Search for rare nuclear decays with HPGe detectors at LNGS STELLA facility

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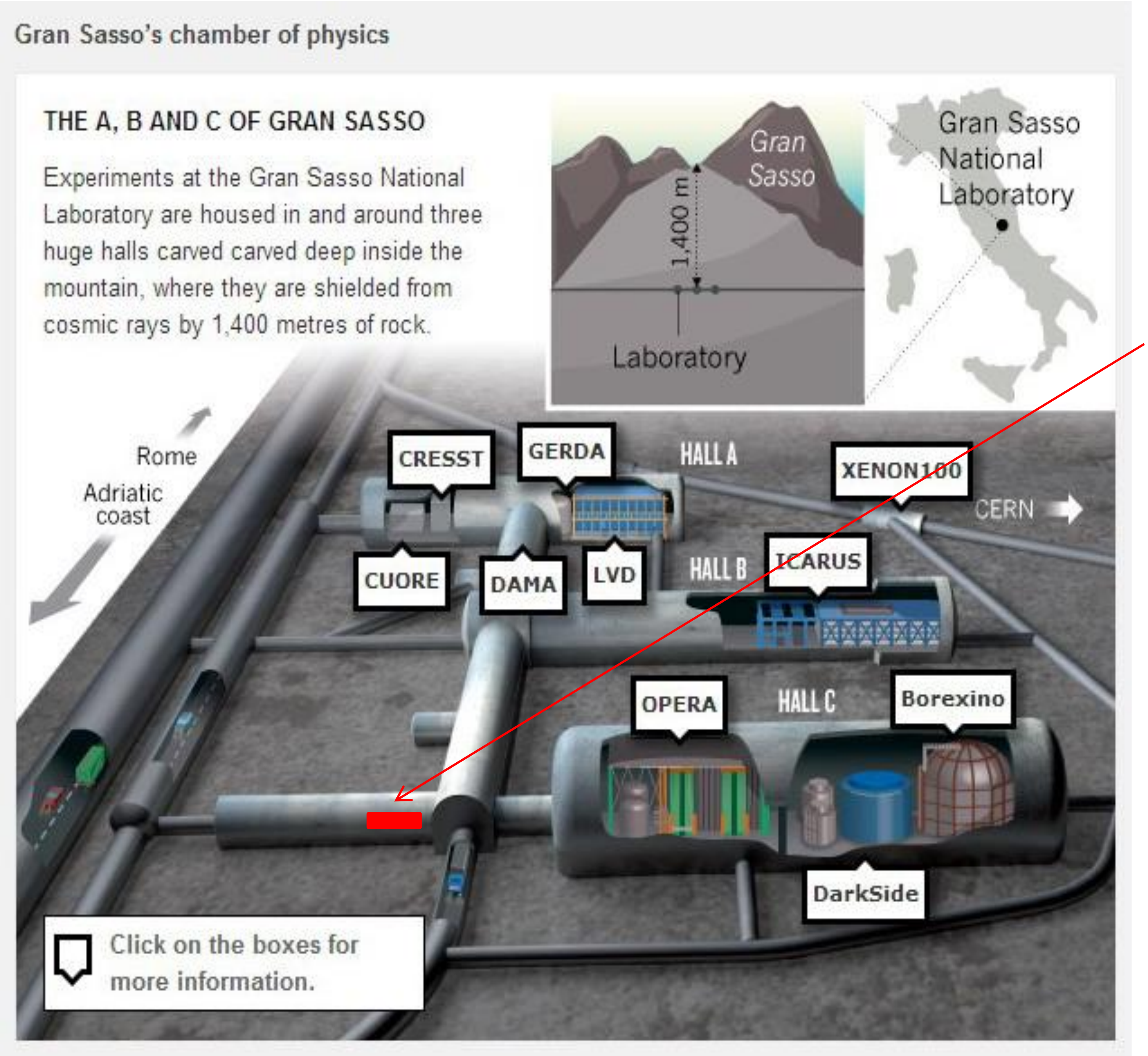


Laboratory Nazionali del Gran Sasso (Italy) – 1400 m underground – 3600 m w.e.

STELLA – SubTErranean Low Level Assay – facilities for ultra low background α and γ spectroscopy

3600 m w.e.
Massive passive shielding from selected materials (Cu, low radioactive Pb, Cd, polyethylene), flushing by Rn-free N_2 gas

http://www.nature.com/news/gran-sasso-s-chamber-of-physics-7.4635?article=1.10696

In 2006 – 2012: ~ 150 – 470 γ spectroscopy measurements per year

Details in: M. Laubenstein et al., Appl. Radiat. Isotopes 61 (2004) 167

M. Laubenstein, report at ASPERA meeting, Durham, UK, 17-19.12.2012

Summary of small-scale DAMA-KINR experiments in fundamental physics in 2011-2013 with the STELLA facility:

Search for 2β processes

^{96,104}Ru	- best $T_{1/2}$ limits	PRC 87 (2013) 034607
^{184,192}Os	- first searches	EPJA 49 (2013) 24
^{156,158}Dy	- first searches	NPA 859 (2011) 126
^{190,198}Pt	- first searches	EPJA 47 (2011) 91

Search for resonant absorption of hadronic solar ^{7}Li axion in LiF crystal

$m_a < 8.6$ keV	- best for ^{7}Li axion	PLB 711 (2012) 41

Search for α decay $^{190}Pt \rightarrow {}^{186}Os^{*}$ (137.2 keV)

$T_{1/2} = 2.6\times10^{14}$ yr	- first observation	PRC 83 (2011) 034603

2β of ^{96,104}Ru – P. Belli et al., Phys. Rev. C 87 (2013) 034607

^{96}Ru: δ=5.54%, $Q_{2\beta}$=2714.51±0.13 keV, $2\varepsilon+\varepsilon\beta^++2\beta^+$ (1 of 6 $2\beta^+$ decayers)

not a good candidate for r-2ε0ν after recent precise $Q_{2\beta}$ measurement

(S. Eliseev et al., PRC 83 (2011) 038501)

^{104}Ru: δ=18.62%, $Q_{2\beta}$=1301.2±2.7 keV, $2\beta^-$

Previous experiments (all – with natural Ru):

1. E.B. Norman, PRC 31 (1985) 1937 – Earth level, HPGe 2×110 cm^3, Ru 50 g, t = 178 h: $T_{1/2} > \sim 10^{16}$ yr
2. Our preliminary measurements, P. Belli et al., EPJA 42 (2009) 171 – LNGS, HPGe 468 cm^3, 473 g, 158 h: 10^{18}–10^{19} yr. However, ^{40}K – ~3.4 Bq/kg + cosmogenic ^{106}Ru (511 keV)
3. E. Andreotti et al., ARI 70 (2012) 1985 – HADES 500 mwe, HPGe 395+325 cm^3, 149 g, 2592 h: ~10^{19} yr
4. Present results – LNGS 3600 mwe, HPGe 4×225 cm^3 (in one cryostat), 720 g, 5479 h: $T_{1/2} > \sim 10^{20}$ yr

