Rare α and β decays

V.I. Tretyak

Institute for Nuclear Research, Kyiv, Ukraine

1. Introduction
2. Recent searches and discoveries of rare α decays (^{151}Eu, ^{180}W, ^{178m2}Hf*, ^{190}Pt*, ^{204,206,207,208}Pb, ^{209}Bi, ^{209}Bi*)
3. Investigations of rare β decays (^{48}Ca, ^{50}V, ^{96}Zr, ^{113}Cd, ^{115}In*, ^{123}Te, ^{180m}Ta, ^{222}Rn)
4. Observation of emission of e^+e^- pairs in α decay of ^{241}Am
5. Conclusions

1. Introduction

Classification of radioactive decays:

Old known α, β, γ decays

α: (A,Z) $\rightarrow$ (A–4,Z–2), starting from ^{106}Te to superheavy;
$T_{1/2}$ from 10^{-8} s (^{217}Ac) to 10^{19} y (^{209}Bi)

β: (A,Z) $\rightarrow$ (A,Z$\pm$1), from ^{3}H; from 10^{-2} s (^{11}Li) to 10^{16} y (^{113}Cd)

γ: $(A,Z)^{*} \rightarrow$ (A,Z), from 10^{-12} s to 10^{5} y (^{186m}Re)

Cluster decays: emission of nuclides heavier than α particle, from ^{14}C to ^{34}Si (~40 mothers from ^{221}Fr to ^{242}Cm, residue close to double magic ^{208}Pb – "lead radioactivity"), 10^{3} – 10^{20} y; predicted in 1980 (or earlier?), observed in 1984

2β decays: allowed in SM $2\beta2\nu$ in 13 nuclei (^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{136}Xe, ^{150}Nd, ^{238}U + ^{78}Kr, ^{130}Ba), 10^{18} – 10^{24} y; forbidden in SM $2\beta0\nu$ $T_{1/2}>10^{25}$ y (in best cases of ^{76}Ge, ^{136}Xe; claim for observation in ^{76}Ge)

Spontaneous fission: heavy nuclei from ^{232}Th; $T_{1/2}$ from 10^{-3} s (^{264}Hs) to 10^{19} y (^{235}U)

p, 2p, 3p, 2n, …: in short living isotopes (~40 mothers); from ps to s

2. Recent searches and discoveries of rare α decays

Recently discovered α decays:

2003 – ^{209}Bi

2003 – ^{180}W

2007 – ^{151}Eu

2007 – ^{178m2}Hf*

2011 – ^{190}Pt*

2012 – ^{209}Bi*

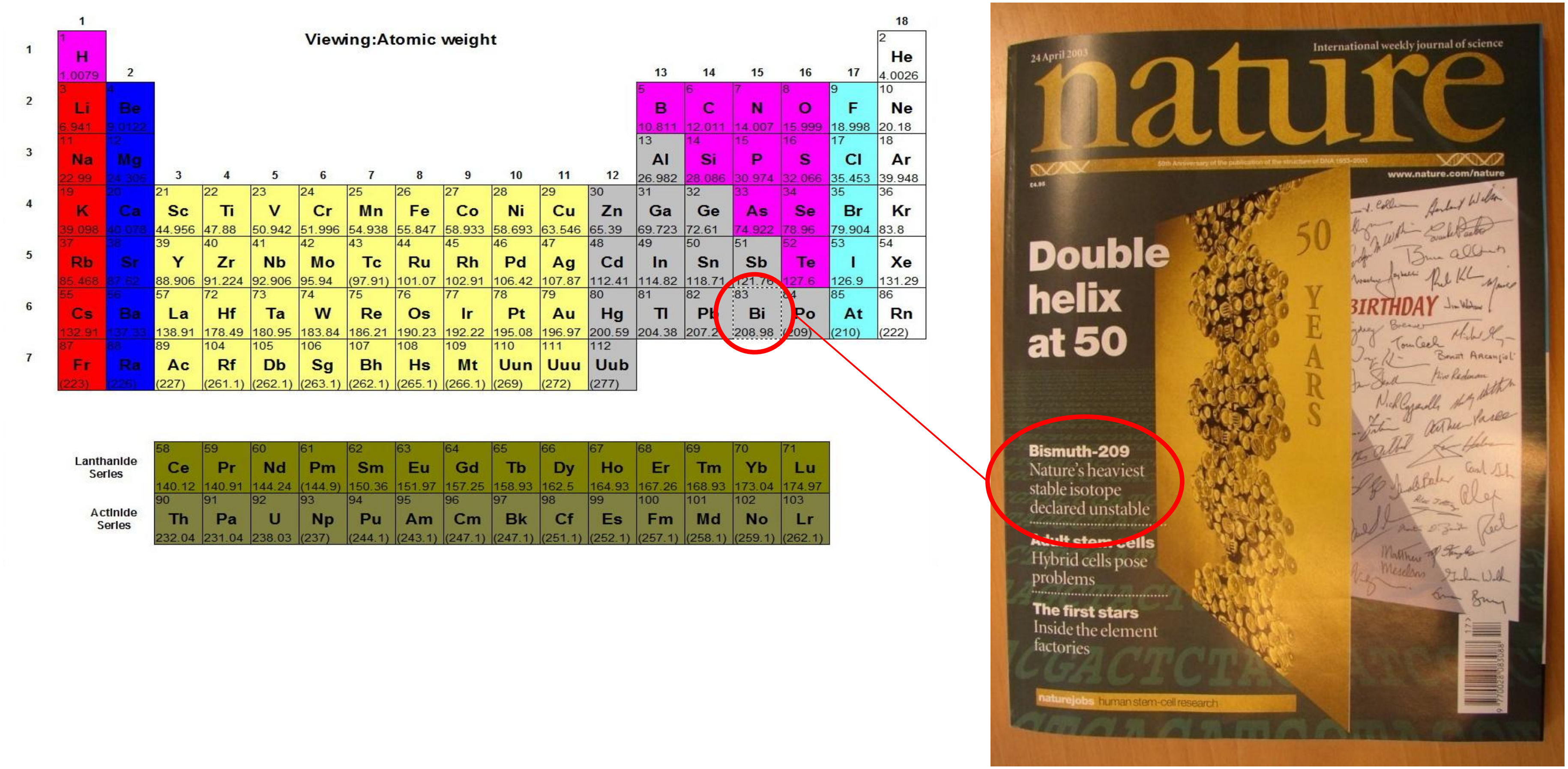
Limits:

2012 – ^{151}Eu*

2013 – ^{204,206,207,208}Pb

Until 2003, ^{209}Bi was considered as the heaviest stable isotope. However, in 2003 its alpha decay was discovered by P. De Marcillac et al., Nature 422 (2003) 876.

To-date, it has the longest $T_{1/2}^{\alpha} \approx 10^{19}$ y (for g.s. to g.s. transition).



^{209}Bi

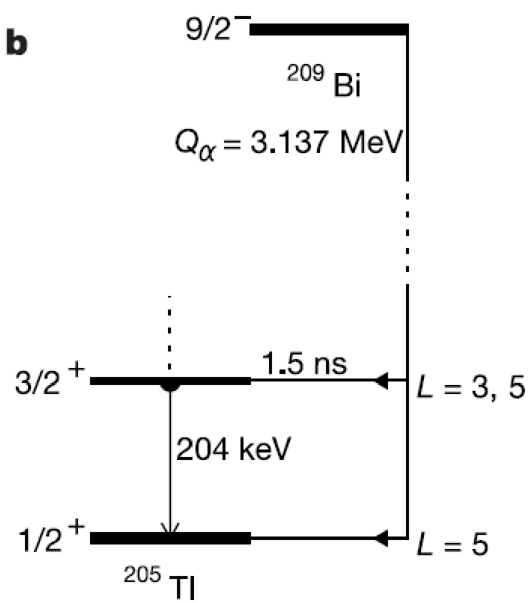
P. De Marcillac et al., Nature 422(2003)876

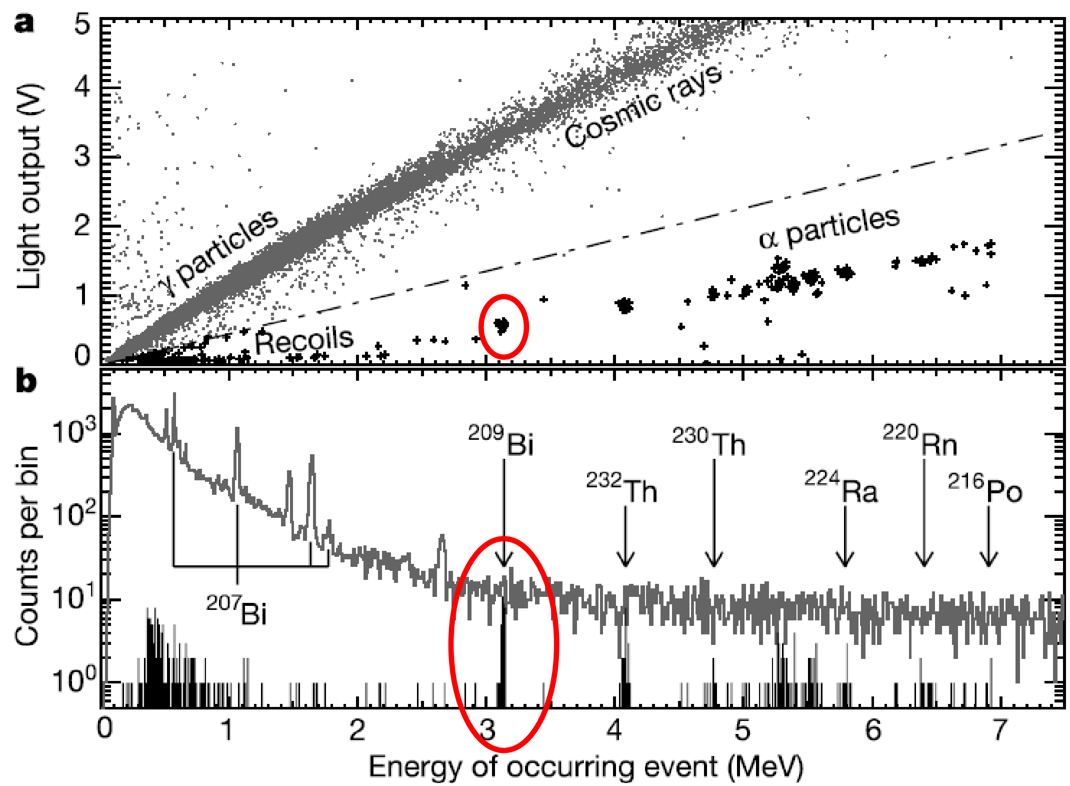
$Bi_4Ge_3O_{12}$ scintillating bolometer 46 g, 20 mK (for ^{209}Bi - δ=100%)

Heat and light signals – discrimination of α and β/γ events by ratio of light/heat

Measurements (at Earth level) – 5 days, 128 observed events at Q_α = 3.137 MeV

$T_{1/2} = (1.9\pm0.2)\times10^{19}$ y – the biggest half life ever measured for α decays (g.s. to g.s.)



