Search for Electron Capture of ^{176}Lu with a LYSO scintillator

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Decay scheme of ^{176}Lu

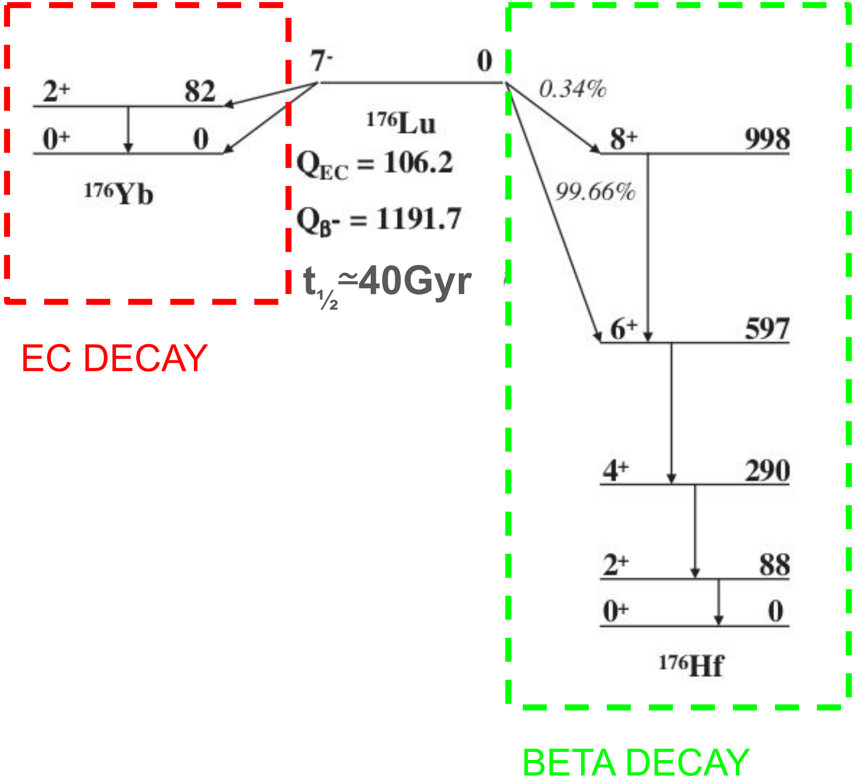
^{176}Lu normally decays by beta decay to ^{176}Hf with a half-life of ≃40 Gyr. Natural abundance of ^{176}Lu is 2.6%

Lu/Hf is useful for radiometric dating age of minerals and cosmic objects, ^{176}Lu/^{176}Hf can be used as an s-process thermometer in star nucleosynthesis.

^{176}Lu is also one of the six naturally occurring isotopes potentially unstable for Electron Capture (EC).

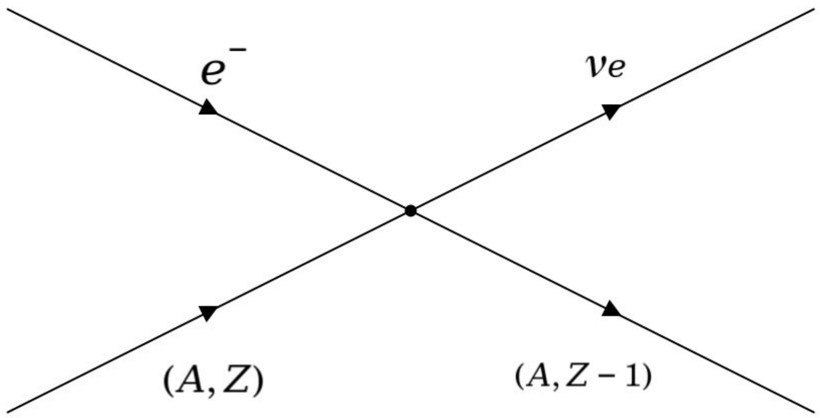
Evidence for EC decay was found for ^{40}K, ^{50}V and ^{138}La, but is still missing for ^{123}Te, ^{176}Lu and ^{180}Ta*

An (unexpectedly) large branching ratio for ^{176}Lu EC could reconcile some discrepancies involving Lu/Hf age comparisons in different samples



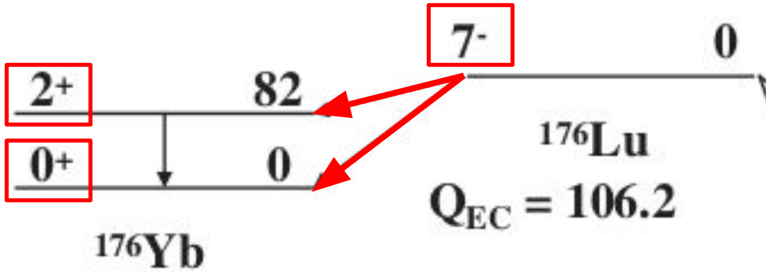
EC decay: pure EC decay and forbiddenness

Electron capture is a process where a proton-rich nuclei absorbs an electron and emits a neutrino. Considering the nucleus size and the ν energy, it is very hard that the ν carries away more than ½ħ



The Forbiddenness of a EC decay is related to the jump total angular momentum and parity.

$$I_i = I_f + L + S$$



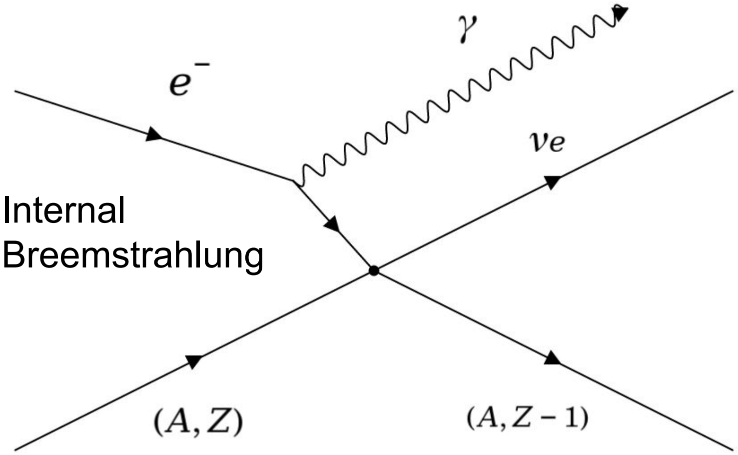
^{176}Lu EC decay is 7th or 5th forbidden!

