Developments, features and perspectives of crystal scintillators of the Cs_2MCl_6 family (M = Hf or Zr) to search for rare processes

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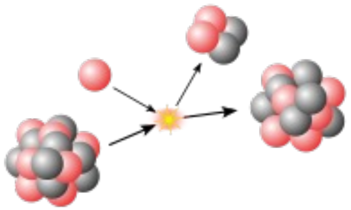
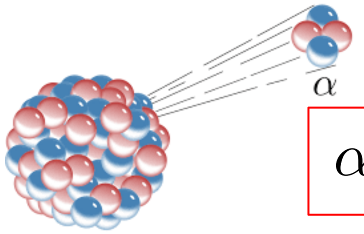
Interest in studying the 2β and rare α decay



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

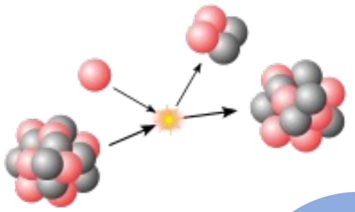


$$\alpha : \ {}^A_Z X \rightarrow {}^A_{Z-2} Y + {}^4_2 He$$

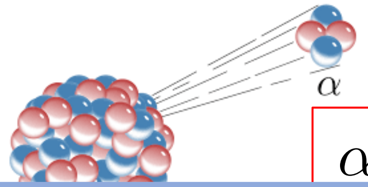
- **2ν2β** decay allowed in the SM → lepton number L conserved
- **0ν2β**, if observed, could open a new window beyond the SM → L violated ($\Delta L = 2$) → massive Majorana neutrino.
- Current sensitivity for $2\nu2\beta^-$ decay: $T_{1/2} \sim 10^{18} - 10^{24}$ yr; for $0\nu2\beta^-$: $T_{1/2} \sim 10^{24} - 10^{26}$ yr.
- **To test,** e.g., **calculations of different nuclear shapes** and the **decay modes** that involve the vector and **axial-vector g_A weak effective coupling constants**.

- **Details** on the **nuclear structure**, the **nuclear levels** and the **properties of nuclei**.
- **Rare** α decay: $T_{1/2} > 10^{14}$ yr.
- Essential also for **nuclear and particle astrophysics studies** (α–capture reactions, β–delayed fission, nucleosynthesis).

Interest in studying the 2β and rare α decay



$$0\nu2\beta^- : \ {}^A_ZX \rightarrow {}^A_{Z+2}Y + 2e^-$$



$$\alpha : \ {}^A_ZX \rightarrow {}^A_{Z-2}Y + {}^4_2He$$

Requirements: high radiopurity (e.g. $\lesssim$ 0.1 ppb), high-sensitivity (energy threshold ~ keV), good detector performances (efficiency > 90%), well known technology, stability over the running conditions (variation < 1%), acceptable cost (1,000 - 10,000 Eur/kg), safety, many isotopes and decay modes explorable etc.

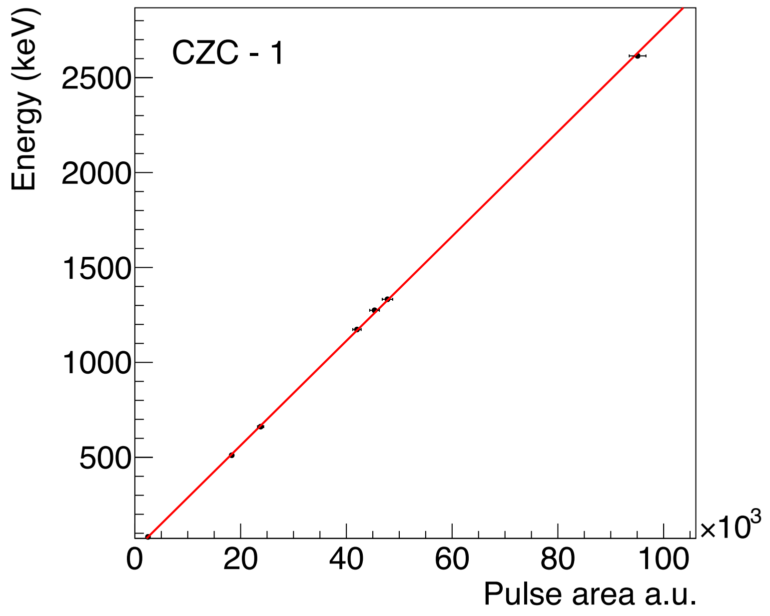
- **2ν2β** de… conserve…
- **0ν2β**, if … SM → L v…
- Current … for 0ν2β…
- **To test,** e.g., **calculations of different nuclear shapes** and the **decay modes** that involve the vector and **axial-vector g_A weak effective coupling constants**.

…**ture**, the …**of nuclei**.

… **particle** … reactions, …s).

Cs_2HfCl_6 (CHC) and Cs_2ZrCl_6 (CZC) crystal scintillators

Some general properties	Cs_2HfCl_6	Cs_2ZrCl_6
Effective atomic number	58	46.6
Density (g/cm^3)	3.9	3.4
Melting point (°C)	820	850
Crystal structure	Cubic	Cubic
Emission maximum (nm)	400 - 430	450 - 470
Scintillation time constants (μs)	0.4; 5.1; 15.2 *	0.4; 2.7; 12.5*
Light Yield	up to 30000 photons/MeV**	up to 41000 photons/MeV**
Linearity of the energy response	Excellent, down to 100 keV	Excellent, down to 100 keV
Energy resolution (FWHM, %) @ 662 keV	3.2 - 3.7***	3.5 - 7.0***
Pulse-shape discrimination ability	Excellent	Excellent
Mass fraction of isotope of interest (%)	27	16



*   *for alpha events at room temperature (Dalton Trans. 2022, 51, 6944-6954)*

** *for gamma quanta at room temperature*

*** *depends on the crystal quality, surface treatment and readout system*

Production and growth of Cs_2HfCl_6 crystals

Produced at **Queen's University, Canada**

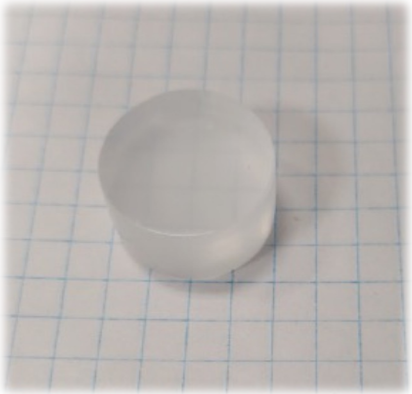
CHC (6.90 g)

- ✓ CsCl (99.998%) + **$HfCl_4$** (99.8%) as starting materials.
- ✓ $HfCl_4$ powder subjected to a three-fold purification process.
- ✓ Grown by **Bridgman technique**: growth at 5° C/cm, at 1 cm/day).

CHC (16.87 g)

- ✓ CsCl (99.9%) + **$HfCl_4$** (98%) as starting materials.
- ✓ $HfCl_4$ powder subjected to a three-stage sublimation process.
- ✓ Grown by **vertical Bridgman technique**: «fast» growth 25° C/cm, at 1.46 mm/hours) + «slow» growth (20° C/cm, at 0.5 mm/hour).

∅21.20(5)×12.8(1) mm



Then polished with 1200 grit sandpaper, mineral oil as lubricant, cleaned by toluene.

Cs_2HfCl_6 chemical contaminants

measured by ICP-MS analysis.

The limits are at 68% C.L.

Nuclide	Concentration (ppb)
	CHC
	6.90 g [1]
^{144}Nd	<2.4
^{147}Sm	0.6(1)
^{148}Sm	0.4(1)
^{151}Eu	19(7)
^{152}Gd	<0.02
^{180}W	<0.4
^{184}Os	<0.003
^{186}Os	<0.25
^{190}Pt	<0.02
^{209}Bi	<2

Element	Concentration (ppb)
	CHC
	16.87 g [2]
U	0.73(22)
Th	0.16(5)
Pb	440(130)
Sm	2(1)
K	1900(570)

[1] V. Caracciolo et al., NPA 1002 (2020) 121941.
[2] P. Belli et al. 2024, to appear

Cs_2HfCl_6 crystal radiopurity

measured with the ultra-low background **HP-Ge** γ spectrometers of the **STELLA** facility at LNGS over ~ 700 hours.

Chain	Nuclide	Activity (mBq/kg)	
		CHC	
		6.90 g [1]	**16.87 g** [2]
^{238}U	^{226}Ra	<23	<13
	^{234}Th	<0.80	<1200
	^{234m}Pa	<0.48	<18
^{235}U	^{235}U	<14	<18
^{232}Th	^{228}Ra	<12	<13
	^{228}Th	<3.6	<17
	^{202}Pb	<9.1	-
	^{190}Pt	<20	-
	^{181}Hf	<11	-
	^{137}Cs	$0.78(8)\times10^3$	<10
	^{134}Cs	79(8)	37(4)
	^{132}Cs	<15	-
	^{60}Co	<25	-
	^{44}Ti	10(4)	-
	^{40}K	$0.4(1)\times10^3$	<240

Natural (^{238}U to ^{228}Th rows)

Artificial (^{137}Cs)

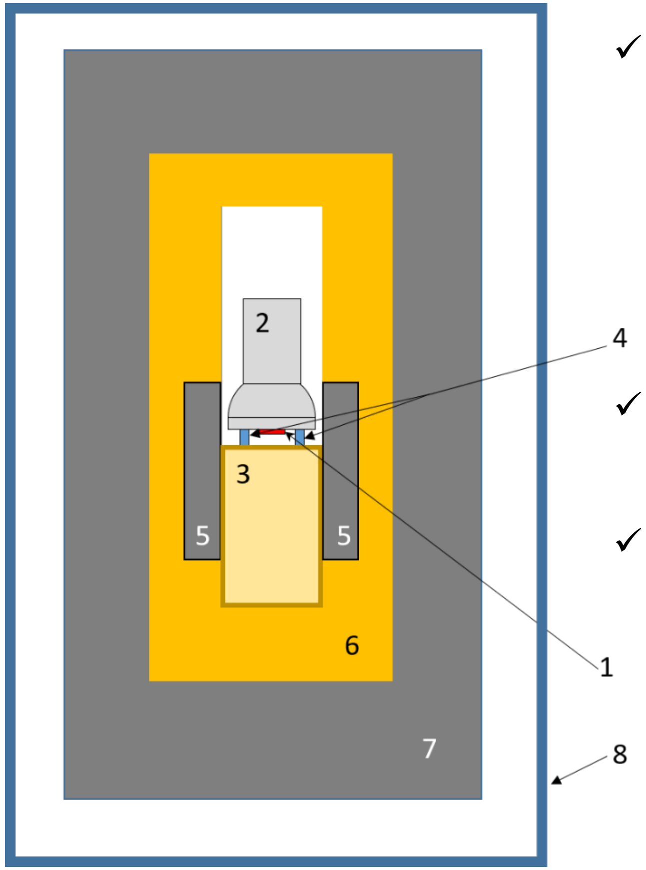
Cosmogenic activation (^{134}Cs, ^{132}Cs)

Natural (^{40}K)

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

[1] V. Caracciolo et al., NPA 1002 (2020) 121941.
[2] P. Belli et al. 2024, to appear