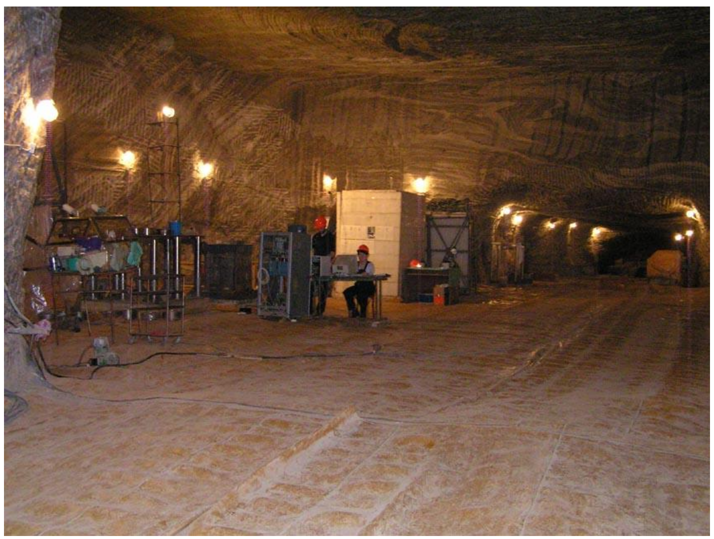


^{180}W

F.A. Danevich et al., Phys. Rev. C 67(2003)014310

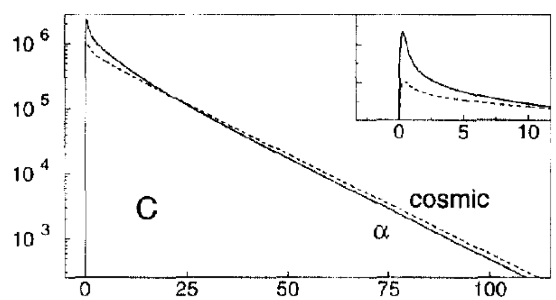
$CdWO_4$ scintillator, 330 g

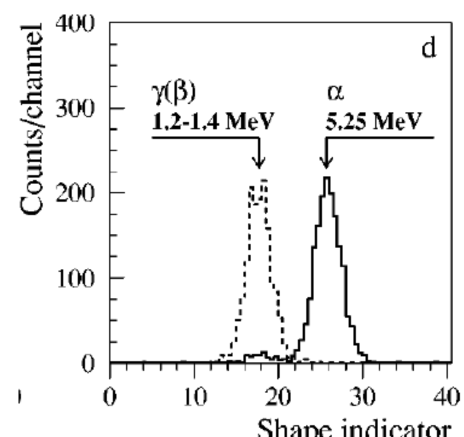
Solotvina underground laboratory (Ukraine, 1000 m w.e.)
2975 h of measurements in low background set-up



$CdWO_4$ crystals, Lviv, Ukraine, 2002

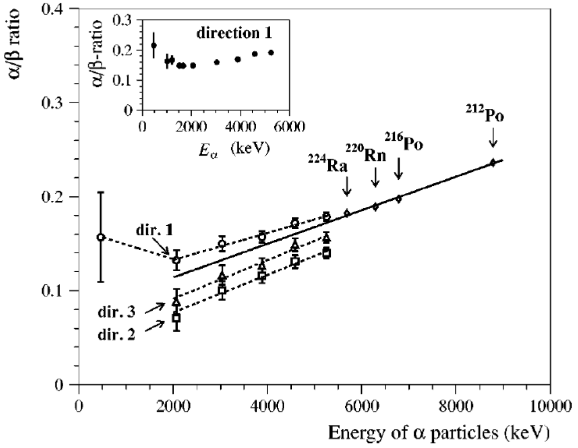
Pulse shape discrimination between α and β/γ events thanks to different evolution of scintillating signal in time:



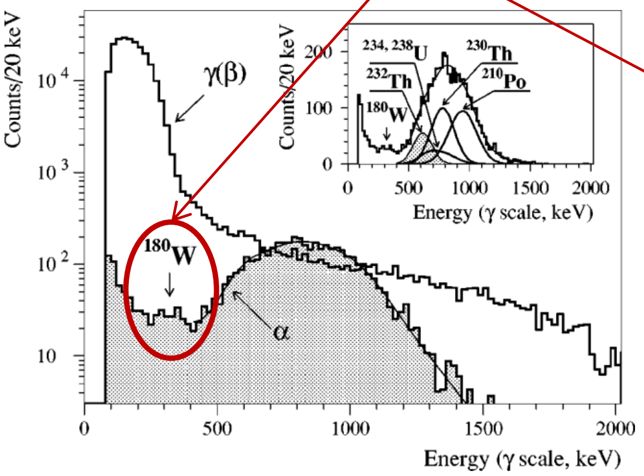


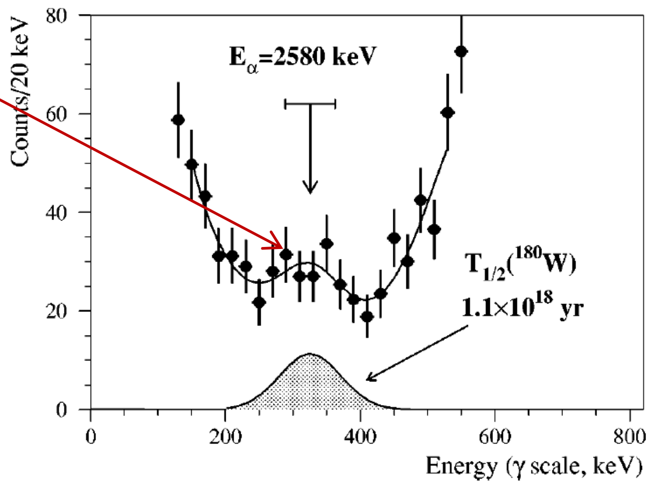
Q_α = 2.516 MeV
^{180}W (δ = 0.12%)

Quenching of scintillation signals from alpha particles (observed energy of α's is ~0.14 of their real energy):



The effect is observed, $T_{1/2} = (1.1^{+0.9}_{-0.5})\times10^{18}$ y



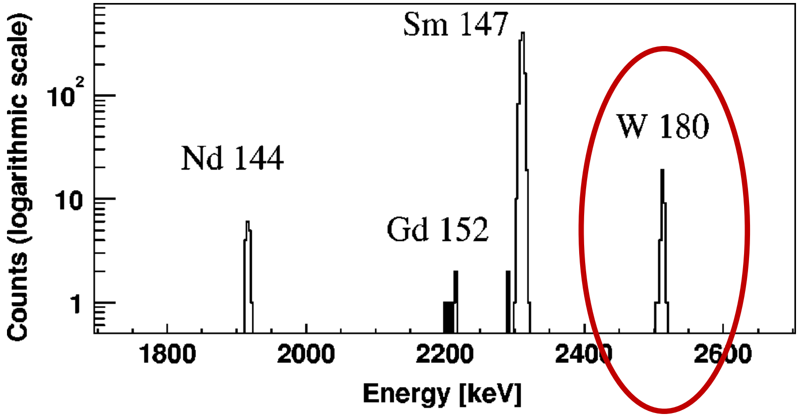


(1) Peak belongs to α particles (thanks to pulse-shape discrimination)
(2) Correct energy
(3) $T_{1/2}$ in agreement with theoretical expectations

Confirmation: C. Cozzini et al., Phys. Rev. C 70(2004)064606

CRESST, $CaWO_4$ scintillating bolometer 300 g, ~15 mK, FWHM = ~18 keV, ~2300 h of measurements, low background set-up at LNGS (3600 m w.e. underground)

$T_{1/2} = (1.8 \pm 0.2) \times 10^{18}$ y
Measured $Q_\alpha = 2516.4 \pm 1.1(stat) \pm 1.2(syst)$ keV



Further observations:
$T_{1/2}$ =
$(1.0^{+0.7}_{-0.3}) \times 10^{18}$ y – $CaWO_4$, Yu.G. Zdesenko et al., NIMA 538(2005)657
$(1.3^{+0.6}_{-0.5}) \times 10^{18}$ y – $ZnWO_4$, P. Belli et al., NIMA 626-627(2010)31

Now it is routine observation in many rare events' experiments.

^{151}Eu

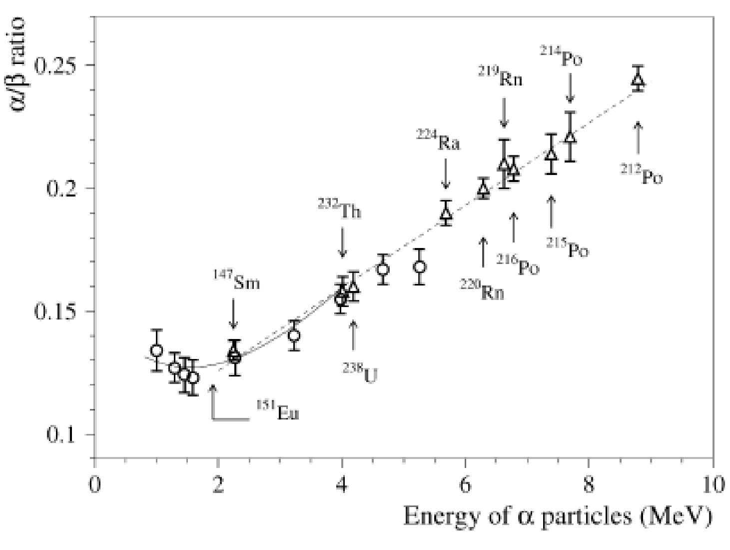
P. Belli et al., Nucl. Phys. A 789(2007)15

α decay ^{151}Eu ($5/2^+$) $\rightarrow$ ^{147}Pm ($7/2^+$), δ = 47.81%, Q_α = 1.964 MeV

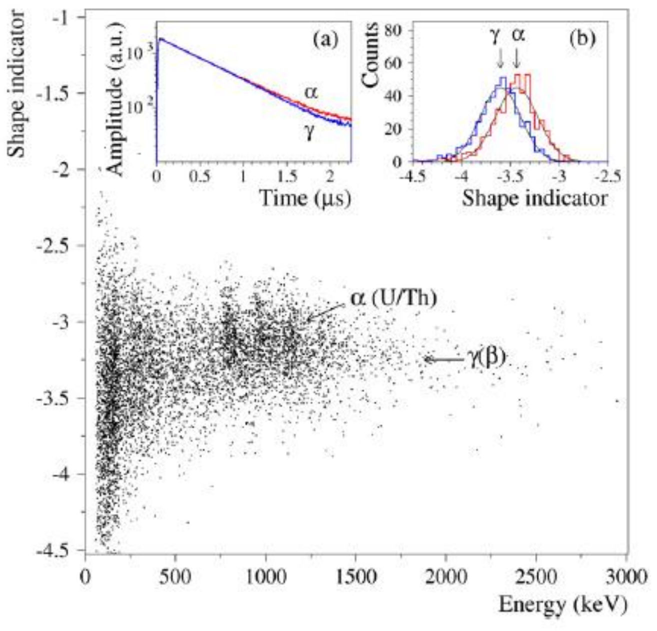
Our theoretical estimations with few models: $T_{1/2} = 3.0\times10^{17} - 3.6\times10^{18}$ y
The effect could be observed with CaF_2(Eu) scintillator with 0.4% Eu.

LNGS (3600 m w.e.), low background set-up, 7426 h, CaF_2(Eu) 370 g

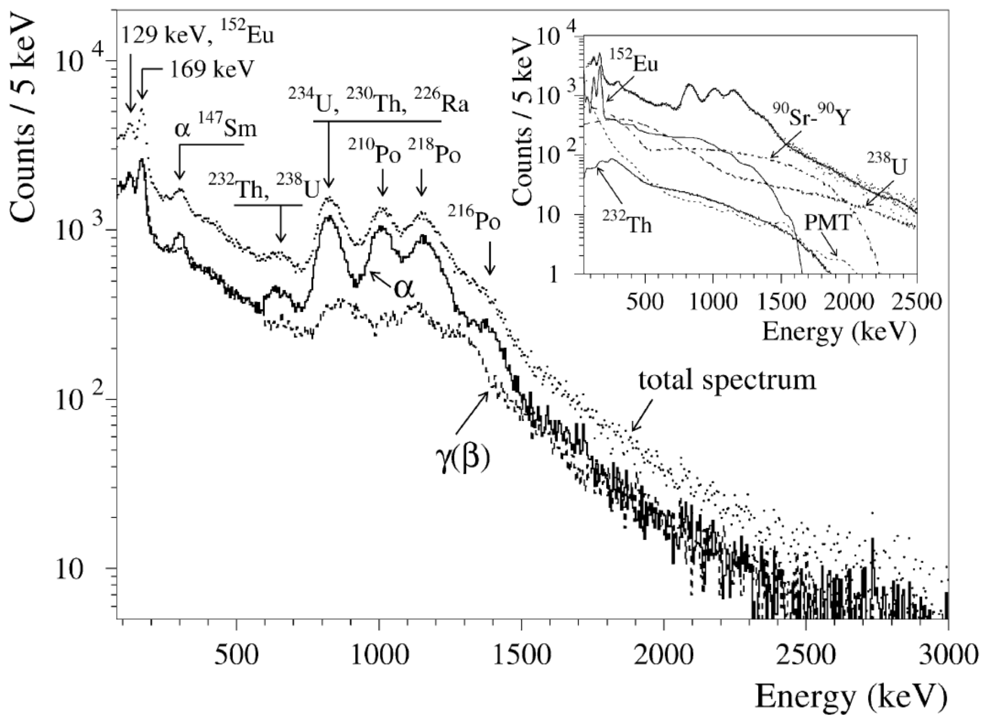
^{147}Sm: α/β ratio = 0.13 $\rightarrow$ expected energy for ^{151}Eu ~250 keV

