Cryogenic detectors for rare alpha decays search: a new approach

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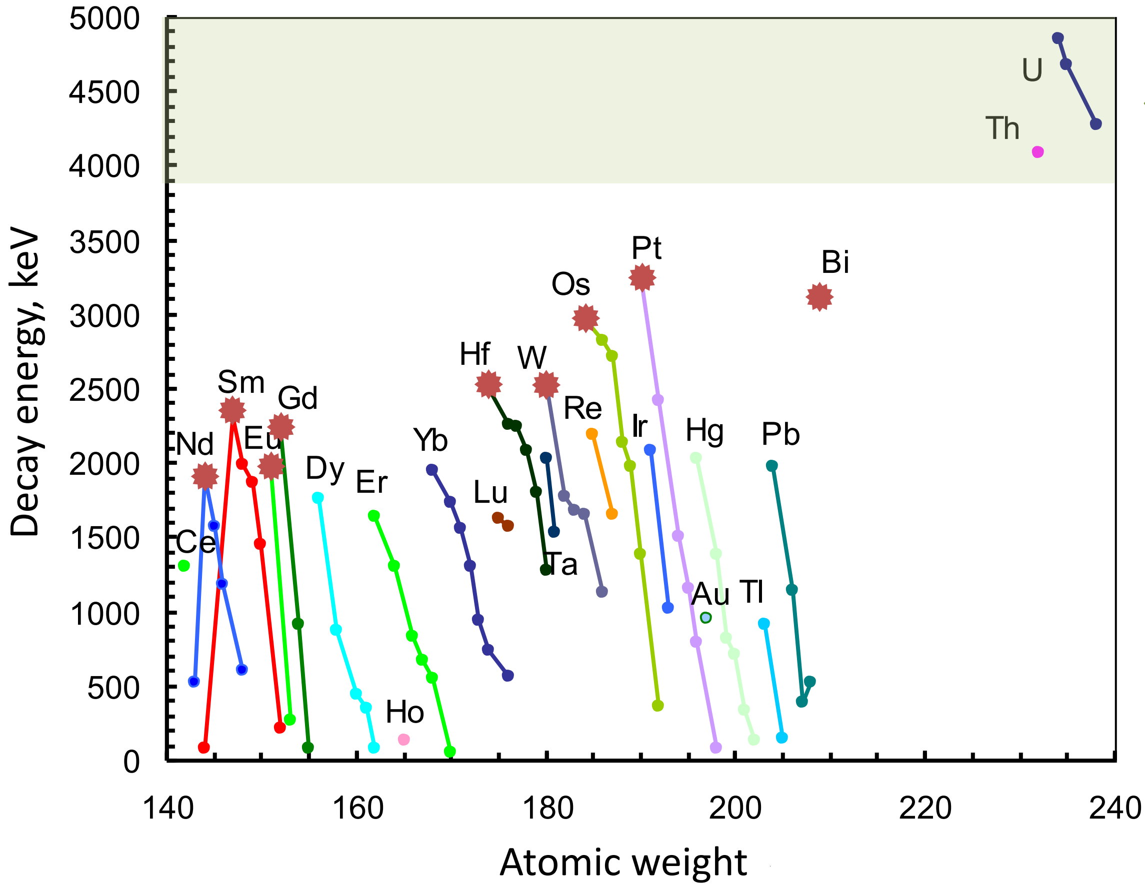
LTD-2015