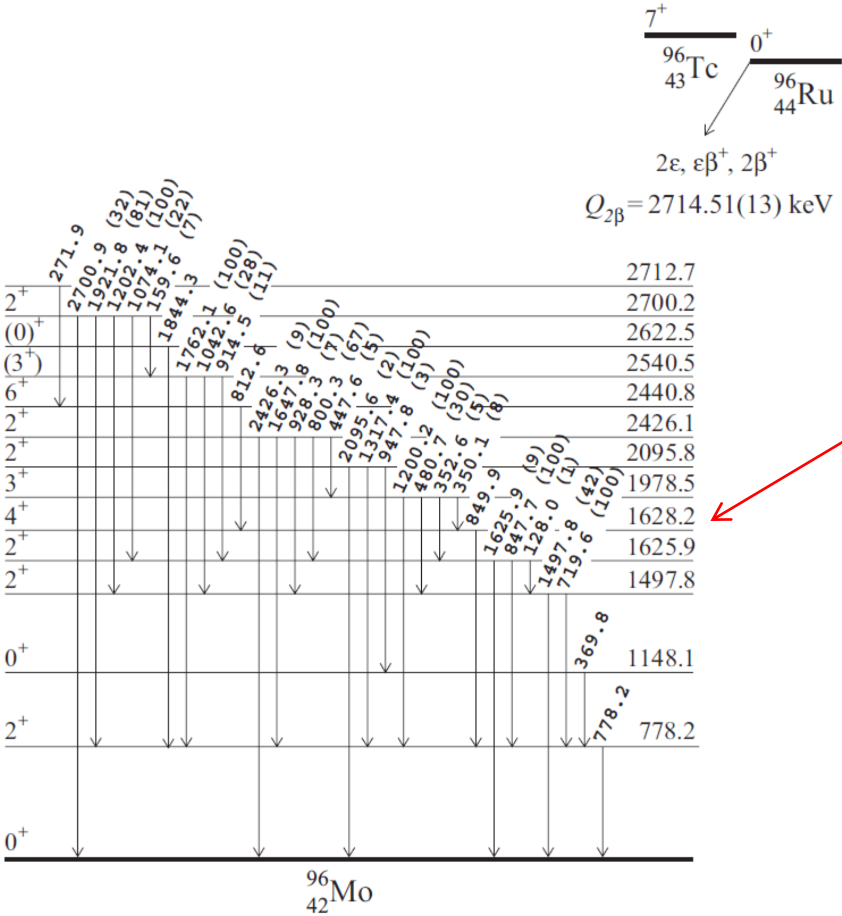
Purification by the electron beam melting:

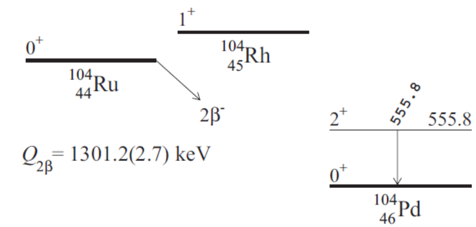
^{40}K 3400 → 150 mBq/kg

Decay of ^{106}Ru ($T_{1/2}$ = 374 d):

