Neutrinoless double electron capture experiment at LSM

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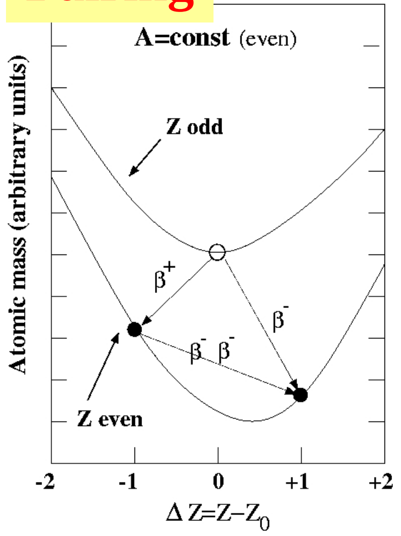
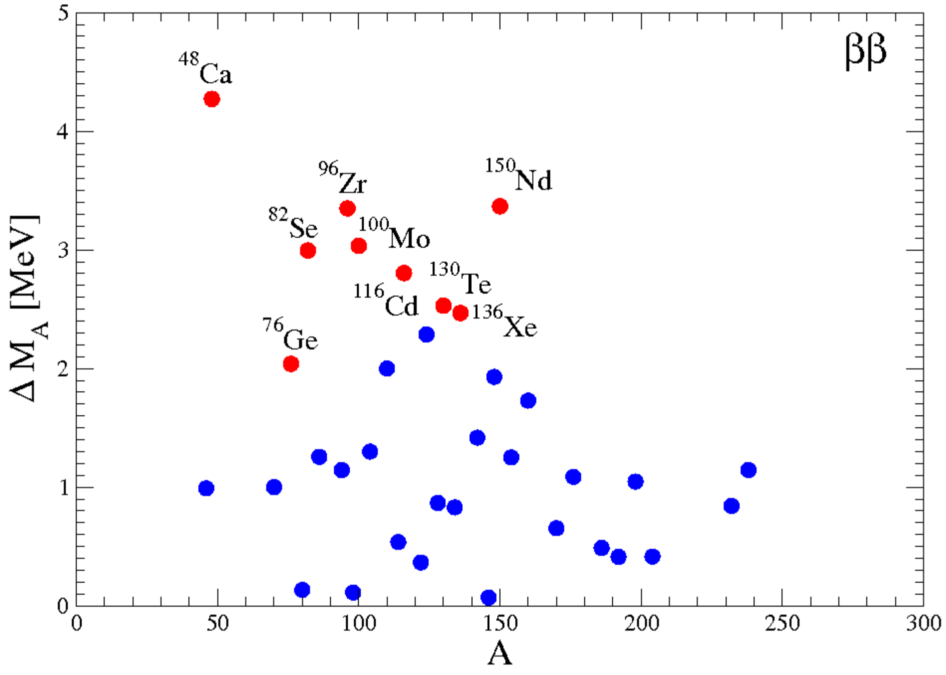
Double Beta Decay Nuclei

Pairing

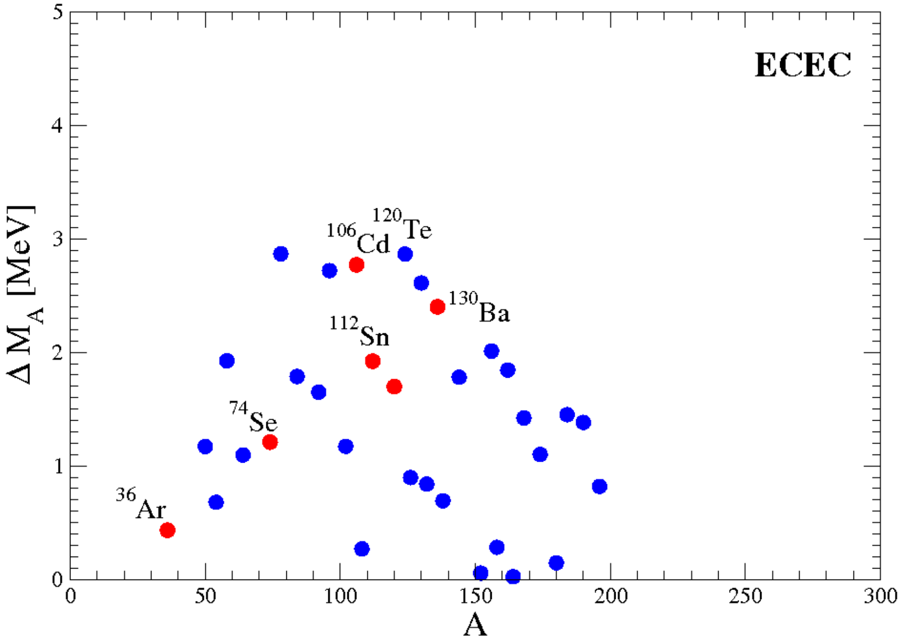


Emission of 2 electrons



Preferable nuclear systems with large ΔM_A (E^5)

Double electron capture



Nuclear systems with small ΔM_A might be also important (resonant enhancement)

Signal from γ- and X-rays

Neutrinoless double electron capture

Modes of the 0νECEC-decay:

$$e_b + e_b + (A,Z) \rightarrow (A,Z-2) + \gamma$$

$$+ 2\gamma$$

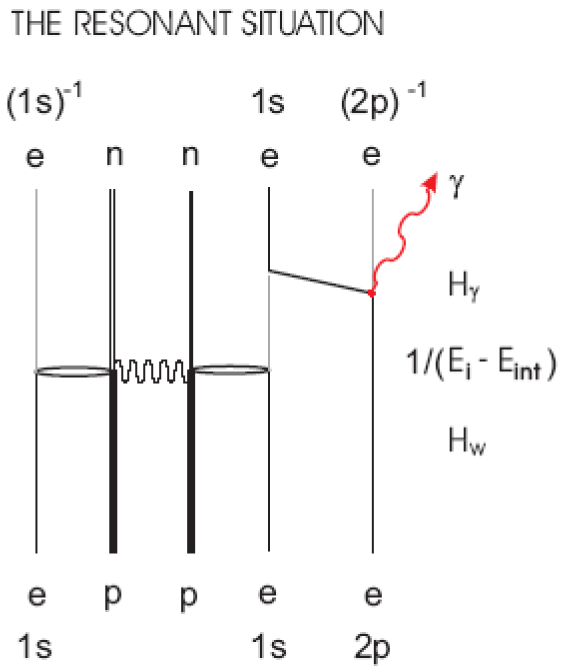
$$+ e^+e^-$$

$$+ M$$

Theoretically,
not well understood yet:

- **which mechanism is important?**
- **which transition is important?**

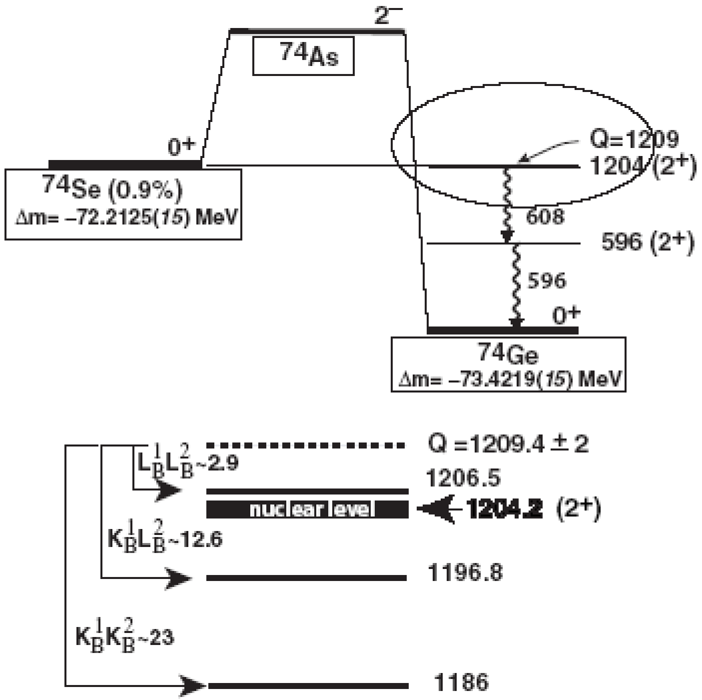
$$e_b + e_b + (A,Z) \rightarrow (A,Z-2) + \gamma$$



$$A = \frac{H_w H_\gamma}{E_i - E_{int}} \approx \frac{H_w H_\gamma}{E_\gamma + E_{1s} - E_{2p}}$$

Sujkowski, Wycech, PRC 70, 052501 (2004)

⇒



$$\Gamma^{0\nu\gamma} = \frac{\Gamma^r(2p \rightarrow 1s)}{[E_\gamma - Q_{res}]^2 + [\Gamma^r/2]^2} |R^{cc}_{0\nu}|^2$$

$$Q_{res} = E_{s_{1/2}} - E_{p_{1/2}}$$

D.Frekers, hep-ex/0506002

Oscillations of stable atoms (Γ=0)

$$|<f|e^{-iH_{eff}t}|i>|^2 = \frac{4V^2}{(M_i-M_f)^2}\sin^2[t\ (M_i-M_f)/2]$$

$$[t\ (M_i-M_f)] \le 1 \qquad |<f|e^{-iH_{eff}t}|i>|^2 = V^2t^2$$

$$[t\ (M_i-M_f)] \ge 1 \qquad |<f|e^{-iH_{eff}t}|i>|^2 \approx \frac{V^2}{(M_i-M_f)^2}$$

$$ {}^{164}_{68}Er \rightarrow {}^{164}_{66}Dy$$

$$(M_i-M_f) = 24.1\ keV \qquad |<f|e^{-iH_{eff}t}|i>|^2 \le 3\ 10^{-55}$$

Double electron capture (Γ≠0)
(resonant enhancement of atom)

$$\Gamma = 4\times 10^{-7}\ Z^4\ \mathrm{eV} = 0.3\ eV \quad (Z=30)$$

$$R_{max} = \frac{1\ \mathrm{ton}}{M_i}\times\frac{4V^2}{\Gamma} \sim 10^4\ yr^{-1}$$