First low-background measurement of CHC at LNGS

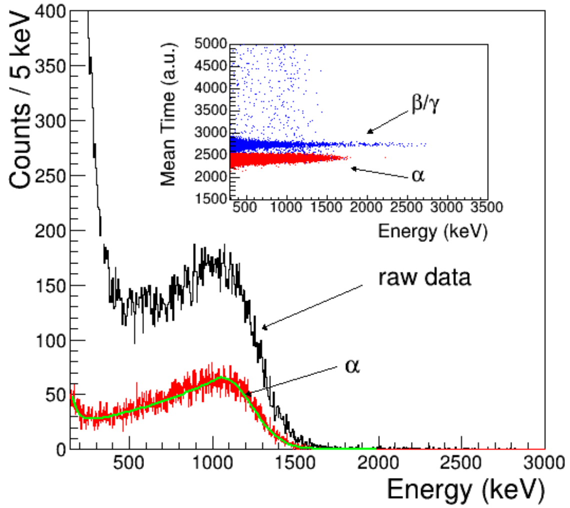


- ✓ CHC crystal (6.90(1) g) coupled low-radioactivity PMT (Hamamatsu R6233MOD) placed above the end-cap of the ultra-low background HP-Ge
- ✓ CAEN DT5720B digitizer 250 MSamples/s;
- ✓ 2848 h data taking

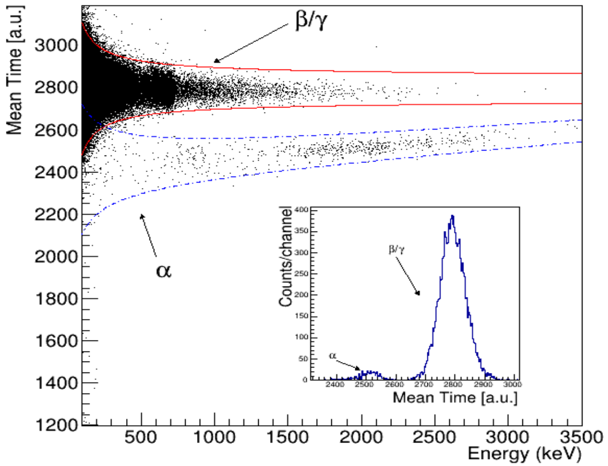
STELLA facility of the LNGS

(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

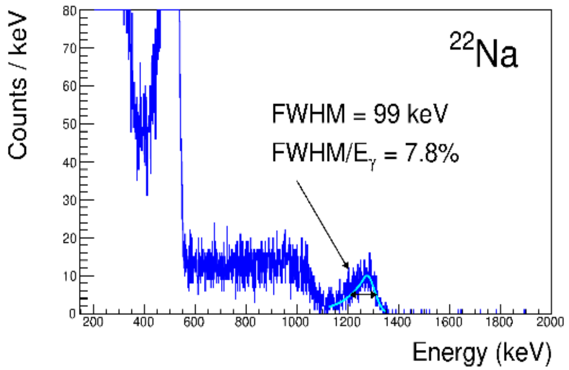
Preliminary quenching factor (QF) estimation → ^{241}Am

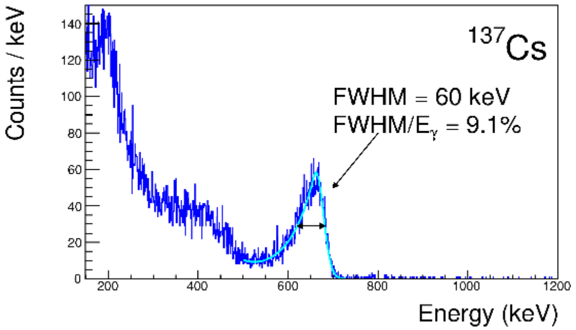


Selection efficiency is 99% in [0.4–3.0] MeV



Energy resolution = 9.1% @ 662 keV, γ



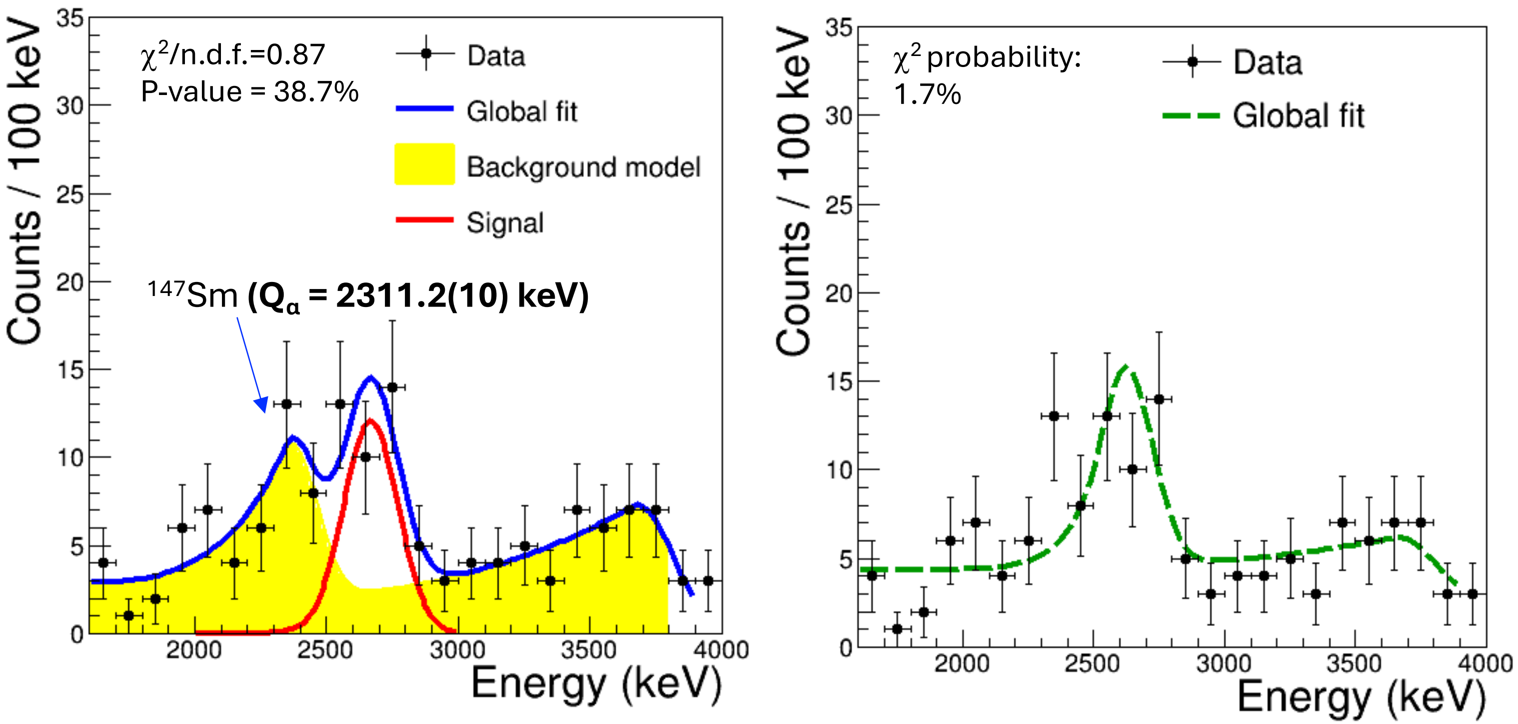


Fit of the α spectrum of CHC crystal and results

Energy spectrum of the α events selected by PSD over 2848 h.

Signal: α decay of ^{174}Hf (Q_α = 2494.5(2.3) keV)

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



In **2848** h of data taking, the measured **553(23)** *α* events (expected number = **1100** counts) **rule out the old result of 2.0(4)x10^{15} yr** (*T.P. Kohman, Phys. Rev. 121, 1758, 1961*) for $T_{1/2}$ *of* α decay of ^{174}Hf.

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

New measurement of the α decay of ^{174}Hf to the g.s. of ^{174}Yb

Fit with 2 gaussians + pol1

Parameters of the fit:

First peak

Area = (36 ± 15) counts

Peak position = (787 ± 18) keV

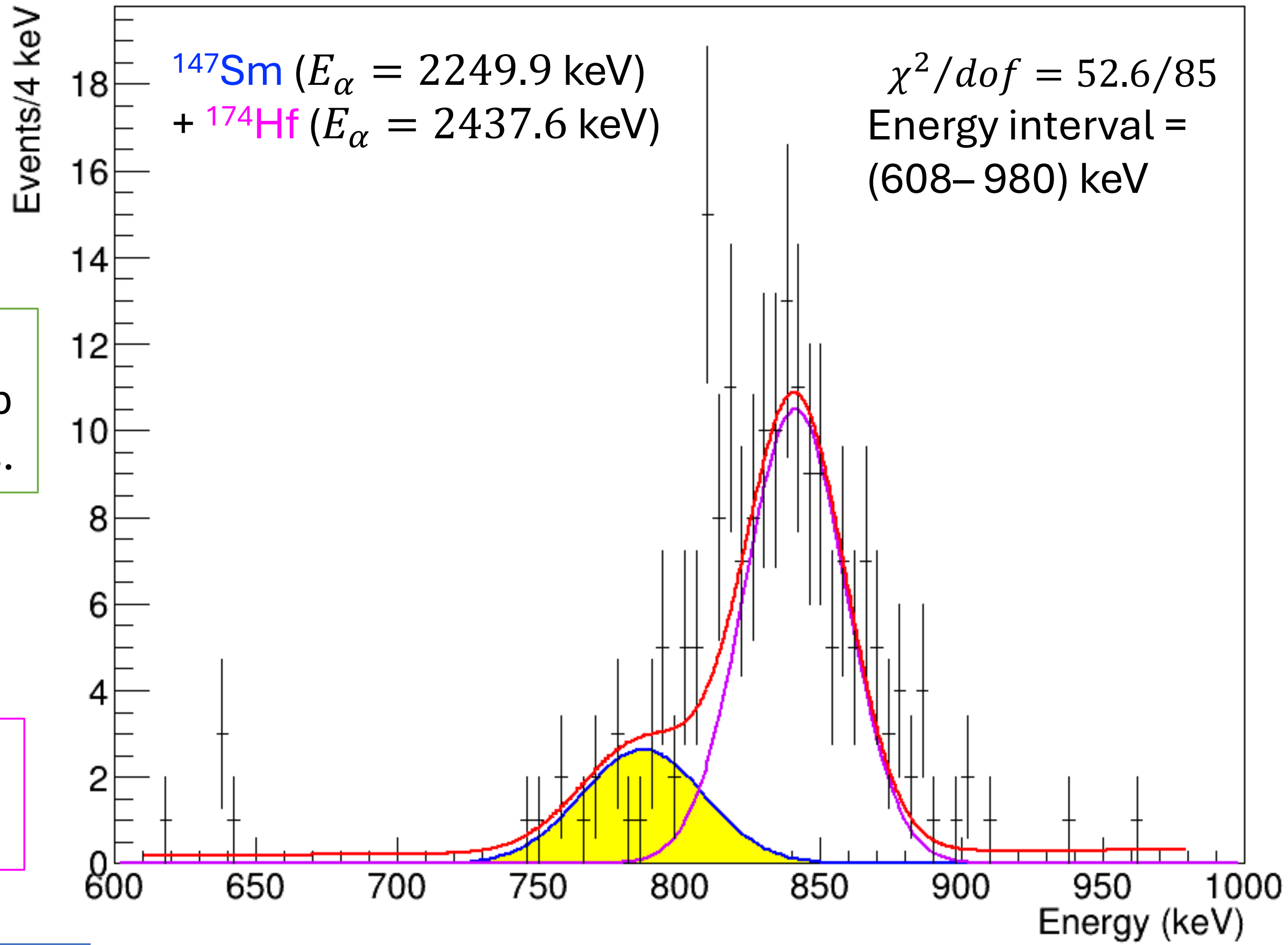
Activity of ^{147}Sm = (0.25 ± 0.10) mBq/kg, corresponding to a concentration of (2.0 ± 0.8) ppb of ^{nat}Sm, in agreement with ICP-MS measurements.