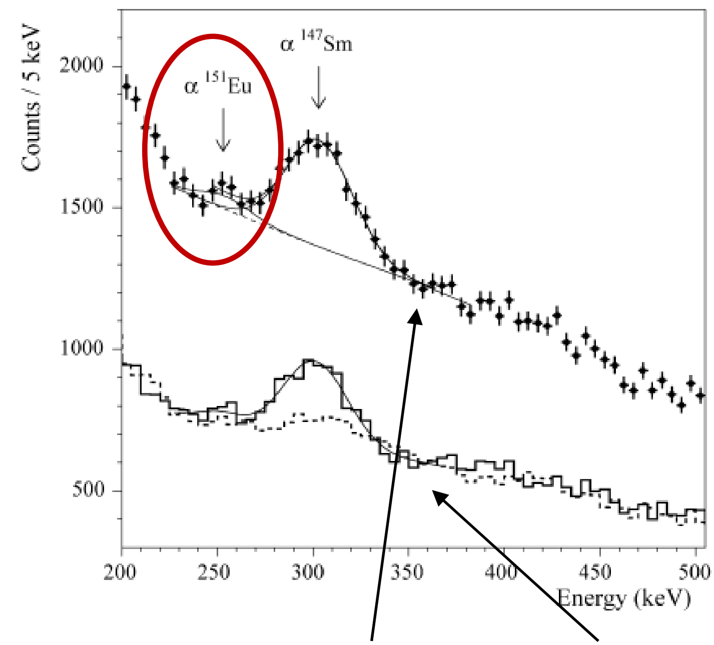


Pulse shape discrimination between α and β/γ events:



Experimental spectrum and its fit by simulated distributions:





Spectra: total and divided on α and β components

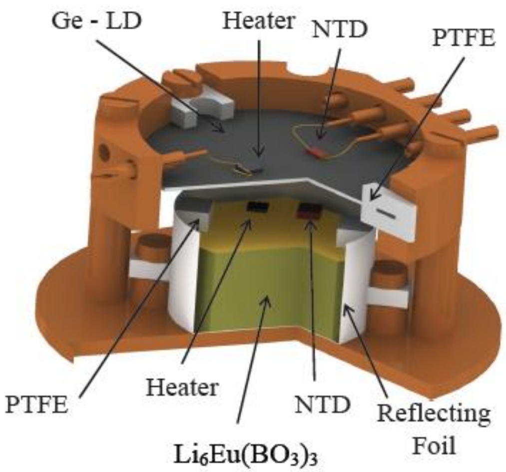
Peak's energy: 255±7 keV → E_α=1.98±0.04 MeV (expected E_α=1.912)
Number of ^{151}Eu nuclei (ICP-MS): (2.8±0.7)×10^{21}; S = 302±232 counts

$T_{1/2} = 5^{+11}_{-3}\times10^{18}$ y

Later calculations: 8.5×10^{18} y – O.A.P. Tavares et al., Phys. Scr. 76(2007)C163
1.3×10^{18} y – Y.B. Qian et al., Phys. Rev. C 84(2011)064307
1.0×10^{19} y – Y.B. Qian et al., Phys. Rev. C 85(2012)027306
8.0×10^{17} y – K.P. Santhosh et al., Int. J. Mod. Phys. E 22(2013)1350081

Confirmation: N. Casali et al., J. Phys. G 41(2014)075101

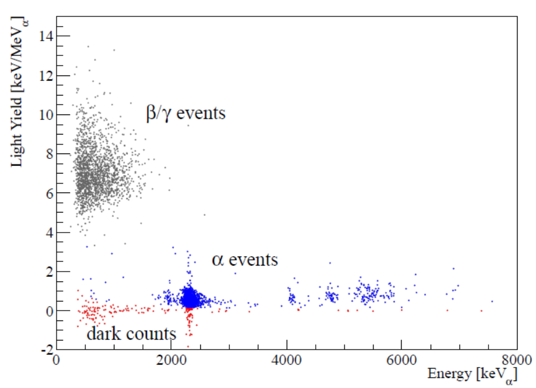
LUCIFER, $Li_6Eu(BO_3)_3$ scintillating bolometer 6.15 g, FWHM = 65 keV, 462 h of measurements, low background set-up at LNGS (3600 m w.e. underground)

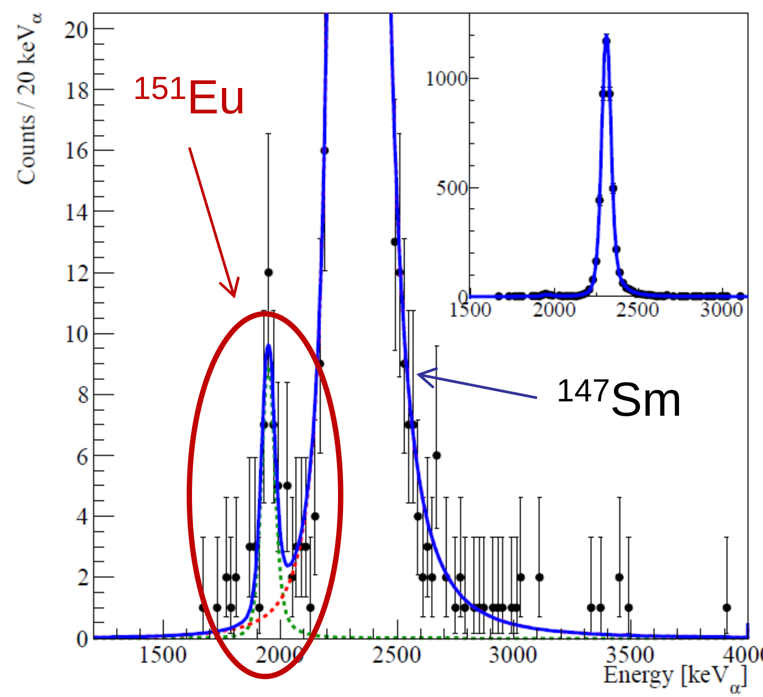


L. Pattavina, talk at RPScint'2013 workshop, Kyiv, 17-20.09.2013

S = 38±8, $T_{1/2}$ = (4.6±1.2)×10^{18} y
Measured Q_α = 1948.9±8.6 keV

Excellent discrimination of β/γ events from α events



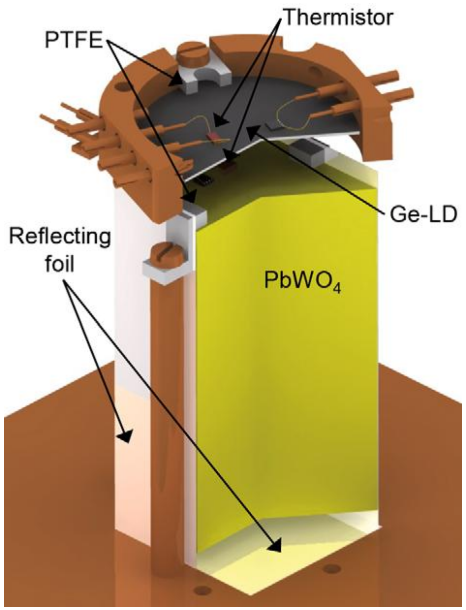


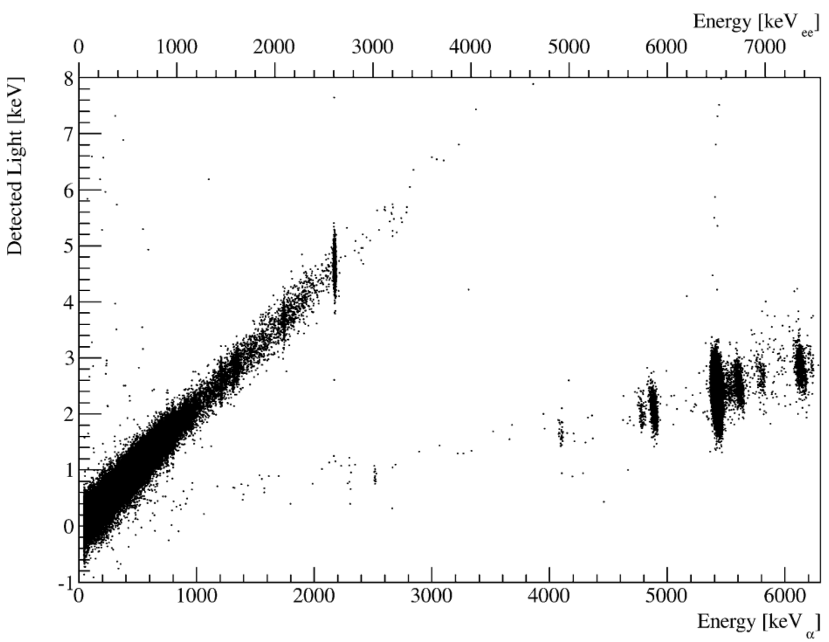
^{204,206,207,208}Pb J.W. Beeman et al., Eur. Phys. J. A 49(2013)50

All naturally occuring Pb isotopes are potentially α decaying, Q_α = 0.392 – 1.970 MeV. Theoretical expectations: $T_{1/2} = 10^{35} – 10^{189}$ y.

LUCIFER, $PbWO_4$ scintillating bolometer (with ancient Roman lead: activity of ^{210}Pb < 4 mBq/kg, while for usual Pb it is ~ $10^2 – 10^3$ Bq/kg), 454 g, LNGS (3600 m w.e.), low background set-up, 586 h

Only limits are derived: $T_{1/2} > 1.4\times10^{20} – 2.6\times10^{21}$ y
(for ^{204}Pb – 3 orders of magnitude better than previous exp. limit)





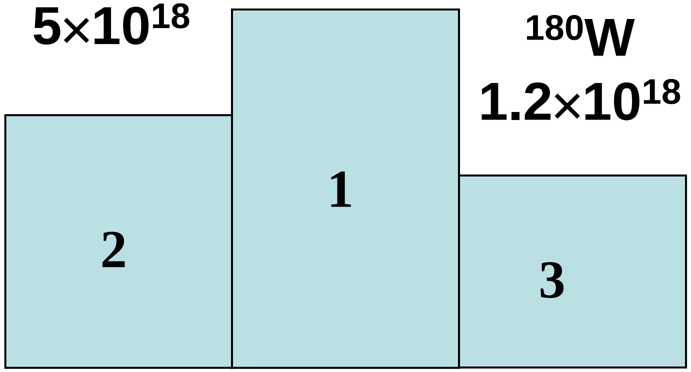
Observations of rare g.s. to g.s. α decays (in sports terminology):

Half life, y

^{209}Bi 1.9×10^{19}

^{151}Eu 5×10^{18}

^{180}W 1.2×10^{18}



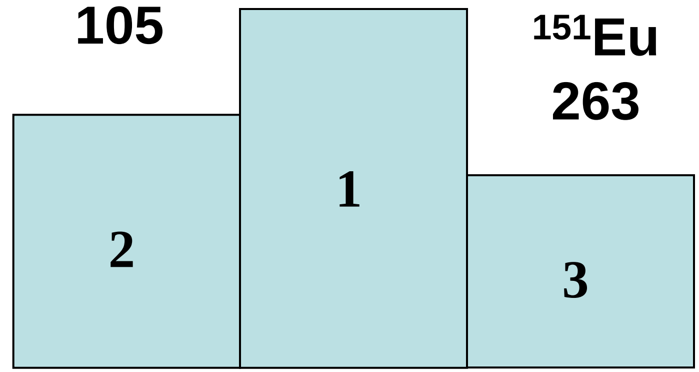
KINR & DAMA | ROSE-BUD | KINR

Activity, decays in 1 g of element (of natural isotopic composition) during 1 year

^{180}W 2.3

^{209}Bi 105

^{151}Eu 263



ROSE-BUD | KINR | KINR & DAMA

$\delta(^{209}\mathrm{Bi}) = 100\%$

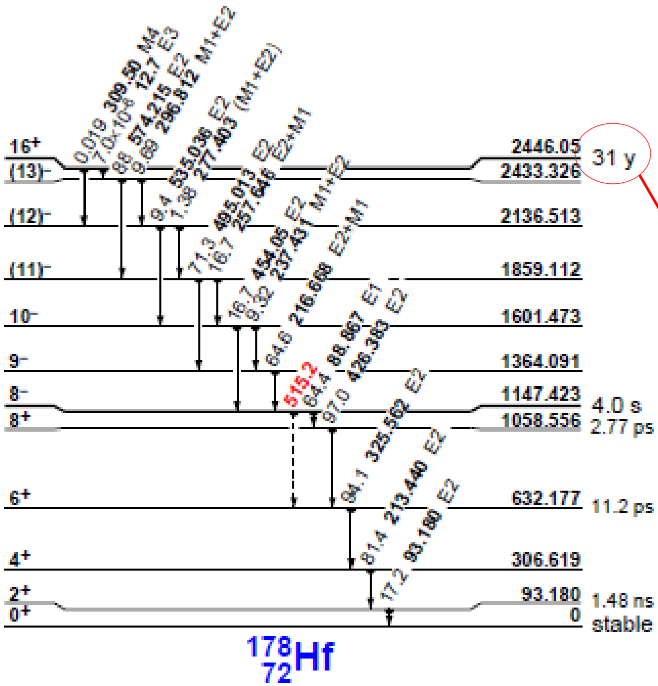
$\delta(^{151}\mathrm{Eu}) = 47.81\%$

$\delta(^{180}\mathrm{W}) = 0.12\%$

$^{178m2}Hf \rightarrow {}^{174}Yb^*$

S.A. Karamian et al., PRC 75(2007)057301

^{178m2}Hf – extremely interesting nucleus: E_{exc} = 2446 keV but $T_{1/2}$ = 31 y



Usually it decays through IT, but potentially it is α decaying, Q=4526 keV; several excited levels of ^{174}Yb can be populated.