Mass difference >> Γ

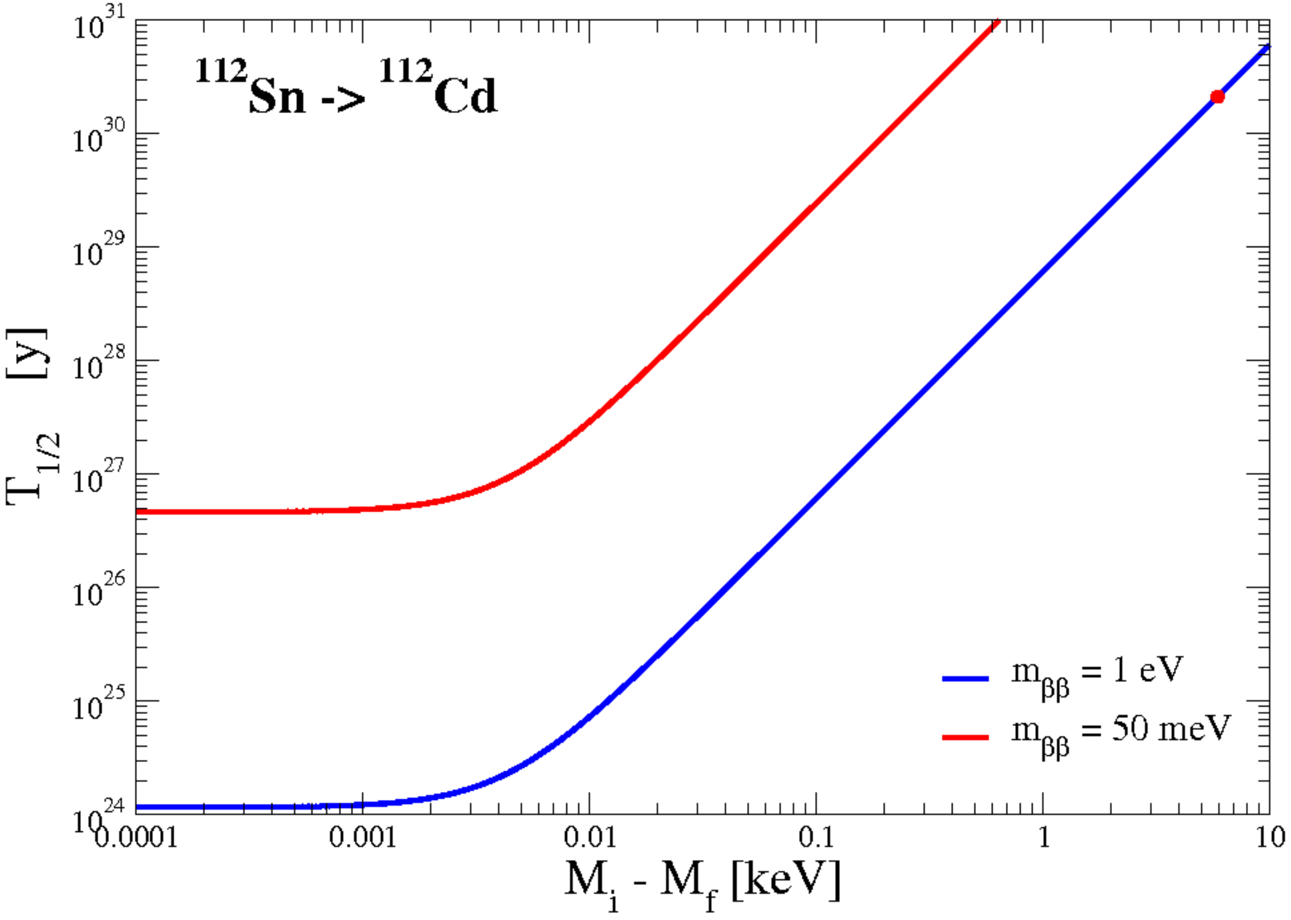
$$\Gamma_1 = \frac{4V^2}{4(M_i-M_f)+\Gamma^2}\ \Gamma \qquad R \sim R_{max}\frac{\Gamma^2}{(M_i-M_f)^2} \sim 10^{-3}\ yr^{-1}$$

Mass difference ~ keV

Double electron capture of ^{112}Sn (perspectives of search)

F. Šimkovic, M. Krivoruchenko, A. Faessler, to be submitted

M_i-M_f	$T_{1/2}^{ECEC}$ ($m_{\beta\beta}$= 50 meV)
1 keV	2.44 10^{31} years
100 eV	2.45 10^{29} years
10 eV	2.91 10^{27} years
0 eV	4.67 10^{26} years



$T_{1/2}^{0\nu}$ (^{76}Ge)= (2.95 – 5.74) 10^{26} years for $m_{\beta\beta}$= 50 meV

$J^{\pi}=0^{+}$

Calculated double electron capture half-lives ($m_{\beta\beta}$ = 1 eV)

Transition	$M^*_{A,Z-2} - M_{A,Z-2}$	$M^{**}_{A,Z-2} - M_{A,Z}$	Holes	$T^{\min}_{1/2}$	$T_{1/2}$
${}^{112}_{50}\mathrm{Sn} \to {}^{112}_{48}\mathrm{Cd}^*$	1871 ± 0.2	$-5.9 \pm 4.2 \pm 2.7$	$1s_{1/2}\ 1s_{1/2}$	2×10^{24}	8×10^{30}
${}^{152}_{64}\mathrm{Gd} \to {}^{152}_{62}\mathrm{Sm}$	0	$-0.3 \pm 2.5 \pm 2.5$	$1s_{1/2}\ 2s_{1/2}$	5×10^{24}	9×10^{29}
	0	$5.9 \pm 2.5 \pm 2.5$	$1s_{1/2}\ 3s_{1/2}$	4×10^{25}	8×10^{29}
	0	$7.4 \pm 2.5 \pm 2.5$	$1s_{1/2}\ 4s_{1/2}$	8×10^{26}	10^{33}
${}^{148}_{64}\mathrm{Gd} \to {}^{148}_{62}\mathrm{Sm}^*$	3045 ± 2	$5.7 \pm 2.5 \pm 2.5$	$2s_{1/2}\ 2s_{1/2}$	8×10^{25}	3×10^{32}
	3045 ± 2	$11.8 \pm 2.5 \pm 2.5$	$2s_{1/2}\ 3s_{1/2}$	3×10^{26}	8×10^{33}
	3045 ± 2	$13.3 \pm 2.5 \pm 2.5$	$2s_{1/2}\ 4s_{1/2}$	4×10^{27}	2×10^{35}
	3045 ± 2	$6.6 \pm 2.5 \pm 2.5$	$2p_{1/2}\ 2p_{1/2}$	2×10^{29}	2×10^{36}
${}^{156}_{66}\mathrm{Dy} \to {}^{156}_{64}\mathrm{Gd}^*$	1988.5 ± 0.2	$7.0 \pm 6.6 \pm 2.5$	$2s_{1/2}\ 2s_{1/2}$	2×10^{27}	8×10^{31}
	1988.5 ± 0.2	$7.9 \pm 6.6 \pm 2.5$	$2p_{1/2}\ 2p_{1/2}$	8×10^{29}	4×10^{35}