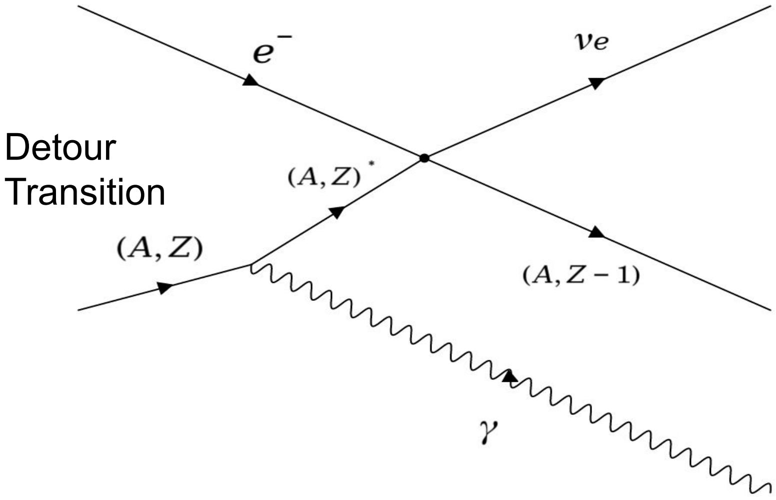
EC decay: Radiative EC

In highly forbidden EC, a photon can be emitted removing ħ angular momentum

REC experimentally observed in ^{41}Ca, ^{59}Ni, ^{71}Ge, ^{81}Kr, ^{137}La, ^{204}Tl …

- Internal Bremsstrahlung (IB), captured electron emits photon(s)
- Detour Transition (DT), nucleus emits photon(s)

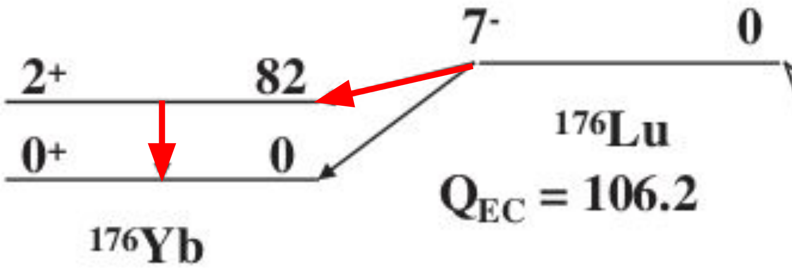




EC decay: visible energy in EC/REC

Example: EC decay to 2^+ ^{176}Yb (the less forbidden).

Signature of this transition is the 82 keV gamma from ^{176}Yb relaxation.



In addition:

$Q' = (Q_{EC} - E_{\gamma 82}) = 24$ keV (k-shell capture not allowed)

VISIBLE ENERGY in this decay:

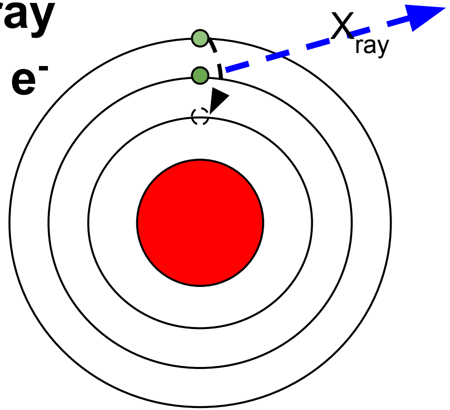
- Pure EC decay (discrete energies):

$$Q - E_\nu = E_{\gamma 82} + E_b < 82+10.5 \text{ keV}$$

- REC decay (continuous spectrum):

$$Q - E_\nu = E_{\gamma 82} + E_b + E_{\gamma rad} = [82 \text{ to } 82+24] \text{ keV}$$

$E_b \longrightarrow$ X-ray or Auger e^-



Detector: LYSO as active ^{176}Lu source

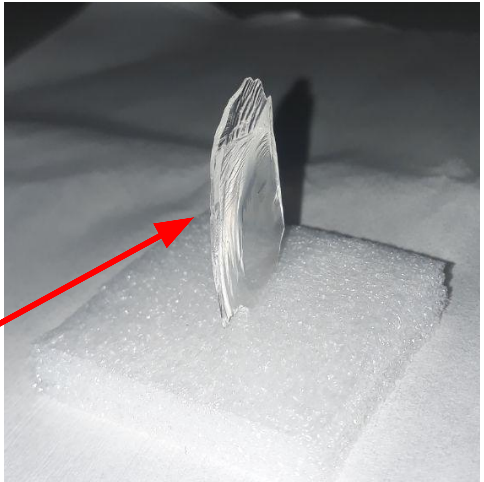
LYSO (Lutetium-yttrium oxyorthosilicate) scintillator coupled with a PMT in coincidence with a HP-Ge detector.
Expected β-decay activity: 40Bq/g

The thin source geometry allows 82keV photon to escape the crystal and to be detected in a nearby HP-Ge.

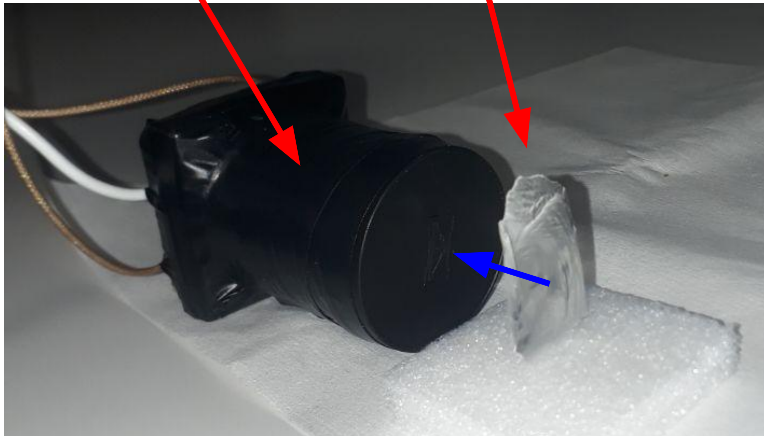
LYSO measures X-rays and Auger e$^-$ from the filling process of the vacancy or the possible radiative photons.

Active ^{176}Lu source:
powerful rejection of β decay bkg.