Natural alpha active isotopes



~ $10^8 – 10^{10}$ y

^{190}Pt ~ 10^{11} y

^{209}Bi ~ 10^{19} y

^{184}Os ~ 10^{14} y

^{180}W ~ 10^{18} y

^{174}Hf ~ 10^{15} y

^{152}Gd ~ 10^{15} y

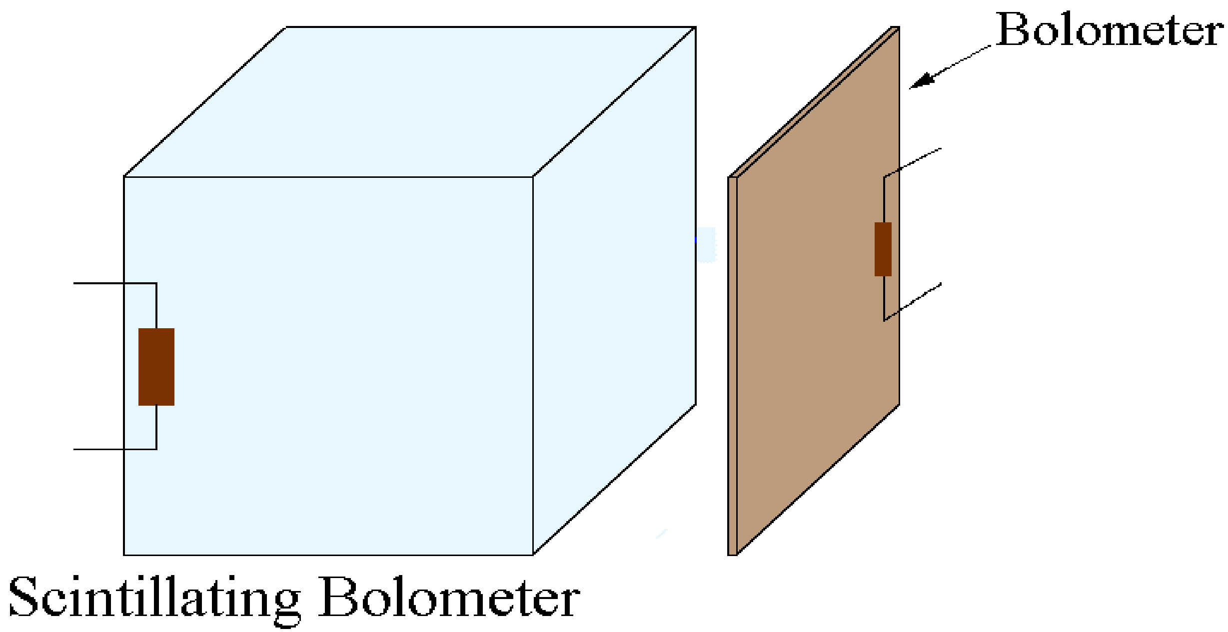
^{151}Eu ~ 10^{18} y

^{147}Sm ~ 10^{11} y

^{144}Nd ~ 10^{15} y

Required highly sensitive experimental technique which is flexible towards isotope of interest

Scintillating bolometers



$Bi_4Ge_3O_{12}$
$CaWO_4$
$Li_6Eu(BO_3)_3$
$PbWO_4$

→

^{209}Bi
^{180}W
^{151}Eu
limits on Pb isotopes

New approach
$ZnWO_4$ doped with isotope of interest

- **Well-developed technology of $ZnWO_4$ production**
- **Non-hygroscopic material**
- **Good mechanical properties and easy handling**
- **High radiopurity**
- **High light yield at low temperatures**
- **Successfully tested as scintillating bolometer**
- **High energy resolution**
- **Can be doped by different elements up to level of about 1 wt.%**
- **Realize "source = detector" approach with close to 100% registration efficiency**

Alpha decay of Sm isotopes

Nuclide	δ, % [1]	Q_α, keV [2]	$T_{1/2}$(exp), yr	$T_{1/2}$(est), yr [4-8]
^{144}Sm	3.07	76	-	-
^{147}Sm	14.99	2310.5	$1.06(2)\cdot10^{11}$	$3.0\cdot10^{10}$ - $4.2\cdot10^{13}$
^{148}Sm	**11.24**	**1986.1**	**$7(3)\cdot10^{15}$**	**$8.4\cdot10^{13}$ - $1.3\cdot10^{17}$**
^{149}Sm	**13.82**	**1870.3**	**$> 2\cdot10^{15}$**	**$1.6\cdot10^{16}$ – $3.2\cdot10^{22}$**
^{150}Sm	7.38	1448.8	-	$3.4\cdot10^{24}$ - $2.0\cdot10^{28}$
^{152}Sm	26.75	219.7	-	-
^{154}Sm	22.75	≤ 0	-	-