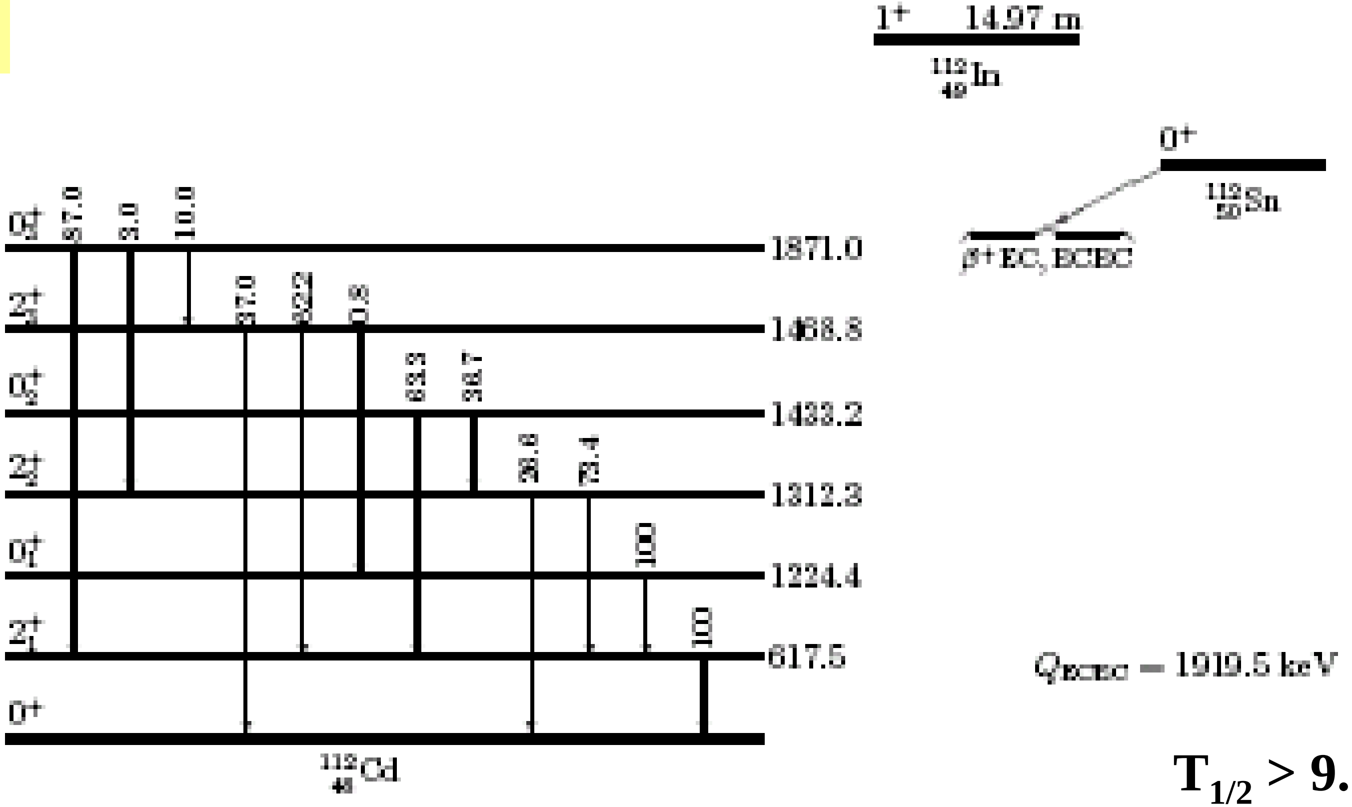
Transition	J^P	$M^*_{A,Z-2} - M_{A,Z-2}$	$M^{**}_{A,Z-2} - M_{A,Z}$	Holes	$T^{\min}_{1/2}$	$T_{1/2}$
${}^{162}_{68}\mathrm{Er} \to {}^{162}_{66}\mathrm{Dy}^*$	1^+	1745.716 ± 0.007	$-10.1 \pm 3.5 \pm 2.5$	$1s_{1/2}\ 1s_{1/2}$	8×10^{23}	2×10^{29}
${}^{156}_{66}\mathrm{Dy} \to {}^{156}_{64}\mathrm{Gd}^*$	1^+	1965.950 ± 0.004	$-12.5 \pm 6.6 \pm 2.5$	$1s_{1/2}\ 2s_{1/2}$	10^{25}	3×10^{30}
	1^+	1965.950 ± 0.004	$-5.8 \pm 6.6 \pm 2.5$	$1s_{1/2}\ 3s_{1/2}$	2×10^{26}	2×10^{31}
	1^-	1946.375 ± 0.006	$8.4 \pm 6.6 \pm 2.5$	$1s_{1/2}\ 2s_{1/2}$	8×10^{26}	4×10^{31}
${}^{74}_{34}\mathrm{Se} \to {}^{74}_{32}\mathrm{Ge}^*$	2^+	1204.204 ± 0.007	$3.0 \pm 1.7 \pm 1.6$	$2p_{1/2}\ 2p_{3/2}$	10^{36}	10^{45}

Lepton number and parity oscillations

$$\Gamma_1 = \frac{4V^2}{4(M_i - M_f) + \Gamma^2}\,\Gamma$$

Experimental activities (^{112}Sn)

^{112}Sn



$T_{1/2} > 9.2\ 10^{19}$ years

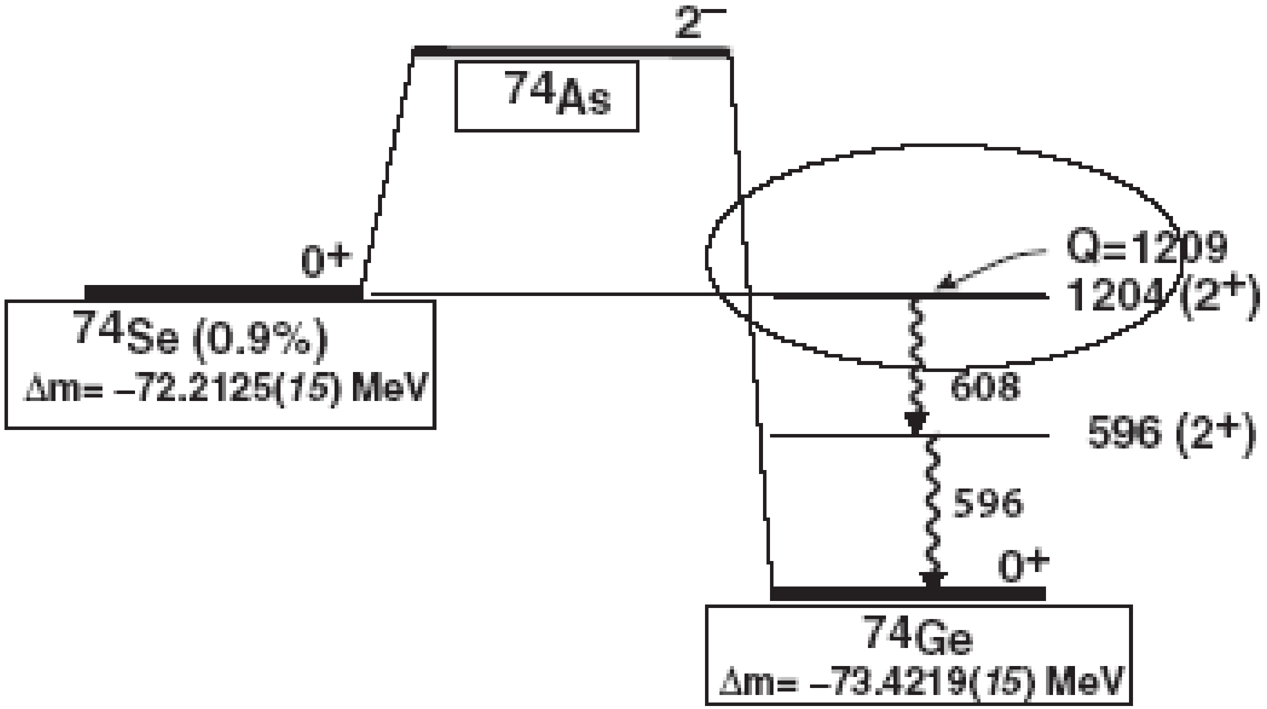
In comparison with the 0νββ-decay disfavoured due:

- process in the 3-rd (4th) order in electroweak theory
- bound electron wave functions

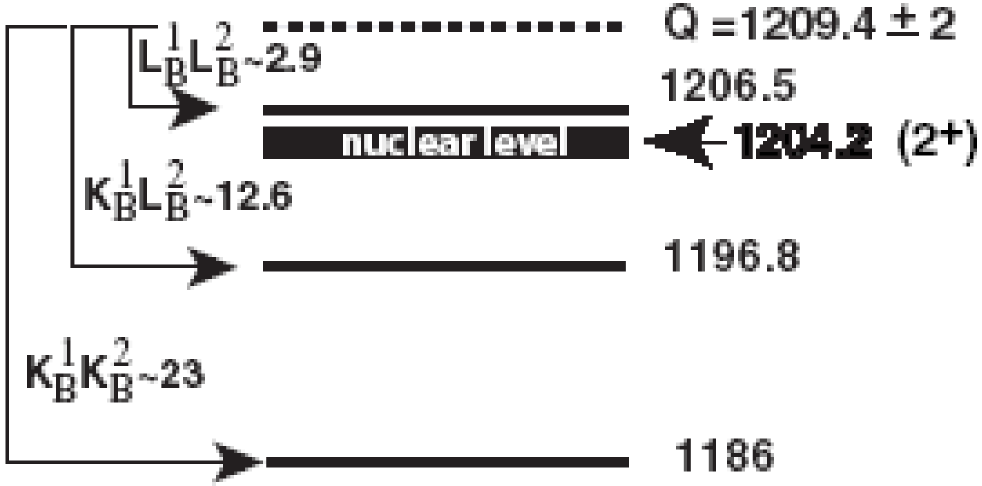
favoured: resonant enhancement ?