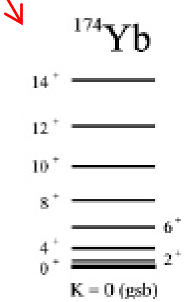


TABLE I. Estimated partial half-lives for α decay of the $^{178}Hf^{m2}$ isomer to levels in the ground-state band of ^{174}Yb. The calculations are discussed in the text.

Transition $I_i \rightarrow I_f$	E_α [MeV]	$T_{1/2}^{\alpha,f}$ [yr]
$16^+ \rightarrow 0^+$	4.43	8.6×10^{10}
$16^+ \rightarrow 2^+$	4.35	3.0×10^{9}
$16^+ \rightarrow 4^+$	4.18	3.4×10^{8}
$16^+ \rightarrow 6^+$	3.91	1.2×10^{8}
$16^+ \rightarrow 8^+$	3.56	2.8×10^{8}
$16^+ \rightarrow 10^+$	3.12	2.7×10^{9}
$16^+ \rightarrow 12^+$	2.61	7.2×10^{10}
$16^+ \rightarrow 14^+$	2.03	5.5×10^{13}

most probable

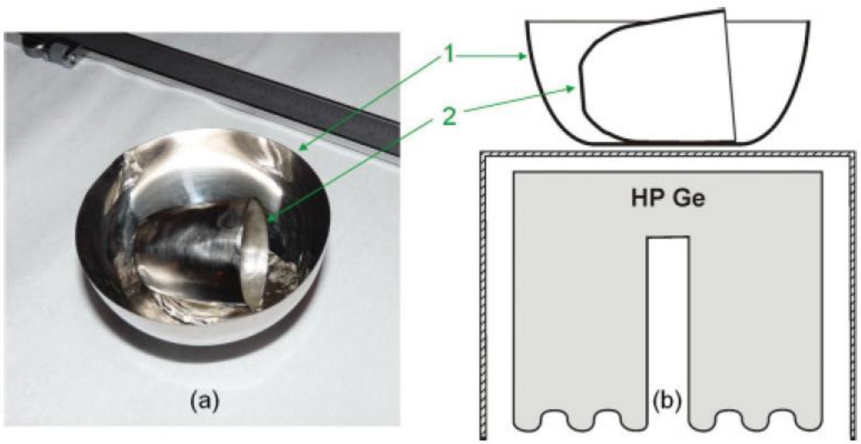
First observed in 2007: source with 3.5×10^{13} nuclei of ^{178m2}Hf (^{176}Yb target exposed to 36 MeV He ion beam) deposited on thin Be foil between 2 CR-39 foils, ~1 y exposure, observation of α tracks after CR-39 etching.

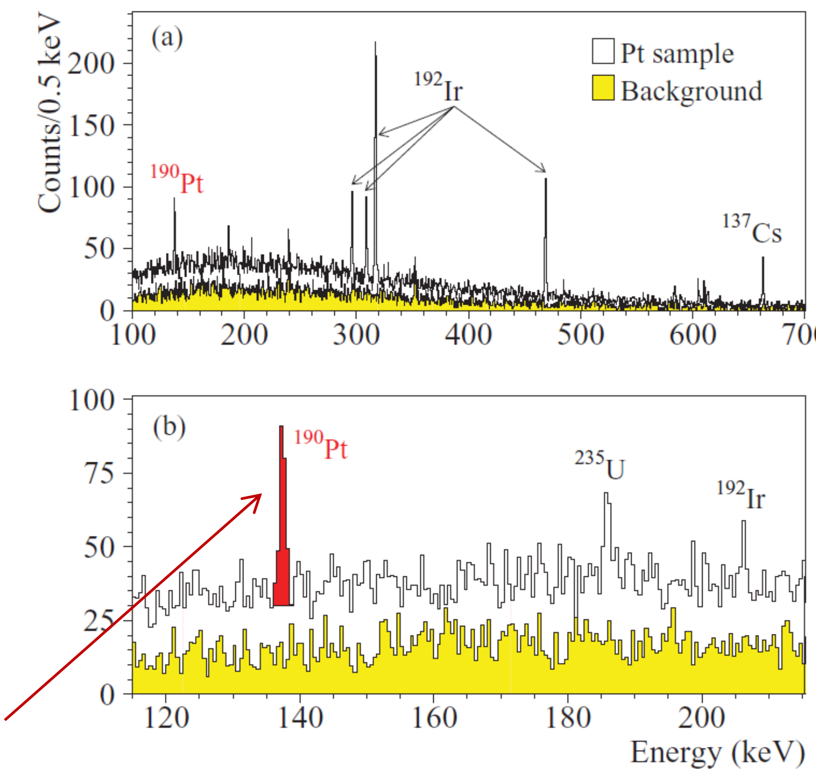
Result: 307 (±25?) α events in excess, $T_{1/2}^*$ = $(2.5\pm0.5)\times10^{10}$ y

$^{190}Pt \rightarrow {}^{186}Os^*$ (E_{exc}=137.2 keV) P. Belli et al., PRC 83(2011)034603

G.s. to g.s. decay $^{190}Pt \rightarrow {}^{186}Os$ is known since 1921: Q=3251 keV, $T_{1/2}=(6.5\pm0.3)\times10^{11}$ y;
Transition to the 1st excited level was observed only in 2011

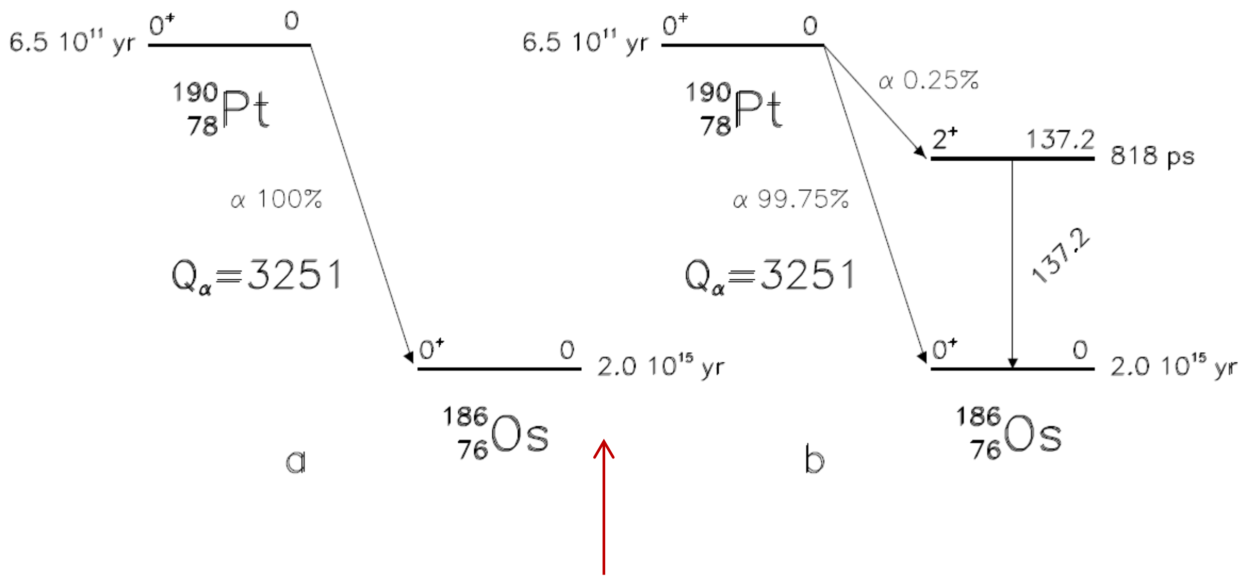
LNGS (3600 m w.e.), HPGe 468 cm^3, low background set-up, 1815 h, 42.5 g of natural Pt (^{190}Pt: δ=0.014%; new value (2011) δ=0.012%)





Measured energy = 137.1±0.1 keV
Peak =132±17 counts (8σ effect)
The peak is absent in background

$T_{1/2}^* = 2.6^{+0.4}_{-0.3}$(stat)±0.6(syst)×10^{14} y



Old and new schemes of ^{190}Pt decay

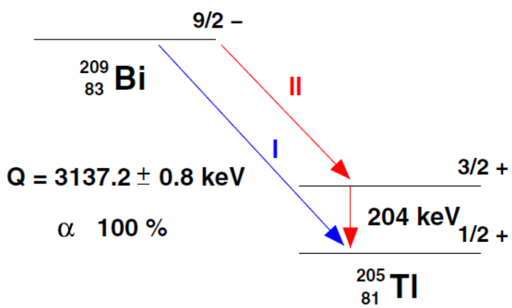
$T_{1/2}$ limits for other Pt isotopes were also set at the level of 10^{16} – 10^{20} y

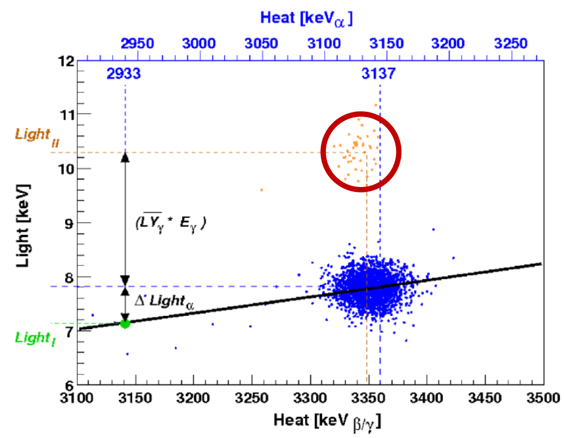
It would be nice to remeasure with different detector and Pt sample

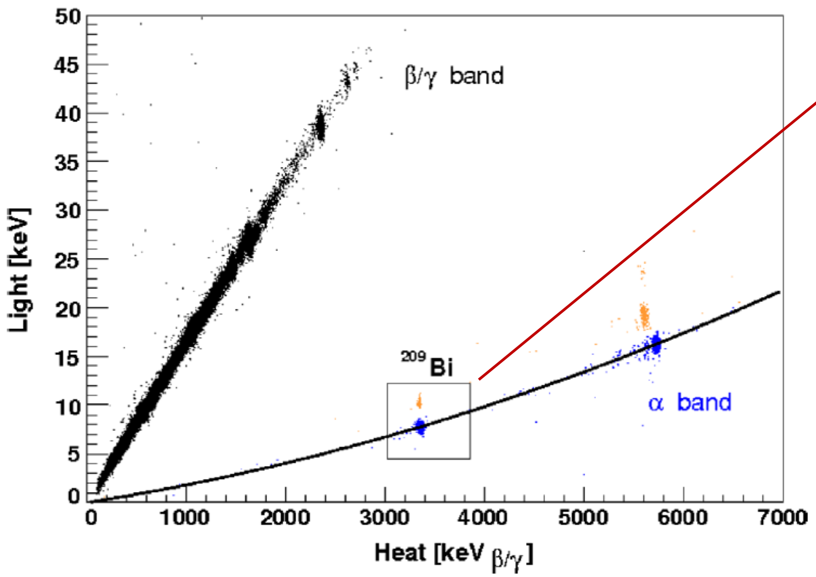
$^{209}Bi \rightarrow {}^{205}Tl^*$ (E_{exc}=204 keV) J.W. Beeman et al., PRL 108(2012)062501