Second peak

Area = (118 ± 37) counts

Peak position = (841 ± 3) keV

$$T_{1/2} = 3.8^{+1.7}_{-0.9} \times 10^{16}\ \mathrm{yr}$$ of α decay of ^{174}Hf to the g.s. of ^{174}Yb



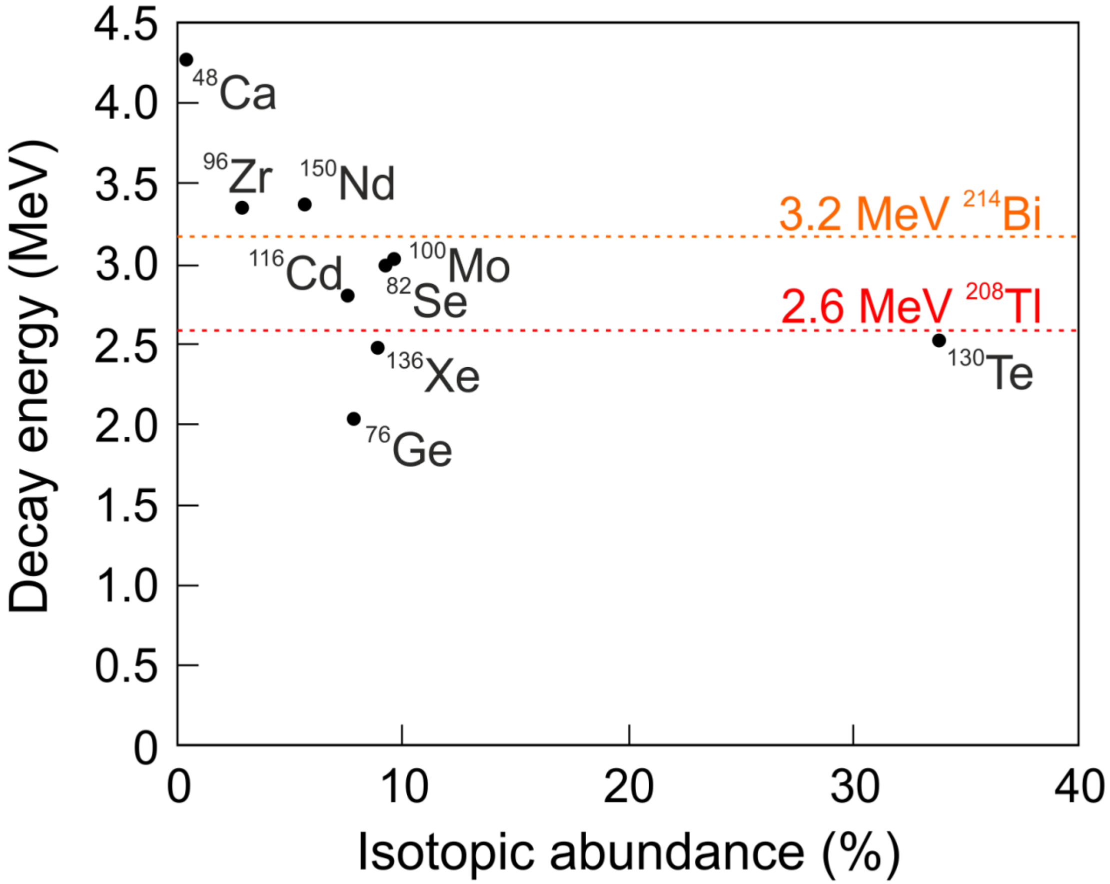
- Currently, 4 CHC crystals (∅ 26 ×20 mm^3) encapsulated in silicone-based sealant, **are ongoing** to improve sensitivity on α decay of ^{174}Hf.

Q.F. $= 0.350 \pm 0.008$ for ^{147}Sm

Q.F. $= 0.345 \pm 0.001$ for ^{174}Hf

$0\nu2\beta$ searches with non-trivial candidates

There are more than 60 potentially 2β-active isotopes, but only few of them are currently under consideration



Recent proposal: to study
$0\nu2\beta$ of **^{96}Zr** with novel Cs_2ZrCl_6 scintillators
via "source = detector" experimental approach

^{76}Ge, ^{130}Te, ^{136}Xe are facing issues with an internal and environmental gamma background, while profiting from well-developed crystal production and material purification technologies.

^{82}Se, ^{100}Mo, ^{116}Cd – only ^{100}Mo is under consideration due to a well-developed detector material and its high radiopurity.

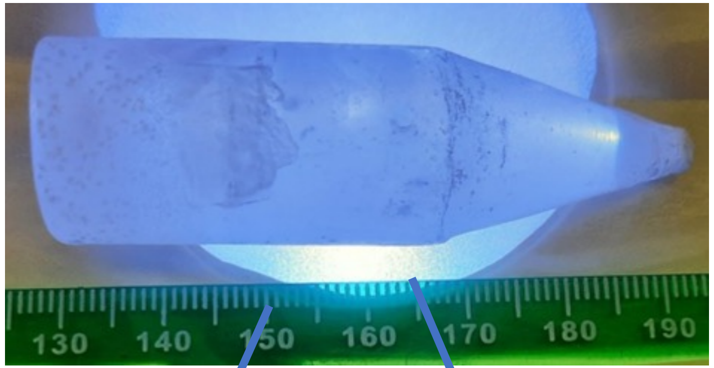
^{48}Ca, ^{96}Zr, ^{150}Nd are the less studied due to combination of unfavorable experimental conditions specific to each of them.

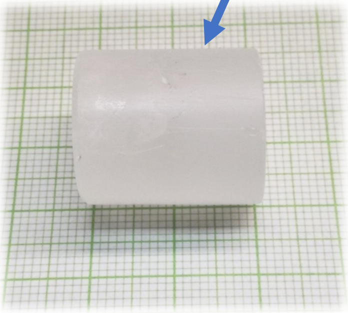
- *$Q_{\beta\beta}(^{96}Zr) = 3.35$ MeV*
- *Favorable from a theoretical point of view $T_{1/2} \sim (Q_{\beta\beta})^5$*
- *Reasonable natural i.a. (2.8%)*
- *New advanced detector material (Cs_2ZrCl_6)*
- *Crystal production under full control*
- *Extensive studies of the detector properties*

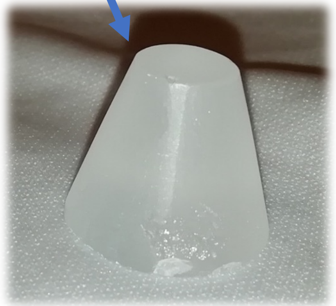
Production and growth of Cs_2ZrCl_6 crystals

Produced at **Queen's University, Canada**

∅21.5×60 mm, about 60 g







CZC cone (10.63 g) & cylinder (23.95 g)

- ✓ CsCl (99.9%) + **$ZrCl_4$** (99.9%) as starting materials
- ✓ $ZrCl_4$ powder subjected to a two-stage sublimation process
- ✓ Grown by **vertical Bridgman technique**: «fast» growth (28° C/cm, at 1.5 mm/hour) + «slow» growth (25° C/cm, at 0.5 mm/hour)

CZC -1 (19.21 g), CZC – 2 (19.86 g), CZC – 3 (20.43 g)

- ✓ CsCl (99.9%) + **$ZrCl_4$** (99.9%) & CsCl (99.999%) + **$ZrCl_4$** (99.99%) as starting materials
- ✓ $ZrCl_4$ powders subjected to a two-stage sublimation process
- ✓ Grown by **vertical Bridgman technique**: «fast» growth 20° C/cm, at 24 mm/day) + «slow» growth (25° C/cm, at 12 mm/day).
- ✓ Then the single crystalline boules cooled-down to room temperature with a temperature gradient of 0.1°C/min.

+ encapsulated using SYLGARD 184™ Silicone Elastomer Kit

Then polished with 1200 grit sandpaper, mineral oil as lubricant, cleaned by toluene.

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Chemical purity of reagents at each production stage

HR-ICP-MS, concentrations are in ppb with 25% uncertainty

	CsCl initial	$ZrCl_4$ initial	$ZrCl_4$ 1st sublimation	$ZrCl_4$ 2nd sublimation	CZC 1st growth, tail	CZC 1st growth, nose	CZC 2st growth, middle
K	300	15000	700	700	2500	200	500
La	0.7	1.5	1	1	1	0.6	0.6
Ce	1.5	2	1	1	2.5	3	2
Pr	0.1	4	6	6	1.5	1	1
Nd	<1	30	25	30	5	3	3
Sm	0.5	1	4	1	1	0.6	0.6
Eu-Lu	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Hf	35	6400	5200	5600	1200	1800	1600
Ta, W, Re, Os, Ir	<2	<2	<2	<2	<2	<2	<2
Pt	<1	<100	<100	<100	<25	<25	<25
Tl	0.4	<0.2	<0.2	0.2	1	<0.2	<0.2
Pb	<1	30	20	30	150	1	13
Bi	<0.5	<0.5	1.5	2.6	1.5	<0.5	1.6
Th	<0.05	70	0.5	0.2	<0.05	<0.05	<0.05
U	<0.05	1000	7	0.36	0.35	0.13	<0.05

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Cs_2ZrCl_6 crystal radiopurity

measured with the ultra-low background **HP-Ge** γ spectrometers of the **STELLA** facility at LNGS over 700 hours.

Chain	Nuclide	Activity (mBq/kg)	
		Cone	Cylinder
		10.63 g	**23.95 g**
^{238}U	^{226}Ra	60(10)	< 8.7
	^{234}Th	< 180	< 260
	^{234m}Pa	< 630	< 160
^{235}U	^{235}U	< 16	< 12
^{232}Th	^{228}Ra	< 16	< 23
	^{228}Th	< 6.7	< 8.2
	^{137}Cs	< 7.1	< 1.6
	^{134}Cs	49(6)	42(5)
	^{132}Cs	< 8.2	< 11
	^{40}K	<120	<95

Surface cross-contamination happened during the sample preparation and installation.

