Studio di processi rari negli isotopi naturali di Hf e Zr utilizzando cristalli scintillatori di Cs_2HfCl_6 e Cs_2ZrCl_6

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Interest in studying the 2β and rare α decay

- **2β** decay without the presence of neutrinos could open a new window beyond the Standard Model.
- To **test calculations** of **different nuclear shapes** and the **decay modes** that involve the vector and **axial-vector weak effective coupling constants**; possible study of the "resonant effect" on the 0ν2ε mode.
- The nuclear matrix elements for the **2ν** mode and for the **0ν mode** can be related to each other through relevant parameters: in the free nucleon interaction, **the g_A value is 1.2701**, but, when considering a nuclear decay, there are indications that the phenomenological axial-vector coupling value is reduced at **$g_A < 1$**, more precisely: **$g_A \approx 1.269\ A^{-0.18}$ or $g_A \approx 1.269\ A^{-0.12}$**, depending on the nuclear model adopted to infer the g_A value.
- **2β investigation with various nuclei would shed new light in constraining these and oher important model-dependent parameters.**

$$0\nu2\beta^- : \ {}^{A}_{Z}X \rightarrow {}^{A}_{Z+2}Y + 2e^-$$

- The study of rare α decay plays a crucial role in developing nuclear physics. It can offer details about the **nuclear structure, the nuclear levels and the properties of nuclei**.
- The phenomenon of α decay can offer information about the fusion-fission reactions since the α decay process involves sub-barrier penetration caused by the interaction between the α particle and the nucleus. In particular the study of rare α decay requires low background techniques and laboratories.
- Understanding the nuclear properties is essential also for nuclear and particle astrophysics studies, for example, α–capture reactions (equivalent to the inverse α–decay process) are important for nucleosynthesis and β–delayed fission, together with other fission modes, determine the so-called "fission recycling" in the r-process nucleosynthesis.

The Cs_2HfCl_6 (CHC) and Cs_2ZrCl_6 (CZC) crystal scintillators

- High light yield (up to 30000 photons/MeV for CHC and up to 35000 photons/MeV for CZC);
- Excellent linearity in the energy response;
- Excellent energy resolution (<3.5% at 662 keV in the best configuration);
- Excellent ability for pulse shape discrimination (PSD) between $\boldsymbol{\beta}(\boldsymbol{\gamma})$ and $\boldsymbol{\alpha}$ particles;
- Cs_2ZrCl_6 crystal contains 16% Zr by weight.
- Cs_2HfCl_6 crystal contains a high fraction of Hf (~ 27% in mass).

Some general properties	CHC	CZC
Effective atomic number	58	46.6
Density (g/cm^3)	3.9	3.4
Melting point (°C)	820	850
Crystal structure	cubic	cubic
Wavelenght of emission (nm)	400-430	440-479
Decay time (μs)	0.4; 5.1; 15.2[1]	0.4; 2.7; 12.5[1]

[1]*Dalton Trans.*, 2022, **51**, 6944-6954

Low background measurements of the CHC and CZC crystals

measured with the ultra-low background **HP-Ge** γ spectrometers of the **STELLA** facility at LNGS.

Chain	Nuclide	Activity (mBq/kg)		
		CHC [2]	CZC	
			Cone	Cylinder
		6.90 g	10.63 g	23.95 g
^{232}Th	^{228}Ra	<12	< 16	< 23
	^{228}Th	<3.6	< 6.7	< 8.2
^{238}U	^{226}Ra	<23	60(10)	< 8.7
	^{234}Th	<0.80	< 180	< 260
	^{234m}Pa	<0.48	< 630	< 160
^{235}U	^{235}U	<14	< 16	< 12
	^{40}K	$0.4(1)\times10^3$	< 120	< 95
	^{44}Ti	10(4)	-	-
	^{60}Co	<25	-	-
	^{137}Cs	$0.78(8)\times10^3$	< 7.1	< 1.6
	^{134}Cs	79(8)	49(6)	42(5)
	^{132}Cs	<15	< 8.2	< 11
	^{181}Hf	<11	-	-
	^{190}Pt	<20	-	-
	^{202}Pb	<9.1	-	-

Preliminary

Under investigation

Natural

Artificial

Cosmogenic activation

Only land transportation! $T_{1/2} \approx 2$ years

[2] NPA 1002 (2020) 121941

Search for 2β and rare α decay in Hf isotopes using passive source approach

HPGe-detector

The isotope ^{174}Hf is one of the potentially 2ε, $\varepsilon\beta^+$ radioactive nuclides with the energy of decay $Q_{2\beta}$=1100.0(23) keV and the isotopic abundance δ=0.156(6)%.

Channel of the decay	Decay Mode	Level of daughter nucleus J^π, energy (keV)	Experimental limit of $T_{1/2}$ (90% C.L.) (y) [25]	[26]
$2K$	2ν	g.s.	$\geq 7.1 \times 10^{16}$	$\geq 1.4 \times 10^{16}$
KL	2ν	g.s.	$\geq 4.2 \times 10^{16}$	$\geq 1.4 \times 10^{16}$
$2K$	2ν	2^+, 76.5	$\geq 5.9 \times 10^{16}$	$\geq 7.9 \times 10^{16}$
KL	2ν	2^+, 76.5	$\geq 3.5 \times 10^{16}$	$\geq 7.9 \times 10^{16}$
$2L$	2ν	2^+, 76.5	$\geq 3.9 \times 10^{16}$	$\geq 7.9 \times 10^{16}$
$2K$	0ν	g.s.	$\geq 5.8 \times 10^{17}$	$\geq 2.7 \times 10^{18}$
KL	0ν	g.s.	$\geq 1.9 \times 10^{18}$	$\geq 4.2 \times 10^{17}$
$2L$	0ν	g.s.	$\geq 7.8 \times 10^{17}$	$\geq 3.6 \times 10^{17}$
$2K$	0ν	2^+, 76.5	$\geq 7.1 \times 10^{17}$	$\geq 2.4 \times 10^{18}$
KL	0ν	2^+, 76.5	$\geq 6.2 \times 10^{17}$	$\geq 3.1 \times 10^{17}$
$2L$	0ν	2^+, 76.5	$\geq 7.2 \times 10^{17}$	$\geq 9.4 \times 10^{17}$
$K\beta^+$	$2\nu + 0\nu$	g.s.	$\geq 1.4 \times 10^{17}$	$\geq 5.6 \times 10^{16}$
$L\beta^+$	$2\nu + 0\nu$	g.s.	$\geq 1.4 \times 10^{17}$	$\geq 5.6 \times 10^{16}$

[25] HADES; NPA 996 (2020) 121703

[26] LNGS; NPA 1012 (2021) 122212

[28] HADES; Eur. Phys. J. A (2020) 56:5

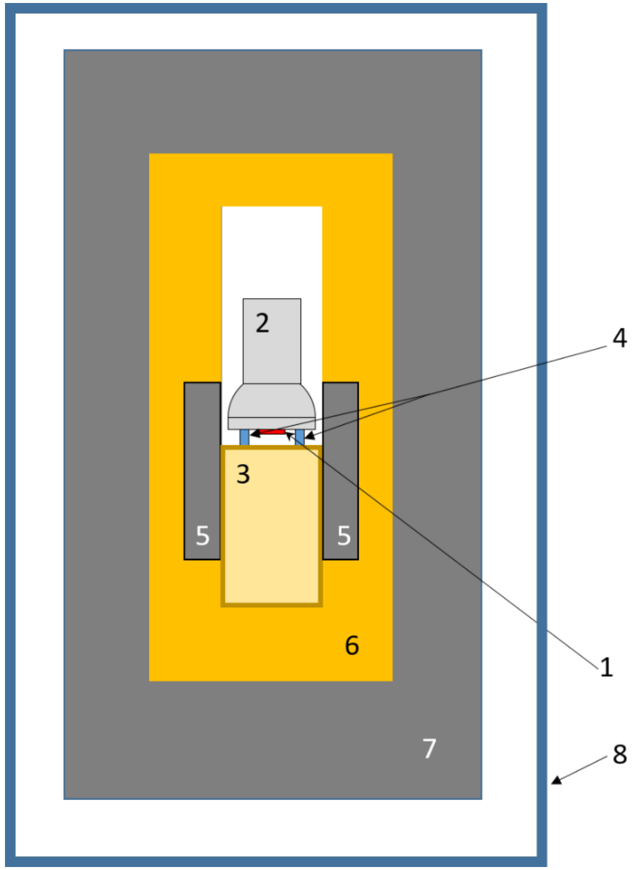
[31] Phys. G (1991) 17 1223
[32] J. Physique (1983) 44 791
[33] Rhys. Rev. C 92 (2015) 014602