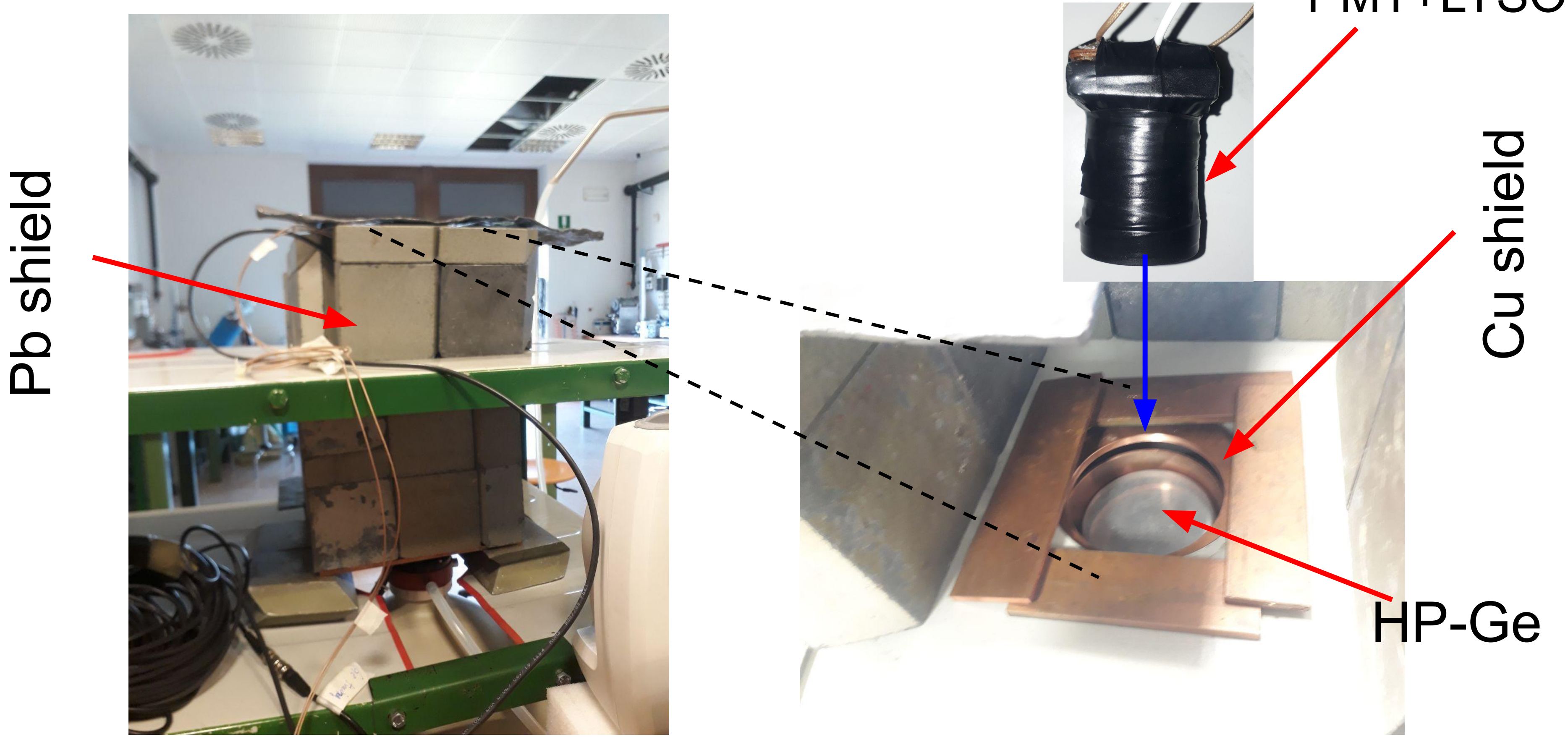
LYSO (7.9 gr)