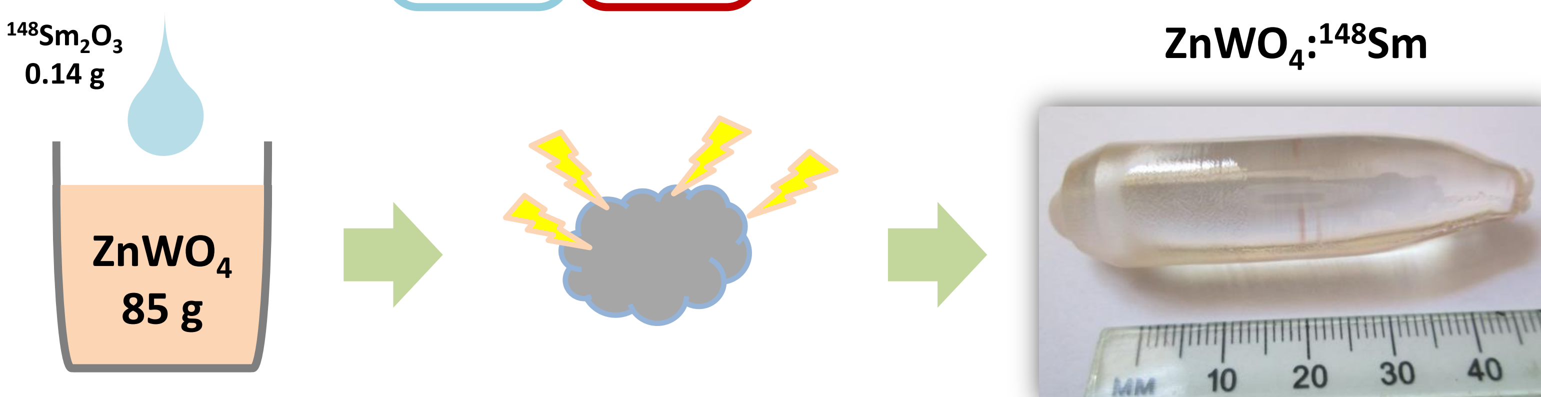
[1] M.Berglund and M.E.Wieser, Pure Appl. Chem., Vol. 83 (2011) 397;
[2] G.Audi, A.H.Wapstra, C.Thibault, Nucl. Phys. A 729 (2003) 337;
[3] E.Browne and J.K.Tuli, Nuclear Data Sheets 110 (2009) 507;
[4] B.Buck, A.C.Merchant, S.M.Peres, J. Phys. G 17 (1991) 1223;
B.Buck, A.C.Merchant, S.M.Peres, J. Phys. G 18 (1992) 143;
[5] D.N.Poenaru, M.Ivascu, J. Phys. 44 (1983) 791;
[6] V.E.Viola, et al., J.Inorg. Nucl. Chem. 28 (1966) 741;
[7] A.H.Wapstra, et al., in Nucl. Specrosc. Tabl., 1959;
[8] B.A.Brown, et al., Phys. Rev. C 46 (1992) 811.

Enriched ^{148}Sm isotope

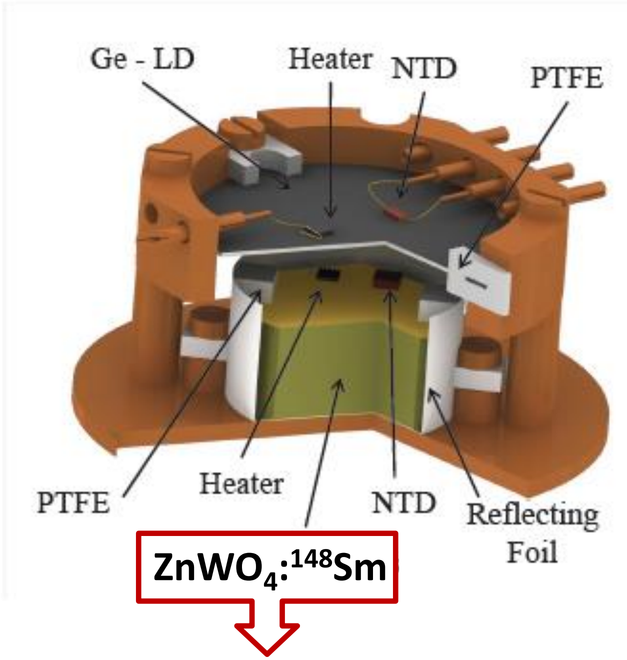
Isotope	144	147	148	149	150	152	154
Natural Sm	3.07(7)	14.99(18)	11.24(10)	13.82(7)	7.38(1)	26.75(16)	22.75(29)
$^{148}Sm_2O_3$	0.063(2)	0.909(8)	95.54(1)	2.569(9)	0.343(9)	0.384(6)	0.193(6)

Energy calibration

Isotope of interest



Detector

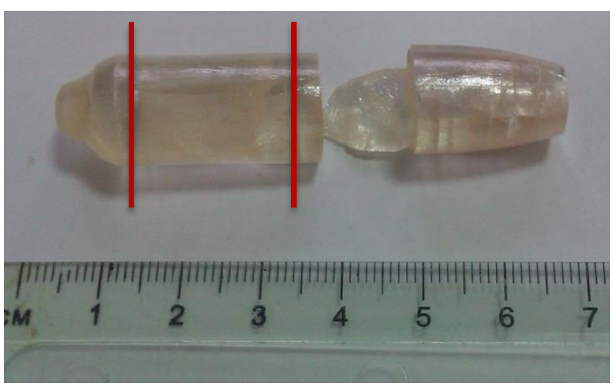


$ZnWO_4$:^{148}Sm crystal

was surrounded by a reflecting foil (3M VM2002)