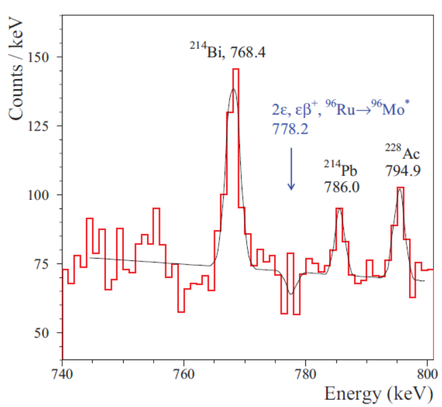
^{106}Ru 24 → 5 mBq/kg

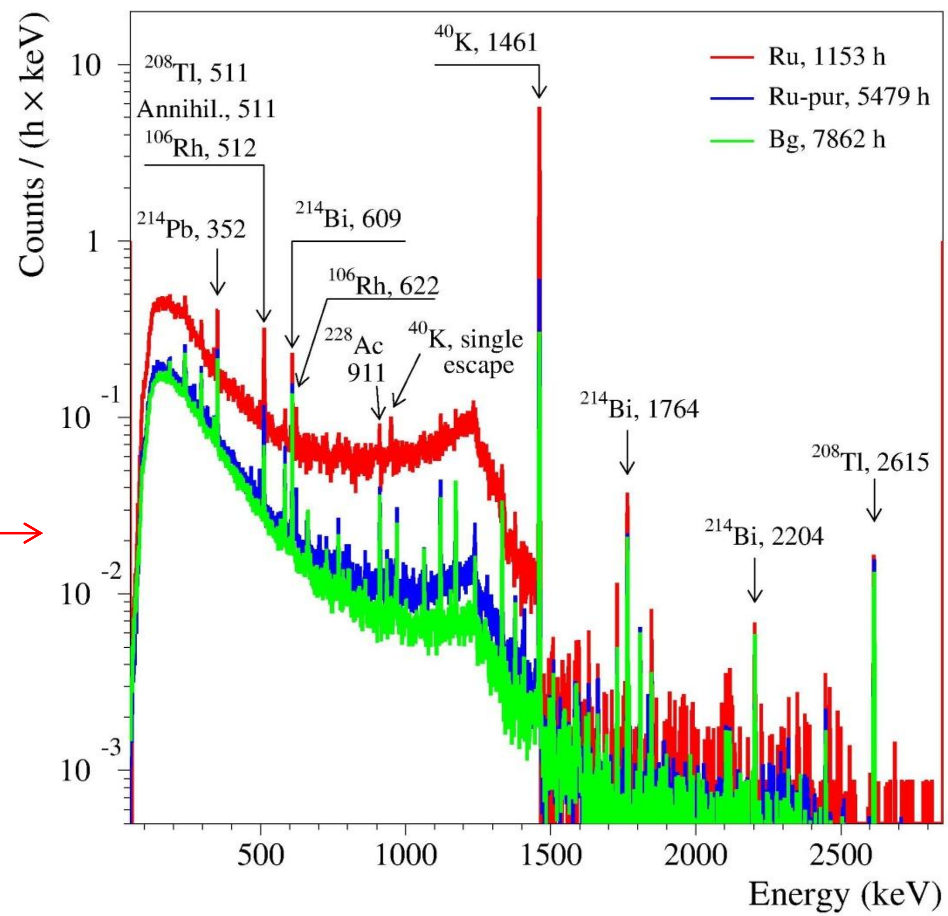
Decay schemes of ^{96}Ru and ^{104}Ru





Results of measurements, 5479 h





Process of decay	Decay mode	Level of daughter nucleus, E, keV	E_γ, keV	$T_{1/2}$, yr (preliminary)	
				HADES'2012	Present work
^{96}Ru → ^{96}Mo					
$2\beta^+$	0ν + 2ν	g.s.	511	$>5.0\times10^{19}$	$>1.3\times10^{20}$
$\varepsilon\beta^+$	0ν	g.s.	511	$>5.5\times10^{19}$	$>7.7\times10^{19}$
	2ν	g.s.	511	$>5.5\times10^{19}$	$>8.0\times10^{19}$
	0ν +2ν	2^+ 778	778	$>2.7\times10^{19}$	$>2.3\times10^{20}$
	0ν+2ν	0^+ 1148	778	$>1.8\times10^{19}$	$>2.1\times10^{20}$
2K	0ν	g.s.	2675	$>5.4\times10^{19}$	$>1.0\times10^{21}$
KL	0ν	g.s.	2692	$>6.9\times10^{19}$	$>2.3\times10^{20}$
2L	0ν	g.s.	2709	$>6.9\times10^{19}$	$>2.3\times10^{20}$
2ε	2ν	2^+ 778	778	$>6.5\times10^{19}$	$>2.6\times10^{20}$
		0^+ 1148	778	$>4.2\times10^{19}$	$>2.5\times10^{20}$
		2^+ 1498	778	$>3.0\times10^{19}$	$>1.7\times10^{20}$
		2^+ 1626	848	$>3.9\times10^{19}$	$>3.6\times10^{20}$
	0ν	2^+ 778	778	$>6.4\times10^{19}$	$>2.4\times10^{20}$
		0^+ 1148	778	$>4.1\times10^{19}$	$>2.3\times10^{20}$
		2^+ 1498	778	$>2.9\times10^{19}$	$>1.6\times10^{20}$
		2^+ 1626	848	$>3.8\times10^{19}$	$>3.3\times10^{20}$
Resonant KL	0ν+2ν	2700	1922	$>2.7\times10^{19}$	$>2.0\times10^{20}$
Resonant 2L	0ν+2ν	2713	813	$>2.0\times10^{19}$	$>3.6\times10^{20}$
^{104}Ru→^{104}Pd					
$2\beta^-$	0ν + 2ν	2^+ 556	556	$>1.9\times10^{20}$	$>6.5\times10^{20}$

2β of $^{184,192}Os$ – P. Belli et al., Eur. Phys. J. A 49 (2013) 24

Natural Os 173 g, purity grade >99.999% (purified in Kharkiv Institute of Physics and Technology; probably the most pure Os in the world)

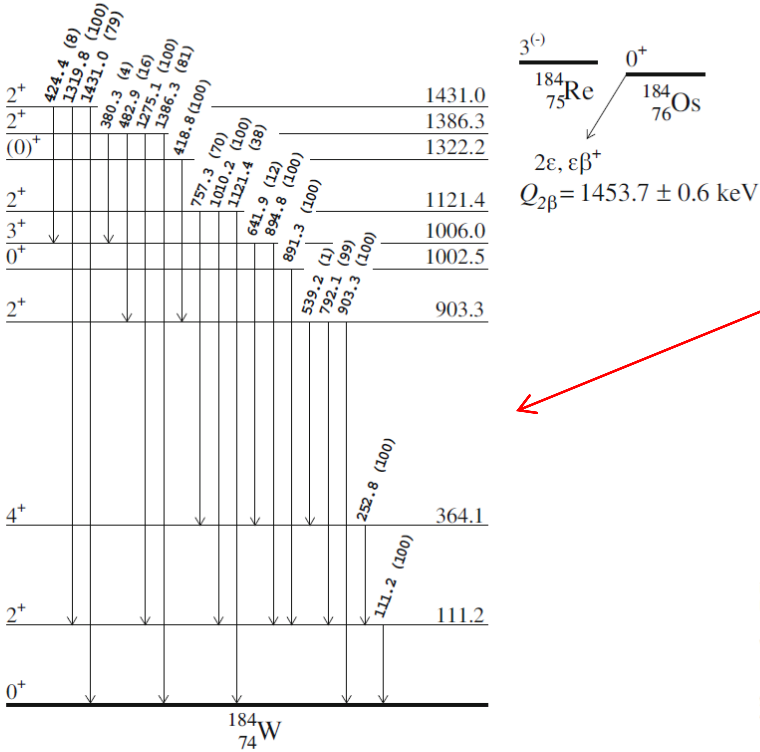
^{184}Os: δ=0.02%, $Q_{2\beta}$=1453.68±0.58 keV, $2\varepsilon+\varepsilon\beta^+$
not a good candidate for r-$2\varepsilon0\nu$ after recent precise $Q_{2\beta}$ measurement
(C. Smorra et al., PRC 86 (2012) 044604)
^{192}Os: δ=40.78%, $Q_{2\beta}$=412.4±2.9 keV, $2\beta^-$

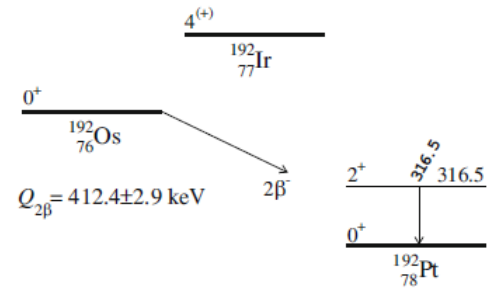
Very poor to-date $T_{1/2}$ limits (10^{10}–10^{13} yr, extracted from old experiment with photoemulsions [J.H. Fremlin et al., Proc. Phys. Soc. A 65 (1952) 911])

Measurements: HPGe 468 cm^3, 2741 h

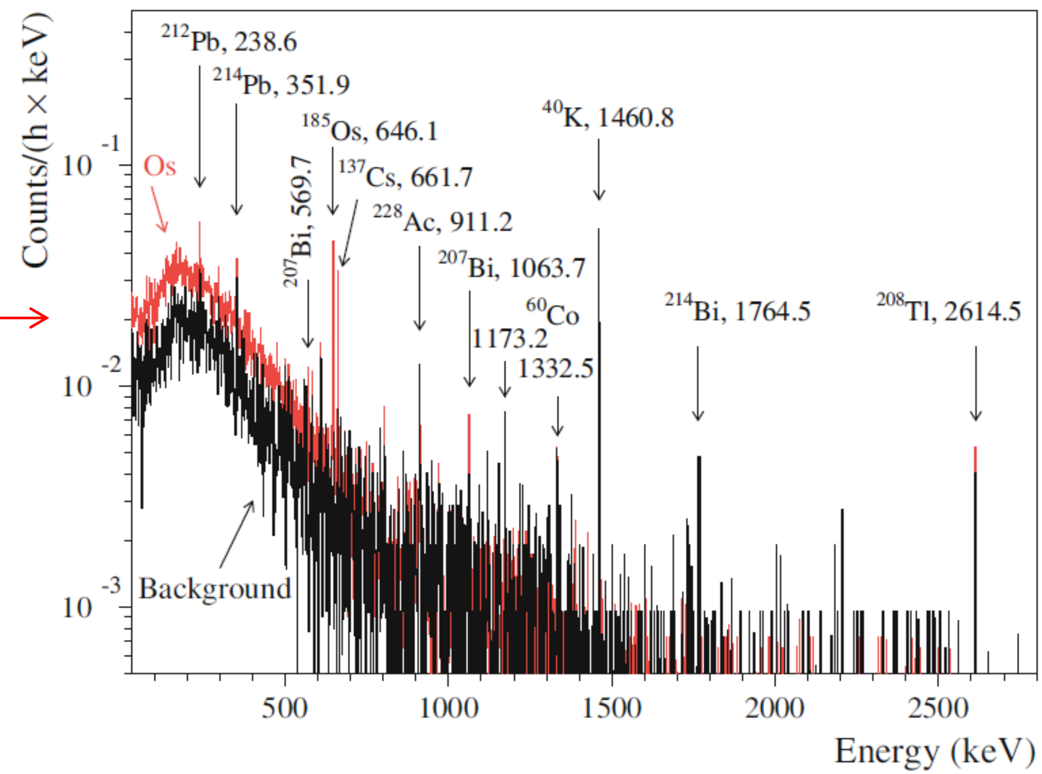
Practically no excess in comparison with background; some presence of cosmogenic ^{185}Os ($T_{1/2}$=93.6 d, 3 mBq/kg), ^{137}Cs (2 mBq/kg), ^{207}Bi (0.4 mBq/kg).

