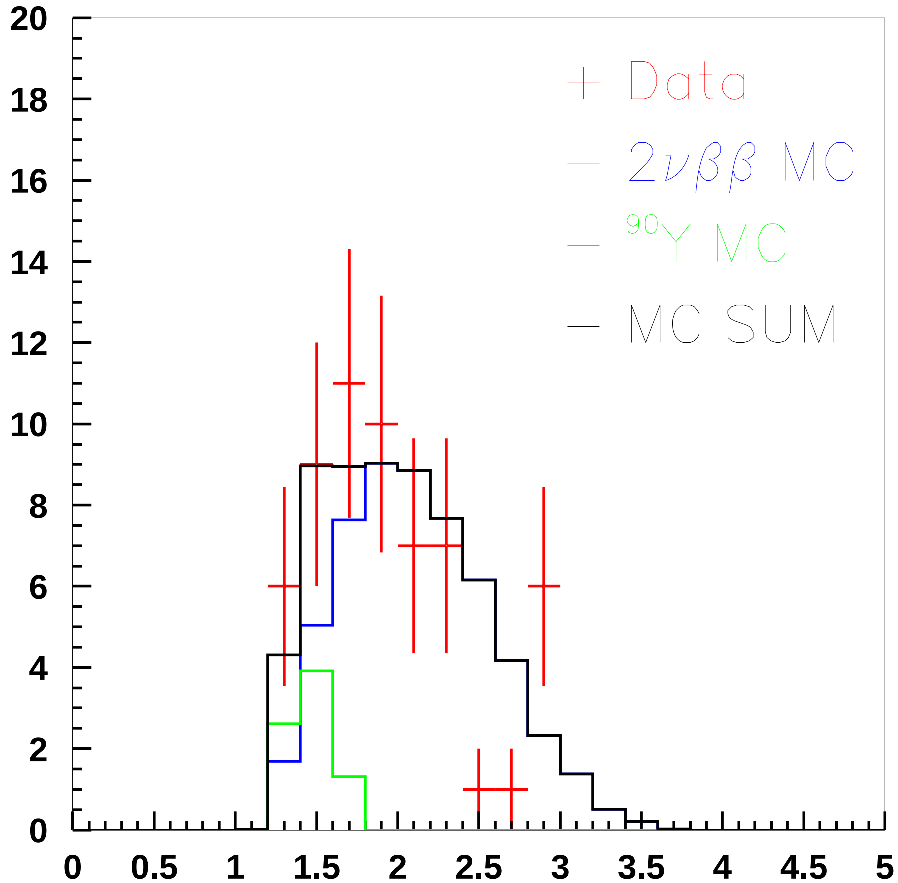
Background subtracted



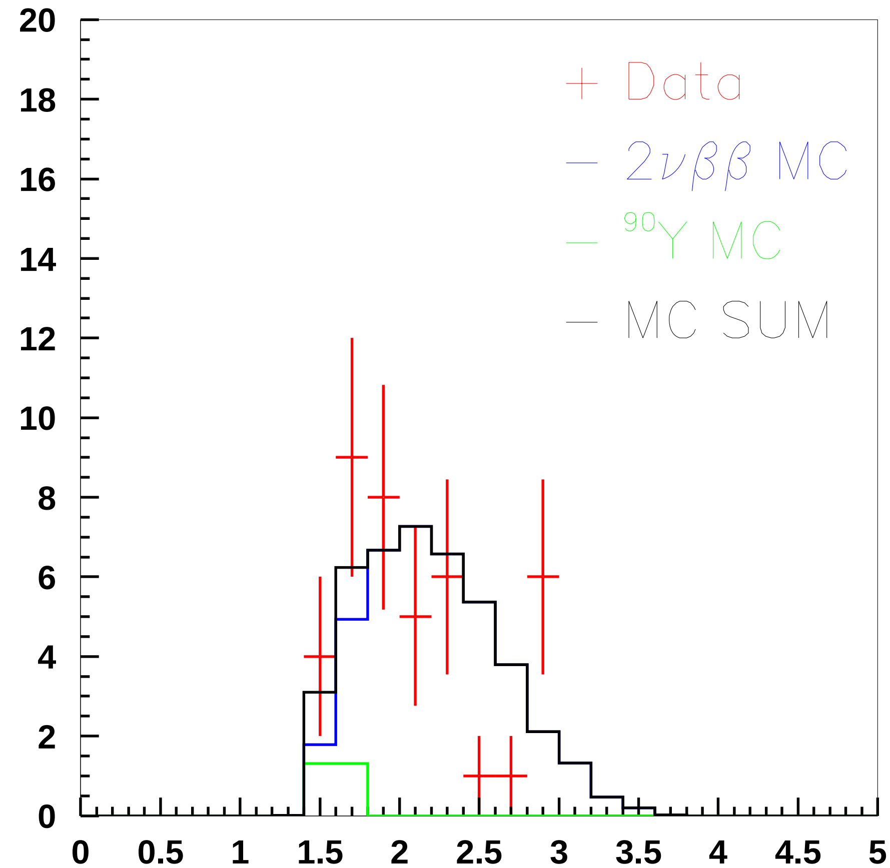




^{48}Ca. 2β2ν preliminary result
(Esmall > 0.6 or 0.7 MeV, cos(θ) < 0.0)



E_{SUM} (MeV) (^{48}Ca-foil, E_{Small}>0.6 MeV, cos(θ)<0.0)



E_{SUM} (MeV) (^{48}Ca-foil,E_{Small}>0.7 MeV, cos(θ)<0.0)

Esmall > 0.6 MeV cos(θ)<0.0

Esmall > 0.7 MeV cos(θ)<0.0

Very Small Background !!

$T_{1/2}$ = [3.9±0.7(stat)±0.6(syst)]·10^{19} y

ββ results for ^{100}Mo

SSD simulation

$T_{1/2} = 7.11 \pm 0.02$ (stat) ± 0.54 (syst) $\times 10^{18}$ y
Phys. Rev. Lett. 95 (2005) 182302

SSD model confirmed

Decay to the excited 0^+ state of ^{100}Ru
$T_{1/2} = 5.7^{+1.3}_{-0.9}$ (stat) ± 0.8 (syst) $\times 10^{20}$ y
To be published soon

HSD, higher levels contribute to the decay

SSD, 1^+ level dominates in the decay

1^+

^{100}Tc

0^+

^{100}Mo

(Abad et al., 1984, *Ann. Fis.* A 80, 9)

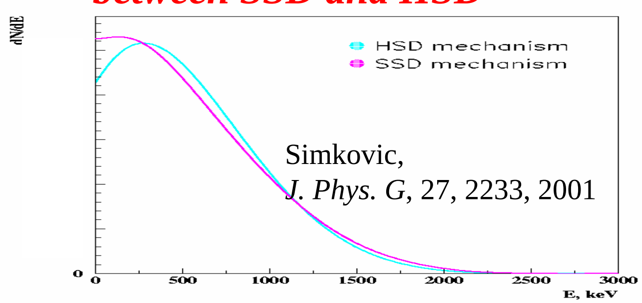
ββ0ν Phase I + II (587d)
Use MC Limit approach: shape information,
different background level for PI and PII