Natural (^{226}Ra to ^{228}Th)

Artificial (^{137}Cs)

Cosmogenic activation (^{134}Cs, ^{132}Cs)

Natural (^{40}K)

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

Our crystals are rather clean, even if they were grown from 99.9% purity grade raw materials

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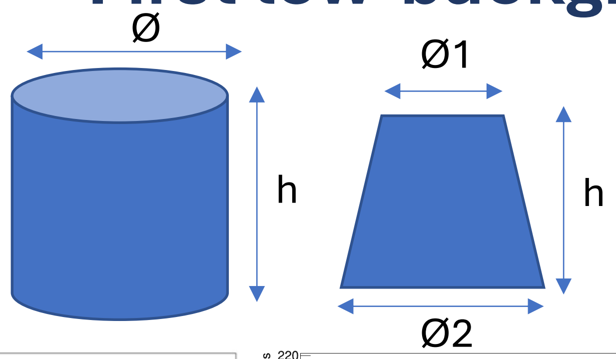
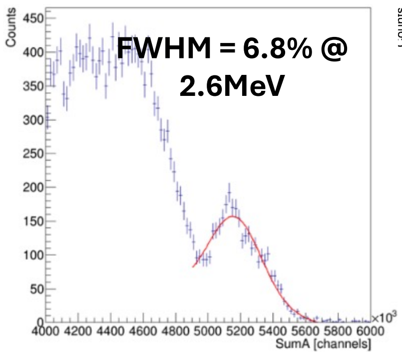
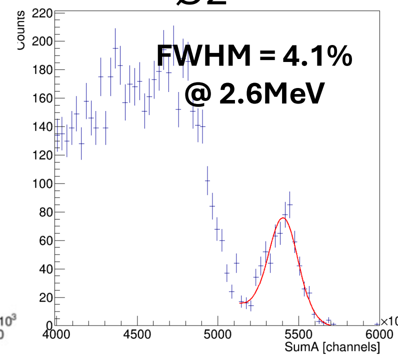
First low-background measurements of CZC at LNGS (Italy)

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

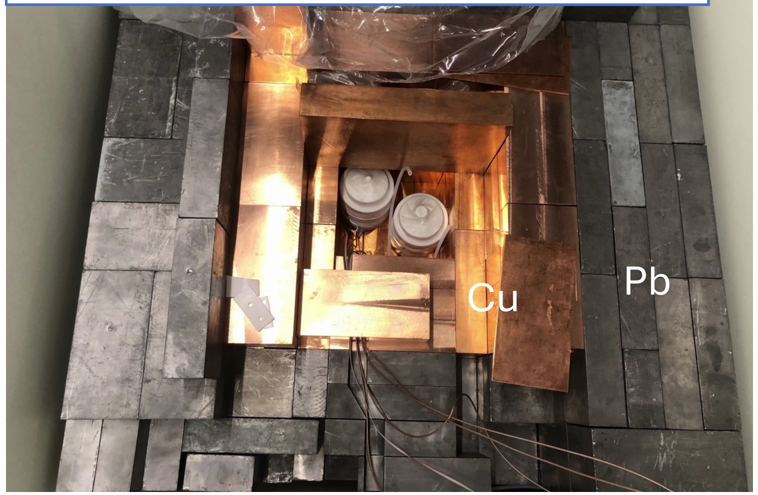


M=10,6(1) g
h =17,90(5) mm
Ø1=8,0(1) mm
Ø2=19,70(5) mm



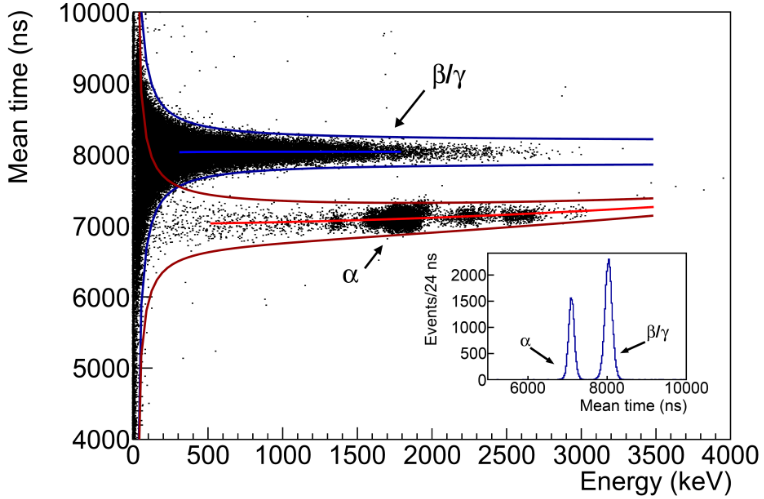


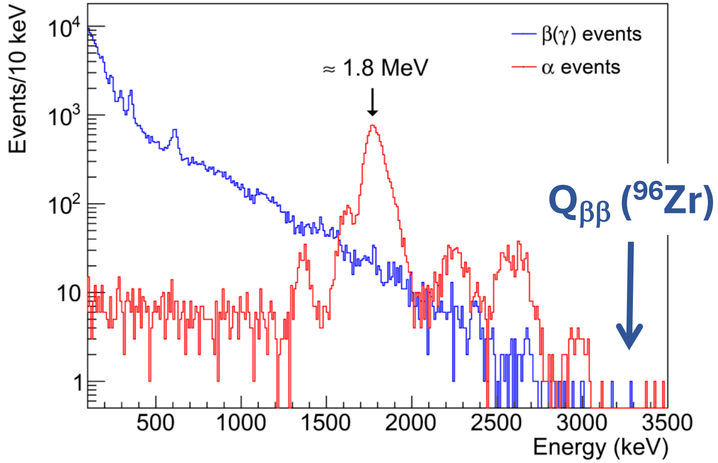
DAMA/CRYS setup (2021-2022)



- OFHC Cu (15 cm)
- Low-activity Pb (20 cm)
- HDPE (5 cm)
- Borated HDPE (5cm)

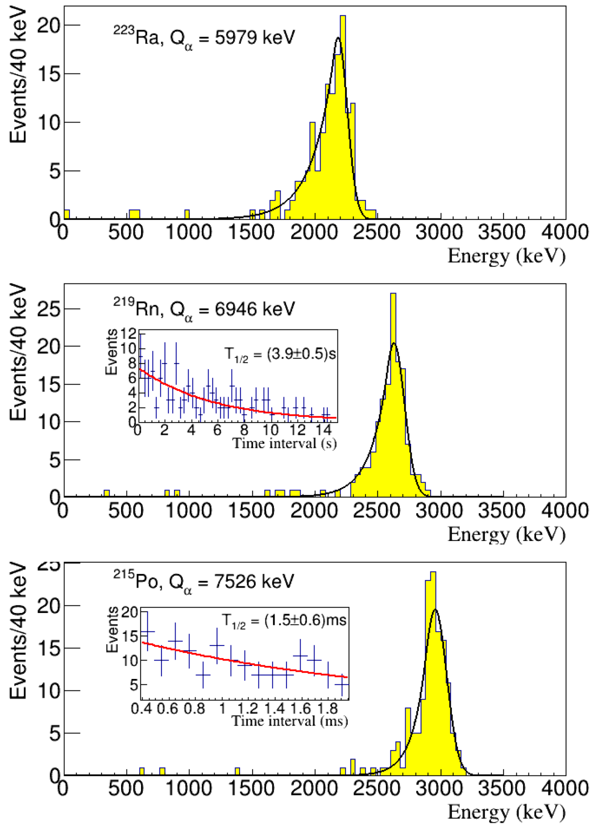
Selection efficiency is 99.7% in [0.2–3.5] MeV





Counting rate at ROI is 0.09 counts/(kg·keV·yr)

Time-amplitude analysis



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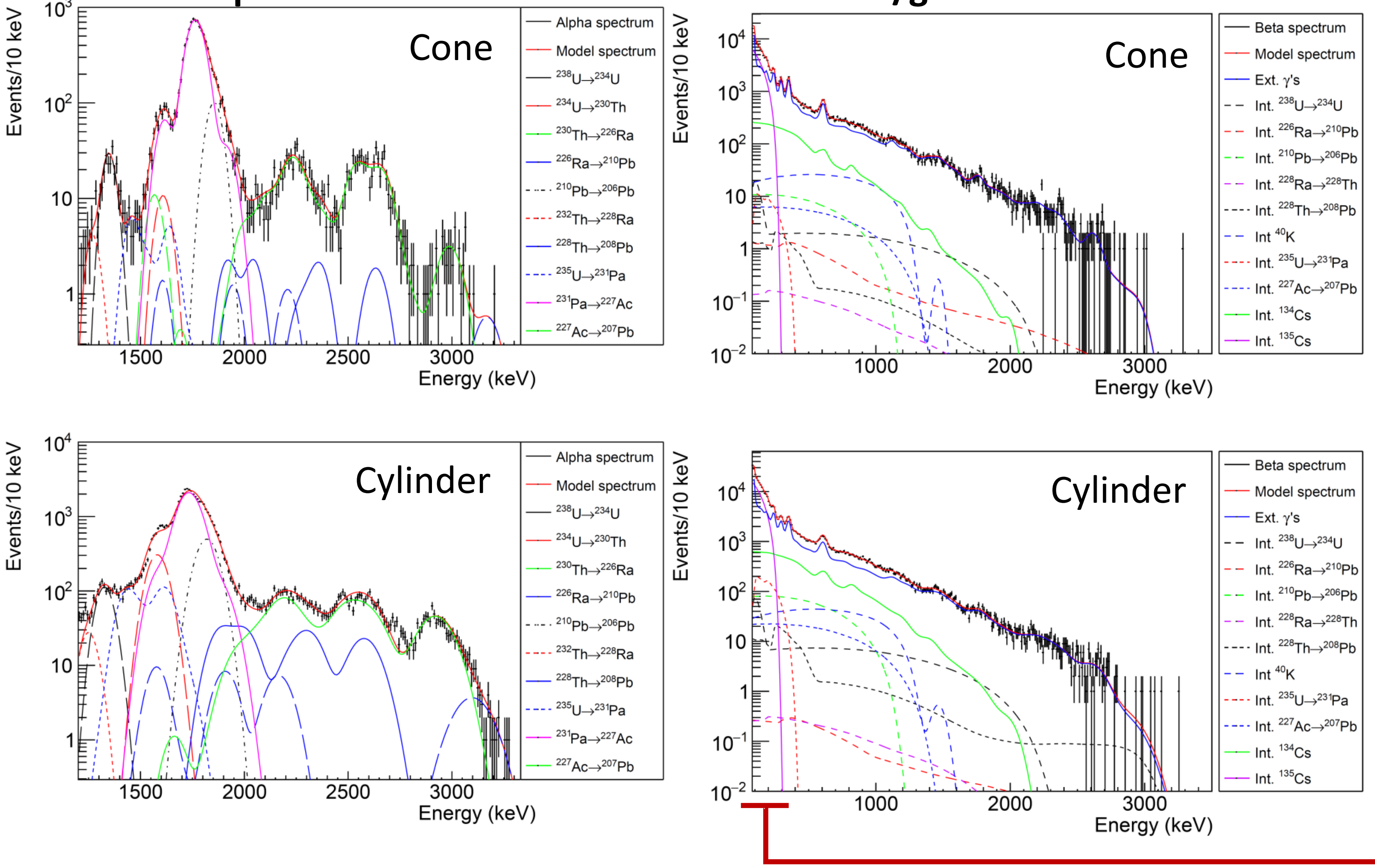
Cs_2ZrCl_6: Background model