Decay schemes of ^{184}Os and ^{192}Os





Results of measurements, 2741 h



^{184}Os: $T_{1/2} > \sim 10^{16} - 10^{17}$ yr (due to low δ=0.02%)

^{192}Os: $T_{1/2} > 5.3\times10^{19}$ yr

2β of ^{156,158}Dy – P. Belli et al., Nucl. Phys. A 859 (2011) 126

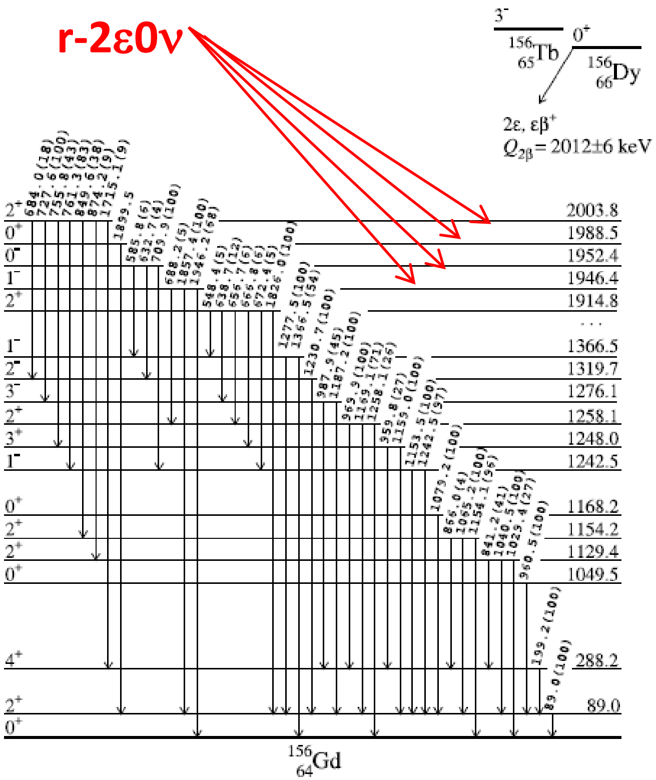
Dy_2O_3 322 g, 99.98% purity grade, HPGe 244 cm^3, 2512 h

^{156}Dy: δ=0.056%, $Q_{2\beta}$=2005.95±0.10 keV, $2\varepsilon+\varepsilon\beta^+$ **r-$2\varepsilon0\nu$ is possible**
^{158}Dy: δ=0.095%, $Q_{2\beta}$=282.7±2.5 keV, 2ε **r-$2\varepsilon0\nu$ is possible**

One more aim for Penning trap

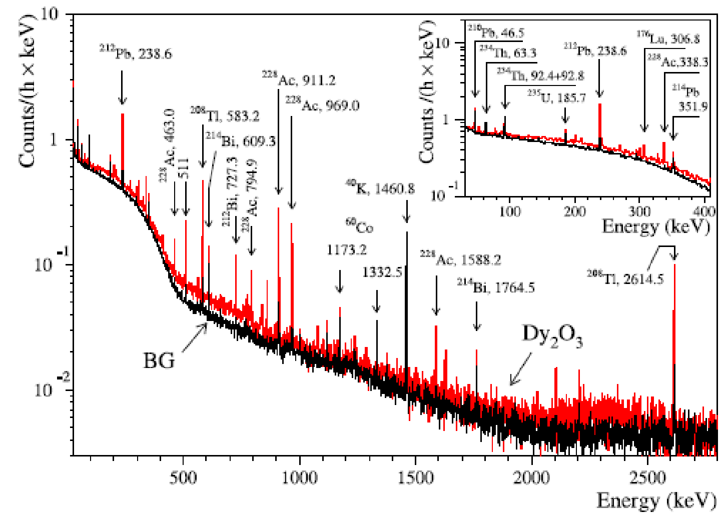
First search for 2β in Dy

r-$2\varepsilon0\nu$



Few levels could be populated in r-$2\varepsilon0\nu$:

E_{exc}=1946 – 1⁻: $T_{1/2} > 9.6\times10^{15}$ yr
E_{exc}=1952 – 0⁻: $T_{1/2} > 2.6\times10^{16}$ yr
E_{exc}=1989 – 0⁺: $T_{1/2} > 2.6\times10^{16}$ yr
E_{exc}=2004 – 2⁺: $T_{1/2} > 2.6\times10^{16}$ yr



Limits for other possible 2β processes in ^{156}Dy and ^{158}Dy: $T_{1/2} > 1.8\times10^{14}$–$7.1\times10^{16}$ yr.
Slight pollution by U/Th and ^{176}Lu (9 mBq/kg).
By-product: limits for α decays of ^{156,158,160,161,162}Dy to ^{152,154,156,157,158}Gd*: $T_{1/2} > 10^{16}$–10^{17} yr.