Nuclide Transition	J^π Parent → Daughter Nuclei and its level (keV)	δ (%) [29]	Q_α (keV) [30]
$^{174}Hf \rightarrow {}^{170}Yb$	$0^+ \rightarrow 0^+$, g.s. $0^+ \rightarrow 2^+$, 84.2	0.156(6) [24]	2494.5(2.3)
$^{176}Hf \rightarrow {}^{172}Yb$	$0^+ \rightarrow 0^+$, g.s. $0^+ \rightarrow 2^+$, 78.7	5.26(70)	2254.2(1.5)
$^{177}Hf \rightarrow {}^{173}Yb$	$7/2^- \rightarrow 5/2^-$, g.s. $7/2^- \rightarrow 7/2^-$, 78.6	18.60(16)	2245.7(1.4)
$^{178}Hf \rightarrow {}^{174}Yb$	$0^+ \rightarrow 0^+$, g.s. $0^+ \rightarrow 2^+$, 76.5	27.28(28)	2084.4(1.4)
$^{179}Hf \rightarrow {}^{175}Yb$	$9/2^+ \rightarrow 7/2^+$, g.s. $9/2^+ \rightarrow 9/2^+$, 104.5	13.62(11)	1807.7(1.4)
$^{180}Hf \rightarrow {}^{176}Yb$	$0^+ \rightarrow 0^+$, g.s. $0^+ \rightarrow 2^+$, 82.1	35.08(33)	1287.1(1.4)

Decay isotope	Level of the daughter nucleus (keV)	$T_{1/2}$ (y) Experimental [28]	Experimental [26]	Theoretical [31]	Theoretical [32]	Theoretical [33]
^{174}Hf	2^+, 84.2	$\geqslant 3.3 \cdot 10^{15}$	$\geqslant 2.8 \cdot 10^{16}$	$1.3 \cdot 10^{18}$	3.0×10^{18}	6.6×10^{17}
^{176}Hf	2^+, 78.7	$\geqslant 3.0 \times 10^{17}$	$\geqslant 2.7 \times 10^{17}$	1.3×10^{22}	3.5×10^{22}	4.9×10^{21}
^{177}Hf	$(7/2)^-$, 78.6	$\geqslant 1.3 \times 10^{18}$	$\geqslant 1.1 \times 10^{18}$	9.1×10^{21}	1.2×10^{24}	3.6×10^{23}
^{178}Hf	2^+, 76.5	$\geqslant 2.0 \times 10^{17}$	$\geqslant 1.3 \times 10^{18}$	2.4×10^{25}	8.1×10^{25}	7.1×10^{24}
^{179}Hf	$(7/2)^-$, g.s.	$\geqslant 2.2 \times 10^{18}$	-	2.0×10^{32}	4×10^{32}	4.7×10^{31}
	$(9/2)^+$, 104.5	$\geqslant 2.2 \times 10^{18}$	$\geqslant 2.7 \times 10^{18}$	2.0×10^{32}	2.5×10^{35}	2.2×10^{34}
^{180}Hf	2^+, 82.1	$\geqslant 1.0 \times 10^{18}$	$\geqslant 4.6 \times 10^{17}$	4.0×10^{49}	4.1×10^{50}	2.1×10^{48}

Search for rare α decay in Hf isotopes using active source approach

NPA 1002 (2020) 121941



- ✓ CHC crystal (6.90(1) g) coupled low-radioactivity PMT (Hamamatsu R6233MOD) placed above the end-cap of the ultra-low background HP-Ge
- ✓ CAEN DT5720B digitizer 250 MSamples/s;
- ✓ 2848 h data taking

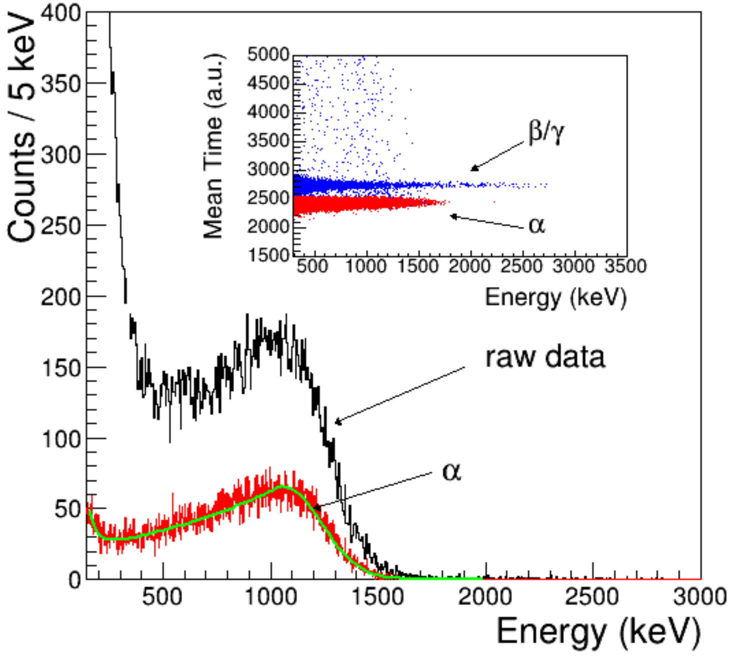
STELLA facility of the LNGS

(1) CHC crystal scintillator
(2) PMT
(3) HP-Ge detector
(4) Teflon ring
(5) Pb, 2.5 cm
(6) HP Cu
(7) Pb, 25 cm
(8) Plexiglas box

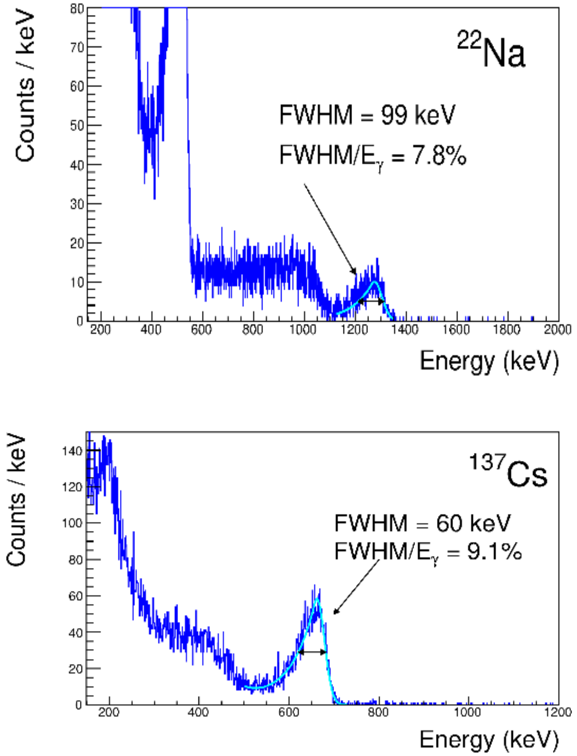
Cs_2HfCl_6 crystal (CHC)