Single electron spectrum different between SSD and HSD

E_1+E_2 >2 MeV

12… 8.1 %

$T_{1/…}$



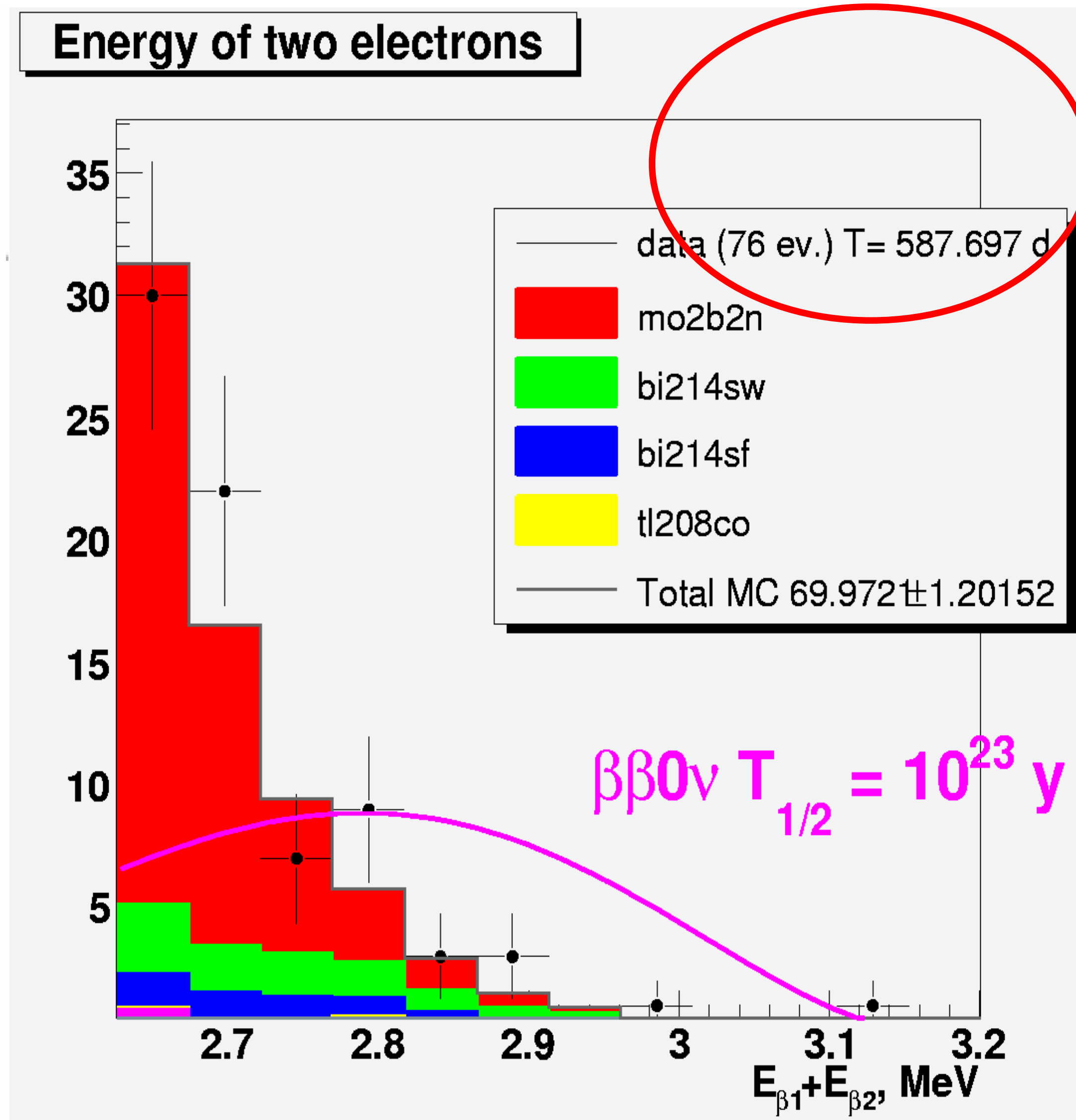
Simkovic,
J. Phys. G, 27, 2233, 2001

E_{single} (keV)

Wi… …90d)