Hamamatsu R5946 PMT



Detector: setup@INFN-TIFPA

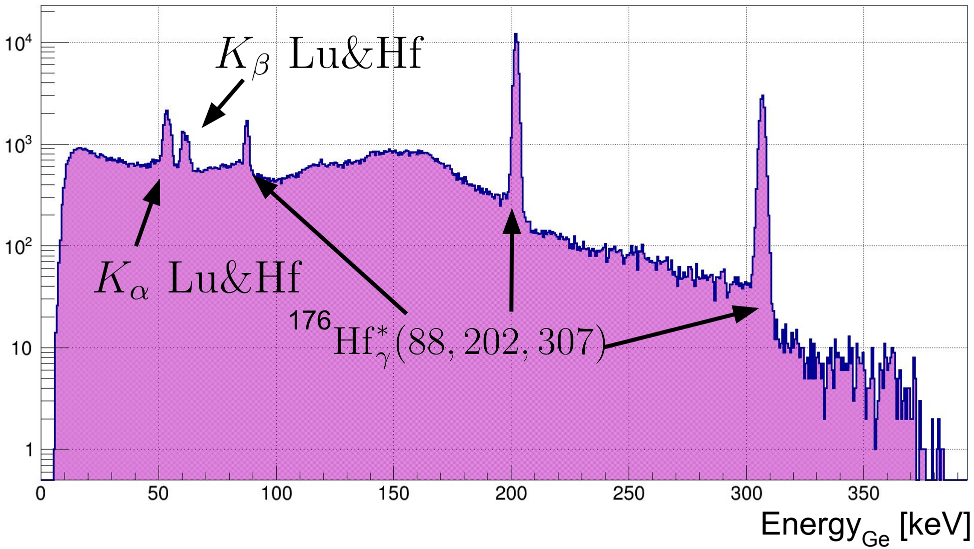


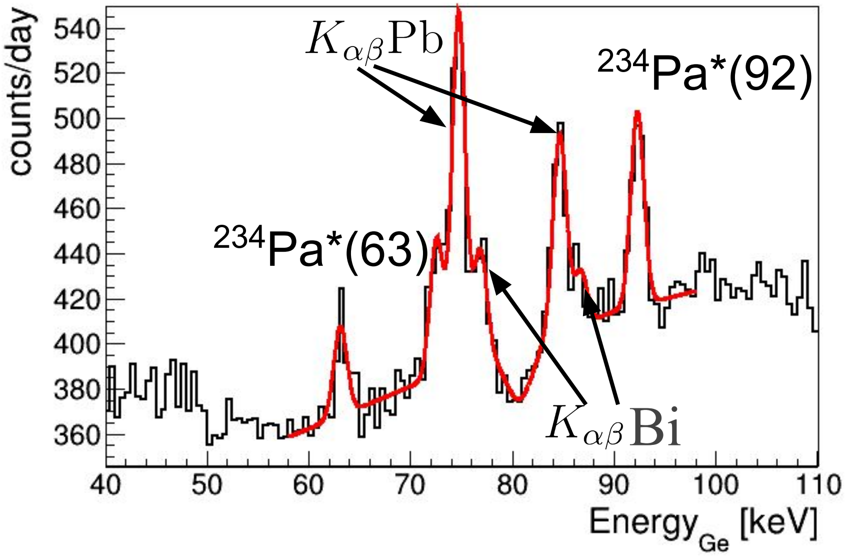
HP-Ge: performances

HP-Ge was self-calibrated with (88, 202, 307) keV gamma of ^{176}Lu

$$\sigma_{HP-Ge}[88] = 0.65 \text{ keV}$$

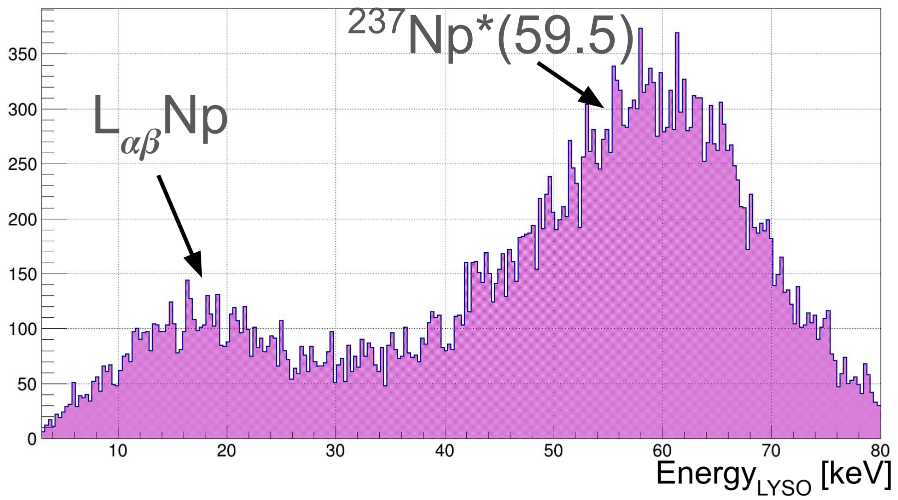
HP-Ge intrinsic/external bkg measured without the LYSO source (Pb x-rays and $^{238}U \to ^{234}Th \to ^{234}Pa$ chain)



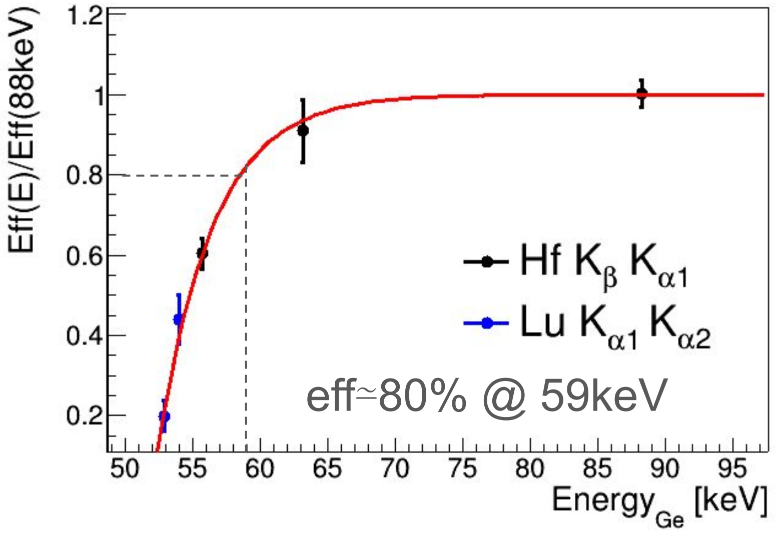


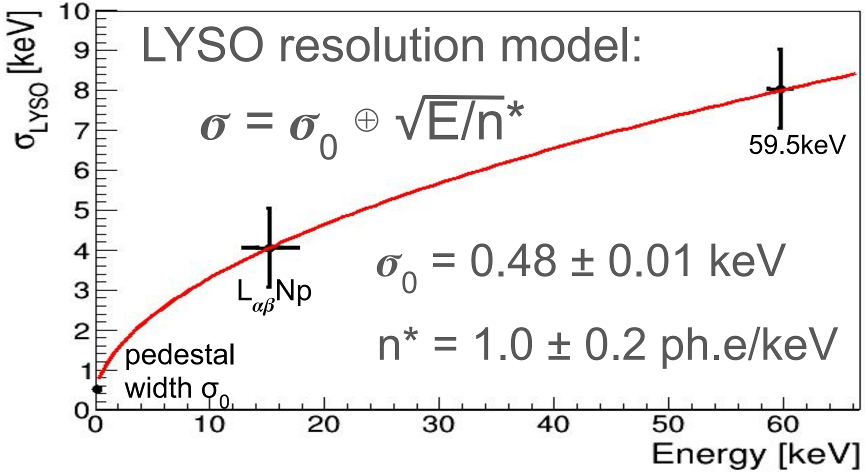
LYSO: performances

LYSO scintillator calibrated with ^{241}Am
59.5keV and 13.8-17.7keV from $^{237}Np^*$
(since ^{176}Lu β spectrum is continuous)