PSD

Preliminary quenching factor (QF) estimation → ^{241}Am



Energy resolution

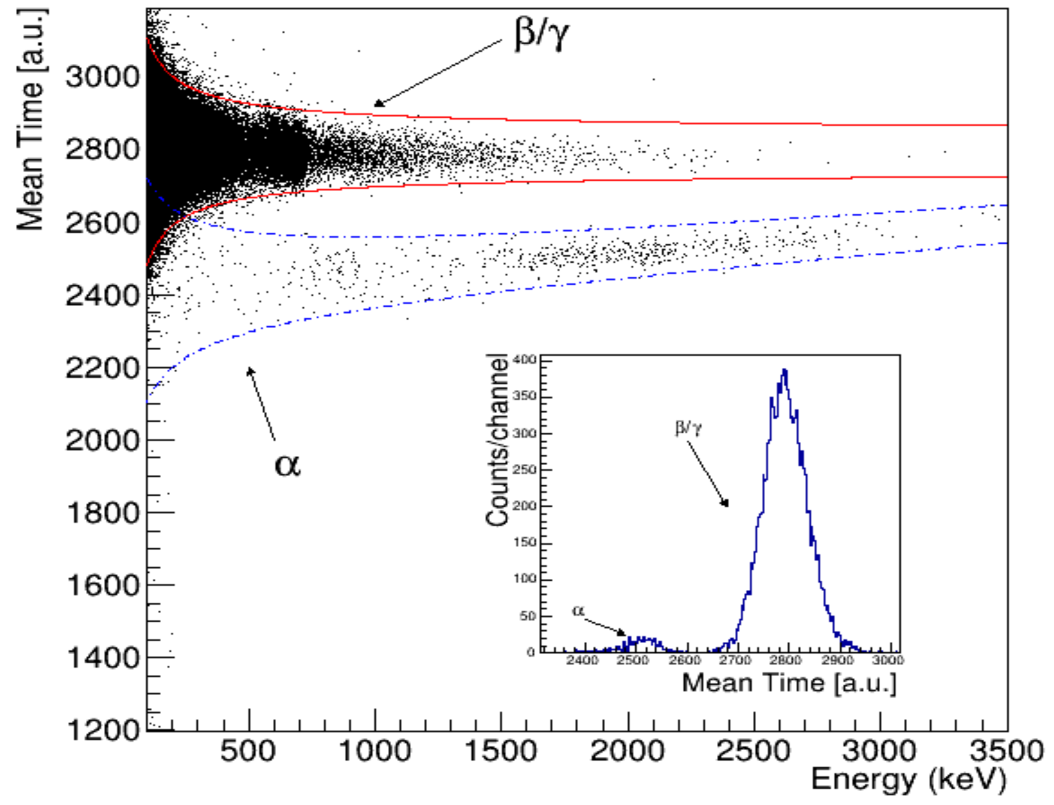


NPA 1002 (2020) 121941

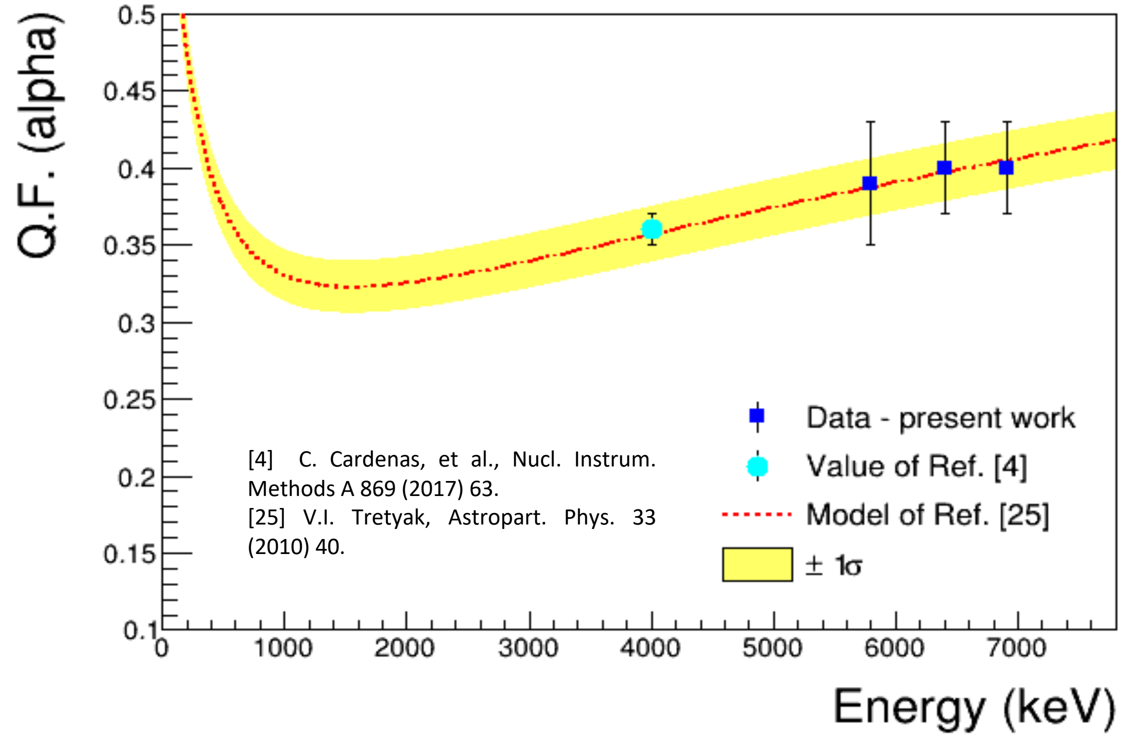
Data analysis for the CHC crystal

Time-amplitude analysis of ^{228}Th sub-chain and the derived Q.F.

Pulse Shape Discrimination (PSD) based on the pulse mean-time



The time-amplitude analysis was used to select the events of the following decay sub-chain of the **^{232}Th family**: **^{224}Ra** (Q = 5789 keV; $T_{1/2}$ = 3.66 d) → **^{220}Rn** (Q = 6405 keV; $T_{1/2}$ = 55.6 s) → **^{216}Po** (Q = 6906 keV; $T_{1/2}$ = 0.145 s) → **^{212}Pb**.



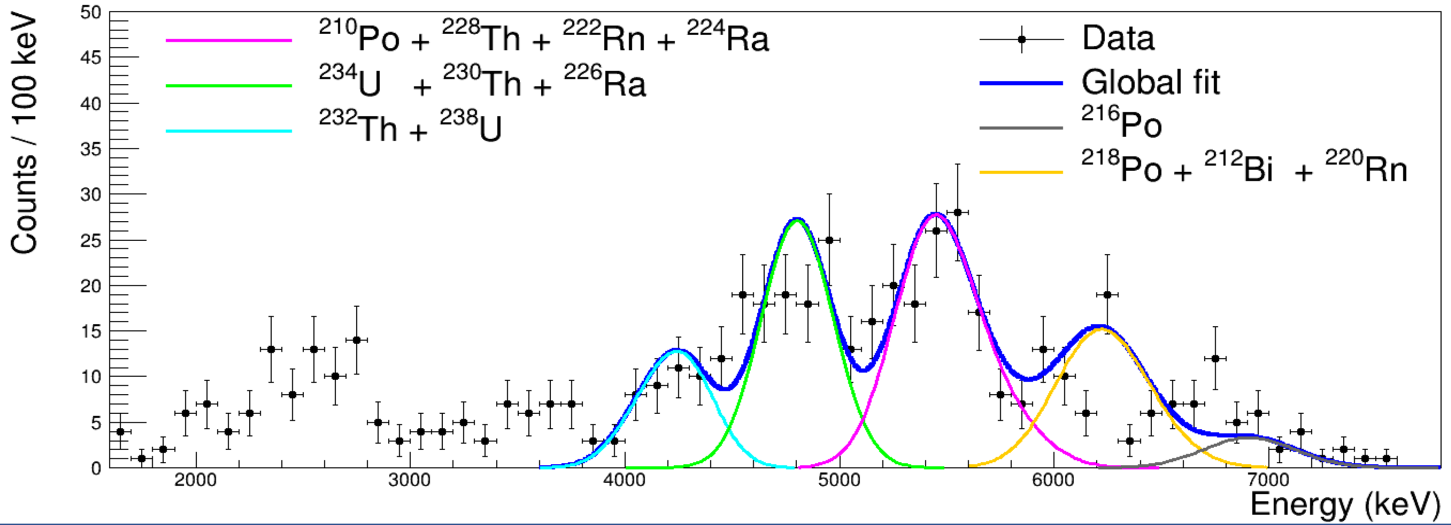
[4] C. Cardenas, et al., Nucl. Instrum. Methods A 869 (2017) 63.
[25] V.I. Tretyak, Astropart. Phys. 33 (2010) 40.

The energies of the peaks of **^{224}Ra**, **^{220}Rn** and **^{216}Po**, selected by the described time-amplitude analysis, are **2260(200) keV**, **2540(200) keV**, **2780(240) keV** (γ scale), respectively.

Fit of the α spectrum of CHC crystal and results on α decays of naturally occurring Hf isotopes

[24] NPA 1002 (2020) 121941

Energy spectrum of the α events selected by PSD from the data of the low-background measurements with the CHC crystal scintillator over 2848 h.