was faced to a Ge disk (⌀45×0.3 mm) used as light detector

Both were equipped with NTD thermistors, glued by epoxy glue

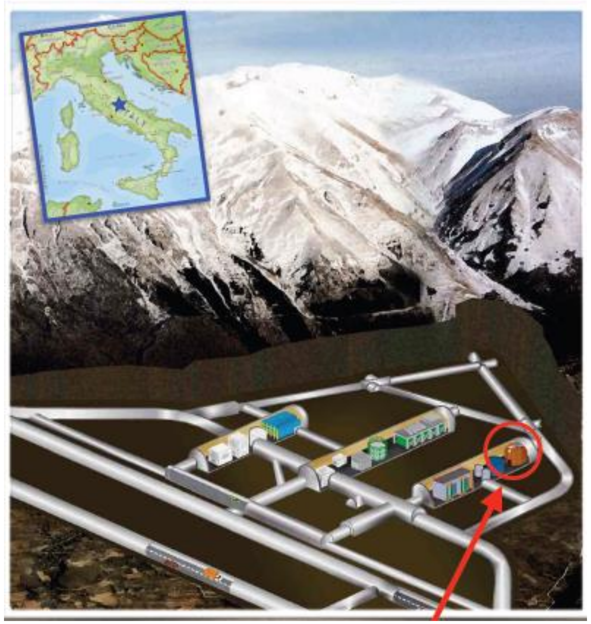


22.014 g $ZnWO_4$:^{148}Sm crystal
diam. 12 × 20.7 mm

growth by Czochralski technique in air

using as raw materials ZnO, WO_3 (99.995% pure)

Data taking at
Gran Sasso Underground Laboratory

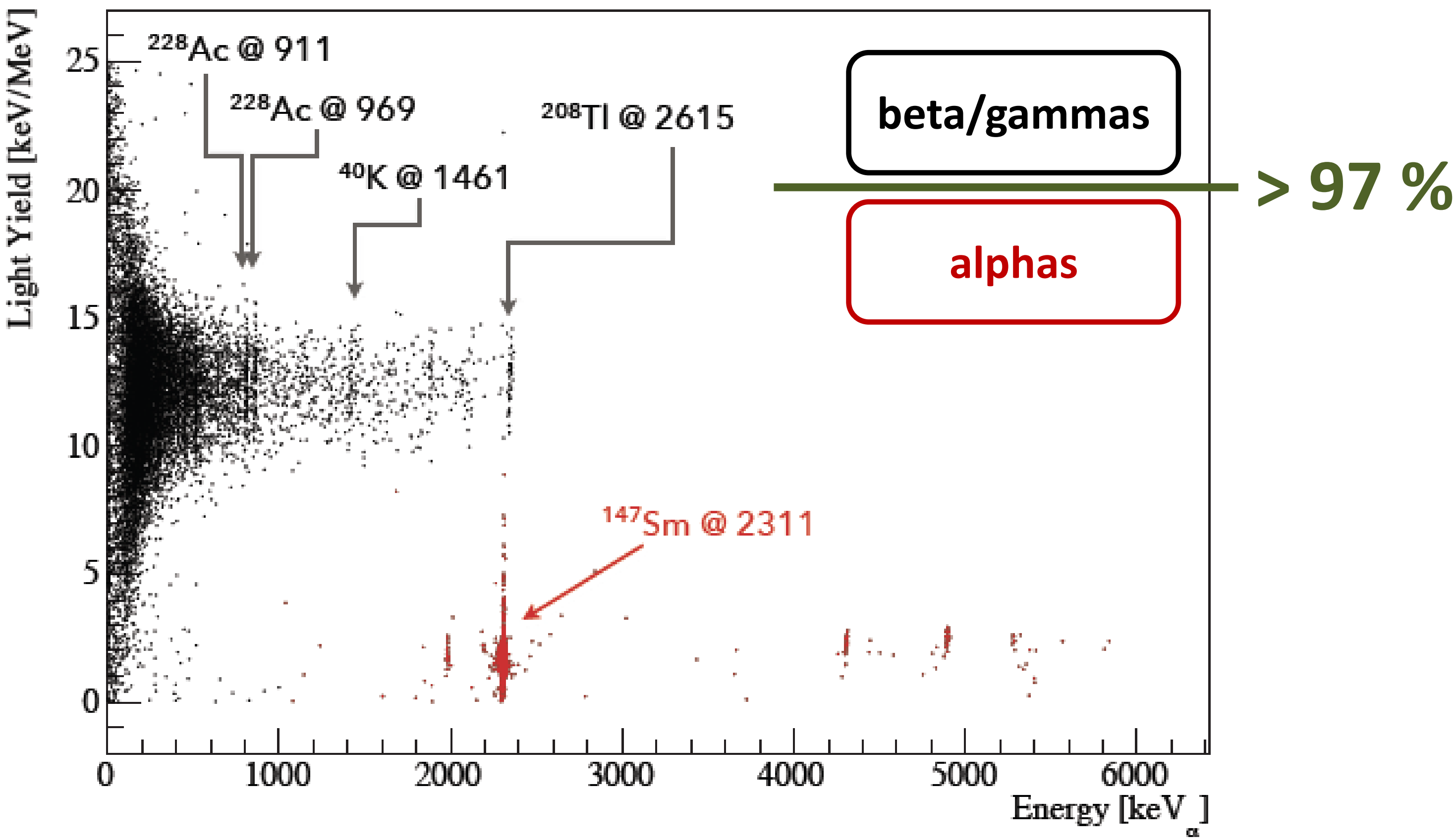


Experimental location:

- Average depth ~ 3650 m w.e.
- Muon flux ~ 2.6×10^{-8} μ/s/cm^2
- Neutrons < 10 MeV: 4×10^{-6} n/s/cm^2
- Gamma < 3 MeV: 0.73 γ/s/cm^2

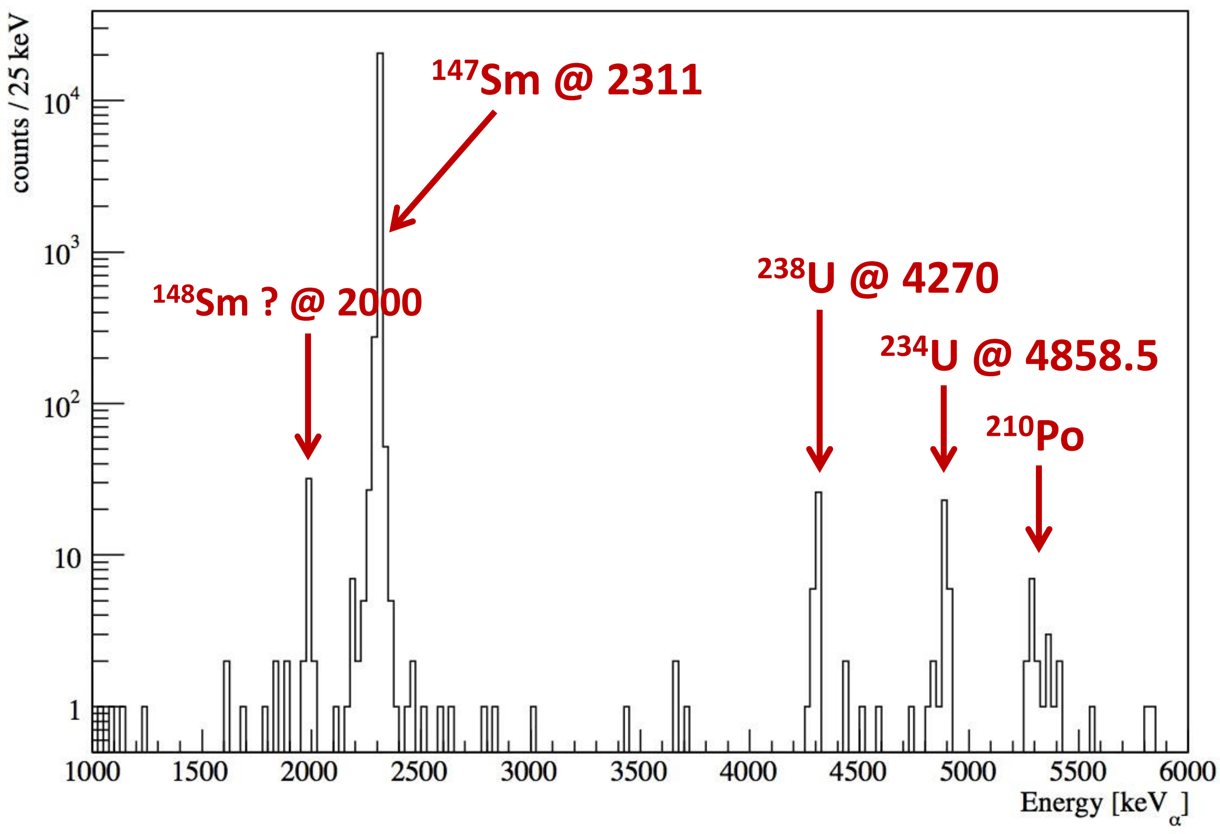
- Operated in Oxford 200 ^{3}He/^{4}He dilution refrigerator
- Data collected for a total live time of 364 h

Light Yield vs Heat scatter plot



Runs of background & gamma calibration

Selected alpha spectrum



22.014 g $ZnWO_4$:^{148}Sm crystal, 364 hours of background

Could it be anything else?