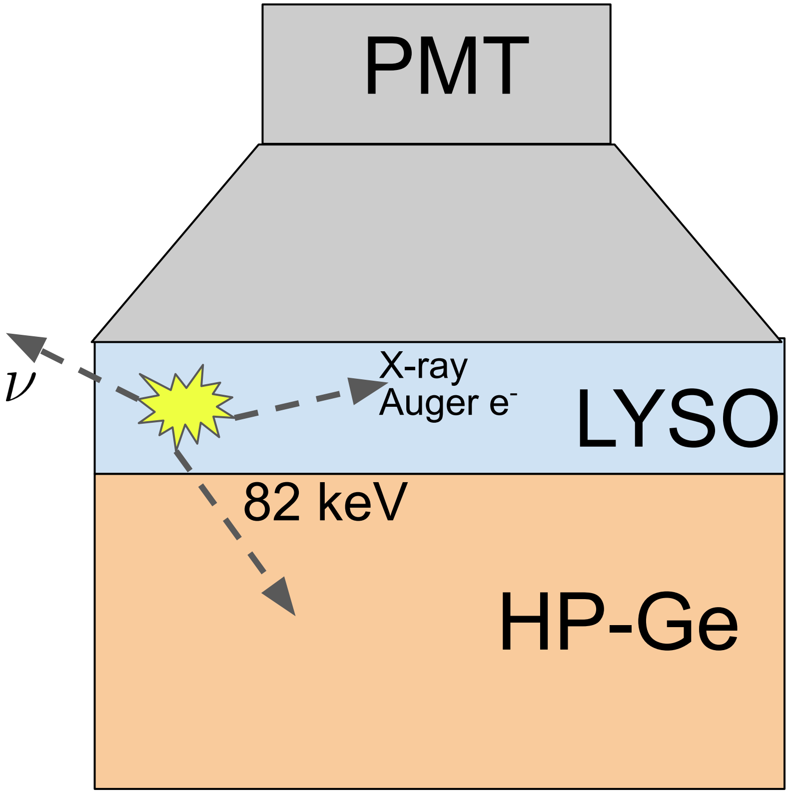


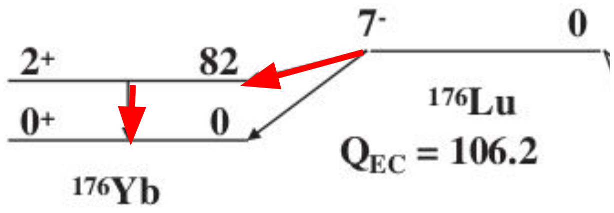
Coincidence efficiency relative to 88 keV
(LYSO self-absorption + Ge eff. + Al housing)





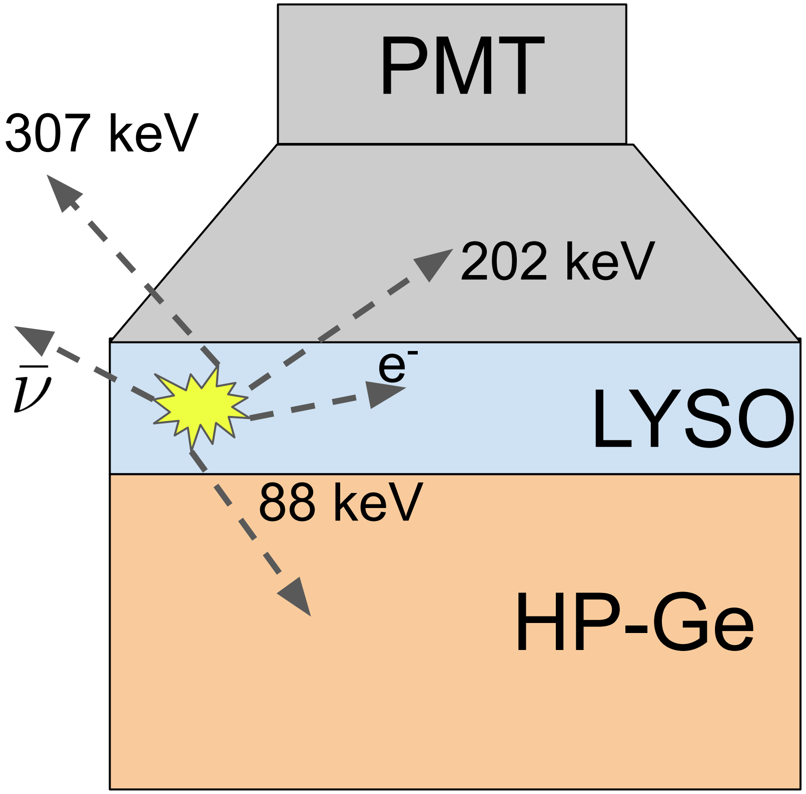
Signal topology: 2^+Yb EC decay

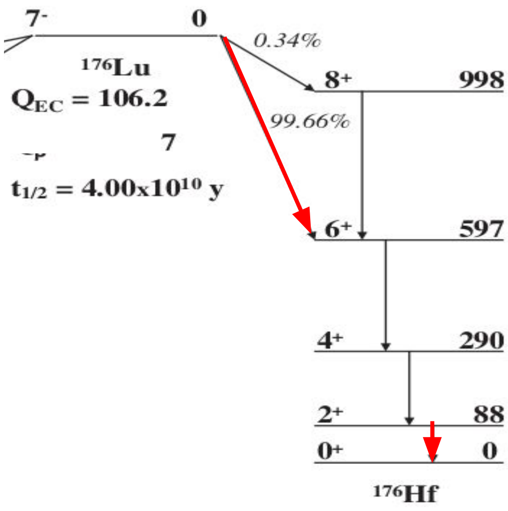




$$Q_{EC} = 106 \text{ keV}$$
$$E_{Ge} = 82 \text{ keV}$$
$$E_{LYSO} < 24 \text{ keV}$$