A.S. Barabash et al.,
NPA 807 (2008) 269

^{74}Se



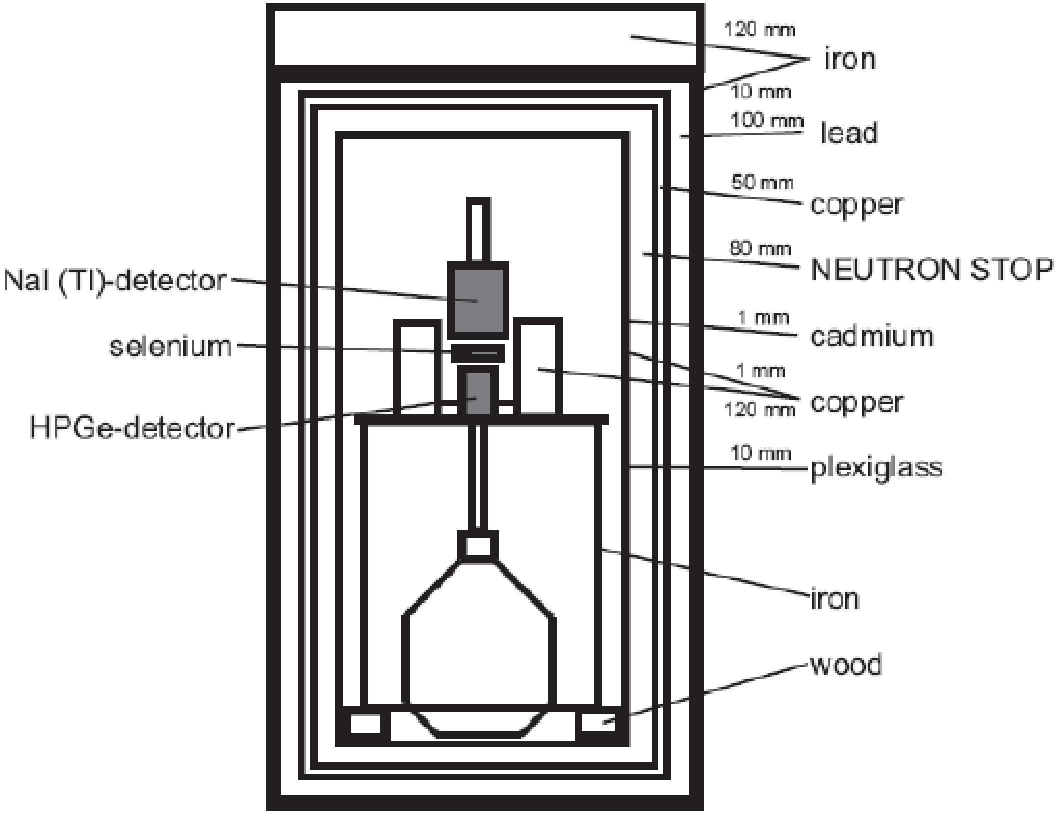
A.S. Barabash et al., NPA 785 (2007) 371

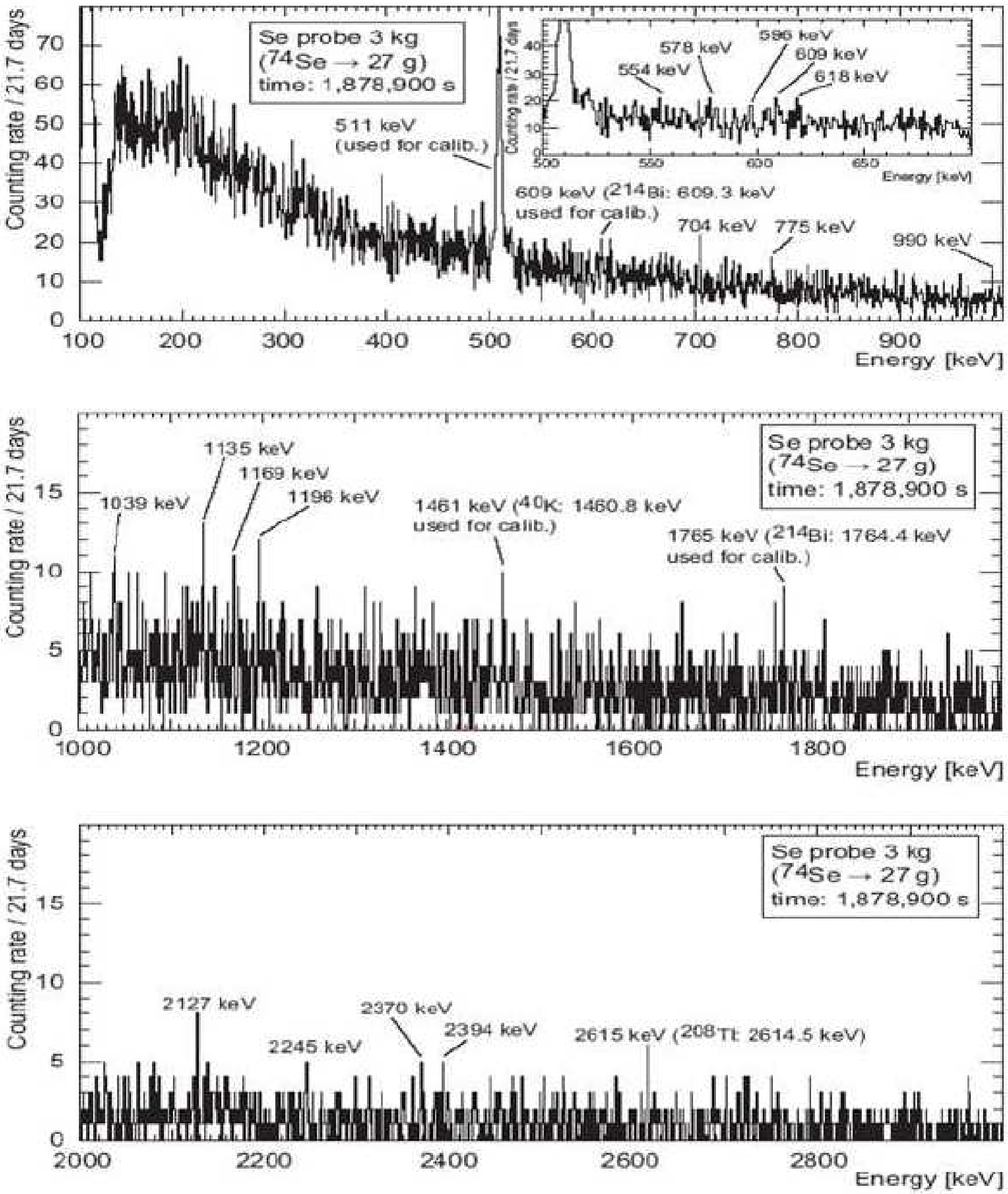


$T_{1/2} > 4 \times 10^{18}$ years

Muenster and Bratislava groups
(exp. in Bratislava)
Frekers et al., in preparation

3 kg of Se (27 g of ^{74}Se)

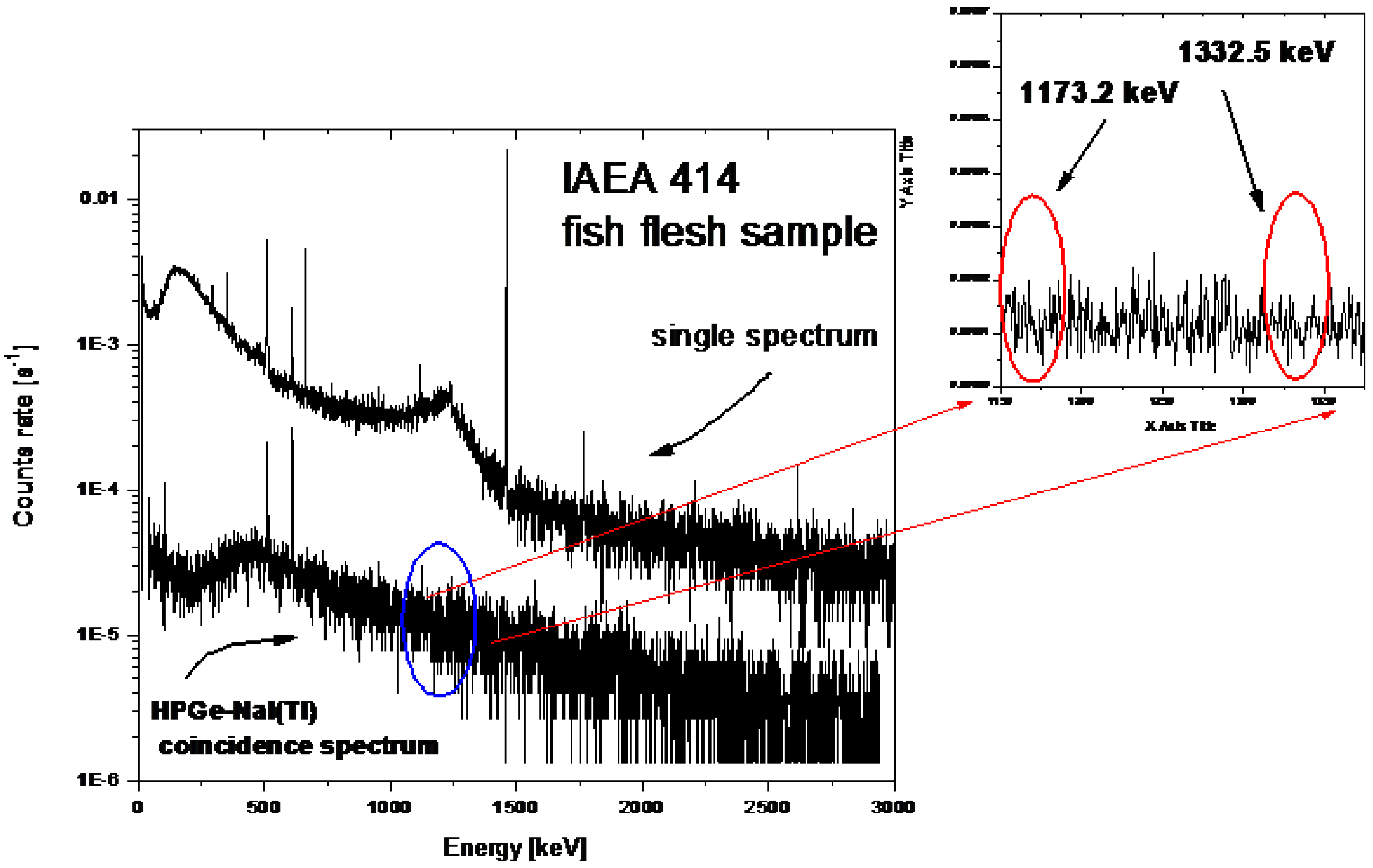




Present limit 5x10^{19} y

FIG. 3: Coincidence γ-ray spectrum of ^{74}Se after 21.7 days of measuring time.