- In the hypothesis of the **half-life** of **1961** ([38] T.P. Kohman, Phys. Rev. 121, 1758) **2.0(4)x10^{15} y** for the ^{174}Hf decay, the expected number of events (**2848** h of data taking) is about **1100** counts.
- The measured α events are **553(23)** in total: even ascribing all of them to ^{174}Hf decay, one **can safely rule out the old result for the $T_{1/2}$**

$$T_{1/2} = (7.0 \pm 1.2) \times 10^{16} \text{ yr}$$

Chain	Sub-Chain	Activity (mBq/kg)
^{232}Th	^{232}Th	0.2(1)
	^{228}Th	0.2(1)
^{238}U	^{238}U	0.6(1)
	^{234}U + ^{230}Th	1.4(2)
	^{226}Ra	0.2(1)
	^{210}Po	1.4(2)

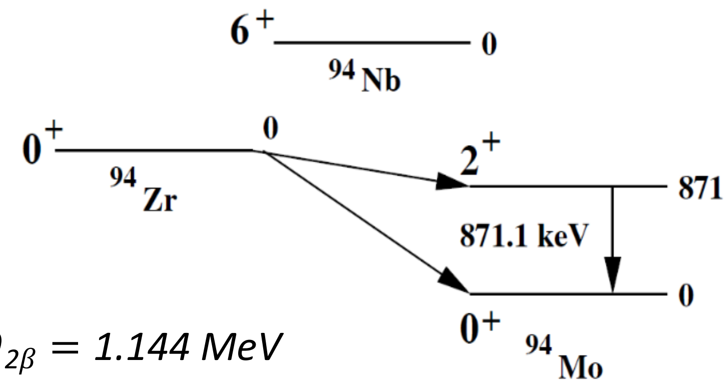
The total internal α activity is **7.8(3) mBq/kg.**

Nuclide Transition	Parent, Daughter Nuclei and its Energy Level (keV)	$T_{1/2}$ (y) Experimental [24]	Experimental [28]	Theoretical [31]	Theoretical [32]	Theoretical [33]
^{174}Hf → ^{170}Yb	$0^+ \to 0^+$, g.s.	$7.0 \pm 1.2 \times 10^{16}$	$2.0 \pm 0.4 \times 10^{15}$[38]	$3.5 \cdot 10^{16}$	7.4×10^{16}	3.5×10^{16}
	$0^+ \to 2^+$, 84.3	$\geqslant 1.1 \times 10^{15}$	$\geqslant 3.3 \times 10^{15}$	$1.3 \cdot 10^{18}$	3.0×10^{18}	6.6×10^{17}
^{176}Hf → ^{172}Yb	$0^+ \to 0^+$, g.s.	$\geqslant 9.3 \times 10^{19}$	–	2.5×10^{20}	6.6×10^{20}	2.0×10^{20}
	$0^+ \to 2^+$, 78.7	$\geqslant 1.8 \times 10^{16}$	$\geqslant 3.0 \times 10^{17}$	1.3×10^{22}	3.5×10^{22}	4.9×10^{21}
^{177}Hf → ^{173}Yb	$7/2^- \to 5/2^-$, g.s.	$\geqslant 3.2 \times 10^{20}$	–	4.5×10^{20}	5.2×10^{22}	4.4×10^{22}
	$7/2^- \to 7/2^-$, 78.6	$\geqslant 7.5 \times 10^{16}$	$\geqslant 1.3 \times 10^{18}$	9.1×10^{21}	1.2×10^{24}	3.6×10^{23}
^{178}Hf → ^{174}Yb	$0^+ \to 0^+$, g.s.	$\geqslant 5.8 \times 10^{19}$	–	3.4×10^{23}	1.1×10^{24}	2.2×10^{23}
	$0^+ \to 2^+$, 76.5	$\geqslant 6.9 \times 10^{16}$	$\geqslant 2.0 \times 10^{17}$	2.4×10^{25}	8.1×10^{25}	7.1×10^{24}
^{179}Hf → ^{175}Yb	$9/2^+ \to 7/2^+$, g.s.	$\geqslant 2.5 \times 10^{20}$	$\geqslant 2.2 \times 10^{18}$	4.5×10^{29}	4.0×10^{32}	4.7×10^{31}
	$9/2^+ \to 9/2^+$, 104.5	$\geqslant 5.5 \times 10^{17}$	$\geqslant 2.2 \times 10^{18}$	2.0×10^{32}	2.5×10^{35}	2.2×10^{34}
^{180}Hf → ^{176}Yb	$9/2^+ \to 7/2^+$, g.s.	–	–	6.4×10^{45}	5.7×10^{46}	9.2×10^{44}
	$9/2^+ \to 9/2^+$, 82.1	–	$\geqslant 1.0 \times 10^{18}$	4.0×10^{49}	4.1×10^{50}	2.1×10^{48}

Search for 2β decay in $^{94,96}Zr$ and for ^{96}Zr's β decay

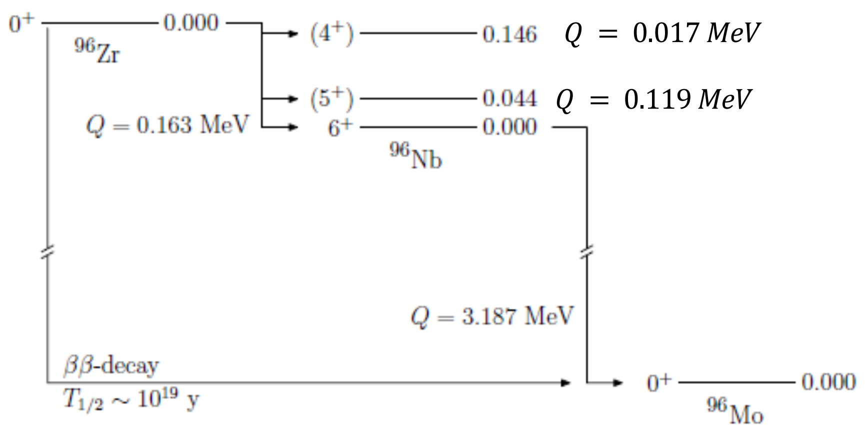
Experiment	Transition	$T_{1/2}$ 90% C.L. (y)	Technique	Ref.
ZICOS, (Kamioka Observatory, Japan)	$^{96}Zr\ 0^+ \rightarrow {}^{96}Mo\ 0^+_1$ (g.s.)	under construction	Organic liquid scintillator	[1]
NEMO I, II, III, Frejus (France) (next: SuperNEMO)	$^{96}Zr\ 0^+ \rightarrow {}^{96}Mo\ 0^+_1$ (g.s.)	$>9.2\times10^{21}$ $>1.29\times10^{22}$	Tracker detector	[2] [3]
Kimballton Underground Research Facility, (USA)	$^{96}Zr\ 0^+ \rightarrow {}^{96}Mo\ 2^+_1$	$>3.1\times10^{20}$	HP-Ge	[4]
Collaboration at Fréjus Underground Laboratory	$^{96}Zr\ 0^+ \rightarrow {}^{96}Mo\ 2^+_1$, 0^+_1, 2^+_2, 2^+_3	$>(2.6-7.9)\times10^{19}$	HP-Ge	[5]
Collaboration at LNGS	$^{96}Zr\ 0^+ \rightarrow {}^{96}Mo\ 2^+_1$	$>3.8\times10^{19}$	HP-Ge	[6]
TILES (TIFR, Mumbai)	$^{94}Zr\ 0^+ \rightarrow {}^{94}Mo\ 2^+_1$	$>5.2\times10^{19}$	HP-Ge	[7]
Kimballton Underground Research Facility, (USA)	$^{96}Zr\ 0^+ \rightarrow {}^{96}Mo\ 6^+$	$>2.4\times10^{19}$	HP-Ge	[8]

Decay scheme of ^{94}Zr



$Q_{2\beta} = 1.144\ MeV$

β and 2β decay of ^{96}Zr. The decay Q-values and excitation energies of the first three states of Nb are also indicated.