14

$T_{1/2} > 5.8 \cdot 10^{23}$ y, 90% CL



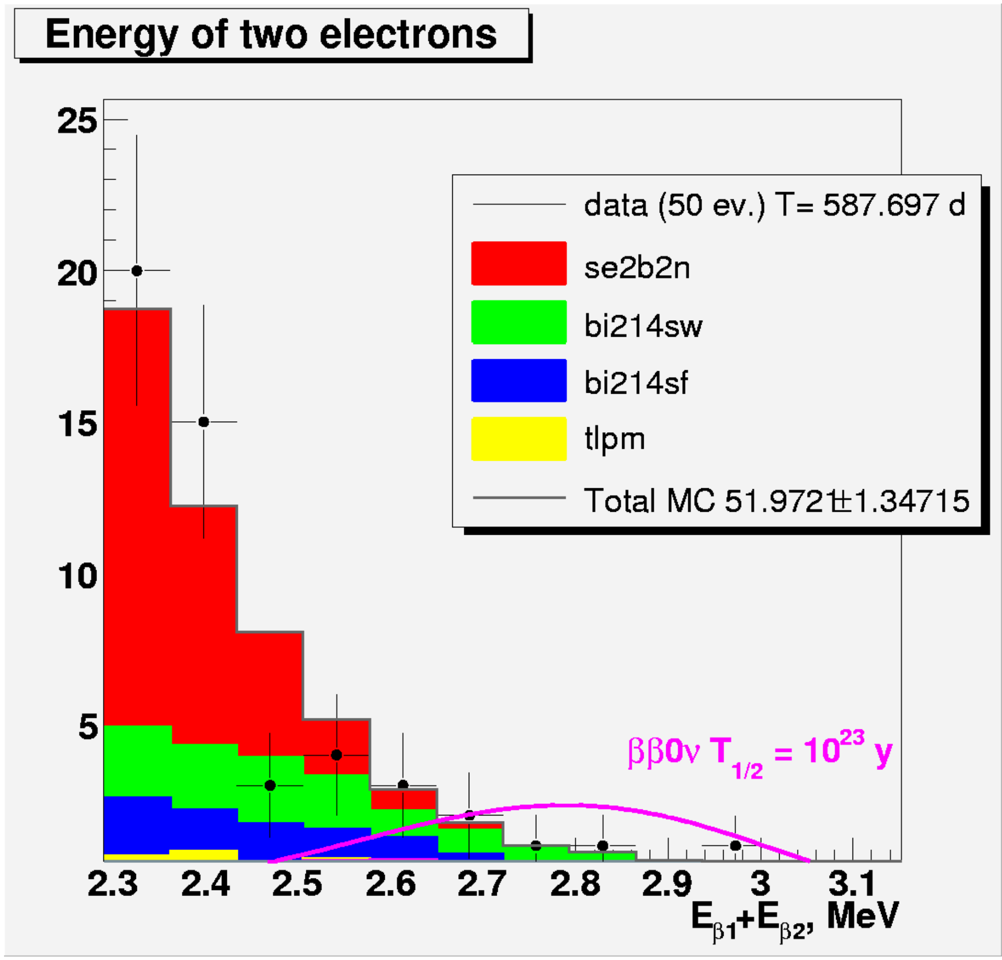
ββ results for ^{82}Se

$T_{1/2} = 9.6 \pm 0.3$ (stat) ± 1.0 (syst) $\times 10^{19}$ y
Phys. Rev. Lett. 95 (2005) 182302

ββ0ν Phase I + II (587d)
Use MC Limit approach

$E_1+E_2>2$ MeV
238 evs, MC = 240.5 ± 7, $\varepsilon_{0\nu}$=17.6 %
$T_{1/2} > 2.7\cdot10^{23}$ y, 90% CL

Window method [2.62-3.20] MeV, (690d)
7 evs, MC = 6.4, $\varepsilon_{0\nu}$=14.4 %
$T > 2.1\cdot10^{23}$ y, 90% CL



II. Best achievements: 2ν decay

- 2ν decay first time was detected 56 years ago in geochemical experiment with ^{130}**Te** (**1950**)
- **1967**- ^{82}**Se** (geochemical. experiment)
- **1987** - 2β2ν decay first time was detected in direct (counting) experiment (M. Moe et al.)

II. Best achievements: 2ν decay

- By present time 2β2ν decay is detected in **10** nuclei:
  ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{150}Nd, ^{238}U
- **2ν** decay to the **0^+ excited state** was detected (**^{100}Mo** and **^{150}Nd)**
- **ECEC(2ν)** decay was detected in **^{130}Ba** (geochemical experiment)

Recommended values for half-lives:

- ^{48}Ca - $(4.2\ ^{+2.1}_{-1.0})\cdot 10^{19}$ y
- ^{76}Ge – $(1.5 \pm 0.1)\cdot 10^{21}$ y
- ^{82}Se – $(0.92 \pm 0.07)\cdot 10^{20}$ y
- ^{96}Zr – $(2.0 \pm 0.3)\cdot 10^{19}$ y
- ^{100}Mo – $(7.1 \pm 0.4)\cdot 10^{18}$ y
- ^{100}Mo – ^{100}Ru (0^+_1) – $(6.8 \pm 1.2)\cdot 10^{20}$ y
- ^{116}Cd – $(3.1 \pm 0.2)\cdot 10^{19}$ y
- ^{128}Te(geo) – $(2.5 \pm 0.3)\cdot 10^{24}$ y