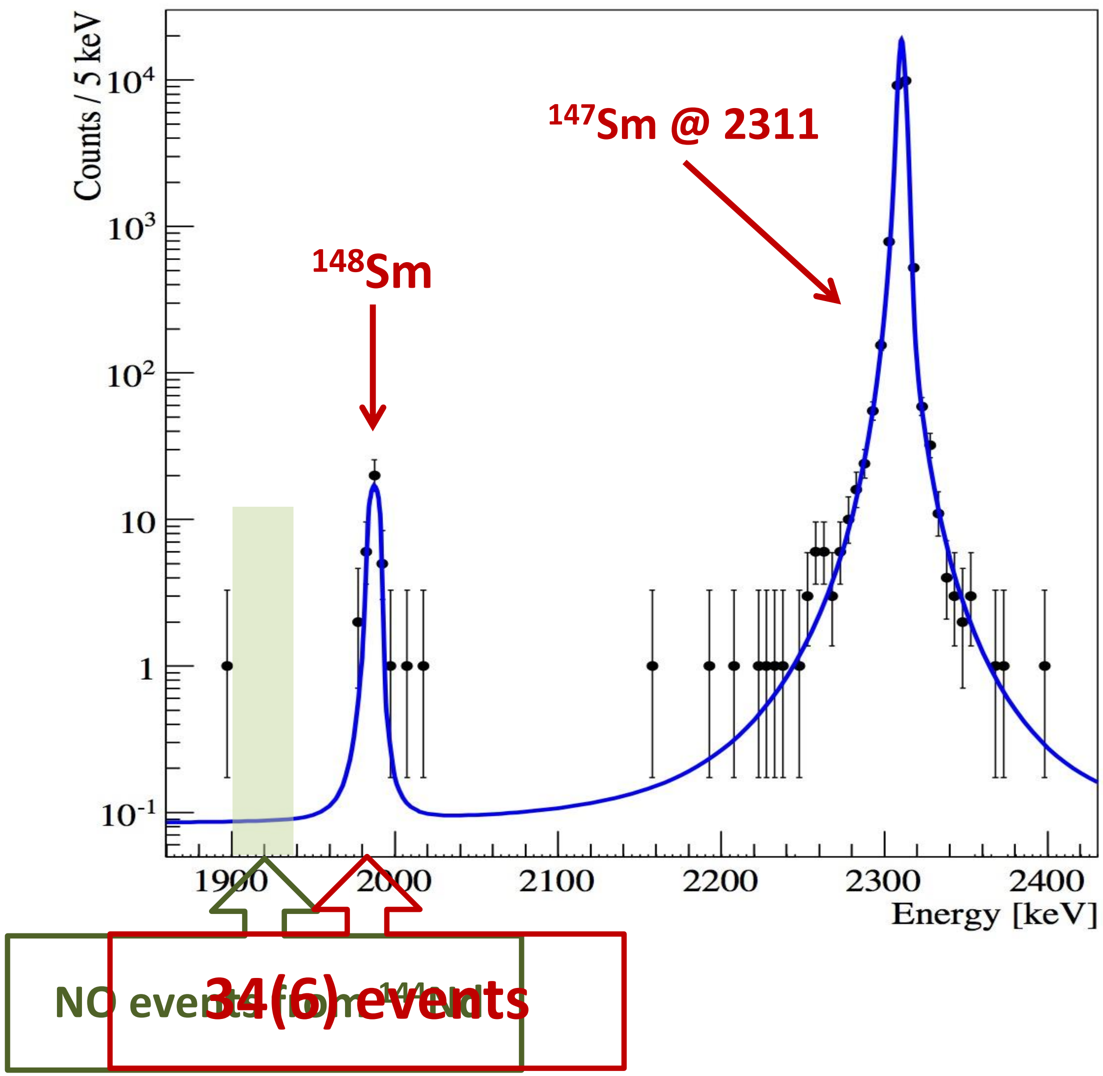
measured by HR-ICP-MS

Isotope	Abundance, %	Q_α, keV	$T_{1/2}$, y	Concentration, 10^{-6} g/g	Expected events
^{144}Nd	23.798(19)	1905(1)	$22.9 \cdot 10^{14}$	72	19.8
^{151}Eu	47.81(6)	1949(7)	$4.62 \cdot 10^{18}$	< 10	< 0.002
^{152}Gd	0.20(1)	2203.0(1.4)	$1.08 \cdot 10^{14}$	< 25	< 1.1

assuming natural isotopic composition

BUT, we see NO such events in background spectrum
Impurities elements have NON-NATURAL isotopic abundance

Resulting fit of ROI



FWHM @ 2311
4.7 ± 0.5 keV

Q-value
1987.3 ± 0.5 keV

Half-life
$(6.4^{+1.2}_{-1.3}) \times 10^{15}$ y

Radioactive contamination

22.014 g $ZnWO_4$:^{148}Sm crystal, 364 hours of background

Chain	Nuclide	Activity, mBq/kg
^{232}Th	^{232}Th	< 0.1
^{238}U	^{238}U	1.2(2)
	^{234}U	1.1(2)
	^{226}Ra	< 0.1
	^{210}Po	0.3(1)
	^{147}Sm	745.4(5)