Single and coincidence IAEA 414 fish flesh sample spectra



Monte Carlo simulation of interaction processes (CERN-GEANT 4)

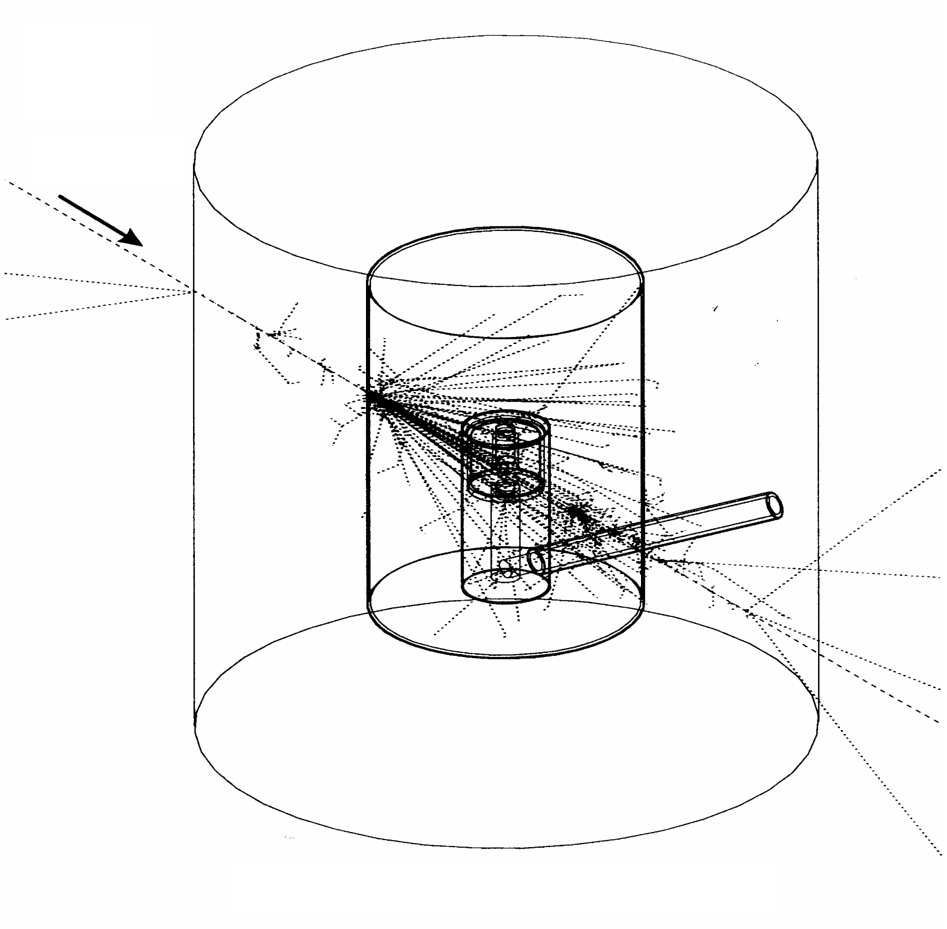
- **Muons** – delta electrons, bremsstrahlung, electron-positron pairs, muon capture

- **Electrons, positrons, photons** – bremsstrahlung, annihilation, phoelectric effect, Compton scattering, pair formation

- **Hadrons** – nuclear reaction, excitations (CERN-GEISHA and FLUKA)