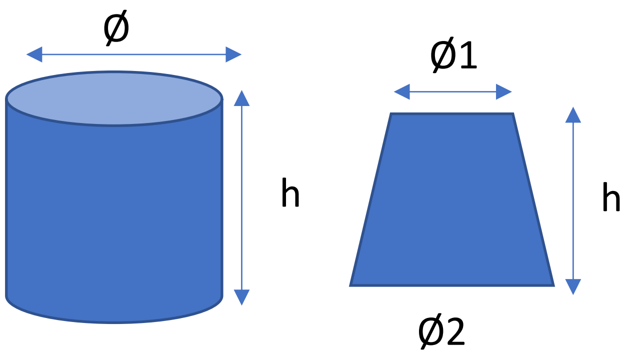


[1] EPS-HEP (2019) 437
[2] NPA 847 (2010) 168
[3] PhD U. Coll. London (2015)
[4] S.W. Finch et W. Tornow, Phys, Rev. C 92 (2015) 045501
[5] J. Phys. G: Nucl. Part. Phys. 22 (1996) 487
[6] C. Arpesella et al. Lett. 27 (I) (1994) pp. 29–34
[7] N. Dokania et al. J. Phys. G: Nucl. Part. Phys. 45 (2018) 075104
[8] S.W. Finch, W. Tornow, Nucl. Inst. Meth. A 806(2016)70–74
[9] J. Heeck and W. Rodejohann 2013 *EPL* 103 32001

Search for 2β decay in Zr isotopes using active source approach

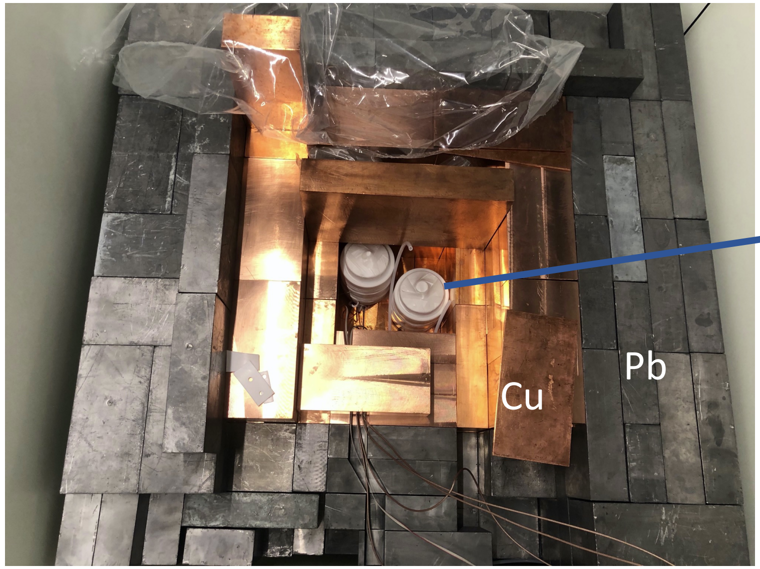
Cs_2ZrCl_6 crystals (CZC)