Free of ^{232}Th chain

broken equilibrium

Residual in $^{148}Sm_2O_3$

^{148}Sm alpha decay theory & experiments

Half-life $T_{1/2}$, 10^{15} y		
Theory [1-5]	Scintillating bolometer $ZnWO_4$:^{148}Sm	Ionization chamber
0.09 ÷ 130	$\mathbf{6.4^{+1.2}_{-1.3}}$	**8 ± 2** [6] **7 ± 3** [7]

[1] B.Buck, A.C.Merchant, S.M.Peres, J. Phys. G 17 (1991) 1223;
B.Buck, A.C.Merchant, S.M.Peres, J. Phys. G 18 (1992) 143;
[2] D.N.Poenaru, M.Ivascu, J. Phys. 44 (1983) 791;
[3] V.E.Viola, et al., J.Inorg. Nucl. Chem. 28 (1966) 741;
[4] A.H.Wapstra, et al., in Nucl. Specrosc. Tabl., 1959;
[5] B.A.Brown, et al., Phys. Rev. C 46 (1992) 811.
[6] V.A.Korolev et al., Yad. Fiz 8 (1968) 227; translation – Soviet J. Nucl. Phys. 8 (1969) 131.
[7] .C.Gupta and R.D.MacFarlane, J.Inorg. nucl. Chem., Vol. 32, 1970, pp.3425-3432.

Summary

✓ The first compelling experimental observation of **^{148}Sm** alpha decay with

$$T_{1/2} = (6.4^{+1.2}_{-1.3}) \times 10^{15}\ y \qquad \& \qquad Q_{\alpha} = 1987.3 \pm 0.5\ keV$$

was obtained using a **22 g $ZnWO_4$** conventional scintillator doped with **^{148}Sm** enriched isotope (contains only of **2 mg**) which operated as scintillating bolometer

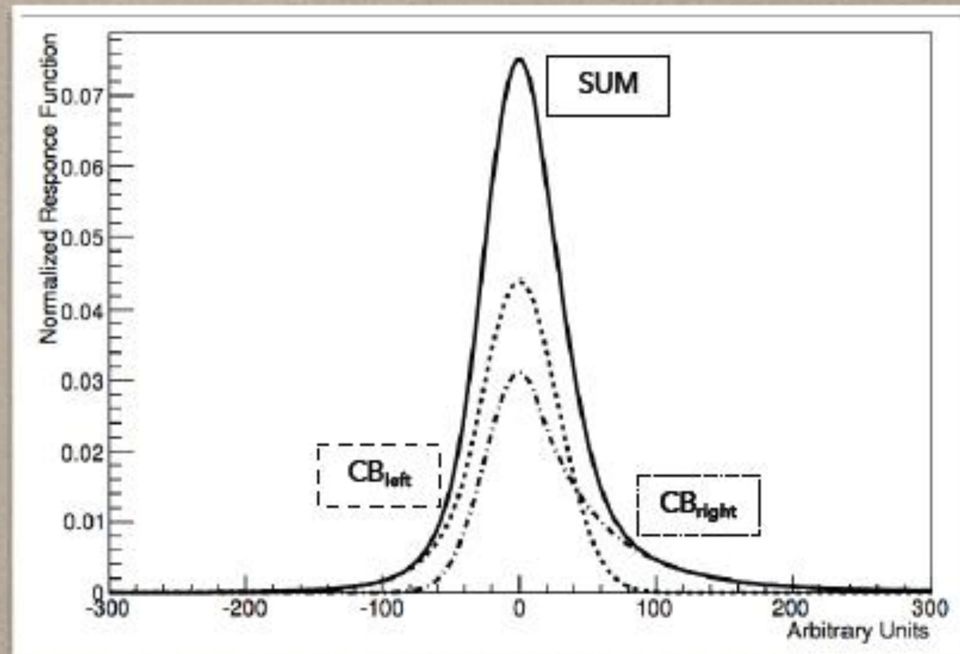
✓ Such double read-out cryogenics scintillating bolometers (Heat&Light channels) doped with an enriched isotope of interest are very perspective for the study of rare nuclear processes with sensitivity up to **10^{19} y**

Looking forward

to discovery of ^{149}Sm alpha decay!..

NON-GAUSSIANITY

- There is no clear physics motivation but the detector response function is not a gaussian.
  - Possible explanations? Position effects, crystal inhomogeneity, surface events...????