G.s. to g.s. decay $^{209}Bi \rightarrow {}^{205}Tl$ – 2003: Q=3137 keV, $T_{1/2}$=(1.9±0.2)e18 y
Transition to the 1st excited level was observed in 2012

LNGS (3600 m w.e.), $Bi_4Ge_3O_{12}$ bolometer 889 g, few tens mK, 375 h
Heat and light signals – discrimination of α and β/γ events by ratio of light/heat







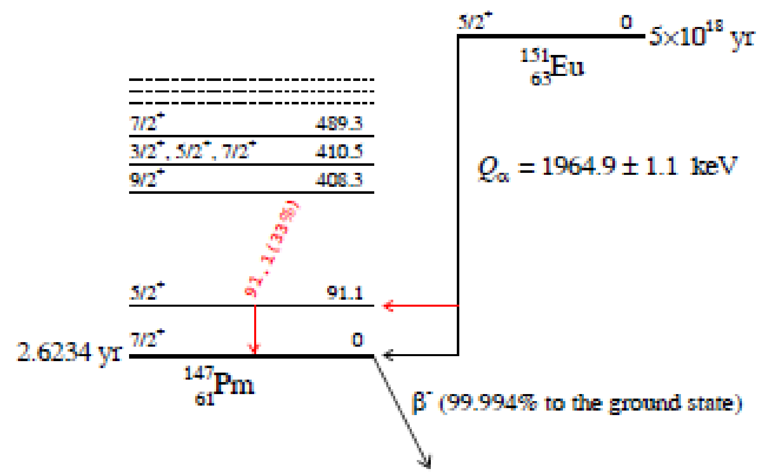
→ g.s.: α + recoil (3137 keV)
→ 204 keV: α + recoil (2933 keV) + γ (204 keV)
The same heat signals, but different light signals because scintillation from α is quenched, and from γ – not quenched
$T_{1/2}$ = (2.04±0.08)×10^{19} y
$T_{1/2}^*$ = (1.4±0.2)×10^{21} y

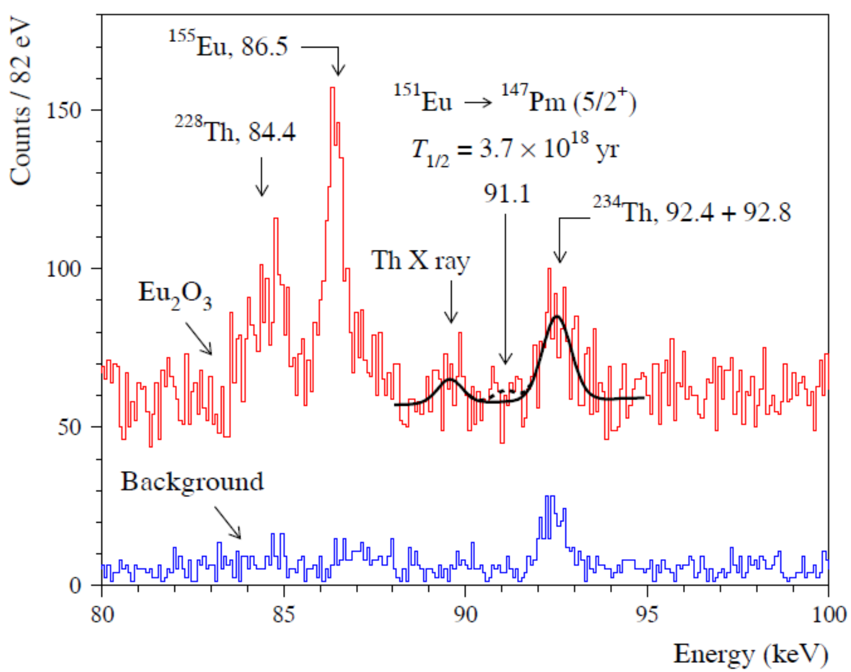
^{151}Eu → ^{147}Pm* (E_{exc}=91 keV) F.A. Danevich et al., EPJA 48(2012)157

G.s. to g.s. decay: $T_{1/2}$ ~ 5×10^{18} y

Decays to excited levels are also possible, the most probable to 1st level, E_{exc}=91 keV

HADES (500 m w.e.), high purity Eu_2O_3 303 g, 2233 h in low-background set-up with HPGe 40 cm^3





The effect is absent, only limit:
$T_{1/2}$ > 3.7×10^{18} y

~1 order of magnitude better than previous exp. limits

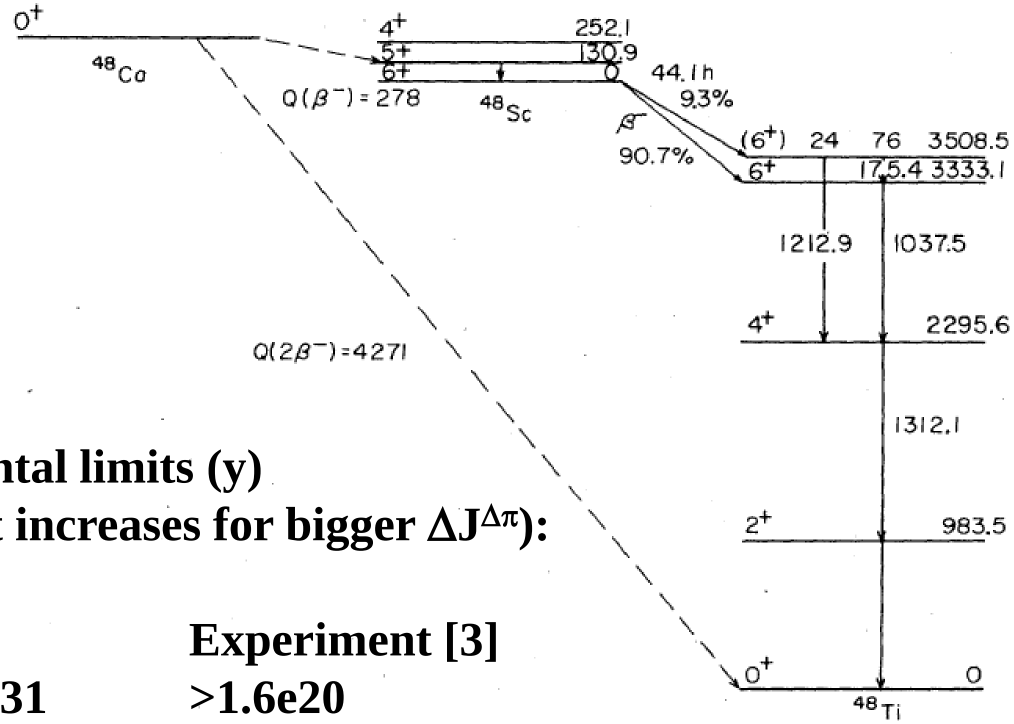
Not far from theor. estimates 10^{19}–10^{20} y

3. Investigations of rare β decays

^{48}Ca ^{50}V ^{96}Zr ^{113}Cd ^{115}In* ^{123}Te ^{180m}Ta ^{222}Rn

^{48}Ca

Q_β=282 keV



Could be populated:

ground state	$\Delta J^{\Delta\pi}=6^+$
level 131 keV	$\Delta J^{\Delta\pi}=5^+$
level 252 keV	$\Delta J^{\Delta\pi}=4^+$

$T_{1/2}$ - theoretical estimates and experimental limits (y)
($T_{1/2}$ decreases for bigger Q as ~$1/Q^5$, but increases for bigger $\Delta J^{\Delta\pi}$):

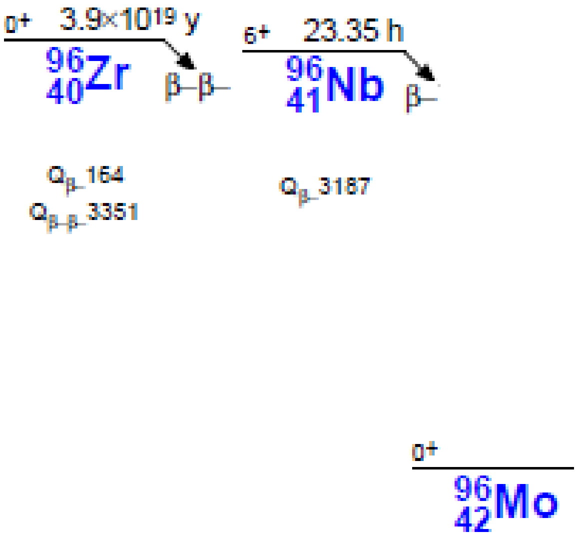
	Theory [1]	Theory [2]	Experiment [3]	
6^+(g.s.)	=4.0e25	=1.5e29-1.3e31	>1.6e20	
5^+(131)	=4.0e22	=$(1.1^{+0.8}_{-0.6})$e21	>2.5e20	the most probable
4^+(252)	=3.0e23	=8.8e23-5.2e26	>1.9e20	

[1] R.K. Bardin et al., NPA 158 (1970) 337
[2] M. Aunola et al., Europhys. Lett. 46 (1999) 577
[3] A. Bakalyarov et al., JETP Lett. 76 (2002) 545
(search for deexcitation γ's of ^{48}Sc, ^{48}Ti with Ge detector; however $\delta(^{48}$Ca$)=0.187\%$)

At the same time, ^{48}Ca can decay also through 2β decay to ^{48}Ti (2nd order process); already observed in few experiments: $T_{1/2}(2\beta2\nu$, g.s.) = 4.3e19 y.
Thus single β decay occurs even with lower probability than 2β decay - due to big ΔJ

^{96}Zr

Q_β=161 keV



Could be populated:

ground state	$\Delta J^{\Delta\pi}=6^+$
level 44 keV	$\Delta J^{\Delta\pi}=5^+$
level 146 keV	$\Delta J^{\Delta\pi}=4^+$

$T_{1/2}$ - theoretical estimates and experimental limits (y):

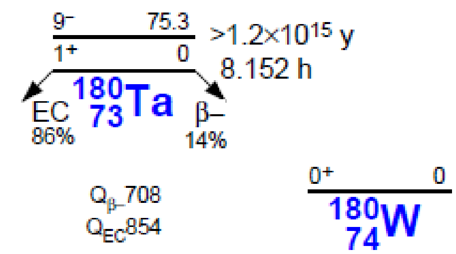
	Theory [1]	Experiment [2]	
6^+(g.s.)	=1.2e29	>3.8e19	
5^+(44)	=2.4e20	>3.8e19	the most probable
4^+(146)	=4.9e22	>3.8e19	

[1] H. Heiskanen et al., J. Phys. G 34 (2007) 837
[2] M. Arpesella et al., Europhys. Lett. 27 (1994) 29
(search for deexcitation γ's of ^{96}Mo with Ge detector; δ(^{96}Zr)=2.80% - much higher than that for ^{48}Ca; worth to remeasure with higher sensitivity?)