2β of ^{190}Pt, ^{198}Pt – P. Belli et al., Eur. Phys. J. A 47 (2011) 91

Pt 42.5 g, HP Ge 468 cm^3, 1815 h

One more aim for Penning trap

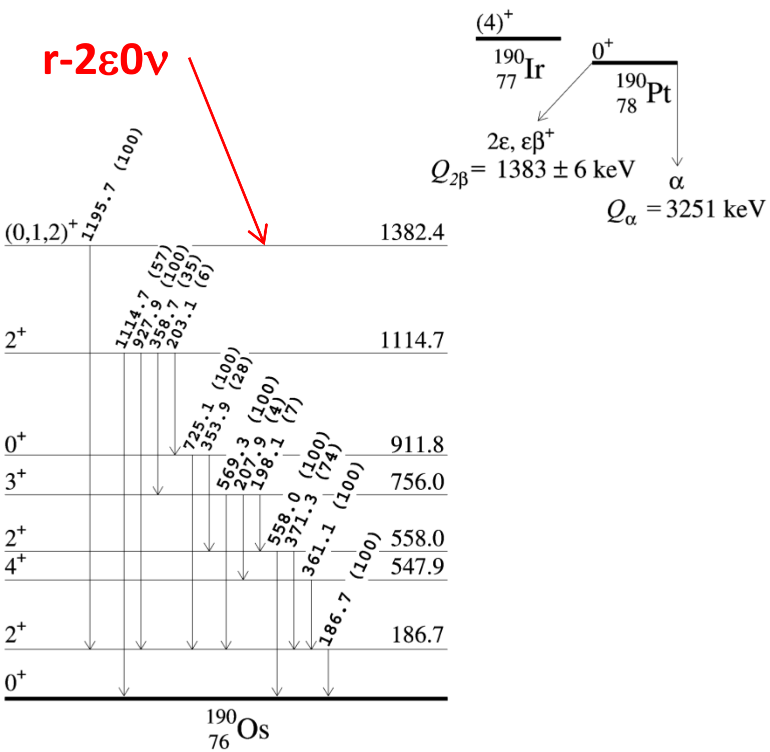
^{190}Pt: δ=0.014%, $Q_{2\beta}$=1384±6 keV, 2ε+εβ$^+$ r-2ε0ν is possible

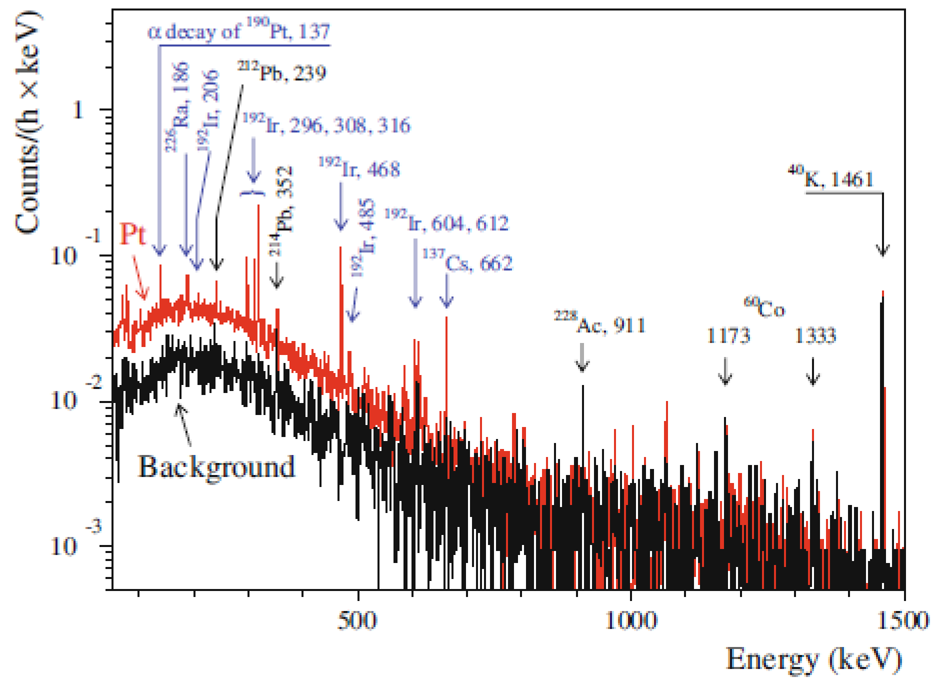
^{198}Pt: δ=7.163%, $Q_{2\beta}$=1049.2±2.1 keV, 2β$^-$

$E_b(M_{1-5})$=3.0–2.0, $E_b(N_{1-7})$=0.65–0.05

E_{exc}=1382 – (0,1,2)$^+$: $T_{1/2}$ > 2.9×10^{16}

r-2ε0ν





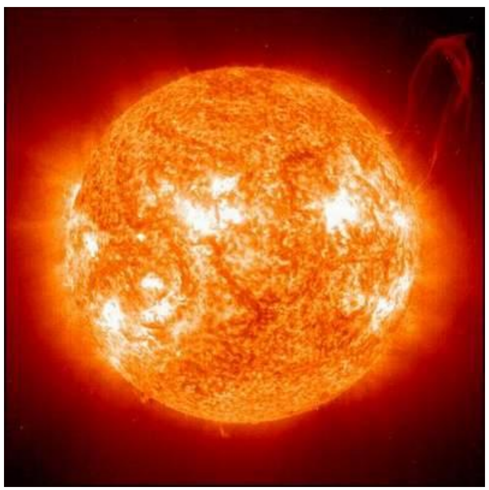
Limits for other possible 2β transitions in ^{190}Pt: $T_{1/2}$ > 8.4×10^{14} – 3.1×10^{16} yr, ^{198}Pt: $T_{1/2}$ > 3.5×10^{18} yr (earlier limits are absent or very poor, ~10^{11} yr from old photoemulsion exp.). The Pt is polluted by ^{192m}Ir (40 mBq/kg) and ^{137}Cs (7 mBq/kg), but not polluted by ^{40}K, ^{60}Co, U/Th (important for growth of crystals in Pt crucibles).

Search for resonant absorption of hadronic solar ^{7}Li axion in LiF crystal – P. Belli et al., Phys. Lett. B 711 (2012) 41

Axion – hypothetical particle which appears as result of solution of the "strong CP problem" by Peccei-Quinn'1977 (further modifications by Kim-Shifman-Vainstein-Zakharov, Dine-Fischler-Srednicki-Zhitnitskii).

Sun could be source of axions; in particular they are emitted instead of γ quanta in magnetic transitions in deexcitations of excited nuclear levels, e.g. in ^{7}Li (pp cycle):

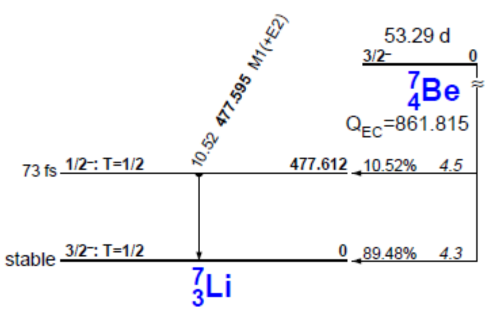
$$^{7}\text{Be} + e^{-} \to {}^{7}\text{Li} + \nu_e .$$

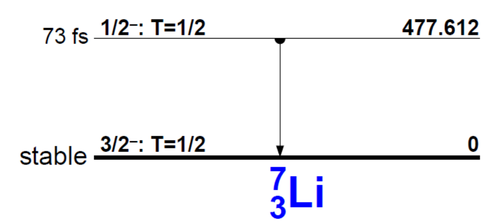


axion →

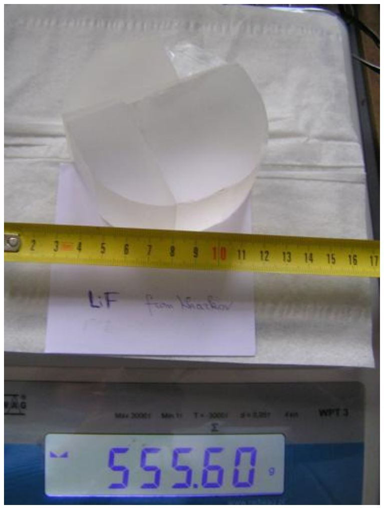
Arriving to the Earth from the Sun, these quasi-monoenergetic axions could excite the same nuclei (^{7}Li).