Example of background: β⁻ decay



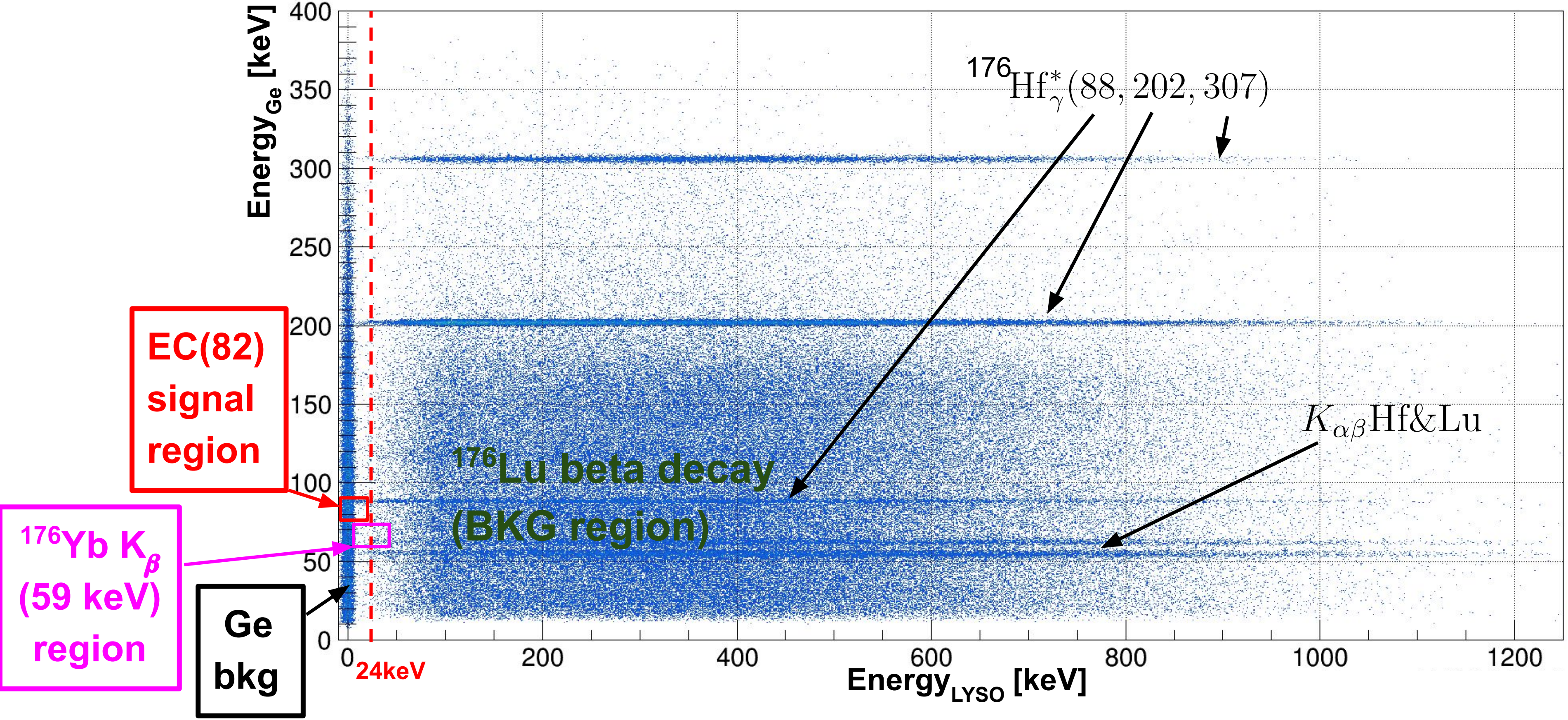


$$Q_{\beta^-} = 1191 \text{ keV}$$

$$E_{Ge} = 88 \text{ keV}$$

$$E_{LYSO} \approx 400 \text{ keV}$$

Two-dimensional spectrum of ^{176}Lu



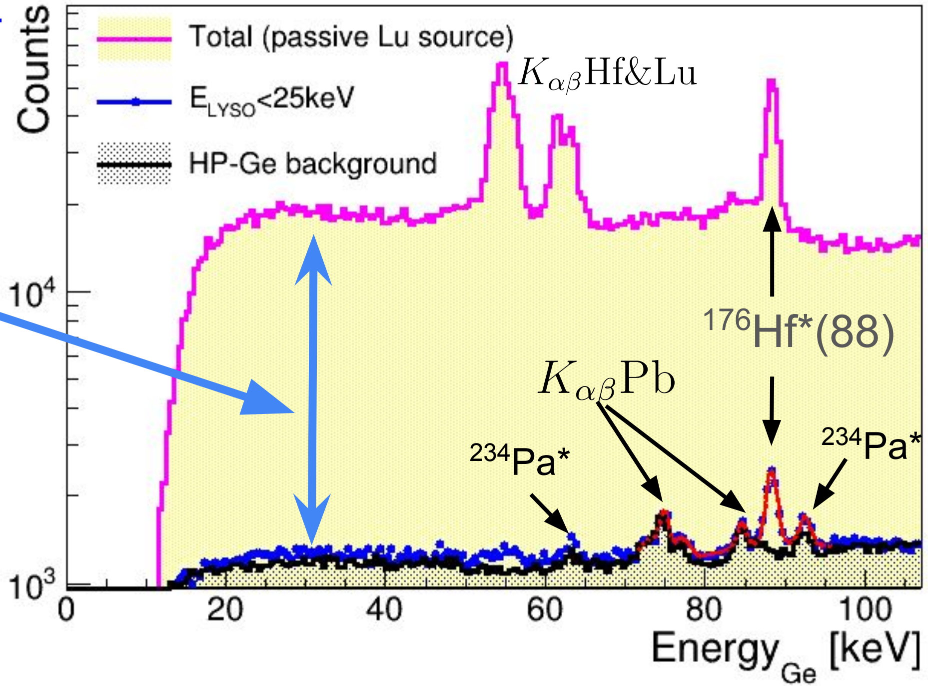
Results: EC decay to ^{176}Yb 2^+

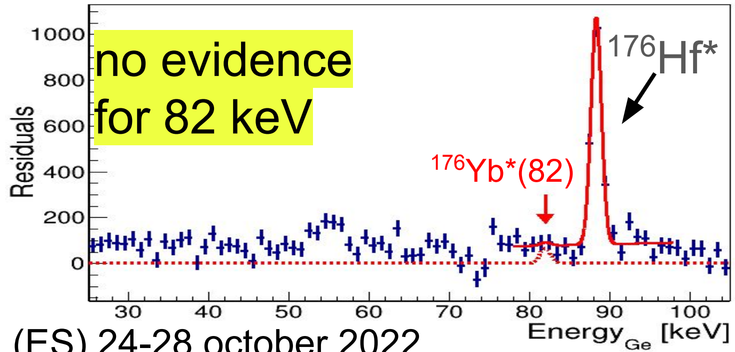
Selection: $Energy_{LYSO}$< 25 keV reduces the bkg of a factor ~ 20. residual bkg due to Ge detector intrinsic cont. or external gamma.

90h exposure: no evidence for 82keV
collected 120k gamma from ^{176}Hf* (88keV)
<220 events in 82keV region (90% C.L.)

Branching ratio limit:
(for all possible channel to ^{176}Yb 2^+)
B < 0.22% (90%C.L.)

Improvement of a factor ~4 wrt previous measurements (10g $LuCl_3$ passive source x 65h) [Appl. Rad. and Isotopes 60 (2004) 767–770]