Alpha events **Beta/gamma events**



Chain	Nuclide	Internal contamination (mBq/kg)	
		Cone	Cylinder
^{238}U	^{238}U	0.53(4)	1.17(5)
	^{234}U	0.2(1)	3.8(1)
	^{230}Th	0.23(7)	< 0.02
	^{226}Ra	0.03(3)	0.12(3)
	^{210}Pb	2.2(2)	6.7(3)
^{235}U	^{235}U	0.29(4)	3.0(1)
	^{231}Pa	**21.0(3)**	**33.9(3)**
	^{227}Ac	0.70(3)	1.08(3)
^{232}Th	^{232}Th	0.07(2)	0.28(7)
	^{228}Th	0.05(2)	0.44(4)
	^{134}Cs	36(4)	42(2)
	^{87}Rb	**≈ 270**	**≈ 290**
	^{40}K	6(1)	5(1)

- Comply with measurements on HPGe
- High contamination by ^{235}U daughters
- Segregation of impurities is observed

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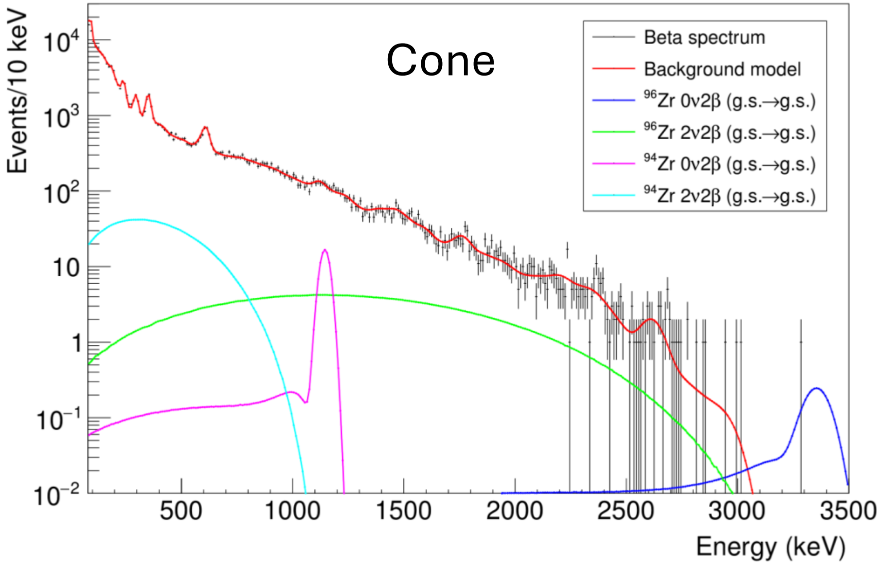
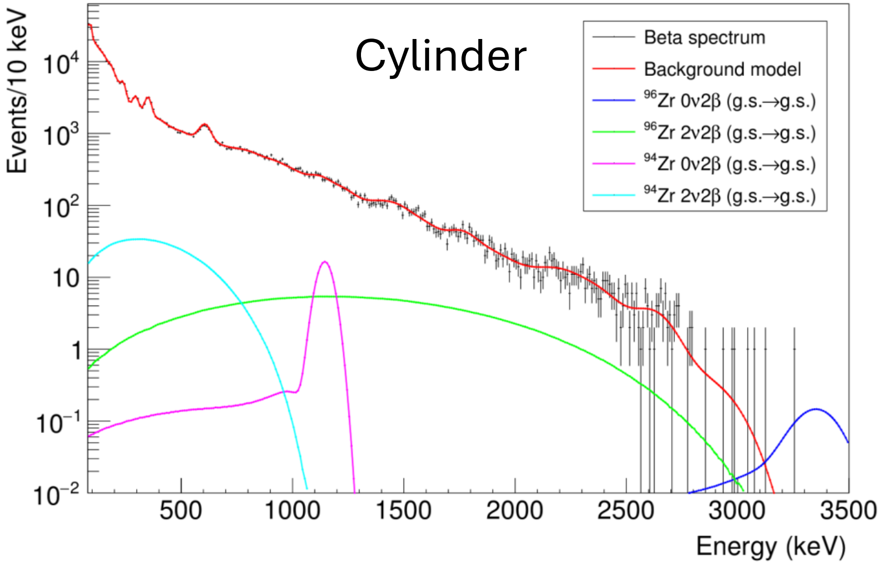
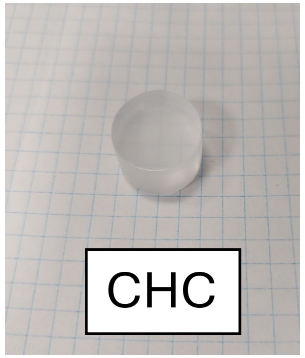
Experimental limits on various decay modes in $^{94,96}Zr$ isotopes

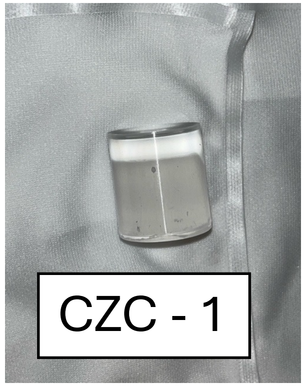


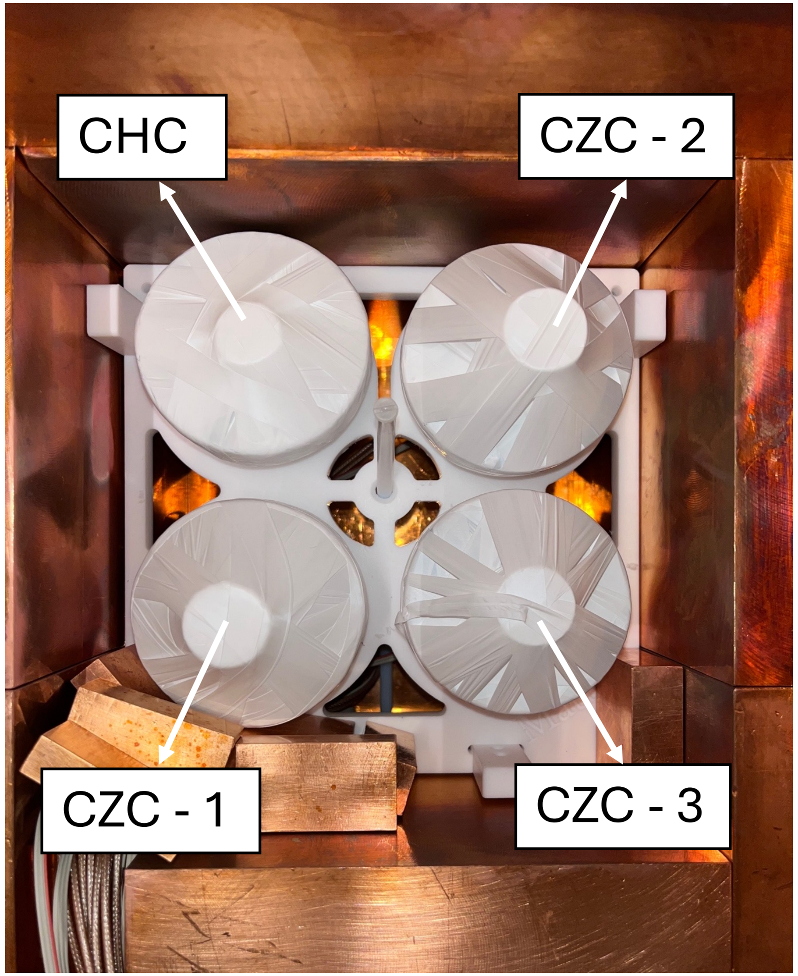


Transition	Decay mode	Final state of daughter nucleus, keV	Experimental limit on $T_{1/2}$ at 90% C.L., yr
$^{96}Zr \to {}^{96}Mo$	$0\nu2\beta$	g.s.	**> 1.5×10^{20}**
		2_1^+, 778	> 1.5×10^{19}
	$2\nu2\beta$	g.s.	> 7.4×10^{17}
		2_1^+, 778	> 3.8×10^{17}
	β	g.s.	> 1.0×10^{17}
$^{94}Zr \to {}^{94}Mo$	$0\nu2\beta$	g.s.	**> 2.6×10^{19}**
		2_1^+, 871	> 3.8×10^{18}
	$2\nu2\beta$	g.s.	**> 2.4×10^{18}**
		2_1^+, 871	> 1.9×10^{17}

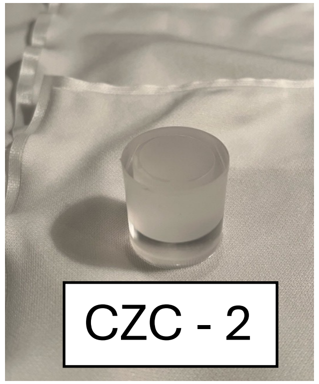
New low-background measurements in DAMA/CRYS setup (LNGS)



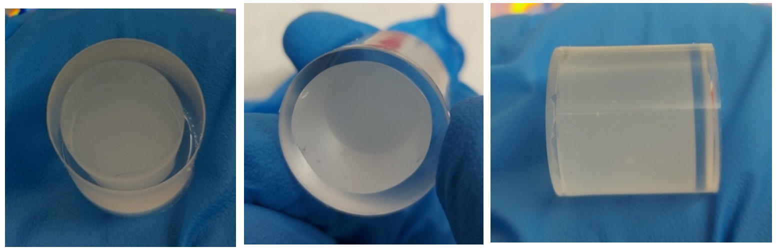




DAMA/CRYS setup at LNGS

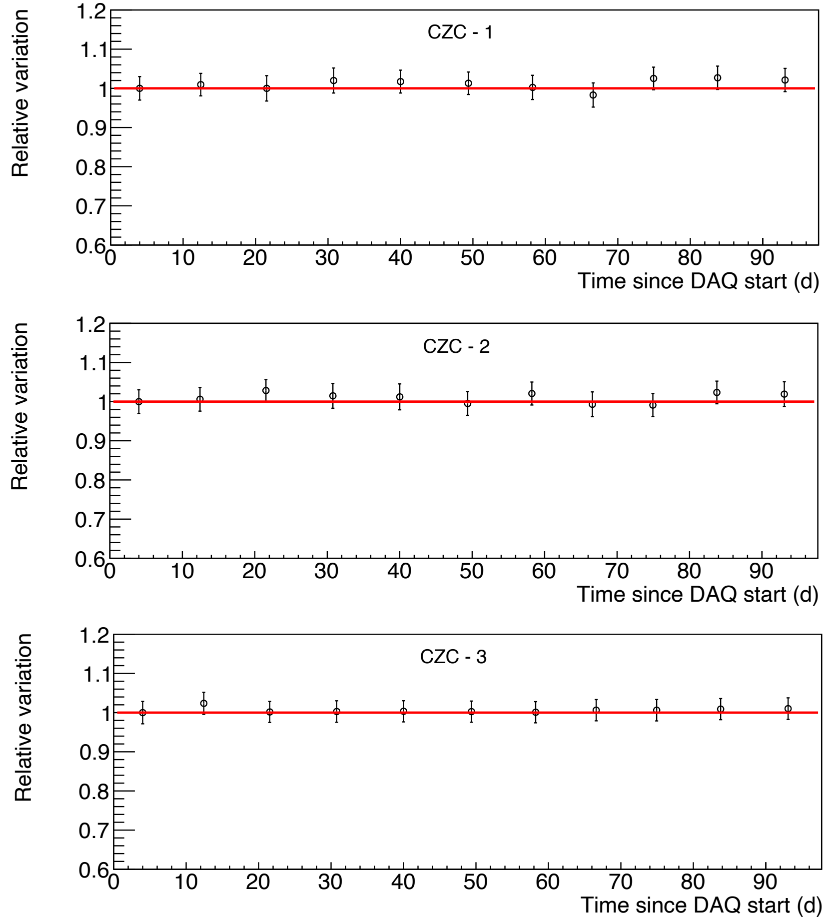


- ✓ Three new Cs_2ZrCl_6 crystals + one Cs_2HfCl_6
- ✓ Total mass of 3 CZC = 59.5 g, mass of CHC= 16.87 g.
- ✓ FWHM = 6-8% @ 662keV
- ✓ Produced from high purity and purified raw materials (> 99.99%)
- ✓ **CZC crystals are encapsulated in a silicon-based resin + quartz window**
- ✓ Modified experimental setup
- ✓ Measurements started on June 30th, 2023, for a total of 97.7 days live time