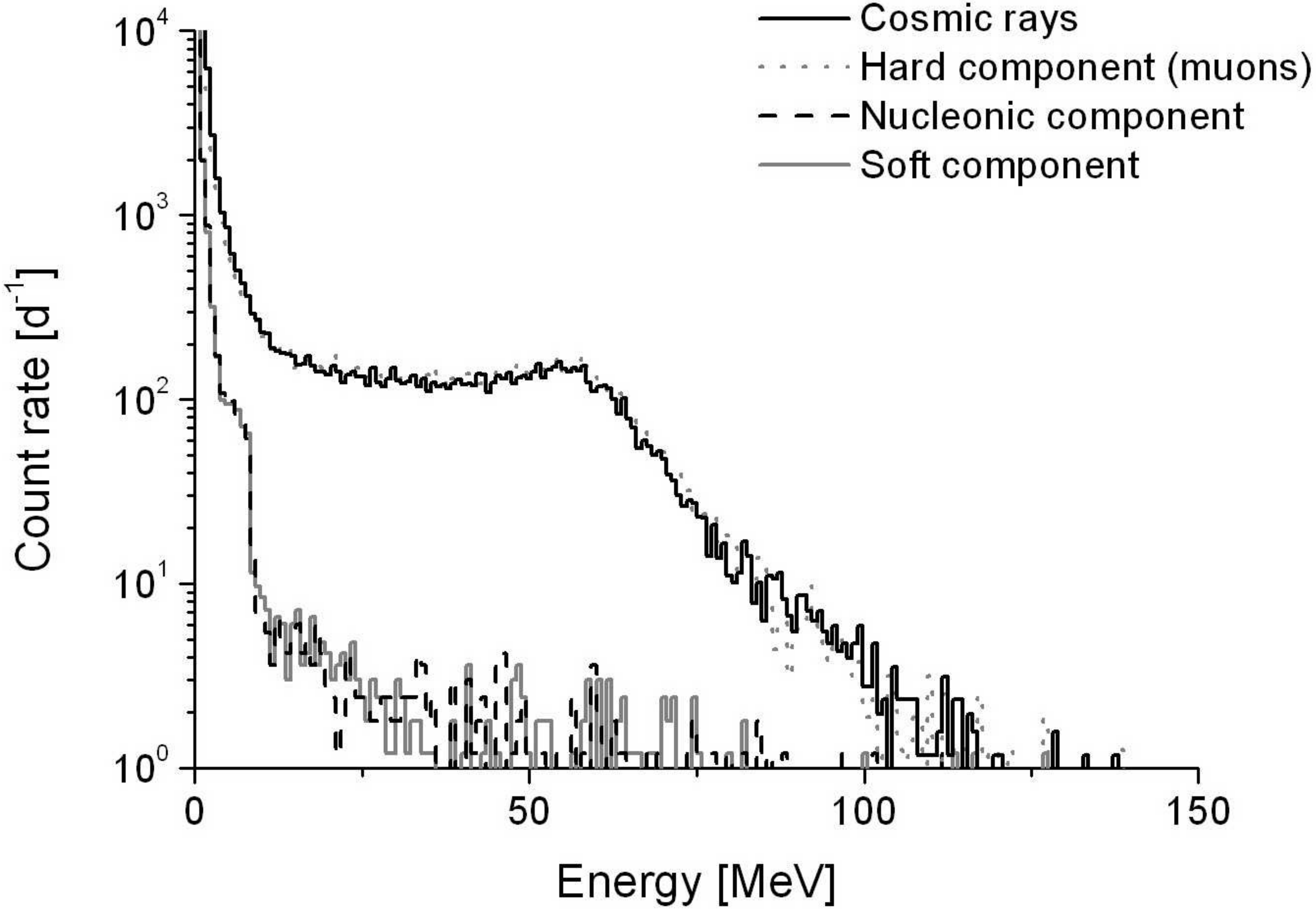
Muons

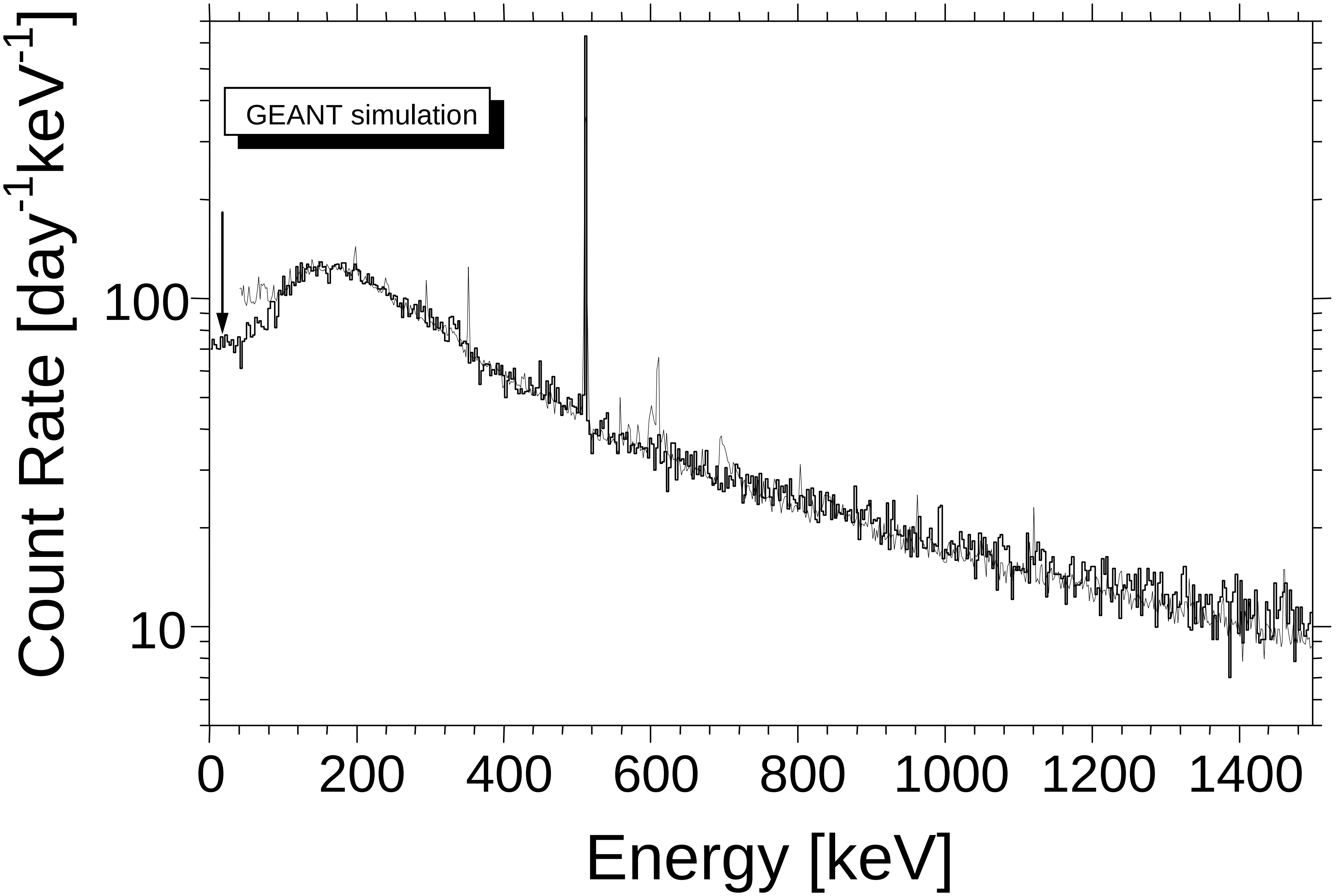
Vertical flux $$\left(\frac{dN}{dSdt}\right)_v = \int dp \int\limits_{\Phi-\pi/2}^{\Phi+\pi/2} d\varphi \int\limits_{0}^{\pi/2} d\vartheta j(p,\vartheta,\varphi)\sin^2\vartheta\cos(\Phi-\varphi)$$



Simulated muon pass through a HPGe detector

(muon momentum 50 GeV/c; energy deposited in the crystal was 1717keV)


Cosmic rays
Hard component (muons)
Nucleonic component
Soft component
Count rate [d^{-1}]
10^4
10^3
10^2
10^1
10^0
0
50
100
150
Energy [MeV]


GEANT simulation
Count Rate [day^{-1}keV^{-1}]
100
10
0
200
400
600
800
1000
1200
1400
Energy [keV]

Background gamma-spectrum

Detector :