M=24,0(1) g
h =21,20(5) mm
Ø=21,00(5) mm

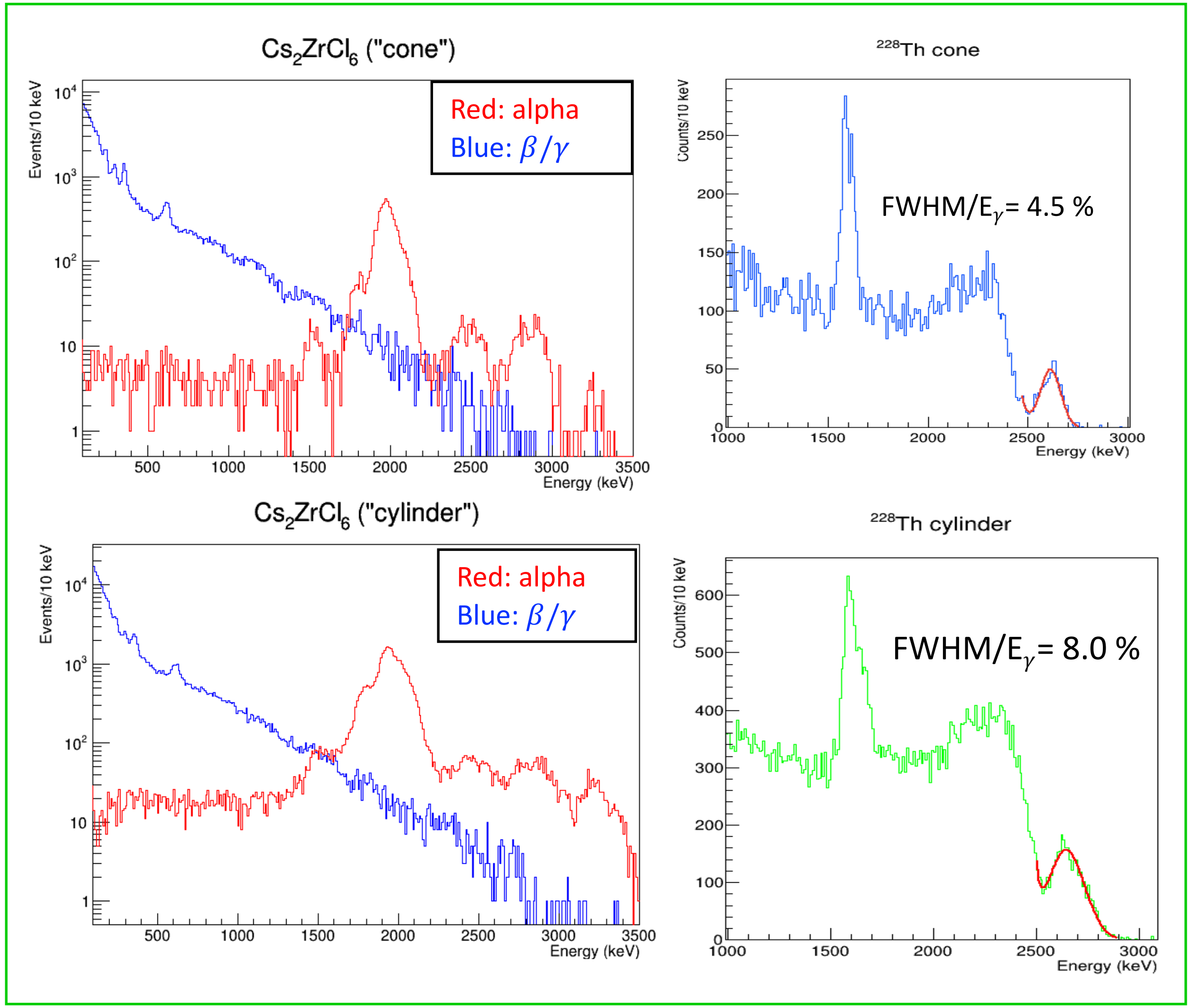


M=10,6(1) g
h =17,90(5) mm
Ø1=8,0(1) mm
Ø2=19,70(5) mm

- ✓ 8736 h data taking

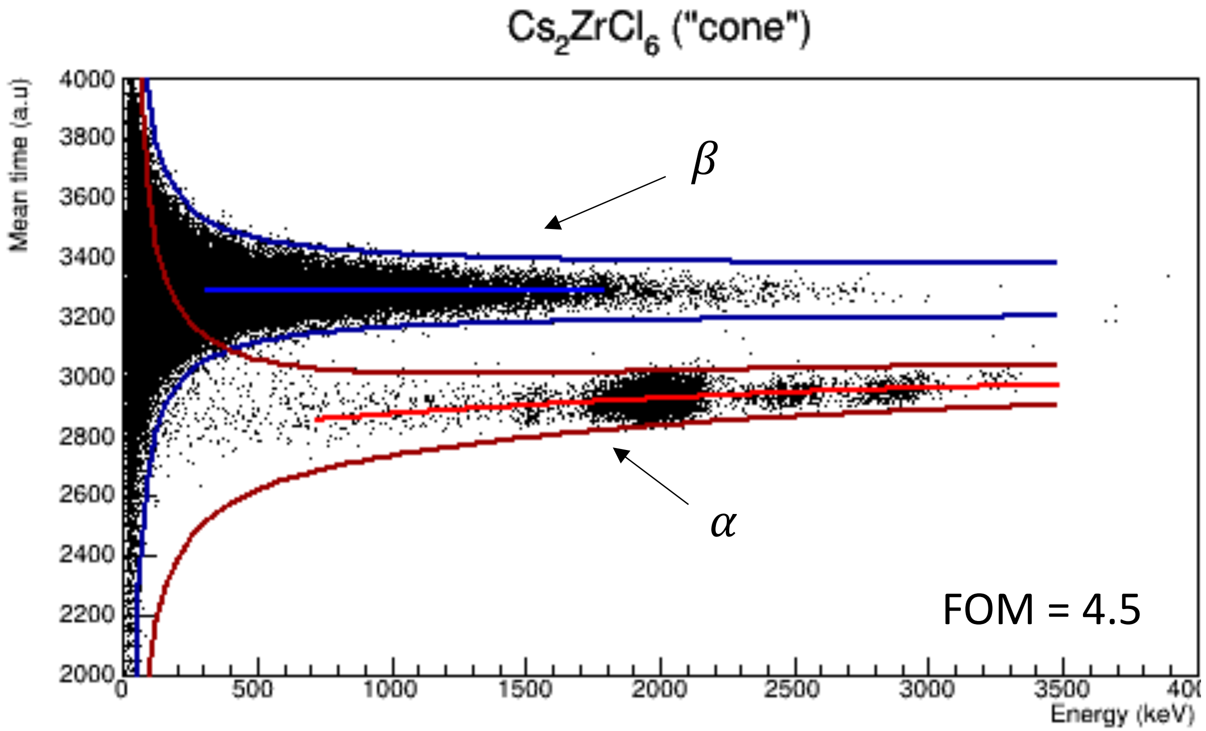


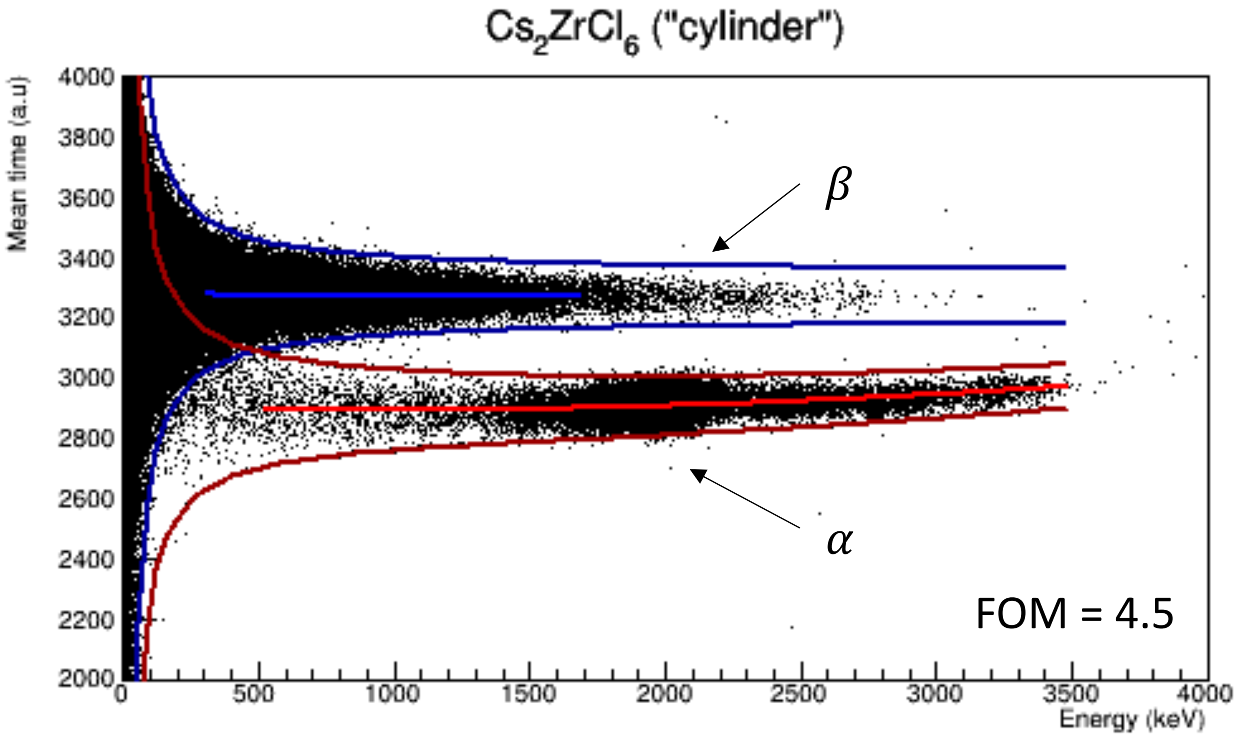
DAMA/CRYS setup at LNGS



Data analysis for the CZC crystals

The mean-time pulse-shape discrimination (PSD) method [10] was used to discriminate $\beta(\gamma)$ events from α events caused by α radioactive contamination of the detectors by ^{232}Th and ^{238}U with their daughters.





[10] L. Bardelli *et al.*, Nucl. Instr. Meth. A **584**, 129 (2008).

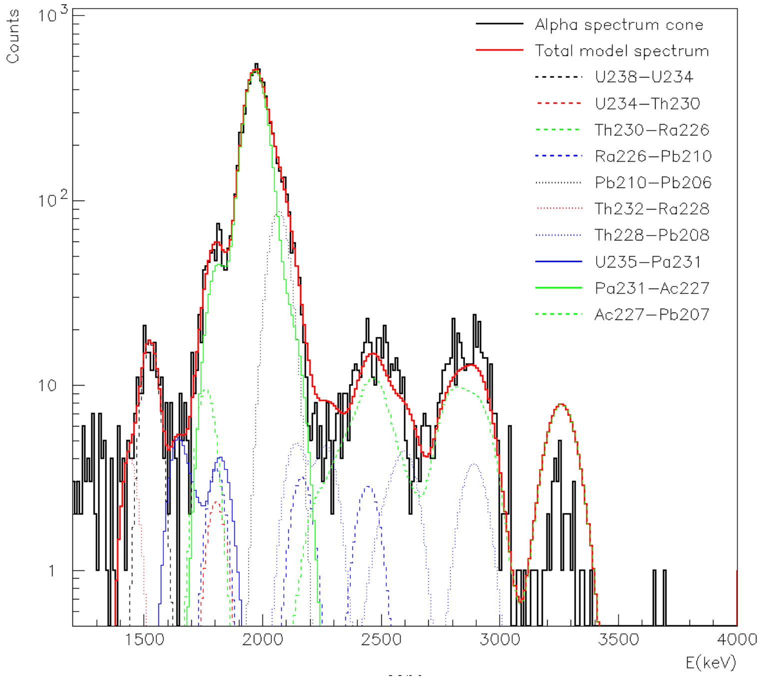
The mean value of the mean time vs energy is represented together with $\boldsymbol{3\sigma}$ intervals for the two CZC crystals.

Preliminary

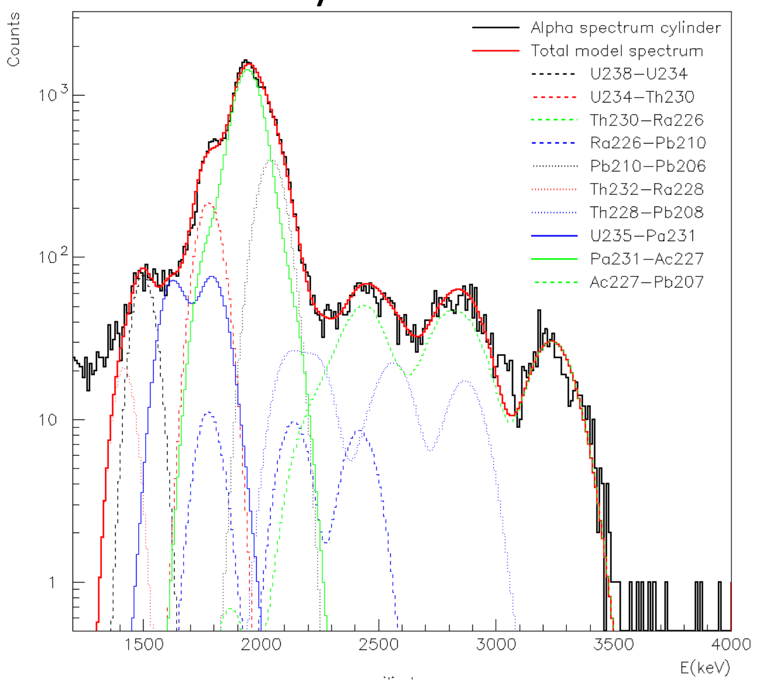
Fit of the α spectra of CZC crystals with α decays from ^{238}U, ^{232}Th and ^{235}U chains

Fit window: [1430, 3400] keV

Cone case



Cylinder case



- Preliminary fits including also α events from ^{235}U chain reproduce well the measured spectra.
- The peak with highest counting rate at ≈ 2 MeVee may be attributed to ^{231}Pa decay from ^{235}U chain for both the crystals.
- **But**, the origin of the 3 α peaks at higher energy (i.e. E = 2.45, 2.85 and 3.25 MeVee), mostly due to ^{227}Ac→…→^{207}Pb sub-chain from ^{235}U chain, is still under study.