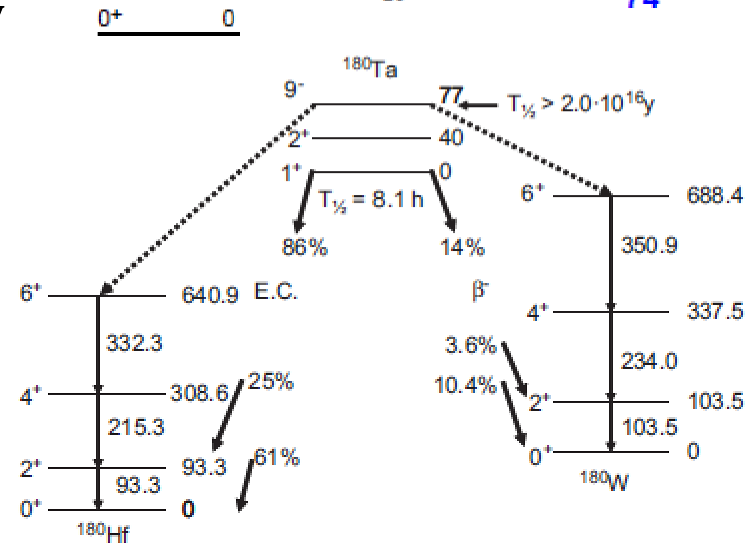
2β decay of ^{96}Zr to ^{96}Mo: $T_{1/2}$(2β2ν, g.s.) =(2.3±0.4)e19 y (NEMO-3'2008).
Geochemical 2β $T_{1/2}$: =(3.9±0.9)e19 Kawashima'1993 and =(0.9±0.3)e19 Wieser'2001.
Contribution of single β decay to geochemical $T_{1/2}$?

^{180m}Ta

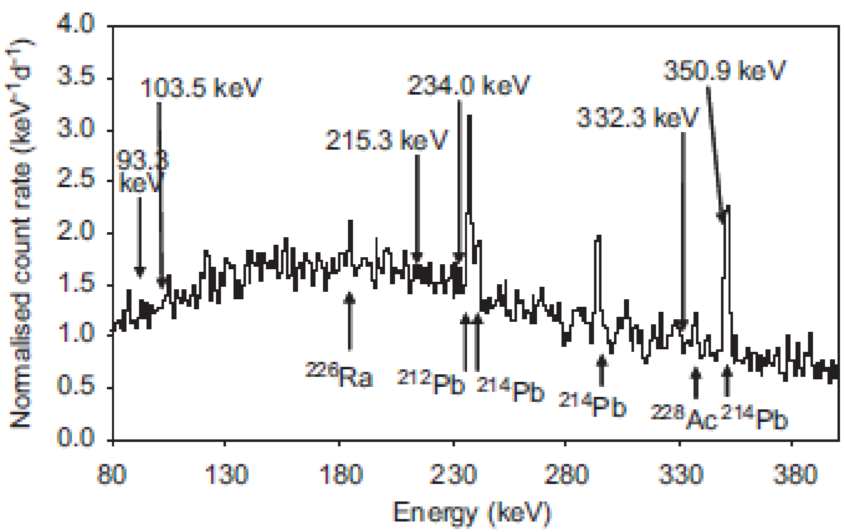
Extremely interesting case:
g.s. state quickly decays ($T_{1/2}$~8 h);
isomeric state (E_{exc}=77 keV) has very big $T_{1/2}$>2e16 y
$\delta(^{180m}$Ta)=0.012%



EC	**$\Delta J^{\Delta\pi}=3^-$**
β^-	**$\Delta J^{\Delta\pi}=3^-$**

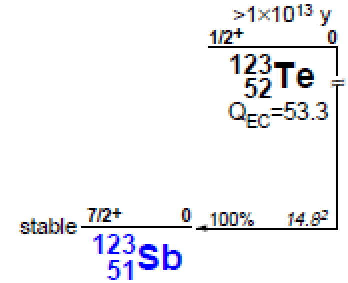


Last experimental search:
M. Hult et al., Appl. Rad. Isot. 67 (2009) 918
1500 g of natural Ta, sandwich HP Ge,
underground HADES laboratory (500 m w.e.), 68 d
$T_{1/2}$(EC) > 4.5e16 y
$T_{1/2}(\beta^-)$ > 3.7e16 y



Theoretical $T_{1/2}$ estimations:
IT > 1e27 y E.B. Norman, PRC 24(1981)2334
EC, β^- calculations are absent

^{123}Te **$\delta(^{123}$Te$)=0.89\%$**



Many puzzling experimental situations (only K EC was searched for):

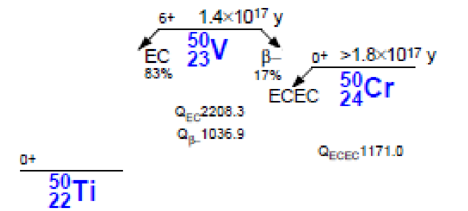
1. D.N. Watt et al., Philos. Mag. 7 (1962) 105
Detection of Sb X rays E_X=26.1 keV after EC with prop. counter, $T_{1/2}=(1.24\pm0.10)$e13 y
This result was present in all nuclear tables many years

2. A. Alessandrello et al., PRL 77 (1996) 3319
Four 340 g TeO_2 bolometers, underground measurements (LNGS, 3600 m w.e.), 1548 h
Peak at total energy release of 30.5 keV (E_K of Sb) is observed,
$T_{1/2}^K=(2.4\pm0.9)$e19 y - 6 orders of magnitude higher!
Result of Watt'1962 was explained by excitation of Te atoms by cosmic rays and nat. radioactivity that gives E_X=27.3 keV, and by not enough good resolution of prop. counter

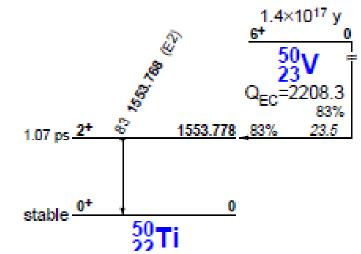
3. A. Alessandrello et al., PRC 67 (2003) 014323
Twenty 340 g TeO_2 bolometers, LNGS (3600 m w.e.), peak at 30.5 keV is not present,
$T_{1/2}^K>5.0$e19 y !

However, this peak appeared once more after all crystals were dismounted for surface cleaning at the sea level for ~2 months period and reinstalled underground.
Explanation of Alessandrello'1996: peak at 30.5 keV is due to EC of ^{121}Te (Q=1036 keV, $T_{1/2}$=16.78 d); ^{121}Te is produced by neutron capture on ^{120}Te (δ=0.09%) !

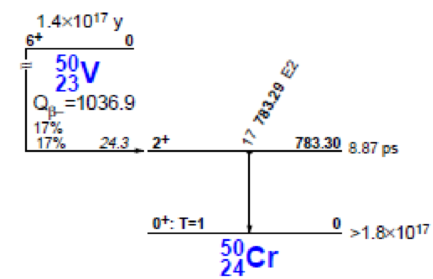
^{50}V δ=0.250%



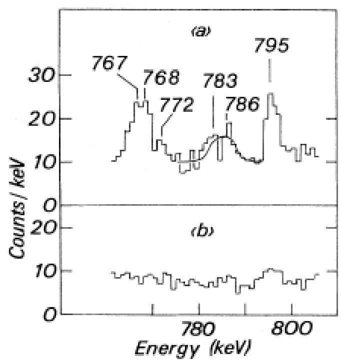
One of only 3 nuclei where β processes with $\Delta J^{\Delta\pi}=4^+$ were observed (other two are ^{113}Cd and ^{115}In)

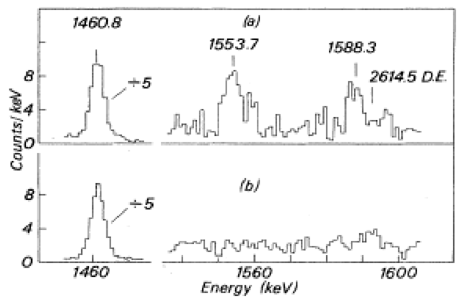


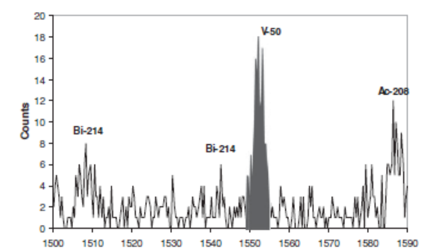
Low natural abundance (δ=0.250%), big $T_{1/2}$ (difficult to study)

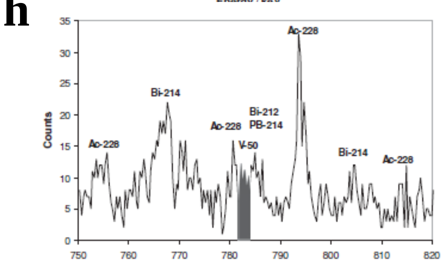


Experiment 1989: J.J. Simpson et al., PRC 39 (1989) 2367
3 Ge detectors, 337.5 g of natural V, salt mine, 1109 h
Search for γ's of 1554 keV (EC) and 783 keV (β^- decay)







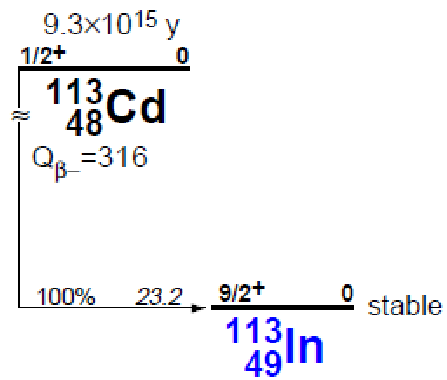


Experiment 2011: H. Dombrowski et al., PRC 83 (2011) 054322
Ge detector, 255.8 g of natural V, Asse salt mine (1200 m w.e.), 2347 h
Peak 783 keV is not observed:
$T_{1/2}$(EC)=(2.3±0.3)e17 y, $T_{1/2}$(β^-)>1.7e18 y

Only γ's are detected; $T_{1/2}$ is measured but not shape of β spectrum

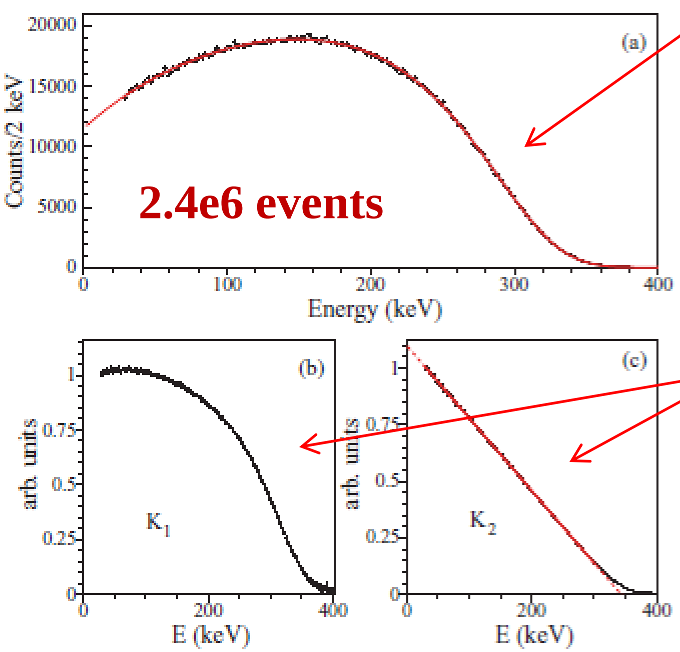
^{113}Cd δ=12.22%

$1/2^+ \rightarrow 9/2^+$ $\Delta J^{\Delta\pi} = 4^+$ classified as 4 FNU



Was searched for since 1940, first observed in 1970,
first measurement of β shape in 1988 with CdTe detector

One of the last experiments: P. Belli et al., PRC 76 (2007) 064603
$CdWO_4$ scintillator 434 g, LNGS (3600 m w.e.), 2758 h



Experimental spectrum (S/B ratio = 1/50) and its fit by:

$$f(E) = \int_0^{Q_\beta} \rho(E')R(E, E')dE' \qquad \rho(E) = wpF(E, Z)(Q_\beta - E)^2 \cdot C(w)$$

$$C(w) = p^6 + 7a_1 p^4 q^2 + 7a_2 p^2 q^4 + a_3 q^6 \qquad R(E, E') = \frac{1}{\sqrt{2\pi}\sigma(E')} \exp\left(-\frac{(E - E')^2}{2\sigma^2(E')}\right)$$