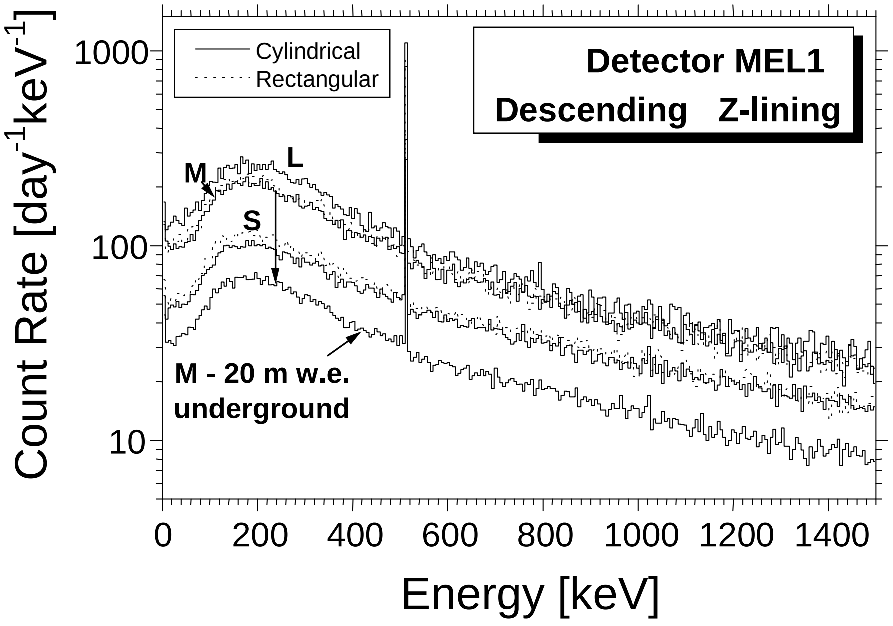
200% relative efficiency

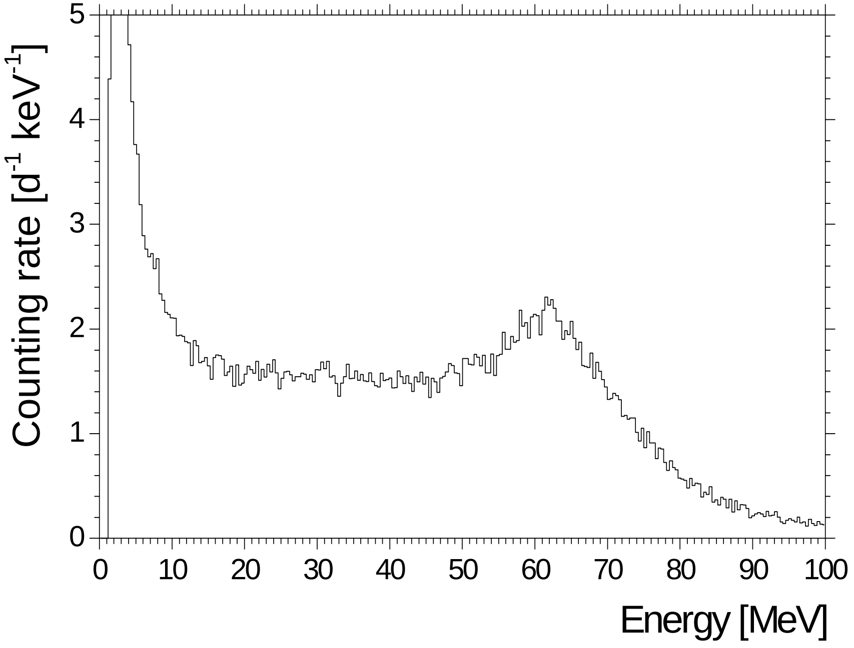
Shield - small, dia. 20 x 50 cm

- medium, dia. 60 x 70 cm

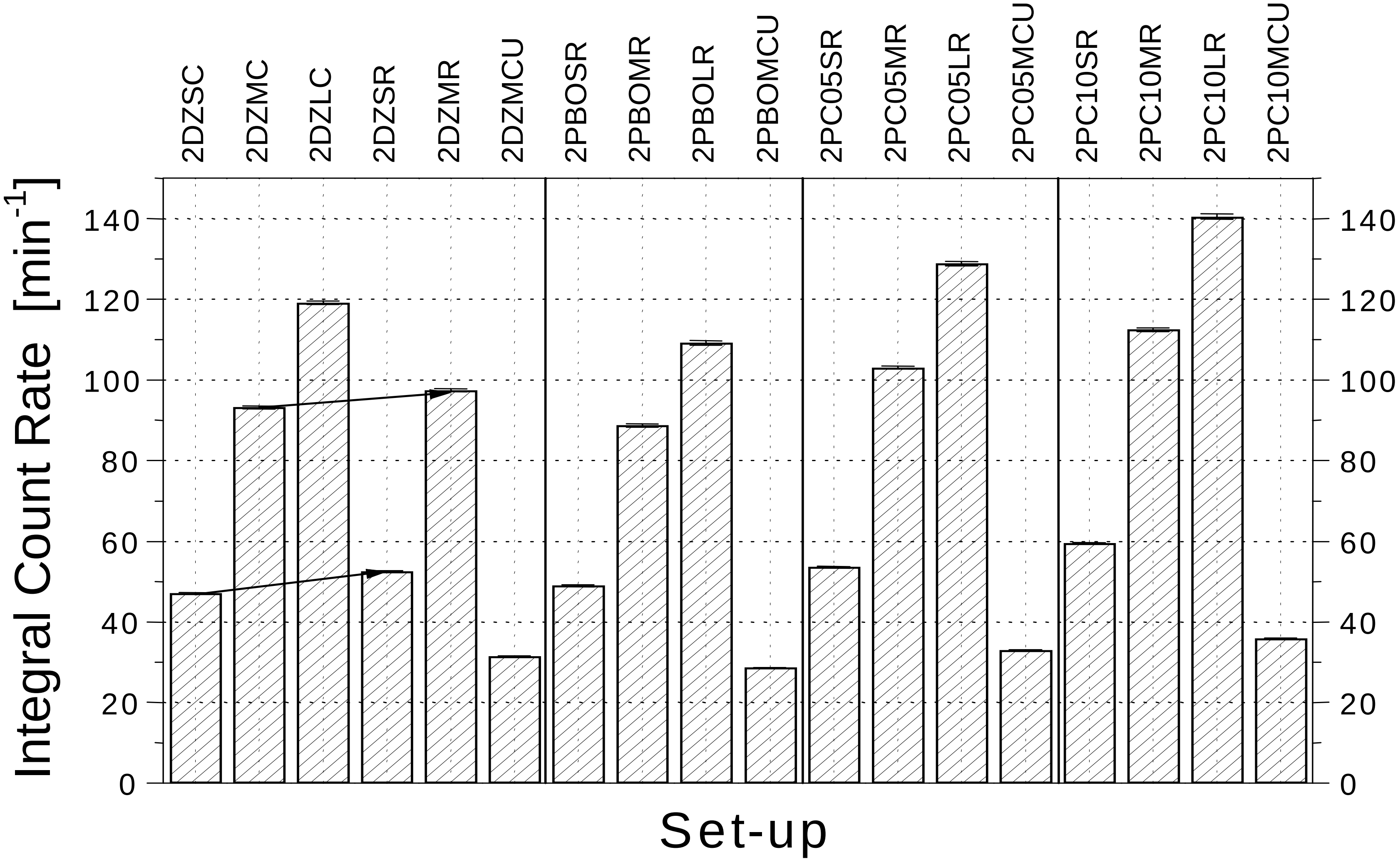
- large, dia. 100 x 120 cm

Shield thickness : 15 cm

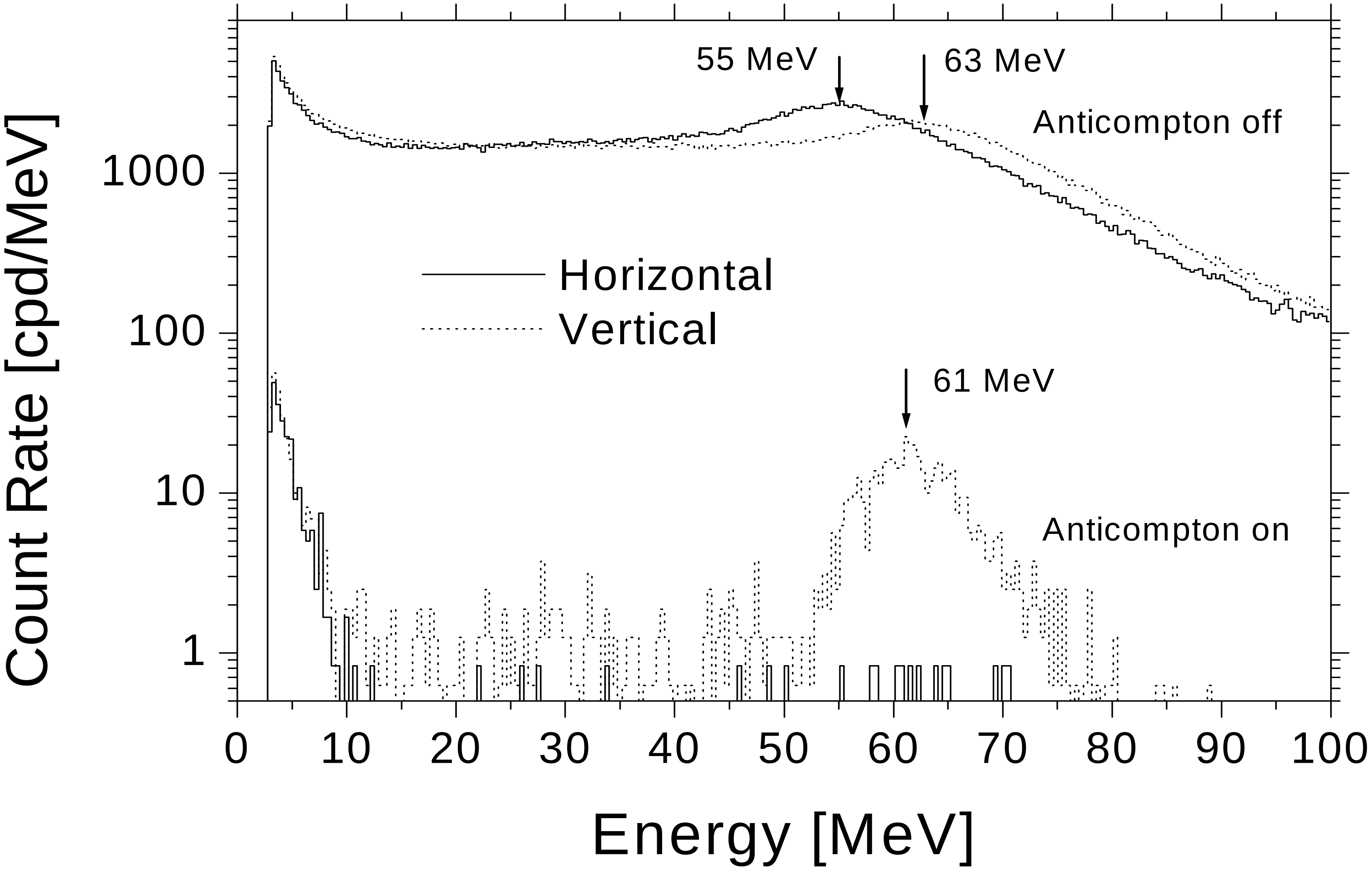


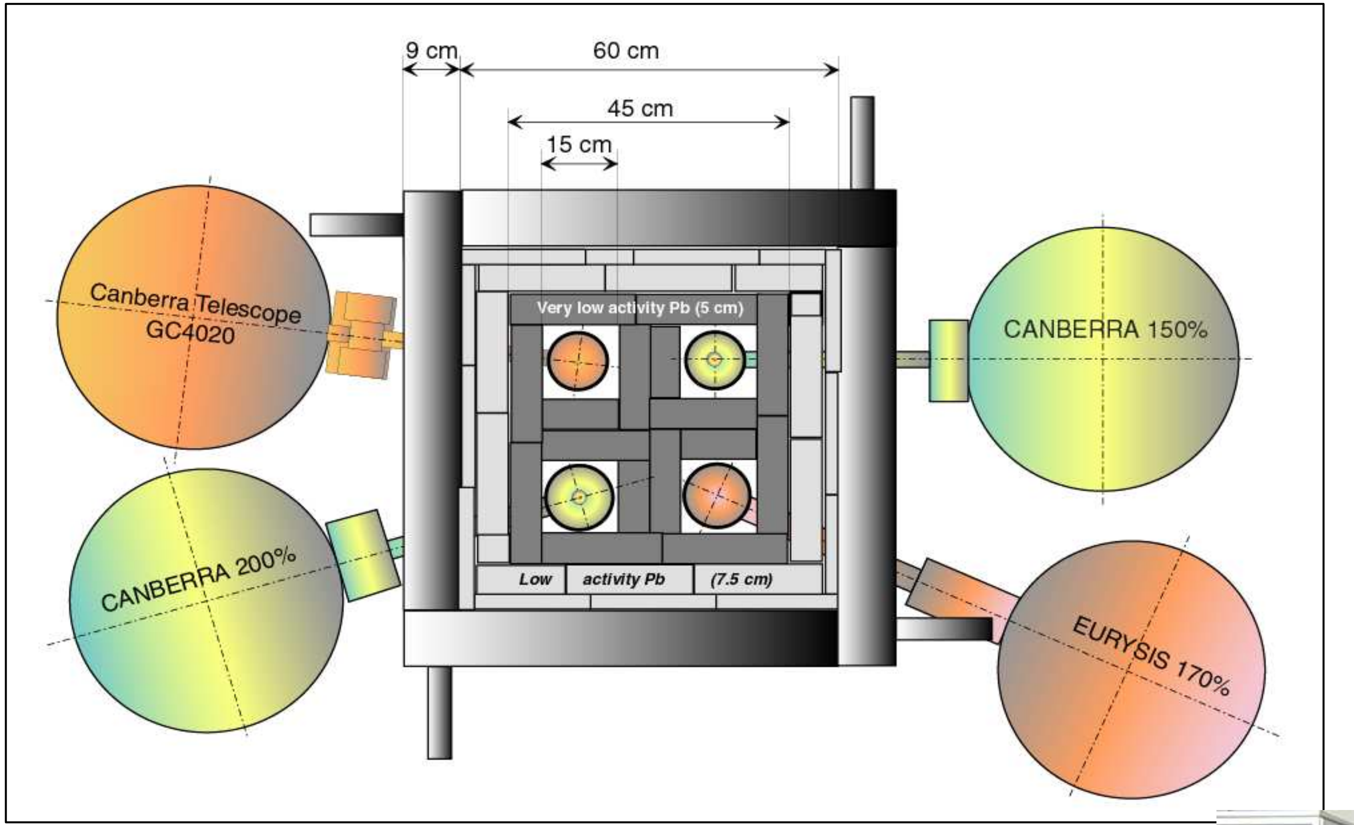


Simulated background in different shields

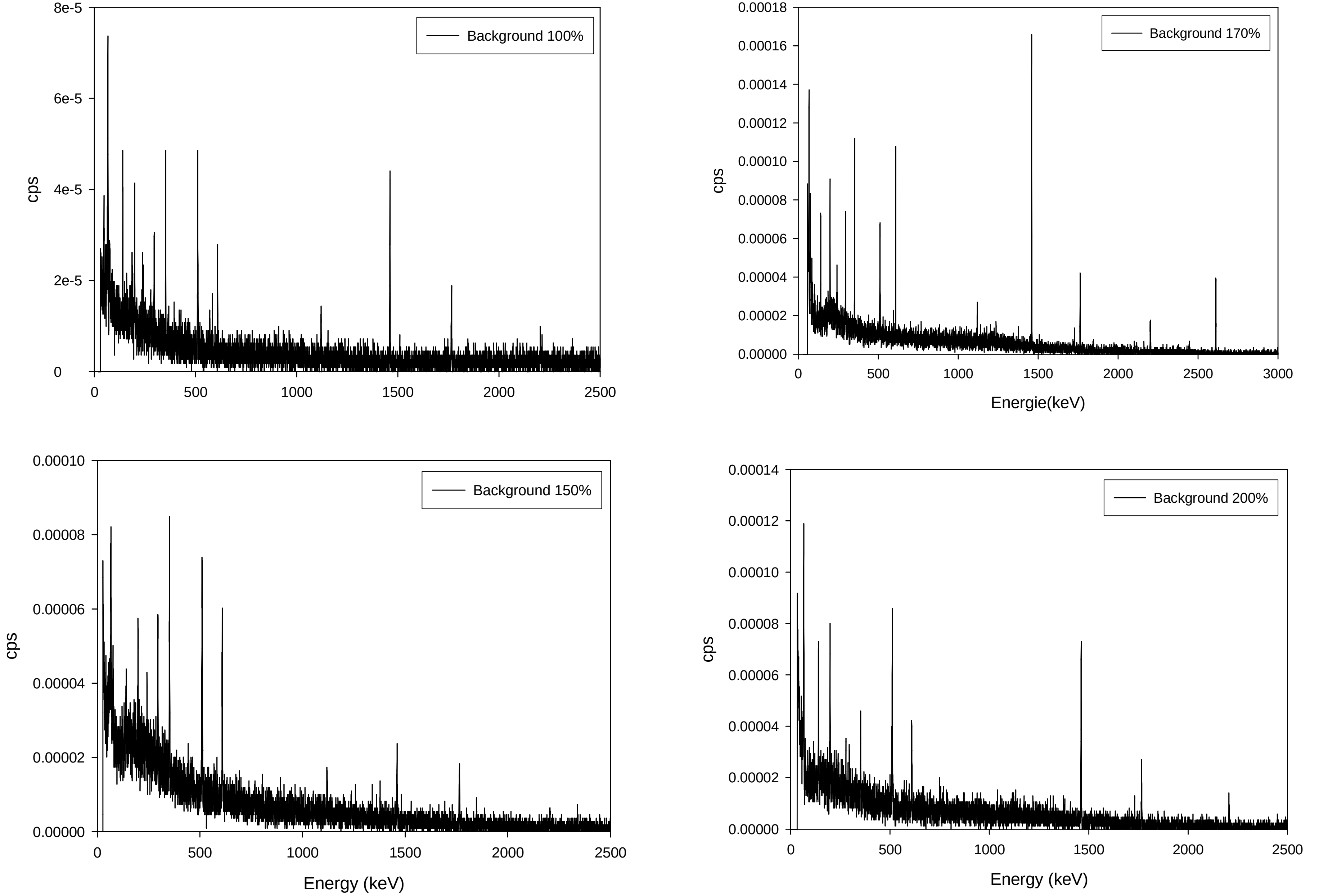


AntiCompton spectrometer

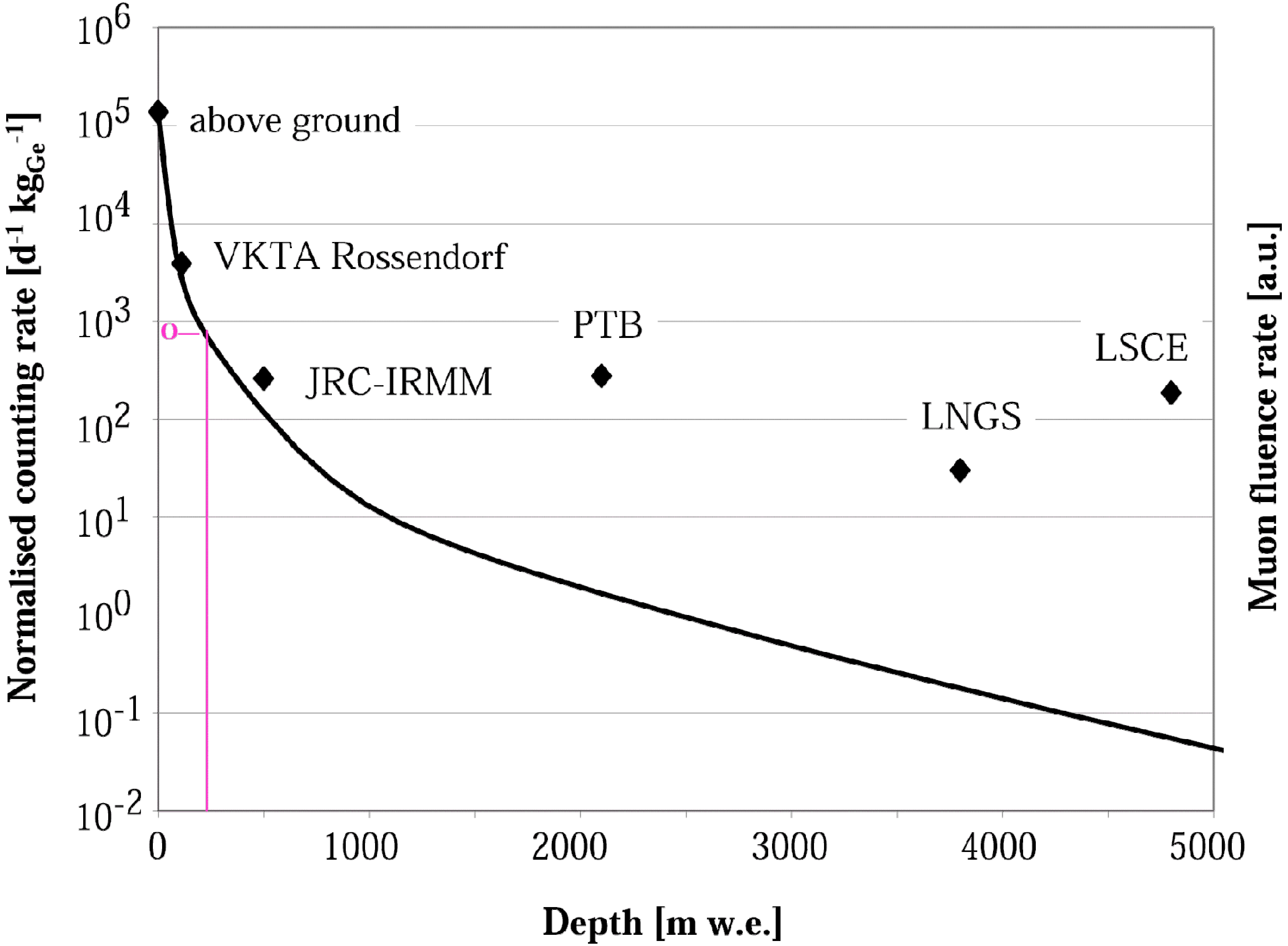



9 cm
60 cm
45 cm
15 cm
Canberra Telescope GC4020
CANBERRA 150%
CANBERRA 200%
EURYSIS 170%
Very low activity Pb (5 cm)
Low activity Pb (7.5 cm)


EURISYS MESURES



Background gamma-spectra of coaxial (top) and well (bottom) detectors in the lead shield with anti-cosmic protection in the CAVE facility.


10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
Normalised counting rate [d^{-1} kg_{Ge}^{-1}]
above ground
VKTA Rossendorf
PTB
LSCE
JRC-IRMM
LNGS
Muon fluence rate [a.u.]
0
1000
2000
3000
4000
5000
Depth [m w.e.]

Possible neutrinoless electron capture experiment in LSM