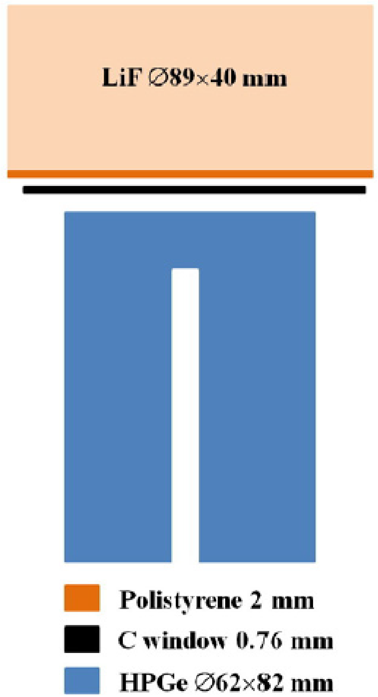
One can look for deexcitation γ quanta of 477.6 keV.

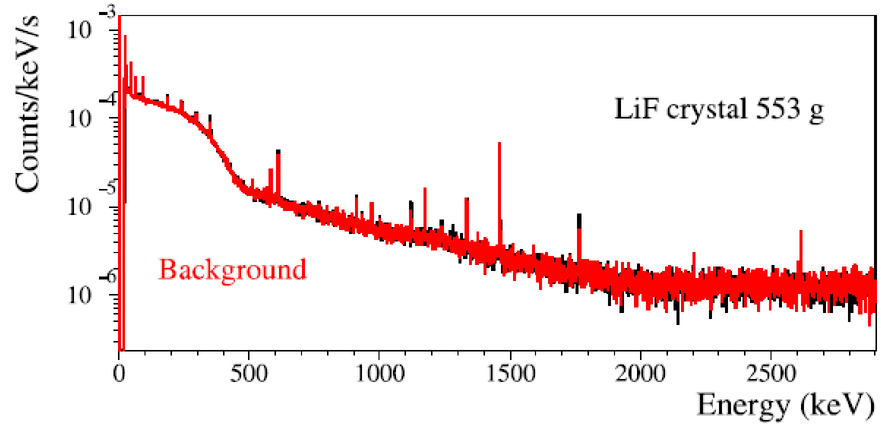


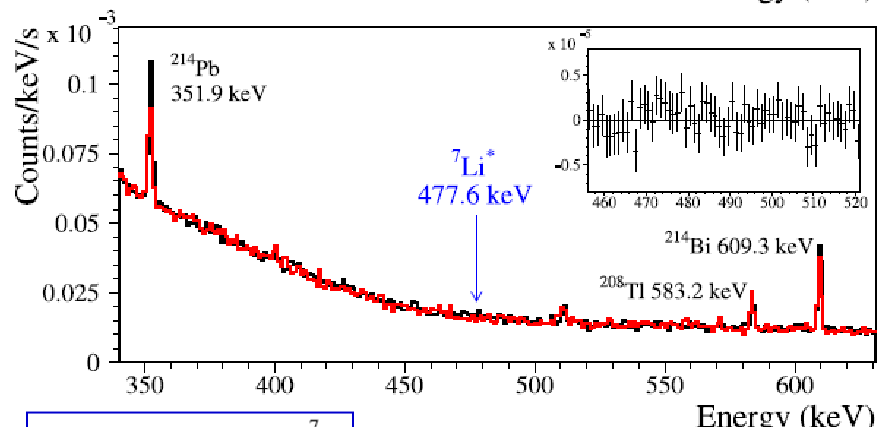


LiF(W) crystal 553 g, HPGe 244 cm^3, 4044 h (pure, U/Th < ~0.01 Bq/kg)



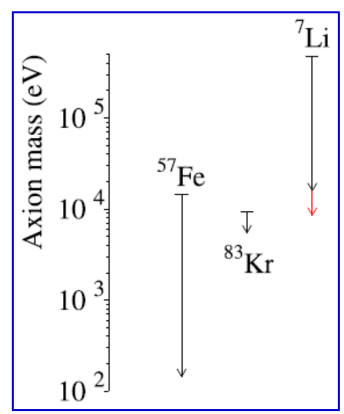




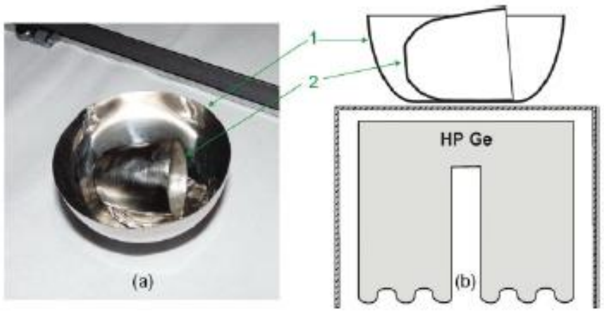


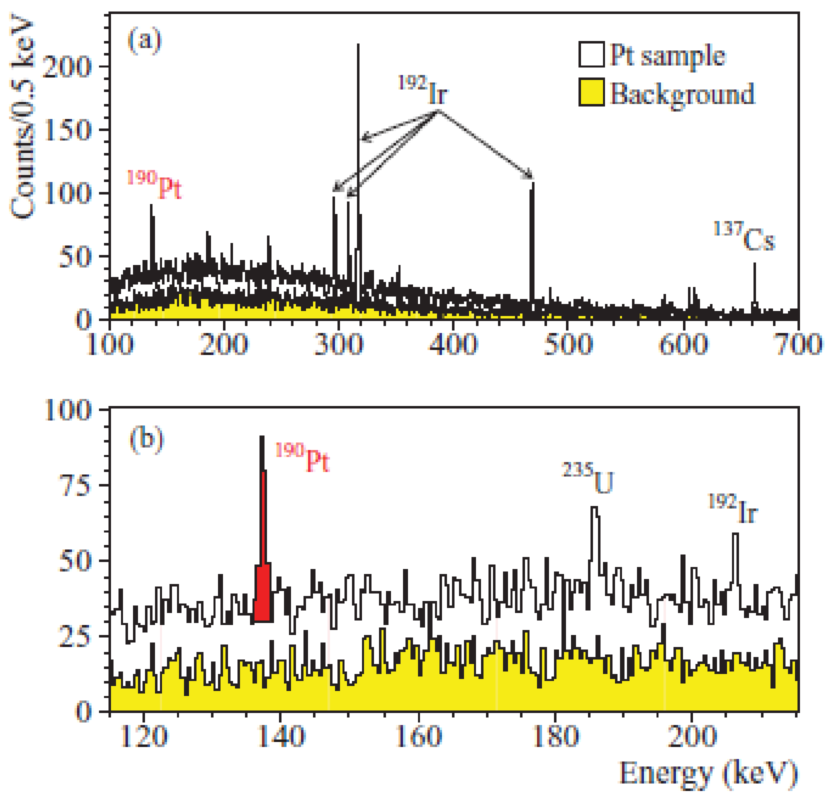
$$m_a = 1.55 \times 10^{11} \times \left(\frac{S(1+\alpha)}{\varepsilon N_7 t} \right)^{1/4} \text{eV}.$$

Result: m_a < 8.6 keV at 90% C.L.
– the best limit for ^{7}Li solar axions.