- We use as detector response function a sum of two crystal balls, evaluating their parameters on the Sm peak

$$\mathrm{RF}(Q,E) = N \cdot [CB_{left}(Q,E) + \delta \cdot CB_{right}(Q,E)]$$

CRYSTAL BALL FUNCTION

$$f(x;\alpha,n,\bar{x},\sigma) = N \cdot \begin{cases} \exp(-\frac{(x-\bar{x})^2}{2\sigma^2}), & \text{for } \frac{x-\bar{x}}{\sigma} > -\alpha \\ A \cdot (B - \frac{x-\bar{x}}{\sigma})^{-n}, & \text{for } \frac{x-\bar{x}}{\sigma} \leqslant -\alpha \end{cases}$$

$$A = \left(\frac{n}{|\alpha|}\right)^n \cdot \exp\left(-\frac{|\alpha|^2}{2}\right),$$

$$B = \frac{n}{|\alpha|} - |\alpha|,$$

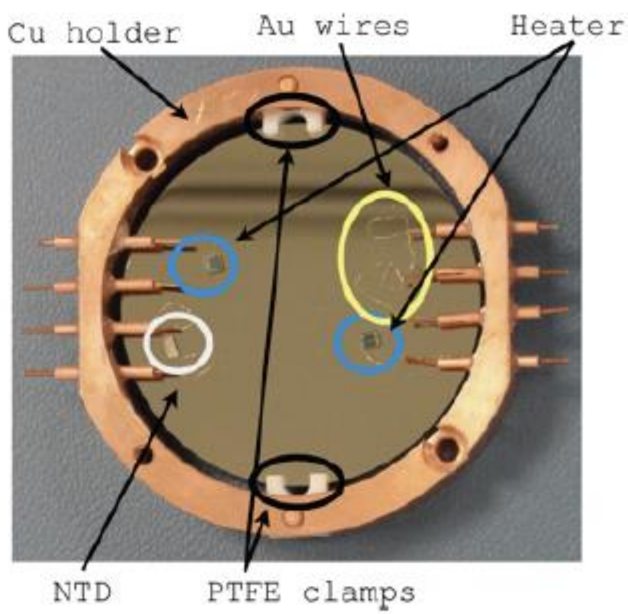
$$N = \frac{1}{\sigma(C+D)}$$

$$C = \frac{n}{|\alpha|} \cdot \frac{1}{n-1} \cdot \exp\left(-\frac{|\alpha|^2}{2}\right)$$

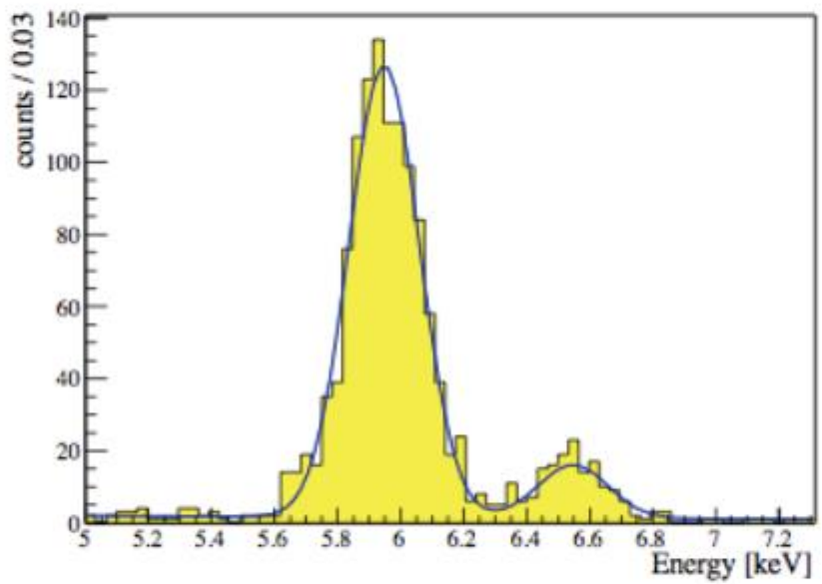
$$D = \sqrt{\frac{\pi}{2}}\left(1 + \operatorname{erf}\left(\frac{|\alpha|}{\sqrt{2}}\right)\right)$$

Bolometric LD

- HP-Ge disk (3-5 cm diameter, 0.1-1 mm thick)
- SiO_2 coating for darkening the surface => reduce light reflections
- Calibration with ^{55}Fe X-rays @ 5.9 keV and 6.5 keV
    - Energy resolution: ~100 eV
    - Energy threshold: ~100 eV



Detector	$FWHM_{baseline}$ [keV]	$FWHM_{^{55}Fe}$ [keV]
	0.144±0.002	0.209±0.003



J.W.Beeman et al., *2013 JINST 8 P07021*