- Segmented very low background HPGe detectors (≤ 10) in LN (4π geometry): 20cm dia x 20cm long, plus 2 stopcoks of 10cm dia x 10cm long
- Multiparameter digital electronics
- Passive shielding made of B+PE and electrolytic copper (muon veto?)
- ^{112}Sn, ^{74}Se,... sources
- Expected half-life ~10^{23} years (for 5 y running, 2012-16)
- Cost ~2 M€

Double electron capture

$e_{1s1/2} + e_{1s1/2} + {}^{112}\mathrm{Sn} \longrightarrow {}^{112}\mathrm{Cd}(0^+_3)$

Reletivistic electron w.f. (j=1/2, l=0, l'=1)

$$\Psi^{(\alpha)}_{jm}(\vec{x}) = \begin{pmatrix} f_\alpha(r)\ \Omega_{jlm} \\ (-1)^{\frac{1+l+l'}{2}} g_\alpha(r)\ \Omega_{jl'm} \end{pmatrix} \quad l = j \pm 1/2,\ l' = 2j - l$$

Potential

0.022

$$V^{1s_{1/2}1s_{1/2}}(0^+_3) = \frac{1}{4\pi}\, m_e\ \left(G^2_\beta m^4_e\right)\ \frac{m_{\beta\beta}}{m_e}\ \frac{1}{R\ m_e}\ \boxed{\frac{\left(\bar{f}_{1s_{1/2}}\right)^2}{4\pi\ m^3_e}}\, g^2_A\ M^{0\nu}(0^+_3).$$

Width

$$\Gamma^{ECEC} = \frac{\left|V^{1s_{1/2}1s_{1/2}}(0^+_3)\right|^2}{(M_i - M_f)^2 + \frac{\Gamma^2_X}{4}}\ \Gamma_X$$

Matrix element

Exc. state	E_{ex} (MeV)	$M^{0\nu}$
$0^+_{g.s.}$	0	2.69
0^+_1 (1 ph.)	1.224	3.02
0^+_2 (2 ph.)	1.433	0.90
0^+_3 (1 ph.)	1.224	2.78