First observation of α decay of ^{190}Pt to the first excited level (E_{exc}=137.2 keV) of ^{186}Os – P. Belli et al., Phys. Rev. C 83 (2011) 034603





^{190}Pt → ^{186}Os* (E_{exc}=137.2 keV):

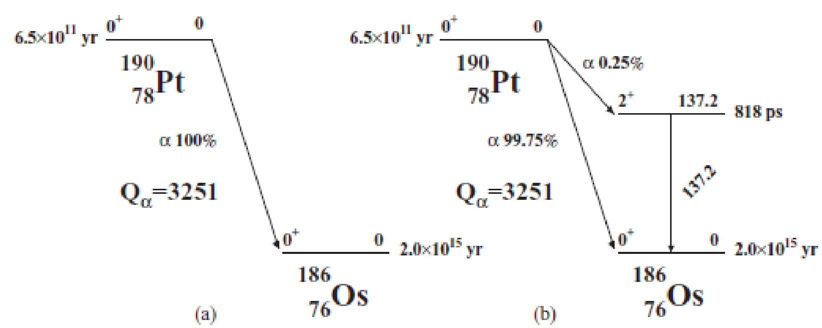
S = 132±17 counts

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

Alternative mimicking processes were not found.

Reasonable agreement with theoretical expectations: (3.2–7.0)×10^{13} yr.

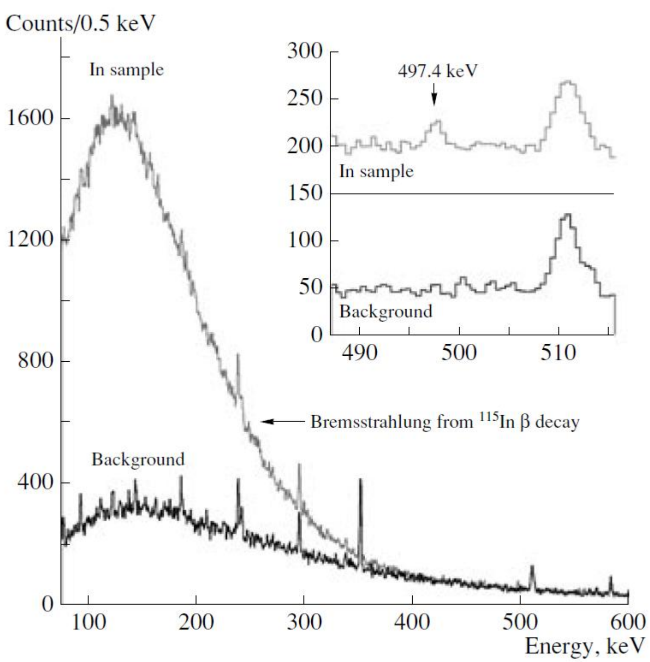
Old and new schemes of ^{190}Pt α decay:



Just to remind of earlier experiment with the STELLA facility:

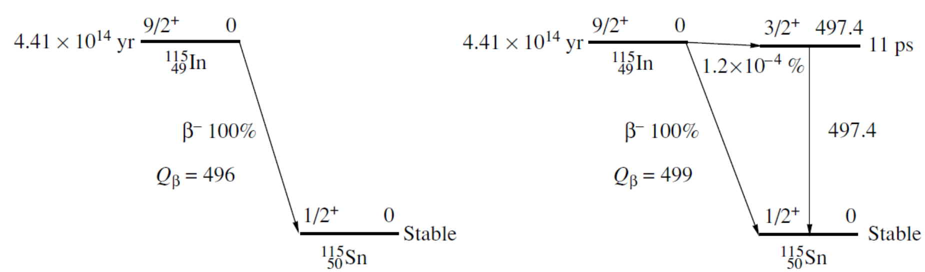
First observation of single β decay $^{115}In \rightarrow {}^{115}Sn^*$ (497.4 keV) – C.M. Cattadori et al., Nucl. Phys. A 748 (2005) 333

4 HP Ge in one cryostat (~225 cm^3 each)
Natural In (95.71% ^{115}In), 929 g, 2762 h (background 1601 h)



$^{115}In \rightarrow {}^{115}Sn^*$ (E_{exc}=137.2 keV): S = 90±22 counts
$T_{1/2}$ = 3.7±1.0×10^{20} yr (p = 1.2±0.3×10^{-6})
Alternative mimicking processes were not found.

Old and new schemes of ^{115}In β decay:



Confirmed by other groups (J.S.E. Wieslander et al., PRL 103 (2009) 122501; E. Andreotti et al., PRC 84 (2011) 044605)

$Q_\beta = \Delta M_a - E_{exc}$ = 497.489(10) – 497.334(22) keV = 155(24) eV ! β decay with the lowest Q_β!

B.J. Mount et al., PRL 103 (2009) 122502 – 10 eV accuracy!

^{187}Re – 2.469(4) keV
^{163}Ho – 2.555(16) keV

Problems with theoretical $T_{1/2}$ – atomic effects? – J. Suhonen et al., JPG 37 (2010) 064008

Conclusions

1. **Various 2β processes, including resonant $2\varepsilon0\nu$ captures, were searched for in $^{96,104}Ru$, $^{156,158}Dy$, $^{184,192}Os$, $^{190,198}Pt$ with HPGe spectrometry. The following $T_{1/2}$ limits were established: $T_{1/2} > 1.8\times10^{14} - 1.0\times10^{21}$ yr. These values are mostly the best today, sometimes better than previous ones by few orders of magnitude, sometimes obtained at the first time.**

   It seems to be interesting to re-measure more precisely $Q_{2\beta}$ values for isotopes where r-$2\varepsilon0\nu$ is possible and where $Q_{2\beta}$ are known with not so good accuracy:
   ^{190}Pt – $Q_{2\beta}$=1384±6 keV
   ^{158}Dy – $Q_{2\beta}$=282.7±2.5 keV

2. **Resonant absorption of hypothetical hadronic solar ^{7}Li axions in LiF crystal was looked for. The effect is not observed, the obtained limit on axion mass m_a < 8.6 keV is the best for ^{7}Li axions.**