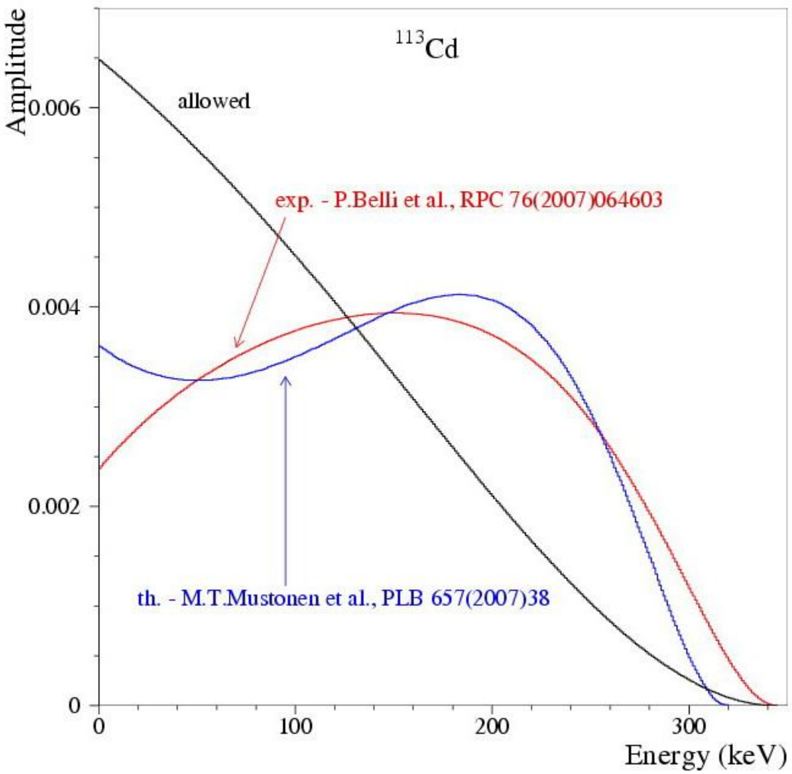
Kurie plots not accounting and accounting for correction factor C(w)

Big statistics, purity of crystal lead to determination of $T_{1/2}$ with small uncertainty:
$T_{1/2}$=(8.04±0.05)e15 y

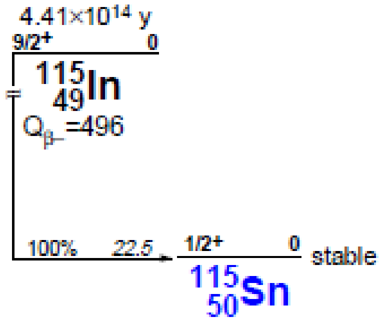
Experimental spectrum is excellently described as 3 FU ($\Delta J^{\Delta\pi} = 4^-$):
$C(E) = P^6+c_1P^4Q^2+c_2P^2Q^4+c_3Q^6$ with $c_1 = 7.112$, $c_2 = 10.493$, $c_3 = 3.034$
(small puzzle …)

Recent theoretical description as 4 FNU:
M.T. Mustonen et al., PRC 73 (2006) 054301 + PRC 76 (2007) 019901(E)
M.T. Mustonen et al., PLB 657 (2007) 38
(shape different from the experimental one)

Last experimental work:
J.V. Dawson et al., NPA 818 (2009) 264
16 CdZnTe detectors, LNGS, 6.58 kg×d
Confirmed $T_{1/2}$ and shape of spectrum,
but gave different Q_β value
(322 keV instead of 345 keV in Belli'2007)
(another small puzzle …)



^{115}In   δ=95.71%



$9/2^+ \rightarrow 1/2^+$ $\Delta J^{\Delta\pi} = 4^+$ classified as 4 FNU

On contrary to ^{113}Cd, spectrum shape was measured only in one work:
L. Pfeiffer et al., PRC 19 (1979) 1035

Liquid scintillator loaded by In at 51.2 g/l, measurements at the sea level

What could be improved:

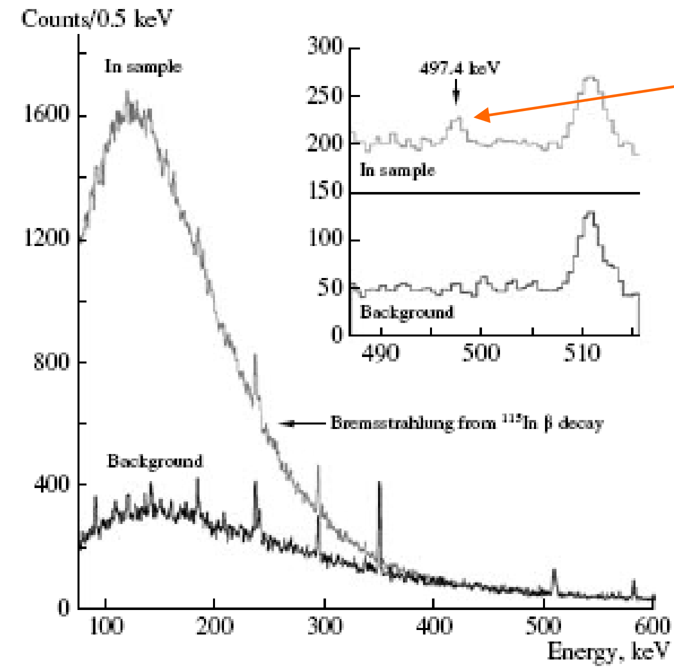
(1) Background, in particular n capture by ^{115}In (and ^{116}In is β^- unstable, Q=3275 keV)
(2) Strong quenching of low-energy electrons in liquid scintillator (was not discussed)
(3) Response function (resolution) “is not known and is not readily measurable”
(4) Q value was obtained as 492.7(13.6) keV and 470.6(5.2) keV; today value is 499(4) keV
(5) $T_{1/2}$=(4.41±0.24)e14 y (since 1979 – in all tables), but in some disagreement with previous results (f.e. G.B. Beard et al., PR 122 (1961) 1576: $T_{1/2}$=(6.9±1.5)e14 y)
(6) Energy threshold – around 50 keV
(7) Shape is described as polynomial in E

Remeasuring in low background conditions would be very interesting!

Recent theoretical description as 4 FNU:
M.T. Mustonen et al., PRC 73 (2006) 054301 + PRC 76 (2007) 019901(E)
M.T. Mustonen et al., PLB 657 (2007) 38

$^{115}In \rightarrow {}^{115}Sn^*$

First observation of β decay of ^{115}In to the first excited level (E_{exc}=497.4 keV) of ^{115}Sn:
C.M. Cattadori et al., NPA 748 (2005) 333 + Phys. At. Nucl. 70 (2007) 127
LNGS, ~1 kg In, 4 HP Ge detectors 225 cm^3 each, 2762 h In + 1601 h background



De-excitation γ's give peak at 497.4 keV (observation with 4σ's), (1.18±0.31)e-6 yield, $T_{1/2}$=(3.7±1.0)e20 y

Situation in 2005:
Implications for neutrino mass:
ΔM_a = 499±4 keV (Audi et al., 2003)
$Q_\beta^* = \Delta M_a - E_{exc}$ = 1.6±4 keV
our calculation: Q_β^* = 460 eV
(possibly the lowest known measured Q_β value)

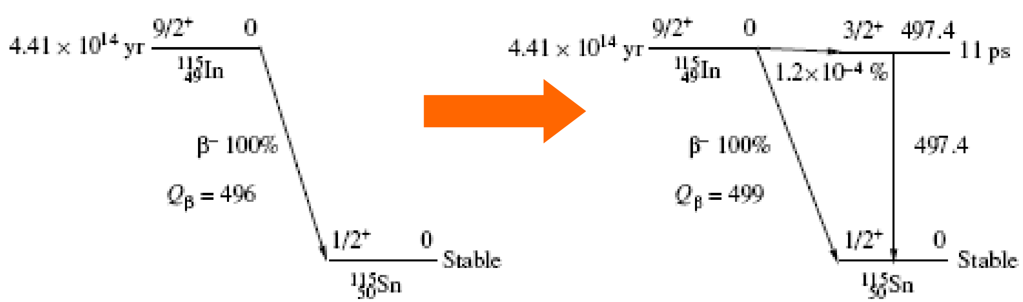


Fig. 2. Old (*a*) and new (*b*) schemes of ^{115}In → ^{115}Sn β decay (energy in keV).

Evidently: $m_\nu < Q_\beta$
Could be Q_β~1 eV?

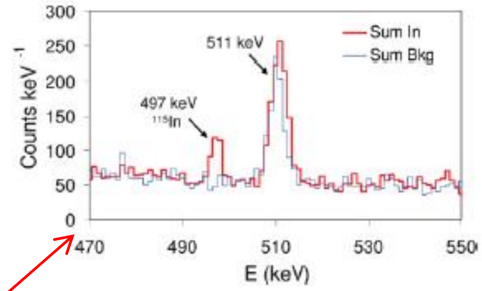
Need to re-measure ΔM_a (^{115}In-^{115}Sn, δ=4 keV) and E_{exc} (δ=22 eV) with greater accuracy

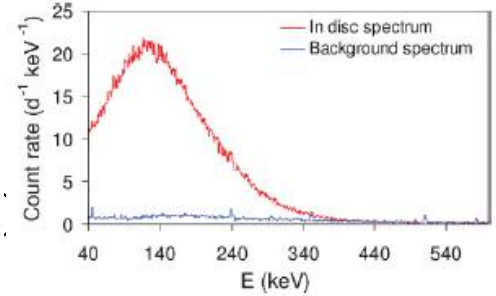
E.G. Myers, Florida St. Un.:
M_a with δ~10 eV for A=100

Subsequent events:

1. Confirmation of observation of $^{115}In \rightarrow {}^{115}Sn^*$ decay

HADES underground laboratory (500 m w.e.), 2566 g of In, 3 Ge:
$T_{1/2}$=(4.1±0.6)e20 y (E. Wieslander et al., PRL 103(2009)122501)
$T_{1/2}$=(4.3±0.5)e20 y (E. Andreotti et al., PRC 84(2011)044605)





2. New measurements of difference Δ of ^{115}In–^{115}Sn masses

Δ= 497.680±0.170 keV (E. Wieslander et al., PRL 103(2009)122501
Δ= 497.489±0.010 keV (B.J. Mount et al., PRL 103(2009)122502)
Thus, Q* value is: $Q^* = \Delta - E_{exc}$ = (497.334±0.022)–(497.489±0.010) = 155±24 eV

Really the lowest Q value of a known β decay (^{163}Ho – 2.555 keV, ^{187}Re – 2.469 keV) (and highest (partial) $T_{1/2}$)
Paradoxical situation: masses of the nuclei (~100 GeV) are known with precision 10 eV while E_{exc} (~500 keV) – with precision 22 eV (needs to be remeasured)

3. Influence of different chemical environment on $T_{1/2}$ (In, $InCl_3$, etc.). If to use dependence $T_{1/2} \sim 1/Q^5$ and change Q on 1 eV only, we will obtain $(155/154)^5$=1.03 – 3% change in $T_{1/2}$. Difficult but maybe possible to see (current accuracy – 12%).

4. Deviations from theoretical spectrum due to non-zero ν mass? Theoretical spectrum ($\Delta J^{\Delta\pi} = 3^+$ – classified as 2 FU) was calculated in R. Dvornicky, F. Simkovic, AIP Conf. Proc. 1417(2011)33. Very difficult experimentally.

BaF_2 scintillator, 1.714 kg, LNGS (3600 m w.e.), 101 h.
High contamination by ^{226}Ra – 7.8 Bq/kg.