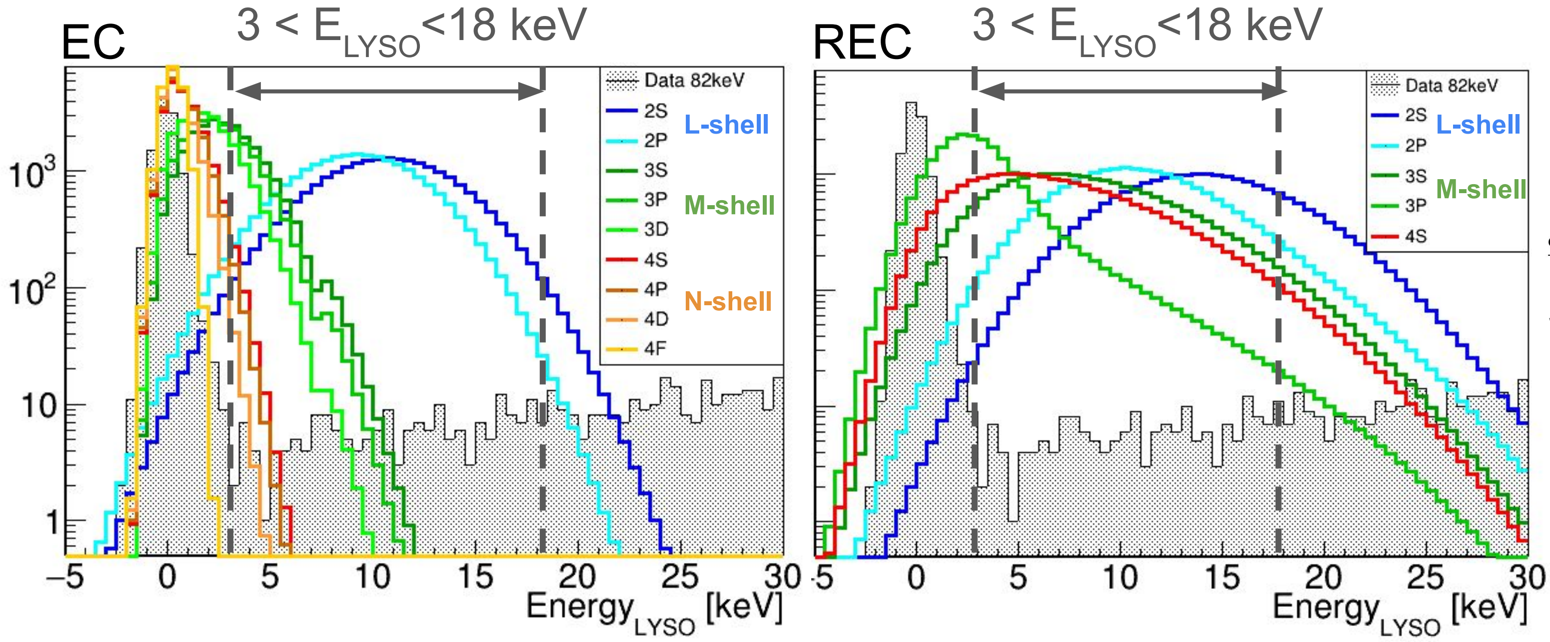


Investigation of the possible EC/REC channels to ^{176}Yb 2^+

In the decay to ^{176}Yb 2^+ a K-shell electron cannot be captured: **$(Q_{EC} - E_{\gamma 82}) < E_{bK}$ = 61.3 keV**

L-shell electrons have the largest overlap with the nucleus: **$(Q_{EC} - E_{\gamma 82}) > E_{bL}$ = 10.5-10-8.9keV**

M-shell electron capture can still provide sizable energy in LYSO **E_{bM}= 2.4-2.2-2.0-1.6-1.5keV**



Models of REC:

-S-capture:

Nuc.Phys.A.728(2003)3

$$\frac{\mathrm{d}w_{1S}(k)}{w_{1S}} = \frac{\alpha}{\pi(m_e c^2)^2}\frac{k(q_{1S}-k)^2}{q_{1S}^2}R_{1S}(k)\,\mathrm{d}k$$

we adopt the most cautious R factor.

-2P and 3P capture: R factor tables in: **Phys.Rev.104(1956)158**

Investigation of the possible EC/REC channels to ^{176}Yb 2^+

selection: 3keV<E_{LYSO}<18keV

(another factor ~50 of bkg rejection)

No evidence for 82 keV peak.

<29 events in 82keV region (90% C.L.)

Branching ratio limits:

$B_{L\text{-}EC\ or\ L\text{-}REC}$ < 0.03%

$B_{3S\text{-}REC}$ < 0.033%

$B_{nS\text{-}REC}$ < 0.04% (n>3)