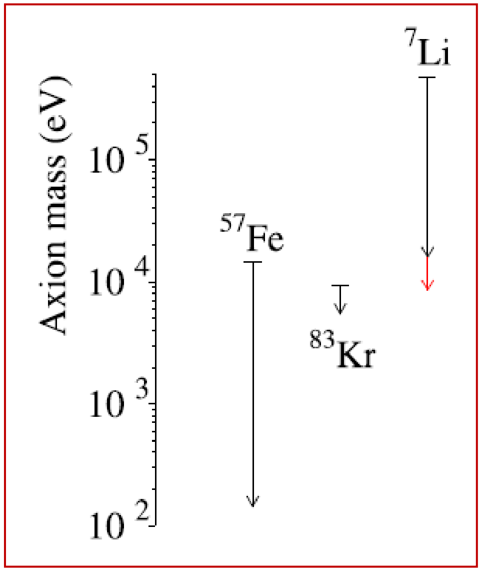
3. **α decay $^{190}Pt \rightarrow {}^{186}Os^{*}$ (137.2 keV) was observed at the first time, probability is 0.25%, $T_{1/2} = 2.6\times10^{14}$ yr.**

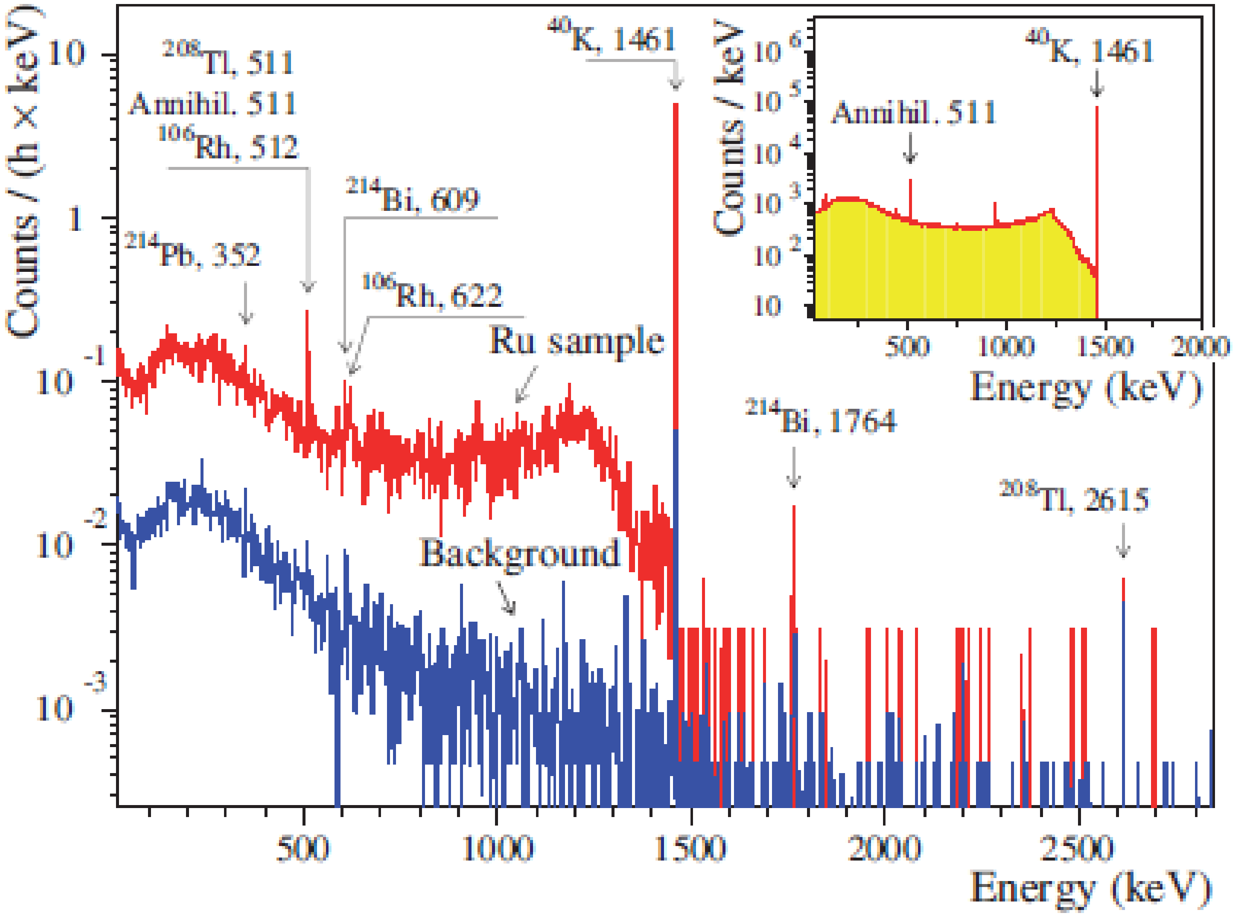
Thank you for attention!

Summary of searches for quasi-monoenergetic solar axions coupled to nucleons through resonant excitation of nuclei.

Axion source, E_γ (keV)	Short description	$\lim m_a$ (keV)	Year [Ref.]
^{7}Li, $E_\gamma = 477.6$	HP Ge 78 cm^3, Li 61.4 g, 2667h	32.0[a]	2001 [19]
	HP Ge 160 cm^3, LiOH 3.9 kg, 3028h	16.0[b]	2005 [20]
	HP Ge 408 cm^3, LiF powder 243 g, 722h	13.9[b]	2008 [14]
	HP Ge 244 cm^3, LiF crystal 553 g, 4044h	8.6[b]	This work
^{57}Fe, $E_\gamma = 14.4$	Si(Li), Fe 33 mg (^{57}Fe 95%), 1472h	0.745[a]	1998 [21]
	Si(Li), Fe 16 mg (^{57}Fe 80%), 712h	0.360[b]	2007 [22]
	Si PIN, Fe 206 mg (^{57}Fe 96%), 334h	0.216[a]	2007 [23]
	Si(Li), Fe 290 mg (^{57}Fe 91%), 2028h	0.159[a]	2009 [24]
	Total Earth heat flux	1.6	2009 [25]
	Si(Li), Fe 1.26 g (^{57}Fe 91%), 1075h	0.145[a]	2010 [26]
^{83}Kr, $E_\gamma = 9.4$	PC[c] 243 cm^3, Kr gas 1.7 g, 564h	5.5[a]	2004 [27]

[a] At 95% C.L.
[b] At 90% C.L.
[c] Proportional counter.





Counts / (h × keV)
10
1
10^-1
10^-2
10^-3
208Tl, 511
Annihil. 511
106Rh, 512
214Bi, 609
214Pb, 352
106Rh, 622
40K, 1461
Ru sample
Background
214Bi, 1764
208Tl, 2615
500
1000
1500
2000
2500
Energy (keV)
Counts / keV
40K, 1461
Annihil. 511
Energy (keV)

How our knowledge on $Q_{2\beta}$ and nuclear levels could be changed:

$Q_{2\beta}$(^{192}Os) = 413.5±3.0 [G. Audi et al., 1995]; 412.4±2.9 [2003]; 408.2±3.3 [2012]

$Q_{2\beta}$(^{102}Pd) = 1173.0±2.4 [G. Audi et al., 2003] but 1203.27±0.36 [M. Goncharov et al., PRC 84 (2011) 028501]

^{106}Pd level 2741 keV – J^{π}=(1,2^{+}) [Tol, 1998] but 4^{+} [NNDC, 12.06.2013]