  ^{130}Te(geo) – $(0.9 \pm 0.1)\cdot 10^{21}$ y
- ^{150}Nd - $(7.8 \pm 0.7)\cdot 10^{18}$ y
- ^{150}Nd – ^{150}Sm (0^+_1) – $(1.4^{+0.5}_{-0.4})\cdot 10^{20}$ y
- ^{238}U(rad) - $(2.0 \pm 0.6)\cdot 10^{21}$ y

ECEC(2ν):

- ^{130}Ba(geo) - $(2.2 \pm 0.5)\cdot 10^{21}$ y

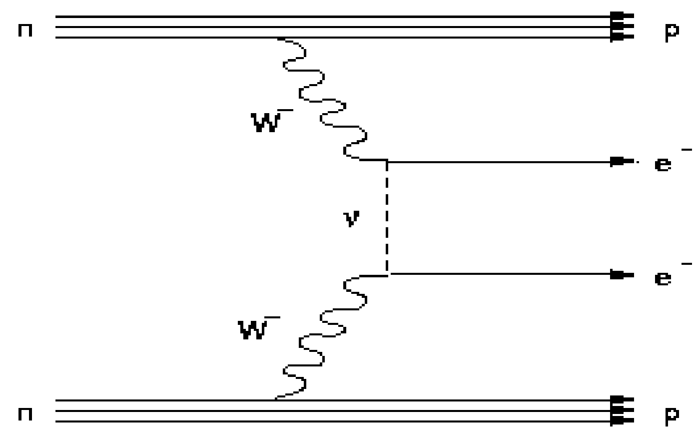
(A.S.B., nucl-ex/0602009)

II. Best achievements:

NEUTRINOLESS DOUBLE BETA DECAY

Experimental signature:

2 electrons
Eβ1+ Eβ2=Qββ



II. Best achievements: 0ν decay

Nuclei	$T_{1/2}$, y	$<m_{\nu}>$, eV [1-3]	$<m_{\nu}>$, eV [4]	Experiment
^{76}Ge	$>1.9 \cdot 10^{25}$ $\approx 1.2 \cdot 10^{25}$(?) $>1.6 \cdot 10^{25}$	< 0.33-0.84 ≈ 0.5-1.3(?) <0.36-0.92	< 0.53-0.59 ≈ 0.7(?) <0.58-0.64	HM Part of HM IGEX
^{130}Te	$>2.2 \cdot 10^{24}$	< 0.4-0.8	< 0.9-1.4	CUORICINO
^{100}Mo	$>5.8 \cdot 10^{23}$	< 0.6-0.9	< 2.1-2.7	NEMO
^{136}Xe	$>4.5 \cdot 10^{23}$	< 0.8-4.7	< 2.9-5.6	DAMA
^{82}Se	$>2.1 \cdot 10^{23}$	< 1.2-2.5	< 2.6-3.2	NEMO
^{116}Cd	$>1.7 \cdot 10^{23}$	< 1.4-2.5	< 3.7-4.3	SOLOTVINO

References

[1] F. Simkovic, G. Pantis, J.D. Vergados and A. Faessler, Phys. Rev. 60 (1999) 055502.

[2] S. Stoica and H.V. Klapdor-Kleingrothaus, Nucl. Phys. A 694 (2001) 269.

[3] O. Civitarese and J. Suhonen, Nucl. Phys. A 729 (2003) 867.

[4] V.A. Rodin, A. Faessler, F. Simkovic and P. Vogel, Nucl. Phys. A 766 (2006) 107.