Radioactive contamination

Chain	Nuclide	Activity, mBq/kg	
		Cone	Cylinder
		10.63 g	**23.95 g**
^{232}Th	^{232}Th	0.10(3)	0.30(8)
	^{228}Th	0.16(3)	0.47(3)
^{238}U	^{238}U	0.43(4)	1.14(6)
	^{234}U	0.07(11)	3.73(16)
	^{230}Th	0.28(2)	< 0.02
	^{226}Ra	0.10(4)	0.20(5)
	^{210}Pb	2.8(2)	7.8(3)
^{235}U	^{235}U	0.32(5)	2.8(1)
	^{231}Pa	**20.0(3)**	**32.0(4)**
	^{227}Ac	0.40(2)	0.91(2)

α/β light ratio:

Cone: $\alpha/\beta = 0.257(2) + 0.0247(4) \cdot E_\alpha$[MeV]

Cylinder: $\alpha/\beta = 0.246(1) + 0.0258(2) \cdot E_\alpha$[MeV]

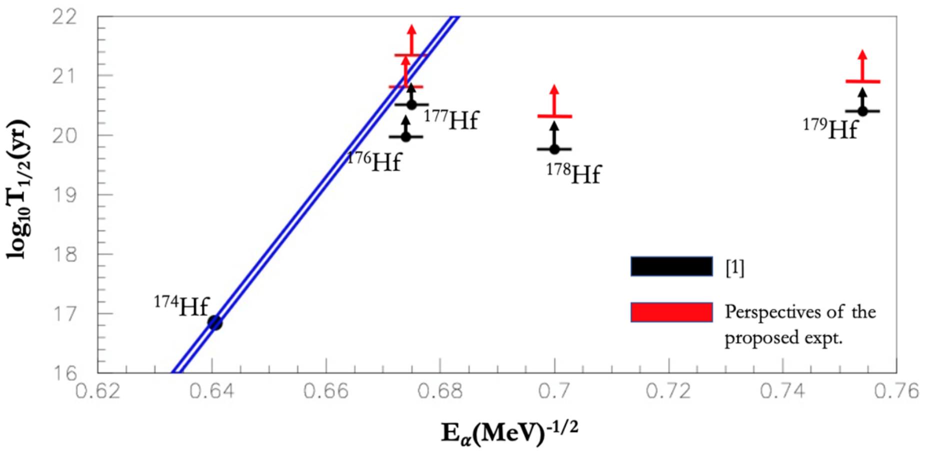
Perspectives and conclusions

Great interest in the development of scintillating crystals from the metal hexachlorides Cs_2MCl_6 (M = Hf or Zr) family

- An experiment using a CHC crystal scintillator in coincidence with a HP-Ge detector has observed α decay of ^{174}Hf to the ground state with a **$T_{1/2}$ = 7.0(1.2) x 10^{16} y**. This value is in good agreement with the theoretical predictions.
- New lower limits of the half-life for **2ε** and **$εβ^+$** decay of ^{174}Hf **(10^{16}-10^{18} y)** have been set.
- New lower limits of the half-life for α decay of ^{174}Hf to the first excited state and for α decays of ^{176}Hf, ^{177}Hf, ^{178}Hf, ^{179}Hf either to the ground states or to the first excited levels of daughter nuclides (**10^{16}-10^{20} y**) have been set.
- Four CHC detectors will be fully characterized in the incoming months: the expected results after 1 year of data taking of the four detectors will allow higher accuracy for the half-life of ^{174}Hf, α decay, of the order of 2.5%.
- Sensitivity for the discovery of the α decay of the ^{176}Hf, ^{177}Hf isotopes will reach $T_{1/2}$~6.5×10^{20} yr and 2.2×10^{21} yr.

- First two Cs_2ZrCl_6 scintillating crystals have been grown in Queen's University and studied at the National Laboratory of Gran Sasso (LNGS, Italy).
- We are planning a new experiment with 4 CZC crystals (∅ 21×21 mm^3) in optimized geometry, with light guides to reduce background from PMT, and active veto to further reduce background and mitigate cosmic muons.
- We are hoping in 1 year of data taking to reach 10^{21}-10^{22} y experimental sensitivity for $T_{1/2}$ of $0\nu2\beta$ of ^{96}Zr.

Diagram $T_{1/2}$ vs the inverse of the square root of α energy in MeV.

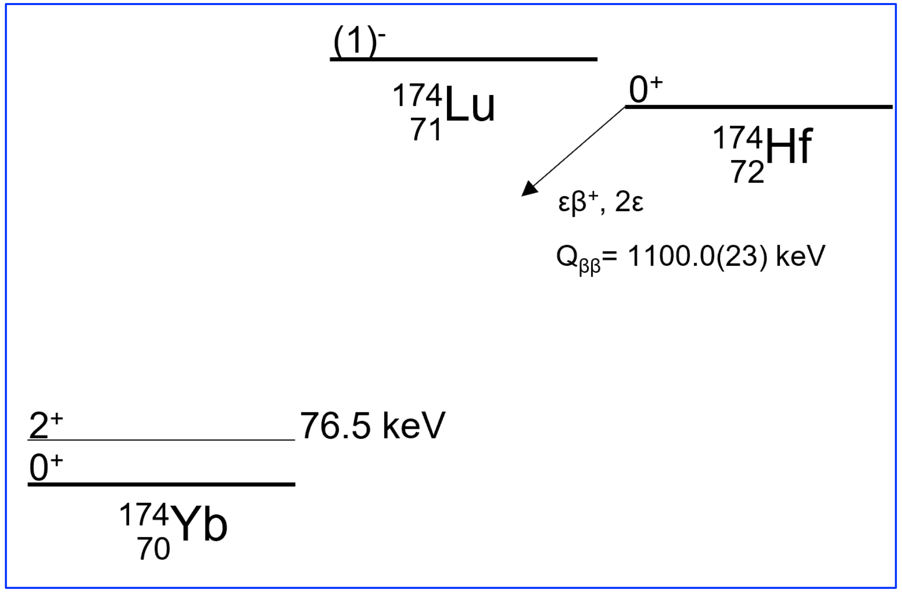


- The blue band is the extrapolation of the predictions on $T_{1/2}$ for all the Hf isotopes using the Geiger-Nuttall scaling law considering the data point observed in Ref. **[1]NPA 1002 (2020) 121941.**
- The red symbols represent the sensitivity that the measurement can reach using CHC crystal scintillators with 43.83 kg × day of total exposure.