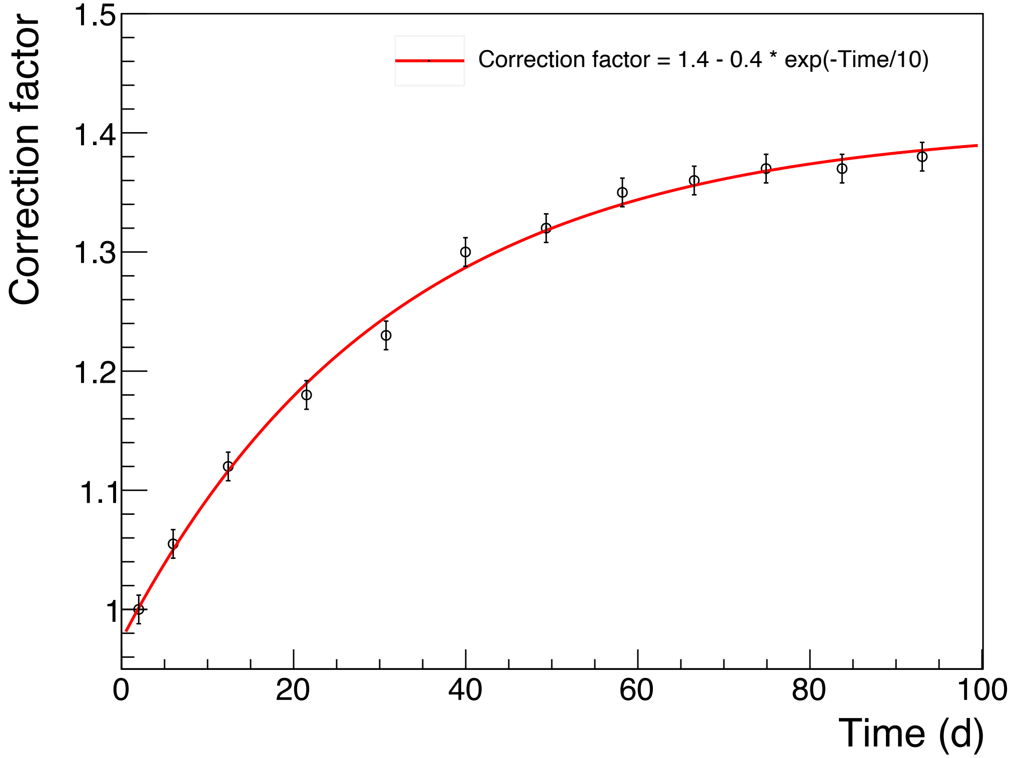
Detectors time stability and determination of the calibration parameters

Percentage variation of the position of a reference peak during the data taking



<u>The reference peaks remain rather stable within the experimental errors, with a typical variation <1%.</u>

Instead for the **CHC** a **small shift in time**: maybe due to the hygroscopicity of crystal (not encapsulated).



Correction factor to the calibration parameters as a function of time.

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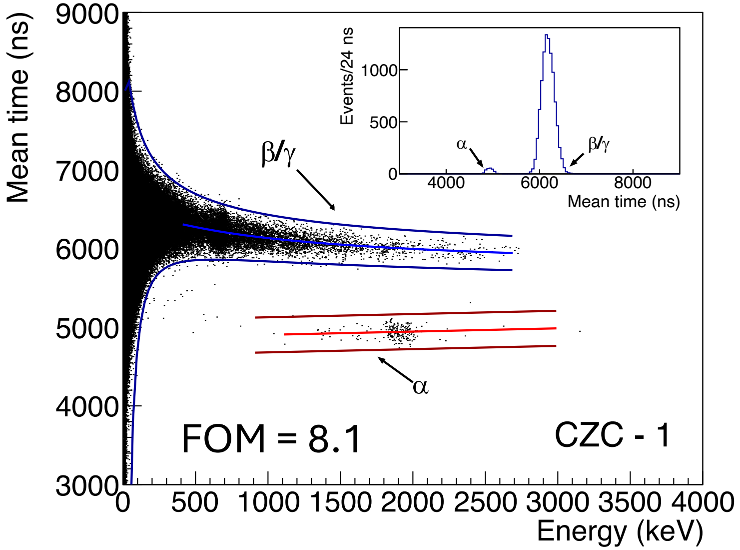
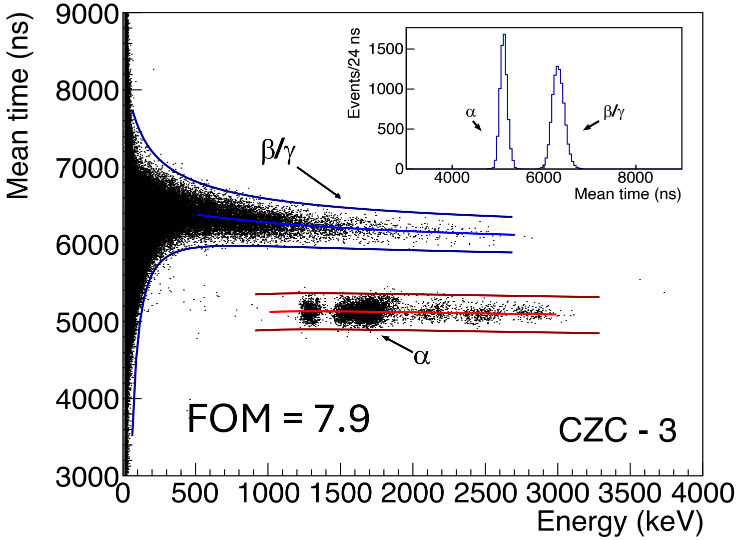
Data analysis of the Cs_2ZrCl_6 crystals

Selection efficiency is 99.7% in [0.5–3.5] MeV

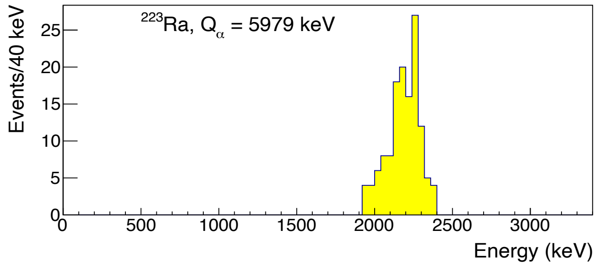


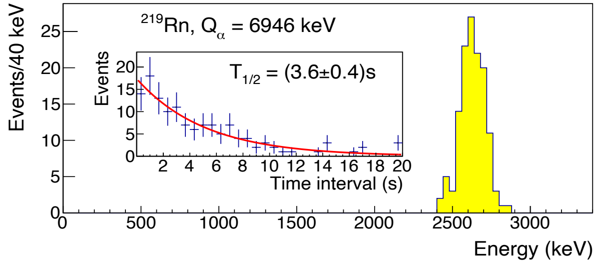


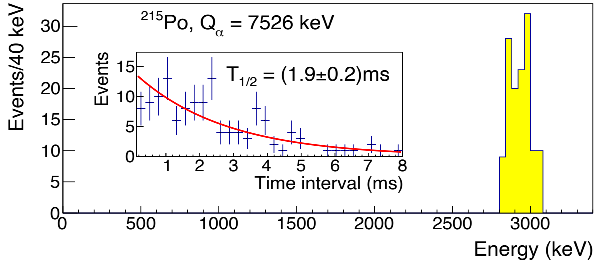
Time-amplitude analysis

A(^{227}Ac)	**< 0.020 mBq/kg in CHC**
	< 0.017 mBq/kg in CZC - 1
	= 0.56(6) mBq/kg in CZC -2
	= 0.88(8) mBq/kg in CZC - 3