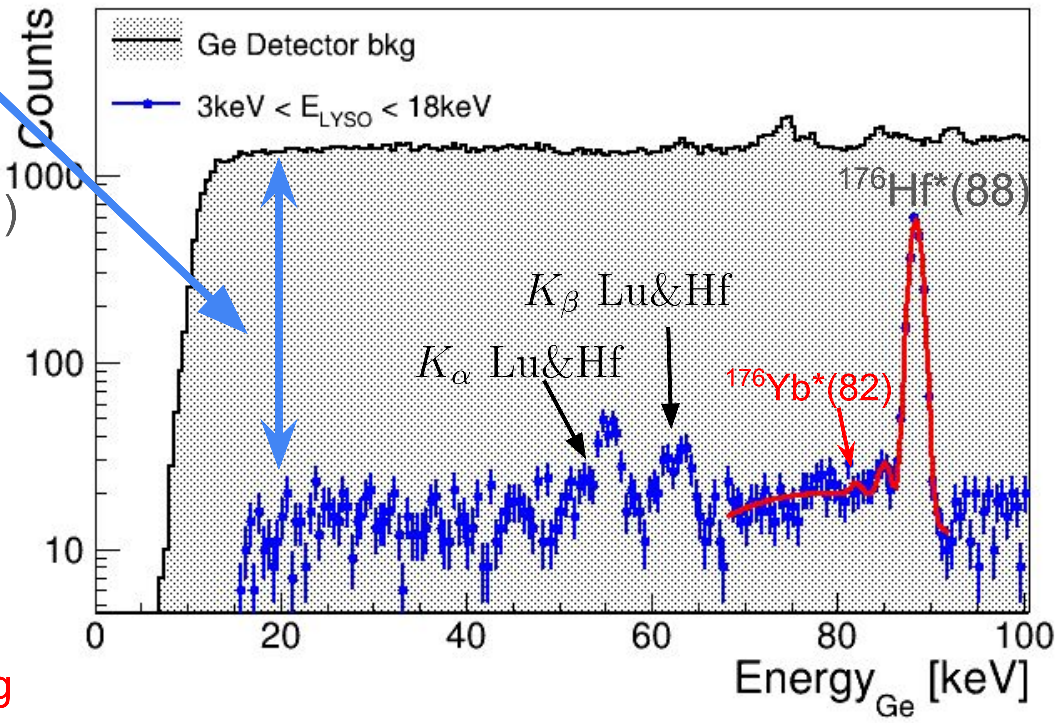
$B_{3P\text{-}REC}$ < 0.06%

$B_{3S\text{-}EC}$ < 0.067%

$B_{3P\text{-}EC}$ < 0.08%

$B_{3D\text{-}EC}$ < 0.14%

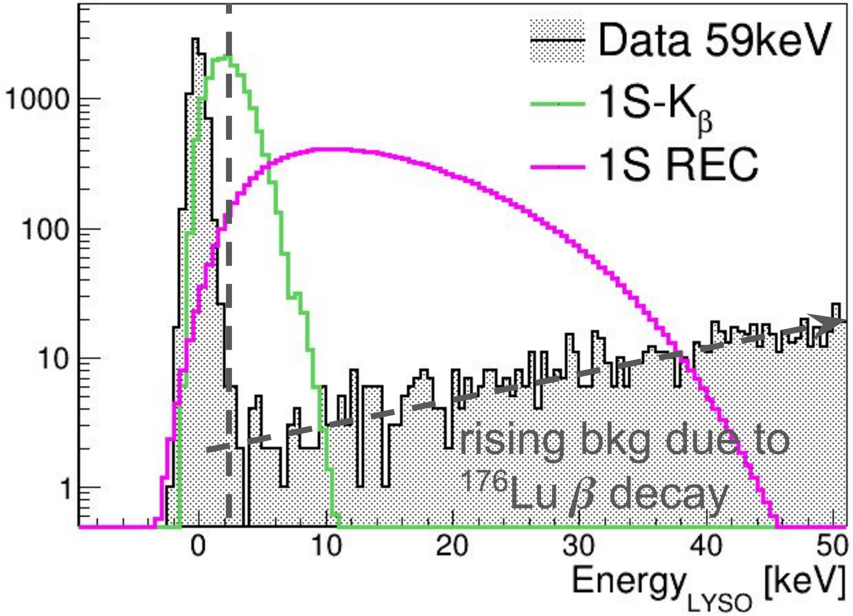
can improve analysing 2-4.5keV (next slides)

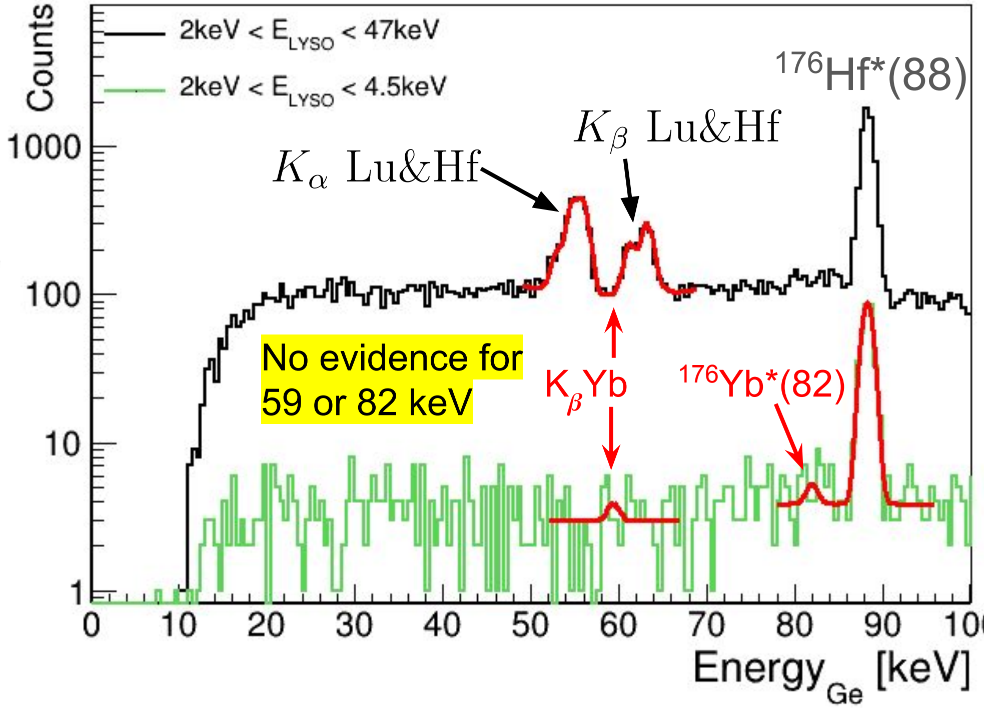


Results: EC/REC decay to ^{176}Yb 0^+

A signature of K-shell electron capture is the Yb K_β x-ray: **59.3keV** (15% of 1S-EC)
The maximum visible energy in LYSO is:

(Q_{EC} - 59.3keV) = 47 keV





<67 Yb K_β events in 2<E_{LYSO}<47keV
<11 Yb K_β events in 2<E_{LYSO}<4.5keV
<13 ^{176}Yb*(82) events in 2<E_{LYSO}<4.5 keV

Conclusions:

Active Lu source: limits to ^{176}Lu EC improved 3 to 30 times (depending on channel)

Further improvements are possible with LYSO scintillating bolometers and low bkg HP-Ge placed underground.

Among the 3/6 naturally occurring EC unstable nuclei ^{176}Lu EC still wait for a lab. measurement

Electron Capture process	**Branching fraction limit (90% C.L.)**	**Previous limits (68% C.L.)** Appl. Rad. & Isot. 60(2004)767 (10g LuCl3 pass. source x 65h)
^{176}Lu->^{176}Yb 0+ 1S-EC	0.018%	0.36%
^{176}Lu->^{176}Yb 0+ 1S-REC	0.055%	
^{176}Lu->^{176}Yb 2+ 2P-EC/REC	0.03%	0.45%
^{176}Lu->^{176}Yb 2+ 3S-REC	0.033%	
^{176}Lu->^{176}Yb 2+ nS-REC	0.04%	
^{176}Lu->^{176}Yb 2+ 3P-REC	0.03%	
^{176}Lu->^{176}Yb 2+ 3S/3P-EC	0.025%	
^{176}Lu->^{176}Yb 2+ 3D-EC	0.032%	
^{176}Lu->^{176}Yb 2+ 4S-EC	0.14%	
^{176}Lu->^{176}Yb 2+ (others)	0.22%	

Teaser: an hint for 4F -EC/REC capture:

4F REC would match the angular momentum requirements (ν s-wave)

We have no prediction for F-shell REC but a very soft energy spectrum expected (and E_b for 4F is neglibible)

186±81 events in 82 keV ROI

$\mathbf{B_{4F\ EC/REC} = 0.18\% \pm 0.08\%}$

2.3σ hint to be investigated in future measurements (it is a fragile excess…)