A Recent Claim

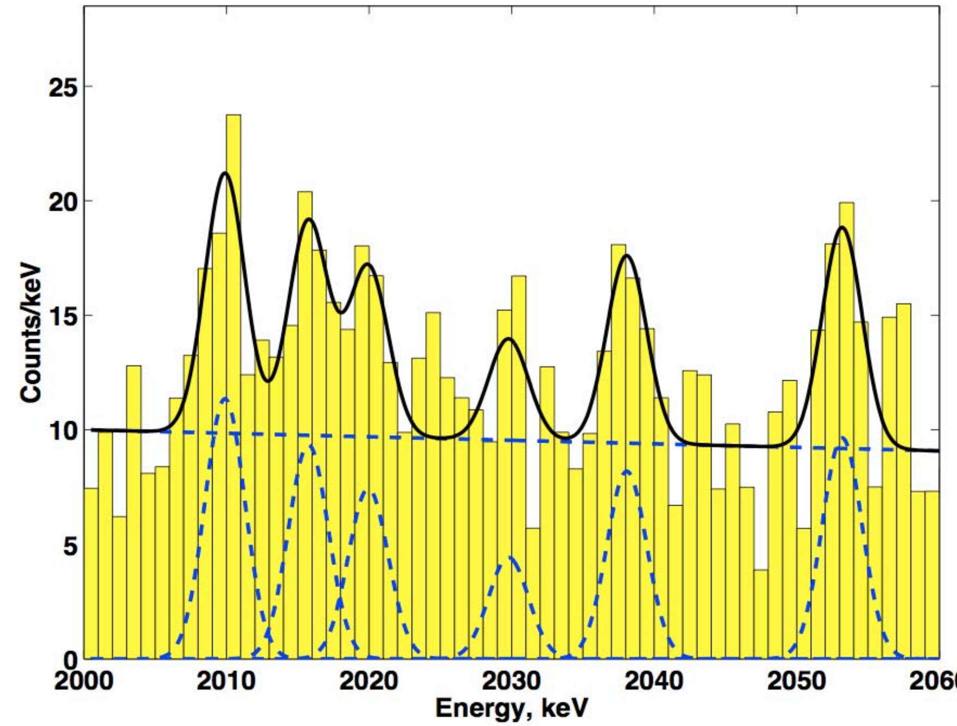
Klapdor-Kleingrothaus H V, Krivosheina I V, Dietz A and Chkvorets O, *Phys. Lett.* B **586** 198 (2004).

Used five ^{76}Ge crystals, with a total of 10.96 kg of mass, and 71 kg-years of data

$\tau_{1/2} = 1.2 \times 10^{25}$ y (4.2 σ)

$0.24 < m_\nu < 0.58$ eV (± 3 sigma)

(NME from Eur. Lett. 13(1990)31)



There are some problems with this result:

1) Only one measurement.
2) Only ~4σ level (independent analysis gives even ~ 2-3 σ).
3) In contradiction with HM'01 and IGEX.
4) Moscow part of Collaboration: **NO EVIDENCE**.
5) ^{214}Bi peaks are overestimated.
6) "Total" and "analyzed" spectra are not the same.
7) 2β or γ ???

"2β community": very careful reaction

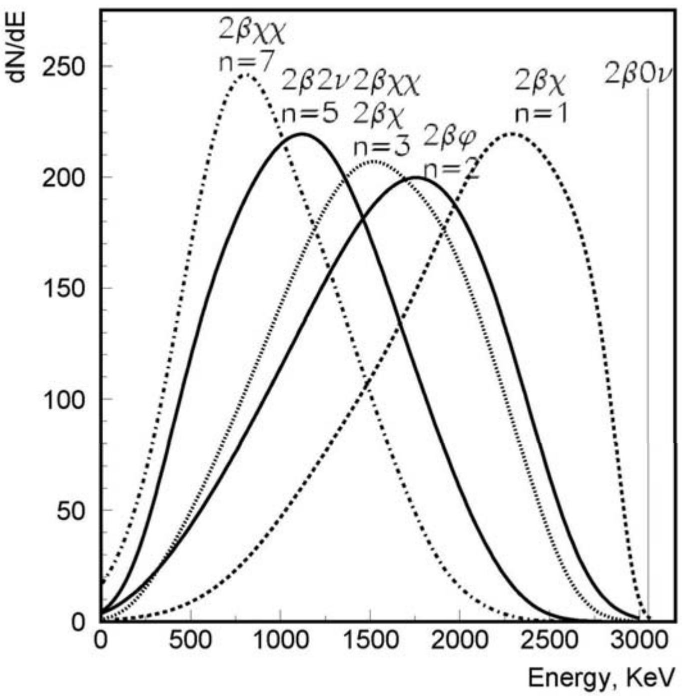
In any case new experiments are needed (and first of all with ^{76}Ge)