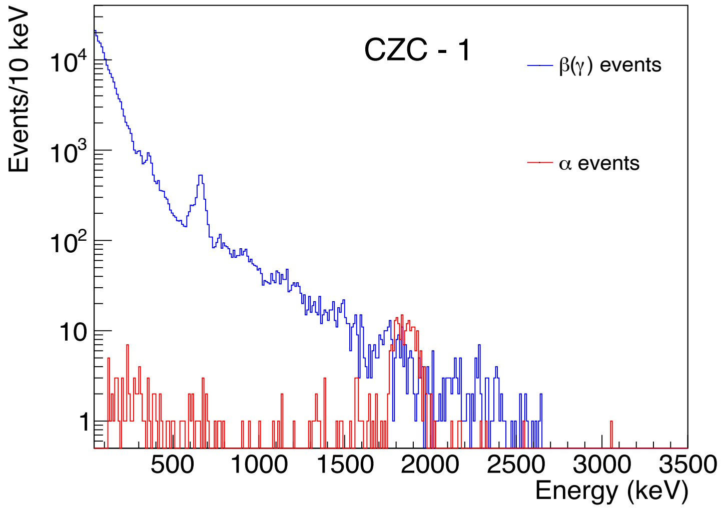
CZC - 3

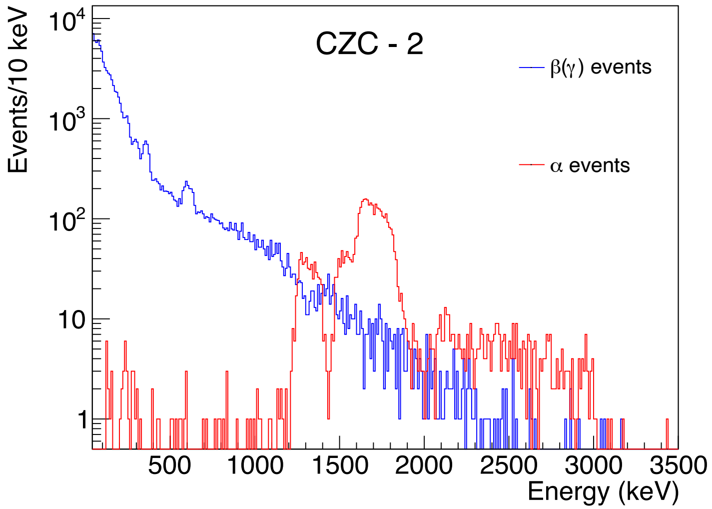






Measured energy spectra over 97.7 days of data taking





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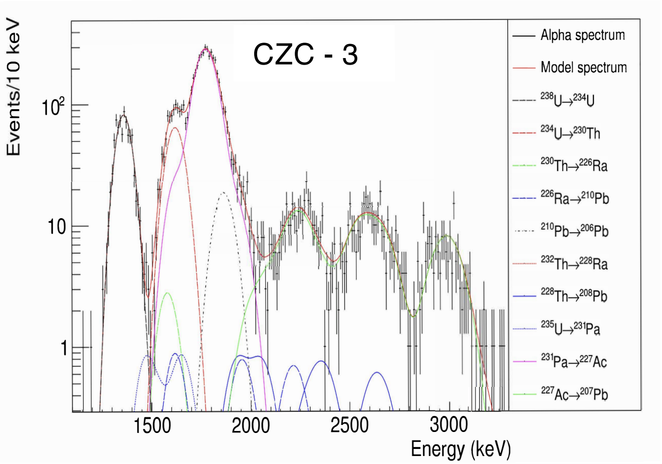
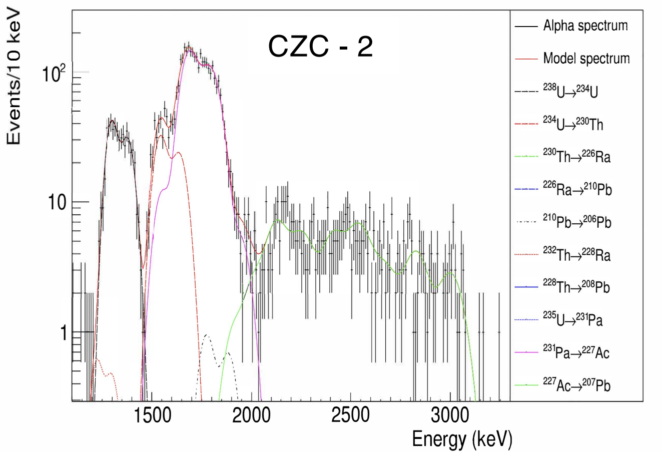
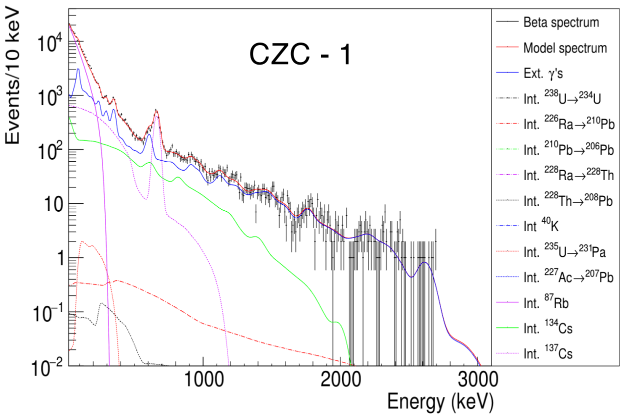
Cs_2ZrCl_6: Background model

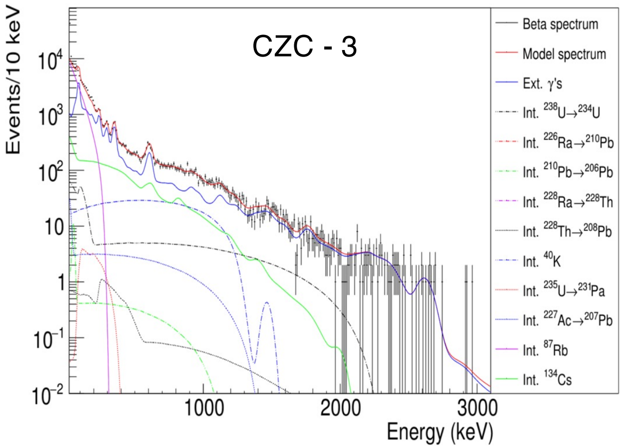
Alpha events





Beta/gamma events



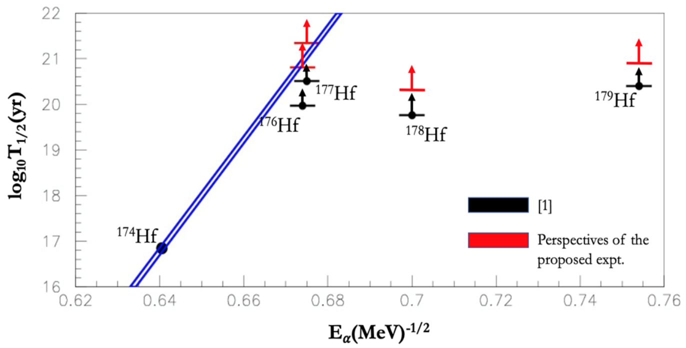


Contribution of external gammas from PMT's is dominant.

Chain	Nuclide	Internal contamination (mBq/kg)		
		CZC - 1	CZC -2	CZC – 3
^{238}U	^{238}U	< 0.08	3.16(14)	4.58(18)
	^{234}U	< 0.12	2.86(22)	4.20(33)
	^{230}Th	< 0.12	< 0.28	< 0.6
	^{226}Ra	< 0.05	< 0.06	< 0.17
	^{210}Pb	< 1.3	< 0.6	1.32(38)
^{235}U	^{235}U	< 0.14	< 0.16	< 0.37
	^{231}Pa	< 1.3	16.95(48)	24.69(56)
	^{227}Ac	< 0.013	0.62(3)	0.94(6)
^{232}Th	^{232}Th	< 0.10	< 0.12	< 0.12
	^{228}Th	< 0.011	< 0.04	< 0.16
	^{137}Cs	100(3)	-	-
	^{134}Cs	58(6)	42(7)	55(7)
	^{87}Rb	1067(5)	318(14)	441(9)
	^{40}K	< 1.1	11(2)	17(3)

Perspectives and conclusions

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



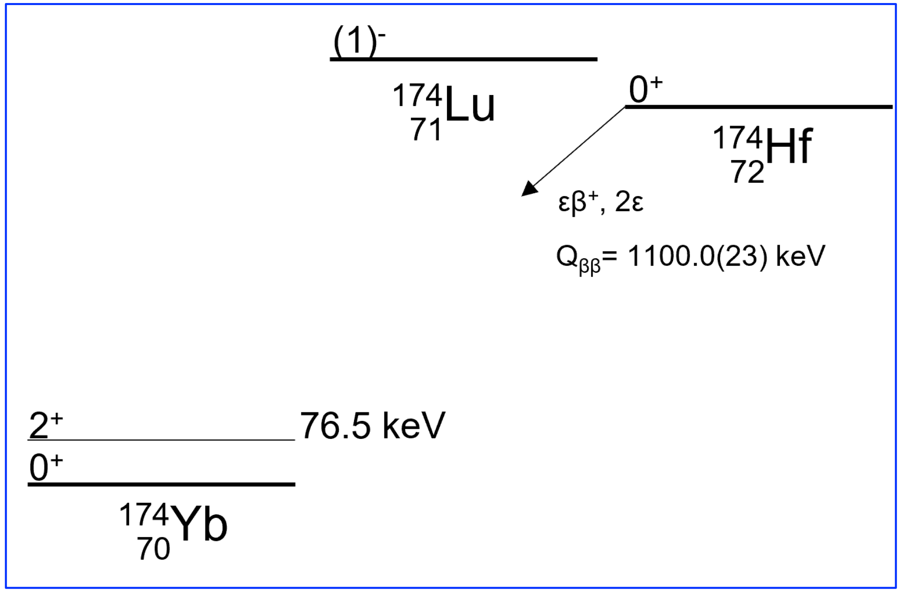
- The blue band is the extrapolation of the predictions on $T_{1/2}$ for all the Hf isotopes using the Geiger-Nuttall scaling law considering the data point observed in Ref. **[1]NPA 1002 (2020) 121941.**
- The red symbols represent the sensitivity that the measurement can reach using CHC crystal scintillators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

- First experiment using a Cs_2HfCl_6 crystal scintillator in coincidence with a HP-Ge detector has observed α decay of ^{174}Hf to the g.s. with a **$T_{1/2}$ = 7.0(1.2) x 10^{16} yr** [*V. Caracciolo et al. NPA 1002 (2020) 121941*].
- First two Cs_2ZrCl_6 scintillating crystals have been grown in Queen's University and studied at the LNGS, Italy to search for 2β decay of ^{94,96}Zr isotopes [*P. Belli et al. Eur. Phys. J. A **59**, 176 (2023)*].
- New experiment using a CHC crystal scintillator and three CZC crystal scintillators has been performed in the DAMA/CRYS setup at LNGS [*P. Belli et al 2024 JINST **19** P05037, and to appear*].
- New measurement of α decay of ^{174}Hf to the g.s.: **$T_{1/2}$ = $3.8^{+1.7}_{-0.9} \times 10^{16}$ yr.**
- A new experiment is ongoing with 4 CHC crystals (∅ 26 ×20 mm^3) encapsulated in silicon-based sealant.
- Compounds with a general formula **A_2MX_6**, where A = Li, Na, K, Rb, Cs, Tl; M = Sn, Te, Hf, Zr, Pt, Os, Re, Ru; and X = Cl, Br, or I, are flexible to the element of interest that can be embedded for its fundamental studies.