In all nuclear tables, ^{222}Rn (in chain of ^{238}U) is 100% α decaying. Usual chain:

$$^{222}_{86}\mathrm{Rn} \xrightarrow[5590\ \mathrm{keV}]{\alpha\quad 3.82\ \mathrm{d}} {}^{218}_{84}\mathrm{Po} \xrightarrow[6115\ \mathrm{keV}]{\alpha\quad 3.10\ \mathrm{m}} {}^{214}_{82}\mathrm{Pb} \xrightarrow[1024\ \mathrm{keV}]{\beta\quad 26.8\ \mathrm{m}} {}^{214}_{83}\mathrm{Bi} \xrightarrow[3272\ \mathrm{keV}]{\beta\quad 19.9\ \mathrm{m}}$$
$$^{214}_{84}\mathrm{Po} \xrightarrow[7833\ \mathrm{keV}]{\alpha\quad 164.3\ \mu\mathrm{s}} {}^{210}_{82}\mathrm{Pb}\ (22.3\ \mathrm{y}).$$

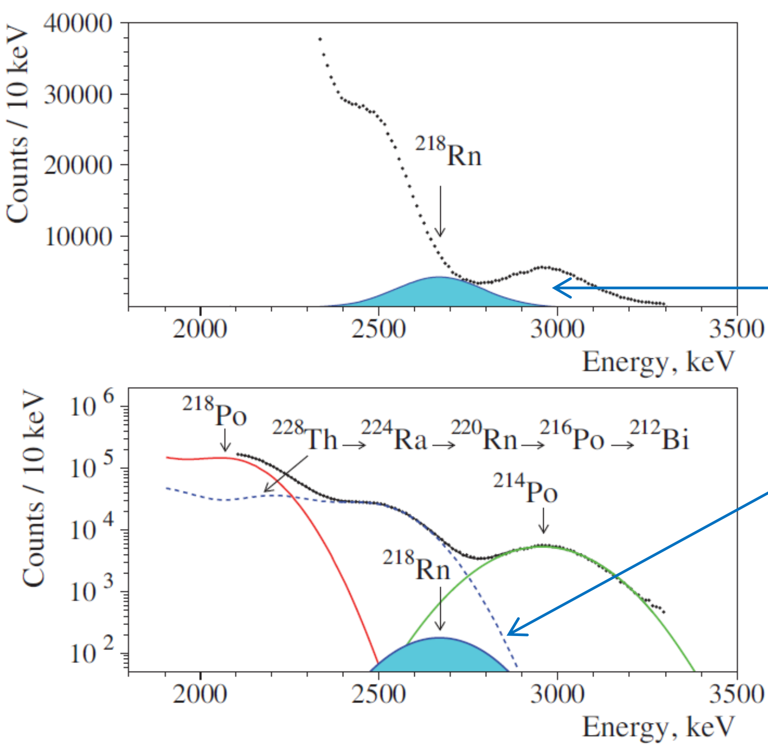
However, β decay of ^{222}Rn also is energetically allowed with Q=24±21 keV. In this case:

$$^{222}_{86}\mathrm{Rn} \xrightarrow[24\ \mathrm{keV}]{\beta?\quad \simeq 4.8\times10^{5}\ \mathrm{y}} {}^{222}_{87}\mathrm{Fr} \xrightarrow[2028\ \mathrm{keV}]{\beta\quad 14.2\ \mathrm{m}} {}^{222}_{88}\mathrm{Ra} \xrightarrow[6679\ \mathrm{keV}]{\alpha\quad 38.0\ \mathrm{s}} {}^{218}_{86}\mathrm{Rn} \xrightarrow[7263\ \mathrm{keV}]{\alpha\quad 35\ \mathrm{ms}}$$
$$^{214}_{84}\mathrm{Po} \xrightarrow[7833\ \mathrm{keV}]{\alpha\quad 164.3\ \mu\mathrm{s}} {}^{210}_{82}\mathrm{Pb}\ (22.3\ \mathrm{y}).$$

$^{222}Rn(0^+) \rightarrow {}^{222}Fr(2^-)$, $\Delta J^{\Delta\pi}=2^-$; $T_{1/2}$ can be estimated using average (for 216 known 1 FU β decays) log ft = 9.5 and LOGFT tool at NNDC as $T_{1/2}$ = 4.8×10^5 y (for Q=24 keV; 6.7×10^4 y for Q=45 keV and 2.4×10^8 y for Q=3 keV).

Expected E and Δt are known, and it is possible to distinguish between α and β events in BaF_2 scintillator because of difference in their time shapes.

The following sequence of events was searched for ($^{222}Fr \rightarrow {}^{222}Ra \rightarrow {}^{218}Rn \rightarrow {}^{214}Po$):
(1) event at 30 – 2207 keV (^{222}Fr Q_β + $FWHM_\beta$) and with β time shape;
(2) next event at 2109 – 2623 keV (^{222}Ra E_α + $FWHM_\alpha$ in γ scale), with α time shape and in time interval [1.65 ms, 1.65 ms + 5×38.0 s];
(3) last event at 2398 – 2946 keV (^{218}Rn E_α + $FWHM_\alpha$ in γ scale), with α time shape and in time interval [1.65 ms, 1.65 ms + 5×35 ms].



7.0×10^5 selected potential ^{218}Rn events.

Maximal effect consistent with exp. data, $T_{1/2}^{\beta}$ > 122 d (too conservative limit)

Limit from fit by model (known α peaks from contamination), $T_{1/2}^{\beta}$ > 8.0 y.

4. Observation of emission of e^+e^- pairs in α decay of ^{241}Am

R. Bernabei et al., EPJA 49 (2013) 64

β decay - internal bremsstrahlung (IB) and internal pair production (IPP) are known effects

α decay - IB is known; what about IPP?

In fact, it was observed previously in 3 experiments (1973, 1986, 1990):

Source	Experiment				Theory		
	λ ($\times 10^{-9}$)	Detectors	Year	Ref.	λ ($\times 10^{-9}$)	Year	Ref.
^{210}Po	5.3 ± 1.7	NaI(Tl)+Ge(Li)	1986	[10]	4.4	1978	[6]
^{239}Pu	7 ± 9	NaI(Tl)+Ge(Li)	1986	[10]	2.2	1978	[6]
^{241}Am	3.1 ± 0.6	NaI(Tl)+Ge(Li)	1973	[2]	1.2	1973	[2]
	2.15 ± 0.25	NaI(Tl)+Ge(Li)	1986	[10]	2.3	1978	[6]
	$1.8 \pm 0.7^{(a)}$	Plastics+Ge	1990	[16]			
	4.70 ± 0.63	NaI(Tl) pairs	2013	This work			

$$\lambda = \frac{A_{e^+e^-}}{A_\alpha}$$

[2] A. Ljubicic, B.A. Logan, Phys. Rev. C 7 (1973) 1541
[6] K. Pisk et al., Phys. Rev. C 17 (1978) 739
[10] J. Stanicek et al., Nucl. Instrum. Meth. B 17 (1986) 462
[16] T. Asanuma et al., Phys. Lett. B 237 (1990) 588

Theory, which describes the effect as creation of bremsstrahlung γ during α acceleration with E_γ > 1.022 MeV which borns e^+e^-, gives λ value of a correct order of magnitude.

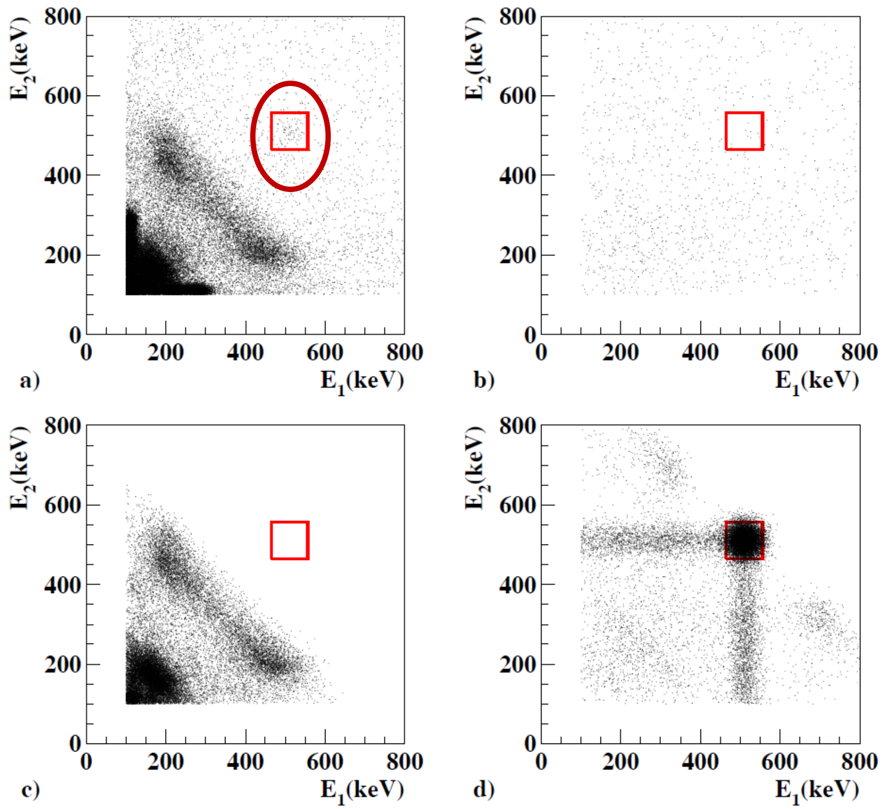
In the DAMA experiment [R. Bernabei et al., Int. J. Mod. Phys. A 28 (2013) 1330022], ^{241}Am sources are used for weekly calibrations. So, an idea appeared to check the old α-IPP results, at the first time deep underground (avoiding influence of cosmic rays) and in low-background high-pure set-up (suppressing presence of β^+ contaminations).

DAMA/LIBRA: 25 NaI(Tl) scintilaltors, 9.70 kg each, 10.2×10.2×25.4 cm.

1st run: 6 ^{241}Am sources and 6 NaI(Tl) pairs (all other NaI(Tl)'s – as anticoincidence); 1.29 d with ^{241}Am and 24.6 d background; total ^{241}Am activity 200.8 kBq; result: excess rate of double coincidences in 465-557 keV ($\pm 2\sigma$ region) s = 4.87±0.87 counts/d/NaI(Tl)pair

2nd run: 3 ^{241}Am sources and 3 NaI(Tl) pairs, 2.63 d (^{241}Am) + 24.6 d (bkg), 98.9 kBq, s = 5.23±0.90 counts/d/NaI(Tl)pair

Exp. spectrum with ^{241}Am



Exp. background

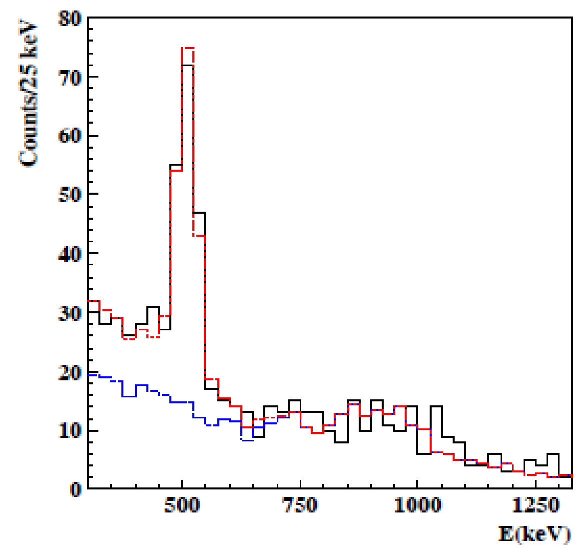
Simulated ^{241}Am decay

Simulated e^+ annihilation

Analysis of data: presence of ^{243}Am, ^{233}Pa, ^{154}Eu

Spectrum of one NaI(Tl) when energy of second is 465-557 keV

S=220±30 counts
$\lambda=(4.70\pm0.63)\times10^{-9}$



Many possible mimicking contributions were analyzed and excluded:

- **β^+ emitters in chain ^{241}Am $\rightarrow$ … $\rightarrow$ ^{209}Bi;**
- **high energy γ rays in chain ^{241}Am $\rightarrow$ … $\rightarrow$ ^{209}Bi;**
- **α decays of ^{241}Am to high energy levels of ^{237}Np;**
- **(α,n) and (α,p) reactions on isotopes of C, N, O, Cu in surrounding materials which lead to creation of β^+ emitters;**
- **(α,nγ) and (α,γ) reactions leading to high energy γ's;**
- **^{241}Am fission and cluster decays.**

The observed excess cannot be explained by any side process.

It would be interesting to repeat such studies with HPGe detectors with high energy resolution.

5. Conclusions

There was a little interest in investigations of rare α and β decays since ~1970's – no $T_{1/2}$ were measured with higher precision, no shapes of β spectra.

However, development of experimental technique lead to improvement in sensitivity, and new decays were observed with extreme characteristics (α with longest $T_{1/2}$ of 10^{19} y for ^{209}Bi; β with lowest Q of 155 eV for $^{115}In^*$; …). Traditional (HPGe, NaI(Tl),…) but also new types of detectors ($Li_6Eu(BO_3)_3$,…) are used in these investigations.

Interest to β shapes also is growing, in particular for nuclides which create background in rare events' searches.

Many theoretical works also appeared last time (especially in α decay: tens of articles per year).

It could be concluded that investigations of rare β and α decays experience revival now.

Thank you for attention!