II. Best achievements: $0\nu\chi^0$ decay (n = 1)

Nuclei	$T_{1/2}$, y	$\langle g_{ee} \rangle$, $\times 10^{-4}$ [1-3]	$\langle g_{ee} \rangle$, $\times 10^{-4}$ [4]	Experiment
^{76}Ge	$>6.4 \cdot 10^{22}$	< 1.2-3.0	< 1.9-2.3	HM
^{82}Se	$>1.5 \cdot 10^{22}$	< 0.66-1.4	< 1.2-1.9	NEMO-3
^{100}Mo	$>2.7 \cdot 10^{22}$	< 0.4-0.7	< 1.6-1.8	NEMO-3
^{116}Cd	$>8 \cdot 10^{21}$	< 1.0-2.0	< 2.8-3.3	SOLOTVINO
^{128}Te	$>2 \cdot 10^{24}$	< 0.7-1.6	< 1.9-2.4	Geochem.
^{136}Xe	$>1.6 \cdot 10^{22}$	< 0.7-5.0	< 3.4-4.4	DAMA

II. Best achievements: $0\nu\chi^0$ decay

NEMO-3 results



	n=1 *	n=2 *	n=3 *	n=7 *
^{100}Mo	$>2.7\cdot10^{22}$ $g<(0.4\text{-}1.8)\cdot10^{-4}$	$>1.7\cdot10^{22}$	$>1.0\cdot10^{22}$	$>7\cdot10^{19}$
^{82}Se	$>1.5\cdot10^{22}$ $g<(0.7\text{-}1.9)\cdot10^{-4}$	$>6.0\cdot10^{21}$	$>3.1\cdot10^{21}$	$>5.0\cdot10^{20}$

* *R.Arnold et al. Nucl. Phys. A765 (2006) 483*

METHODICAL ACHIVEMENTS

- Low background **HPGe** detectors (**HM, IGEX**)
- Low background low temperature detectors (**TeO_2**; **CUORICINO**)
- Low background crystal scintillators (**$^{116}CdWO_4$; SOLOTVINO**)
- Low background **tracking detectors** (**NEMO-3, TPC**)

BACKGROUND

How to reach low level of background?

- Underground location
- Passive and active shield
- Low radioactive materials (investigated material, constructive materials, passive shield)
- Background rejection methods (granularity, pulse shape discrimination,…)

BACKGROUND

Experiment	B, (kev·kg·y)$^{-1}$	<B>=B·ΔE/η, (kg·y)$^{-1}$
^{76}Ge HM, IGEX	~ 0.2 ~ 0.06 (PSD)	~ 0.8 ~ 0.25 (PSD)
TeO_2 CUORICINO	~ 0.18	~ 1.4
$^{116}CdWO_4$ SOLOTVINO	~ 0.037	~ 10
^{136}Xe, DAMA	~ 0.06	~ 30
^{100}Mo NEMO-3	~ 10^{-3}	~ 2.5
^{136}Xe TPC	~ 0.02	~ 15

ΔE – energy resolution, keV; η - efficiency

ISOTOPES

- In first experiments **~ 0.2-20 g** of enriched isotopes were used
- Now "usual" mass is **~ 1-10 kg**
- Recently **200 kg** of ^{136}**Xe** and **37 kg** of ^{76}**Ge** were produced (in Russia)

CONCLUSION

- Conservative limit on **$\langle m_\nu \rangle$** is **~ 0.9 eV**
- Conservative limit on **$\langle g_{ee} \rangle$** is **~ $2 \cdot 10^{-4}$**
- **2ν** decay:
  - is detected in **10** nuclei
  - is detected for transition to **0^+** excited state (**^{100}Mo** and **^{150}Nd**)
  - **ECEC(2ν)** is detected
  - **SSD** mechanism is confirmed for **^{100}Mo**

CONCLUSION (Continuation)

- **METHODICAL ACHIVEMENTS:**
  - low background **HPGe** detectors (made of ^{76}**Ge**)
  - low background low temperature bolometers (**TeO_2**)
  - low background crystal scintillators (**$^{116}CdWO_4$**)
  - low background tracking detectors (**NEMO-3**, **TPC**)
  - enriched isotopes **(~ 10 kg)**