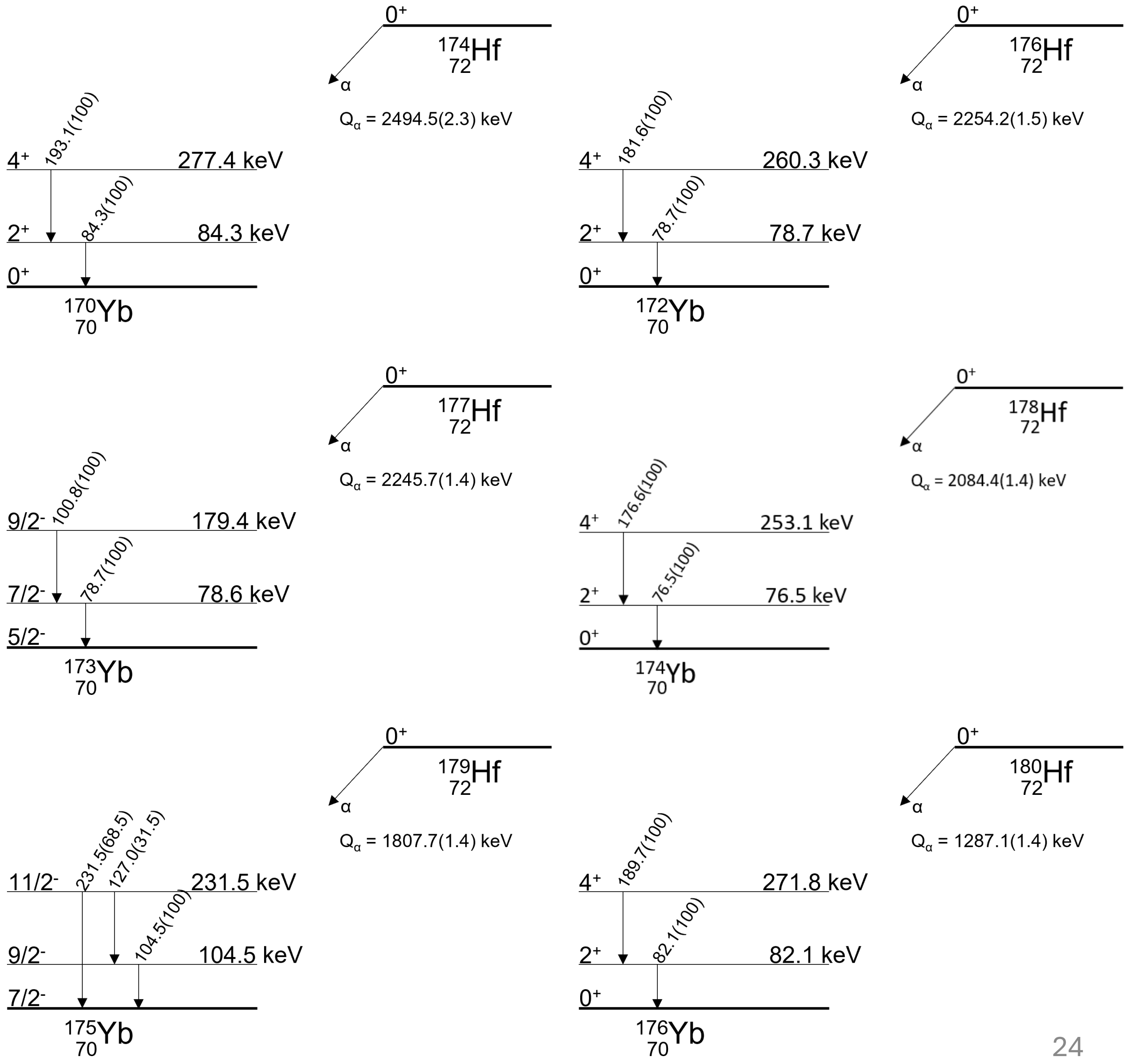
BACKUP SLIDES

Simplified decay schemes of naturally occurring Hf isotopes

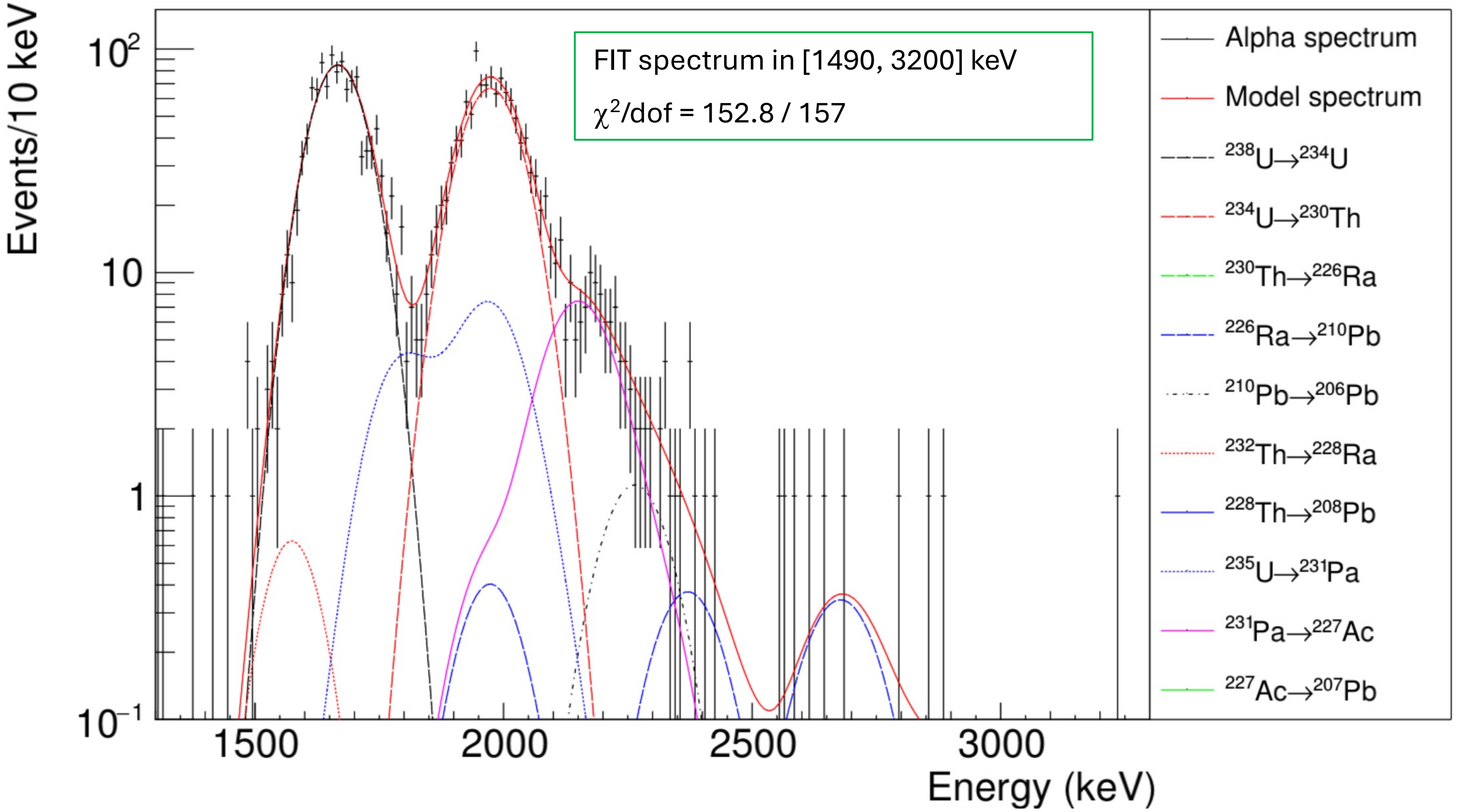
2ε, εβ+ decay of ^{174}Hf



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.



Cs_2HfCl_6: background model of the α spectrum



$\alpha/\beta = 0.2777(65) + 0.0278(14) \cdot E_\alpha[\mathrm{MeV}]$

$\mathrm{FWHM(keVee)} = \sqrt{5.97 * E[keVee] + 0.0014 \cdot E^2[keVee]}$

Chain	Nuclide	Internal contamination (mBq/kg)
		CHC (16.87 g)
^{238}U	^{238}U	7.6(3)
	^{234}U	6.7(5)
	^{230}Th	< 0.5
	^{226}Ra	0.04(2)
	^{210}Pb	0.12(7)
^{235}U	^{235}U	1.3(5)
	^{231}Pa	0.92(13)
	^{227}Ac	<0.005
^{232}Th	^{232}Th	< 0.22
	^{228}Th	<0.02
	^{147}Sm	0.25(10)
	^{134}Cs	44(8)
	^{87}Rb	< 400
	^{40}K	< 2.3

Half-life of α decay of ^{174}Hf to the g.s. of ^{174}Yb

Area of 2nd peak = $118 \pm 11(\text{stat}) \pm 35\ (sys) = 118 \pm 37$

Half-life:

$$T_{1/2} = \ln 2 \cdot N \cdot \epsilon \cdot t/S$$

M = 16.87 g;
W(Cs_2HfCl_6) = 657 g/mole;
δ(^{174}Hf) = 0.156(6) %

- N (number of nuclides) $= \frac{\mathrm{M}}{\mathrm{W}} \cdot \delta \cdot \mathrm{N_A} = 2.412 \times 10^{19}$
- ϵ is the PSD efficiency which corresponds to 99%;
- t is the measurement time (= 2344.8 h = 0.26767 yr);

$\Longrightarrow T_{1/2} = [3.8^{+0.4}_{-0.3}(stat)^{+1.6}_{-0.9}(sys)] \times 10^{16} = 3.8^{+1.7}_{-0.9} \times 10^{16}$ yr of α decay of ^{174}Hf

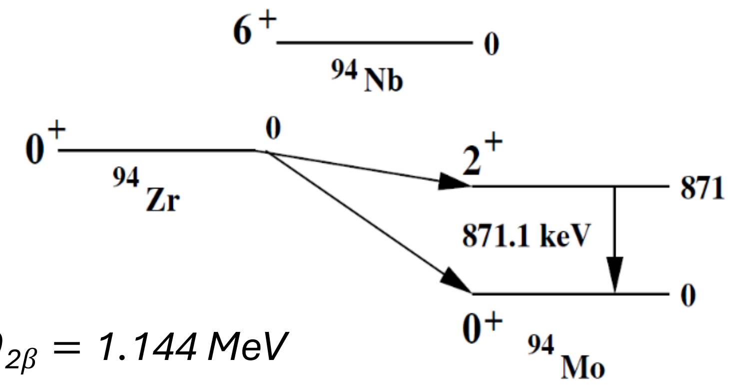
Comparing with result in [*NPA 1002 (2020) 121941*]: $\frac{|3.8-7.0|}{\sqrt{(1.7)^2 + (1.2)^2}} = 1.5$

Theoretical predictions: $(3.5 - 7.4) \times 10^{16}\ yr$.

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

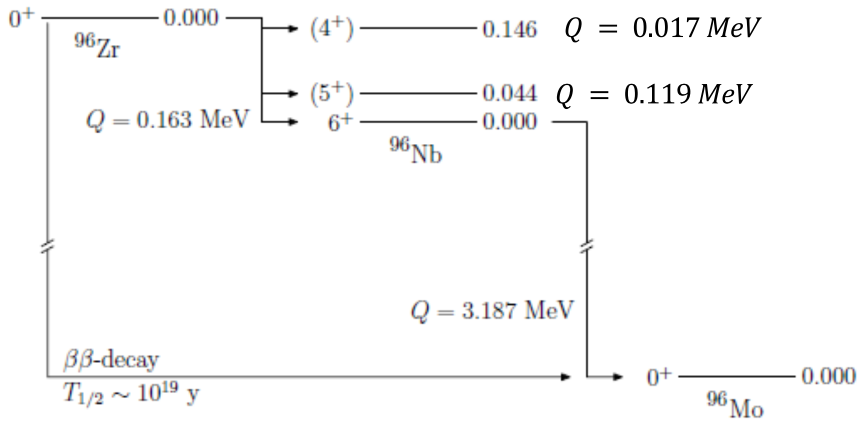
Experiment	Transition	$T_{1/2}$ 90% C.L. (y)	Technique	Ref.
ZICOS, (Kamioka Observatory, Japan)	$^{96}Zr\ 0^+ \rightarrow {}^{96}Mo\ 0^+_1$ (g.s.)	under construction	Organic liquid scintillator	[1]
NEMO I, II, III, Frejus (France) (next: SuperNEMO)	$^{96}Zr\ 0^+ \rightarrow {}^{96}Mo\ 0^+_1$ (g.s.)	$>9.2\times10^{21}$ $>1.29\times10^{22}$	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
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[8] S.W. Finch, W. Tornow, Nucl. Inst. Meth. A 806(2016)70–74
[9] J. Heeck and W. Rodejohann 2013 *EPL* 103 32001