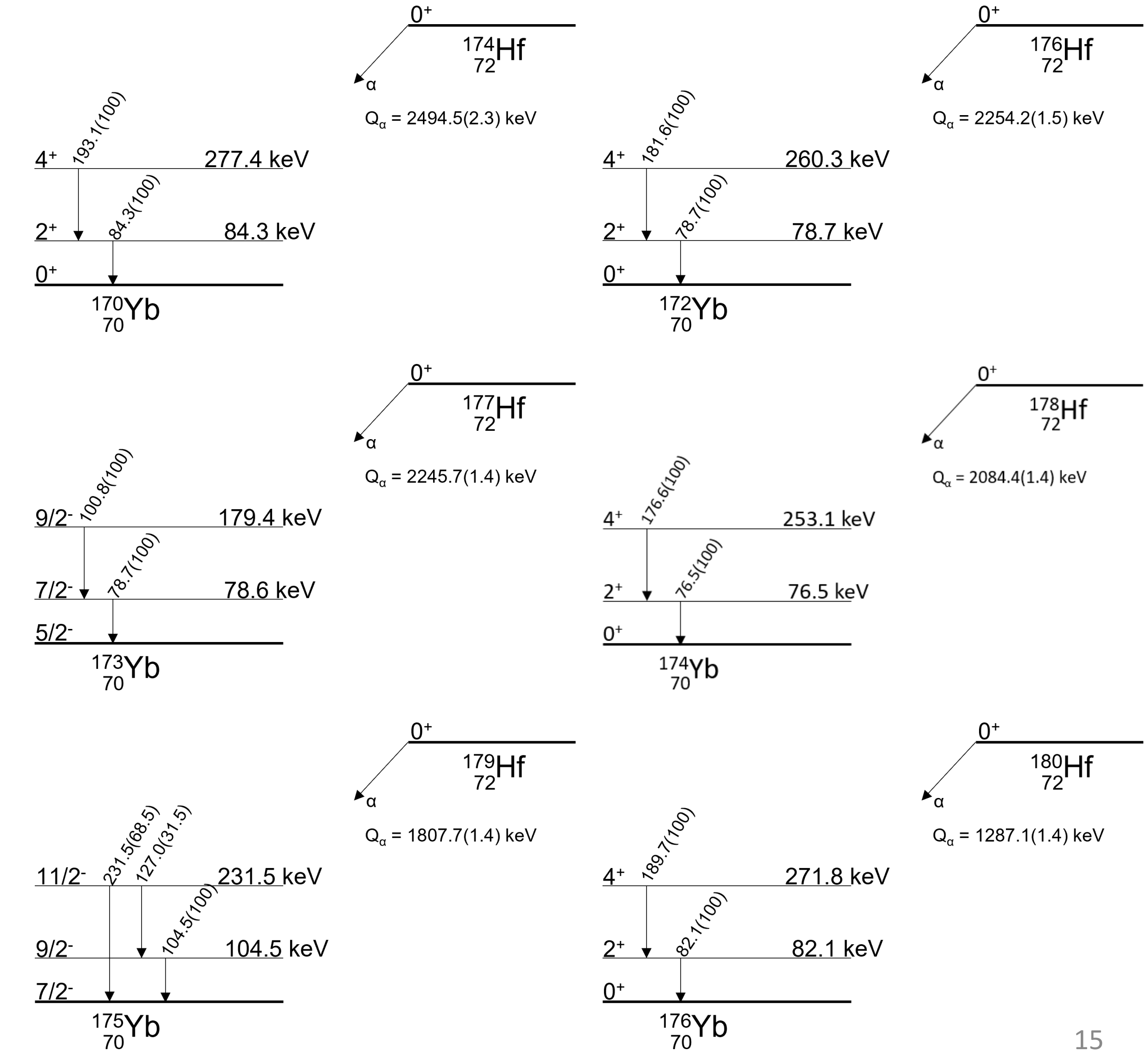
BACKUP SLIDES

Simplified decay schemes of naturally occurring Hf isotopes

2ε, εβ⁺ decay of ^{174}Hf



α decays of Hf isotopes considering the first two excited energy levels of the daughter nuclei. Energies of the excited levels and of the emitted γ quanta are shown. Relative probabilities of a single energy level are given in parentheses. The ^{175}Yb isotope decays via β^- with $T_{1/2}$ = 4.185(1) d, while all the other Yb nuclei are stable.



Pulse shape discrimination (PSD) based on pulse mean time

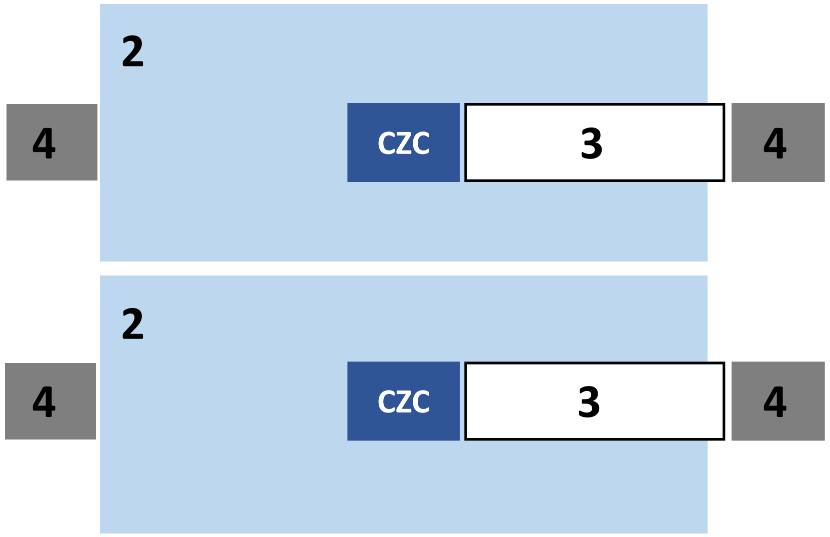
The difference in scintillation time profile of each event was used in order to determine its “mean time” ($\langle t \rangle$) according to:

$$\langle t \rangle = \sum f(t_k) t_k \Big/ \sum f(t_k)$$

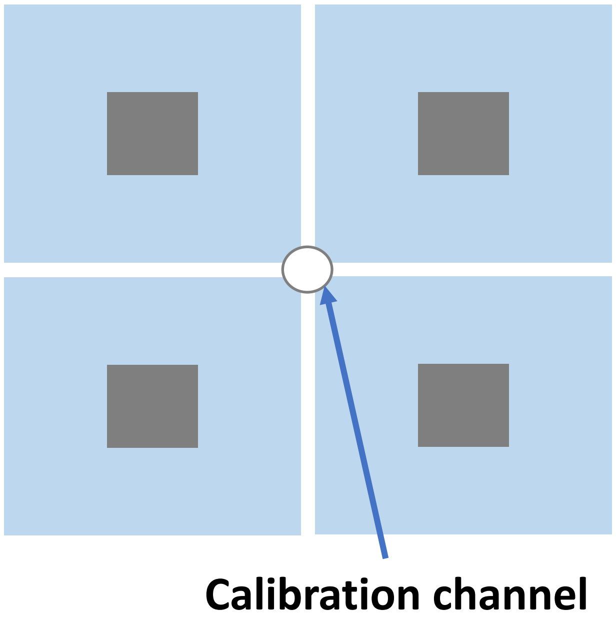
where the sum is over the time channels, *k*, starting from the origin of the pulse up to 8 μs. Moreover, *f(t)* is the digitized amplitude (at the time t) of a given signal.

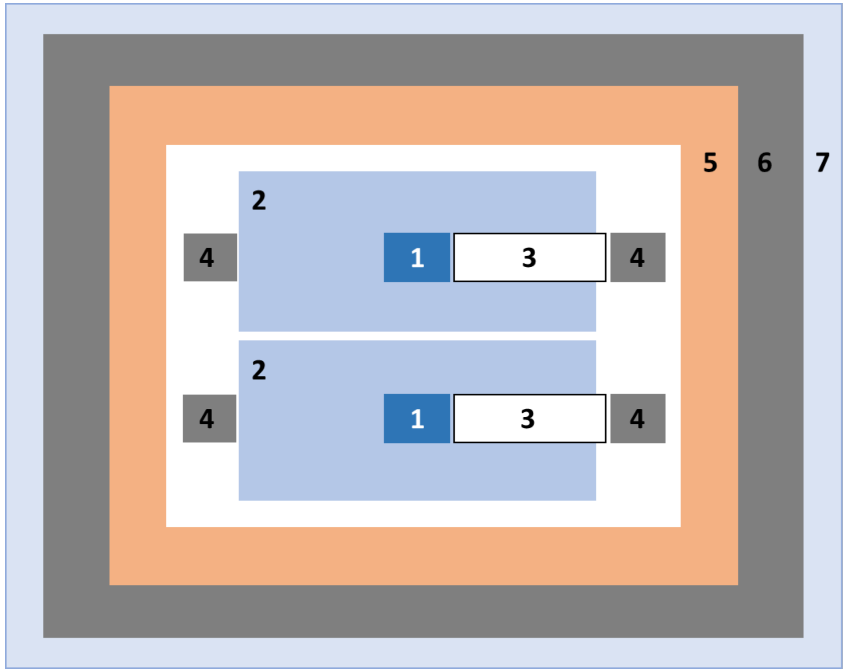
BREEZE detector array schematic (1st phase planned @ Queen's)

Side view



Front/back view





NEWS-G3 low-background setup

<u>Four separate detector's modules, each consist of:</u>

(1) CZC ∅ 21×21 mm^3

(2) Plastic scintillator block roughly 200×200×300 mm^3

(3) Quartz light guide ∅ 25×(100-150) mm^3

(4) 2 low-background PMTs

(5) OFHC Cu, 10 cm

(6) Pb, 20 cm

(7) HDPE, 10 cm

(8) 4π muon veto